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Best Practices for Resilience Investment Benefit-Cost Analysis

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Abbreviations and Acronyms

Abbreviation	Term
AADT	average annual daily traffic
BCA	benefit-cost analysis
BIP	Bridge Investment Program
cfs	cubic feet per second
CMIP	Coupled Model Intercomparison Project
EMS	emergency medical services
EPA	Environmental Protection Agency
FEMA	Federal Emergency Management Administration
FHWA	Federal Highway Administration
FIRM	Flood Insurance Rate Maps
HAZUS	Hazards-United States
LRFD	Load and Resistance Factor Design
MOVES	Motor Vehicle Emission Simulator
mph	miles per hour
MSC	Map Service Center
NBI	National Bridge Inventory
NFHL	National Flood Hazard Layer
NOAA	National Oceanic and Atmospheric Administration
NWS	National Weather Service
OD	origin-destination
O&M	operation and maintenance
RAPT	Resilience Analysis and Planning Tool
RDR	Resilience and Disaster Recovery Tool Suite
SLOSH	Sea, Lake and Overland Surges from Hurricanes
TDM	Traffic Demand Model
U.S. DOT	United States Department of Transportation
USACE	United States Army Corps of Engineers
USGS	United States Geological Survey
VMT	vehicle miles traveled

1. Introduction

This document provides additional information and resources for analysts completing a benefit-cost analysis (BCA) for resilience investment. This resource expands on several topics covered in the U.S. Department of Transportation (U.S. DOT) *Benefit-Cost Analysis Guidance for Discretionary Grant Programs* (U.S. DOT BCA Guidance), but it does not supersede or have any effect on that resource (U.S. DOT 2025a). Readers are encouraged to read the U.S. DOT BCA Guidance before using this resource, as it provides a comprehensive and clear description of the fundamentals of BCA in transportation investments.

BCA for resilience investments presents additional challenges that analysts may be unfamiliar with, particularly how to translate project impacts into transportation impacts, explain the effects of hazardous events on the transportation system, identify hazard frequency data sources, and appropriately incorporate probability into a BCA. The purpose of this document is to provide information and resources to analysts to overcome these challenges. It discusses a wide range of topics, each of which may not be useful to all readers. Readers are encouraged to focus on sections that pertain to their analysis. The structure of the document and the purpose of each section are described below:

1) **Summary of Existing U.S. DOT BCA Guidance on Resilience**: This section provides the existing U.S. DOT BCA Guidance on incorporating resilience into BCAs for easy reference.
2) **Primer on Incorporating Resilience into Benefit-Cost Analysis**: Section 3.1 Developing Hazard Event Probability and Deriving Benefits and section 3.2 Changing Hazard Event Probability over the Period of Analysis provide a general discussion of economic theory for incorporating resilience into a BCA. These sections will be useful for readers who do not have a background in BCA and resilience investment return-on-investment evaluation generally. Section 3.3 Advanced Probability Topics provides information on topics in probability that are commonly encountered but may not apply to all projects. Each topic in section 3.3 clearly identifies when the topic area would apply so readers can identify sections that pertain to their project.
3) **Common Impacts and Benefits**: This section provides information on the seven common benefit categories for transportation resilience investments: avoided repair and replacement costs; avoided debris clean-up costs; avoided operations and maintenance costs; avoided travel time costs and external highway use costs; avoided fatalities and injuries due to adverse events; improved emergency response; and improved property values. Readers may want to familiarize themselves with each benefit category to better determine whether a category applies to their project. If analysts have already identified the benefits of the project, they may consult the relevant sections as needed.
4) **Common Natural Hazards Typology: Transportation Impacts and Data Resources**: This section describes the common direct transportation impacts and data resources for the following hazards: coastal and inland flooding; levee and dam failures; drought; wildfires; extreme temperatures; rockslides, landslides, mudslides, and avalanches; earthquake and volcanic activity; and extreme weather. Readers are encouraged to focus on hazards that pertain to their project.

5) **Other Resilience Project Resources:** This section provides other U.S. Department of Transportation or academic resources and tools for completing a BCA for resilience investment.
6) **Example Benefit Calculations**: This section provides example benefit calculations for each of the benefit categories listed in section 4 (except improved property values). The examples are intended to help readers understand common calculation approaches but may not capture all potential components or relevant details. The examples are not intended to be fully realistic. These examples are not a source of information for benefit parameters or project costs.

2. Existing U.S. DOT BCA Guidance on Resilience

Starting on page 30, the December 2025 version of the *U.S. DOT's Benefit-Cost Analysis Guidance for Discretionary Grants Programs* (U.S. DOT BCA Guidance) describes the following resilience considerations when calculating costs and benefits (U.S. DOT 2025a):

> *Some projects are aimed at improving the ability of transportation infrastructure to withstand adverse events such as severe weather, flooding, seismic activity, and other threats and vulnerabilities that can severely damage or even destroy transportation facilities. The resulting costs to users from lost access to the damaged facility (such as additional travel time and vehicle operating costs from detours or delays) or the costs of emergency maintenance or repairs to restore the facility can be significant, and improvements that mitigate those impacts can provide significant benefits through avoiding those costs. Under certain circumstances, natural or manmade hazards may necessitate mass evacuations of vulnerable areas, leading to excessive burdens on existing infrastructure.*
>
> *Incorporating resilience-related benefits into a BCA requires an understanding of both the expected frequency with which different levels of each stressor are expected to be experienced in the future, and the economic damages that different stressor levels are likely to inflict on specific infrastructure assets. This includes the anticipated frequencies of events such as extreme precipitation, seismic events, or coastal storm surges, as well as the range of potential severities of each event and the estimated cost of the resulting damages to specific assets, expressed as dollar figures.*
>
> *Benefits associated with increased resilience may be difficult to calculate due to the unpredictable occurrence of disruptive events, some of which could occur many decades in the future. Applicants may draw on previous experiences with facility outages to calculate the value of restricted infrastructure capacity or service outages, such as costs incurred by travelers when bridge capacity is reduced or if a facility is closed temporarily, and include those potential impacts in their estimates of the user benefits associated with the project. Hydrological and geological data and forecasts of the expected frequency or future incidence of flood and seismic events can also be an important source.[(1)] However, applicants should be careful to only consider the frequency and magnitude of those events in the area where the proposed improvement is to take place, rather than using frequencies that may apply to a much broader area. The frequency of the event should also be calculated as the expected probability of the disruptive event(s) occurring within a given year within the analysis period, producing a projected benefit stream of the improvement, rather than assuming that such events will occur with certainty at some point during the analysis period.*
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> ---
>
> *[(1)] The National Oceanic and Atmospheric Administration database on storm surges and floor risks is one possible tool that applicants could use to estimate flood risk potential. See* http://www.nhc.noaa.gov/surge/inundation/.

3. Primer on Incorporating Resilience into Benefit-Cost Analysis

This section provides additional background and information on important topics related to BCA for resilience projects, including probability, description of common benefits, and example calculations for common types of problems.

Sections 3.1 Developing Hazard Event Probability and Deriving Benefits and 3.2 Changing Hazard Event Probability over the Period of Analysis, provide a general discussion of economic theory for incorporating resilience into BCA. These sections will be useful for readers who do not have a background in BCA and resilience investment return-on-investment evaluation generally. Section 3.3 Advanced Probability Topics provides information on topics in probability that are commonly encountered but may not apply to all projects. Each topic in section 3.3 clearly identifies when the topic area would apply so readers can identify sections that pertain to their project.

Resilience investment analyses typically incorporate hazard probability to demonstrate benefits. However, for some analyses it may not be feasible to incorporate hazard probability explicitly into the BCA, or it may not be necessary to demonstrate the project benefits. For example, in cases where the analysis involves primarily operations and maintenance (O&M) investments that do not provide specific resilience benefits, the probability of future hazard events may not be required. For those projects, section 3 may not be applicable.

3.1 Developing Hazard Event Probability and Deriving Benefits

It can be challenging to incorporate hazard probabilities into a BCA. In a typical BCA, the analysis compares the outcomes of the baseline scenario (which represents the best forecast of future conditions described at an annual level without the project) compared to the build scenario in which the project is deployed, holding all else constant. BCAs for resilience projects use the same general approach but also need to consider the probabilistic chance of the adverse event, for which the consequences would be mitigated or prevented in the build case. The U.S. DOT BCA Guidance section on resilience suggests using the "Probability-Consequence" approach. This method treats the expected value (or risk) of the adverse event as a function of the probability of the event occurring and the consequences of that event.

Hazard data are typically provided as frequencies (i.e., how often a hazard event has occurred), but what is typically needed for a BCA is the annual probability, which is the annual chance that a hazard will occur. The annual probability or likelihood of occurrence is a key piece of information for a BCA because the analysis considers the total expected impacts over a range of future years in which the hazard event could occur.

Frequency data can often be translated into an annual probability by taking the historical number of hazard events or future event frequency (estimated based on a scientific or engineering study) and dividing over the sampled period. For example, if an extreme event happened 1 time in 100 years, the assumed annual probability would be 1 percent (1/100). Hazard events may be rare, occurring with low frequency over a longer period, or they may be common, occurring with high frequency over a few years or even multiple times per year (e.g., recurrent riverine flooding or tidal flooding in low-lying areas).[1]

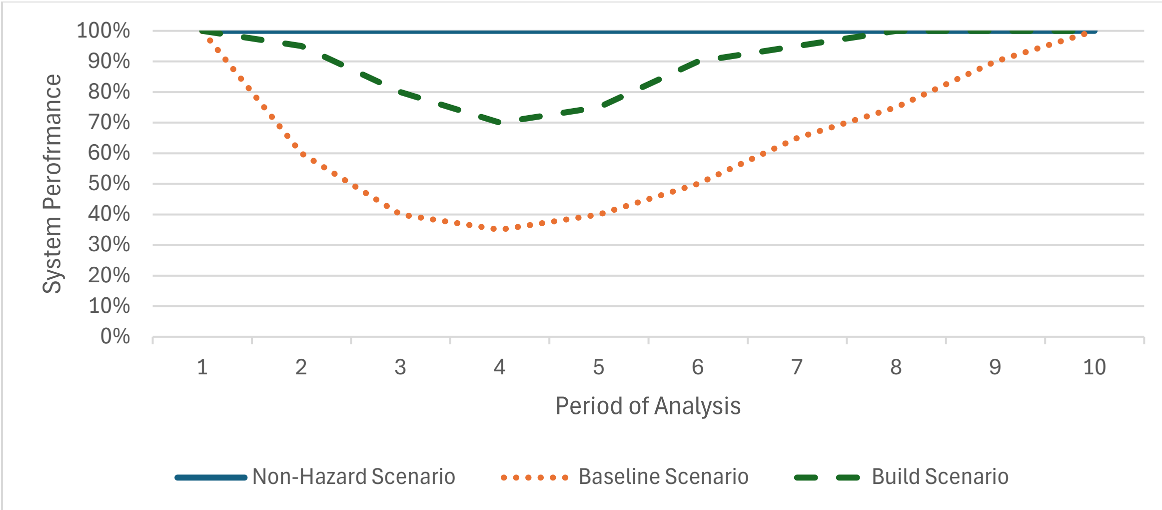
More advanced approaches may be necessary to translate frequency into probabilities, depending on the hazard type and context. Hazard events may become more frequent or more severe over time such that calculating the future annual probability may require more advanced statistical methods to determine how the event probability is expected to change. Similarly, advanced techniques may be needed for some hazards, such earthquakes, where the occurrence of the event may impact the probability of a future recurrence.

Within the BCA framework, apply probability to the benefits that are a result of the project mitigating or preventing the impact of the hazardous event. Do not apply hazard probability to the components of the project that generate benefits separate from the hazard, like improved safety through crash modification factors and improved amenities.

A typical approach is to select one magnitude or level of the adverse event magnitude to estimate benefits of the project in a BCA. For example, the analysis could focus on the project's ability to reduce the negative impacts of the 100-year flooding event in specific. That is, the analysis estimates the benefits of the project's ability to mitigate the impact of a 100-year storm event (an event with an annual probability of 1 percent) over the 30 years of the analysis period. There are several reasons for focusing the analysis on one adverse event magnitude. Data may not be available to estimate the expected frequency of multiple levels of the event (e.g., the best available flooding data for the facility only includes the 100-year flooding event), or the engineering assessment of the potential impact of multiple levels of adverse event may not be available (e.g., the only hydrological engineering study estimating the inundation of a facility is the 100-year flood event).

Generically, the resilience benefits of these projects come from their ability to reduce the effects of the hazard event on system performance (and/or asset condition) compared with the baseline. Figure 1 demonstrates this concept. The figure shows system performance, which could include travel times, safety outcomes, or other travel benefits, over the period when a given hazard event impacts the system (i.e., hours, days, weeks, months, etc.). In the non-hazard scenario, system performance is 100 percent during the entire period of analysis. System performance varies, but the graph assumes the average performance of the system without a hazard event is the full performance. During the baseline scenario, the hazard has a significant effect on system performance throughout the period of analysis; the system quickly deteriorates to only 35 percent of full performance and gradually recovers over time (e.g., in a case where a regional flood rises quickly and subsides over an extended period). In the build scenario, the overall impact to system performance is mitigated by the project and the system, limiting the lowest system performance to 70 percent and allowing recovery to full performance more quickly. The hazard impact demonstrated in this example is notional, and different hazard conditions will have different patterns of impact; e.g., there may not be a gradual recovery period.

[1] Rare events have low annual probabilities (e.g., 1 percent), while frequent events may have high annual probabilities (e.g., 80 percent), and events occurring multiple times a year are represented with annual probabilities greater than 100 percent (e.g., 300 percent, occurring three times annually).



Source: FHWA.

Figure 1. Notional resilience system performance.

3.2 Changing Hazard Event Probability over the Period of Analysis

In many cases, the annual probability of a hazard event may change over the period of analysis due to various factors. The severity of a hazard event for a given probability could become more severe (e.g., a 100-year storm becomes more severe), or a hazard event of a given severity could become more frequent (e.g., recurrent riverine flooding occurs several more days a year). Incorporate any changes in the probability and severity of the given hazard event into the analysis only when these changes are documented and well-supported. A clear demonstration of how to compute this in the flooding context is shown in Hydraulic Engineering Circular 7: Highways in the River Environment - Floodplains, Extreme Events, Risk, and Resilience, 2nd Edition on page 6-6 "Example: Computing Evolving Risk Over a Service Life" and the Hydraulic Engineering Circular 25: Highways in the Coastal Environment, 3rd Edition in chapter 9 on page 177 (Kilgore et al. 2016; Douglass and Webb 2019).

Generally, if a data resource provides an annual frequency/probability forecast that is non-constant over the life of the asset, this forecast can be used to generate the hazard probability for the analysis. Alternatively, use a linear interpolation if the data resource provides only the probability of occurrence in the current year and some future year (e.g., 2050).

3.3 Advanced Probability Topics

This section covers several additional topics in probability that an analyst may encounter. Some of these might be more useful for some hazard types and more complex projects where a simple probability × consequence approach does not adequately capture the expected benefits of the project.

Each section qualifies which types of projects or hazards the section may apply to ease review.

3.3.1 Expected Impact Conditional on the Hazard Event Occurrence

This section is useful for most projects that protect an asset from a probabilistic hazard risk.

The above discussion assumes that if a given hazard event with a given severity occurs (e.g., a 100-year flood event that causes traffic detouring due to flooding on the roadway), then the impact on the highway assets would be certain to occur. However, the impact of the hazard event on the transportation asset may be probabilistic. For instance, the impact of a 100-year storm event may only have a 75 percent probability of flooding that requires detour, with a 25 percent probability of flooding that does not require detouring.

Many factors can contribute to probabilistic impacts conditional on an event's occurrence, such as geography, duration of the event, degree of advanced warning, and preconditions that are probabilistic (prior precipitation in a season). Engineering studies may demonstrate a range of consequences on the asset given the hazard event. In those cases, incorporate the expected value of the impacts, which accounts for damage probabilities and consequences. For example, an engineering study may determine that a particular hazard event has an 80 percent chance of causing $0.1 million in damages and a 20 percent chance of causing $1.0 million in damages. The BCA would then use the probability weighted–estimated damage cost from this event, which in this case would be $0.28 million (0.8 × $0.1 + 0.2 × $1.0). This weighted damage cost would then be combined with the underlying probability of the event occurring and other parameters to calculate the project's benefits.

3.3.2 Alternative Probability Distributions

This section is useful for analysts with resilience projects where the risk of one event affects the risk of another, such as seismic risk.

The conventional approach to defining the probability of a hazard event of a uniform distribution may not be appropriate in all cases, particularly where the risk of future hazard events is not uniform but instead depends on prior events. For example, the occurrence of an earthquake may make future earthquakes somewhat less likely due to the dissipation of seismic energy. In these cases, consider more sophisticated models that rely on past events to generate annual event probability. In these cases, consult the support of a technical expert with experience calculating hazard event frequencies using historical data and other relevant factors.

Additionally, there are cases where the hazard event is expected to damage the asset to the extent that it requires reconstruction. In these cases, it is generally more appropriate to calculate the probability of the event using a binomial or similar probability distribution. These distributions more accurately account for the possibility of the hazard event not occurring at all. For example, consider an event that has a 2 percent annual probability of occurring if no prior event has occurred in the last 30 years. The simplified approach would in this case incorrectly suggest that there is a cumulative 60-percent chance of the event occurring during a typical 30-year BCA period, while a binomial distribution would imply only a roughly 45-percent chance ($1 - (1 - 0.02)^{30} = \sim 0.45$) of the event occurring at least once during the same period (Douglas and Webb 2020).[2] Conversely, it is also possible, albeit less likely, for the transportation asset to experience multiple hazard events of the same severity over a defined period. If the hazard events are independent, then use

[2] See Hydraulic Engineering Circular-25 - Highways in the Coastal Environment - 3rd Edition page 278 for derivation (Douglass and Webb 2019).

multiplication to combine all probabilities. If they are dependent, then estimate the conditional probabilities.

There are different approaches for calculating these alternative probability distributions. The list below includes some methodological resources for these different approaches:

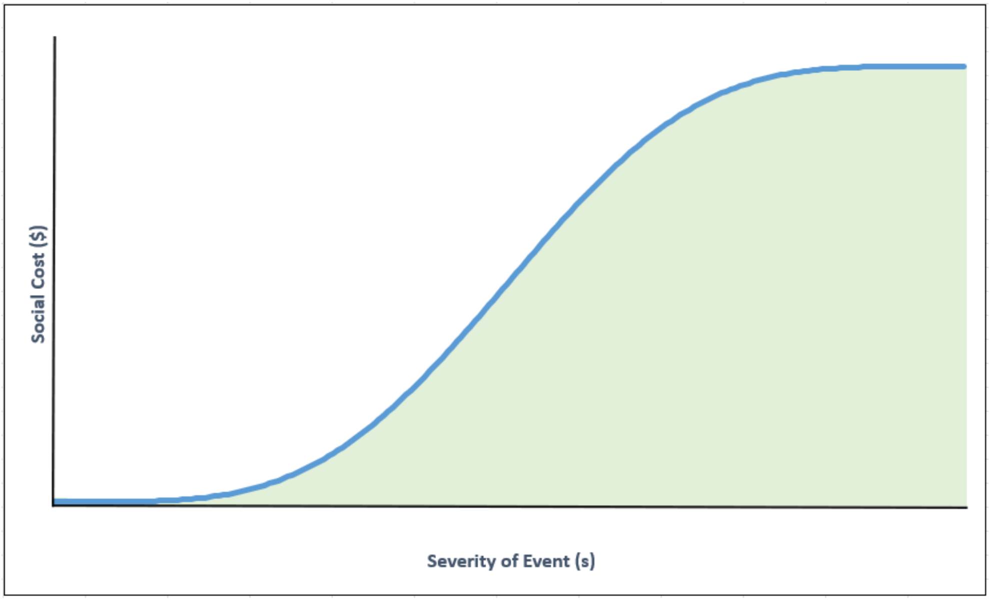
- USGS's Probabilistic Methodology for Estimation of Number and Economic Loss (Cost) of Future Landslides in the San Francisco Bay Region, California, which has a highly technical treatment of each probability distribution in the context of landslides (Crovelli and Coe 2008).
- FHWA's Load and Resistance Factor Design (LRFD) Seismic Analysis and Design of Bridges Reference Manual, which includes several sections on seismic hazard analysis including a discussion of probabilistic versus deterministic analysis methods (Marsh, Buckle, and Kavazanjian 2014).
- Defining and Measuring Economic Resilience from a Societal, Environmental and Security Perspective, which is a textbook that provides a treatment of both the relevant statistical background and the economic theory of measuring resilience benefits (Rose 2017).
- FHWA's Highway Hydrology: Hydraulic Design Series, Number 2, Second Edition, which gives treatments of different frequency and probability distributions. In particular, section 3.3.2 Risk Assessment discusses the binomial distribution (McCuen, Johnson, and Raga 2002).

3.3.3 Multiple Hazard Event Severities

This section is useful for projects that address different levels of hazard event risk where the analysis would be improved by demonstrating the benefits for those different hazard levels. For example, a project that mitigates a range of levels of flooding that would cause markedly different outcomes in the baseline in terms of detouring, asset damage, or loss of life.

Thus far this document has assumed that the analysis includes only one hazard severity level (e.g., a 100-year flood event, or a 1,000-year seismic event). However, most hazard types have a range of possible severities with varying effects on transportation infrastructure. A more complex analysis could attempt to capture the probability of all these events along with their corresponding social costs.

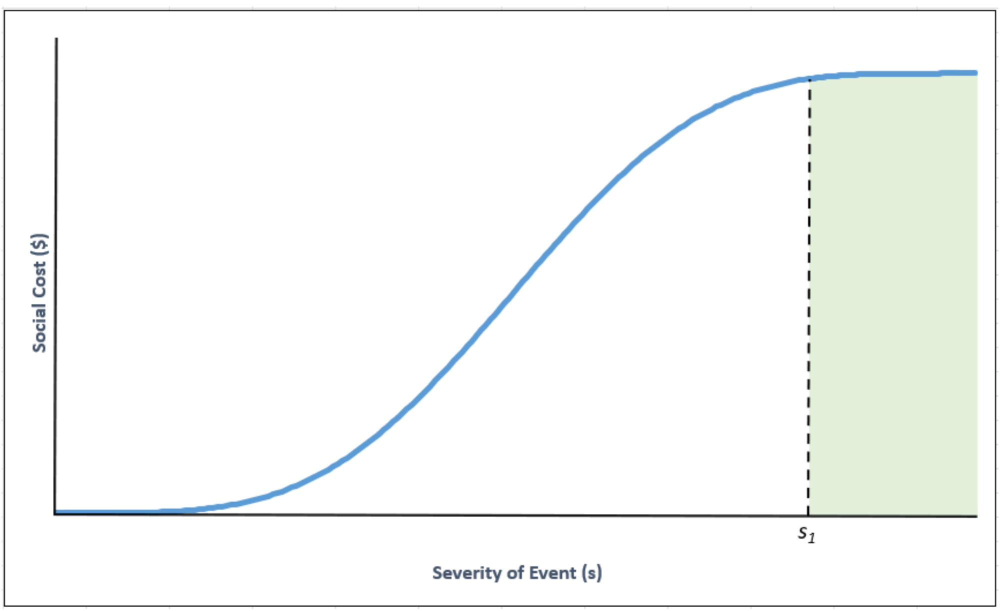
The impact of the total resilience benefit can be modeled as the relationship between the total impact that would occur without the resilience component and the severity of the hazard event. As the severity of the hazard event increases (e.g., the flooding depth increases, maximum structural (spectral) accelerations for a seismic event, etc.), the total impact generally increases as more transportation assets are damaged and travel is impacted (up to a theoretical maximum) as shown in figure 2 below. The area below the curve and up to any given hazard severity level represents the total social cost that would be prevented by a resilience project that could mitigate impacts for that hazard severity. The shaded area below the curve represents all the risk faced by the facility without any measure of resilience.



Source: FHWA.

Figure 2. Social cost of event in the baseline.

For instance, suppose a project is deployed that will mitigate seismic impacts for events up to and including level s_1, as shown in figure 3. The social benefits derived from the resilience investment would be the total area under the curve from 0 to s_1, which could be estimated using integration.[3]



Source: FHWA.

Figure 3. Social cost of event in the build scenario.

[3] This is a stylistic model where perfect information is available. In most cases, when attempting to quantify events with varying levels of severity, quantify only scenarios where sufficient engineering reports and probabilities are available. Additionally, be careful to not double count when quantifying different severity outcomes.

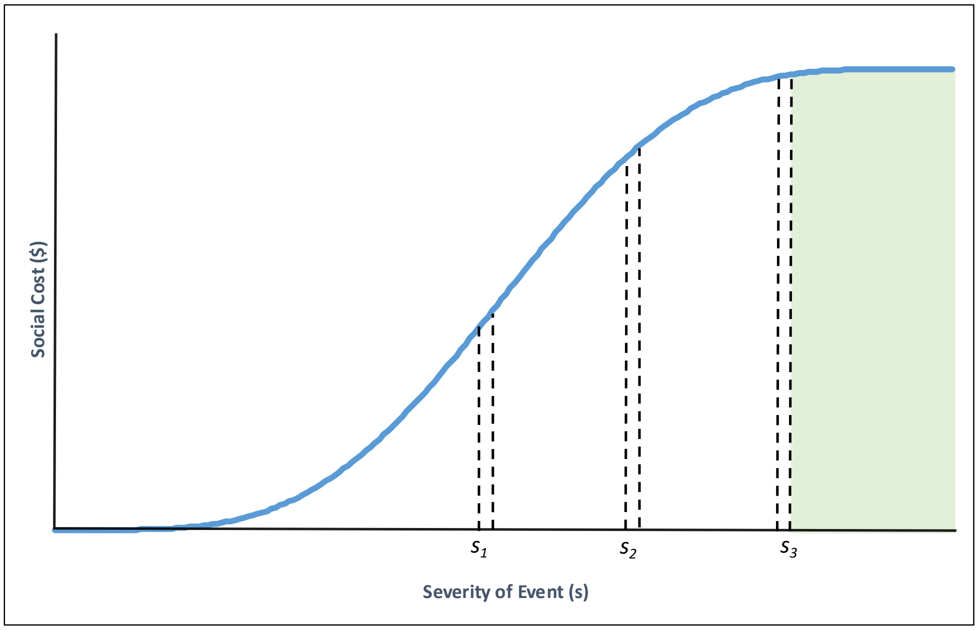
Practically, analyses that consider multiple hazard severities typically choose a limited number of hazard event severities and quantify the avoided costs at each level. An example of this methodology is in the Bridge Investment Program (BIP) BCA Tool (an overview of the tool is provided in section 6.1 of this document) (FHWA 2025a). The BIP BCA tool quantifies benefits at the following three levels (FHWA 2025b):

- ***"Closure, Traffic Restriction, or Load Restriction Only****: This consequence level refers to closure of the asset reducing some amount of capacity for at least one day a year but will not cause any structural damage requiring repair. Traffic restriction may occur when a lane or speed reduction is imposed on the bridge, or results from an onsite temporary detour. A load restriction occurs when a load posting is imposed (i.e., no trucks over a certain weight allowed). An example event that could cause this consequence is a recurring flood event that overtops the bridge or inundates roadways on approach to the bridge."*
- ***"Lesser Structural Damage (Level one)****: This consequence level can be any level of damage if it is correctly correlated with the appropriate event and its probability as supported in the application narrative or BCA memo. The user inputs the days of closure, travel reduction, and repair costs for both the build and baseline scenarios."*
- ***"Larger Structural Damage (Level two)****: This is a higher consequence level of damage to the bridge, which might cause fatalities or injuries on the structure itself. Alternatively, the number of fatalities or injuries could be left at zero to model a higher impact but less frequent event. Repair costs should restore the bridge to its condition and service life before the hazardous event. Per U.S. DOT BCA Guidance, the baseline scenario cannot include rebuilding the bridge, so any maintenance, repair, or operational costs under the larger structural damage consequence cannot amount to bridge reconstruction."*

To estimate these benefits, BIP tool users enter:

1) The annual probability of occurrence for each event severity for the first and last years of the benefit period.
2) The impact on travel for each hazard event severity level (including the days of closure or service disruption, the passenger/truck/bus/bike/ped volume capacity reduction).
3) The maintenance, repair, and operation costs.
4) The expected number of fatalities and injuries due to the hazard event impacting the bridge (e.g., if the larger structural damage to the bridge could cause fatalities and injuries).

Figure 4 represents the approach from the BIP tool that analysts can use to capture additional benefits of their resilience project. In the figure, the area under the curve to the left of s_3 represents the total benefits achieved by the project. The lines at s_1, s_2, and s_3, represent severity levels for Closure, Traffic Restriction, or Load Restriction Only, Lesser Structural Damage (Level One), and Larger Structural Damage (Level One). Benefits would be estimated for each of these levels. The event levels are represented as areas to capture the idea that each event level modeled represents some real share of the total risk faced rather than some fractional amount (i.e., we do not need to model a 99-year event, a 98-year event, a 97-year event, and so on, in order to have reasonably captured the benefits of the project). This approach captures more of the project's expected resilience benefits by estimating the benefits achieved at multiple hazard event severities.



Source: FHWA.

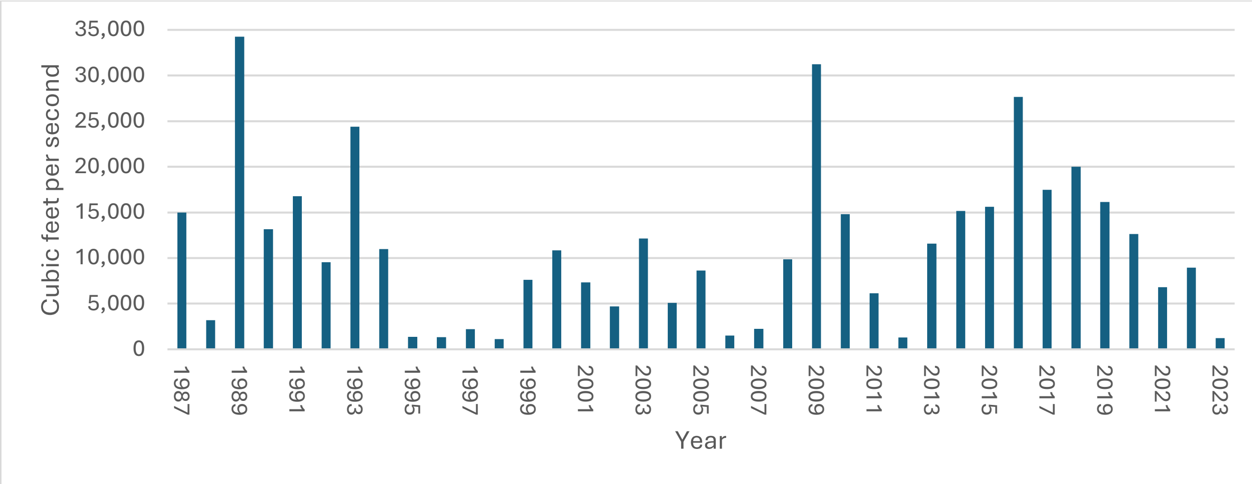
Figure 4. Social cost of event in the build scenario; three event severities.

3.3.4 Developing Hazard Event Probabilities for One or More Event Severities

This section is useful for projects where the hazard event(s) probability needs to be generated from historical data.

In most cases, analysts will have access to existing hazard event probability and severity data through Federal or State resources, e.g., Federal 100-year flood event data. In those cases, analysts only need the additional information on how a hazard event of that severity would impact the asset and travel from an engineering or similar study. However, in some cases an analyst will not have readily available hazard event probability and severity data and will need to calculate both using historical hazard event data. Similarly, analysts may want to estimate benefits for a project that mitigates a range of hazard events. In cases where the hazard probability and severity data are not available or are limited to a single event level that does not match the BCA need (e.g., 100-year flood event data are available, but 50- and 500-year event data are needed), calculate those event probabilities and severities based on historical data.

For an example of how to generate a hazard event probability and severity, the FHWA report Highways in the River Environment - Floodplains, Extreme Events, Risk, and Resilience, 2nd Edition showcases how to translate annual peak river flow to a storm flood probability curve that provides probabilities for different flood hazard event severity levels (Kilgore et al. 2017). Another FHWA resource with similar methodologies for seismic activity is the LRFD Seismic Analysis and Design of Transportation Geotechnical Features and Structural Foundations NHI Course No. 130094 Reference Manual Geotechnical Engineering Circular No. 3 (Kavazanjian et al. 2011). Figure 5 shows historical peak cubic feet per second (cfs) each year for a hypothetical river.



Source: FHWA.

Figure 5. Annual peak river flow, 1987-2023.

Using the data in figure 5, table 1 can be generated using the statistical methods outlined in the FHWA report [Highway Hydrology, Hydraulic Design Series No. 2, Second Edition (2002)] to produce a table of annual peak river flow by probability and return period, which can be used directly in the analysis when including multiple hazard event severities (McCuen, Johnson, and Ragan 2002).

Table 1. Probability, return period, and annual peak river flow.

Annual Peak River Flow (cfs)	Return Period (years)	Annual Probability of Occurrence
34,250	1,000	0.0010
27,650	500	0.0020
24,380	250	0.0040
21,350	100	0.0100
20,000	80	0.0125
18,780	75	0.0133
15,000	50	0.0200
12,643	25	0.0400
9,859	10	0.1000
6,133	5	0.2000
3,200	2	0.5000

cfs = cubic feet per second.

Whether using one or multiple hazard event levels, develop the best estimate of the consequences of the event at the given severity levels that will be incorporated into the analysis. After developing the probability and severity (annual peak river flow) in table 1, a transportation study could be used to determine the consequences of the events at different levels along the curve for use in the BCA. As an illustrative example, table 2 shows hypothetical event consequences for each annual peak river flow level. While the event consequences in this example are hypothetical, for real project analyses, carefully ensure event consequences are justified using an engineering study supported with historical data. Under 15,000 cfs, no impact is expected to the roadway or to travel. At

15,000 cfs, engineers anticipate there would be flooding on the roadway requiring detouring for 1 day. At 21,350 cfs, engineering assessment expects 2 days of detouring and lesser structural damage requiring repair. At 27,650 cfs, engineering assessment expects 5 days of detouring and greater structural damage requiring repair. At 34,250 cfs, engineering assessment determined the asset would be destroyed. In this case, the benefits can be calculated based on the project's ability to mitigate the hazard event consequences at peak river flow of 15,000, 21,350, and 27,650 cfs, and those benefits could be incorporated into the BCA.

Table 2. Probability, return period, annual peak river flow, and hazard event consequences.

Annual Peak River Flow (cubic feet per second)	Return Period (years)	Annual Probability of Occurrence	Event Consequence
34,250	1,000	0.0010	Destruction of asset[4]
27,650	500	0.0020	5 Days of Detouring, Greater Structural Damage
24,380	250	0.0040	Not Estimated
21,350	100	0.0100	2 Days of Detouring, Lesser Structural Damage
20,000	80	0.0125	Not Estimated
18,780	75	0.0133	Not Estimated
15,000	50	0.0200	1 Day of Detouring
12,643	25	0.0400	Not Estimated
9,859	10	0.1000	Not Estimated
6,133	5	0.2000	Not Estimated
3,200	2	0.5000	Not Estimated

Additional examples are provided below that demonstrate how analysts have successfully produced reasonable estimates of hazard probability and severity using historical data. These examples have been simplified and anonymized.

3.3.4.1 Example Approach #1

An FHWA grant applicant provided the time series of daily river stages from the U.S. Army Corps of Engineers (USACE), as partially shown in table 3, and then converted those results to a share of time spent at various stage levels relevant to their analysis, as shown in table 4 (USACE n.d.). The future probability of annual days spent at a given gage over the next 30 years was then assumed to be consistent with the 2000-2020 data; the applicant estimated benefits based on the probability and severity determined from this method.

[4] Note, per U.S. DOT BCA Guidance, in the event of destruction of the asset, it would not be an appropriate baseline to assume a reconstruction of the asset: "Baselines should not assume that the same (or similar) proposed improvement will be implemented later. For example, if the project applying for funding were to include the replacement of a deteriorating bridge, it would be incorrect for the baseline to include the same bridge replacement project occurring at a later date" (U.S. DOT 2025a, 10).

Table 3. Daily river stages, September 2000 to September 2020.

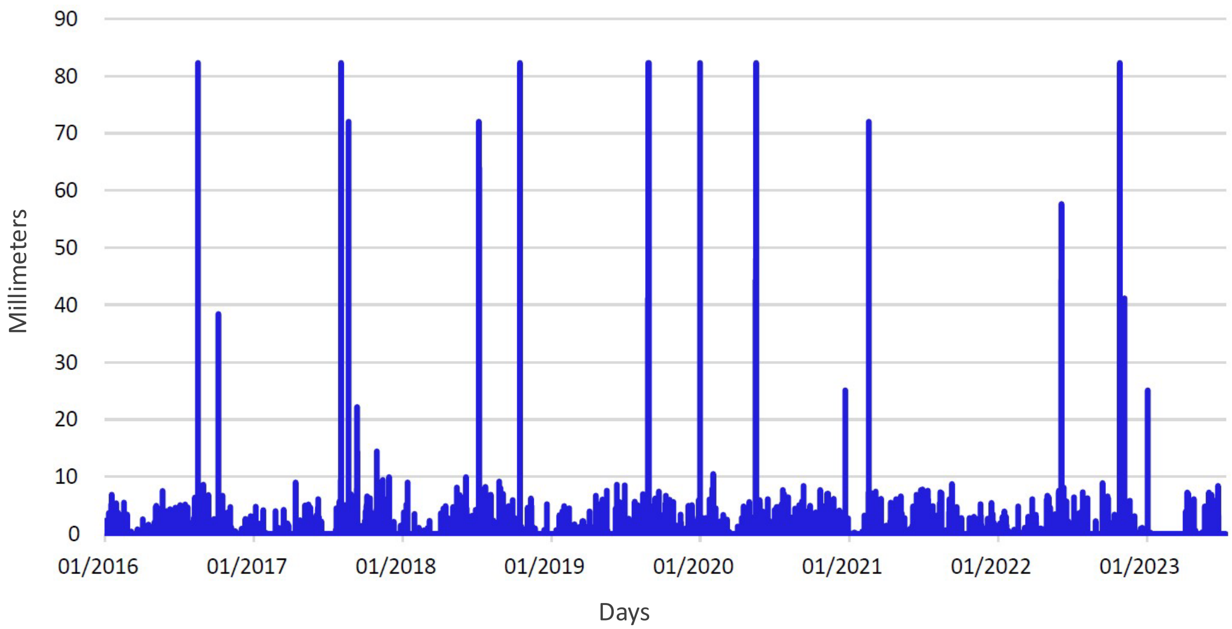
Date	Stage
2000-09-24	8.58
2000-09-25	9.34
2000-09-26	9.52
2000-09-27	10.1
2000-09-28	10.48
2000-09-29	10.98
...	...
2020-09-21	7.14
2020-09-22	6.83
2020-09-23	6.82
2020-09-24	6.13
2020-09-21	7.14

Table 4. Share of days at daily river stage thresholds, September 2000 to September 2020.

Stage	Days River at or Greater than Stage	Percentage of Total Days
14.5	450	12.36
15.5	313	8.60
16.5	203	5.58
17.5	116	3.19
18	95	2.61
19	61	1.68
19.5	47	1.29
20	39	1.07
21	11	0.30
22	4	0.11
23	0	0.00

3.3.4.2 Example Approach #2

Another applicant provided forecasts for different event levels and estimated the project's ability to reduce the impact to travel under those conditions. The event levels considered were severe flooding, which occurred every 10 years on average; moderate flooding, which occurred every 5 years on average; slight flooding, which occurred once annually on average; and King Tides, which occur twice a year. The probabilities of the severe and moderate flooding events were calculated based on historic rainfall data from 2016 through 2023, as shown in figure 6. On average, there was a daily rainfall event of approximately 80 mm once per year over this period, which led to a flooding event lasting 5 to 6 hours. The 5-year and 10-year events were based on historic events that occurred in the last 10 years as described by the applicant in the project description and BCA narrative.



Source: FHWA.

Figure 6. Daily rain rate, 2016-2023.

3.3.5 Multiple or Adjacent Facilities and Their Independent Probabilities

This section is useful in cases where the failure of an adjacent facility may impact the social cost of the project. For example, if the project improved the seismic resilience of a bridge, the seismic resilience of the primary detour is also relevant to the costs of the primary bridge closing.

For some projects, analysts will need to consider the impact of the hazard event on multiple assets. Some natural hazards will have widespread impacts throughout an area larger than the project, such as floods, earthquakes, and wildfires. These impacts would affect travel on different relevant assets, and those assets may be differently susceptible to a given hazard event. These cases include projects where the detour route has some probability of being affected by the hazard event. Typically, analyses focus on the direct impacts of the hazard event to the project asset, holding all else equal, but in the case of projects that deploy resilience investments to multiple assets, the broader impact to travel beyond the asset is a necessary component of the analysis.

In the case of multiple or adjacent facilities, assuming a hazard has the same probability of impact for all facilities may not be appropriate, i.e., bridges along the same river could use the same probability of failure only if that assumption can be demonstrated by engineering assessments. If the event would have a wider impact on the transportation network, then support this with additional engineering assessments for these other facilities. In the absence of these assessments, assume the most conservative scenario (conservative from a BCA perspective) in which only the facilities with sufficient engineering assessments are assumed to be impacted during the event.

To incorporate different probabilities of impact to different assets, develop a matrix of impacts based on the independent probabilities of these outcomes. To demonstrate this approach, assume there are two bridges crossing the same river: bridge A, the bridge receiving investments in the build case to be flood resilient, with an 80-percent chance of closing due to a 100-year flood event in the no-build scenario based on an engineering study supported by historical data, and bridge B, the detour route of bridge A, built more recently with improved resilience to flooding, with a 20-percent chance of closing due to a 100-year flood event based on a separate engineering study supported by historical data.

Analysts in this case would calculate the consequences of each outcome based on the probability of each outcome.

- To calculate the probability of both bridge A and B failing from the 100-year flood event, multiply the probabilities together: 80% × 20% = 16%.
- To calculate the probability of bridge A closing and bridge B remaining open, apply the same equation but use the opposite probability for bridge B: 80% × (100% − 20%) = 64%.
- To calculate the probability of bridge A remaining open and bridge B closing, multiply the following: 20% × 20% = 4%.
- The probability that neither bridge closes calculated as 20% × (100% − 20%) = 16%.

The probabilities of these separate outcomes add up to 100 percent, providing a comprehensive understanding of the likely consequences during an adverse event. Use the probabilities in conjunction with each scenario's costs, to determine the likely societal cost in the event of the 100-year flood event.

In the case where multiple assets are part of the project and where changes in travel on one asset may impact another, the best approach for capturing resilience benefits is to use a travel demand model (TDM) to project changes in travel due to the hazard and the project. TDMs are stylized models of travel on a regional roadway network that can estimate changes in travel patterns due to changes in the generalized cost of travel due to the hazard event.[5] If assets have different probabilities of failure under the same hazard, each combination of asset survivability outcome could be modeled in the TDM and aggregated by summation after applying the outcome's probability.[6] Consult with experts in engineering, travel modeling, and statistical modeling, if they are not already part of the analysis team, to ensure that impacts are captured appropriately. For example, hydraulic engineers have a better understanding of the statistics used for flood modeling, while geotechnical engineers have a better understanding of the statistics used for seismic modeling.

[5] For more information, see the FHWA resources on Travel Demand Modeling and Traffic Analysis Tools at https://www.fhwa.dot.gov/pgc/index.cfm?ddisc=95&dsub=1525.

[6] The Resilience and Disaster Recovery Tool assesses return on investment (including BCA) in the context of multiple projects or projects with a regional scope of impact. See https://volpeusdot.github.io/RDR-Public/ for more information.

4. Common Impacts and Benefits

To assess a resilience investment in BCA, analysts demonstrate how the project will improve conditions in the build scenario relative to the baseline scenario in which the project is not deployed. This section discusses common benefits from resilience projects, how they are often quantified, and mistakes that are often made.

4.1 Avoided Repair and Replacement Costs

These costs refer to repairing and/or replacing transportation infrastructure after the occurrence of the hazardous event. Analysis supports these costs with an engineering study of the damage caused by the event that reflects the timespan in which these repairs and replacements would occur. If the repair and replacement will take less than 1 year, multiply the probability of the disruptive event by the cost of repair and replacement to estimate the baseline annual cost. For example, if the repair and replacement cost for a disruptive event is $1 million with an annual probability of 10 percent, then the expected annual cost would be $0.1 million (0.1 × $1.0 million).

In some cases, the repair and replacements may occur over several years following an event. If the repair and replacement will take more than 1 year, analysts should consider the cost of repair and replacement in each year in addition to the cost of repair and replacement in that year if the disruptive event occurred in a previous year. For example, suppose the repair and replacement cost after a disruptive event is $1.0 million in the same year and $0.5 million in the second year after the event. The annual expected cost represented for a given year is the probability of the disruptive event in that year multiplied by $1.0 million plus the probability of the disruptive event having occurred in the previous year multiplied by $0.5 million.

Generally, the U.S. DOT BCA Guidance recommends against assuming that the same or similar improvements outlined in the build case will be implemented later in the baseline case. However, after a hazard event, it is likely that some reconstruction effort will be completed. Analysts should avoid assuming that the resilience elements of the project would be constructed in the baseline, as that would simply be a comparison of the proposed project being constructed sooner rather than later. Instead, assume that the minimum required reconstruction would be completed to resume safe operations on the damaged facility.

4.2 Avoided Debris Clean-Up Costs

These costs are all clean-up costs from a disruptive event—not associated with the reopening of the transportation infrastructure impacted by the event (which would be covered by avoided repair and replacement costs). These costs can range from damage to property, farmland, and environmental cleanup as well as many other costs that could come from damaged transportation infrastructure. This benefit category can be handled similarly to the avoided repair and replacement costs category with similar care taken around the duration of these costs (i.e., 1 year versus multiple years after the disruptive event).

4.3 Avoided Operations and Maintenance Costs

Many components of O&M costs are independent of the probability of the disruptive event occurring. The construction of new infrastructure that requires less maintenance will often reduce O&M costs compared to the baseline. This is covered in detail in the U.S. DOT BCA Guidance. However, for resilience projects, consider how the probability of the disruptive event impacts baseline operation and maintenance costs. Often, when a disruptive event occurs, standard annual O&M costs are not accurate, at least for the repair and reconstruction period. In addition, analysts should consider whether and how repair and reconstruction will impact future O&M costs.

To approach this, analysts should consider the likelihood that any given year within the analysis period is experiencing the different O&M costs possible. This dynamic is expressed more quantitatively in figure 7 below.

$$M_n = P(x) \times M_{dx} + F(x) \times M_{ax} + \big(1 - F(x) - P(x)\big) \times M_{bx}$$

Figure 7. Baseline O&M costs in the presence of a disruptive events.

Where:

- M = maintenance costs
  - n = baseline scenario
  - dx = during transportation infrastructure repair and replacement
  - ax = after the transportation infrastructure has been repaired or replaced
  - bx = before the transportation infrastructure has been or is currently being repaired or replaced
- $P(x)$ = annual probability the transportation infrastructure is being repaired or replaced currently
- $F(x)$ = cumulative probability the transportation infrastructure has been repaired or replaced previously[7]

Equation 1 is the estimated baseline O&M cost using the probability of the event occurring. It is simply the probability the transportation infrastructure is currently being repaired or replaced ($P(x)$), the probability the transportation infrastructure has been repaired or replaced ($F(x)$), and the probability the transportation infrastructure has not been or is currently being repaired or replaced ($\big(1 – F(x) – P(x)\big)$) multiplied by the O&M cost of each respective future scenario. The summation of the three probabilistic terms is 1, representing the three scenarios each future year could potentially realize.

In the case where the repair or replacement will take more than one year, a more complex approach for quantifying O&M may be more appropriate. In these cases, $P(x)$ would incorporate not just the probability of the event happening in a given year, but also in the years prior, which would lead to the given year still being in the repair or replacement period. Conversely, $F(x)$ would incorporate the cumulative probability up to the earliest year in which the disruptive event could happen and

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[7] The best approach for calculating cumulative probabilities is to use a binomial or Poisson distribution, as simply adding the probabilities naively assumes an event will happen with certainty (i.e., a 100-year flood *will* happen in 100 years).

impact the current analysis period. For example, if the repair or replacement period is 2 years, the cumulative probability would be taken from 3 years prior as if that were the last year in which the event could have occurred, which would place the current year in the post repair or replacement period.

4.4 Avoided Travel Time Costs and External Highway Use Costs

These avoided costs are from service disruptions on transportation infrastructure, often leading to increased travel time, operating costs, and external highway use costs. Natural hazards will often reduce capacity through a partial closure or full closure in extreme cases, where the capacity of the roadway is reduced, often by closing lanes or full road closures, in which case users will be required to detour around the facility. This section discusses both partial and full facility closures and the implications of each.

4.4.1 Capacity Reduction such as Partial Closure or Reductions in Speed

In a partial closure, the reduced capacity of the roadway will often lead to increased travel times and emissions that directly affect human health, which include sulfur oxides, nitrogen oxides, and fine particulate matter. The most appropriate way to estimate delays from a partial closure would be to model traffic under this scenario calculating the delays to traffic and increased emissions using a model such as the Environmental Protection Agency's (EPA) MOtor Vehicle Emission Simulator (MOVES) model (EPA 2025). When using this traffic model, consider that travel demand is not consistent throughout the day so be careful about assuming peak-period congestion would be experienced by all road users.

While congestion and emissions would likely increase, it would not be appropriate to attempt to use the U.S. DOT BCA Guidance (table A-4) vehicle miles traveled (VMT) costs to quantify external highway use costs (congestion, emissions, etc.) caused by capacity losses as these are only intended for increased VMT.[8] When estimating these costs, use vehicle miles traveled (VMT) benefits from the U.S. DOT BCA Guidance (table A-14) only in the context that the disruptive event has occurred. If properly estimated, the per-mile external highway use costs would be appropriate for quantifying the costs caused by user-initiated detours around the partial closure. As with previous benefit categories, analysts should carefully consider the duration of these costs (1 year versus multiple years after the disruptive event).

4.4.2 Full Closure with Detouring

In a full closure, users are required to detour around the facility, increasing both VMT and VHT. When estimating the average detour distance, the ideal approach is to conduct an origin-destination (OD) pair analysis to determine how facility users will likely detour. It is not reasonable to assume that users will detour from one end of the facility to the other end without proper explanation or reasoning as most users' origins and destinations will not be at the beginning and end of the facility. After constructing the likely detour route, analysts should carefully consider the non-detour route assumptions. For example, it would be incorrect to use an OD pair analysis for the

[8] Consider using EPA's MOVES model to estimate changes in emissions in such cases, as the distance traveled would not change in the build scenario relative to the no build scenario, but vehicle use (speed, acceleration, etc.) may change impacting vehicle emissions.

detour route but then compare those estimates to the VMT and travel time on the facility length alone. The non-detour route follows the same assumptions (ideally the same OD pair analysis) as the detour route to ensure a reasonable comparison. Some natural hazards might also impact potential detour routes (e.g., earthquakes or floods impacting multiple bridges on the same river). If this is the case, analysts should carefully consider each facility's probability of closure and how those probabilities interact (see section 3.3.5 for a more detailed discussion).

If proper traffic modeling is conducted, travel speeds on the detour can include increased congestion. In the absence of these more complex approaches, common navigational apps are usually sufficient at providing average speed along a route. Once the analyst has calculated the difference between the baseline VMT and VHT (considering the probability of the disruptive event) and the build case, they can apply the U.S. DOT BCA Guidance (tables A-2, A-3, A-4, and A-14) values to monetize these benefits. As with previous benefit categories, analysts should ensure the correct application of the duration of these costs (1 year versus multiple years after the disruptive event).

4.5 Avoided Fatalities and Injuries due to Adverse Events

This benefit is the result of users not being killed or injured on the facility during the adverse event due to the project. Using average annual daily traffic (AADT) estimates, occupancy rates, modal speeds, hazard duration, and facility length can produce a rough starting point for determining the number of users who would likely be on a facility during the event. However, these estimates are usually ambitious for most hazard types, so the analyst should consider carefully before using this initial estimate. While most, if not all, hazard types can happen quickly and without warnings, some come with advanced warnings (news releases, road signs, etc.) which would reduce traffic significantly before the hazard event, thus reducing the overall risk. The duration of the hazard can also greatly impact the number of impacted users. Use realistic assumptions about whether users would continue onto the facility when the hazard is apparent (during an earthquake, flood, wildfire, etc.). Additionally, the entire facility length may not fail, so ensure only at-risk parts of the facility are captured in this calculation.

In addition to the number of impacted users, a methodology is required to estimate the distribution of fatalities and injuries of those users. Carefully consider the risk profile across the facility and justify any fatality and injury distribution used. The resulting fatalities and injuries avoided in the build case can be monetized based on U.S. DOT BCA Guidance (table A-1).

4.6 Improved Emergency Response

This category refers to faster, more efficient emergency response in the build case where a facility would not have reduced capacity of closure during and due to the adverse event. Natural hazards can cause injuries across the greater project area, overwhelming emergency response staff and requiring rapid response times after the adverse event. When this is the case, a critical piece of transportation infrastructure can reduce response times leading to a reduction in injuries and fatalities. Post event, when a facility has capacity reduction or detours, emergency medical services (EMS) may take longer to respond to time-sensitive emergencies, like cardiac arrest, increasing the likelihood of death (Federal Emergency Management Agency (FEMA) 2023).

If an analyst is considering this benefit for their project, they should use a credible source for the increased risk of fatalities from reduced EMS response time for their chosen injury, the likelihood of the specific injury in the greater project area, as well as the delays EMTs would experience post adverse event. Also, analysts should carefully study the greater project area, including the locations of ambulance stations and hospitals. Monetize estimated reduced fatalities and injuries using U.S. DOT BCA Guidance (table A-1). As with previous benefit categories, the analyst should cautiously consider the assumptions around the duration of these costs (1 year versus multiple years after the disruptive event).

4.7 Improved Property Values

The U.S. DOT BCA Guidance discusses improved property values in detail and can be consulted before monetizing these benefits. In summary, the guidance discourages the use of property value increases, as these often reflect the capitalized value of benefits such as decreased travel times and improved amenities. It is preferable to quantify these benefits directly in the BCA rather than using an indirect measure such as property value increases. Including property value increases in addition to direct impacts would be double counting.

This benefit category may be included if the project reduces the risk of the natural hazard damaging property, therefore increasing its value, although it would generally be preferable to quantify the avoided repair costs directly (see section 4.2). For example, these benefits may be applicable for some nature-based solutions. Once the set of relevant properties is identified and the appropriate property value increase is calculated, analysts should include this as a one-time benefit rather than a stream of future benefits. The benefit would typically be realized only for the first year of the benefit-period after the completion of the relevant improvements, with discounting applied as described in the U.S. DOT BCA Guidance.

5. Common Natural Hazards Typology: Transportation Impacts and Data Resources

This section provides information on common natural hazards that resilience investments may be designed to address. Each section describes how the hazard event may impact highway facilities and performance and provides data resources for identifying hazard event frequency and severity (or magnitude). This information is generally presented from the BCA perspective and may not include all relevant engineering-related considerations and impacts, particularly with respect to potential damage to transportation assets from hazardous events.

Note: The data resources listed were available at the time of publication, but their capabilities may change in the future and/or become unavailable.

5.1 Coastal and Inland Flooding

Coastal and inland flooding are significant natural hazards that occur when excessive rainfall, storm surges, or rising water levels inundate areas that are typically dry. Information and resources for this hazard type include the following Coastal Flooding | National Risk Index; Inland Flooding | U.S. Resilience Toolkit; Riverine Flooding | National Risk Index; Flood | FEMA.gov (FEMA 2026a; National Oceanic and Atmospheric Administration (NOAA) n.d.-a; FEMA 2026a; FEMA 2020). Coastal flooding is often driven by high tides, hurricanes, or nor'easters, affecting low-lying coastal regions, while inland flooding typically results from heavy rainfall, rapid snowmelt, or the overflow of rivers and streams, impacting areas further from the coast. Both types of flooding can occur suddenly or develop gradually, depending on weather patterns and geographic features.

Floodwater can submerge roads, bridges, and railways, leading to closures that disrupt travel and isolate communities. Coastal flooding can also result in erosion and damage to infrastructure due to the force of waves and saltwater intrusion. Moisture trapped in bound and granular pavement can accelerate pavement damage, and heavy vehicles may also cause damage from surface deflections resulting from the moisture in the pavement and foundation layers (Nadkarni et al. 2024). Flooding caused by heavy precipitation can also cause sinkhole formation (U.S. Geological Survey (USGS) n.d.-a.). Floodwater that is quickly moving can cause bridge scour, which is the erosion of soil around the bridge foundation, and can eventually lead to bridge failure (Kattell and Eriksson 1998).

The common highway transportation benefit categories for resilience projects that mitigate or prevent impacts due to coastal or inland flooding include:

- Avoided repair and replacement costs
- Avoided debris clean-up costs
- Avoided operations and maintenance (O&M) costs
- Avoided travel costs and external highway use costs
  - Capacity reduction such as partial closure or reductions in speed
  - Full closure with detouring

- Avoided fatalities and injuries due to an adverse event, e.g., expected fatalities or injuries sustained due to bridge failure
- Improved emergency response
- Improved property values

Data resources available for coastal flooding and sea level rise include:

- FEMA Flood Data Viewers and Geospatial Data (FEMA 2025a). This site explains and links to two tools users can access to create Flood Insurance Rate Maps (FIRM) or their smaller version (FIRMette) export files that display floodplain information for a selected location. The tools are listed below and use the same FEMA source data.
    - FEMA Flood Map Service Center (MSC) is the official public source for flood hazard information produced in support of the National Flood Insurance Program (FEMA n.d.-a). Users can type in an address, and a page will load with options to download the floodplain map that is displayed on the page. The maps are complex but typically include areas with a 0.2 percent annual chance flood hazard, areas of 1 percent annual chance flood with average depth less than 1 foot or with drainage areas of less than 1 square mile, as well as future conditions of 1 percent annual chance of flood hazard.
    - FEMA's National Flood Hazard Layer (NFHL) Viewer is a geospatial database that contains current effective flood hazard data (FEMA 2024a). This site presents a global map for the user to explore, and users can also enter an address and print FIRM and FIRMette files, similar to the above MSC tool.
- Sea Level Rise Viewer (NOAA 2025). This resource (updated with regional sea level rise scenarios published in 2022) allows users to look up historic and future projected data on sea level rise for their region.
    - Users can review NOAA high tide gauges to find the number of historical major, moderate, and minor floods recorded at those gauges.
    - After clicking Get Started, a map will appear with five options on the left of the screen. Clicking High Tide Flooding will show tide gauges along the coast of the United States. Each gauge can be clicked on, which will pull up a graph of historical yearly inundation events from high tide. Users can choose between major, moderate, and minor flooding graphs.

- NASA Sea Level Projection Tool (National Aeronautics and Space Administration (NASA) n.d.-a). This tool allows users to visualize and download the sea level projection data from the IPCC 6th Assessment Report (AR6). The goal of this tool is to provide improved access and visualization to the consensus projections found in the report.
    - Users can select various points along the coastline (both US and globally) to see how much higher the sea level is projected to rise relative to the 1995-2024 baseline at that point.
    - The menu on the left allows the user to select the projected environmental process (Total Sea Level will usually be most useful for coastal flooding BCAs), projection year, and scenario level on which to base projections. Updating the map refreshes all the coastal points with the sea level change predicted under those conditions.

- NASA Flooding Analysis Tool (NASA n.d.-b). This tool provides data on observed flooding through 2020, projected flooding through 2050, and projected sea level rise through 2100. These projections are provided at various confidence intervals. Users can select several thresholds to filter historical flood data including National Weather Service (NWS) thresholds and a 100-year flood threshold.
  - Users can select various points along the U.S. coastline and select three different tabs of data: observed flooding, sea-level rise, or projected flooding. The observed flooding tab provides 100-year, 10-year, 2-year and 1-year flood level in feet under the extreme water levels section, and it provides the average observed flooding days in the section that includes data over the full record.
- NOAA Coastal Inundation Dashboard (NOAA n.d.-b). Links to more detailed coastal flooding data than the Sea Level Rise Viewer.
  - Users can click on a tide gauge that provides station details. Once in the tide gauge pages, users can click on the Inundation History page at the bottom left of the popup to see more options for that tide gauge. On this page, users can use the tabs to view the historical flood days, inundation frequency and duration, and exceedance probabilities to inform users how often high sea levels impact that specific gauge. This information can help determine how often transportation infrastructure in that area may be flooded.
- Hazard Exposure Reporting and Analytics (HERA) (USGS n.d.-b.). This resource is also similar to the FEMA flood maps and provides statistics on annual recurrence interval flood elevations. It provides costal storm hazard exposure forecasts for daily, annual, 20-year and 100-year storm events under different assumptions of sea level rise (up to 300 centimeters). Data are available for American Samoa, California, Florida, Georgia, Guam, Hawaii, Commonwealth of the Northern Mariana Islands, North Carolina, South Carolina, Virginia, and Washington. The model uses the USGS Coastal Storm Modeling System (CoSMoS) data set, which can be used to get more specific data (USGS 2021).
  - The main page opens to the map view. Users can select the locations and flood hazard details to update the map with hazard exposure based on the hazard scenario selected.
- National Hurricane Center Storm Surge Risk Maps (NOAA n.d.-c.). This resource depicts storm surge flooding vulnerability for hurricane-prone coastal areas and provides Storm Surge Risk Maps for the U.S. Gulf and East Coasts, Hawaii, Southern California, and the U.S. territories of Puerto Rico, U.S. Virgin Islands, Guam, and American Samoa. This resource uses the Sea, Lake and Overland Surges from Hurricanes (SLOSH) model which is a computerized numerical model developed by the NWS. The SLOSH model tends to be conservative relative to other forecasting tools.
  - This resource does not show the frequency or probability of the hurricane-induced storm surge each year, which would be needed for any hazard probability-based BCA calculations. However, users may be able to combine another resource that describes annual hurricane risk by category with this storm surge risk map to give a comprehensive picture on annual storm surge probabilities. Data on this page are available under the Data Availability and Download section.

- NOAA Storm Events Database (NOAA n.d.-d.). Users can search for reports of storms and floods, among other weather events, down to the county level to gather historical data for the project area. The data span from 1950 to 2024 and include many event types (see National Weather Service Directive 10-1605 (NWS 2016)) including coastal flooding, flash flood, lakeshore flood, flood, excessive heat, drought, extreme cold/wild chill, heavy rain, high wind, hurricane, tropical storm, tropical depression, wildfire, volcanic ash, winter storm, and winter weather. These historical records can be translated into annual probabilities of each respective event type.
- Coupled Model Intercomparison Project (CMIP) Processing Tool Version 2.1 (FHWA 2020). This tool is an FHWA product that processes readily available temperature and precipitation projections at the local level into relevant statistics for transportation planners. The tool accesses and calculates projections for temperature and precipitation variables; it can be used to develop projections for precipitation depths under future conditions and uses methods developed in National Cooperative Highway Research Program 15-61 (discussed below). Alternatively, more experienced users can access temperature and precipitation projections directly from the Downscaled CIMP3 and CIMP5 Projections for some future period for a localized area (Archive Collaborators 2025). It is relatively straightforward to use data, but there is a potentially steep learning curve to understand the differences between the various projections. Generally, CMIP data are a more advanced resource only recommended for users who have a strong understanding of the various forecasts that comprise the CMIP data. As an alternative, the CMIP6-LOCA2 Temperature and Precipitation Variables for Resilient Roadway Design from 1950-2100 for the Contiguous United States provides more up-to-date forecasts using similar methods to the CMIP Processing Tool data (Alder and Sharar-Salgado 2025).
- Resilience Analysis and Planning Tool (RAPT) (FEMA n.d.-b). The RAPT tool provides users with a single-entry point to access key risk assessment information for decision-making. RAPT has incorporated the National Risk Index (NRI) data, which includes historical data for hazards by state that can be downloaded by county or census tract in table format (FEMA 2026a). NRI data can also be downloaded through RAPT in geodatabase format or shapefile format. The NRI data provides annualized frequency for generic hazard events by category but may provide an appropriate hazard level and probability for some users. The data sources and methodology for the NRI's calculation of annualized frequency for each hazard is provided in the technical documentation (FEMA 2025b).

5.2 Levee and Dam Failures

Levee and dam failures occur when these structures, which are intended to control water flow and protect against flooding, fail due to factors such as overtopping, soil erosion, structural deficiencies, or extreme weather events. Even highly engineered structures can experience extraordinary conditions and possibly fail (Department of Homeland Security (DHS) 2018). These failures can lead to catastrophic flooding in adjacent areas, posing significant risks to human safety, property, and the environment. When dams and levee structures fail, they can unleash large volumes of water that inundate or damage roads and bridges, disrupting transportation networks and isolating communities. The sudden influx of water can also wash away critical components of infrastructure and lead to extensive damage that requires costly repairs and reconstruction.

Moreover, the subsequent erosion and sediment deposition can complicate recovery efforts and hinder access to affected areas.

The common highway transportation benefit categories for resilience projects that mitigate or prevent impacts due to levee and dam failure include:

- Avoided repair and replacement costs
- Avoided debris clean-up costs
- Avoided travel costs and external highway use costs
  - Capacity reduction such as partial closure or reductions in speed
  - Full closure with detouring
- Avoided fatalities and injuries due to an adverse event, e.g., expected fatalities or injuries sustained due to levee or dam failure
- Improved emergency response
- Improved property values

Data resources available for levee and dam failure risk include:

- National Levee Database Web Map (USACE 2024). This tool allows users to visualize the locations of levees and provides risk information. Reports on each levee or dam can be generated by using the map function or by searching for the facility by name or location (which also takes the user to the map view). Once identified, users can click on the levee or dam in the map, and a report will be generated if one is available. Flooding hazard data includes the historic loading by percentage of height of the dam or level, which could be used to determine risk. This database focuses on levees and aims to cover all levees in the United States but does not cover all dams.

5.3 Drought

A drought is a deficiency of precipitation over an extended period resulting in a water shortage (FEMA 2026a). Droughts often occur with extremely high temperatures, but not always (see section 5.5). Drought conditions can also be caused by human overuse of water.

The major impact of drought independent of high heat is subsidence, which occurs when the ground sinks due to groundwater removal (NOAA n.d.-e.). Subsidence can lead to deformation of the roadway such as introducing cracks or reducing pavement quality, and in some cases it leads to the formation of sinkholes (FEMA n.d.-a.). Subsidence and sinkholes can reduce the number of passable lanes or make the roadway impassable altogether. Rapid sinkhole formation can endanger travelers in real time and pose a danger if the roadway is open or traffic is unmanaged. Drought can impact water-based transportation routes or water-highway intermodal activity, or impact vegetation leading to slope erosion.

The common highway transportation benefit categories for resilience projects that mitigate or prevent impacts due to drought include:

- Avoided repair and replacement costs
- Avoided O&M costs
- Avoided travel costs and external highway use costs

    - Capacity reduction such as partial closure or reductions in speed
    - Full closure with detouring
- Avoided fatalities and injuries due to an adverse event; e.g., expected fatalities or injuries sustained due to sinkhole formation

Data resources available for drought risk include:

- NOAA Storm Events Database (NOAA n.d.-d.). See NOAA Storm Event database description in section 5.1. The event types include drought.
- CMIP Processing Tool Version 2.1 (FHWA 2020). See CMIP Processing Tool description in section 5.1. This resource could be used to project future precipitation which may affect drought risk.
- RAPT (FEMA n.d.-b). See the Resilience Analysis and Planning Tool description in section 5.1.

Long-term forecasts of droughts, soil moisture, and water table stability would need to be conducted locally for specific sites of concern.

5.4 Wildfires

Wildfires are uncontrolled fires that spread rapidly through vegetation, often exacerbated by dry conditions, high winds, and heat (FEMA 2026a). They can be ignited by natural causes such as lightning or by human activities like campfires and discarded cigarettes. Wildfires pose significant threats to ecosystems, air quality, and public safety, leading to evacuation orders and destruction of property. They can lead to the closure of roads and highways due to flames, smoke, and the risk of falling debris, which disrupts travel and emergency response efforts (Ram et al. 2025). Additionally, wildfires can damage bridges, tunnels, and other critical infrastructure, necessitating extensive repairs and preventive measures. Rain events following wildfires can lead to increased risk to flooding or debris flows, endangering downslope infrastructure (see section 5.6). The resulting air quality issues and road obstructions can further complicate transportation logistics. In addition to the direct impacts on transportation assets, wildfires can impact the risk of flooding or mud slides due to loss of vegetation, chemical changes in the soil, and soil erosion (USGS 2025a).

The common highway transportation benefit categories for resilience projects that mitigate or prevent impacts due to wildfires include:

- Avoided repair and replacement costs
- Avoided debris clean-up costs
- Avoided O&M costs
- Avoided travel costs and external highway use costs
    - Capacity reduction such as partial closure or reductions in speed
    - Full closure with detouring
- Avoided fatalities and injuries due to an adverse event; e.g., expected fatalities or injuries sustained due to bridge failure
- Improved emergency response
- Improved property values

Data resources available for wildfire risk include:

- NOAA Storm Events Database (NOAA n.d.-d.). See NOAA Storm Event database description in section 5.1. The event types include wildfire.
- Wildfire Risk to Communities (U.S. Department of Agriculture 2026). Allows users to view and compare the risk to homes, exposure type, wildfire likelihood, and vulnerable populations at the community, county, state, and national levels. Although the data are primarily oriented toward damage to homes rather than transportation assets, this resource could be used in combination with historical county level data (such as from the NOAA Storm Events Database) to assess whether a specific project area is highly likely to be impacted by wildfire occurring in the county.
- USGS Wildfire Hazard and Risk Assessment Clearinghouse (USGS n.d.-c.). Provides an inventory of links to national, regional, and state wildfire hazard and risk assessments. Includes links to assessment data when publicly available. Users can search by map/location or individual wildfire assessment that may provide frequency and severity information.
- The National Interagency Fire Center (NIFC n.d.). Provides historical data on wildland fires, boundaries, and fire progression which can be used to construct historical frequencies. Historical wildfire data can be found identified using the interactive map of historical fire perimeters. The data are downloadable, and data can be filtered by year, location or fire name.
- RAPT (FEMA n.d.-b). See the Resilience Analysis and Planning Tool description in section 5.1.

5.5 Extreme Temperatures

Extreme high or low temperatures can occur with one or more of the other hazard types described in this document, or independently of those other hazards. A heat wave is a period of abnormally and uncomfortably hot and unusually humid weather typically lasting two or more days with temperatures outside the historical averages for a given area (FEMA 2026a). Excessive heat can cause asphalt to soften, deform, or crack, or more generally cause road surfaces to buckle. Extreme heat can exacerbate drought conditions (see section 5.3) and contribute to wildfires (see section 5.4). Conversely, a cold wave is a rapid fall in temperature within 24 hours and extreme low temperatures for an extended period (FEMA 2026a). Cold waves can result in roadway surface or subsurface contraction and associated cracking, as well as frozen or damaged traffic signals and other equipment. Cold conditions also influence snowfall and ice accretion, which can cause roadway damage from de-icing salt and other treatments.

Extreme high and low temperatures place stress on bridges and other structures due to the expansion and contraction associated with temperature changes. Freeze-thaw cycles and other changes in temperature also contribute to potholes, frost heaves, and other damage to roadways.

The most common highway transportation benefit categories for resilience projects that mitigate or prevent impacts due to extreme temperatures include:

- Avoided repair and replacement costs
- Avoided O&M costs

- Avoided travel costs and external highway use costs
    - Capacity reduction such as partial closure or reductions in speed
    - Full closure with detouring

Data resources available for extreme temperatures include:

- CMIP Processing Tool Version 2.1 (FHWA 2020). See CMIP Processing Tool description in section 5.1. This tool is an FHWA product that processes readily available downscaled temperature and precipitation projections.
- NOAA Storm Events Database (NOAA n.d.-d.). See NOAA Storm Event database description in section 5.1. The event types include excessive heat and extreme cold/wild chill.
- RAPT (FEMA n.d.-b). See the Resilience Analysis and Planning Tool description in section 5.1.
- NOAA Mapping for Resilience and Adaptation Assessment Tool (NOAA n.d.-f.). Users can query for data at specific locations including projections of extreme heat days (days of heat index greater than 90, 100, and 105 degrees Fahrenheit).

5.6 Rockslides, Landslides, Mudslides, and Avalanches

Rockslides, landslides, mudslides, and avalanches are all phenomena characterized by the downward movement of materials on slopes due to gravity (FEMA 2026a). While they differ in their specific compositions and triggers—rockslides primarily involve the movement of rock masses, landslides encompass a broader range of material types, mudslides consist of saturated soil and debris, and avalanches consist of snow and ice—they share the common feature of destabilizing slopes and can occur rapidly, often with little warning. Slides can be exacerbated by increases in precipitation and flooding, especially after wildfires; and by increased temperatures where ice melt is a factor. These events can obstruct roads, railways, and bridges with debris, leading to closures and disruptions in travel, and some can even displace the transportation infrastructure.

The common highway transportation benefit categories for resilience projects that mitigate or prevent impacts due to rockslides, landslides, mudslides, and avalanches include:

- Avoided repair and replacement costs
- Avoided debris clean-up costs
- Avoided O&M costs
- Avoided travel costs and external highway use costs
    - Capacity reduction such as partial closure or reductions in speed
    - Full closure with detouring
- Avoided fatalities and injuries due to an adverse event; e.g., expected fatalities or injuries sustained due to landslides
- Improved emergency response
- Improved property values

Data resources available for rockslide, landslide, mudslide, and avalanche risk include:

- NASA's Landslide Viewer (NASA n.d.-c.). An online tool that visualizes landslide events using satellite imagery. It is used to evaluate historical landslides including their location, size, and contributing environmental factors. Landslide location is determined from both citizen reports and scanning satellite imagery. Data are only available between 2007 and 2018, but this resource could be used to generate an annual probability of landslides in a project area.

- U.S. Landslide Inventory and Susceptibility Map (USGS 2025b) - Contains both historical landslide information as well as a RASTER file measuring landslide susceptibility across the United States. This source can be overlapped with historical landslide frequency information gathered in other sources to assess if the project specific area is also likely to be impacted in the near future. For more information on the landslide susceptibility measure please see Mirus et al. 2024.
- Post-Fire Debris Flow Hazard Assessment Viewer (USGS n.d.-d.). Uses empirical models to estimate the likelihood and volume of debris flows at the drainage-basin scale and along drainage networks within each basin. The viewer displays results on a GIS-based map. This resource is for recent fires and provides risk information for the immediate term as areas recover from wildfire. Users can select specific wildfire events on the map to show potential mudslide impacts for given rainfall event levels.
- RAPT (FEMA n.d.-b.). See the Resilience Analysis and Planning Tool description in section 5.1.

5.7 Earthquake/Seismic Activity and Volcanic Activity

An earthquake is a shaking of the earth's surface by energy waves (seismic waves) emitted by slowly moving tectonic plates overcoming friction with one another underneath the earth's surface (FEMA 2026a). Earthquakes can damage highways, bridges, tunnels, and railways, leading to road closures and severe disruptions in travel and the movement of goods. Earthquakes can cause tsunamis, which can have devastating impacts on transportation infrastructure and take many lives, especially if evacuation routes are damaged from the preceding earthquake.

Volcanic activity occurs via vents that act as a conduit between the Earth's surface and inner layers. Volcanos erupt gas, molten rock, and volcanic ash when gas pressure and buoyancy drive molten rock upward and through zones of weakness in the Earth's crust (FEMA 2026a). Volcanic activity can result in ash clouds, lava flows, and pyroclastic flows. Similarly, volcanic eruptions can bury roads in ash, destroy transportation routes with lava flows, and create hazardous conditions due to falling ash that reduces visibility and affects vehicle operation. The consequences of both types of events can hinder emergency response efforts and travel.

The common highway transportation benefit categories for resilience projects that mitigate or prevent impacts due to earthquakes and volcanic activity include:

- Avoided repair and replacement costs
- Avoided debris clean-up costs
- Avoided O&M costs
- Avoided travel costs and external highway use costs
    - Capacity reduction such as partial closure or reductions in speed
    - Full closure with detouring

- Avoided fatalities and injuries due to an adverse event; e.g., expected fatalities or injuries sustained due to bridge failure
- Improved emergency response

Data resources available for earthquake and volcanic activity risk include:

- Earthquake Scenarios Web Tool (USGS n.d.-e). This tool displays nearly 800 earthquake scenarios derived from the National Seismic Hazard Model. Importantly, this is a predictive ShakeMap which contains the results of various earthquake scenarios, but it does not present the probability of each individual scenario occurring. This tool might be useful in determining impact if an earthquake's probability is already known.
- Volcano Hazards Program (USGS n.d.-f.). This tool shows the location and alert level (grouped into unassigned, normal, advisory, and watch) for 161 volcanoes in the United States. If a project area is anticipated to be within a volcano's vicinity, this resource also lists volcano specific research under the Volcano Hazards Assessments section.
- FEMA's HAZUS Program (FEMA 2026b). Provides standardized tools and data for estimating risk from earthquakes, floods, tsunamis, and hurricanes, though it is not recommended as a tool for estimating impacts to transportation. HAZUS models combine expertise from many disciplines to create actionable risk information that increases community resilience. This can be a key resource for seismic probability risk as HAZUS includes USGS's shake maps which can be used along with the tool's native probability information to produce seismic scenarios. See section 4 of the HAZUS 6.1 Earthquake technical manual for more information on the USGS data integrated into the HAZUS tool (FEMA 2024b).
- NOAA Storm Events Database (NOAA n.d.-d.) See NOAA Storm Event database description in section 5.1. The event types include volcanic ash.
- RAPT (FEMA n.d.-b.). See the Resilience Analysis and Planning Tool description in section 5.1.

5.8 Extreme Weather

Extreme weather for this typology encompasses all other extreme weather that may cause damage to highway assets or disruption to highway travel. This includes:

- Strong winds which could cause loss of power or damaging of traffic control devices, or could otherwise cause debris to block roadways, and in some cases damage bridges (FEMA 2025c).
- Lightning also poses risks to traffic control devices and power systems (Lightning | National Risk Index (FEMA 2025c).
- Ice, hail, and other wintery inclement weather that impacts the flow of travel and increases crash risk due to unsafe conditions (FEMA 2025c).

The common highway transportation benefit categories for resilience projects that mitigate or prevent impacts due to extreme weather include:

- Avoided debris clean-up costs and avoided repair costs for damaged roads, bridges, traffic control devices, and supporting power systems
- Avoided O&M costs

- Avoided travel costs and external highway use costs
    - Capacity reduction such as partial closure or reductions in speed
    - Full closure with detouring
- Avoided fatalities and injuries due to an adverse event; e.g., expected fatalities or injuries sustained due to ice-related crashes
- Improved emergency response

Data sources available for these risks include:

- NOAA Storm Prediction Center (NOAA/NWS 2026). This resource provides real-time severe thunderstorm forecast data and other storm prediction data collected by NOAA. It provides average weekly (the anticipated probability in any given week of the year, rather than a near-term forecast) probability maps for tornados, wind, and hailstorms based on a 30-year period from 1982 to 2011. This could be used to indicate risk to a project area with additional more project-specific information.
- NOAA Storm Events Database (NOAA n.d.-d.). See NOAA Storm Event database description in section 5.1. The event types include high wind, hurricane, tropical storm, tropical depression, winter storm, and winter weather.
- RAPT (FEMA n.d.-b.). See the Resilience Analysis and Planning Tool description in section 5.1.

6. Other Resilience Project Resources

6.1 Bridge Investment Program (BIP) BCA Tool

FHWA developed the Microsoft Excel-based Bridge Investment Program Benefit-Cost Analysis Tool (BIP BCA Tool) to help applicants for either BIP Bridge Projects or Large Bridge Project grants to summarize project costs and benefits, and to obtain data from the National Bridge Inventory (NBI) in preparation of the economic analysis required for both Bridge Project and Large Bridge Project applications (FHWA 2025). The tool is capable of handling U.S. DOT BCAs on any bridge contained within the National Bridge Inventory (NBI) and has built-in capability to handle resilience components of projects by including the probability and consequence of disasters at three different severity levels (discussed in section 3.3.3). The tool also makes it easy to consider and include many other benefits approved by the U.S. DOT.

Analysts with a bridge project may consider using the tool as it is U.S. DOT approved, follows U.S. DOT BCA methodology, and may lower the level of effort to complete the BCA. An NBI identifier will be required for the bridge in question and can be found on infobridge.fhwa.dot.gov. The latest tool along with frequently asked questions, user manual, and training video can be found at https://www.fhwa.dot.gov/bridge/bip/bca/.

6.2 Resilience and Disaster Recovery (RDR) Tool Suite

U.S. DOT developed the RDR Tool Suite (U.S. DOT 2025b) which allows analysts to assess transportation resilience return on investment for specific transportation assets over a range of potential future conditions and hazard scenarios, which can then be used as a consideration in existing project prioritization processes. The tool suite uses established robust decision-making concepts developed to build on current TDM analyses and addresses deeply uncertain future scenarios.

RDR is a good option if the proposed project is large enough or has multiple components that would have regional significance during a hazardous event, as it uses a TDM to estimate the impact of deploying the project on regional-level travel behavior. Projects that would otherwise primarily affect travel on a single roadway—particularly where the best detour route is a single path for most or all users—would not be best fit for this tool.

6.3 FEMA BCA Resources

FEMA has many BCA resources available on their website that are potentially relevant for analysts producing a resilience investment BCA. While these tools can aid in developing a sound BCA in general, it may not be appropriate in some contexts where it is not fully consistent with the U.S. DOT BCA Guidance. The FEMA tools use different monetization values than outlined in the U.S. DOT BCA Guidance and also incorporate transfer payments, which are otherwise not incorporated into a standard BCA approach. FEMA resources are useful when trying to monetize benefits not outlined in the U.S. DOT BCA Guidance and when those benefits are appropriate for the BCA purpose. Beyond the BCA monetization and calculations, the FEMA tool provides other helpful capabilities including the functionality to calculate recurrence intervals for some hazards, such as wildfires.

FEMA BCA resources are available on the Resources to Support Benefit-Cost Analysis web page (FEMA 2024c). If using multiple sources for benefit monetization, consider converting dollar values to the same dollar year used as the base year in your analysis.

7. Example Benefit Calculations

This section provides example calculations for each of the benefit categories described in section 3. The examples are intended only to demonstrate how benefits of each type are calculated, with consideration given to common issues for that benefit type. Each example benefit below includes a description of the hypothetical hazard event and the resilience component of the project to provide context for the calculations.

These examples are not meant to be realistic in terms of the probability and consequences of the hypothetical events, or to be realistic in terms of the potential for resilience investments to mitigate hazards at the given level. For simplicity, these examples consider only one benefit category at a time and do not present the full spectrum of benefits or compare total benefits against costs, as a full BCA would.

The approaches used in these examples could be used for any hazard type when the impact is relevant. The hazards are generically represented in the calculations by their impact on travel or facility condition and the annual probability of occurrence. Note that some values within the tables in this section have been rounded.

7.1 Avoided Repair and Replacement Costs

In this simplified example, a bridge is vulnerable to hurricanes. Based on available data, it is estimated that there is a 2-percent chance per year that hurricanes will damage a bridge, incurring a $30-million cost (in 2024 dollars) to repair the damage. The proposed project would strengthen the bridges to reduce the annual probability of hurricane damage to 1 percent.

The parameters for this scenario are as follows:

- Baseline risk of hurricane damage: 2 percent per year
- Build case risk of hurricane damage: 1 percent per year
- Repair cost: $30 million
- Discount rate: 7 percent (real)
- Discounting base year: 2024
- Dollar base year: 2024

The project to strengthen the bridge could be completed by the end of 2026, so 2027 is the first year of benefits. The strengthening would have a 30-year lifespan, after which the bridge would revert to baseline levels of risk. The annual baseline expected repair cost equals the repair cost of $30 million multiplied by the baseline damage probability of 2 percent, or $30,000,000 × 2% = $600,000. The annual build case expected repair cost equals the repair cost of $30 million multiplied by the build damage probability of 1%, or $30,000,000 × 2% = $300,000. The annual repair cost savings are therefore $300,000. The total discounted repair and replacement benefits of $3.2 million are derived by applying the relevant discount factor to each year's values, as shown in table 5, and summing across years.

Table 5. Example annual calculations of avoided repair costs.

Year	Repair Cost (2024 dollars)	Baseline Risk in this Year (percent)	Baseline Expected Repair Cost (2024 dollars)	Build Case Risk in this Year (percent)	Build Case Expected Repair Cost (2024 dollars)	Cost Savings (2024 dollars)	Discount Factor	Discounted Benefits (2024 dollars)
2027	30,000,000	2		1	300,000	300,000	0.816	244,889
2028	30,000,000	2	600,000	1	300,000	300,000	0.763	228,869
2029	30,000,000	2	600,000	1	300,000	300,000	0.713	213,896
2030	30,000,000	2	600,000	1	300,000	300,000	0.666	199,903
2031	30,000,000	2	600,000	1	300,000	300,000	0.623	186,825
2032	30,000,000	2	600,000	1	300,000	300,000	0.582	174,603
2033	30,000,000	2	600,000	1	300,000	300,000	0.544	163,180
2034	30,000,000	2	600,000	1	300,000	300,000	0.508	152,505
2035	30,000,000	2	600,000	1	300,000	300,000	0.475	142,528
2036	30,000,000	2	600,000	1	300,000	300,000	0.444	133,204
2037	30,000,000	2	600,000	1	300,000	300,000	0.415	124,489
2038	30,000,000	2	600,000	1	300,000	300,000	0.388	116,345
2039	30,000,000	2	600,000	1	300,000	300,000	0.362	108,734
2040	30,000,000	2	600,000	1	300,000	300,000	0.339	101,620
2041	30,000,000	2	600,000	1	300,000	300,000	0.317	94,972
2042	30,000,000	2	600,000	1	300,000	300,000	0.296	88,759
2043	30,000,000	2	600,000	1	300,000	300,000	0.277	82,952
2044	30,000,000	2	600,000	1	300,000	300,000	0.258	77,526
2045	30,000,000	2	600,000	1	300,000	300,000	0.242	72,454
2046	30,000,000	2	600,000	1	300,000	300,000	0.226	67,714
2047	30,000,000	2	600,000	1	300,000	300,000	0.211	63,284
2048	30,000,000	2	600,000	1	300,000	300,000	0.197	59,144
2049	30,000,000	2	600,000	1	300,000	300,000	0.184	55,275
2050	30,000,000	2	600,000	1	300,000	300,000	0.172	51,659
2051	30,000,000	2	600,000	1	300,000	300,000	0.161	48,279
2052	30,000,000	2	600,000	1	300,000	300,000	0.150	45,121
2053	30,000,000	2	600,000	1	300,000	300,000	0.141	42,169
2054	30,000,000	2	600,000	1	300,000	300,000	0.131	39,410
2055	30,000,000	2	600,000	1	300,000	300,000	0.123	36,832
2056	30,000,000	2	600,000	1	300,000	300,000	0.115	34,422
Total	N/A	N/A	N/A	N/A	N/A	N/A	N/A	3,251,562

N/A = not applicable.

7.2 Avoided Debris Clean-Up Costs

In this scenario, a bridge is vulnerable to destruction by natural disasters, with a 1 percent annual probability of destruction. Debris removal would cost $50 million (in 2024 dollars) if the bridge were destroyed, but the proposed project would eliminate the possibility of destruction for 30 years. For simplicity, only these debris removal costs are presented in the calculations below.

The parameters for this scenario are as follows:

- Baseline risk of destruction: 1 percent per year
- Build case risk of destruction: 0 percent per year[9]
- Repair cost: $50 million
- Discount rate: 7 percent (real)
- Discounting base year: 2024
- Dollar base year: 2024

The project could be completed by the end of 2026, so 2027 is the first year of benefits. The annual baseline expected clean-up cost equals the clean-up cost of $50 million multiplied by the baseline damage probability of 1 percent, or $50,000,000 × 1% = $500,000. The annual clean-up cost savings are therefore $500,000 because the project eliminates the risk of clean-up costs. The total discounted debris and clean-up benefits of $5.4 million are derived by applying the relevant discount factor to each year's values, as shown in table 6, and summing across years.

Table 6. Example annual calculations of avoided debris removal costs.

Year	Repair Cost (2024 dollars)	Baseline Damage Probability (percent)	Baseline Expected Repair Cost (2024 dollars)	Build Case Damage Probability (percent)	Build Case Expected Repair Cost (2024 dollars)	Cost Savings (2024 dollars)	Discount Factor	Discounted Benefits (2024 dollars)
2027	50,000,000	1	500,000	0	0	500,000	0.816	408,149
2028	50,000,000	1	500,000	0	0	500,000	0.763	381,448
2029	50,000,000	1	500,000	0	0	500,000	0.713	356,493
2030	50,000,000	1	500,000	0	0	500,000	0.666	333,171
2031	50,000,000	1	500,000	0	0	500,000	0.623	311,375
2032	50,000,000	1	500,000	0	0	500,000	0.582	291,005
2033	50,000,000	1	500,000	0	0	500,000	0.544	271,967
2034	50,000,000	1	500,000	0	0	500,000	0.508	254,175
2035	50,000,000	1	500,000	0	0	500,000	0.475	237,546
2036	50,000,000	1	500,000	0	0	500,000	0.444	222,006
2037	50,000,000	1	500,000	0	0	500,000	0.415	207,482
2038	50,000,000	1	500,000	0	0	500,000	0.388	193,909
2039	50,000,000	1	500,000	0	0	500,000	0.362	181,223
2040	50,000,000	1	500,000	0	0	500,000	0.339	169,367
2041	50,000,000	1	500,000	0	0	500,000	0.317	158,287
2042	50,000,000	1	500,000	0	0	500,000	0.296	147,932
2043	50,000,000	1	500,000	0	0	500,000	0.277	138,254
2044	50,000,000	1	500,000	0	0	500,000	0.258	129,210

[9] Realistically, resilience projects will not eliminate the probability of the impact of a given event level (particularly in cases when the event is significant and the project impact to the facility is serious), but in cases when the probability of impact is very small it can be treated as 0 percent for the purposes of simplifying the analysis.

Year	Repair Cost (2024 dollars)	Baseline Damage Probability (percent)	Baseline Expected Repair Cost (2024 dollars)	Build Case Damage Probability (percent)	Build Case Expected Repair Cost (2024 dollars)	Cost Savings (2024 dollars)	Discount Factor	Discounted Benefits (2024 dollars)
2045	50,000,000	1	500,000	0	0	500,000	0.242	120,757
2046	50,000,000	1	500,000	0	0	500,000	0.226	112,857
2047	50,000,000	1	500,000	0	0	500,000	0.211	105,473
2048	50,000,000	1	500,000	0	0	500,000	0.197	98,573
2049	50,000,000	1	500,000	0	0	500,000	0.184	92,125
2050	50,000,000	1	500,000	0	0	500,000	0.172	86,098
2051	50,000,000	1	500,000	0	0	500,000	0.161	80,465
2052	50,000,000	1	500,000	0	0	500,000	0.150	75,201
2053	50,000,000	1	500,000	0	0	500,000	0.141	70,281
2054	50,000,000	1	500,000	0	0	500,000	0.131	65,684
2055	50,000,000	1	500,000	0	0	500,000	0.123	61,387
2056	50,000,000	1	500,000	0	0	500,000	0.115	57,371
Total	N/A	N/A	N/A	N/A	N/A	N/A	N/A	5,419,271

N/A = not applicable.

7.3 Avoided Operations and Maintenance Costs

In this example, there is a 3 percent annual probability of a wildfire of a given severity occurring in the project area. Such an event will negatively impact the roadway and lead to higher future maintenance costs. Specifically, it is assumed that, based on an engineering study, a wildfire of that severity will result in damage to the asphalt pavement and cause increased annual O&M costs until a major reconstruction project is completed. Exposure to the wildfire at any point in the period of analysis would weaken the asphalt pavement, requiring costly routine maintenance for the remainder of the period of analysis. Per U.S. DOT BCA Guidance, the baseline should not assume the build project will be constructed at a later time, so the baseline does not assume the fire-resilient pavement reconstruction is completed after the wildfire, but rather that increased O&M costs are incurred each year instead. As a simplifying assumption, there is no surface reconstruction planned during the analysis period. In the build case, the roadway would instead be fully reconstructed with fire-resistant pavement, such that there would not be any increase in O&M costs even if a wildfire occurs.

The parameters for this scenario are as follows:

- Baseline risk of fire damage to roadway: 3 percent per year
- Build case risk of fire damage to roadway: 0 percent per year
- Baseline annual additional O&M cost after fire damage: $50,000
- Build case annual O&M cost: $0 (not impacted by fire damage)
- Discount rate: 7 percent (real)
- Discounting base year: 2024
- Dollar base year: 2024

The project could be completed by the end of 2026 and would have a 20-year lifespan. Baseline O&M costs reflect the cumulative probability of the wildfire occurring to account for the probability that the fire occurs in that year or any prior year of the benefit period. This cumulative probability was calculated using the binomial distribution discussed in section 3.3.2. The total discounted O&M benefits of $3.2 million are derived by applying the relevant discount factor to each year's values, as shown in table 7, and summing across years.

Table 7. Example annual calculations of avoided O&M costs.

Year	Additional Annual O&M Costs After Wildfire (2024 dollars)	Annual Wildfire Damage Risk Probability in Baseline (percent)	Cumulative Wildfire Damage Risk Probability in Baseline (percent)	Expected O&M Costs (2024 dollars)	Discount Factor	Discounted Benefits (2024 dollars)
2027	50,000	3	3	1,500	0.816	1,224
2028	50,000	3	6	2,955	0.763	2,255
2029	50,000	3	9	4,366	0.713	3,113
2030	50,000	3	11	5,735	0.666	3,820
2031	50,000	3	14	7,063	0.623	4,400
2032	50,000	3	17	8,351	0.582	4,861
2033	50,000	3	19	9,601	0.544	5,223
2034	50,000	3	22	10,813	0.508	5,493
2035	50,000	3	24	11,988	0.475	5,695
2036	50,000	3	26	13,129	0.444	5,829
2037	50,000	3	28	14,235	0.415	5,907
2038	50,000	3	31	15,308	0.388	5,939
2039	50,000	3	33	16,349	0.362	5,918
2040	50,000	3	35	17,358	0.339	5,884
2041	50,000	3	37	18,337	0.317	5,813
2042	50,000	3	39	19,287	0.296	5,709
2043	50,000	3	40	20,209	0.277	5,598
2044	50,000	3	42	21,102	0.258	5,444
2045	50,000	3	44	21,969	0.242	5,317
2046	50,000	3	46	22,810	0.226	5,155
Total	N/A	N/A	N/A	N/A	N/A	98,597

N/A = not applicable; O&M = operations and maintenance.

7.4 Avoided Travel Time Costs and External Highway Use Costs

7.4.1 Capacity Reduction such as Partial Closure or Reductions in Speed

In this simplified example, a bridge is vulnerable to hurricanes. Based on available data, it is estimated that there is a 2% annual probability of a hurricane of a given severity level. At that severity, an engineering study concludes would cause a given level of damage to the project bridge with a 100% probability. Damage to the bridge would require a 3-mile-long, 100-day work zone in which the speed limit would be reduced from the current 30 mph to 20 mph. The proposed project would strengthen the bridge to reduce the risk of damage to the bridge conditional on the hurricane occurring to 1 percent (2% × 100% × 0.5 = 1%). The bridge has an AADT of 24,000 light-duty vehicles. For simplicity, AADT is assumed to be the same for the build and no-build scenarios and with and without the work zone in place, and all vehicles are assumed to be non-commercial, light-duty vehicles.

The parameters for this scenario are as follows:

- Baseline risk of damage from hurricane: 2 percent per year
- Build risk of damage from hurricane: 1 percent per year
- Repair duration: 100 days
- Work zone length: 3 miles
- Normal speed limit: 30 mph
- Work zone speed limit: 20 mph
- Starting AADT: 24,000 light-duty vehicles
- AADT growth rate: 0 percent per year
- Discount rate: 7 percent (real)
- Discounting base year: 2024
- Dollar base year: 2024
- Average vehicle occupancy: 1.52 (U.S. DOT BCA Guidance)
- Travel time valuation: $21.80 per person-hour (U.S. DOT BCA Guidance)

The bridge area would normally be crossed in 0.1 hours (3 miles at 30 mph) and is crossed in 0.15 hours with the work zone speed limit in place (3 miles at 20 mph), so the work zone generates 0.05 hours of delay per vehicle trip. The baseline expected number of delayed vehicle-hours per year is 2% × 100 × 0.05 × 24,000 = 2,400, and in the build scenario the expected number of delayed trips per year is 1% × 100 × 0.05 × 24,000 = 1,200. The expected number of vehicle hours saved per year is therefore 1,200. When adjusting for average vehicle occupancy and applying the value of travel time per person-hour, the expected benefit (i.e., the value of the avoided travel time cost per year is 1,200 × 1.52 × $21.80 = $39,763). The total discounted travel time costs and external highway use benefits of $0.4 million are derived by applying the relevant discount factor to each year's values, as shown in table 8, and summing across years.

Table 8. Example annual calculations of avoided operations and maintenance costs.

Year	AADT	Partial Closure Delay per Vehicle	Partial Closure Days	Baseline Damage Probability (percent)	Baseline Delay VHT	Build Damage Probability (percent)	Build Delay VHT	Time Cost Savings (2024 dollars)	Discount Factor	Discounted Benefits (2024 dollars)
2027	24,000	0.05	100	2	2,400	1	1,200	39,763	0.816	32,447
2028	24,000	0.05	100	2	2,400	1	1,200	39,763	0.763	30,339
2029	24,000	0.05	100	2	2,400	1	1,200	39,763	0.713	28,351
2030	24,000	0.05	100	2	2,400	1	1,200	39,763	0.666	26,482
2031	24,000	0.05	100	2	2,400	1	1,200	39,763	0.623	24,772
2032	24,000	0.05	100	2	2,400	1	1,200	39,763	0.582	23,142

Year	AADT	Partial Closure Delay per Vehicle	Partial Closure Days	Baseline Damage Probability (percent)	Baseline Delay VHT	Build Damage Probability (percent)	Build Delay VHT	Time Cost Savings (2024 dollars)	Discount Factor	Discounted Benefits (2024 dollars)
2033	24,000	0.05	100	2	2,400	1	1,200	39,763	0.544	21,631
2034	24,000	0.05	100	2	2,400	1	1,200	39,763	0.508	20,200
2035	24,000	0.05	100	2	2,400	1	1,200	39,763	0.475	18,888
2036	24,000	0.05	100	2	2,400	1	1,200	39,763	0.444	17,655
2037	24,000	0.05	100	2	2,400	1	1,200	39,763	0.415	16,502
2038	24,000	0.05	100	2	2,400	1	1,200	39,763	0.388	15,428
2039	24,000	0.05	100	2	2,400	1	1,200	39,763	0.362	14,394
2040	24,000	0.05	100	2	2,400	1	1,200	39,763	0.339	13,480
2041	24,000	0.05	100	2	2,400	1	1,200	39,763	0.317	12,605
2042	24,000	0.05	100	2	2,400	1	1,200	39,763	0.296	11,770
2043	24,000	0.05	100	2	2,400	1	1,200	39,763	0.277	11,014
2044	24,000	0.05	100	2	2,400	1	1,200	39,763	0.258	10,259
2045	24,000	0.05	100	2	2,400	1	1,200	39,763	0.242	9,623
2046	24,000	0.05	100	2	2,400	1	1,200	39,763	0.226	8,986
2047	24,000	0.05	100	2	2,400	1	1,200	39,763	0.211	8,390
2048	24,000	0.05	100	2	2,400	1	1,200	39,763	0.197	7,833
2049	24,000	0.05	100	2	2,400	1	1,200	39,763	0.184	7,316
2050	24,000	0.05	100	2	2,400	1	1,200	39,763	0.172	6,839
2051	24,000	0.05	100	2	2,400	1	1,200	39,763	0.161	6,402
2052	24,000	0.05	100	2	2,400	1	1,200	39,763	0.15	5,964
2053	24,000	0.05	100	2	2,400	1	1,200	39,763	0.141	5,607
2054	24,000	0.05	100	2	2,400	1	1,200	39,763	0.131	5,209
2055	24,000	0.05	100	2	2,400	1	1,200	39,763	0.123	4,891
2056	24,000	0.05	100	2	2,400	1	1,200	39,763	0.115	4,573
Total	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	430,993

AADT = average annual daily traffic; N/A = not applicable; VHT = vehicle hours traveled.

7.4.2 Full Closure with Detouring

In this simplified example, a roadway is subject to periodic flooding during heavy rains and high tides. Based on available data, it is estimated that there is a 1-percent chance per year that the flood rises to the level where the road is not safely passable, with these conditions remaining in place for a period of 6 days. In the baseline, all users will detour during these closure periods. In the build case, there is still a 1-percent chance of flooding closing the road, but the project makes the roadway more resilient (e.g., with a higher profile), significantly reducing the associated road closure to only 1 day per event. The build case yields benefits from avoided detour time and other detour costs (vehicle operating costs, crash costs, and avoided congestion and other externalities). The benefits of the project are the difference in detour costs between the build and baseline scenarios over a 20-year project lifespan.

The parameters for this scenario are as follows:

- 2027 AADT: 1,000 (for simplicity, all vehicles are assumed to be light-duty vehicles)
- AADT growth rate: 1 percent per year
- Days of detouring, no-build: 6 days per adverse flooding event
- Days of detouring, build: 1 days per adverse flooding event
- Risk of adverse flooding event: 1 percent per year
- Roadway distance: 2 miles
- Average detour distance: 12 miles
- Net detour distance: 10 miles
- Average speed (regular route and detour route): 25 mph
- Average vehicle occupancy: 1.52 (U.S. DOT BCA Guidance)
- Travel time valuation: $21.80 per person-hour (U.S. DOT BCA Guidance)
- Discount rate: 7 percent (real)
- Discounting base year: 2024
- Dollar base year: 2024
- Monetization factors per VMT (U.S. DOT BCA Guidance):
    - Light-duty vehicles urban congestion cost: $0.147
    - Light-duty vehicles urban noise cost: $0.0021
    - Light-duty vehicles urban safety cost: $0.19 (this is the total social safety cost per mile, both internal and external, calculated by dividing the external safety cost of $0.019 by the 10% external cost share from footnote 25)
    - Light-duty vehicles urban emission cost: $0.013
    - Vehicle operating costs: $0.56

AADT in a given future year is equal to the prior year's AADT, adjusted for the 1 percent annual growth rate. The partial mitigation is incorporated into the analysis by comparing the days of detouring between the baseline and project case. Avoided detour mileage equals AADT multiplied by the number of days per year that detouring would be in effect (i.e., 6) minus the days of detouring that still occur during the event (i.e., 1) multiplied by the net detour mileage (i.e., 10). In the first year, this yields a total of 50,000 VMT of avoided detour mileage in the build scenario. The cost of each avoided detour VMT is equal to the sum of estimated direct vehicle operating and safety costs plus the costs of externalities from congestion, noise, and emissions, which together are $0.9121/VMT. When applied to the first year's avoided detour mileage estimate, this yields $45,605 in detour costs. The time costs of the avoided detour can be estimated using the avoided detour mileage and the estimated speed of 25 mph, yielding 2,000 vehicle-hours of detour travel. When adjusting for average vehicle occupancy and applying the value of travel time per person-hour, the detour time cost in the first year is $66,272 (2000 × 1.52 × $21.80). Total avoided detour costs are thus $45,605 + $66,272 = $111,877. However, this value needs to be adjusted for the annual likelihood of the flooding event occurring, which is 1 percent, yielding a risk-adjusted value of $1,119.

The build case would avoid detours and associated costs for the 5 days of the event. The calculated risk-adjusted values represent the undiscounted benefits of the build case relative to the baseline case in each year. The total discounted, avoided full closure, and detour benefits of $0.01 million are derived by applying the relevant discount factor to each year's values, as shown in table 9, and summing across years.

Table 9. Example annual calculations of full closure with detouring.

Year	AADT	Avoided Detour VMT	Costs of Avoided Detour VMT (2024 dollars)	Avoided Detour VHT	Costs of Detour VHT (2024 dollars)	Total Avoided Detour Benefits* (2024 dollars)	Flood Risk in this Year (percent)	Benefits Adjusted for Probability (2024 dollars)	Discount Factor	Discounted Benefits (2024 dollars)
2027	1,000	50,000	45,605	2,000	66,272	111,877	1	1,119	0.816	913
2028	1,010	50,500	46,061	2,020	66,935	112,996	1	1,130	0.763	862
2029	1,020	51,005	46,522	2,040	67,597	114,119	1	1,141	0.713	814
2030	1,030	51,515	46,987	2,061	68,293	115,280	1	1,153	0.666	768
2031	1,041	52,030	47,457	2,081	68,956	116,413	1	1,164	0.623	725
2032	1,051	52,551	47,932	2,102	69,652	117,584	1	1,176	0.582	684
2033	1,062	53,076	48,411	2,123	70,348	118,758	1	1,188	0.544	646
2034	1,072	53,607	48,895	2,144	71,044	119,939	1	1,199	0.508	609
2035	1,083	54,143	49,384	2,166	71,773	121,156	1	1,212	0.475	575
2036	1,094	54,684	49,877	2,187	72,468	122,346	1	1,223	0.444	543
2037	1,105	55,231	50,376	2,209	73,197	123,574	1	1,236	0.415	513
2038	1,116	55,783	50,880	2,231	73,926	124,806	1	1,248	0.388	484
2039	1,127	56,341	51,389	2,254	74,689	126,077	1	1,261	0.362	456
2040	1,138	56,905	51,903	2,276	75,418	127,321	1	1,273	0.339	432
2041	1,149	57,474	52,422	2,299	76,180	128,602	1	1,286	0.317	408
2042	1,161	58,048	52,946	2,322	76,942	129,887	1	1,299	0.296	384
2043	1,173	58,629	53,476	2,345	77,704	131,179	1	1,312	0.277	363
2044	1,184	59,215	54,010	2,369	78,499	132,509	1	1,325	0.258	342
2045	1,196	59,807	54,550	2,392	79,261	133,811	1	1,338	0.242	324
2046	1,208	60,405	55,095	2,416	80,057	135,152	1	1,352	0.226	305
Total	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	$11,152

* Time and mileage.
AADT = average annual daily traffic; N/A = not applicable; VMT = vehicle miles traveled; VHT = vehicle hours traveled.

7.5 Avoided Fatalities and Injuries due to Adverse Events

This example is based on a 1.56-mile double-decker freeway segment that is vulnerable to collapsing in an earthquake, with a 0.1 percent annual risk of collapse (that is, a 0.1 percent annual probability of an earthquake at a given severity, which, at that severity level, will cause the deck to collapse with 100-percent probability). If a collapse occurs, vehicles on the upper deck may crash and vehicles on the lower deck may be crushed by the collapsing upper deck, exposing vehicle occupants to the risk of injuries and fatalities. The AADT of the freeway is 100,000 passenger vehicles, and its average speed is 65 mph.

It is expected that occupants on the freeway segment at the start of an earthquake that leads to facility collapse may be injured (60-percent probability of an injury of unknown severity) or killed

(20-percent probability), but that there is no risk of death or injury for occupants who are not on the freeway segment at the beginning of an earthquake. In the build scenario, the upper deck is improved with a seismic resilience investment. The project would prevent full collapse of the deck, but some debris may still fall, causing some injuries and fatalities. The project has a 30-year lifespan and eliminates the risk of the facility collapsing starting in 2027. The resilience improvement would not change the geometry of the roadway or address other traffic safety risks, such as those related to speeding or inattention.

The parameters for this scenario are as follows:

- Starting AADT: 100,000 (for simplicity, all vehicles are assumed to be light-duty vehicles)
- AADT growth rate: 0 percent per year
- Baseline annual risk of collapse due to earthquake: 0.1 percent per year
- Build case annual risk of falling debris due to earthquake: 0.1 percent per year
- Segment length: 1.56 miles
- Average speed: 65 mph
- Average vehicle occupancy: 1.52 (U.S. DOT BCA Guidance)
- Fatality valuation: $13,700,000 (U.S. DOT BCA Guidance)
- Injury valuation (unknown severity): $238,500 (U.S. DOT BCA Guidance)
- Discount rate: 7 percent (real)
- Discounting base year: 2024
- Dollar base year: 2024

The freeway segment's length and speed imply that a vehicle takes approximately 0.024 hours to cross it (1.56 mi ÷ 65 mph). Thus, on average, the freeway segment is occupied by 0.1 percent of its daily traffic at any moment (0.024 ÷ 24), which corresponds to approximately 100 vehicles (0.1% × 100,000). Based on the BCA guidance occupancy rates, 100 vehicles correspond to 100 × 1.52 = 152 occupants. If a collapse occurs, the expected number of fatalities is 20% × 152 = 30.4, and the expected number of injuries is 60% × 152 = 91.2. In the build scenario, most injuries and fatalities would be avoided due to the resilience improvements, although falling debris would still cause some level of injury. Assuming that this risk reduction is 90 percent, the would be 30.4 × 90% = 27.36 avoided fatalities and 91.2 × 90% = 82.08 avoided nonfatal injuries. Applying BCA guidance monetization rates for fatalities and injuries implies a net avoided fatality benefit of 27.36 × $13,700,000 = $374,832,000 and a net avoided injury benefit of 82.08 × $238,500 = $19,576,080 if a collapse occurs. If a collapse occurs, the total fatality and injury benefit relative to the baseline is $394,408,080. Multiplying by the 0.1 percent annual baseline risk of collapse yields an expected annual benefit for fully preventing this risk of 0.1% × $94,408,080 = $394,408. The total discounted avoided fatalities and injuries due to the adverse event benefits of $4.3 million are derived by applying the relevant discount factor to each year's values, as shown in table 10, and summing across years.

Table 10. Example annual calculations of avoided fatalities and injuries due to adverse events.

Year	AADT	Baseline Damage Probability (percent)	Net Expected Fatalities per Earthquake Event	Net Expected Injuries per Earthquake Event	Annual Fatality/Injury Cost Savings (2024 dollars)	Discount Factor	Discounted Benefits (2024 dollars)
2027	100,000	0.1	27.36	82.08	394,408	0.816	321,837
2028	100,000	0.1	27.36	82.08	394,408	0.763	300,933
2029	100,000	0.1	27.36	82.08	394,408	0.713	281,213
2030	100,000	0.1	27.36	82.08	394,408	0.666	262,676
2031	100,000	0.1	27.36	82.08	394,408	0.623	245,716
2032	100,000	0.1	27.36	82.08	394,408	0.582	229,546
2033	100,000	0.1	27.36	82.08	394,408	0.544	214,558
2034	100,000	0.1	27.36	82.08	394,408	0.508	200,359
2035	100,000	0.1	27.36	82.08	394,408	0.475	187,344
2036	100,000	0.1	27.36	82.08	394,408	0.444	175,117
2037	100,000	0.1	27.36	82.08	394,408	0.415	163,679
2038	100,000	0.1	27.36	82.08	394,408	0.388	153,030
2039	100,000	0.1	27.36	82.08	394,408	0.362	142,776
2040	100,000	0.1	27.36	82.08	394,408	0.339	133,704
2041	100,000	0.1	27.36	82.08	394,408	0.317	125,027
2042	100,000	0.1	27.36	82.08	394,408	0.296	116,745
2043	100,000	0.1	27.36	82.08	394,408	0.277	109,251
2044	100,000	0.1	27.36	82.08	394,408	0.258	101,757
2045	100,000	0.1	27.36	82.08	394,408	0.242	95,447
2046	100,000	0.1	27.36	82.08	394,408	0.226	89,136
2047	100,000	0.1	27.36	82.08	394,408	0.211	83,220
2048	100,000	0.1	27.36	82.08	394,408	0.197	77,698
2049	100,000	0.1	27.36	82.08	394,408	0.184	72,571
2050	100,000	0.1	27.36	82.08	394,408	0.172	67,838
2051	100,000	0.1	27.36	82.08	394,408	0.161	63,500
2052	100,000	0.1	27.36	82.08	394,408	0.15	59,161
2053	100,000	0.1	27.36	82.08	394,408	0.141	55,612
2054	100,000	0.1	27.36	82.08	394,408	0.131	51,667
2055	100,000	0.1	27.36	82.08	394,408	0.123	48,512
2056	100,000	0.1	27.36	82.08	394,408	0.115	45,357
Total	N/A	N/A	N/A	N/A	N/A	N/A	4,274,989

AADT = average annual daily traffic; N/A = not applicable.

7.6 Improved Emergency Response

As noted in the U.S. DOT BCA Guidance, if there are benefits from avoided emergency response delays, one should carefully document any assumptions, including the affected population and the location of care facilities in the baseline and build cases. A clear nexus between emergency response benefits and the project impacts should be established.

In this simplified example, a roadway is subject to significant flooding due to heavy rains and high tides, which can trigger flooding that can persist due to the roadway passing through low-lying areas, poor drainage, and other hydrological factors. Based on historical data, it is estimated that there is a 10-percent chance per year that the flood rises to the level where the road is not safely passable, with these conditions remaining in place for a period of 5 days. Thus, in the baseline case, all users will detour using other roadways. In the build case, there is still a 10-percent chance of flooding, but the roadway will be rebuilt in a more resilient way (e.g., with a higher profile) that eliminates the need for the associated road closure and detouring.

In addition to other benefits, this project would yield benefits in the form of avoided emergency response delays. Specifically, it is assumed that the flooding detour route increases average EMS response time from 7 minutes to 16 minutes when using the most efficient route to a medical care facility. The benefits of the project are constructed using the difference in emergency response times between the build and baseline cases and the associated impacts on health outcomes using a FEMA statistical model for cardiac arrest survival.

The parameters for this scenario are as follows:

- Affected population: 30,000 who live within the EMS response radius
- Days of detouring, no-build: 5 days per adverse flooding event
- Days of detouring, build: 0 days per adverse flooding event
- Risk of adverse flooding event: 10 percent per year
- No Detour EMS response time: 7 minutes
- Detour EMS response time: 16 minutes
- Out-of-hospital cardiac arrest rate: 92.3 per 100,000 people per year (FEMA Benefit-Cost Analysis Sustainment and Enhancements)
- Cardiac arrest survival probability: $\left(1 + e^{-0.26+0.106I_{CPR}+0.139I_{Defib}}\right)^{-1}$ (FEMA Benefit-Cost Analysis Sustainment and Enhancements)
- I_{CPR}: EMS response time plus 1 minute (FEMA Benefit-Cost Analysis Sustainment and Enhancements)
- $I_{Defib:}$ EMS response time plus 2 minutes (FEMA Benefit-Cost Analysis Sustainment and Enhancements)
- Fatality valuation: $13,700,000 (U.S. DOT BCA Guidance)
- Discount rate: 7 percent (real)
- Discounting base year: 2024
- Dollar base year: 2024

The expected number of daily cardiac arrests for this population is 30,000 × 92.3 ÷ 100,000 ÷ 365 = 0.0759. When the roadway is open, the EMS response time is 7 minutes, so I_{CPR} = 8 and I_{Defib} = 9. If flooding delays emergency response, EMS response time is 16 minutes, so I_{CPR} = 17 and I_{Defib} = 18. Cardiac arrest survival probability is thus $(1 + e^{-0.26+0.106\times 8+0.139\times 9})^{-1}$ = 0.1372 during normal roadway operations and $(1 + e^{-0.26+0.106\times 17+0.139\times 18)\ -1}$ = 0.0172 with the detour. To calculate the increased fatalities due to the flood per year, we take the product of the number of cardiac arrests per day, the number of days of closure, and the difference between the no detour survival rate and the detour survival rate (0.0759 × 5 × (0.1372 − 0.0172) = 0.0455). This value is then multiplied by the annual flood probability and the fatality monetization factor to result in annual benefits (0.0455 × 10% × $13,700,00 = $62,335). The total discounted avoided fatalities and injuries due to the adverse event benefits of $0.7 million are derived by applying the relevant discount factor to each year's values, as shown in table 11, and summing across years.

Table 11. Example annual calculations of improved emergency response.

Year	Number of Cardiac Arrests per Day	Days of Closure	No Detour Cardiac Arrest Survival Rate	Detour Cardiac Arrest Survival Rate	Increased Fatalities due to Flood	Annual Flood Probability (percent)	Reduced Fatalities Benefits (2024 dollars)	Discount Factor	Discounted Benefits (2024 dollars)
2027	0.0759	5	0.1372	0.0172	0.0455	10	62,335	0.816	50,865
2028	0.0759	5	0.1372	0.0172	0.0455	10	62,335	0.763	45,822
2029	0.0759	5	0.1372	0.0172	0.0455	10	62,335	0.713	42,820
2030	0.0759	5	0.1372	0.0172	0.0455	10	62,335	0.666	39,997
2031	0.0759	5	0.1372	0.0172	0.0455	10	62,335	0.623	37,415
2032	0.0759	5	0.1372	0.0172	0.0455	10	62,335	0.582	34,952
2033	0.0759	5	0.1372	0.0172	0.0455	10	62,335	0.544	32,670
2034	0.0759	5	0.1372	0.0172	0.0455	10	62,335	0.508	30,508
2035	0.0759	5	0.1372	0.0172	0.0455	10	62,335	0.475	28,526
2036	0.0759	5	0.1372	0.0172	0.0455	10	62,335	0.444	26,665
2037	0.0759	5	0.1372	0.0172	0.0455	10	62,335	0.415	24,923
2038	0.0759	5	0.1372	0.0172	0.0455	10	62,335	0.388	23,302
2039	0.0759	5	0.1372	0.0172	0.0455	10	62,335	0.362	21,740
2040	0.0759	5	0.1372	0.0172	0.0455	10	62,335	0.339	20,359
2041	0.0759	5	0.1372	0.0172	0.0455	10	62,335	0.317	19,038
2042	0.0759	5	0.1372	0.0172	0.0455	10	62,335	0.296	17,776
2043	0.0759	5	0.1372	0.0172	0.0455	10	62,335	0.277	16,635
2044	0.0759	5	0.1372	0.0172	0.0455	10	62,335	0.258	15,494
2045	0.0759	5	0.1372	0.0172	0.0455	10	62,335	0.242	14,533
2046	0.0759	5	0.1372	0.0172	0.0455	10	62,335	0.226	13,573
2047	0.0759	5	0.1372	0.0172	0.0455	10	62,335	0.211	12,672
2048	0.0759	5	0.1372	0.0172	0.0455	10	62,335	0.197	11,831
2049	0.0759	5	0.1372	0.0172	0.0455	10	62,335	0.184	11,050
2050	0.0759	5	0.1372	0.0172	0.0455	10	62,335	0.172	10,330
2051	0.0759	5	0.1372	0.0172	0.0455	10	62,335	0.161	9,669
2052	0.0759	5	0.1372	0.0172	0.0455	10	62,335	0.15	9,008
2053	0.0759	5	0.1372	0.0172	0.0455	10	62,335	0.141	8,468
2054	0.0759	5	0.1372	0.0172	0.0455	10	62,335	0.131	7,867

Year	Number of Cardiac Arrests per Day	Days of Closure	No Detour Cardiac Arrest Survival Rate	Detour Cardiac Arrest Survival Rate	Increased Fatalities due to Flood	Annual Flood Probability (percent)	Reduced Fatalities Benefits (2024 dollars)	Discount Factor	Discounted Benefits (2024 dollars)
2055	0.0759	5	0.1372	0.0172	0.0455	10	62,335	0.123	7,387
2056	0.0759	5	0.1372	0.0172	0.0455	10	62,335	0.115	6,906
Total	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	652,801

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