NOVEMBER 30, 2017

East Entrance to Hanging Lake Tunnels, I-70

I-70 CORRIDOR RISK & RESILIENCE PILOT

FINAL REPORT

13880 Dulles Corner Lane
Suite 300
Herndon, VA 20171
Principal Investigator:
Aimee Flannery, Ph.D., PE
(703) 464-7030

Executive Summary

The I-70 Corridor Risk and Resilience (R&R) Pilot demonstrated the benefits of examining a highway transportation network in terms of both its capacity to serve demand in the event of physical hazards. The R&R for Highways process provides a framework accommodating uncertainty, incorporating a probabilistic approach to assessing risk, and for making ensuing investment decisions to increase system resilience and reduce annual risk from physical hazards. It is a strategic approach, explicitly trading off the risk of failure against the cost of greater system resilience. The R&R for Highways Framework can assist CDOT and other highway agencies to understand how its system will perform under a range of potential physical hazards, inform project selection and investment decisions, maintenance decisions, operational procedures, and the design process as to risk reducing investments and actions.

CDOT's pilot efforts grew out of their experience with the RAMCAP Plus^{SM} framework adopted in response to the devastating 2013 flood event that caused over $750 million in damage to highway systems alone. CDOT capitalized on language in the Federal Highway Administration's Emergency Relief (ER) Program that highlighted the desire for agencies to address system resilience and reduce future requests of the ER Program for similar events damaging assets in the future (5). Working within the confines of the ER Program, CDOT analyzed several damaged sites that staff anticipated could be at risk from future subsequent flood damage given previous historical performance (6). The process provided data-driven information that supported the decision-making process for investments to build back better after the 2013 floods.

Since the 2013 flood event, CDOT has experienced additional emergencies eligible for FHWA ER funds, including a dramatic rock-fall event in 2016 that closed I-70 in the Glenwood Canyon area for a period of approximately two weeks. In addition to the damage that incurred when a vehicle sized boulder fell onto I-70, alternative routes also experienced damage due to increased traffic volumes and heavy vehicle traffic on roadways not necessarily designed to accommodate such demand. Recognizing the need to better proactively address potential vulnerabilities in the CDOT system, in August 2016, CDOT initiated the I-70 Risk and Resilience Pilot from the Utah to Kansas borders. The goal of the pilot was to determine if the findings of the study are useful to typical CDOT programs ranging from operations, planning, asset management, maintenance, and engineering design and how the data generated can be incorporated into these management programs to reduce system risk and improve resilience.

The Pilot utilized a layered, or tiered, approach to oversight and management to increase visibility for the study and foster agency-wide buy-in on the relatively novel approach to quantifying system resilience. The project management team worked closely with the Executive Leadership of CDOT and the Transportation Commission throughout the project. The Pilot engaged CDOT staff from the Executive Leadership Team in the form of an Executive Oversight Committee that served as a liaison to the Transportation Commission Sub-Committee assigned to the Pilot that was briefed multiple times throughout the study. Next, a group was formed known as the Data Advisory Committee that served to ensure the best available data sources were identified and utilized in the study. Finally, a Working Group of CDOT staff ranging from region to headquarters staff with experience reflective of the entire project life-cycle were utilized in a series of all-day workshops to make decisions about the application of the 7-step process described in detail in this report as it pertained to CDOT.

The project team utilized the expertise of the Working Group in four all-day workshops to set the course for the application of the R&R for Highways Framework for proactive management of system resilience. The workshops were held approximately three months apart and began in late September 2016 and completed in September 2017. The 7-step R&R Framework calls for decisions to be made that determine items such as what highway assets to include in the analysis, what threats to study, what factors determine how critical an asset is to system resilience, how vulnerable are agency assets to applicable threats, and what mitigation measures may be pursued to reduce annual risk and increase system resilience. The Working Group provided guidance and direction to the project team throughout these workshops and through correspondence between meeting times.

In the first workshop, the Working Group determined the threat-asset pairs to be included in the analysis. In total, eleven asset types and nine potential physical threats to highway assets were included in the analysis ranging from bridges to overhead ITS signs and flooding to avalanche. A Criticality Model for System Resilience was developed that provides context as to the criticality of each asset in terms of system resilience. The final Criticality Model reflects the State of Colorado's Resiliency Framework and its established pillars of resilience including Environmental, Economic, and Social factors and includes factors relevant to CDOT operations.

In the second workshop, the Working Group considered what consequences to include in the estimates of potential financial losses from physical threats. The Working Group determined that inclusion of owner costs (replacement costs of assets lost from physical threats) and user costs (vehicle running costs and lost wages for additional travel time) should be included in the analysis. Vulnerability assessments were also discussed in this workshop and the information needed to support the estimation of asset performance under various threats.

In the third workshop, the Working Group was presented with the findings of the risk assessment for each threat-asset pair studied along the corridor. Data generated were presented in a variety of formats to demonstrate the potential uses of the information through a typical project life-cycle. The Working Group next selected five locations along the corridor to analyze two potential mitigation strategies to reduce annual risk from physical threats and improve system resilience. The findings were presented in workshop four and included an economic analysis of each mitigation under consideration. Finally, in this last workshop the Working Group discussed potential next steps for risk and resilience analysis within CDOT including:

1. Development of a base risk map for the CDOT system
2. Development of a CDOT standard for economic analyses of potential mitigation strategies
3. Development of case studies to demonstrate the application of risk and resilience analyses
4. Review of CDOT policies, manuals, standards, and models for funding allocation to determine appropriate locations for inclusion of risk and resilience analysis findings and procedures

Contents

Introduction

Recent weather events demonstrate that some highway infrastructure is vulnerable to a variety of natural hazards. In September of 2013, Colorado experienced the most devastating natural catastrophe in the state's 138-year history (State of Colorado, 2015). Ten persons lost their lives and more than 18,000 persons were rendered homeless by flooding in and around the Colorado Front Range. Twenty-four counties in Colorado were impacted by the floods, extending north from Boulder, Colorado to nearly the Wyoming border. Eighteen of these counties were included in the Federal Major Disaster Declaration (DR-4145). The 2013 floods were preceded by the June, 2012 High Park fire, which burned approximately 87,300 acres in Larimer County--much of the watershed involved in the 2013 floods ("High Park Fire | Colorado Fire Maps," n.d.).

As part of the emergency response, the Colorado Department of Transportation (CDOT) established a flood recovery office (FRO) to coordinate and oversee recovery efforts (CDOT, n.d.). From its inception, one objective of the FRO was to adapt the RAMCAP Plus^{SM} methodology to quantify expected losses, evaluate consequences, and develop mitigation alternatives related to the flood. This approach was informed by the 1976 Big Thompson River/ Cache la Poudre River floods, previous severe flooding that occurred in the same areas as the 2013 floods (Shroba et al., 1979). Recovery decisions were guided by the definition of risk adopted by CDOT, "Risk is the expected annualized monetary loss of an asset from any defined threat that reflects the likelihood of that threat as well as the vulnerability of that asset to that threat" (Flannery, Aimee et al., 2015). As part of the flood recovery efforts, CDOT received concurrence from the Colorado Division Office of Federal Highway Administration (FHWA) to pilot test an approach to assess the anticipated reduction of future losses from similar emergency events using mitigation or betterments in lieu of "Replace-in-Kind". The approved pilot approach reflects:

- probabilistic threat analysis;
- asset condition;
- threat geographic location and context;
- inter-dependency of nearby assets;
- vulnerability, based on asset condition and mitigation strategies;
- asset engineering design standards
- and proposed permanent repairs (also known as betterments).

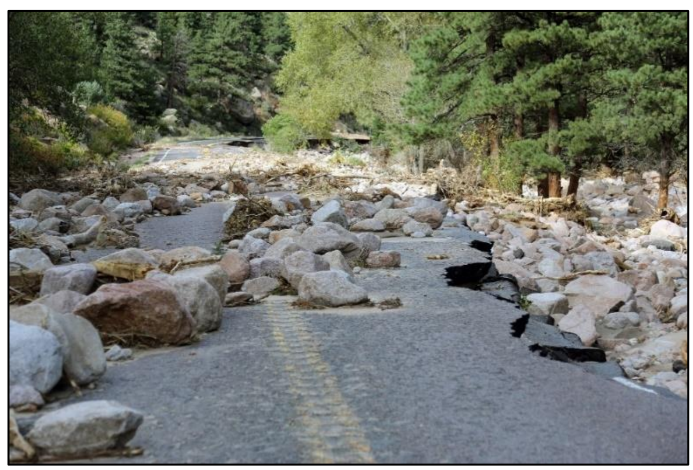


Figure 1. Flood-roadway Damage

At approximatley the same time as the floods, CDOT completed its first federally mandated Risk-Based Asset Management Plan (AMP), addressing MAP-21 legistlation risk-based analysis requirements (Cambridge Systematics, Inc. and Redd, Larry, 2013). Per this AMP, the stated goal of CDOT's asset management program is "to minimize life cycle costs for managing and maintaining the department's assets subject to acceptable levels of risk." In pursuit of this goal CDOT developed a set of performance metrics and asset management objectives for eleven major assets: bridges; pavement; maintenance; buildings; Intelligent Transportation System (ITS); fleet; culverts; rockfall; tunnels; signals; and walls. In its approach to risk management CDOT also consided three levels of management: projects/assets; programatic; and agency. Each of these management levels uses specific tools to prioritize investments based on asset inventory, condition (including attainment of performance measure objectives), and existing and projected budgets.

One of the challenges to incorporating risk and resilience assessment within asset management is the lack of a standard framework with which to identify and prioritize critical assets, and to quantify the impact of physical threats to highway assets for incorporation into funding allocation processes. This study demonstrates the feasibility of the Risk and Resilience (R&R) for Highways process as an analytical framework to prioritize highway assets and to determine potential financial impacts to highway asset owners and their users from various physical threats. This report outlines the approach taken by CDOT to pilot a standardized threat evaluation framework enabling proactive highway asset risk and resilience assessment. The 7-step R&R for Highways process employed, data utilized, decisions made, and findings are discussed herein.

R&R for Highways Application

The 7-step R&R for Highways process utilized in the Pilot is shown in Figure 2. As shown, the process consists of seven steps that begin with asset identification and end with risk management. The process is based on the Risk Analysis and Management for Critical Asset Protection (RAMCAP) Plus methodology developed for all critical infrastructure by the American Society of Mechanical Engineers (Engineers, 2009)). While RAMCAP Plus is applicable to all critical infrastructure sectors, R&R for Highways was developed to reflect the unique characteristics of highway infrastructure.

The Pilot utilized the expertise of the project team and CDOT staff to shape the seven steps to reflect important features, concerns, and data availability within the agency. The process, while it is transferable to other highway agencies, reflects the characteristics, priorities, and data maturity of CDOT asset management systems.

1. Asset Characterization	• What assets exist, which are critical, and what should be considered?
2. Threat Characterization	• What threats and hazards should be considered?
3. Consequence Analysis	• What happens to assets if a threat or hazard occurs? What are the expected asset losses, economic impacts, injuries, and lives lost?
4. Vulnerability Analysis	• What are the asset vulnerabilities that would allow a threat or hazard to result in expected consequences? How vulnerable is the asset to the identified threat?
5. Threat Assessment	• What is the likelihood of the identified threat?
6. Risk/Resilience Assessment	• What is the anticipated asset total risk and resilience? • **Risk= Consequences x Vulnerability x Threat** • **Resilience= Service Outage x Vulnerability x Threat**
7. Risk/Resilience Management	• What options are there to reduce risk and increase resilience? What is the risk reduction? What is the economic analysis of mitigation alternatives?

Figure 2. R&R for Highways Process (based on RAMCAP Plus Risk Analysis and Management for Critical Asset Protection (*(Engineers, 2009)*)

The Pilot demonstrated the utility and outcomes of establishing a Risk and Resilience baseline, a gauge of the impact of applicable threats on existing infrastructure. Such a baseline is particularly important in forecasting the impact of well-understood threats on aging infrastructure. Similarly, the R&R baseline is essential in understanding the potential magnitude of future climate change and severe weather impacts. The Pilot also demonstrated an economic analysis of potential mitigation measures to reduce annual risk and improve system resilience for five specific locations on I-70. This approach is similar to the approach used by CDOT in response to the 2013 flood event to economically evaluate betterments (alternatives to Replace-In-Kind) that were estimated to reduce future losses based on historical threat information, cost information, and asset design standards. Utilizing such an approach to assess the economic viability of mitigation measures may provide CDOT with additional information to consider such measures in a fiscally constrained environment.

An additional benefit of the Pilot is an understanding of the data maturity and availability within CDOT's asset management systems to support quantitative risk assessment at the asset, segment, and corridor levels. By utilizing CDOT's own data sets for asset information, the condition and age of assets was included within the overall analysis. Finally, the process was developed in a manner to support a replicable decision-making process to reduce asset risk from physical threats and improve system resilience.

A series of recommendations have been developed based on the results of the I-70 Corridor R&R Pilot. Many of these recommendations are far-reaching, cutting across nearly all CDOT's business processes, and aligned with CDOT strategic goals and objectives. The R&R for Highways process is not a panacea for aging infrastructure, marginal capital construction and maintenance budgets, federal reporting mandates, or the implications of climate change/extreme weather events. However, the process and outcomes from the R&R for Highways Framework do provide CDOT a mechanism to further evolve the insight and discipline to better coordinate its diverse business processes and myriad of public interests while delivering the transportation services demanded in a robust population boom.

Figure 3 demonstrates the potential integration of the R&R for Highways Framework and outcomes into typical planning and project development phases. The steps labeled A, B, and, C have been demonstrated through the I-70 R&R Pilot and recommendations have been made by the Working Group for inclusion of R&R outcomes into Steps labeled D, E, and F.

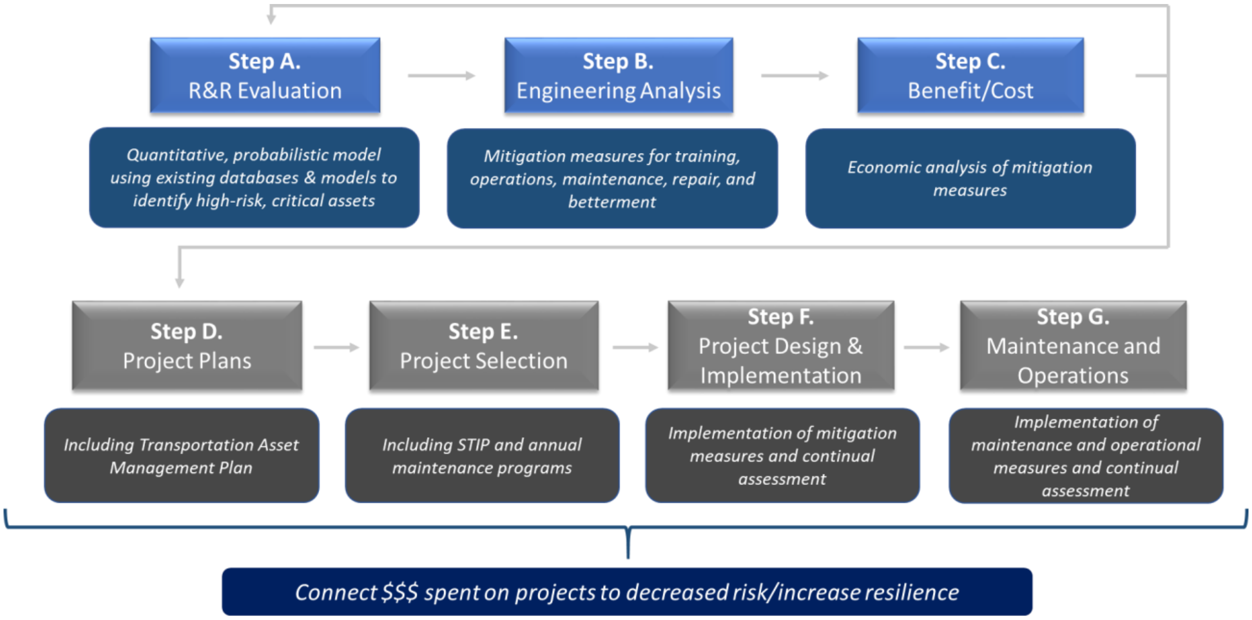


Figure 3. Leveraging R&R for Highway results with strategic planning and resource management.

Study Area

The I-70 Corridor R&R Pilot project focused on approximately 450 miles of interstate extending the width of Colorado from the Utah border in the west, to the Kansas border in the east. The Pilot covered urban and rural areas, with physical geography ranging from high plains to mountains—including the highest and longest mountain tunnel in the United States—to near-desert landscapes. Communities and climates were similarly diverse along the study corridor, notably including the Glenwood Canyon, an environmentally sensitive area and one of the most expensive rural sections of the interstate system. The Pilot also addressed many significant natural threats found in Colorado, ranging from avalanche to wildfire. In summary, the Pilot encompassed the full range of threats and geographies present in Colorado, although it was limited to only a single type of facility—Interstate.

Figure 4. Schematic of I-70 Study Area

I-70 R&R Pilot Organization

One of the outstanding issues for the mandated risk assessment of highway assets is what approaches may be taken to mitigate risk. Most often professionals turn towards solutions that require capital investments to build to higher design standards or realignment of facilities to reduce threats. Leadership at CDOT recognized that this often would not be feasible and envisioned mitigation approaches that could range from maintenance activities, operational strategies, and investments to alternative routes to prepare those facilities to accept potential detoured traffic. Given the potential range of solutions to mitigate risk, care was taken to select individuals from across CDOT's specialty groups (maintenance, operations, design, planning, engineering) and across the agency's geographic regions to serve on a Working Group.

The Working Group (WG) was established with key individuals with field experience, knowledge of the system, and in-depth experience with specific assets and threats. The WG also represented the diverse disciplines and different CDOT Maintenance Regions. The dark blue boxes in Figure 4 indicate the WG members and disciplines within CDOT. The WG determined the scope of the analysis, identifying the assets to be analyzed, and the specific threats to be considered. WG members were instrumental in the development of asset replace-in-kind (RIK) cost, vulnerability pathways and degree of vulnerability, and determining consequence magnitude. The WG oversaw performance of the R&R Analysis, including Pilot objectives, outcomes, and deliverables.

The light green box in Figure 5 indicates the Data Advisory Team (DAT) membership. The DAT was composed of key CDOT headquarters supervisory managers. It was charged with ensuring the R&R Analysis had access to readily available datasets. The DAT brokered data acquisition, ensuring the most representative and recent data was available for the Pilot. Finally, the DAT also provided this critical level of CDOT management an early view into potential business and organizational changes the Pilot might ensue, including recommendations for additional data acquisition.

The Executive Oversite Committee (EOC) was comprised of key CDOT executives. EOC membership is indicated in the large, salmon-colored box on the right side of the organizational diagram. The EOC reviewed WG decisions and suggestions, determining potential impact and changes arising from the R&R Pilot. Not least of the EOC decisions is weighing the benefit of extending the R&R Analysis beyond the Pilot to additional CDOT facilities, integrating R&R Analysis with CDOT business processes, and leveraging R&R Analysis processes for asset management and strategic planning.

Colorado's transportation system is managed by CDOT under direction of the Colorado Transportation Commission. The Commission is represented by the salmon-colored box at the upper left of the organizational diagram. The commission is comprised of 11 commissioners appointed by the governor, representing specific districts within the state. The Transportation Commission (TC) also formed a Risk & Resilience subcommittee to oversee the Pilot and future R&R efforts. Other Offices and Agencies involved included the Governor's Office of Resilience, and the Colorado Division of FHWA.

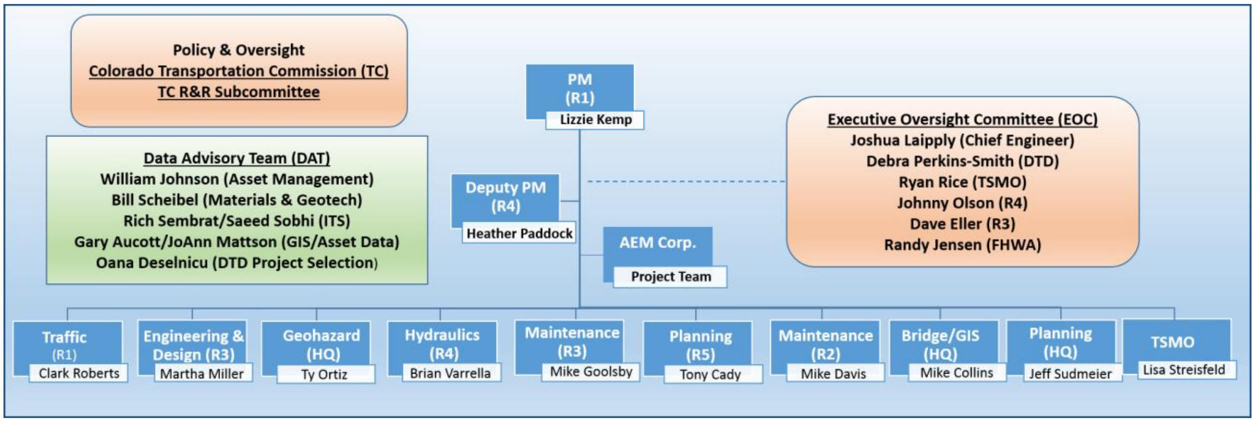


Figure 5. I-70 Risk and Resilience Pilot Oversight Organization

Pilot Delivery

The key vehicle for directing the Pilot and validating outcomes was a series of four workshops with the WG, facilitated by AEM Corporation. Among other roles, the workshops functioned as formal information exchanges and key project milestones. Figure 6 provides an overview of the tasks accomplished in each workshop, key outcomes and date of workshops. A brief description of the purpose and objectives of each workshop follows.

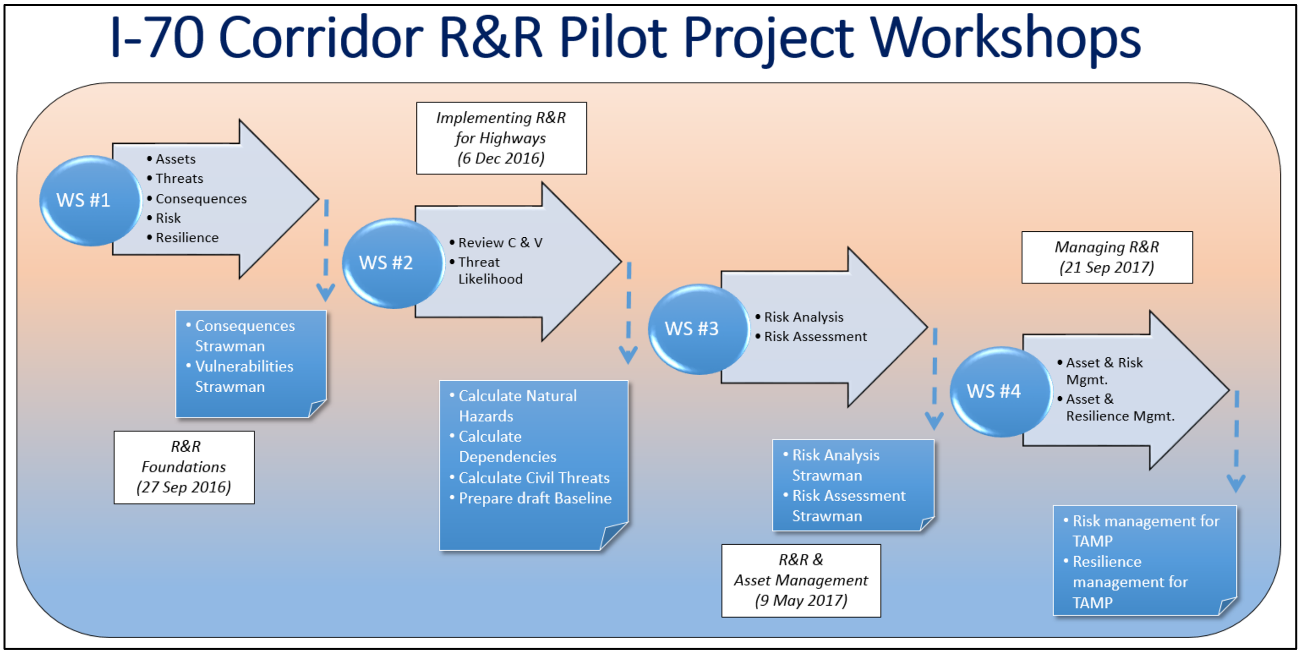


Figure 6. I-70 R&R Pilot Project Workshop Timeline and Accomplishments

Workshop #1

Workshop #1 followed a virtual kick-off meeting, with the aim of solidifying roles and responsibilities within the project team, or Working Group (WG), and verifying scheduled workshop dates. During Workshop #1, the WG set the scope of Pilot, identified goals and objectives for the Pilot project, and discussed outcomes and expectations. The WG further established lines of communication, ground rules, and limitations of the Pilot. In addition, workshop phases and results were outlined and key concepts introduced to the WG. With this groundwork, the WG determined the assets and threats to be addressed in the Pilot (Steps 1 and 2 in the R&R for Highways Process). The WG also developed the threat-asset pairs to be studied, and identified the data required to develop and analyze these assets. This discussion dictated how assets were characterized for this project, including essential asset characteristics and locational accuracy. The WG was introduced to the concept of asset criticality, and a first pass at developing a Criticality Model for the R&R for Highways analysis framework was completed.

Workshop #2

Workshop #2 continued development of an asset Criticality model, with examination of various criteria to be potentially be included in the final Criticality Model for System Resilience. The WG also completed an examination of the key components of the equation used to calculate annual risk from physical threats. Agreement on the terms and their application within the R&R framework was accomplished, laying the foundation for the quantitative analysis to come. During Workshop #2 the WG completed an in-depth review and preliminary validation of Vulnerability, Consequence, and Restore-in-Kind costs, as applied to several classes of CDOT assets. The WG examines the Vulnerability and Consequence models generally, and detailed examples of these models were discussed for bridges and roadway prism. Major outcomes from this phase of Workshop #2 were further clarification as to how CDOT classified assets, identification of supporting data and points of contact within CDOT, and some threat data was identified from potential sources within CDOT (such as bridge strike data).

Workshop #3

In Workshop #3, the WG was provided information on the final Criticality Model for System Resilience to be used in the Pilot as approved by the EOC. The WG discussed application of the Criticality model within CDOT Regions, and CDOT at large, commenting on the insights the model provides, and its potential use for resource and asset management decisions. Results of the risk analysis for the I-70 corridor were also presented to the WG in Workshop #3. Results were presented from a variety of perspectives, including risk results by asset class, by specific asset, by Resilience Segment (see Figure 8), by specific threat, and for the entire I-70 facility. For each perspective, Total Risk was deconstructed into Owner Risk (based on CDOT's RIK asset cost) and User Risk (derived from lost time, lost wages, and vehicle operating costs of potential travelers). With this information, the WG identified five sites on the I-70 facility to perform economic analyses of mitigation alternatives (R&R for Highways steps 6 and 7), to be presented in workshop #4. During this final phase of the workshop, the WG discussed applying R&R analysis to the entire CDOT system. The WG also proposed an initiative to continue the WG beyond the I-70 Pilot project, as an aid to incorporating R&R for Highways analysis with CDOT business practices. A draft R&R Implementation Roadmap for CDOT was also discussed by the WG.

Workshop #4

Workshop #4 encompassed the final two steps of the R&R for Highways analysis process. Workshop #4 began with presentation of economic analysis of mitigation alternatives for five sites identified in Workshop #3. Two mitigation strategies, as selected by the WG and CDOT regional staff, for each of the five sites were presented, comprised of planning-level engineering and economic analyses for mitigation strategies based on CDOT-provided data and design standards. Benefit-Cost metrics were presented, as well as the annual reduction in risk and annual resilience metric provided by each mitigation strategy. These steps of the R&R for Highways analysis process provided the WG an understanding of the annual financial risk present at each asset, the potential reduction in risk through mitigation measures, and a measure of system resilience. The results also assisted the WG in understanding the potential risk reduction/resilience enhancement available via capital investment, maintenance, operation, training, and design alternatives.

Extending the R&R for Highways analysis to the remainder of the CDOT system was discussed, including exploring the effort required to further refine hazard consequence and asset vulnerability models through further engagement with CDOT specialty staff. Also addressed in this workshop was integrating R&R for Highways with CDOT business practices, and within CDOT Regions. Data requirements, collection, distribution and related recommendations were considered by the WG. The WG discussed applying the R&R results as an extension to existing project, agency, and program risk analyses, and supporting a more comprehensive TAMP. In addition, the WG offered insights into applying results gleaned from the Pilot as support for resource allocation decisions within a CDOT's strategic planning framework.

In the next section of the report, the key outcomes for each of the seven steps accomplished in the Pilot are explained in detail.

I-70 Corridor R&R Pilot Key Outcomes

CDOT facilities have been damaged by physical events and are vulnerable to future events (e.g., floods, rockfall, etc.). The vulnerability of transportation infrastructure to natural hazards is a function of its robustness and its degree of protection from these hazards. (National Research Council (U.S.) et al., 2008) Robustness has three dimensions. The first dimension of robustness is the ability of the system to withstand a hazard and remain functional, e.g., bridges designed to remain operable following a magnitude 7 earthquake. The second dimension of robustness is the amount of redundancy in the system. Network redundancy can mitigate the negative consequences of losing critical links, shifting users to redundant routes. Alternatively, system redundancy can magnify the effects of losing critical links by increasing Owner Cost of repairing alternative routes, and increasing users' costs associated with of traveling greater distances than the original route. The third dimension of robustness is resilience. Resilience is a measure of how quickly the damaged portion of the network (the critical links) can be repaired to establish a minimum service threshold.

Highway transportation networks are comprised of assets with varying useful service lives. Pavement surface life is on the order of 10 to 15 years; bridges are built for a service life of (at least) 100 years. Furthermore, infrastructure was built to serve forecast transportation demand, not necessarily natural hazards. Building this infrastructure to withstand natural hazards is an engineering demand that was first systematically considered with standards developed during the construction of the Interstate system. Advances in engineering, modeling, hazard documentation and hazard forecasting have supported continued development of standards, with regimes for bridges (hydraulic capacity, earthquake resistance), roadway drainage, and sign/lighting (ice and wind) as notable examples.

The I-70 Corridor R&R Pilot demonstrates the benefits of examining a network in terms of both its capacity to serve demand and ability to withstand hazards, while overtly accounting for the varied useful service lives and conditions of different asset classes. The R&R for Highways process provides CDOT a framework accommodating uncertainty, incorporating a probabilistic approach to assessing risk and making ensuing investment decisions. It is a strategic approach, explicitly trading off the risk of failure against the cost of greater resilience. The R&R for Highways framework can assist CDOT in understanding how its system will perform under a range of potential hazards, informing maintenance procedures, and operating procedures, and asset designs with the greatest return on investment. These decisions may then be folded into CDOT's investment decisions in the long-range transportation plan and a short-term transportation improvement program.

The workshops provided an opportunity for the project team to engage with CDOT staff with a range of experience and geographic location. Throughout the course of the 15-month project, several key decisions were made by the WG and the EOC. These key outcomes are described herein.

Asset-Threat Pairs

One of the first decisions made by the WG was the types of assets and threats to be included in the analysis. The WG debated a number of threats and assets to be included in the Pilot analysis and efforts were made to identify data sets to support all threat-asset pairs. In some cases, however, data were not available to support such analyses, for example, the WG expressed a desire to study the potential impacts of damn breaks along I-70, however, at the time of the data collection phase of this study, the data needed to support such analysis was not available. Other threats considered by the WG included the environmental impact of chemicals used in high-snow/ice portions of I-70, however, the data needed to support that analysis was not readily available for the I-70 corridor. Similarly the WG suggested including the impact of hazardous material spills, however, within the timeframe of the project this data was not able to be acquired. The WG also provided key insights as to the availability of data to support the analysis of asset classes. For example, recent data collection efforts at CDOT provided information on small culverts located in the study facility, however, this information was not at the time compiled by CDOT staff into a single database. The AEM Project Team worked to “stitch” this data together to allow for analysis of small culverts in the study. Table 1 includes the final list of asset classes and physical threats included in the analysis.

Table 0-A. Threat-Asset Pairs Included in the I-70 R&R Pilot

Threat/Asset	Bridge	Bridge Approach	Roadway Prism	PTCS	NBI Culverts	Minor Culverts	Wall	ITS-VMS	Control Centers
Avalanche	R&R	R&R	R&R	R&R	R&R	R&R	R&R	R&R	R&R
Flood (scour)	R&R	R&R	R&R	R&R	—	—	R&R	R&R	R&R
Flood (Overtopping/debris)	R&R	R&R	R&R	R&R	R&R	R&R	R&R	R&R	R&R
Fire (wildland)	R&R	R&R	R&R	R&R	R&R	R&R	R&R	R&R	R&R
Landslide	R&R	R&R	R&R	R&R	R&R	R&R	R&R	R&R	R&R
Rockslide	R&R	R&R	R&R	R&R	R&R	R&R	R&R	R&R	R&R
High Wind (CO. special wind zone)	R&R	R&R	R&R	R&R	R&R	R&R	R&R	R&R	R&R
Tornado	R&R	R&R	R&R	R&R	R&R	R&R	R&R	R&R	R&R
Bridge Strike	R&R	—	—	—	—	—	—	—	—

Table 1 depicts each relevant threat-asset pair that was considered in the I-70 Pilot. For example, the threat of Bridge-Strikes from high vehicles are only relevant to bridges, therefore that cell of the table includes “R&R” indicating efforts were made to gather data and assess this threat-asset pair.

For each of the threat-asset pairs, information was developed or gathered to support the following:

- Locating the asset or threat on the I-70 facility
- Gathering characteristic data for each asset (length, width, depth, condition, etc.)
- Determining a replacement cost for each asset
- Establishing an estimated service life for each asset
- Estimating (if not known) the design standard for each asset
- Establishing which magnitudes of each threat were to be studied
- Information gathered on the likelihood of occurrence of each magnitude of each threat

With the establishment of the threat-asset pairs to be included in the analysis, next a metric referred to as asset criticality was established.

Asset Criticality

Determining asset criticality is a portion of the first step in the R&R for Highways process, “Asset Characterization”. Criticality is a measure of the importance of an asset to the resilience of the system and the success of CDOT to carry out its mission of delivering service to its travelers. Criticality is therefore not a measure of the cost of an asset, nor the likelihood an asset may fail in response to a hazard; these asset characteristics are captured in other parts of the R&R for Highways analysis framework.

There are two primary reasons for determining asset criticality. First, no agency has sufficient resources to bring every asset to the highest standard to withstand every hazard and magnitude of hazard. For example, it is not cost effective to build a rockshed for entire length of Glenwood Canyon, approximately 12.5 miles, as a measure to mitigate rockfall. Rather, CDOT has utilized rock netting, rock fences, and other mitigation measures at locations with high probability of significant rockfall and potential damage to the roadway and other assets. Second, understanding the relative criticality of all assets in the CDOT system is necessary if one is to evaluate risk for any asset and hazard in the context of CDOT's entire transportation network and mission. This information makes it possible to weigh mitigation alternatives, to know where emergency response plans are most urgently needed, and to identify alternate routes that should be examined for improvement should a critical link be highly susceptible to failure.

Over the course of the Pilot project, the WG and EOC collectively developed an asset criticality model. Over nine iterations of the model with various criteria, weights of criteria, etc., were developed for consideration by the WG and EOC. Ultimately, six criteria were included in CDOT's objective model of Asset Criticality, as indicated in Table 2.

Table 0-B. Final CDOT Asset Criticality Model for System Resilience

	Criticality Score					
Criteria	**1 Very Low Impact**	**2 Low Impact**	**3 Moderate Impact**	**4 High Impact**	**5 Very High Impact**	**Weight**
AADT	40 - 720	721 - 1,900	1,901 - 4,600	4,601 - 15,000	>15,000	1/6
AASHTO Roadway Classification	Minor Collectors	Major Collectors	Minor Arterial	Principal Arterial	Interstate Freeway Expressway	1/6
Freight ($M)	<=4,422	6,423 - 6,513	6,514 - 6,685	6,686 - 8,806	>8,806	1/6
Tourism ($M)	<152	153 - 479	480 - 1,050	1,051 - 3,414	>3,414	1/6
SoVI	(-9.69) - (-2.93)	(-2.92) - (-1.24)	(-1.23) - 0.67	0.68 - 2.51	2.52 - 6.23	1/6
Redundancy (CDOT 2015v)	4.51 - 50.5	3.01 - 4.5	2.01 - 3	1.51 - 2.0	1.0 - 1.5	1/6

The criteria included in the model, as shown in Table 2, include Average Annual Daily Traffic (AADT); the Association of American State Highway and Transportation Officials (AASHTO) Roadway Classification factor; Freight value per Ton at the county level in millions of dollars per year; Tourism dollars generated at the county level in millions of dollars per year (Colorado Tourism Office June 2015 Report); Social Vulnerability Index (SoVI) at the county level (University of South Carolina Hazards & Vulnerability Research Institute 2010-2014); and system Redundancy. The criteria were suggested by the Consultant Team and various versions of the model with a range of criteria and weights were considered by the WG and the EOC. Ultimately the criteria shown in Table 2 were selected as the WG and the EOC believed that this version of the model best represent three pillars of system resilience including: environmental, social, and economic impacts to the citizens of Colorado.

The criticality score was derived by summing the six criteria. This score was then appended to all assets (i.e., bridge, pavement prism, culvert, wall) between pairs of mile points for each roadway. Roadways were grouped into Low-, Moderate-, and High-Criticality by setting criticality score cut-offs so that approximately 50% of centerline miles were ranked as Low-Criticality, 25% ranked as Moderate-Criticality, and 25% of centerline miles were ranked as High-Criticality. The Criticality score was also assessed for distributional equity across CDOT Engineering Regions. Table 3 indicates the results of the final Asset Criticality Model, as expressed in percent of centerline miles statewide.

Table 0-C. Criticality for System Resilience as a Percent of Centerline Miles by Region

	Region I	Region II	Region III	Region IV	Region V	
	CL%	**CL%**	**CL%**	**CL%**	**CL%**	**Total**
Low	**2.5%**	**13.9%**	**13.3%**	**14.7%**	**9.4%**	**53.8%**
Moderate	**4.4%**	**4.8%**	**5.1%**	**7.6%**	**3.5%**	**25.5%**
High	**3.7%**	**4.2%**	**4.3%**	**5.7%**	**2.9%**	**20.7%**
Total	**11%**	**23%**	**23%**	**28%**	**16%**	**100%**

Several reviews of the resulting criticality scores were conducted with members of the WG, the EOC, the CDOT Commission, and CDOT regional staff. Many discussions ensued as to the potential use of the resulting criticality and it should be noted that the purpose of the ranking is simply to reflect those assets of the CDOT system that are important to the capability of CDOT to provide system resilience and allow for movement of travelers across the state. Figure 7 is a map of CDOT asset criticality by CDOT Region. Red indicates assets rated High-Criticality; brown-orange indicates assets of Moderate-Criticality. Low-Criticality assets are represented in green.

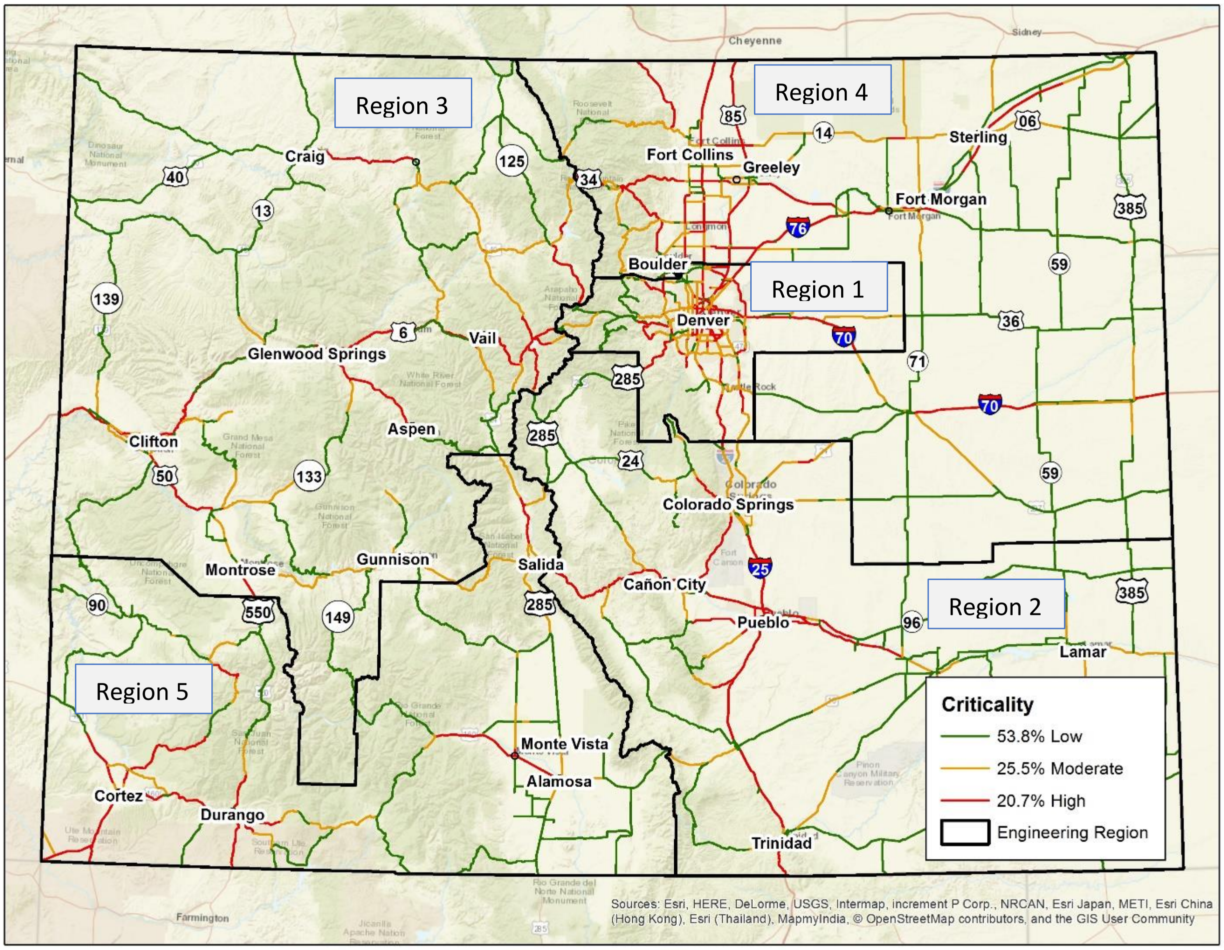


Figure 7. CDOT Asset Criticality Map for System Resilience

For the I-70 facility, the interstate was broken into logical on and off points of the facility onto CDOT owned and operated facilities. For each of these segments, known as resilience segments, the criticality for system resilience metric was also calculated and is shown in Figure 8.

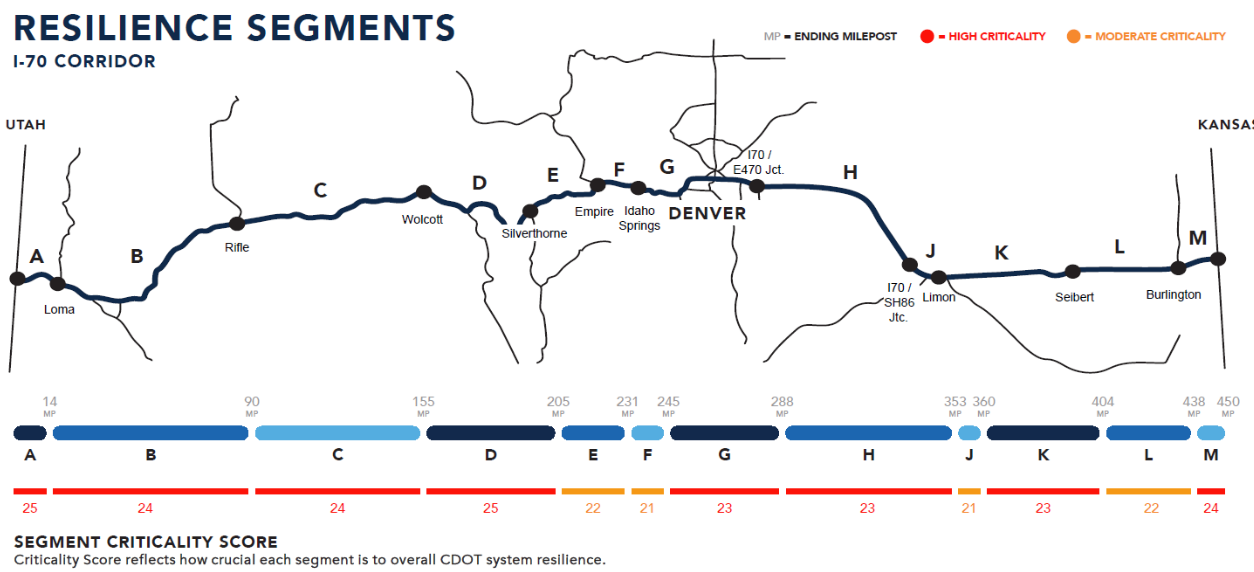


Figure 8. Resilience Segments for I-70 and Criticality Score for System Resilience

Consequences Considered

With input from the WG, which financial losses to include in the estimation of consequences that are expected to incur from each threat included in the analysis was next determined. For example, an owner may consider financial and economic losses to the agency (e.g., asset replacement costs); human losses (e.g., fatalities and serious injuries); environmental impacts (e.g., permanent damage to environment); user costs (e.g., vehicle running costs and lost wages for additional travel time); and revenue losses (e.g., loss of toll revenue). Each of the consequences can be quantified in terms of dollars and directly related to each threat scenario considered. For example, consequences would be considered higher for a higher magnitude threat as compared to a threat of lower magnitude (e.g., Hurricane Category 5 versus Hurricane Category 2) dependent on the design standard of the asset in question.

An example consequence model follows:

*Consequences ($) = Human Impact (Fatalities + Injuries) + User Cost (Vehicle Running Cost + 15 Lost Wages) + Owner Cost (Asset Damage + Asset Loss) + Impact*$_1$ *+ Impact*$_2$ *+…Impact*$_i$ *Model 1*

When considering consequences, the RAMCAP PlusSM Framework calls for the estimation of “worst reasonable case” for each threat/asset pair under consideration. For example, estimation of the anticipated consequences from a 100-year flood event as well as a 500-year flood event should be developed. In the case of highway assets, additional information is gleaned for each threat-asset pair when considering the design standard to which the asset has been built.

The CDOT WG considered including environmental costs (through the additional emissions that would be generated through detours around damaged assets after an event); user costs; and owner costs within their consequences model. After a review of the negligible additional costs that could be captured through modeling efforts of environmental costs, the WG determined that the user cost component of the model, which captures the additional vehicle running costs from detours, could reflect the additional environmental costs associated with events. After discussions with the WG, owner and user costs within their final consequences model as shown in the following equation where *i* represents the range of applicable threats and relevant magnitudes of each threat.

$$\sum_i Consequences_i = Owner\ Losses_i + User\ Costs_i \qquad \textit{Model 2}$$

Owner losses are based on the Replace-in-Kind (RIK) costs of each potentially affected asset within a hazard area. These costs were developed based on CDOT bid-item costs published in 2016 and a multiplier to account for construction costs associated with anticipated damage from applicable threats. Users costs were estimated using a modified version, eliminating factors not related to user costs, of the FHWA HYRISK model to estimate financial impact to travelers from closures on I-70 from damaged assets. User costs include running time costs and value of time to both commercial and personal vehicle drivers. Information used in the user cost portion of the consequences model included the anticipated detour lengths around closures along I-70 mainline in terms of additional travel distance and anticipated travel time as shown in Table 4, please note, traffic was assumed to only detour onto CDOT owned and operated facilities from I-70. Members of the WG suggested that detour routes only include CDOT owned and operated facilities, as these are the facilities that CDOT typically detours traffic onto without prior arrangements with local agencies. As might be expected, it is quite possible that travelers familiar with local routes may elect to detour onto facilities not owned and operated by CDOT in times of closures which has not been reflected in this analysis. Detour lengths were calculated through simple mapping of on and off points of I-70 utilizing CDOT owned and operated facilities. Travel times were estimated using posted speed limits.

Table 0-D. Detour Lengths Used in User Costs Calculations

Closure Between		Detour Delta	
MP Start	MP End	Miles	Minutes of Travel
1	14	146	189
14	90	90	112
90	155	140	167
155	205	98	126
205	231	83	109
231	245	49	77
245	288	3	7
288	353	15	24
353	360	71	96
360	404	76	73
404	438	69	70
438	450	63	77

Threats Considered

As noted previously, the WG considered a range of physical threats for the Pilot ranging from natural, direct, and proximity threats. In the end, nine physical threats were considered including:

- Avalanche
- Flood (scour)
- Flood (Overtopping/debris)

- Fire (wildland)
- Landslide
- Rockslide
- High Wind
- Tornado
- Bridge Strike from High Vehicles

For those threats that had available threat layers, these were mapped to each asset under consideration. In cases where this data did not exist in such a format, the annual probability of occurrence was developed based on historical data (for example bridge strikes from high vehicles).

Figure 9 contains an example threat map developed for the I-70 facility.

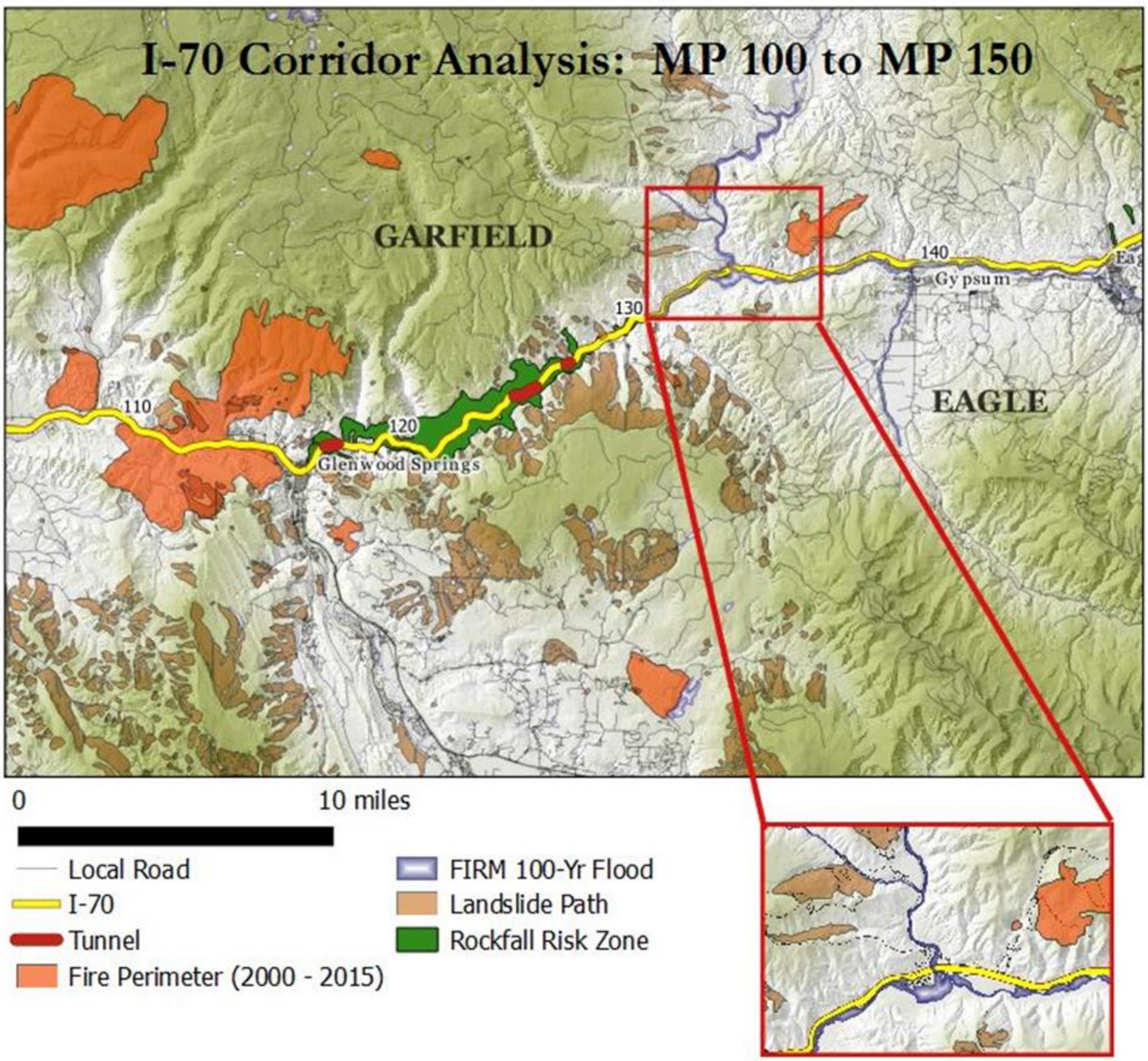


Figure 9. Example Threat Mapping for I-70 Facility

Vulnerability Assessment

Vulnerability is a relatively unique factor in the risk calculation as outlined in RAMCAP Plus. Vulnerability is a conditional probability that the consequences estimated will be realized given that the threat has occurred. In the case of highway assets, vulnerability can be used to reflect the condition and age of assets and their ability to withstand a specific event under analysis. For example, a poorly maintained asset at the end of its service life, could be expected to perform more poorly as compared to a well-maintained, newer asset of the same design standard. In addition, actions or investments made by the agency to protect or harden an asset can be reflected within the vulnerability factor. For example, the addition of wing-walls to culverts or the addition of rip-rap to a culvert may further protect that asset from flood damage just as the use of rockfall fencing may reduce the vulnerability of a section of roadway from potential rockfall. Utilizing the information available in CDOT's asset management databases for each of the assets included in the study and experienced gained through empirical analyses and literature reviews conducted over a period of years in multiple sectors, vulnerability models were developed for each threat/asset pair that reflect the anticipated likelihood of the consequences estimated to be realized given that the threat has occurred.

Utilizing the three major components of the risk calculation (Consequences, Vulnerability, and Threat), the anticipated annual risk by threat and asset type as well as by resilience segment was calculated for both owner risk (CDOT) and user risk (traveler) as shown in Equation 1.

$$Risk = C \times V \times T \qquad\qquad Equation\ 1$$

Where,

R = Potential loss due to analyzed event, $
C = Outcome of an event occurrence, $
V = Given event has occurred, probability of that estimated consequences will be realized, %
T = Likelihood event will occur, %

The next section of this report outlines the findings of the analysis.

I-70 Corridor R&R Pilot Project Analysis Results

The results of the Pilot presented CDOT a comprehensive framework for understanding the relative impacts of hazards on different assets in the I-70 corridor. Figure 10 summarizes the risk on the I-70 corridor by each hazard by annual owner and user risk.

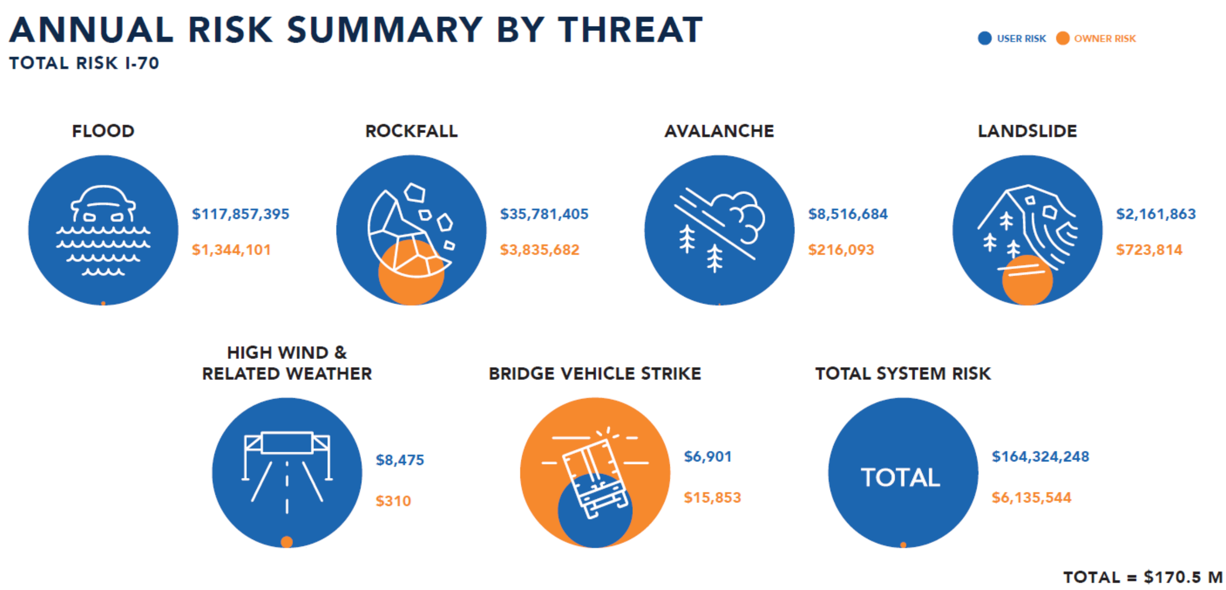


Figure 10. Annual Risk Summary by Threat for I-70 Facility

Note that high wind and tornado pose negligible risk to CDOT assets, although there are likely to be operational impacts not modeled in this study. While wildfire was assessed in the Pilot, results of this analysis are not included in Figure 10, as there were no recent wildfires in proximity to the I-70 study corridor to convey significant Owner Risk.

Rockfall poses the greatest Owner Risk to I-70 corridor with this risk predominately in the 12.5 mile Glenwood Canyon section of I-70, from near Dotsero, CO to Glenwood Springs, CO (see Figure 8). While this is not the only area with high rockfall potential, the specialized roadway construction in the canyon magnifies the impact to CDOT Owner Risk of any damage in this area, as it is "one of the most expensive rural highways per mile built in the United States." (https://en.wikipedia.org/wiki/Interstate_70_in_Colorado) User Risk for rockfall is also high, due to the limited number of alternate routes and the lengthy distances such detours entail in this area.

Flooding (overtop and debris, scour) is the second highest Owner Risk for CDOT. With bridges at MP 261 and MP 262 (both bridges in west Denver) are at greatest annual Owner Risk for CDOT. User Risk for these bridges is also high, given the volume of traffic in this area, although the number of alternative routes available in case of bridge closure somewhat mitigates this risk to users.

Landslide is the third greatest risk to CDOT assets in the corridor. The single site of greatest Owner Risk extends between MP 244 and MP 246 also known as Floyd Hill, a recognized "severe" landslide potential area on the I-70 corridor according to *the I-70 Mountain Corridor PEIS Geological Hazards Technical Report* published by CDOT in 2010 and reissued in 2011.

In addition to looking at risk resulting from specific hazards on individual assets, risk can be summarized for sections of I-70 as shown previously in Figure 8. These segments were delineated by locating key intersections to exit or join the Interstate. These key intersections are the beginning or terminus of alternate routes, should the corresponding section of I-70 be closed. Figure 11 summarizes the owner and user expected annual risk for all hazards within each Resilience Segment. In addition, Appendix B contains additional figures with more details about the calculated risks by segment, by threat. Also, Appendix C contains tables of the most at-risk assets by threat for the I-70 corridor.

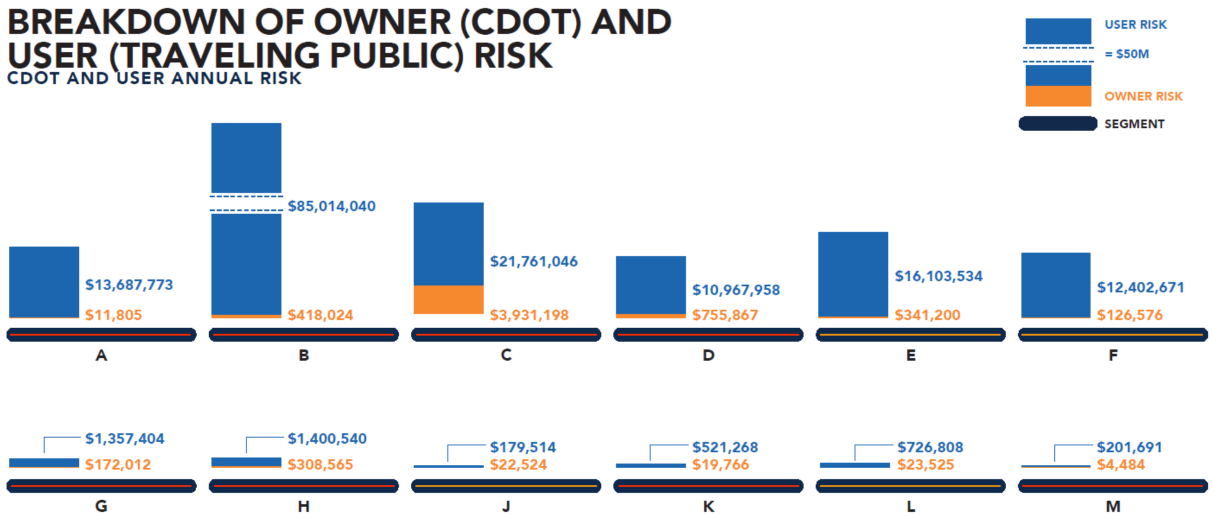


Figure 11. Annual Risk by Resiliency Segment to CDOT and the Traveling Public

Resilience Segment "B" extends from Loma, CO (MP 14) to Rifle, CO (MP 90). Most of the risk in this segment is due to threat of flooding, and the vulnerability of I-70 in this area. Resilience Segment "C" extends from Rifle, CO (MP 90) to Wolcott, CO (MP 155). This Segment includes the previously discussed Glenwood Canyon section of I-70. Again, the very expensive construction in Glenwood Canyon accounts for much the Owner Risk in this segment of I-70. This is readily apparent when comparing Segment "C" with Segment "D". Segment "D" is another mountainous segment, with several tunnels, but not the specialized expensive roadway construction found in Glenwood Canyon. A significant portion of the Owner Risk in Segment "E" is the Eisenhower-Johnson Memorial Tunnel, the longest mountain tunnel in the Interstate system, the highest point in the Interstate system, and one of the highest vehicle tunnels in the world. (https://en.wikipedia.org/wiki/Eisenhower_Tunnel)

Figure 12. GAZEX Avalanche Control Site Near EMJT Tunnel on I-70

Additional charts and graphics have been included in Appendix A for each resilience segment to better understand the type of threats present within each segment and the resulting anticiapted owner and user annual risks.

With the completion of the risk assessment, the WG next selected five locations along I-70 to which two mitigation strategies were developed, with help from CDOT regional staff, and analyzed to determine if economically feasible. The next section of the report provides an overview of the locations selected, mitigations tested, and end results.

Mitigation Site Analysis Results

Following presentation of the risk results in Workshop #3, the WG selected five specific sites for further study. Two mitigation measures were developed for each of these sites with assistance from CDOT regional staff, and an economic analysis completed for each of these potential mitigations. These activities completed steps 6 and 7 of the R&R for Highways analysis, the final analysis steps in the Pilot project. A synopsis of the candidate sites and mitigation measures are listed below.

Site 1: Milepost 112.9. Flood - Non-NBI Culvert

Mitigation Option A: Replace corrugated metal pipe with larger concrete pipe and headwalls

Mitigation Option B: Replace corrugated metal pipe with larger concrete box culvert

Site 2: Milepost 123.7. Rockfall – PTCS.

Mitigation Option A: Replace existing rockfall fences with more and higher capacity fences

Mitigation Option B: Add capture wall at slope toe

Site 3: Milepost 244.5. Landslide - Roadway

Mitigation Option A: Remove entire potential landslide material

Mitigation Option B: Raise I-70, protect with MSE wall, remove part of potential landslide material

Site 4: Milepost 356. Flood – Bridge Approach.

Mitigation Option A: Additional riprap on embankment and approach slopes

Mitigation Option B: Add cross-culverts at roadway low points, reducing stream's flow at approach

Site 5: Milepost 356. Flood - Bridge

Mitigation Option A: Additional riprap on embankment and approach slopes

Mitigation Option B: Add cross-culverts at roadway low points, reducing stream's flow at approach

Sites 4 and 5 were combined into a system analysis with the addition of the adjacent overtopped roadway segments.

Next a detailed review of the analysis approach and the results of the economic analysis is provided for each location and mitigation. Standard engineering economics equations were used to determine annualized costs of proposed mitigation measures. In addition, for each site analyzed, information was provided by CDOT staff regarding anticipated life expectancy of each mitigation measure as noted for each site and a standard 3.3% discount rate was utilized as provided by CDOT.

Site 1 Analysis: Flood-non NBI Culverts

Site 1 is located at MP 112.9 in Garfield County west of Glenwood Springs in CDOT Region 3. The AADT of this segment of I-70 is approximately 24,000 vehicles with 12.8% truck traffic. Based on the Criticality Model discussed previously, this site was rated as High Criticality. This site includes a combination of three 54" diameter corrugated metal pipes (CMP) and an asphalt roadway with two 12 ft lanes, 10 ft outside and 4 ft inside shoulders in each traffic direction (eastbound and westbound) as shown in Figure 13. However, only improvements to culverts 070A112910WL located on westbound I-70 and 070AA112930EL located on eastbound I-70 were considered in the analysis, based on recommendations from the CDOT Region 3 hydraulic team.

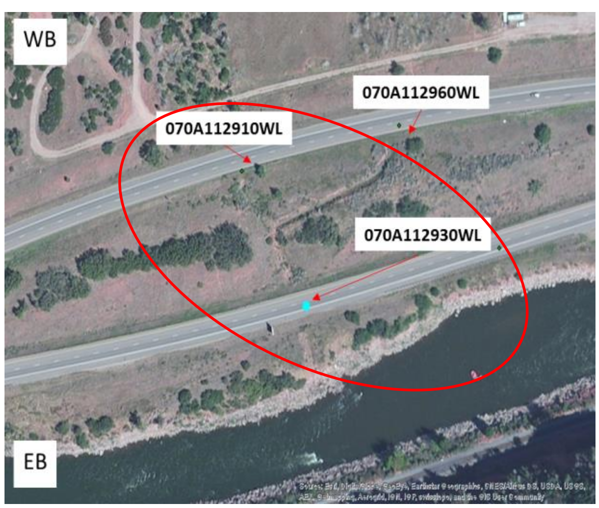


Figure 13. Site 1 Location near MP 112.9

The drainage area for this site crosses I-70 through the two minor culverts as depicted in Figure 13. Information regarding the flow conditions of the drainage was provided by CDOT and is shown in Table 5.

Table 0-E. Anticipated Flow from Specific Events

Flood Event	Flow (cfs)
25-yr Event	225
50-yr Event	300
100-yr Event	500

As shown in the Table 5, the flows in this area range from 225 cubic feet per second (cfs) for a 25-year flood event to 500 cfs for a 100-year flood. Flows for events above 100 year floods were not provided for the analysis.

Data for the two culverts in terms of dimensions and hydraulic capacity was also provided for analysis. A replacement cost was also calculated for each of the culverts and is presented on Table 6.

Table 0-F. Culvert Information

<table>
<tr><th>Culvert ID</th><th>Type</th><th>Dimensions</th><th>Existing Hydraulic Capacity</th><th>Drainage Description</th><th>Replacement Cost</th></tr>
<tr><td>070A112910WL</td><td>Corrugated Metal Pipe (CMP)</td><td>Diameter= 54”
Length = 78 ft
2-6 ft cover</td><td>100 cfs
(<25-yr)</td><td rowspan="2">0.81 mi^2
Highly erosive.
Low vegetation cover.
49% slope</td><td>$ 94,800</td></tr>
<tr><td>070A112930EL</td><td>Corrugated Metal Pipe (CMP)</td><td>Diameter= 54”
Length = 78 ft
2-6 ft cover</td><td>100 cfs
(<25-yr)</td><td>$ 90,464</td></tr>
</table>

Further information was provided regarding the condition of the culverts, as well as the condition of the channel and drainage. This information is critical to the current vulnerability assessment of the culverts. Based on the information provided, the vulnerability of both culverts was calculated at 25, 50, 100 and 500-year flood events and presented in Table 7. These vulnerabilities represent the probability of failure of the culverts and the full roadway prism at site 1 under various flood events.

Table 0-G. Vulnerability Assessment for Site 1 Existing Conditions

Culvert ID	Culvert Material	Culvert Rating	Channel Rating	Last Inspection	Scour Critical	Vulnerability (V)	Threat Likelihood (T)
070A112910WL	Metal	Fair	Good	June 2011	No noticeable deficiencies that affect condition	V_{25yr} = 0.50 V_{50yr} = 0.90 V_{100yr} = 0.99 V_{500yr} = 0.99	T_{25yr}= 0.04 T_{50yr}= 0.02 T_{100yr}= 0.01 T_{500yr}= 0.002
070A112930EL	Metal	Fair	Fair	June 2011	No noticeable deficiencies that affect condition	V_{25yr} = 0.50 V_{50yr} = 0.90 V_{100yr} = 0.99 V_{500yr} = 0.99	T_{25yr}= 0.04 T_{50yr}= 0.02 T_{100yr}= 0.01 T_{500yr}= 0.002

The estimated worst reasonable case to calculate the annual Owner and User Risks, was based on the full replacement cost of the roadway prism (including culverts) and a change in traffic operations, which includes 7 days of total closure in both directions of traffic. The estimated detour of traffic due to total roadway closure includes a 140-mile detour with 167 minutes of extra travel time. The estimated worst reasonable losses along with the vulnerabilities and threat likelihoods from the different flood events was used to calculate the annual total risk of the site from flooding.

The annual Owner Risk (cost of damaged infrastructure) and User Risk (cost to the user due to traffic delays and closures) calculations were performed for both culverts. The total annual risk is a combination of the Owner Risk and User Risk for each flood event. The results of the risk assessment at the current site conditions is presented on Table 8.

Table 0-H. Annual Risk at Site 1 for Existing Conditions from Flooding

Culvert ID	Owner Consequence (C)	Total Annualized Owner Risk	User Consequence (C)	Total Annualized User Risk	Total Annualized Risk	Site Total Annualized Risk
070A112910WL	$ 94,787	$ 4,743	$ 12,310,642	$ 616,025	$ 620,768	**$ 1,325,151**
070A112930EL	$ 90,464	$ 5,138	$ 12,310,642	$ 699,244	$ 704,383	

The total annual Owner Risk for the site is approximately $9,881 and the annual User Risk $1,315,270. Combining Owner and User Risk, the current total annual risk from flood for Site 1 is $1,325,151.

To reduce the current site risk from flooding, CDOT proposed the analysis of two mitigation options. These mitigations are summarized in Table 9.

Table 0-I. Proposed Mitigations for Site 1

Proposed Mitigation	Description	Proposed Hydraulic Design	Cost of Mitigation
Option 1	Replacement of existing culverts with Two 72" concrete pipes (1 each direction) with headwalls	50-yr (roadway overtopping at 100-yr event)	$500,000/culvert $1M/site
Option 2	Replacement of existing culverts with Two 8' x 8' CBC (1 each direction) connected with a concrete chute and improvements to private crossing above interstate	100-yr (NO roadway overtopping at 100-yr event)	$800,000/culvert $1.6M/site

Based on the proposed mitigations, the estimated annual risk to the site was calculated for each alternative (Options 1 and 2). The results for Option 1 (72" concrete pipes) and Option 2 (8' x 8' CBCs) are presented in Table 10. A reduction in risk was obtained due to improvements of the hydraulic capacity of the site from a <25-year to a 50-yr flood for Option 1 and to 100-yr flood for Option 2. An economic analysis was performed for both mitigation alternatives based on the obtained annual reduction in risk (benefit) and the annual cost of each mitigation as shown in Equation 2. Each mitigation was analyzed assuming a 100-yr expected service life.

$$\frac{B}{C} = \frac{Annual\ Expected\ Risk_{Existing\ Condition} - Annual\ Expected\ Risk_{Proposed\ Mitigation}}{Annual\ Cost\ of\ Proposed\ Mitigation} \qquad \text{Equation 2}$$

Results of the economic analysis are presented in Table 10.

Table 0-J. Economic Analysis of Mitigation Options at Site 1

Mitigation Option	Reduction in Annualized Owner Risk	Reduction in Annualized User Risk	Reduction in Annualized Total Risk	B/C Owner Risk	B/C Total Risk
Option 1 (72" concrete pipes)	$ 5,900 (76%)	$ 1,217,276 (92%)	$ 1,223,176 (92%)	0.17	35.6
Option 2 (8' x 8' CBCs)	$ 7,481 (76%)	$1,278,337 (97%)	$1,285,819 (97%)	0.14	23.4

As presented in Table 10, both mitigation options obtained the same percent reduction in Owner Risk (76%) and similar reductions on User Risk (92% and 97%). Even though there was substantial reduction in owner risk, none of the mitigation alternatives obtained a B/C greater than 1.0 (0.17 for Option 1 and 0.14 for Option 2) when only considering Owner Risk; however, when Owner and User Risks were combined (total risk) both mitigation strategies obtained B/C ratios greater than 1.0. Typically, public agencies consider investments that achieve B/C ratios greater than 1.0 worthy of consideration.

Next a site near Glenwood Canyon was analyzed for rockfall mitigation.

Site 2 Analysis: Rockfall-PTCS

Site 2 is located at MP 123.7 in Glenwood Canyon in Garfield County in CDOT Region 3. The AADT of this segment of I-70 is approximately 26,000 vehicles with 13.5% truck traffic. The Criticality Rating for this site was High utilizing the criteria described previously. This site includes a post-tension concrete slab (PTCS) roadway with two 12 ft lanes and 6 ft shoulders in each traffic direction, and five 2,000 KJ rockfall fences as shown in Figure 14.

Figure 14. Site 2 near MP 123.7 in Glenwood Canyon

Simulations using RocScience™ version 6.0 software were conducted to a portion part of the site where fences overlap for the different rockfall size events under analysis (small, medium and large). These simulations were performed to observe the effectiveness of the existent fences to mitigate the different rockfall magnitudes. Figure 15 represents the results of the simulations.

Figure 15. Rockfall Event Simulation Graphics for Existing Conditions

Data for the PTCS roadway and existing fences were provided for analysis by CDOT Geotechnical Manager Ty Ortiz. The worst reasonable case for calculating expected consequences for rockfall on

PTCS segments was estimated to be $4.4 million in repair cost for both the entire site with an estimated 7 days of total closure plus 7 days of head-to-head traffic operations. The expected detour length when this site is completely closed was calculated as 140 miles with 167 minutes of extra travel time for the users.

The vulnerabilities of the site and potential rockfall event probabilities (threat likelihoods) were developed based on the existing site conditions (2,000 KJ fencing and depressed median less than 50 feet) for the different event magnitudes (small, medium and large). Table 11 presents the vulnerabilities and threat likelihoods for the existing site conditions.

Table 11. Site 2 Vulnerabilities and Threat Likelihood for Various Event

Traffic Direction	Vulnerability (Small) (V)	Vulnerability (Medium) (V)	Vulnerability (Large) (V)	Probability (Small-1 yr) (T)	Probability (Medium-6 yr) (T)	Probability (Large- 20 yr) (T)
EB	0.00	0.014	0.29	1	0.167	0.05
WB	0.00	0.051	0.68	1	0.167	0.05

Based on the vulnerabilities, probabilities of event occurring (threat likelihood) and the expected worst reasonable case, the site Owner, User and Total Risks were calculated for the existing conditions and are presented in Table 12.

Table 12. Site 2 Annual Risk from Rockfall

Traffic Direction	AADT	Owner Consequence (C)	Total Annualized Owner Risk	User Consequence (C)	Total Annualized User Risk	Total Annualized Risk	Site Total Annualized Risk
EB	26,000 (13.5 % trucks)	$ 2.2M	$ 37,049	$ 17,612,440	$296,599	$ 333,647	**$1,233,853**
WB	26,000 (13.5 % trucks)	$ 2.2M	$ 154,493	$ 17,612,440	$ 745,712	$ 900,205	

The total annual Owner Risk for the site is approximately $191,542 and the annual User Risk $1,042,311. Combining Owner and User Risk, the current total annual risk from rockfall for Site 2 is $1,233,853.

To reduce the current site risk from rockfall, CDOT proposed the analysis of two mitigation options. These mitigations are summarized in Table 13. Option 1 was estimated to have a 10-yr service life and Option 2 was estimated to have a 50-yr service life.

Table 13. Site 2 Proposed Mitigation

Proposed Mitigation	Description	Cost of Mitigation
Option 1	Replacement of existing 2,000KJ fences with 5,000KJ fences (5 fences total)	$ 290,000/fence $ 1,450,000/site
Option 2	New 140 feet wall to existing site with 2,000 KJ fences	$ 350,000

Simulations were also performed for both mitigation options to study the remaining vulnerabilities of the site with mitigation options in place. The simulation results are presented in Figures 16 and 17 for mitigation Options 1 and 2 respectively.

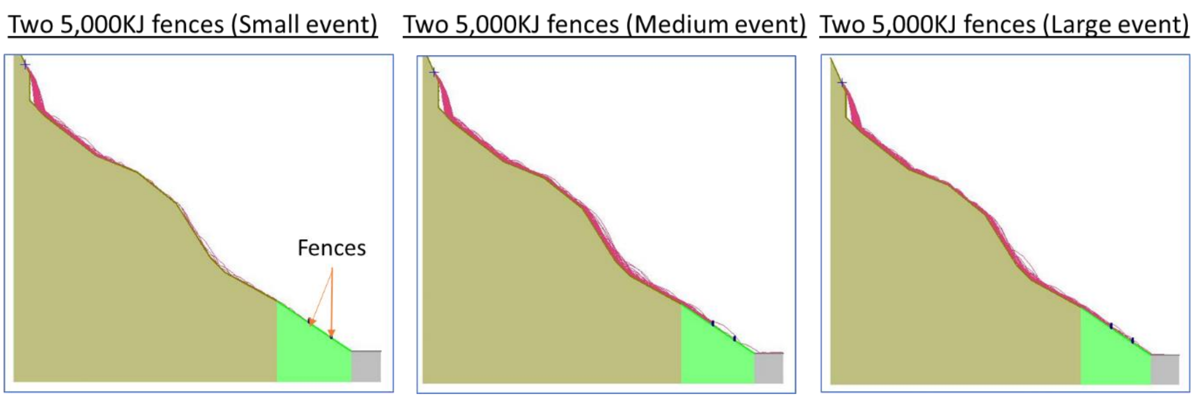


Figure 16. Rockfall Event Simulation for Mitigation Option 1

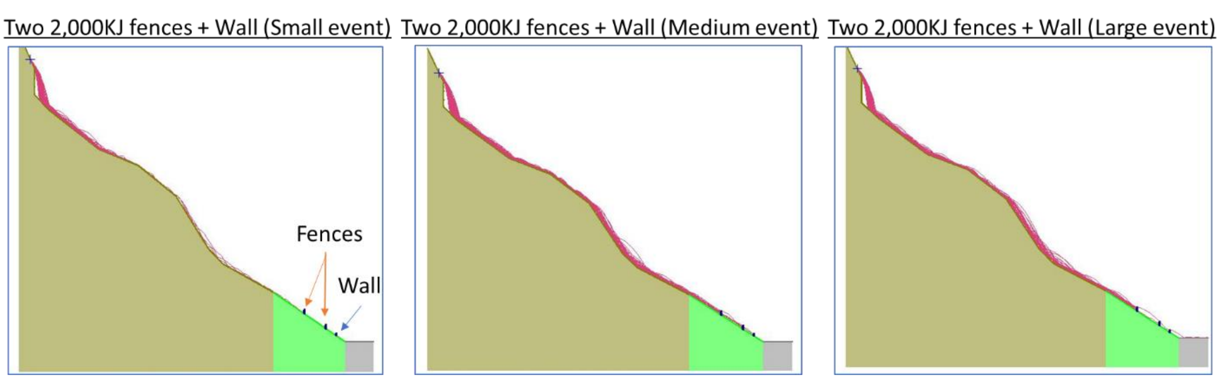


Figure 17. Rockfall Event Simulations for Mitigation Option 2

Figures 16 and 17 demonstrate how both mitigation options are expected to reduce the vulnerability of the roadway from *small* rockfall events. For *medium* events, only Option 2 demonstrates anticipated complete effectiveness of the mitigation to contain rockfall before reaching the roadway while the simulation of Option 1 depicts some of the rocks reaching the roadway.

Based on the proposed mitigations, the estimated annual risk to the site were calculated for each alternative (Options 1 and 2) and the results are presented in Table 14. A reduction in risk was obtained due to improvements to the site rockfall mitigations from 2,000 KJ fencing to 5,000 KJ fencing for Option 1 and 2,000 KJ fencing plus a wall for Option 2. An economic analysis was performed for both mitigation alternatives based on the obtained annual reduction in risk (benefit) and the annual cost of each mitigation as shown in Table 14.

Table 14. Economic Analysis of Mitigation Alternatives

Mitigation Option	Reduction in Annualized Owner Risk	Reduction in Annualized User Risk	Reduction in Annualized Total Risk	B/C Owner Risk	B/C Total Risk
Option 1 (5,000 KJ fencing)	$ 64,306 (29%)	$ 346,782 (28%)	$ 411,088 (28%)	0.37	2.7
Option 2 (2,000 KJ fencing + Wall)	$ 47,286 (21%)	$ 310,188 (25%)	$ 357,474 (24%)	3.29	24.8

As presented in Table 14, mitigation Option 1 obtained a slightly higher percent reductions in Owner Risk (29%) and User Risk (28%) than Option 2 (21% Owner Risk and 25% User Risk). Even though there was higher reduction in both Owner and Total Risk (28%) for Option 1 compared to Option 2 (24% total risk), the Option with higher B/C ratios was Option 2 with a B/C of 3.29 based when considering Owner Risk only and 24.8 based on Total Risk. These results are a consequence of the difference in cost of mitigation Options with Option 1 having an initial cost for the site of $1.45 million and Option 2 of $350,000. Each option, when considering both Owner and User Annual Risk, provide B/C ratios greater than 1.0 and as noted previously, would warrant additional consideration by most public agencies.

Site 3 Analysis: Landslide-Roadway

Site 3 is located at MP 244.5 (Floyd Hill slide) in Clear Creek County (CDOT Region 1). The AADT of this segment of I-70 is approximately 40,000 vehicles with 6% truck traffic. Utilizing the Criticality Criteria previously described, this location was rated as Low to system resilience. This site includes an asphalt roadway with five 12 ft lanes (two lanes eastbound and five westbound) and 10 ft shoulders in each direction. Figure 18 includes a graphic of the landslide area and of I-70 near MP 244.5.

Figure 18. Site 3 near MP 244.5

Data for the existing site was obtained from ArcGIS online (Landslides Monitored by CDOT), CDOT files and a report published by Yeh and Associates for CDOT in 2005 for this landslide. CDOT monitoring data and the geotechnical report describe the Floyd Hill slide as a large landslide area with an estimated 20 acres and with moderate frequency of movement. The potential landslide impact area is approximately 500 to 700 linear feet of the existing roadway alignment perpendicular to the landslide. The worst reasonable case of losses this size landslide is estimated to be $15 million including clean up and repair costs for the roadway. Also, the worst reasonable consequences to travelers should the landslide occur was estimated to be 25 days of total closure plus 25 days of head-to-head traffic operations. The expected detour length when this site is completely closed was calculated as 49 miles with 77 minutes of extra travel time for users based on available CDOT routes around the potential landslide area. The Floyd Hill landslide is located at mile post 244.6, part of resilience segment F. The detour for segment F starts from the west, at mile post 231, and runs east through Empire Rd/US-6, south through SH-103 in Idaho Springs and east until it intersects SH-74, then north on SH-74 until SH-74 intersects US- 40, and then west on US-40 until it intersects I-70 for a total distance of approximately 49 miles.

The vulnerabilities of the site and potential landslide events probabilities (threat likelihoods) were developed based on the existing site conditions, such as landslide size, for the different event magnitudes (small, medium and large). Table 15 presents the vulnerabilities and threat likelihoods for the existing site conditions.

Table 15. Site 3 Vulnerabilities and Probability of Occurrence of Landslide

Traffic Direction	Vulnerability (Small) (V)	Vulnerability (Medium) (V)	Vulnerability (Large) (V)	Probability (Small) (T)	Probability (Medium) (T)	Probability (Large) (T)
EB +WB	0.025	0.143	0.743	0.1876	0.0473	0.0108

Based on the vulnerabilities, probabilities of event occurring (threat likelihood) and the expected worst reasonable consequences, the Owner, User and Total Risks were calculated and are presented in Table 16.

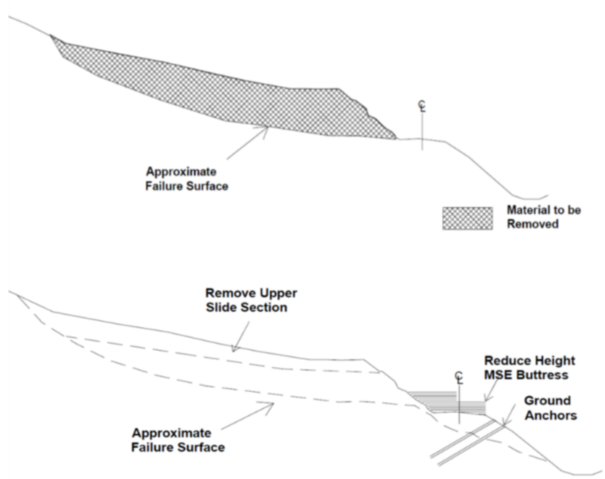
Table 16. Annual Risk from Landslides

Traffic Direction	Owner Consequence (C)	Total Annualized Owner Risk	User Consequence (C)	Total Annualized User Risk	Total Annualized Risk
EB +WB	$ 15M	$ 290,797	$ 72,696,385	$1,409,324	**$ 1,700,121**

The total annual Owner Risk for the site was calculated to be $290,797 and the annual User Risk was calculated to be $1,409,324. Combining Owner and User Risk, the current total annual risk from landslide at this location is $1,700,121. To reduce the current site risk from landslide, two mitigation options were chosen from the Yeh and Associates Geotechnical report (Yeh and Associates, Inc., 2008) with approval from CDOT. These mitigations are summarized in Table 17.

Table 17. Proposed Mitigations for Site 3

Proposed Mitigation	Description	Cost of Mitigation
Option 1	Removal of entire landslide section	$ 30 M
Option 2	Moderate Raising of I-70 Alignment with MSE wall for increase in grade with partial removal of the landslide material	$ 18.4 M



A reduction in risk was obtained due to improvements to the site in terms of landslide mitigations based on the two proposed options. An economic analysis was performed for both mitigation alternatives based on the obtained annual reduction in risk (benefit) and the annual cost of each mitigation. The expected life of Option 1 was estimated to be 150 years and for Option 2 to be 100 years. Results of the economic analysis are presented in Table 18.

Table 18. Economic Analysis of Mitigation Alternatives for Site 3

Mitigation Options	Reduction in Annualized Owner Risk	Reduction in Annualized User Risk	Reduction in Annualized Total Risk	B/C Owner Risk	B/C Total Risk
Option 1	$ 260,482 (90%)	$ 1,262,409 (90%)	$ 1,522,891 (90%)	0.26	1.53
Option 2	$ 100,786 (35%)	$ 488,451 (35%)	$ 589,237 (35%)	0.16	0.93

As presented in Table 18 mitigation Option 1 obtained a higher percent reductions in Owner Risk and User Risk (90% both Owner and User Risk) while Option 2 is estimated to expect a 35% reduction in both Owner and User Risk. Given the relatively low estimated reduction in annual risk and the high cost associated with Option 2, a B/C ratio greater than 1.0 was not able to be achieved, however, Option 1, despite its high initial investment cost, is able to achieve a B/C ratio greater than 1.0 given the estimated high reduction in annual risk. Floyd Hill has been an area of study for many years by CDOT and the results of this analysis support the continued efforts by CDOT to reduce potential landslide potential in this area.

Site 4 & 5 Analysis: Flood-Bridge/Approach/Roadway (System Analysis)

Site 4 and 5 are located at MP 356 in Elbert County in CDOT Region 4. The AADT of this segment of I-70 is approximately 11,000 vehicles with 25% truck traffic. Utilizing the Criticality Model for System Resilience previously describe, this location was rated as High. This site has multiple assets including a concrete roadway with two 12 ft lanes, 10 ft outside and 3 ft inside shoulders in each direction of traffic, and two bridges on I-70 mainline. Due to the combination of multiple assets into the analysis, this site was analyzed as a system of roadway, bridge and approaches as shown in Figure 19.

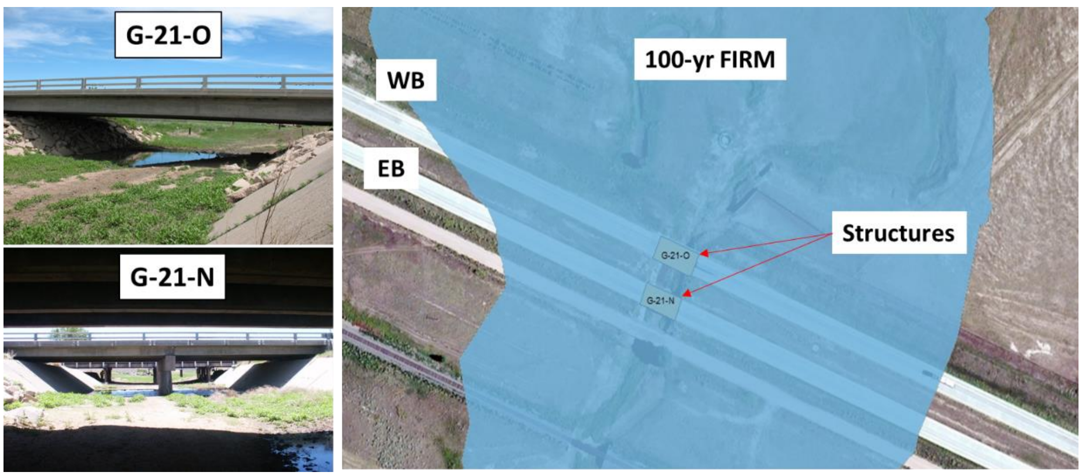


Figure 19. Site 4 & 5 near MP 356

Data for the existing site was obtained from the National Bridge Inventory (NBI) database, FEMA Flood Map Service Center and CDOT files. The potential flood threat to the site was based on asset overtopping from the FEMA Flood Insurance Rate Maps (FIRM) for 100-year and 500-year flood events. The worst reasonable consequences from flooding was estimated for each asset based on full replacement costs if overtopped by a 100 or 500-yr flood event. The worst reasonable consequences to users was estimated to be 180 days of total closure for replacement of both bridges, 1 day of total closure for replacement of roadway approaches, and 5 days of total closure plus 15 days head-to-head traffic operations for roadway segment damage. The expected detour length when this site is completely closed was calculated as 71 miles with 96 minutes of extra travel time for users.

The vulnerabilities of the site and potential flood events probabilities (threat likelihoods) were developed based on the existing site conditions for each asset and engineering judgement. Table 19 includes the estimated vulnerabilities and threat likelihoods for the existing site conditions.

Table 19. Vulnerabilities and Occurrence Probabilities to Flooding

Asset	Overtopping (Asset Dimensions)	Vulnerability ($V_{100\text{-}yr}$)	Vulnerability ($V_{500\text{-}yr}$)	Scour Failure Probability (P)	Flood Probability ($T_{100\text{-}yr}$)	Flood Probability ($T_{500\text{-}yr}$)
Bridges: G-21-N (EB) G-21-O (WB)	83 ft. W x 41.99 ft. L 89.9 ft. W x 44.62 ft. L	0.008	0.21	0.00025	0.01	0.002
Approaches: G-21-N East G-21-N West G-21-O East G-21-O West	37 ft. W x 20 ft. L each approach	0.66 0.60 0.30 0.30	0.99 0.99 0.60 0.60	N/A	0.01	0.002
Roadway: Eastbound Westbound	37 ft. W x 890.5 ft. L 37 ft. W x 1,072.2 ft. L	0.24	0.60	N/A	0.01	0.002

Based on the vulnerabilities, probabilities of event occurring (threat likelihood) and the expected worst reasonable consequences, the Owner, User and Total Risks were calculated as shown in Table 20.

Table 20. Site 4 & 5 Annual Risk Assessment from Flooding

Asset Type	Owner Consequence (C)	Total Annualized Owner Risk	User Consequence (C)	Total Annualized User Risk	Total Annualized Risk	Site Total Annualized Risk (System)
Bridges	$ 3,298,613	$ 2,487	$ 179,016,205	$ 134,978	$ 137,465	**$ 156,021**[1]
Approaches	$ 757,020	$ 4,724	$ 994,534	$ 6,206	$ 10,930	
Roadway	$ 3,842,182	$ 13,832	$ 9,745,811	$ 17,542	$ 31,374	

[1] Based on the combination of all assets Owner Risk and the ***highest*** User Risk for the site

The total annual Owner Risk for the site as a system is approximately $21,043 (combination of all assets) and the annual User Risk $134,978 (highest of all assets). Combining Owner and User Risk, the current total annual risk from flooding for Site 4 is $156,021. To reduce the current site risk from flooding and scour, two mitigation options were recommended by CDOT. These mitigations are summarized in Table 21.

Table 21. Mitigation Options for Site 4 & 5

Proposed Mitigation	Description	Hydraulic Capacity	Cost of Mitigation
Option 1	Additional riprap around channel embankments and approach side slopes	50-yr (bridge overtopping at 100-yr event)	$ 150,000/structure $ 300,000/site
Option 2	Flow relief structures (cross culvert) at low points along highway	75-yr (bridge overtopping at 100-yr event)	$ 500,00/structure $ 1M/site

Option 1 and 2 were estimated to have an expected service life of 100 years. An economic analysis was performed for both mitigation alternatives based on the obtained annual reduction in risk and the annual cost of each mitigation. Results of the B/C analysis are presented in Table 22.

Table 22. Economic Analysis of Mitigation Alternatives (System Analysis)

Mitigation Option	Reduction in Annualized Owner Risk	Reduction in Annualized User Risk	Reduction in Annualized Total Risk	B/C Owner Risk	B/C Total Risk
Option 1 (additional riprap)	$ 10,016 (48%)	$ 0 (0%)	$ 10,016 (6%)	0.97	0.97
Option 2 (flow relief culverts)	$ 11,601 (55%)	$ 6,767 (5%)	$ 18,368 (12%)	0.26	0.41

As presented in the Table 22, mitigation Option 2 obtained higher percent reductions in both Owner and User Risk (48% Owner and 5% User Risk) than Option 1 (48% Owner and 0% User Risk). Even though Option 2 had a greater percent reduction in Total Risk than Option 1, the B/C ratios for Option 1 (0.97 based on Owner and Total Risk) is much higher than the B/C ratios for Option 2 (0.26 based on Owner and 0.41 based on Total Risk). One of the main factors on the difference in B/C ratios, is the cost of the mitigation Options ($300,000 for Option 1 and $1,000,000 for Option 2) which reduces the B/C ratio for Option 2. Given the relatively high B/C ratio for Option 1, this option may be something to consider by CDOT to reduce Owner Risk. A more detailed analysis of cost and design may provide a B/C ratio greater than 1.0.

Summary of Site Mitigation Analysis

The purpose of the site mitigation analysis was to demonstrate the potential use of the information developed through the 7-step R&R for Highways Process to support decision making. While not specifically called out through these examples and mitigation measures, this same approach could be used to assess the return on investment provided by operational, maintenance, or alternative route mitigation measures. Next, key results from the Pilot are presented.

Key Results and Findings

I-70 from MP 90 to MP 155 has the greatest Owner Risk of any segment.

This risk is predominately from rockfall, and is largely a result of the extremely expensive construction in the Glenwood Canyon area, the high probability of rockfall based on the area's topography, and the very narrow right of way. The dis-proportional influence of the very expensive PTCS (post-tensioned concrete slab) construction located in a narrow, high-threat canyon is evident in the Owner Risk results. This is further visible when comparing rockfall Owner Risk for westbound and eastbound lanes in the Canyon. The westbound lanes are closest to the canyon walls in nearly all cases, thus facing a greater threat probability than the eastbound lanes. The westbound lanes also have a greater proportion of very expensive PTCS construction than do eastbound lanes. A total of approximately 32 centerline miles of roadway (of 450 centerline miles comprising I-70) are threatened by rockfall.

Figure 20. Rockfall Potential near Twin Tunnels on I-70

Flooding Risk is the second highest Owner Risk to CDOT.

Roadways, as an asset class, are at the greatest Owner Risk for flooding, however, this must be taken in context of the I-70 corridor. There are approximately 22 centerline miles (of the total 450 centerline miles of I-70) subject to 100-year and/or 500-year floods. In most cases, roadway flooding is shallow and low velocity, conditions to which the roadway prism is only minimally vulnerable. In the case of bridges, most of the risk to flooding-susceptible CDOT bridges is from scour, with little risk from overtopping or debris. Culverts ranked third in Owner Risk for flooding. While some culverts are in CDOT's bridge monitoring and reporting system, most culverts are not. Lack of data on culvert and channel condition for these culverts makes calculating the likely effect of peak rain events and increased debris flows and sedimentation due to wildfires difficult to calculate. With wildfire an increasing threat due to forest pestilence, and historical droughts in the region, understanding such impacts is important so that maintenance and/or replacement can be scheduled.

Given I-70's east-west alignment, we anticipated relatively little risk from flooding; the Pilot bore this out when considering the total estimated annual risk from flooding to CDOT (Owner) of only $1.3 million for an estimated 450 centerline miles of I-70. Conversely, we expect significant flooding risk for the north-south I-25 corridor, oriented as it is parallel to the Colorado Front Range. This alignment has historically resulted in greater, deeper, faster flows, making I-25 more vulnerable to flooding than is I-70. However, given the relatively lengthy detours on I-70, flooding is estimated to have a greater impact on travelers annually (approximately $117 million) than what may be expected on I-25 which has a higher density of alternative routes available to travelers than I-70.

Figure 21. Eastern Colorado High Plains Area I-70

High *Vehicle Strikes to bridges, tornados, and very high winds (the front range is designated as an ASCE-7 Special Wind Region) have negligible Owner Risk across all CDOT asset classes.*

High vehicle strikes on bridges (vertical strikes) are infrequent events in the CDOT system, based on CDOT records. When strikes have historically occurred, bridge damage has been relatively minor. Extensive review of available literature failed to result in a single Interstate bridge that has been damaged by a tornado. Documented roadway prism damage from tornados is limited to very rare instances of minor pavement scour caused by EF4 and EF5 tornados. No cases of tornado damage to culverts were located. ITS/VMS and wall damage from tornados is possible, with vulnerability dependent on asset design standards and asset condition. Risk for ITS/VMS and walls was calculated to be negligible for the assets we could locate in the I-70 corridor. Note that tornado risk will be higher for ITS/VMS assets and wall assets in other areas of the larger CDOT system, more historically prone to tornados than is the I-70 corridor. VMS/ITS assets in the I-70 corridor are designed to meet the ASCE-7 Special Wind Region conditions. Accordingly, Owner Risk from this threat is negligible.

Figure22. Variable Message Signs (VMS) in Denver Metro

Multiple hazards impacting any single asset are uncommon; most assets that are threatened by any natural hazard at all are subject to only a single hazard.

For example, there are few bridges that are susceptible to flooding (scour, overtopping, and debris) and to rockfall. Assets impacted by three or more hazards are even more uncommon (e.g., a bridge threatened by flooding, rockfall and avalanche). Resilience Segments (or corridors) can be characterized by the predominant hazard in that area. For example, the Rockfall Owner Risk for Resilience Segment "C" outweighs the next most consequential Owner Risk. Understanding the relative degree of Owner Risk can assist CDOT in developing mitigation alternatives, by focusing on the greater threat, thereby greatly reducing risk.

There are few alternate routes for the portions of the I-70 west of Denver.

The available alternate routes are lengthy, and not built to accommodate a large percentage of typical I-70 traffic volume detouring for any protracted duration. Even brief closures of these portions of I-70 and re-routing of traffic impart significant damage to these alternate routes, and saddle communities on these routes with unusual noise, vehicle emissions, and traffic congestion. Pressing these alternate routes into use during I-70 closures increases CDOT expense in repairing these alternate routes. The distances and travel time required to traverse these alternates is also reflected as greatly increased User Risk.

Recommendations from Working Group

At the conclusion of Workshop #4, the WG discussed potential next steps to incorporate risk and resilience analysis into CDOT business practices. The WG recognized the value produced through the process applied to the I-70 facility through the R&R Pilot to a range of CDOT daily business practices ranging from operational planning to long range planning and maintenance. Many of the WG members made specific recommendations as to where they could envision the output from an R&R analysis being used within their day to day activities. In addition, a presentation was made to the Executive Team including Division Heads and Regional Transportation Directors in late August 2017, this group also had recommendations for inclusion of R&R analyses into maintenance prioritization activities, Planning and Environmental Linkage Studies, and Asset Management Prioritization Models.

The four-primary recommendation from the WG for next steps with regard to risk and resilience analysis and application in CDOT are:

1. Development of a base risk map for the CDOT system for a prioritized set of corridors
2. Development of a CDOT standard for risk and resilience assessment
3. Development of case studies to demonstrate the application of risk and resilience analyses
4. Review of CDOT policies, manuals, standards, and models for funding allocation to determine appropriate locations for inclusion of risk and resilience analysis findings and procedures

The purpose and intended use of each recommendation are discussed further herein.

The first recommendation of the WG is to develop a base-risk map for the CDOT system for a prioritized set of corridors. The intended use of the map is to provide CDOT staff with a base-risk map developed with consistent models, data sets, threat maps from the same data sources and dates, and consistent input into user and owner risk models. With a base-risk map, CDOT can be assured that risk assessments for potential mitigation measures will be compared consistently across the system. The development of such a map will also feed CDOT's next Risk-Based Asset Management Plan and meets the desire of FHWA for CDOT to integrate the process used in response to the 2013 flood event to replace damaged assets with betterments. The WG envisioned the proposed base map being housed within a system regularly utilized by CDOT staff.

The second recommendation of the WG is to develop a CDOT standard for risk and resilience assessment. The purpose of a standard is to nail down data sources, inputs, models, and procedures used to analyze risk and system resilience for future applications including mitigation assessments. The standard would bound variable ranges and limits to provide CDOT confidence in the results it may be presented by the consulting industry when analyzing mitigation strategies to reduce risk and increase system resilience. The standard could also be a location to establish standard threats to be considered and the sources for the maps allowed to be used in analyses.

The third recommendation of the WG is to develop case studies to demonstrate the application of risk and resilience analyses. Utilizing members of the WG, case studies are recommended to be developed and distributed to CDOT staff to increase awareness of the risk and resilience process and its potential applications. Recommended initial case studies include Planning and Environmental Linkage Studies in Region 4, development and usage of a prioritized culvert list based on annual risk for I-70 Region 3 Maintenance or Hydraulics Staff to determine usefulness of risk information, and Operations case study where assessments of alternative routes near high risk areas would be assessed to determine their ability to carry additional traffic or withstand similar threats.

The final recommendation of the WG is a review of CDOT business practices to determine applicable areas for inclusion of risk and resilience analysis and findings. The review could be conducted in part through business process mapping and again would utilize the WG and their varied areas of expertise to determine applicable policies, manuals, standards, and models that could benefit from information available from risk and resilience analyses. Initial practices and policies identified by the WG include the CDOT Project Design Manual, Planning and Environmental Linkage Studies, Asset Management Program Procedures and Models, TSMO Program, and Maintenance Project Prioritization.

Recommendations for Risk and Resilience Implementation from the Project Team

Bridging the processes and results of the R&R Pilot to asset management entails expanding risk management from the asset level into an organizational framework. CDOT will need to establish processes to ensure STIP projects are evaluated for risk, consistent with asset management principles, and integrated with long-range planning. This will entail integrating R&R for Highways with the current life cycle cost (LCC) approach for bridges, and pavements, and extending LCC to CDOT's remaining asset classes, all documented in a "living" strategic plan.

With the preceding objectives, and based on 15 months of interaction with CDOT personnel, work with CDOT data, and feedback collected during the Pilot, we have developed a series of strategic recommendations for CDOT consideration as the Department continues its work to implement Risk and Resilience. These recommendations have been grouped into three areas: Data (D); Management (M); and R&R Implementation (R).

Data Recommendations

CDOT has a wealth of data in-house or resident with partner agencies and organizations (e.g., Colorado Avalanche Information Center). This data is a significant CDOT asset, but is not yet managed in the same fashion and with the same attention as data concerning bridges and pavements. The result is that CDOT data is an undervalued and underutilized resource. One significant implication is that data is not readily available to help field personnel, managers, CDOT partners and those with oversight responsibility in planning for and managing CDOT assets. CDOT implicitly recognized this at the outset of the Pilot, designating the DAT (Data Advisory Team) to assist in the WG in performance of the Pilot. AEM Corporation has provided CDOT with a separate Technical Memorandum that outlines the data sources used in this Pilot Study and any challenges associated with obtaining that data.

In broad terms, CDOT has need of an overarching asset data strategy. This includes a set of governing objectives aligned with CDOT organizational goals to "…improve the CDOT website and COTRIP," and to "…update and launch C-Plan data repository. Promote data consistency with web-based mapping tool and data repository for CDOT staff, planning partners, other stakeholders, and the public." An asset data inventory plan establishing the level of detail required for each asset class is a key element of the data strategy.

An asset data inventory plan requires a standardized approach for assets beyond the extensive data in-hand for pavement and bridge assets. This plan, prioritized by corridor to collect data in the "right of way" for select corridors (e.g., vehicle based LIDAR/4-band imaging) would form a key tenet of CDOT's larger asset data strategy. A second component of the asset data inventory strategy is the development of a data warehouse--a central repository for all data, and a "single source of truth". Optimally, the warehouse will integrate and house planning, operational, and technical data. Such a data warehouse can provide employees from across the organization access to condition, inventory, and other key asset management data for decision-making purposes. Further, it is a foundation for future cross-asset data integration and decision-making capabilities. As a component of larger data governance efforts at CDOT, the asset management data warehouse--when fully integrating technical and financial data--is a means of closing the gaps business intelligence and analytics. Serving inventory and condition data to the public as "raw" data and GIS files also serves CDOT's transparency, communication and outreach goals; it also obviates the need to guess what data is needed internally or by the public.

This discussion and recommendations align with CDOT initiatives in the Department's 2015 Action Plan. Developing a strategic, comprehensive management approach to data, and associated structures, processes, personnel, and funding will permit CDOT to use its data to support data-driven resource decisions. This will also greatly assist CDOT in complying with federal reporting requirements, and better communicate with the Colorado Transportation Commission, partner departments, and the public at large.

D1. Label all CDOT assets (individual assets) with location information. Location information ideally includes both high-precision Latitude and Longitude, and the associated MP (to the nearest 0.01 mile). All assets should be developed as GIS feature classes in the appropriate geometry(ies) (e.g., culverts as GIS polyline feature classes).

D2. Conduct a trade study on costs and benefits of collecting vehicle-based LIDAR and imagery of CDOT assets. The study should include a plan for and the cost of periodic updates.

D3. Conduct a trade study on costs and benefits of collecting aerial LIDAR and 4-band imagery (Red, Green, Blue (RGB) near Infra-red (NIR)) of CDOT assets. Investigate Colorado Office of Emergency Preparedness and Response, counties, MPOs and other agencies and jurisdictions as funding partners. The study should include a plan for and the cost of a statewide, omnibus contract with product options (LIDAR, imagery, resolution) and periodic updates.

D4. Provide access throughout CDOT to the data, tools, and resources developed during the Pilot via a centralized, web-based asset data portal.

> D4A. Develop a web-based GIS to host and serve CDOT asset data ("raw data and GIS files), with access throughout CDOT. At a minimum, the GIS should support access via the map, by asset class, by specific asset identifier, or by threat.
>
> D4B. Develop web-based asset management dashboards, tied to CDOT business processes (e.g., asset management), accessible throughout the agency.
>
> D4C. With the active participation of the Regions, develop the business plan (including user requirements, system requirements, performance metrics, CDOT process strategic integration plan, and IT systems, schedule, cost, funding and implementation schedule) to implement D4A – D4C.

D5. Develop roadway elevation data for each roadway segment CDOT manages.

D6. Develop upslope/downslope rockfall vulnerability for each roadway segment CDOT maintains, in areas subject to this hazard.

D7. Publish AADT truck statistics for CDOT Major Roads, and AADT (including trucks) for *Local Roads*. Also publish roadway components for all Major and Local Roads (e.g., number of lanes, lane width, shoulder width, median type, surface type, IRI, etc.).

D8. Resolve location and attribute information for Signs. The Pilot uncovered mis-labeled ITS signs coded as overhead signs. Control boxes were also mis-labeled as ITS signs.

The following recommendations are specific asset attributes to collect, based on asset class. These recommendations can be used to support CDOT's GIS data capture strategic plan.

D9. Wall attributes

- Resolve location and attribute information for Walls
- Wall age/installation date
- Date of most recent inspection
- Wall condition (consistent, objective rating scale)
- Date/type of last maintenance.
- Wall physical dimensions:
    - Length, height (mean, max, min)
- Wall material, and facing material
- Include detail on wall anchor/footing system, and drainage system.
- Footing type

D10. Culvert attributes

- Useful service life
- Annual maintenance cost (deterioration curve)

D11. Bridge/Bridge Approach attributes

- Abutment type
- Approach material/construction
- Bridge Hydraulic Capacity
- Bridge Water Surface Elevations (WSE) at 100-yr and 500-yr floods and lower chord elevation
- Guidance on obtaining bridge information from BRM (NBI data not up to date with latest inspection reports from BRM)
- Publish bridge clearance height for all bridges over roadways, regardless of roadway class beneath the bridge.

D12. VMS/Signs attributes

- Age/installation date
- Date of most recent inspection
- Condition (consistent, objective rating scale)
- Useful service life
- Develop classification for ITS sign types, to distinguish among sign/pole designs/cost.
- Capture date/type of last maintenance.
- Annual maintenance cost (deterioration curve)

D13. Study the benefit-cost of establishing a CIO (Chief Information Officer). Establishing this position would provide CDOT a focus for planning, organizing, and leveraging CDOT data, an asset currently underutilized. *NOTE: Since the time of the initial development of this report, CDOT has hired a CIO who is currently establishing procedures for CDOT related to data and information.*

D14. With stakeholder participation, plan for and implement a strategic, comprehensive CDOT data strategy. The dramatic increase CDOT data, proliferation of databases and information systems, and various data-intensive initiatives (asset management systems, the I-70 Corridor R&R Pilot to identify two) underscore the importance to CDOT and the public of managing CDOT's growing data resources. Adoption of new data sources such as vehicle-based LIDAR and high-resolution imagery of CDOT assets further underscore the need for a strategic, comprehensive data plan.

D15. Secure multi-year funding for the preceding recommendations.

Management Recommendations

CDOT leadership has taken a variety of strategic initiatives to formally integrate Risk and Resilience planning in the agencies daily operations and business processes. An early, visible and continuing initiative is CDOT's Risk-Based Asset Management Plan (AMP), first published in 2014. Expectations for the AMP as a foundational document guiding R&R activities are discussed in the CDOT 2015 Action Plan,

> *Due to increased demand and diminishing funding, previous approaches to maintaining the transportation system are no longer sufficient…As a result, CDOT's executive director and the Transportation Commission directed staff to develop the Risk-Based Asset Management Plan (RB AMP) to chronicle CDOT's history of asset management, and define a framework for implementing new asset management strategies…*
>
> (Colorado Department of Transportation, 2015)

CDOT has committed to further expanding asset management integration across its day-to-day operations, business practices, and strategic planning. CDOT has plans to develop and adopt an improved Statewide Transportation Improvement Program (STIP). The new STIP will be based on an updated STIP framework to support cash management practices, streamline project/program budget processes, and be more public friendly. On a long-range, strategic basis, CDOT should commit to incorporating R&R processes in its Statewide Transportation Plan (SWP).

CDOT's Action Plan enumerates the following specific R&R initiatives:

- Develop a framework for addressing risk and resiliency and incorporating strategies into planning, programming, and project development.
- Develop a framework to ensure that the risk and resiliency of the statewide transportation system in the face of natural, economic, or other disasters is considered as part of planning, programming, and project development processes.
- Develop a framework for risk and resiliency plan.
- Coordinate with Colorado Resiliency Working Group.
- Develop framework for identifying and assessing transportation system vulnerabilities.
- Identify strategies and develop framework for incorporation into CDOT processes.

In its Action Plan, CDOT has also identified initiatives supporting its R&R efforts. Although not R&R initiatives per se, operational and business practices identified below must be aligned with R&R efforts, if the Department's objectives are to be met. Such key R&R enablers include:

- Implement and report performance measures for the Department
- Improve key business processes and financial controls
- Improve maintenance business processes to focus on accomplishments and target setting

- Develop 10-year Capital Program
- Implement I-70 mountain corridor and I-25 operations improvements
- Integrate Benefit Cost Analysis and economic evaluation in planning and programming

The following Management recommendations are offered to further the initial steps CDOT has taken to incorporate Risk and Resilience analysis into its daily and strategic business practices. In some cases assignment of responsibilities could be assigned to existing CDOT committees, however, AEM Staff is not familiar with CDOT committees that may exist currently.

M1. Create a new governance structure to provide recommendations to the Transportation Commission based on R&R results for approval.

M2. Establish a standing R&R asset management committee within CDOT, chaired by a PE and reporting directly to the CDOT Chief Engineer. The focus is on "ensuring horizontal and vertical communication and integration across CDOT relative to R&R and asset management" and, in general, evaluating the direction of CDOT's asset management program annually. Membership should include the Asset Management Director and designated division leaders.

M3. Transition the Pilot Project Working Group to a standing R&R WG to support the R&R asset management committee by "enhancing communication flow between the strategic work of the R&R office and the 'boots on the ground'" technical experts. R&R WG should reflect the membership and organization of the Pilot Project Working Group.

M4. Fund R&R efforts at the level of 1% to 2.5% of CDOT annual budget. Apply R&R to all CDOT assets, develop data, update Risk-Based Asset Management Plan, complete twice-damaged reporting, enhance LCC and performance reporting. Develop R&R Roadmap (see Appendix for initial concept).

M5. Educate and train asset managers, PEs, and HQ staff in R&R concepts. Determine applicability to daily tasks and responsibilities.

M6. Incorporate R&R analysis in the STIP funding process, as part of project review.

M7. Develop methods to use SAP to track losses from events that could be used in the future to feed the R&R model. Code "events" that require expenditures of any funds (those under the ER limits of $750,000 as well) so that we could analyze all events, even those that CDOT would address internally. This would provide "single source of truth" for both small and large events.

M8. Conduct peer exchange with other DOTs to share knowledge and experience.

M9. Advocate with FHWA and AASHTO for an AASHTO R&R for Highways standard, similar to the AWWA J-100 Standard for Risk and Resilience Analysis for Water and Wastewater.

M10. Expand existing processes to formally and routinely engage transportation partners and stakeholders in R&R analysis, results, and recommendations. Stakeholders range from public interest (e.g., Glenwood Canyon) to Colorado Agencies (Colorado Water Resources Board) and federal organizations (US Geological Survey).

M11. Set up R&R dissemination mechanisms including webinars, speaking engagements, case studies, and online resources.

M13. Integrate results with Colorado emergency management and Governor's Resilience Office.

Risk and Resilience Implementation Recommendations

One of the most overt examples of CDOT's commitment to developing and implementing R&R processes in the Department is the I-70 Risk and Resilience (R&R) Pilot, initiated in August 2016. This 15-month study builds on the work completed by CDOT in the wake of the 2013 flood event, and represents an attempt to more proactively address potential vulnerabilities in Colorado's transportation infrastructure. It focuses on approximately 450 miles of I-70 that extends the width of Colorado, from the Utah border in the west to the Kansas border in the east. The Pilot covers an incredible and diverse range of geographies and climates in both urban and rural areas and considers multiple significant threats facing the state's infrastructure—ranging from avalanche to wildfire as well as direct threats such as bridge strikes. The Pilot also makes use of the expertise of CDOT staff from all five regions of the agency (engineering, maintenance, operational, planning, and executive staff). This allows for buy-in and coordination across the Department, so that the most proactive and cost-effective ideas can be implemented. In this way, CDOT continues to ensure that the state's infrastructure remains operational and that taxpayer funds are spent responsibly.

Application of the R&R for Highways framework is a translation of CDOT goals and values into asset management decisions:

- Risk is an objective measure of asset value--per asset, and within the system
- Risk is a tie-breaker for prioritizing projects and/or funds
- Risk can be used to identify, implement, and refine asset management practices

R1. Establish a standing Risk and Resilience Working Group (R&R WG), with responsibilities commensurate with the maturity of CDOT's R&R implementation efforts. At the outset, the R&R WG should be chartered to: 1) refine and develop a final criticality model, 2) to develop R&R metrics to be used in evaluating projects, and 3) to integrate R&R within CDOT Engineering Regions. In refining the criticality model, the WG should refine the Redundancy model, as suggested during the Pilot. The R&R WG should also explore including hazardous material routes as a criterion in the criticality model. Also, it has been suggested that the Redundancy Map developed by CDOT and utilized as a criterion in the criticality model for system resilience should be refined to reflect origin-destination pairs and potentially reflect travel demand.

R2. Develop and maintain a web-based R&R map service. A highly-detailed service, focused on the data the Department needs for daily operations, and managerial decisions. Existing datasets (e.g., bridge management, pavement management) should be integrated with this mapping service, providing CDOT a single Departmental asset data portal.

R3. Develop user-specific R&R dashboards, aligned with CDOT Business Intelligence planning. Specific dashboards should be developed to be used in the CDOT's Engineering Regions, by Asset Managers, and by the Public. Focus on supplying data, rather than attempting to guess what the public wants to know, or what CDOT wants to public to know. The R&R WG should assist in developing CDOT's Strategic, Analytical, and Operational dashboards. Figure 23 below is an example dashboard from the Michigan Asset Management Council, and is offered for illustrative purposes.

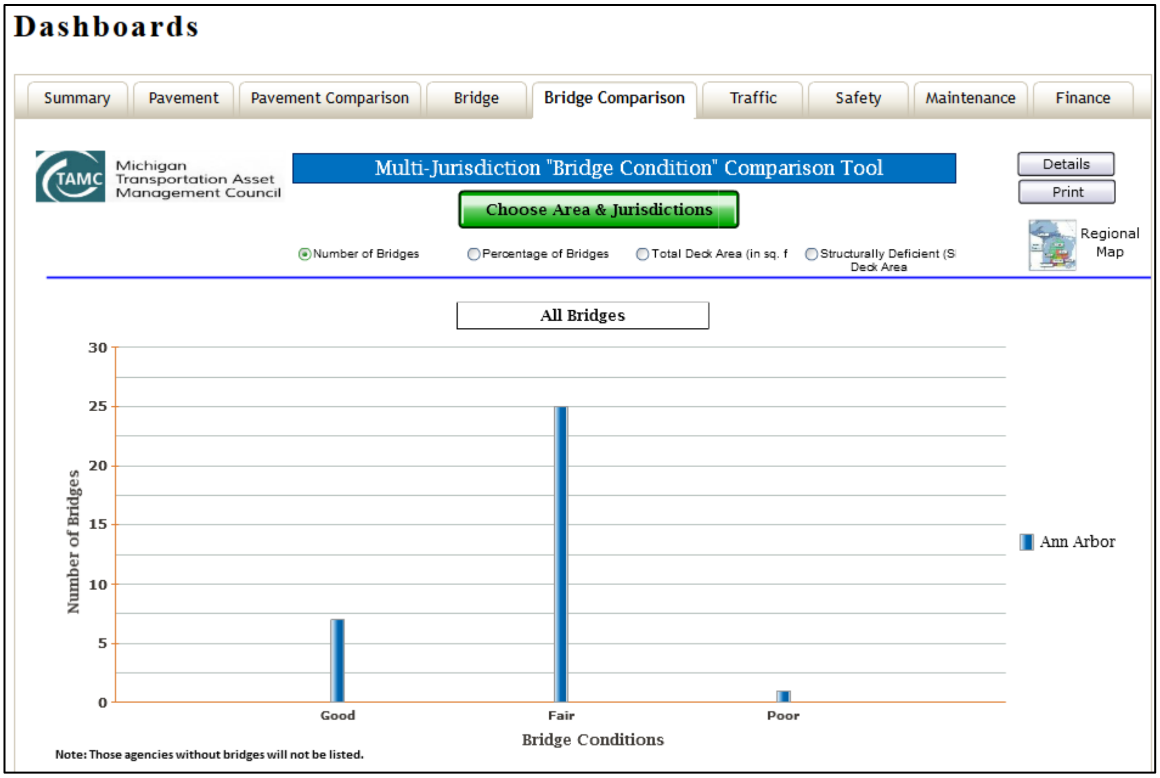


Figure 23. Example Dashboard (Michigan Asset Management Council)

R4. Extend the R&R for Highways analysis to all CDOT facilities. Develop a phased plan for conducting the initial, baseline R&R analysis, and for periodic R&R re-evaluations as CDOT improves the resilience of the system, collects and integrates higher quality data, and modifies business processes to incorporate R&R.

R5. Develop R&R metrics for CDOT internal use as aids in project selection, and for informing the public of CDOT's R&R successes and initiatives.

R6. Publish an R&R for Highways Report, detailing CDOT's R&R successes, initiatives, and future R&R strategies that aligns with typical CDOT reporting requirements for Risk-Based Asset Management plans.

R7. Develop an R&R for Highways website, to parallel and support the Annual R&R Report, the AMP, R&R dashboards, mapping services, and asset data warehouse. Target integration of the R&R site with existing CDOT web pages, the Colorado Resilience web site, and the Colorado Hazard and Incident Response and Recovery Plan.

R8. After planning an R&R baseline for existing conditions, develop a plan for conducting an R&R Highways analysis focused on climate change. This will entail running multiple R&R for Highways analyses, supporting each of the climate change models.

R9. Outreach with other organizations, departments and agencies, to coordinate CDOT's R&R for Highways findings and analytical work. Some examples of other organizations include USGS, US Forest Service, the Colorado Water Resources Board, and metropolitan planning organizations (MPOs).

R10. Develop and execute an R&R for Highways Public Affairs outreach campaign, seeking to educate the general public and special interest groups regarding CDOT's R&R for Highways initiatives. Elicit public comment, and formally respond to this input.

R11. Continue to expand CDOT's leadership role among DOTs and MPOs in developing and employing R&R for Highways. Lead an initiative within AASHTO to develop a national standard for Risk and Resilience Analysis of Highways, analogous to the J-100 R&R standard for water and waste water. This would benefit DOTs and MPOs across the nation, while advancing CDOT's interests, with likely outcomes including further development of, and potential funding for, enhanced datasets and R&R processes.

R12. Integrate I-70 Corridor R&R Pilot results and processes with CDOT's AMP, and AMP planning and processes.

R13. Integrate I-70 Corridor R&R Pilot results and processes with CDOT's STIP, and STIP planning and processes.

R14. Integrate I-70 Corridor R&R Pilot results and processes with the CDOT long-range transportation plan (Statewide Transportation Plan, SWP), and long-range planning and processes.

R15. Continue work to develop and implement a consistent and comprehensive methodology to inventory, inspect, and evaluate culverts and pipes. The goal is to put a complete Culvert Management System (CMS) in place, on par with current pavement, bridge (PONTIS), and sign management systems. (Wyant, 2002) The end result will be a proactive rather than reactive system for dealing with all culverts, combining those currently tracked in PONTIS and those culverts not in PONTIS. This will support a systematic preventative maintenance program to include planning, projecting, forecasting, and funding, and determining inspection schedules. This system includes inspection records, maintenance records, and is tied to the inspection and maintenance program. The CMS should include:

- a comprehensive inventory of all culverts, to include location, culvert condition, composition, installation date (estimated), dimensions, hydraulic capacity, channel condition, roadway condition, height to roadway, and inspection date.

Figure 24. Mudslide on I-70 near Parachute, Colorado

- standardized condition assessment procedures for all culverts (including channel condition)

- incorporation of culvert service life cycle cost modeling suitable for use with the full CDOT culvert inventory. , to support maintenance, repair, replace decisions (American Concrete Pipe Association Least Cost Analysis (“PipePac,” n.d.) , and National Corrugated Steel Pipe Association (“Service Life Calculator,” n.d.).

- a decision support system to assist in managing maintenance, repair, and replacement decisions; standardized methods for identifying and correcting deficiencies (e.g., maintenance, rehabilitation, upgrade, replacement) across culvert sites. (Hunt et al., 2010) Integrated culvert assessment and decision-making took for selecting replacement or rehabilitation alternatives. At a minimum, the following factors should be included: hydraulic capacity, load capacity, width deficiency, and maintenance costs. (Wyant, 2002) p31

Summary

The I-70 Corridor Risk and Resilience Pilot provided CDOT new insights into its system, and provided quantitative support for "known" hazards and problem locations. Within the limited scope and resources of a pilot project, CDOT was able to:

- Develop a detailed, replicable, quantitative analysis process supporting daily operations and strategic planning, such as the federally-mandated risk-based asset management plan, the CDOT STIP and CDOT's long-range transportation plans.
- Identify strengths and shortcomings in existing datasets and data management, with the potential of employing these results in developing a comprehensive data strategy, making fuller use of this critical CDOT asset.
- Develop criteria to understand and rank the criticality of assets on the CDOT system
- Evaluate the benefit-cost of the R&R for Highways analysis in generating information to support on-going Department strategic initiatives in data management, asset management, business, processes, and public outreach.
- Extend the dialog with the Colorado Transportation Commission and the public at large regarding maintaining the current CDOT system and increasing its resilience, in a time of decreasing fiscal resources and aging infrastructure.
- Continue to integrate transportation in Colorado's resiliency planning and efforts, fulfilling its mission, "…to provide the best multi modal transportation system for Colorado that most effectively moves people, goods, and information".
- Understand the benefits of an R&R analysis of the entire CDOT system, and the implications of this analysis for developing climate change scenarios, and "building climate resilient transportation".
- Continue in its role as a national leader in Risk and Resilience, laying the groundwork for a national standard for Risk and Resilience for Highways.

CDOT is currently considering areas for application of the results developed through the I-70 R&R Pilot that extend beyond Risk-Based Asset Management including potential applications to planning, maintenance, and operational planning activities. CDOT staff is also assessing the threats and assets included in the Pilot to determine if changes to these should be made in future applications. Also under consideration is how Owner, User, and Total Annual Risk can be used in the decision-making process.

The Pilot study has been monitored by the CDOT Commission throughout the study period and to date has been well received by the Commission. Efforts have also been made by AEM Corporation and CDOT Staff to actively seek opportunities to present the study in professional settings to gain insight from other transportation professionals as to uses of the information developed through the R&R for Highways Process. In the next few months, CDOT will determine if the process can contribute to their daily business processes and if additional corridors should be analyzed utilizing the R&R for Highways Procedure.


COLORADO
United
Shahn Sederberg | CDOT

Acknowledgements

This I-70 Corridor R&R Analysis Pilot project involved the support and assistance of many staff of the Colorado Department of Transportation (CDOT). The Pilot would not have been possible without the support of senior CDOT staff including Josh Laipply, Debra Perkins-Smith, Ryan Rice, Johnny Olson, Dave Eller, and the membership of the Data Acquisition Team. The active participation and guidance of the Working Group, including the program managers, Lizzie Herrera-Kemp and Heather Paddock, were a steady influence pushing the project forward. Randy Jensen of the Federal Highway Division Office of Colorado, was invaluable for his insights on the R&R process and federal initiatives. The many CDOT staff who assisted the AEM Team in collecting and understanding the Department's data were essential to the Pilot's success. Multiple agencies and departments beyond CDOT were also critical in assisting with developing and validating models and Pilot results. We respectfully acknowledge the contributions of all these individuals and their support.

Glossary

4-band imagery: Multi-spectral imagery captured as 4-bands or channels—Red, Green, Blue, and NIR (near infrared). These bands can be processed in different combinations to highlight vegetation and vegetative health.

AADT truck: Annual Average Daily Traffic, trucks. An annualized count of trucks, recorded at specific locations within a highway corridor.

AADT: Annual Average Daily Traffic. An annualized count of vehicles and trucks, recorded at specific locations within a highway corridor.

AASHTO Roadway Classification: Functional classification is the process by which streets and highways are grouped into classes, or systems, according to the character of service they are intended to provide.

AASHTO: American Association of State and Highway Transportation Officials. This body produces and maintains many of asset design standards for highway infrastructure.

AEM: Applied Engineering Management Corporation.

AMP/TAMP: Risk-based Asset Management Plan. A focal point for information about the assets, their management strategies, long-term expenditure forecasts, and business management processes. Each State is required to develop a risk-based asset management plan for the National Highway System (NHS) to improve or preserve the condition of the assets and the performance of the system. (23 U.S.C. 119(e)(1), MAP-21 § 1106)

ASCE-7 Special Wind Region: American Society of Civil Engineers-specified region requiring special asset design standards to accommodate extreme wind speeds.

Asset Management: A strategic and systematic process of operating, maintaining, and improving physical assets, with a focus on engineering and economic analysis based upon quality information, to identify a structured sequence of maintenance, preservation, repair, rehabilitation, and replacement actions that will achieve and sustain a desired state of good repair over the lifecycle of the assets at minimum practicable cost (23 U.S.C. 101(a)(2)).

Asset: Individual components of highway infrastructure. Examples of assets range from bridges, to roadway prism, to signs, to walls. When combined, assets form corridors and ultimately transportation systems.

Avalanche: A mass of snow, ice, and debris; flowing and sliding rapidly down a steep slope.

AWWA J-100: American National Standards Institute (ANSI) standard for the water industry. Voluntary consensus standard encompassing an all-hazards risk and resilience management process for use specifically by water and wastewater utilities.

AWWA: American Water Works Association. An international, nonprofit, scientific and educational society dedicated to providing total water solutions assuring the effective management of water.

Bridge approach: Segment of intermediate pavement between typical roadway section and a bridge. The bridge approach may contain an approach slab, making the approach significantly more expensive than the typical roadway prism segment.

CDOT Engineering Region: Geographic divisions of the CDOT system, responsible for implementing the Department's goals and managing all activities within the geographic area.

CDOT: Colorado Department of Transportation.

Centerline-mile (CL): A measure of the total length (in miles) of highway facility in-place or proposed, as measured along the highway centerline.

Consequence: The value—in dollars—of the result of asset failure

Corridor: A combination of assets functioning together to provide transportation services.

Culvert: A structure that allows water to flow under a road, railroad, trail, or similar obstruction from one side to the other side. Typically embedded to be surrounded by soil, a culvert may be made from a pipe, reinforced concrete or other material.

CWCB: Colorado Water Conservation Board. Represents each major water basin, Denver and other state agencies in a joint effort to use water wisely and protect water for future generations.

DAT: Data Acquisition Team. CDOT Headquarters subject area managers assisting and overseeing the progress of the I-70 R&R Pilot Project.

DEM: USGS (U.S. Geological Survey) Digital Elevation Model. A geospatial file format for storing topographic bare-earth surface--elevation. Typically, available at 10-meter and 30-meter horizontal resolutions, although the USGS has undertaken a multi-year campaign to produce 1-meter DEMs.

Detour table: A listing of the alternate routes (detours) between roadway mile points. Suitable alternates may be limited by hazards, bridge capacity or other considerations.

DOT: Department of Transportation.

EOC: Executive Oversight Committee. Group of CDOT senior-level executives overseeing the progress and strategic direction of the I-70 R&R Pilot Project.

FHWA: U.S. Federal Highway Administration.

FIRM: Flood Insurance Rate Map produced by the Federal Emergency Management Agency (FEMA), indicating the probability of flooding.

Flood: An overflowing of a large amount of water beyond its normal confines, especially over what is normally dry land. Flooding is modeled by various effects—scour, debris, and structure overtopping.

GIS: Geographic Information System. A computerized system designed to capture, store, manipulate, analyze, manage, and present all types of geographical data.

HAZMAT: Hazardous material. Hazardous materials and items as transported on or stored near highways.

HYRiSK: FHWA model for assessing the relative risk of scour failure for bridges with foundations subject to scour. The relative risk of scour failure is calculated as the product of the cost associated with failure and the probability of failure. The method is based on data contained in the NBI database.

Landslide: Per the Colorado Geological survey, "… landslide is a form of mass wasting resulting in deep failure of a slope. The term Landslide is restricted to mean those mass movements where there is a distinct surface of rupture or zone of weakness that separates the slide material from more stable underlying material…Such slides involve en masse downward and outward movement of a relatively dry body of rock and/or surficial material in response to gravitational stresses.

Lane-mile: A measure of the total length of traveled pavement surface. Lane-miles is the centerline length (in miles) multiplied by the number of lanes.

LCC: Life-Cycle Cost: A methodology to determine the most cost-effective option among different competing alternatives. The sum of all recurring and one-time (non-recurring) costs over the full life span or a specified period of a good, service, structure, or system. It includes purchase price, installation cost, operating costs, maintenance and upgrade costs, and remaining (residual or salvage) value.

LIDAR: Light Detection and Ranging. Specialized, high/very high-resolution imagery. Airborne LIDAR can be used to generate high resolution DEMs. Vehicle-based LIDAR can be used to generate highway infrastructure asset databases, with products rivaling "as-builts" and/or surveys of these assets.

LRFD: Load and Resistance Factor Design. Asset design specifications, published by AASHTO.

LRS: Linear Reference System. A system where features (points or segments) are localized by a measure along a linear element. The LRS can be used to reference events for any network of linear features, for example roads, railways, rivers, pipelines, electric and telephone lines, water and sewer networks.

Map service: Making maps available to the web using GIS.

Model: A systematic description of an object or phenomenon that shares important characteristics with the object or phenomenon.

MPO: Metropolitan Planning Organization. A federally mandated and federally funded transportation policy-making organization made up of representatives from local government and governmental transportation authorities.

NBI: National Bridge Inventory. FHWA-compiled database with information on all bridges and tunnels in the U.S.

NCEI: National Oceanic and Atmospheric Administration (NOAA) National Center for Environmental Information. Hosts and provides comprehensive oceanic, atmospheric, and geophysical data; the Nation's leading authority for environmental information (geophysical, oceans, coastal, weather and climate data).

NCHRP: National Cooperative Highway Research Program, a forum for coordinated and collaborative research of issues integral to state Departments of Transportation.

Owner Risk: Cost, in dollars, to the transportation agency of replacing asset(s) damaged by a hazard. Cost is limited to replacement-in-kind of the impacted asset(s). As an equation, Owner Risk = Consequence x Vulnerability x Threat. Calculated for each Threat-Asset pair.

PONTIS: A software application developed to assist in managing highway bridges and other structures.

PTCS: Post-Tensioned Concrete Slab. Post tensioning is a technique for reinforcing concrete. This specialized construction technique is used extensively in the Glenwood Canyon section of Colorado I-70. PTCS assets are significantly more expensive than typical roadway prism segments.

R&R: Risk and Resilience.

RAMCAP Plus$^{SM:}$ Risk and Resilience Management for Critical Asset Protection. The most recent iteration of the Department of Homeland Security's (DHS) Risk and Resilience analysis methodology framework.

Resilience Segment: Division of I-70 determined by entrance/exit to suitable detour route.

Resilience: The product of Service Outage, Asset Vulnerability, and Threat probability of occurrence'

Retaining Wall: A structure designed and constructed to resist the lateral pressure of soil, when there is a desired change in ground elevation that exceeds the angle of repose of the soil.

Risk: Level of operational uncertainty in a threat-filled environment.

Roadway: Roadway prism. The roadway prism extends from the toe of one fill material slope to the other toe of fill. The roadway prism fill is the foundation that supports the roadway pavement and an integral part of the roadway structure.

Rockfall: From the Colorado Geological survey, "…Falling rocks are a special category of the large family of gravitationally-driven phenomena called landslides. Rockfall which involves either direct fall or forward rotation of a rock mass followed by free-fall and/or rolling, bounding, or rapid sliding motions with only intermittent contact with the ground surface."

Scour: Bridge scour. The removal of sediment such as sand and gravel from around bridge abutments or piers.

SoVI: Social Vulnerability Index. Developed and maintained by the University of South Carolina, the SoVI index measures the social vulnerability of all United States counties to environmental hazards. The index was created using 29 socioeconomic variables, which research literature suggests contribute to the reduction in a community's ability to prepare for, respond to, and recover from hazards.

StreamStats: A web-based tool that provides streamflow statistics, drainage-basin characteristics, and other information for USGS streamgaging stations and for user-selected ungaged sites on streams.

TC: Colorado Transportation Commission. 11 commissioners appointed by the governor, managing the Colorado transportation system. Provided policy and priorities for conducting the I-70 R&R Pilot Project.

Threat: Terrorist, natural hazard, or dependency/locational hazard. Measured as a probability—the likelihood of occurrence.

Threat-Asset pair: The pairing of one specific threat with one specific asset. The simplest analytical element in the R&R for Highways process.

Total Risk: The sum of Owner Risk and User Risk for each Threat-Asset pair.

Transearch: Commercial planning tool (database) for US freight flows by origin, destination, commodity, and transportation mode.

Tunnel: An underground passageway, dug through the surrounding soil/earth/rock and enclosed except for entrance and exit, commonly at each end

Twice-damaged Asset Rule: Under new provisions (2016) in 23 CFR Part 667, State DOTs must conduct periodic evaluations to determine if reasonable alternatives exist to roads, highways, or bridges that repeatedly require repair and reconstruction activities. At a minimum, State DOTs must include summaries of the evaluations relating to NHS pavements and bridges in their AMPs.

User Risk: Cost, in dollars, to the traveling public of losing the transportation service provided by asset(s) damaged by a hazard. User Risk includes vehicle operating costs incurred during travel delays and/or detour distance over the planned route. User Risk also include the value of time or lost wages incurred during travel delays and/or detour distance over the planned route. As an equation, User Risk = Consequence x Vulnerability x Threat. Calculated for each Threat-Asset pair.

USGS: U.S. Geological Survey. U.S. government agency providing science about the natural hazards that threaten lives and livelihoods; the water, energy, minerals, and other natural resources we rely on; the health of our ecosystems and environment; and the impacts of climate and land-use change.

Vulnerability: The value—in dollars—of the actions an agency has taken to protect their assets from threats through maintenance activities, design, operational strategies, etc.

Web-based GIS: The process of using maps delivered by geographic information systems (GIS) via a web browser or other user agent capable of client-server interactions.

WG: CDOT Risk and Resilience I-70 Pilot Project Working Group. Comprised of subject matter experts, and representing all CDOT Engineering Regions and Headquarters.

Wildfire: A large, destructive fire that spreads quickly over woodland or brush. Distinct from a structure fire.

Selected References

AASHTO Standard Specifications for Highway Bridges (1991)

Marsh, M. L., & Stringer, S. J. (2013). *NCHRP Synthesis 440 Performance-Based Seismic Bridge Design* (p. 138). Washington D. C.: National Academy of Sciences Transportation Research Board.

FHWA, HYRISK Model. 2002

AASHTO LRFD Bridge, 2012

Post-Extreme Event Damage Assessment and Response for Highway Bridges. NCHRP Synthesis 497. Alice Alipour. 2016.

Failure mechanisms of bridge infrastructure in an extreme flood event. Lebbe, Mohamed F.K.; Lokuge, Weena; Setunge, Sujeeva and Zhang, Kevin. Proceedings of the First International Conference on Infrastructure Failures and Consequences. 2014

Bridge Failure rates, Consequences, and Predictive Trends. Wesley Cook. May 2014

An Analysis of Recent Bridge Failures in the United States (2000-2012). Michael Robert Taricska. 2014. https://etd.ohiolink.edu/!etd.send_file?accession=osu1397600086&disposition=inline

Assessment of Integrity of Bridges under Extreme Scour Conditions. J. Klinga, A Alipour. 2014

Development of A Risk-Based Scorecard to Assess Scour Vulnerability of Georgia's Bridges. GDOT Research Project No. RP-11-27. June 2013. http://www.dot.ga.gov/BuildSmart/research/Documents/11-27.pdf

A Study of U.S Bridge Failures (1980-2012). Lee et all. Technical Report MCEER-13-0008. June 2013

Hydraulic Design of Safe Bridges. FHWA Report HIF-12-018/HDS 7. L.W. Zevenbergen; L.a. Arneson; J.H. Hunt and A.C. Miller April 2012

Analysis of Recent Bridge Failures in the United States. Kumalasari Wardhana and Fabian C. Hadipriono. Journal of Performance of Constructed facilities. August 2003

A Statistical Summary of the Cause and Cost Bridge Failures. Chang, FFM. September 1973

Vulnerability of road bridge infrastructure under extreme flood events. Sujeeva Setunge, Weena Lokuge, Hessam Mohseni, Warna Karunasena.

Transportation Research Circular E-C128. International Bridge and Structure Management. TRB. October 2008.

Vulnerability Assessment of Bridges Exposed to Scour. Nikola Tanasić. Journal of the Transportation Research Board. 2012

Controlling Debris at Pennsylvania Bridges. Final Report. S. A. Sheeder and P. A. Johnson. October 2008

Potential Drift Accumulation at Bridges. FHWA-RD-97-028. Timothy H. Diehl. April 1997.

Prioritizing Scour Vulnerable Bridges Using Risk. Stein et all. Journal of Infrastructure Systems. 1999

Risk-Based Management Guidelines for Scour at Bridges with Unknown Foundations. NCHRP Project 24-25. Stein and Sedmera. October 2006

Debris Forces on Highway Bridges. NCHRP Report 445. Parola et all.

Jansuwan, S., 2013. A Quantitative Framework for Assessing Vulnerability and Redundancy of Freight Transportation Networks (Doctoral Dissertation). Utah State University.

Goodchild, A., Jessup, E., McCormack, E., Andreoli, D., Rose, S., Ta, C., Pitera, K., Ivanov, B., 2009. Development and analysis of a GIS-based statewide freight data flow network. Washington State Department of Transportation.

ICF International, 2013. Assessment of the Body of Knowledge on Incorporating Climate Change Adaptation Measures into Transportation Projects (No. FHWA-HEP-14-016). Federal Highway Administration, Washington, DC.

Federal Highway Administration, 2012. Climate Change & Extreme Weather Vulnerability Assessment Framework.

Sevtsuk, A., Mekonnen, M., Kalvo, R., 2013. Urban Network Analysis Toolbox Help v1,01.

Perrin Jr., J., Jhaveri, C., 2003. The Economic Costs of Culvert Failures.

CTC & Associates, 2015. State of the Practice for Managing, Maintaining and Operating Culverts; A Review of Deterioration Curves and Tools (MnDOT Research No. TRIS 1508), Transportation Research Synthesis. MnDOT/Research, Minneapolis, MN.

Barthelmess, A., Rigby, E., 2011. Estimating Culvert & Bridge Blockages - A Simplified Procedure. Presented at the 33rd Hydrology & Water Resources Symposium, Brisbane, Australia.

Barthelmess, A., Rigby, E., 2009. Quantification of Debris Potential and the Evolution of a Regional Culvert Blockage Model, in: 32nd Hydrology and Water Resources Symposium, New Castle. Presented at the Adapting to Change, Barton A. C. T., Australia, pp. 218–229.

Walter, T., DeGaetano, A., Meyer, A., Marjerison, R., 2014. Determining Peak Flow Under Different Scenarios and Assessing Organism Passage Potential: Identifying and Prioritizing Undersized and Poorly Passable Culverts: year 2. Cornell University, Ithaca, NY.

Balog, J.N., United States, Federal Transit Administration, Transit Cooperative Research Program, Transit Development Corporation, National Research Council (U.S.), Transportation Research Board, 2002. Public transportation security. NCHRP Report 525, Volume 12. *Making Transportation Tunnels Safe and Secure.* National Academy Press, Washington, D.C.

Jizba, G., N.D. TSA/USACE Bridge and Tunnel Assessments- Explosives Vehicular Impact chem/bio/radiological.

Scoble, M.J., Lizotte, Y.C., Paventi, M., Mohanty, B.B., 1997. Measurement of blast damage. Mining Engineering 49, 103–108.

Risk Management Solutions, Inc. 2008. "Terrorism Risk: 7-Year Retrospective, 7-Year Future Perspective," RMS, Newark, CA.

Willis, H.H., LaTourette, T., Kelley, T.R., Hickey, S. Neill, S. 2007. *Terrorism Risk Modeling for Intelligence Analysis and Infrastructure Protection,* Rand Corporation, Santa Monica, CA.

Bier, V.M., Cox, L.A., Azaiez, M.N. 2009. "Why Both Game Theory and Reliability Theory Are Important in Defending Infrastructure Against Intelligent Attacks," Chapter 1 in Bier V.M., and Azaiez, M.N., *Game Theoretic Risk Analysis of Security Threats,* New York: Springer.

University of Maryland Global Terrorism Database. https://www.start.umd.edu/gtd/

Retaining Walls and Steep Reinforced Slopes (No. M 22-01.05), 2009. Washington State Department of Transportation.

Gerber, T.M., 2012. Assessing the long-term performance of mechanically stabilized earth walls, NCHRP synthesis. Transportation Research Board, Washington, D.C.

Brutus, O., Tauber, G., 2009. Guide to asset management of earth retaining structures. US Department of Transportation, Federal Highway Administration, Office of Asset Management.

Vessely, Mark, 2013. Geotechnical Asset Management Implementation Concepts and Strategies (FHWA No. FHWA-CFL/TD-13-003).

Shannon & Wilson, Spy Pond, Inc., 2015. Economic Impacts of Geologic Hazard Events on Colorado Transportation Facilities. Colorado Department of Transportation, Denver, CO.

Yiang, R.Y., 2007. Landslide Hazard Rating Matrix and Database (Vol. 1) and (Vol. 2). FHWA, Washington D.C.

Tunnel Security for Public Transit, 2015. North American Transit Services Association.

Carvel, R., Beard, A., 2005. The Handbook of Tunnel Fire Safety. Thomas Telford.

Gehandler, J., 2015. Road Tunnel Fire Safety and Risk: a Review. Fire Science Reviews 4.

Larkin, B., J., 2011. Survey of New Tunneling Projects, Their Costs, Application, and Effect on Rail System Performance.

Dexter, R. J., & Ricker, M. J. (2002). *NCHRP Report 469 Fatigue-Resistant Design of Cantilevered Signal, Sign and Light Structures.* Washington D.C.: Transportation Research Board of the National Academies.

Meyer, D., Chowdhury, A. G., & Irwin, P. (2015). Investigation of wind-induced dynamic and aeroelastic effects on variable message signs. *Wind and Structures*, 793-810.

Puckett, J. A., Garlich, M. G., Nowak, A., & Barker, M. (2014). *NCHRP Report 796 Development and Calibration of ASHTO LRFD Specifications for Structural Supports for Highway Signs, Luminaries and Traffic Signals.* Washington D. C.: Transportation Research Board of the National Academies.

Peterka, J.A., 2013. Colorado Front Range Gust Map (ASCE 7-10). Cermak, Peterka, Petersen, Fort Collins, CO.

NOAA National Centers for Environmental Information. https://www.ncdc.noaa.gov/stormevents/ftp.jsp

Cyber Threat Susceptibility Assessment | The MITRE Corporation [WWW Document], n.d. URL https://www.mitre.org/publications/systems-engineering-guide/enterprise-engineering/systems-engineering-for-mission-assurance/cyber-threat-susceptibility-assessment (accessed 4.17.17).

Buckshaw, D.L., Parnell, G.S., Unkenholz, W.L., Parks, D.L., Wallner, J.M., Saydjari, O.S., 2005. Mission oriented risk and design analysis of critical information systems. Military Operations Research 10, 19–38.

Wynn, J., et al., "Threat Assessment & Remediation Analysis (TARA)", Version 1.4, MITRE Technical Report 110176, MITRE Corporation, October 2011.

Colorado Department of Transportation. (2010). *I-70 Mountain Corridor PEIS Geologic Hazards Technical Report.*

Highland, Lynn. (2011) *Landslides in Colorado, USA: Impacts and Loss Estimation for the Year 2010.* USGS. Reston, VA

Arndt, B. P., & Ortiz, T. (2012). Rockfall and Rockslide Mitigation Options with Rocksheds and Real-time Slope Monitoring along Interstate 70 in Glenwood canyon, Colorado. 63rd Highway Geology Symposium (p. 18). Redding, CA: Highway Geology Symposium. Retrieved from http://www.highwaygeologysymposium.org/uploads/pastmeetings/63_HGS.pdf

Arndt, B., Ortiz, T., & Turner, A. K. (2009). Colorado's Full-Scale Field Testing of Rockfall Attenuator Systems: Transportation Research Circular Number E-C141. Washington D. C.: Transportation Research Board.

Colorado Department of Transportation. (2010). I-70 Mountain Corridor PEIS Geologic Hazards Technical report. August. Retrieved from https://www.codot.gov/projects/i-70mountaincorridor/final-peis/final-peis-documents/technical-reports/Vol4_I-70_Mntn_Corridor_Final_PEIS_Geologic_Hazards_TR.pdf

Highland, L. M. (2012). Landslides in Colorado, US -- Impacts and Loss Estimation for the Year 2010, Geological Survey Open-File Report 2012 - 1204. Reston, VA: US Geological Survey.

Jones, C. L., Higgins, J. D., & Richard, A. D. (2000, March). Colorado Rockfall Simulation Program Version 4.0. Denver, CO: Colorado Department of Transportation.

Rocscience. (2016, Nov 21). Duplicating CRSP Results using RockFall. Retrieved from Rocscience: https://www.rocscience.com/help/rocfall/webhelp6/pdf_files/Developer_Tips/Duplicating_CRSP_results_using_RocFall.pdf

Siel, B. D. (2005, August 3). Thanksgiving Day 2004 ROCKFALL! Retrieved from Marshall University CEGAS Services - Geohhazards: https://www.marshall.edu/cegas/geohazards/2005pdf/Session4/ROCKFALL.pdfhttps://www.marshall.edu/cegas/geohazards/2005pdf/Session4/ROCKFALL.pdf

Vessely, M., Richrath, S., Weldemicael, E. (2015, December). Economic Impact of Geologic Hazard Events on Colorado Transportation White Paper.

Yeh and Associates, Inc. (2010, August). I-70 Mountain Corridor PEIS Geologic Hazards Technical Report.

Yeh and Associates, Inc. (2008, August 25). Final Geotechnical Investigation Report I-70 Flyod Hill Lanslide Clear Creek Country, Colorado. Project Number 27-207.

Regmi, N., Giardino, J. Vitek, J. (2013, June 5). Characteristics of Landslides in Western Colorado, USA. Landslides (2014) 11: 589.

Appendices

A. Overview of Methodologies Employed in the Pilot
B. Summary of Risk Findings by Resilience Segment
C. Top 20 Annualized Risk Tables for Select Threat-Asset Pairs
D. Distributed Flyer of I-70 Risk and Resilience Pilot
E. Tunnel Analysis – For Official Use Only

Appendix A Overview of Methodologies Employed in the Pilot

The following discussion is an overview of the methodologies used modeling the many threat-asset pairs developed for the I-70 Corridor R&R Pilot project. Many varied data sources, models, assumptions and constraints were used in developing, applying, and refining these models for use in the Pilot project. A list of selected references used in developing and applying the various models used in the Pilot is also included in the Appendix. The following overview indicates some of the principal models and data sources used; it is necessarily by no means comprehensive.

Flooding

Flooding was modeled as two separate hazards—scour, and overtopping/debris. The FHWA HyRisk model was used to calculate bridge scour; results were compared with CDOT's existing bridge-scour monitoring program. FEMA flood rate insurance maps (FIRMs) were used as the basis for determining vulnerability to overtopping and debris for bridges and roads. Culverts not tracked in the CDOT bridge database ("non-NBI culverts") were modeled for flow capacity with a mechanistic pipe flow equation. Flows at these pipe locations were based on USGS StreamStats results.

Avalanche

A *snow avalanche* is a mass of snow, ice, and debris; flowing and sliding rapidly down a steep slope. (http://coloradogeologicalsurvey.org/geologic-hazards/avalanches-snow/definition/) Avalanche threat probabilities, asset vulnerability and consequences were developed from Colorado Avalanche Information Center (CAIC) historical data and with the assistance of CDOT Region engineers.

Landslide

In the Pilot, landslide was modeled as a hazard distinct from rockfall. Per the Colorado Geological survey, "… landslide is a form of mass wasting resulting in deep failure of a slope. The term Landslide is restricted to mean those mass movements where there is a distinct surface of rupture or zone of weakness that separates the slide material from more stable underlying material…Such slides involve en masse downward and outward movement of a relatively dry body of rock and/or surficial material in response to gravitational stresses. In contrast, "Rockfall refers to quantities of rock falling freely from a cliff face." (https://en.wikipedia.org/wiki/Rockfall). Landslide threat probabilities asset vulnerability and consequences were developed from Colorado Geologic Survey data, historical information, and with the assistance of CDOT Region engineers.

Rockfall

In the Pilot, rockfall was modeled as a hazard distinct from landslide. From the Colorado Geological survey, "…Falling rocks are a special category of the large family of gravitationally-driven phenomena called landslides. Rockfall which involves either direct fall or forward rotation of a rock mass followed by free-fall and/or rolling, bounding, or rapid sliding motions with only intermittent contact with the ground surface." "Rockfall refers to quantities of rock falling freely from a cliff face," (https://en.wikipedia.org/wiki/Rockfall). Rockfall vulnerabilities were developed from the CDOT Rockfall Hazard database. Threat probabilities were developed with the input CDOT geohazards engineers. Rockfall consequences were developed from the CDOT Rockfall Hazard database, CDOT geohazards engineers, and historical (occurrence) data. Specific rockfall chutes were modeled with Rocscience RockFall™ software to further refine asset vulnerabilities and consequences.

Vehicle Strike (Bridge)

Vertical strikes of trucks and tall vehicles on bridges were considered; these are strikes to the bridge deck from vehicles failing to cleanly pass under the bridge (or overpass). Lateral strikes of vehicles, that is ground-level strikes of vehicles on bridge piers or abutments were not included in this analysis. Vehicle strikes on bridge threat probabilities, asset vulnerability and consequences were developed from CDOT's statewide historical strike data. As CDOT has few vehicle bridge strikes, national bridge strikes data supplemented the CDOT data to develop a more robust model of CDOT strike probabilities, vulnerabilities and consequences.

High Wind

Minimum Design Loads for Buildings and Other Structures (ASCE-7) designates the Colorado "front range" as a "special wind region," an area subject to extremely high winds recorded as anomalous events when compared with the surrounding topography. The Pilot relied on NCHRP Report 796 (the AASHTO LRFD for signs and signal masts), and the Colorado Front Range Gust Map study completed (Cermak, et al.) in developing threat probabilities. Asset vulnerability and consequences for high winds relied on ASCE-7 standards.

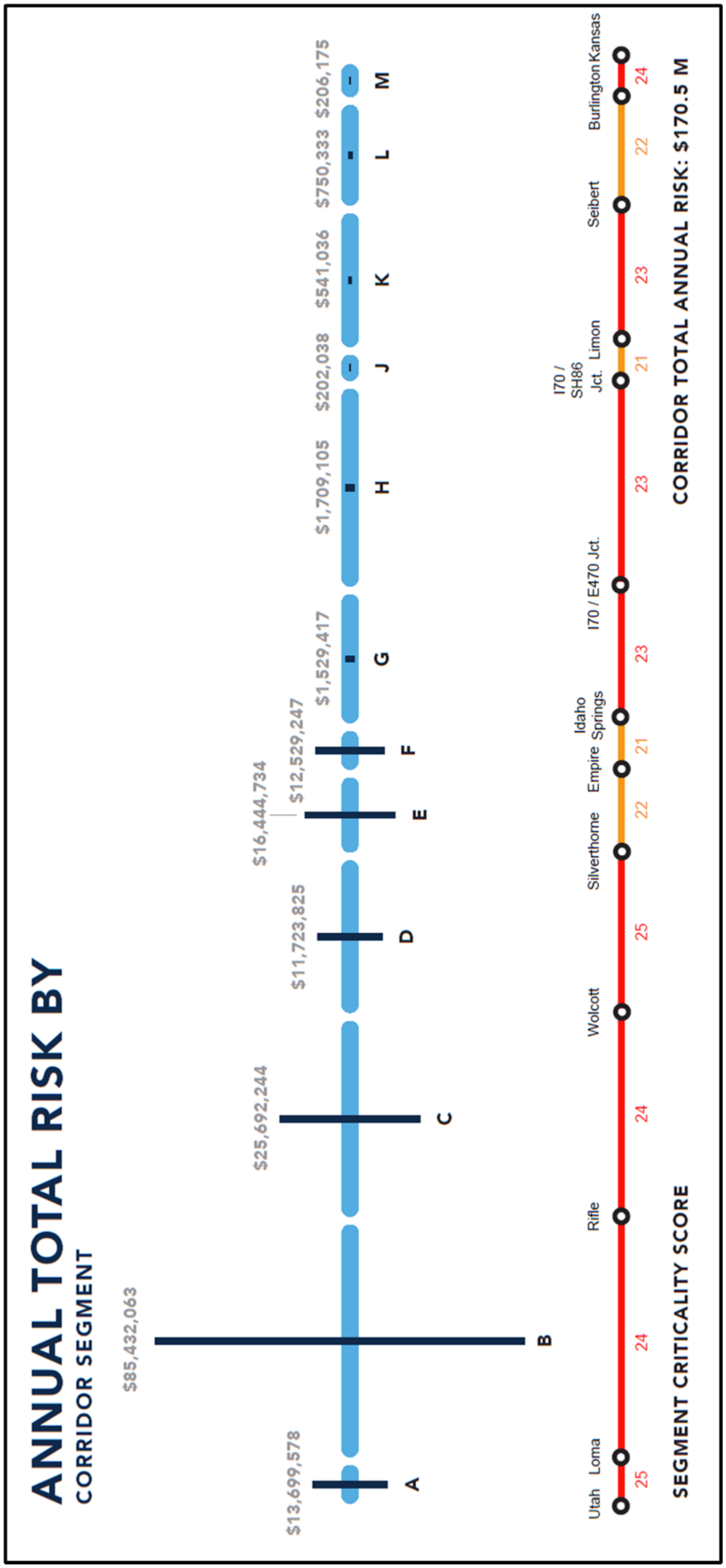
Tornado

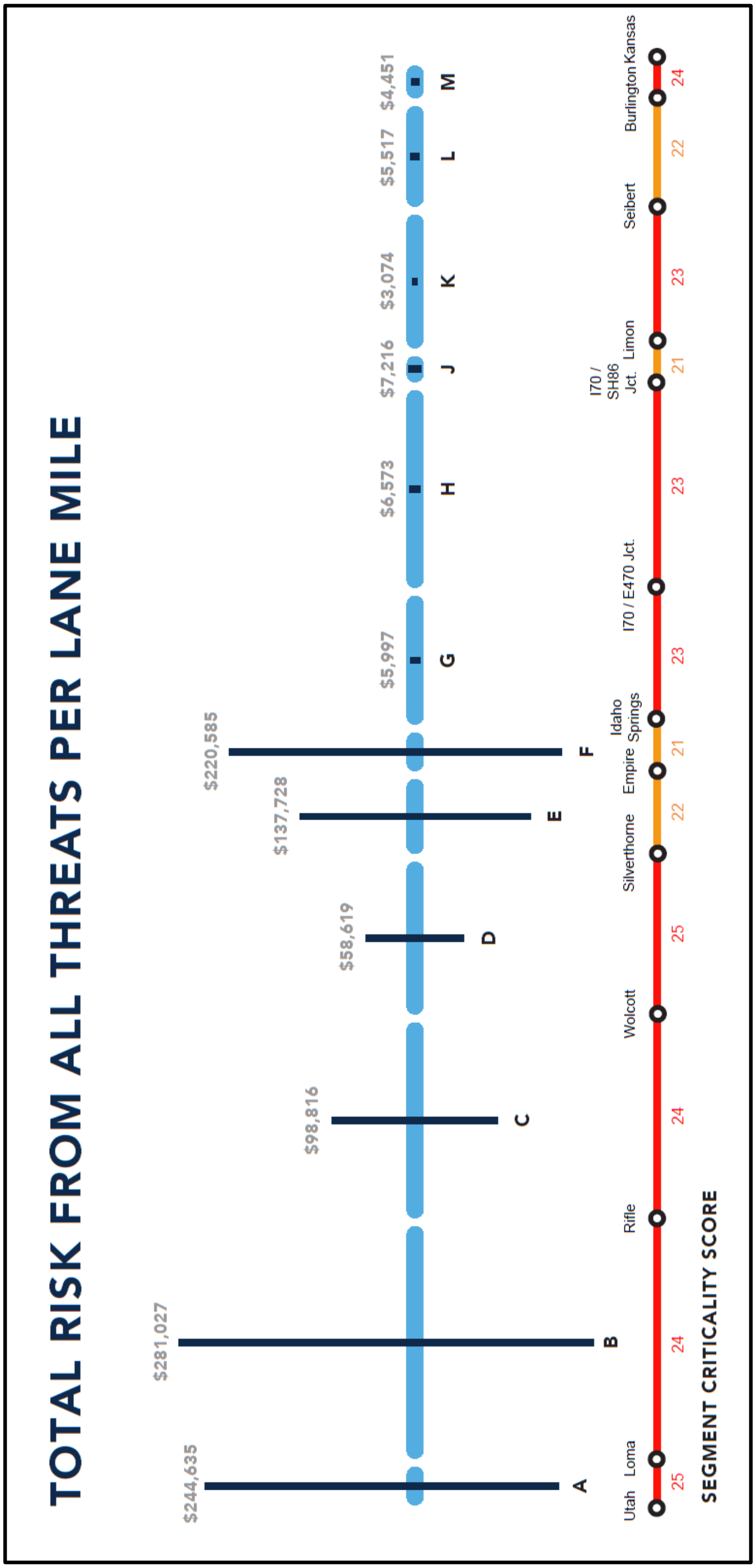
Tornado incidence data was sourced from the NOAA National Centers for Environmental Information (NCIE) for the years 1950 -2014. Tornado frequency and magnitude (enhanced Fujita scale) were normalized per NCIE recommendations and methods, resulting in threat probabilities. Asset vulnerability and consequences were developed based on asset design standards, and historical records.

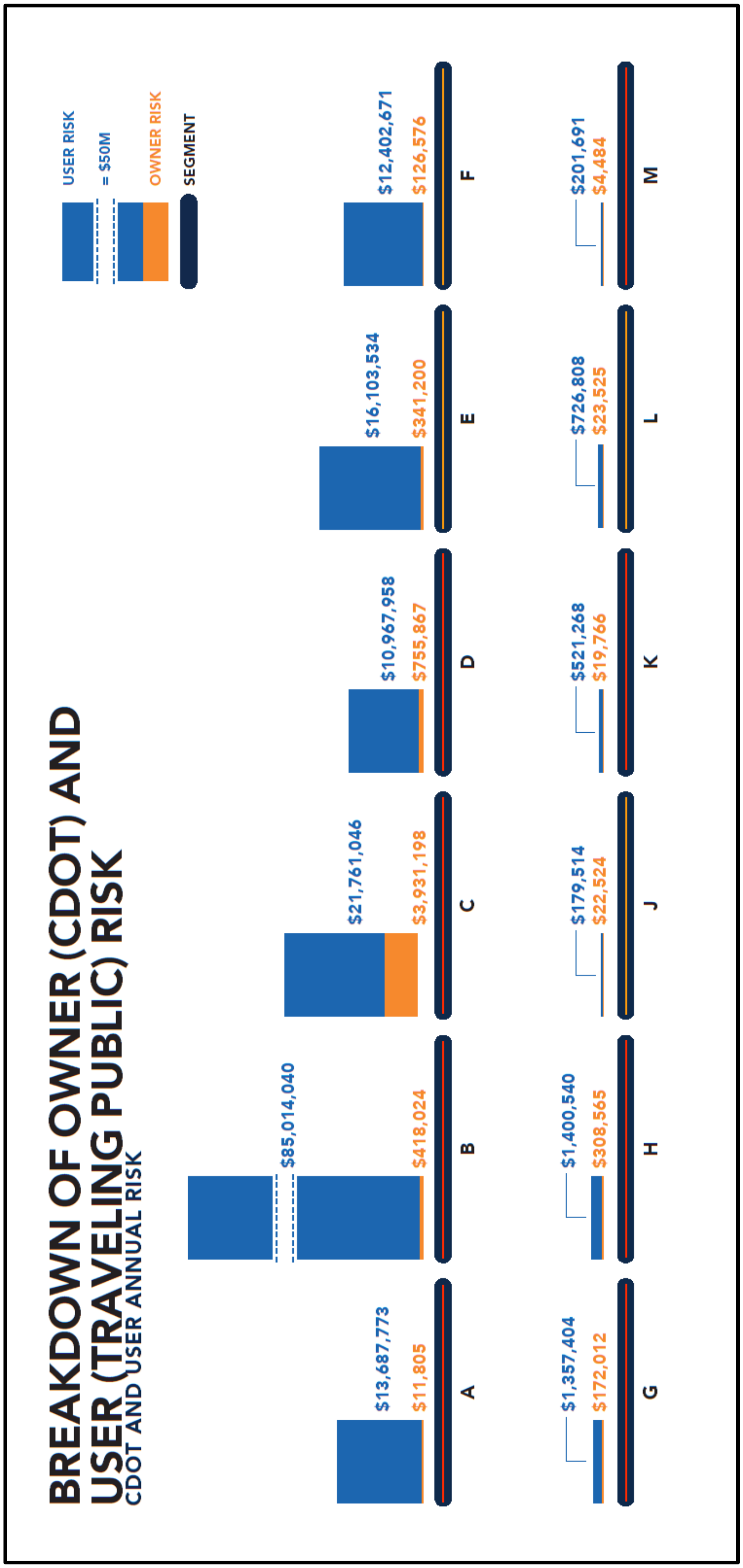
Wildfire

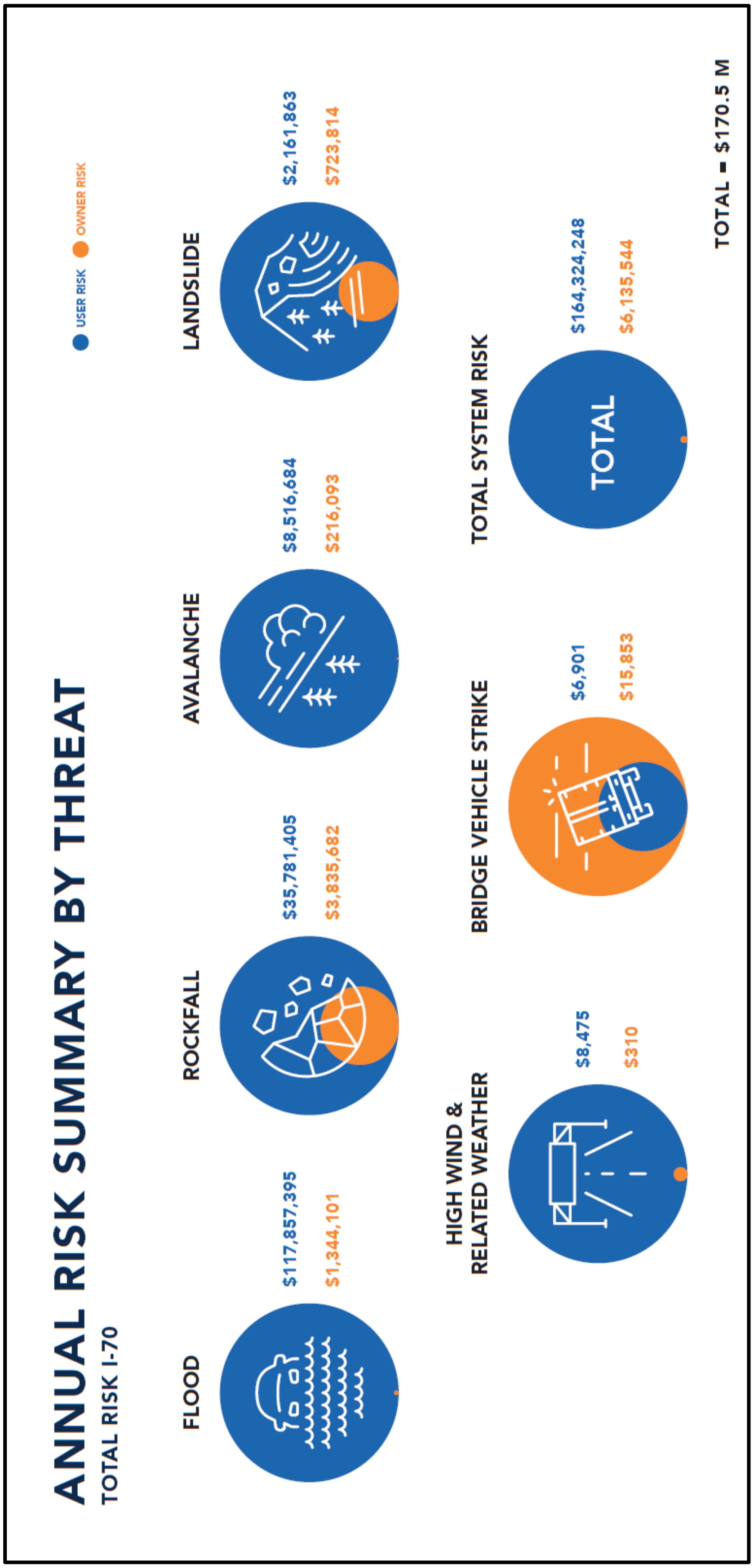
The U.S. Forest Service defines a wildland fire as any nonstructural fire, other than prescribed fire, that occurs in a wildland: **http://www.fs.fed.us/database/feis/glossary.html** Wildfire threat information was based on the Colorado Forest Service Wildfire Risk Assessment Portal (CO-WRAP), supported with historical MODIS satellite imagery. Post-fire erosion was modeled with the USFS Water Erosion Prediction Project (WEPP) model, supplemented with post-fire erosion equations developed specifically for Colorado, rounding out wildfire threat probabilities. Asset vulnerability and consequences were developed from historical records.

Appendix B Summary of Risk Findings by Resilience Segment


ANNUAL TOTAL RISK BY
CORRIDOR SEGMENT
$13,699,578
A
$85,432,063
B
$25,692,244
C
$11,723,825
D
$16,444,734
E
$12,529,247
F
$1,529,417
G
$1,709,105
H
$202,038
J
$541,036
K
$750,333
L
$206,175
M
Utah
Loma
Rifle
Wolcott
Silverthorne
Empire
Idaho Springs
I70 / E470 Jct.
I70 / SH86 Jct.
Limon
Seibert
Burlington
Kansas
25
24
24
25
22
21
23
23
21
23
22
24
SEGMENT CRITICALITY SCORE
CORRIDOR TOTAL ANNUAL RISK: $170.5 M


TOTAL RISK FROM ALL THREATS PER LANE MILE
$244,635
A
$281,027
B
$98,816
C
$58,619
D
$137,728
E
$220,585
F
$5,997
G
$6,573
H
$7,216
J
$3,074
K
$5,517
L
$4,451
M
Utah
Loma
Rifle
Wolcott
Silverthorne
Empire
Idaho Springs
I70 / E470 Jct.
I70 / SH86 Jct.
Limon
Seibert
Burlington
Kansas
25
24
24
25
22
21
23
23
21
23
22
24
SEGMENT CRITICALITY SCORE


BREAKDOWN OF OWNER (CDOT) AND USER (TRAVELING PUBLIC) RISK
CDOT AND USER ANNUAL RISK
USER RISK
= $50M
OWNER RISK
SEGMENT
$13,687,773
$11,805
A
$85,014,040
$418,024
B
$21,761,046
$3,931,198
C
$10,967,958
$755,867
D
$16,103,534
$341,200
E
$12,402,671
$126,576
F
$1,357,404
$172,012
G
$1,400,540
$308,565
H
$179,514
$22,524
J
$521,268
$19,766
K
$726,808
$23,525
L
$201,691
$4,484
M


ANNUAL RISK SUMMARY BY THREAT
TOTAL RISK I-70
USER RISK
OWNER RISK
FLOOD
$117,857,395
$1,344,101
ROCKFALL
$35,781,405
$3,835,682
AVALANCHE
$8,516,684
$216,093
LANDSLIDE
$2,161,863
$723,814
HIGH WIND & RELATED WEATHER
$8,475
$310
BRIDGE VEHICLE STRIKE
$6,901
$15,853
TOTAL SYSTEM RISK
TOTAL
$164,324,248
$6,135,544
TOTAL = $170.5 M

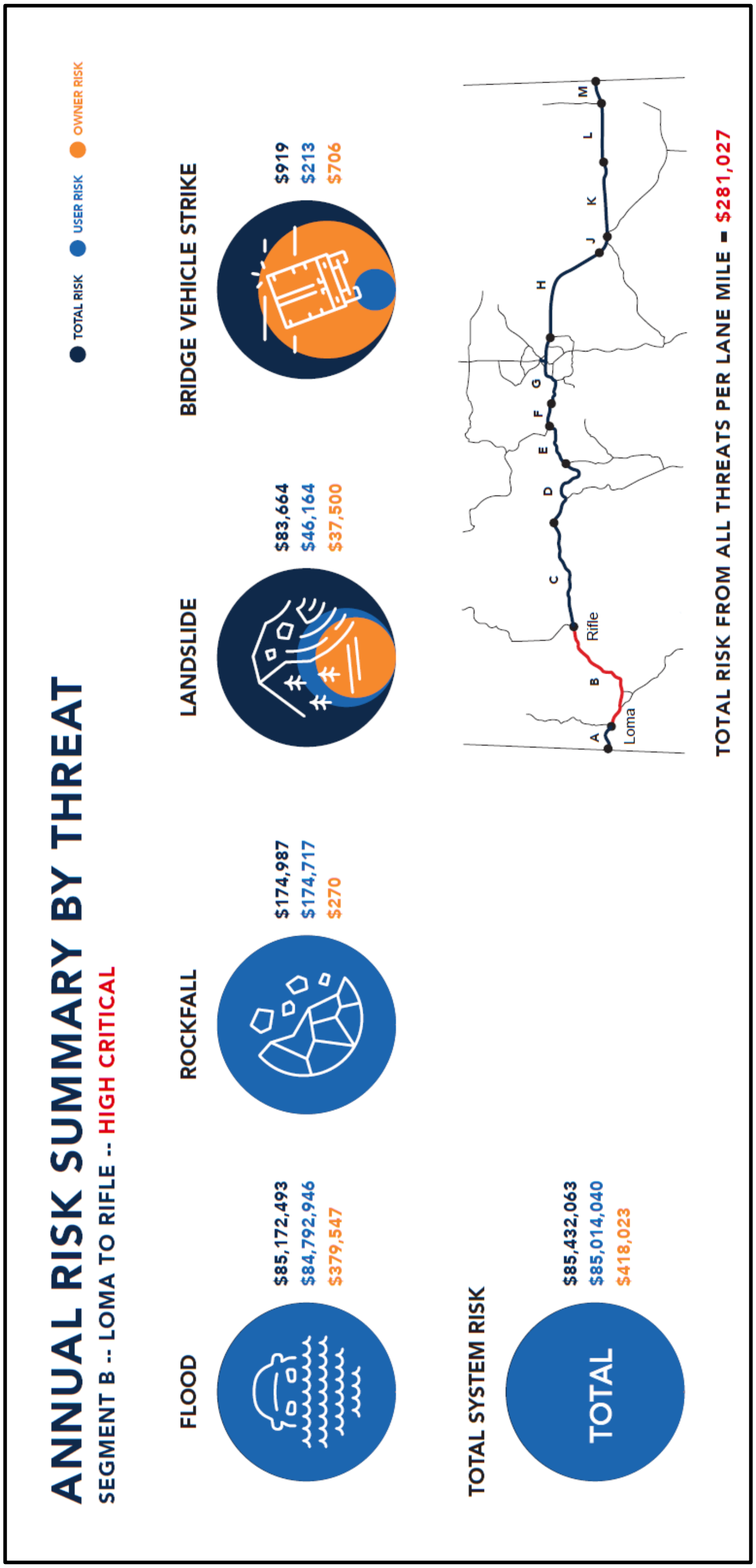
ANNUAL RISK SUMMARY BY THREAT

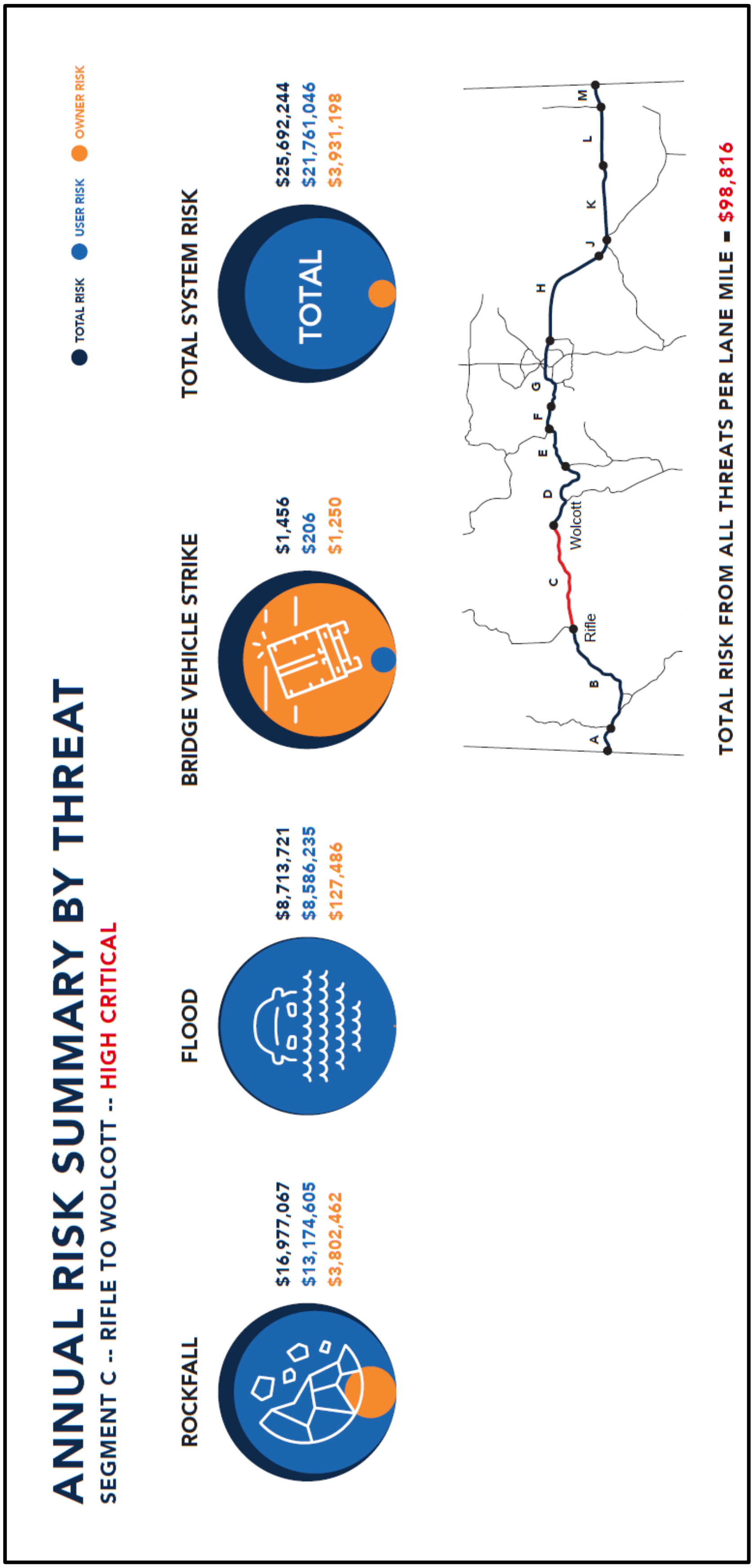
SEGMENT A -- UTAH STATE LINE TO LOMA -- HIGH CRITICAL

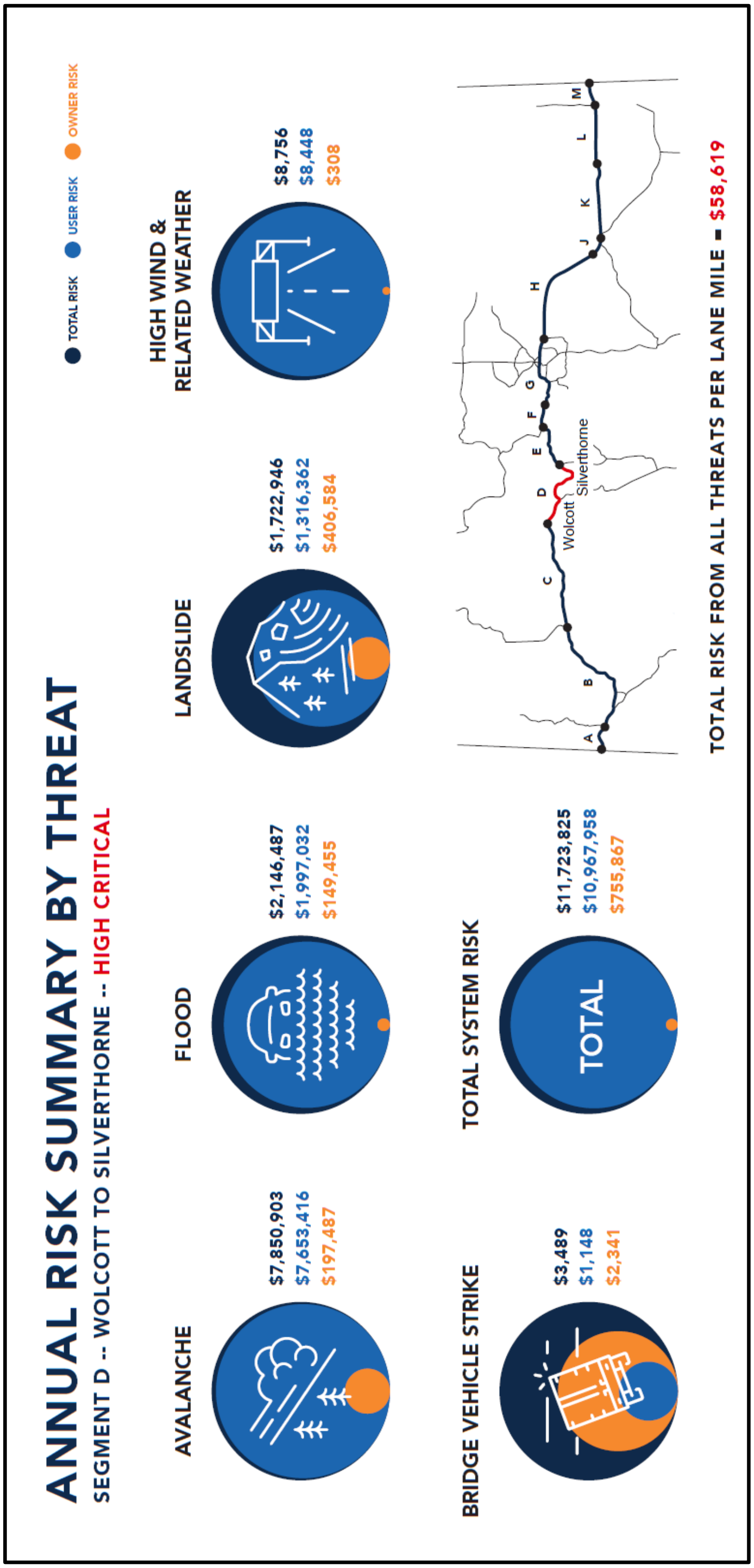
TOTAL RISK · USER RISK · OWNER RISK

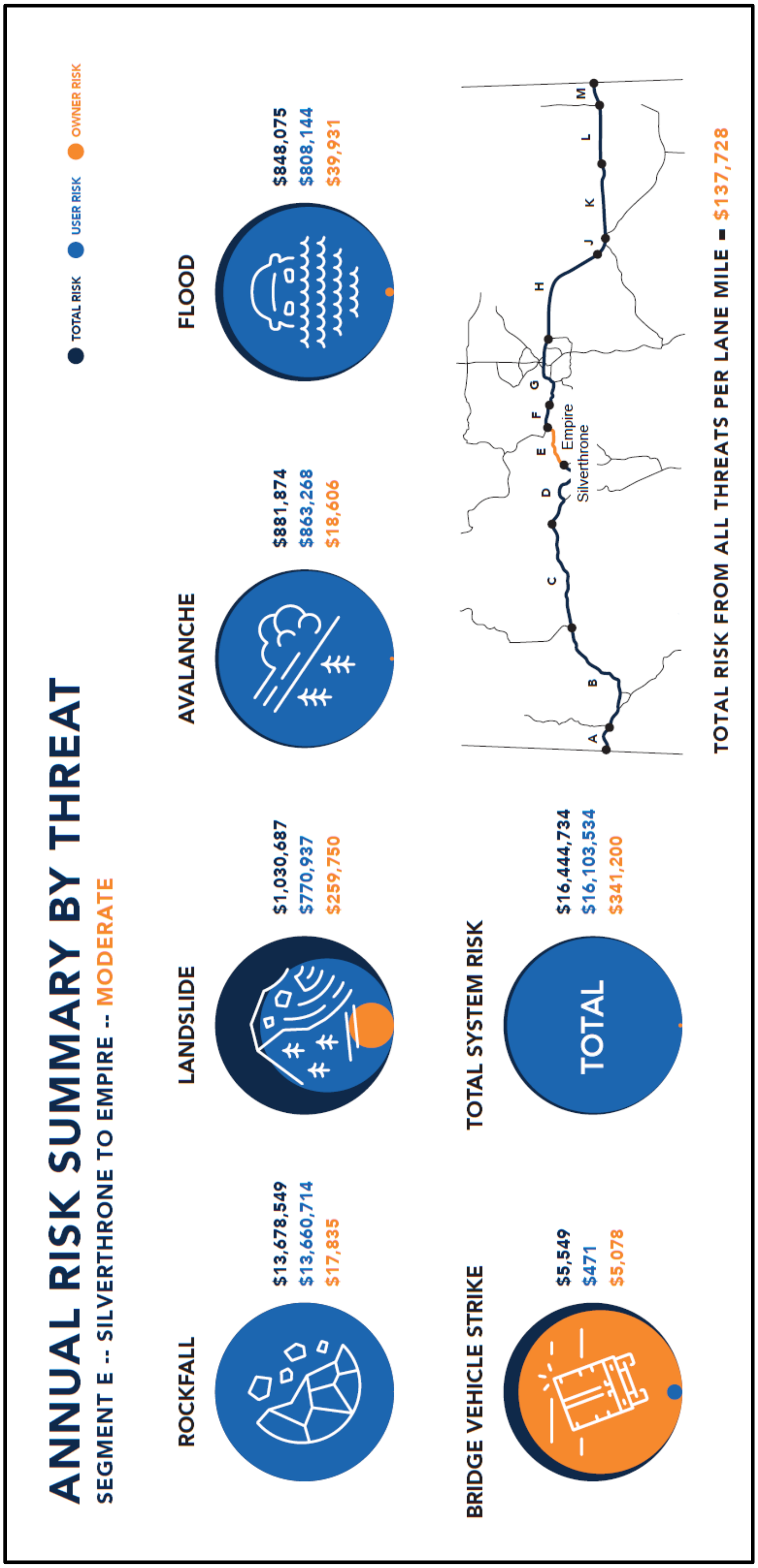
	FLOOD	BRIDGE VEHICLE STRIKE	TOTAL SYSTEM RISK
TOTAL RISK	$13,699,545	$33	$13,699,578
USER RISK	$13,687,771	$2	$13,687,773
OWNER RISK	$11,774	$31	$11,805

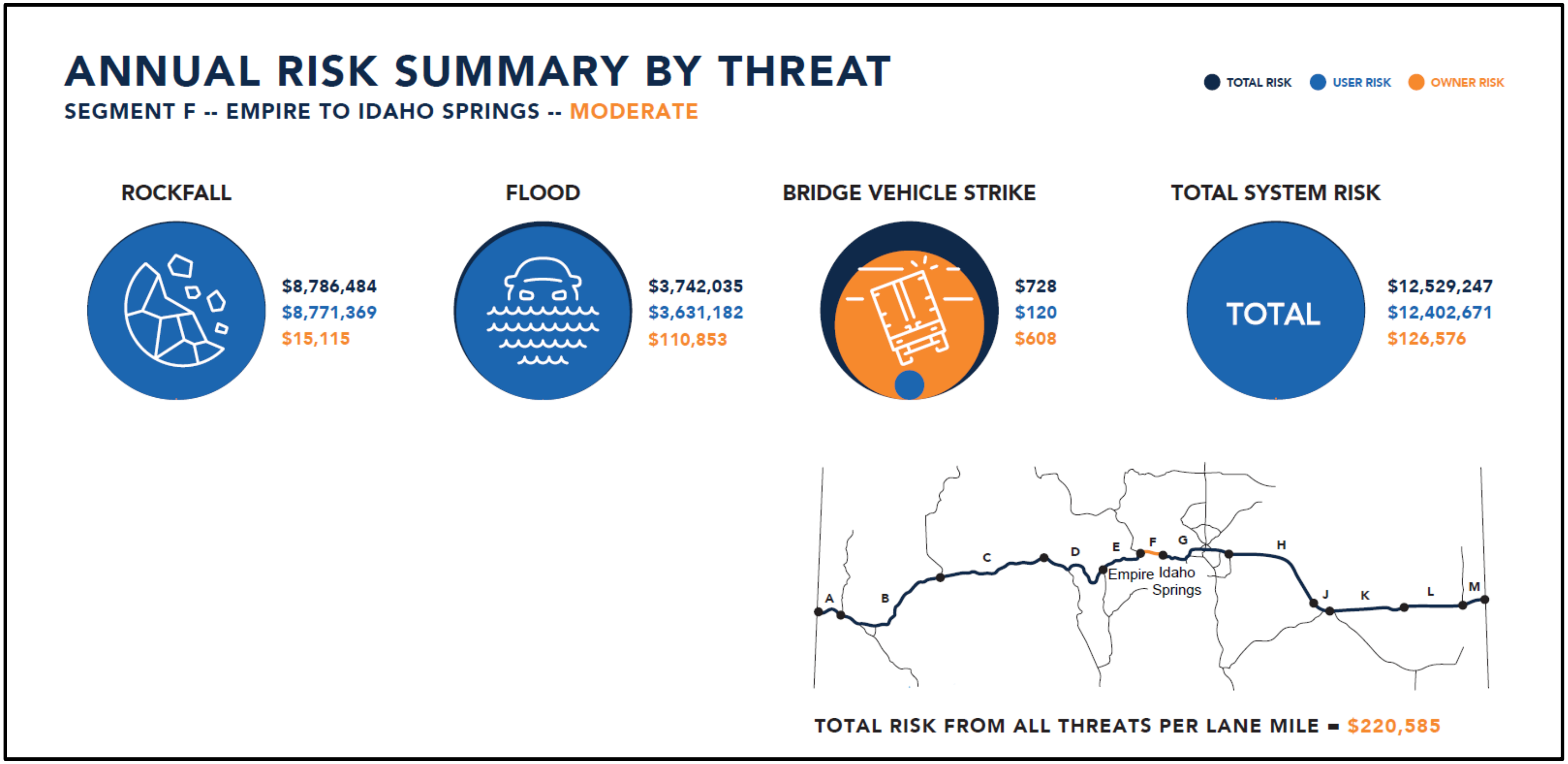
TOTAL RISK FROM ALL THREATS PER LANE MILE = $224,635

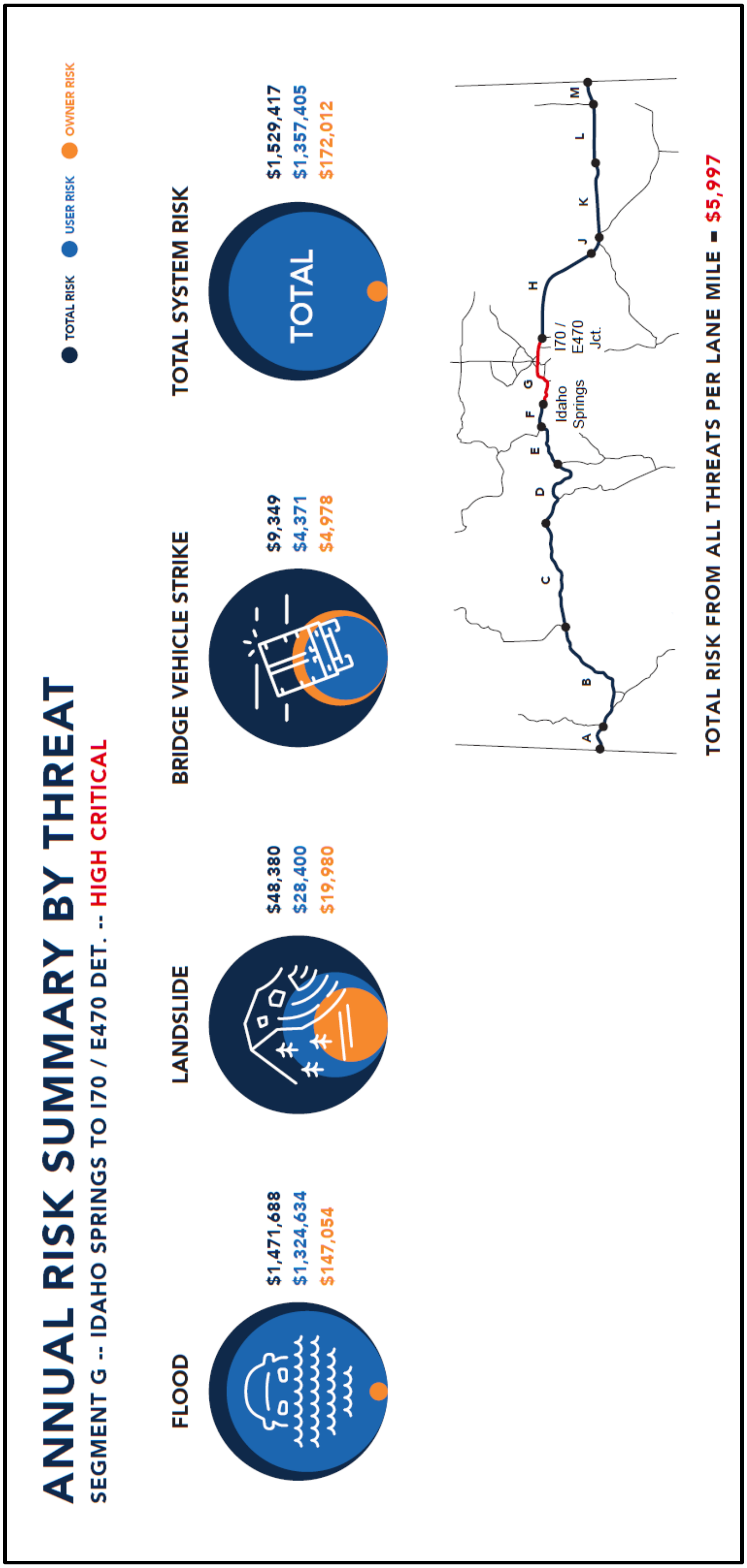

ANNUAL RISK SUMMARY BY THREAT
SEGMENT B -- LOMA TO RIFLE -- HIGH CRITICAL
TOTAL RISK
USER RISK
OWNER RISK
FLOOD
$85,172,493
$84,792,946
$379,547
ROCKFALL
$174,987
$174,717
$270
LANDSLIDE
$83,664
$46,164
$37,500
BRIDGE VEHICLE STRIKE
$919
$213
$706
TOTAL SYSTEM RISK
TOTAL
$85,432,063
$85,014,040
$418,023
A
B
C
D
E
F
G
H
J
K
L
M
Loma
Rifle
TOTAL RISK FROM ALL THREATS PER LANE MILE = $281,027

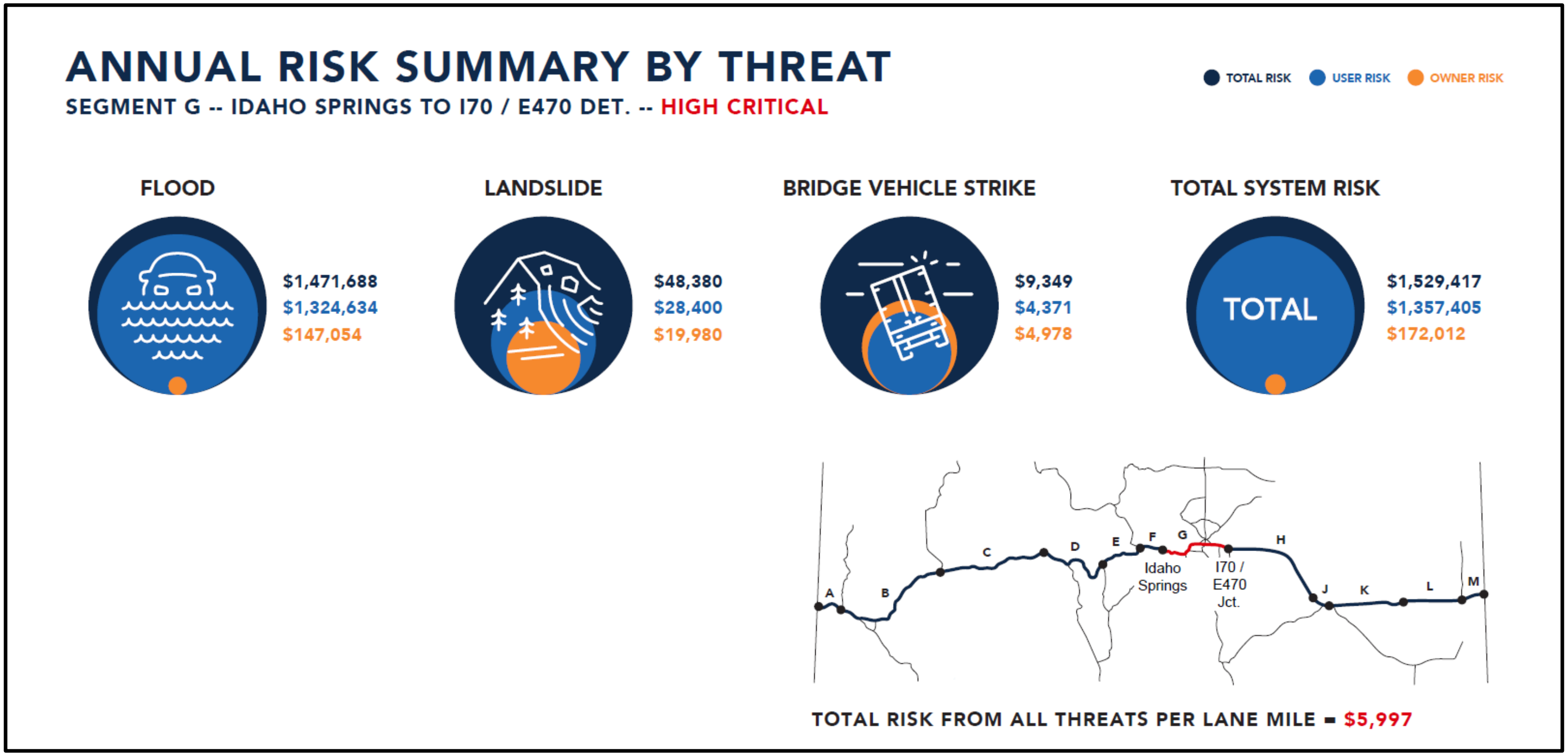

ANNUAL RISK SUMMARY BY THREAT
SEGMENT C -- RIFLE TO WOLCOTT -- HIGH CRITICAL
TOTAL RISK
USER RISK
OWNER RISK
ROCKFALL
$16,977,067
$13,174,605
$3,802,462
FLOOD
$8,713,721
$8,586,235
$127,486
BRIDGE VEHICLE STRIKE
$1,456
$206
$1,250
TOTAL SYSTEM RISK
TOTAL
$25,692,244
$21,761,046
$3,931,198
A
B
Rifle
C
Wolcott
D
E
F
G
H
J
K
L
M
TOTAL RISK FROM ALL THREATS PER LANE MILE = $98,816


ANNUAL RISK SUMMARY BY THREAT
SEGMENT D -- WOLCOTT TO SILVERTHORNE -- HIGH CRITICAL
TOTAL RISK
USER RISK
OWNER RISK
AVALANCHE
$7,850,903
$7,653,416
$197,487
FLOOD
$2,146,487
$1,997,032
$149,455
LANDSLIDE
$1,722,946
$1,316,362
$406,584
HIGH WIND & RELATED WEATHER
$8,756
$8,448
$308
BRIDGE VEHICLE STRIKE
$3,489
$1,148
$2,341
TOTAL SYSTEM RISK
TOTAL
$11,723,825
$10,967,958
$755,867
A
B
C
D
E
F
G
H
J
K
L
M
Wolcott
Silverthorne
TOTAL RISK FROM ALL THREATS PER LANE MILE - $58,619

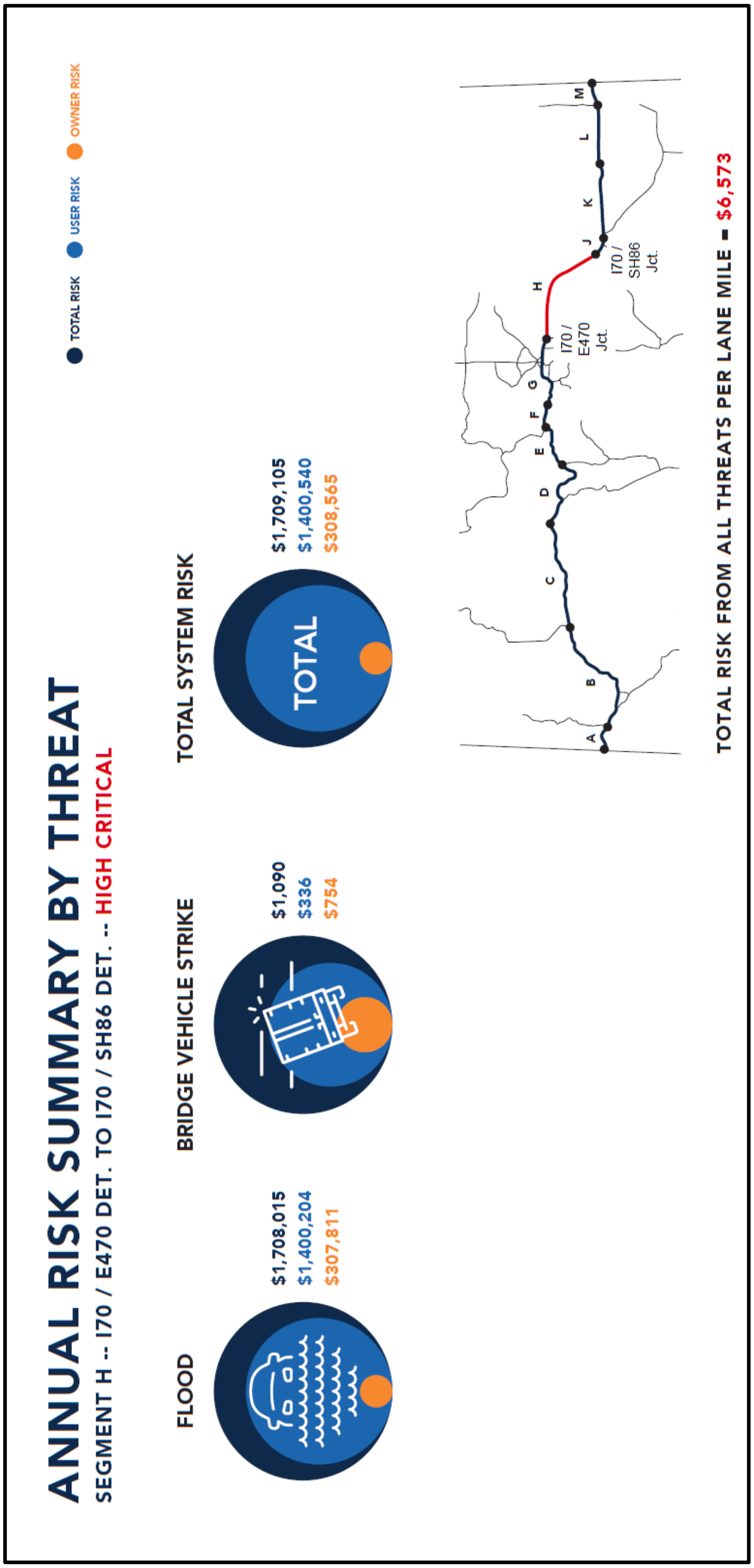

ANNUAL RISK SUMMARY BY THREAT
SEGMENT E -- SILVERTHRONE TO EMPIRE -- MODERATE
TOTAL RISK
USER RISK
OWNER RISK
ROCKFALL
$13,678,549
$13,660,714
$17,835
LANDSLIDE
$1,030,687
$770,937
$259,750
AVALANCHE
$881,874
$863,268
$18,606
FLOOD
$848,075
$808,144
$39,931
BRIDGE VEHICLE STRIKE
$5,549
$471
$5,078
TOTAL SYSTEM RISK
TOTAL
$16,444,734
$16,103,534
$341,200
A
B
C
D
E
F
G
H
J
K
L
M
Empire
Silverthrone
TOTAL RISK FROM ALL THREATS PER LANE MILE — $137,728

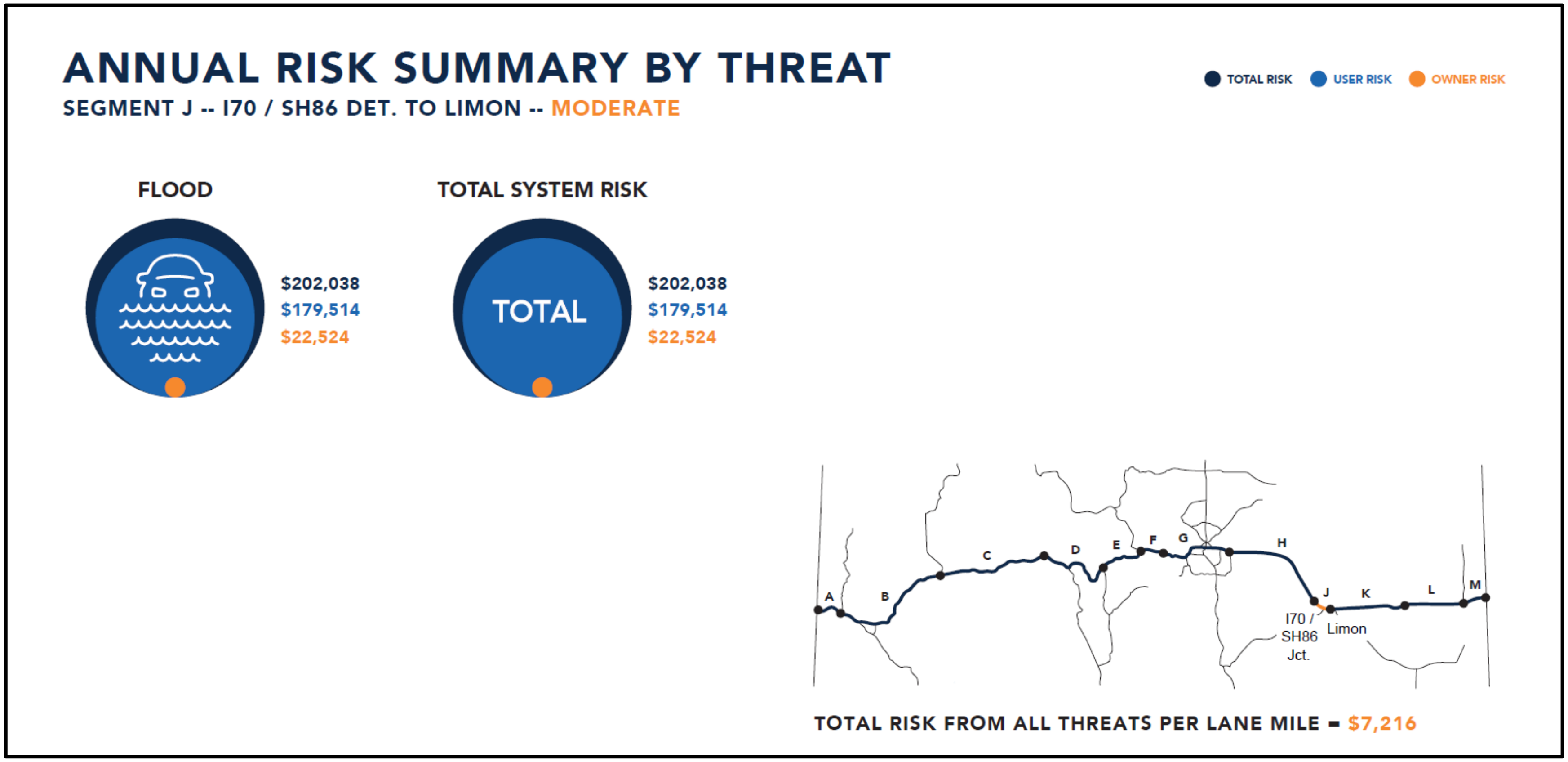

ANNUAL RISK SUMMARY BY THREAT
SEGMENT F -- EMPIRE TO IDAHO SPRINGS -- MODERATE
TOTAL RISK
USER RISK
OWNER RISK
ROCKFALL
$8,786,484
$8,771,369
$15,115
FLOOD
$3,742,035
$3,631,182
$110,853
BRIDGE VEHICLE STRIKE
$728
$120
$608
TOTAL SYSTEM RISK
TOTAL
$12,529,247
$12,402,671
$126,576
A
B
C
D
E
F
G
H
J
K
L
M
Empire
Idaho Springs
TOTAL RISK FROM ALL THREATS PER LANE MILE = $220,585

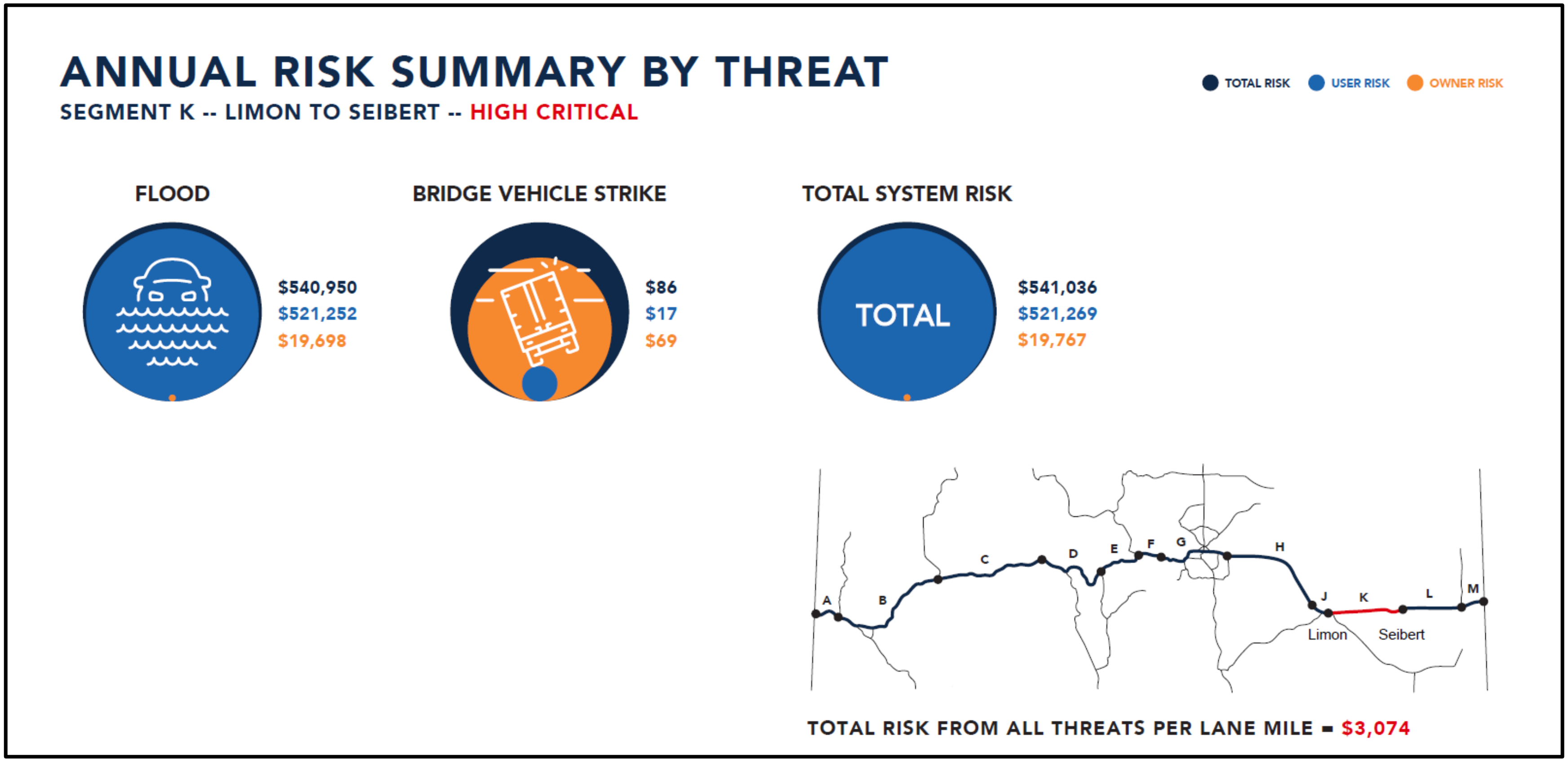

ANNUAL RISK SUMMARY BY THREAT
SEGMENT G -- IDAHO SPRINGS TO I70 / E470 DET. -- HIGH CRITICAL
TOTAL RISK
USER RISK
OWNER RISK
FLOOD
$1,471,688
$1,324,634
$147,054
LANDSLIDE
$48,380
$28,400
$19,980
BRIDGE VEHICLE STRIKE
$9,349
$4,371
$4,978
TOTAL SYSTEM RISK
TOTAL
$1,529,417
$1,357,405
$172,012
A
B
C
D
E
F
G
H
J
K
L
M
Idaho Springs
I70 / E470 Jct.
TOTAL RISK FROM ALL THREATS PER LANE MILE = $5,997



ANNUAL RISK SUMMARY BY THREAT
SEGMENT G -- IDAHO SPRINGS TO I70 / E470 DET. -- HIGH CRITICAL
TOTAL RISK
USER RISK
OWNER RISK
FLOOD
$1,471,688
$1,324,634
$147,054
LANDSLIDE
$48,380
$28,400
$19,980
BRIDGE VEHICLE STRIKE
$9,349
$4,371
$4,978
TOTAL SYSTEM RISK
TOTAL
$1,529,417
$1,357,405
$172,012
A
B
C
D
E
F
G
H
J
K
L
M
Idaho Springs
I70 / E470 Jct.
TOTAL RISK FROM ALL THREATS PER LANE MILE = $5,997


ANNUAL RISK SUMMARY BY THREAT
SEGMENT H -- I70 / E470 DET. TO I70 / SH86 DET. -- HIGH CRITICAL
TOTAL RISK
USER RISK
OWNER RISK
FLOOD
$1,708,015
$1,400,204
$307,811
BRIDGE VEHICLE STRIKE
$1,090
$336
$754
TOTAL SYSTEM RISK
TOTAL
$1,709,105
$1,400,540
$308,565
A
B
C
D
E
F
G
H
J
K
L
M
I70 / E470 Jct.
I70 / SH86 Jct.
TOTAL RISK FROM ALL THREATS PER LANE MILE = $6,573


ANNUAL RISK SUMMARY BY THREAT
SEGMENT J -- I70 / SH86 DET. TO LIMON -- MODERATE
TOTAL RISK
USER RISK
OWNER RISK
FLOOD
$202,038
$179,514
$22,524
TOTAL SYSTEM RISK
TOTAL
$202,038
$179,514
$22,524
A
B
C
D
E
F
G
H
J
K
L
M
I70 / SH86 Jct.
Limon
TOTAL RISK FROM ALL THREATS PER LANE MILE = $7,216

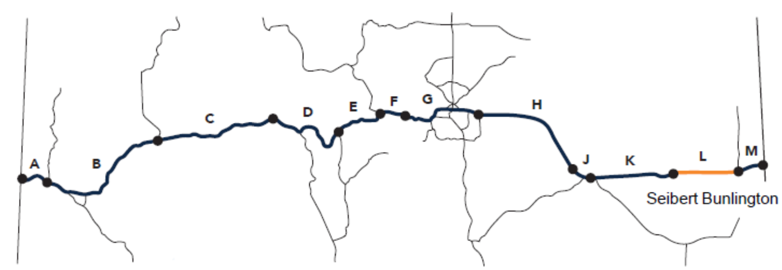

ANNUAL RISK SUMMARY BY THREAT
SEGMENT K -- LIMON TO SEIBERT -- HIGH CRITICAL
TOTAL RISK
USER RISK
OWNER RISK
FLOOD
$540,950
$521,252
$19,698
BRIDGE VEHICLE STRIKE
$86
$17
$69
TOTAL SYSTEM RISK
TOTAL
$541,036
$521,269
$19,767
A
B
C
D
E
F
G
H
J
K
L
M
Limon
Seibert
TOTAL RISK FROM ALL THREATS PER LANE MILE = $3,074

ANNUAL RISK SUMMARY BY THREAT

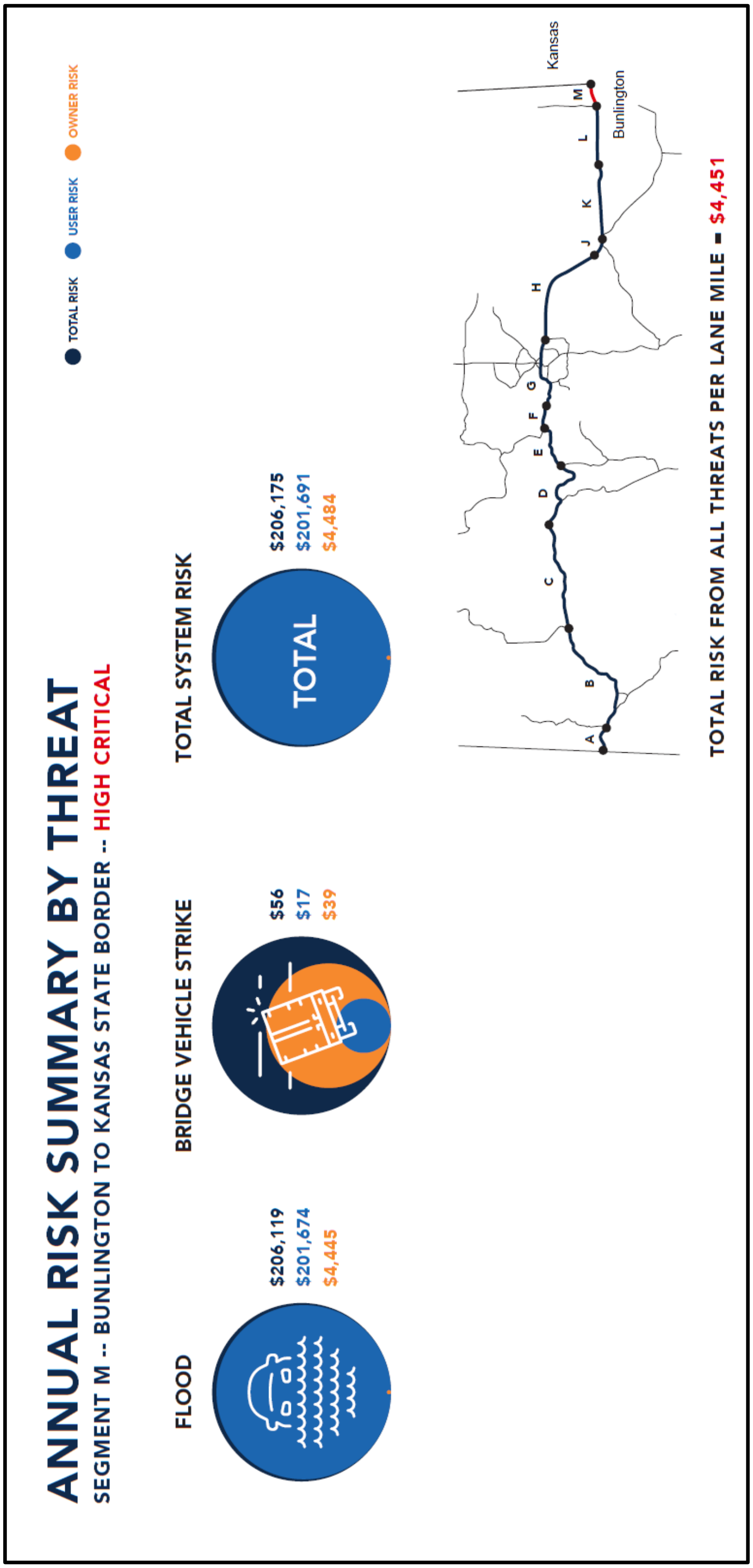
SEGMENT L -- SEIBERT TO BUNLINGTON -- MODERATE

TOTAL RISK · USER RISK · OWNER RISK

Threat	Total Risk	User Risk	Owner Risk
FLOOD	$750,333	$726,808	$23,525
TOTAL SYSTEM RISK	$750,333	$726,808	$23,525
HIGH WIND & RELATED WEATHER	$29	$27	$2



TOTAL RISK FROM ALL THREATS PER LANE MILE = $5,517


ANNUAL RISK SUMMARY BY THREAT
SEGMENT M -- BUNLINGTON TO KANSAS STATE BORDER -- HIGH CRITICAL
TOTAL RISK
USER RISK
OWNER RISK
FLOOD
$206,119
$201,674
$4,445
BRIDGE VEHICLE STRIKE
$56
$17
$39
TOTAL SYSTEM RISK
TOTAL
$206,175
$201,691
$4,484
A
B
C
D
E
F
G
H
J
K
L
M
Kansas
Burlington
TOTAL RISK FROM ALL THREATS PER LANE MILE = $4,451

Appendix C Top 20 Annualized Risk Tables for Select Threat-Asset Pairs

(Full Tables Provided to CDOT in Electronic Form)

Table C.1 Bridge Approach - Flood

Unique Identification Number	Resiliency Segment Reference	Starting Milepost	Ending Milepost	Roadway Traffic Direction	Region	Annualized Owner Risk - Flood	Annualized User Risk - Flood	Annualized Total Risk - Flood
A24	J	355.52	355.53	E	4	$1,249	$5,027	$6,276
A30	H	310.76	310.77	W	1	$1,176	$1,449	$2,625
A28	H	310.50	310.50	W	1	$1,176	$1,449	$2,625
A23	J	355.50	355.50	E	4	$1,136	$4,570	$5,706
A22	H	310.68	310.69	E	1	$1,069	$1,317	$2,386
A29	H	310.68	310.69	W	1	$1,069	$1,317	$2,386
A37	B	17.25	17.26	W	3	$893	$4,371	$5,264
A38	B	17.33	17.33	W	3	$813	$3,976	$4,789
A4	B	16.76	16.77	E	3	$677	$3,313	$3,990
A33	B	15.60	15.60	W	3	$677	$3,313	$3,990
A34	B	15.70	15.70	W	3	$677	$3,313	$3,990
A2	B	15.70	15.70	E	3	$677	$3,313	$3,990
A1	B	15.60	15.60	E	3	$677	$3,313	$3,990
A6	B	17.33	17.33	E	3	$677	$3,313	$3,990
A27	H	310.41	310.42	W	1	$641	$790	$1,431
A44	B	23.99	23.99	W	3	$640	$5,502	$6,142
A12	B	23.99	23.99	E	3	$640	$5,502	$6,142
A11	B	23.92	23.92	E	3	$640	$5,502	$6,142
A43	B	23.92	23.92	W	3	$640	$5,502	$6,142
A20	H	310.50	310.50	E	1	$632	$1,317	$1,949

Table C.2 Bridge - Avalanche

Unique Identification Number	Structural ID	Resiliency Segment Reference	Starting Milepost	Ending Milepost	Roadway Traffic Direction	Region	Annualized Owner Risk - Avalanche	Annualized User Risk - Avalanche	Annualized Total Risk - Avalanche
B263	F-11-AQ	D	183.06	183.09	E	3	$300	$553	$853

Table C.3 Bridge - Flood

Unique Identification Number	Structural ID	Resiliency Segment Reference	Starting Milepost	Ending Milepost	Roadway Traffic Direction	Region	Annualized Owner Risk - Flood	Annualized User Risk - Flood	Annualized Total Risk - Flood
B95	E-16-JO	G	265.13	265.20	E	1	$1,565	$57,356	$58,921
B100	F-19-AW	H	310.75	310.78	E	1	$2,212	$53,469	$55,681
B77	F-11-AD	D	171.03	171.18	BOTH	3	$4,130	$47,237	$51,367
B96	F-19-AU	H	310.47	310.51	E	1	$2,117	$27,425	$29,542
B338	H-01-AE	B	16.72	16.81	E	3	$4,407	$24,365	$28,772
B337	H-01-AC	B	17.29	17.37	E	3	$4,042	$24,365	$28,407
B94	G-21-N	J	355.51	355.54	E	4	$1,156	$26,057	$27,213
B156	F-15-BH	F	242.74	242.83	BOTH	1	$2,209	$24,765	$26,974
B243	F-15-BX	F	242.98	243.10	BOTH	1	$3,880	$22,000	$25,880
B335	H-02-FE	B	23.98	24.01	E	3	$679	$25,191	$25,870
B363	H-03-AY	B	43.47	43.90	BOTH	3	$8,421	$14,682	$23,103
B13	F-08-AI	C	122.38	122.94	W	3	$5,703	$17,225	$22,928
B30	F-08-AR	C	125.61	126.11	E	3	$5,096	$17,225	$22,321
B3	F-08-AD	C	128.10	128.53	W	3	$4,655	$17,225	$21,880
B170	E-16-JM	G	265.13	265.20	W	1	$1,982	$19,897	$21,879
B169	E-16-PM	G	269.36	269.44	W	1	$2,039	$19,484	$21,523
B327	F-10-AB	C	153.90	154.32	E	3	$5,528	$15,851	$21,379
B330	F-10-AA	C	153.90	154.32	W	3	$5,526	$15,851	$21,377
B278	F-12-AP	D	193.64	193.88	E	3	$2,992	$18,057	$21,049
B5	F-08-BI	C	124.88	125.24	E	3	$3,789	$17,225	$21,014

Table C.4 Bridge - Landslide

Unique Identification Number	Structural ID	Resiliency Segment Reference	Starting Milepost	Ending Milepost	Roadway Traffic Direction	Region	Annualized Owner Risk - Landslide	Annualized User Risk - Landslide	Annualized Total Risk - Landslide
B77	F-11-AD	D	171.09	171.16	BOTH	3	$6,759	$2,863	$9,622

Table C.5 Bridge - Rockfall

Unique Identification Number	Structural ID	Resiliency Segment Reference	Starting Milepost	Ending Milepost	Roadway Traffic Direction	Region	Annualized Owner Risk - Rockfall	Annualized User Risk - Rockfall	Annualized Total Risk - Rockfall
B7	F-07-AP	C	120.62	120.71	W	3	$234,800	$28,838	$263,638
B18	F-08-AV	C	126.95	127.45	W	3	$234,800	$28,838	$263,638
B9	F-07-AO	C	120.51	120.58	W	3	$234,800	$28,838	$263,638
B8	F-07-AQ	C	120.76	120.84	W	3	$234,800	$28,838	$263,638
B12	F-08-BJ	C	125.33	126.51	W	3	$234,800	$28,838	$263,638
B30	F-08-AR	C	125.61	126.11	E	3	$100,075	$0	$100,075
B32	F-08-AK	C	124.40	124.48	W	3	$40,700	$0	$40,700
B34	F-08-AG	C	121.83	121.90	W	3	$40,700	$0	$40,700
B252	F-15-BL	F	244.16	244.36	W	1	$1,250	$1,099	$2,349
B16	F-07-AL	C	119.64	119.87	W	3	$1,250	$154	$1,404
B11	F-07-AR	C	120.90	121.03	W	3	$1,250	$154	$1,404
B31	F-08-AS	C	125.72	125.99	W	3	$1,250	$154	$1,404
B27	F-08-BH	C	127.03	128.22	W	3	$1,250	$154	$1,404

Table C.6 Bridge – Vehicle Strike

Unique Identification Number	Structural ID	Resiliency Segment Reference	Starting Milepost	Ending Milepost	Roadway Traffic Direction	Region	Annualized Owner Risk - Bridge Strike	Annualized User Risk - Bridge Strike	Annualized Total Risk - Bridge Strike
B276	F-12-Y	E	205.04	205.25	E	3	$4,875	$391	$5,266
B163	E-17-JP	G	280.53	280.61	BOTH	1	$2,659	$1,191	$3,850
B261	F-11-X	D	177.41	177.44	E	3	$509	$764	$1,273
B271	F-11-AH	D	179.84	179. 89	W	3	$895	$88	$983
B236	F-16-AS	G	260.98	261.08	E	1	$128	$537	$665
B199	E-17-GA	G	278.52	278.57	W	1	$57	$515	$572
B125	E-17-GB	G	278.52	278.57	E	1	$57	$511	$568
B160	E-16-DI	G	270.46	270.53	BOTH	1	$183	$225	$408
B2	F-08-AE	C	128.04	128.49	E	3	$356	$5	$361
B238	E-16-MR	G	273.63	274.50	E	1	$112	$206	$318
B363	H-03-AY	B	43.47	43.90	BOTH	3	$310	$5	$315
B159	E-16-GW	G	268.39	268.44	BOTH	1	$203	$101	$304
B5	F-08-BI	C	124.88	125.24	E	3	$288	$4	$292
B255	E-16-MS	G	273.62	274.50	W	1	$114	$173	$286
B277	F-11-AU	D	181.78	182.04	E	3	$245	$5	$250
B244	E-17-FX	G	275.51	276.65	BOTH	1	$226	$9	$235
B109	E-16-GY	G	267.37	267.43	E	1	$32	$170	$202
B239	E-17-UR	G	274.46	275.17	E	1	$177	$5	$182
B237	F-16-HH	G	261.56	261.70	E	1	$82	$98	$180
B257	E-17-UU	G	274.46	275.17	W	1	$169	$11	$179

Table C.7 Minor Culvert - Flood

Unique Identification Number	Structural ID	Resiliency Segment Reference	Starting Milepost	Ending Milepost	Region	Annualized Owner Risk - Flood	Annualized User Risk - Flood	Annualized Total Risk - Flood
20561943	CUL070A209726337	B	71.99	72.01	3	$754	$1,620,391	$1,621,144
4741216	CUL070A184135597	B	38.99	39.01	3	$53	$1,395,246	$1,395,299
4601632	CUL070A142566509	B	35.99	36.01	3	$19	$1,395,246	$1,395,265
4511280	CUL070A139464904	B	31.99	32.01	3	$669	$1,259,322	$1,259,990
1988712	CUL070A131243466	B	75.99	76.01	3	$434	$1,084,126	$1,084,560
6381	CUL070A869743075	A	3.99	4.01	3	$0	$1,070,584	$1,070,584
1991734	CUL070A132317525	B	19.21	19.23	3	$253	$1,028,467	$1,028,720
821703	CUL070A602732133	A	3.99	4.01	3	$195	$1,027,246	$1,027,440
20491251	CUL070A170017431	B	71.99	72.01	3	$743	$969,551	$970,294
340766	CUL070A965418361	B	55.99	56.01	3	$504	$969,551	$970,055
4701277	CUL070A111841968	B	37.99	38.01	3	$269	$881,797	$882,066
421278	CUL070A168845995	B	40.99	41.01	3	$194	$881,797	$881,991
409303	CUL070A128625213	B	40.99	41.01	3	$22	$881,797	$881,819
1981719	CUL070A912715774	B	19.21	19.23	3	$627	$876,356	$876,984
4901568	CUL070A897313508	B	35.99	36.01	3	$437	$876,356	$876,794
19721321	CUL070A965661133	B	79.99	80.01	3	$265	$849,235	$849,500
2721482	CUL070A686096871	B	66.99	67.01	3	$230	$849,235	$849,465
4081858	CUL070A179431404	B	39.99	40.01	3	$131	$849,235	$849,366
2043244	CUL070A188705159	B	71.99	72.01	3	$38	$849,235	$849,273
1429	CUL070A160406242	A	6.99	7.01	3	$16	$849,235	$849,251

Table C.8 NBI Culvert - Flood

Unique Identification Number	Structural ID	Resiliency Segment Reference	Starting Milepost	Ending Milepost	Roadway Traffic Direction	Region	Annualized Owner Risk - Flood	Annualized User Risk - Flood	Annualized Total Risk - Flood
CN18	H-02-FT	B	24.74	24.76	BOTH	3	$10,822	$2,103,560	$2,114,382
CN7	E-14-AV	F	232.22	232.25	BOTH	1	$27,260	$1,597,052	$1,624,312
CN41	H-02-FS	B	24.74	24.76	BOTH	3	$12,762	$1,370,858	$1,383,620
CN19	H-02-EP	B	32.35	32.39	BOTH	3	$22,970	$1,071,303	$1,094,273
CN33	H-03-BF	B	34.73	34.78	BOTH	3	$18,752	$1,071,303	$1,090,055
CN22	G-04-AW	B	60.92	60.98	BOTH	3	$11,973	$612,711	$624,684
CN15	F-16-HR	G	262.32	262.38	BOTH	1	$50,283	$552,853	$603,136
CN31	G-04-AV	B	59.28	59.34	BOTH	3	$7,056	$492,140	$499,195
CN30	F-16-BB	G	261.61	261.74	BOTH	1	$56,782	$340,287	$397,069
CN26	G-04-AX	B	62.39	62.42	BOTH	3	$8,965	$386,758	$395,723
CN39	F-07-U	C	109.16	109.20	BOTH	3	$5,942	$380,205	$386,147
CN28	F-09-AJ	C	139.14	139.24	BOTH	3	$10,095	$371,222	$381,317
CN32	G-04-AU	B	58.96	59.04	BOTH	3	$14,928	$297,794	$312,721
CN5	F-05-U	B	83.49	83.54	BOTH	3	$4,819	$293,755	$298,574
CN20	G-25-M	L	407.53	407.57	BOTH	4	$5,782	$286,901	$292,683
CN9	H-03-G	B	44.39	44.40	BOTH	3	$2,463	$267,826	$270,289
CN6	G-22-AT	K	366.30	366.36	BOTH	4	$6,333	$250,564	$256,898
CN42	G-24-P	K	389.35	389.41	BOTH	4	$5,699	$239,111	$244,811
CN17	G-04-BB	B	75.39	75.48	BOTH	3	$9,818	$228,258	$238,076
CN29	G-05-M	B	78.21	78.23	BOTH	3	$1,596	$225,381	$226,978

Table C.9 PTCS - Rockfall

Unique Identification Number	Resiliency Segment Reference	Starting Milepost	Ending Milepost	Roadway Traffic Direction	Region	Annualized Owner Risk - Rockfall	Annualized User Risk - Rockfall	Annualized Total Risk - Rockfall
PW75	C	122.07	122.17	W	3	$206,624	$1,095,267	$1,301,891
PW46	C	125.45	125.48	W	3	$206,624	$1,095,267	$1,301,891
PW4	C	124.97	125.08	W	3	$206,624	$1,095,267	$1,301,891
PW81	C	121.99	122.07	W	3	$206,624	$1,095,267	$1,301,891
PW34	C	125.59	125.64	W	3	$206,624	$1,095,267	$1,301,891
PE72	C	124.68	124.77	E	3	$110,066	$583,434	$693,500
PW18	C	124.48	124.58	W	3	$77,044	$408,393	$485,437
PW44	C	125.64	125.74	W	3	$77,044	$408,393	$485,437
PW31	C	125.48	125.59	W	3	$77,044	$408,393	$485,437
PW41	C	125.74	125.83	W	3	$77,044	$408,393	$485,437
PW6	C	125.16	125.23	W	3	$77,044	$408,393	$485,437
PW25	C	122.58	122.65	W	3	$77,044	$408,393	$485,437
PW7	C	125.08	125.16	W	3	$77,044	$408,393	$485,437
PW0	C	124.86	124.97	W	3	$77,044	$408,393	$485,437
PE74	C	124.48	124.58	E	3	$62,348	$330,493	$392,841
PE92	C	124.29	124.39	E	3	$62,348	$330,493	$392,841
PE73	C	124.87	124.90	E	3	$62,348	$330,493	$392,841
PE36	C	122.42	122.46	E	3	$62,348	$330,493	$392,841
PE88	C	124.09	124.20	E	3	$62,348	$330,493	$392,841
PE68	C	124.58	124.68	E	3	$62,348	$330,493	$392,841

Table C.10 Roadway - Avalanche

Unique Identification Number	Resiliency Segment Reference	Starting Milepost	Ending Milepost	Roadway Traffic Direction	Region	Annualized Owner Risk - Avalanche	Annualized User Risk - Avalanche	Annualized Total Risk - Avalanche
RW2679	D	186.00	186.10	W	3	$59,940	$2,237,221	$2,297,161
RW2683	D	186.30	186.40	W	3	$59,940	$2,237,221	$2,297,161
RE2807	D	187.23	187.37	E	3	$59,940	$2,237,221	$2,297,161
RW2859	D	196.90	197.00	W	3	$14,985	$821,076	$836,061
RW3119	E	212.90	214.36	W	3	$14,985	$694,816	$709,801
RW3084	E	211.01	211.05	W	3	$1,798	$83,378	$85,176
RE2979	D	197.83	197.89	E	3	$1,284	$70,378	$71,662
RW3094	E	211.56	211.59	W	3	$1,499	$69,482	$70,981
RE2999	D	199.04	199.12	E	3	$499	$27,369	$27,868
RE2759	D	183.88	183.92	E	3	$599	$22,372	$22,971
RW3275	E	222.50	222.55	W	1	$300	$14,505	$14,805
RE3239	E	212.90	213.01	E	3	$15	$696	$711
RE3223	E	212.85	213.14	E	3	$3	$139	$142
RE3202	E	211.82	212.09	E	3	$2	$83	$85
RE3214	E	212.48	212.74	E	3	$2	$70	$72
RW3124	E	213.11	213.17	W	3	$2	$70	$72

Table C.11 Roadway - Flood

Unique Identification Number	Resiliency Segment Reference	Starting Milepost	Ending Milepost	Roadway Traffic Direction	Region	Annualized Owner Risk - Flood	Annualized User Risk - Flood	Annualized Total Risk - Flood
RE21	D	205.00	205.05	E	3.00	$1,247	$115,909	$117,156
RW1277	C	97.50	97.56	W	3.00	$10,445	$106,570	$117,015
RW2986	E	205.05	205.08	W	3.00	$1,054	$115,909	$116,963
RE9	C	97.50	97.56	E	3.00	$10,225	$106,570	$116,795
RE14	D	196.62	196.70	E	3.00	$20,152	$93,050	$113,202
RW3625	F	241.35	241.40	W	1.00	$3,765	$97,775	$101,540
RE47	F	242.70	242.79	E	1.00	$2,934	$97,775	$100,709
RE43	F	241.35	241.40	E	1.00	$1,908	$97,775	$99,683
RE17	D	199.60	199.70	E	3.00	$4,118	$93,050	$97,168
RW2895	D	199.53	199.60	W	3.00	$3,146	$93,050	$96,196
RW2929	D	201.86	201.87	W	3.00	$1,281	$89,281	$90,562
RE20	D	201.82	201.86	E	3.00	$858	$89,281	$90,139
RE23	E	220.97	221.00	E	1.00	$5,371	$83,828	$89,199
RW3655	F	243.00	243.04	W	1.00	$2,335	$78,109	$80,444
RE49	F	243.04	243.08	E	1.00	$2,057	$78,109	$80,166
RE52	F	244.30	244.40	E	1.00	$446	$74,456	$74,902
RE12	C	133.00	133.10	E	3.00	$2,835	$69,787	$72,622
RW2412	D	170.40	170.50	W	3.00	$88	$71,994	$72,082
RE86	D	170.40	170.50	E	3.00	$75	$71,994	$72,069
RE39	F	237.50	237.60	E	1.00	$1,198	$69,658	$70,856

Table C.12 Roadway - Landslide

Unique Identification Number	Resiliency Segment Reference	Starting Milepost	Ending Milepost	Roadway Traffic Direction	Region	Annualized Owner Risk - Landslide	Annualized User Risk - Landslide	Annualized Total Risk - Landslide
RE11001	E	213.14	213.25	E	3	$249,750	$741,257	$991,007
RW4003	D	158.86	159.00	W	3	$150,000	$432,380	$582,380
RE11002	D	158.60	158.73	E	3	$149,850	$431,948	$581,798
RE11005	D	171.06	171.09	E	3	$24,975	$123,451	$148,426
RW4004	D	178.54	179.26	W	3	$25,000	$78,568	$103,568
RE11003	D	171.55	171.74	E	3	$12,500	$61,788	$74,288
RE11007	D	171.91	172.11	E	3	$12,500	$61,788	$74,288
RW4002	D	171.92	172.36	W	3	$12,500	$61,788	$74,288
RW4001	D	171.82	172.00	W	3	$12,500	$61,788	$74,288
RE11006	G	245.57	245.63	E	1	$19,980	$28,400	$48,380
RW4006	B	51.45	51.68	W	3	$25,000	$23,082	$48,082
RW4005	E	213.36	213.47	W	3	$10,000	$29,680	$39,680
RE11004	B	51.35	51.59	E	3	$12,500	$23,082	$35,582

Table C.13 Roadway - Rockfall

Unique Identification Number	Resiliency Segment Reference	Starting Milepost	Ending Milepost	Roadway Traffic Direction	Region	Annualized Owner Risk - Rockfall	Annualized User Risk - Rockfall	Annualized Total Risk - Rockfall
RW3394	E	229.30	229.40	W	1	$1,944	$2,290,228	$2,292,172
RW3391	E	229.17	229.20	W	1	$1,944	$2,290,228	$2,292,172
RW3392	E	229.20	229.25	W	1	$1,944	$2,290,228	$2,292,172
RW3393	E	229.25	229.30	W	1	$1,944	$2,290,228	$2,292,172
RW3390	E	229.10	229.17	W	1	$1,944	$2,290,228	$2,292,172
RW3361	E	227.30	227.40	W	1	$1,944	$1,903,812	$1,905,756
RW3499	F	235.42	235.50	W	1	$1,944	$1,754,054	$1,755,998
RW3506	F	235.82	235.90	W	1	$1,944	$1,754,054	$1,755,998
RW3509	F	236.00	236.07	W	1	$1,944	$1,754,054	$1,755,998
RW3507	F	235.90	235.97	W	1	$1,944	$1,754,054	$1,755,998
RW3508	F	235.97	236.00	W	1	$1,944	$1,754,054	$1,755,998
RW1468	C	110.38	110.40	W	3	$10	$15,960	$15,970
RW1467	C	110.31	110.38	W	3	$10	$15,960	$15,970
RW1515	C	112.77	112.80	W	3	$10	$15,960	$15,970
RW1469	C	110.40	110.48	W	3	$10	$15,960	$15,970
RW1513	C	112.63	112.70	W	3	$10	$15,960	$15,970
RW1472	C	110.53	110.59	W	3	$10	$15,960	$15,970
RW1474	C	110.60	110.70	W	3	$10	$15,960	$15,970
RW1516	C	112.80	112.90	W	3	$10	$15,960	$15,970
RW1475	C	110.70	110.80	W	3	$10	$15,960	$15,970

Table C.14 VMS - Wind

Unique Identification Number	Resiliency Segment Reference	Structural ID	Starting Milepost	Ending Milepost	Region	Annualized Owner Risk - Wind	Annualized User Risk - Wind	Annualized Total Risk - Wind
V48	D	SIGN-F-12-BX	195.87	195.88	3.00	$136	$4,848	$4,984
V50	D	SIGN-F-12-BZ	195.62	195.62	3.00	$36	$4,848	$4,884
V19	M	SIGN-G-28-P	438.38	438.39	4.00	$2	$35	$38
V23	B	SIGN-H-03-CE	49.70	49.71	3.00	$0	$4	$5
V4	B	SIGN-H-01-F	14.30	14.30	3.00	$0	$2	$2

Table C.15 Wall - Precipitation/Flood

Unique Identification Number	Resiliency Segment Reference	Structural ID	Starting Milepost	Ending Milepost	Region	Annualized Owner Risk - Rainfall/Flood	Annualized User Risk - Rainfall/Flood	Annualized Total Risk - Rainfall/Flood
W23	G	R070A256968LRA	256.97	256.97	1	$1	$26,103	$26,104
W41	G	N070A263280RRA	262.95	263.61	1	$189	$19,319	$19,507
W19	G	N070A263232LRA	263.22	263.25	1	$9	$19,319	$19,327
W6	G	N070A271536LRA	271.52	271.55	1	$3	$19,322	$19,325
W40	G	N070A271537RRA	271.52	271.55	1	$3	$14,095	$14,098
W30	G	N070A272489RRA	272.48	272.50	1	$3	$14,095	$14,098
W7	G	N070A271035LRA	271.02	271.05	1	$3	$14,095	$14,098
W13	G	N070A272488LRA	272.48	272.50	1	$2	$14,095	$14,097
W8	G	R070A259722RRA	259.66	259.78	1	$25	$14,010	$14,035
W36	G	R070A273156LRA	273.10	273.21	1	$22	$13,257	$13,279
W2	G	B070A273791MCA	273.78	273.80	1	$2	$13,125	$13,127
W31	G	B070A259738LRA	259.73	259.75	1	$2	$11,503	$11,505
W14	G	R070A258865LRA	258.85	258.88	1	$4	$10,705	$10,709
W1	G	R070A269428RRA	269.39	269.47	1	$36	$10,305	$10,342
W3	G	R070A270461LRA	270.45	270.47	1	$3	$9,612	$9,615
W39	G	R070A283658RRA	283.56	283.75	1	$31	$9,378	$9,409
W12	G	R070A283672RRA	283.60	283.74	1	$23	$9,378	$9,401
W4	G	B070A279599LRA	279.59	279.61	1	$2	$8,264	$8,265
W5	G	B070A264322LRA	264.29	264.36	1	$15	$7,972	$7,987
W38	G	B070A284217RRA	284.20	284.23	1	$4	$7,874	$7,878

Appendix D Distributed Flyer of I-70 Risk and Resilience Pilot

Putting the Brakes on Future Disasters:

Colorado Takes Leadership Role In Protecting Against Future Risks.

In September 2013, flood damage on US-34 destroyed an entire section of roadway.

In February 2016, a rockfall closed I-70 in Glenwood Springs for two weeks.

In May 2017, a fire on I-25 closed roadway during rush hour and damaged pavement.

BACKGROUND

The September 2013 flood event in Colorado lasted seven days, and left behind a path of destruction that spanned some 2,380 square miles. More than 3,000 evacuations were carried out, over 17,000 homes damaged, and an estimated 1,800 homes completely destroyed. The Colorado roadway network suffered severe damage, requiring more than $700 million in repairs.

Unfortunately, Colorado has experienced six major declarations of disasters in the past seven years. Since the 2013 flood event, Colorado endured a major rockfall event in 2016 that closed I-70 in the Glenwood Canyon for approximately two weeks. Alternative routes not designed to accommodate the detouring traffic also experienced damage. In May 2017, a tanker truck carrying fuel crashed and caught fire resulting in several hours of closure of all lanes in the Metro Denver area. The fire burned off several inches of asphalt resulting in emergency repairs.

Building on the lessons learned from these events, the Colorado Department of Transportation (CDOT) and the Colorado Division Office of Federal Highway Administration (FHWA) have developed a data driven approach to proactively identify and address vulnerabilities of the system from potential physical threats such as rockfall, flooding, and landslides.

PROACTIVE MANAGEMENT OF THREATS

The I-70 Risk and Resilience (R&R) Pilot began in August 2016, and builds on the work completed by CDOT in the wake of the 2013 flood event. It is a first-of-its kind approach, one meant to address vulnerabilities in Colorado's highway infrastructure before they ever become a concern. 450 miles of I-70 from the Utah border in the west to the Kansas border in the east have been analyzed for the potential of future damage and closures from physical threats. The Pilot covers an incredibly diverse range of geographies and climates in both urban and rural areas, and considers multiple significant threats—ranging from avalanche to wildfire, as well as human-made threats, such as high-vehicle bridge strikes.

The decision to initiate this work is not unlike the everyday, commonsense choices made by Coloradans in their personal lives. Installing an alarm system in your home, or purchasing a car with air bags, protects you and your loved ones while simultaneously reducing insurance premiums. It pays to plan ahead.

CDOT Project Manager
Lizzie Kemp Herrera
CDOT Region 1 Planning and Program Management
303.757.9629

CDOT Co-Project Manager
Heather Paddock, PE
CDOT Region 4
Central Program Engineer
970.290.8723

Principal Investigator
Aimee Flannery, Ph.D., PE
AEM Corporation
703.328.2423

RISK AND RESILIENCE FOR HIGHWAYS

COLORADO Department of Transportation

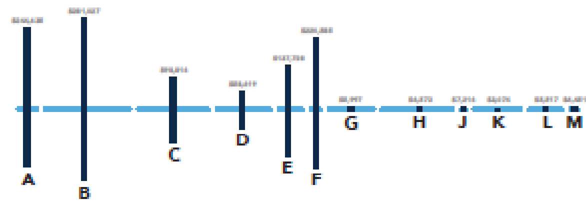
I-70 RISK AND RESILIENCE FINDINGS

STUDY AREA

I-70 CORRIDOR

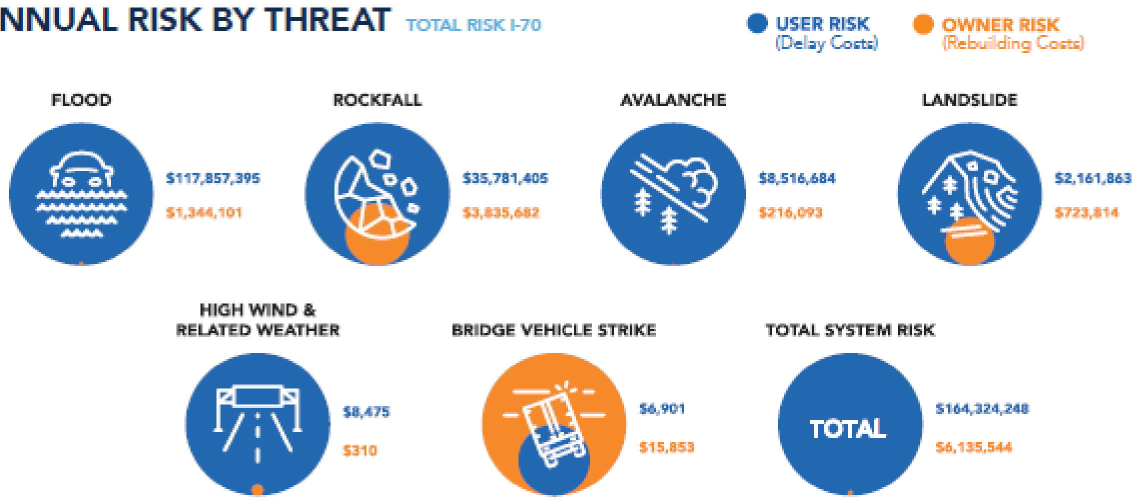
TOTAL ANNUAL RISK PER LANE MILE

USER RISK + OWNER RISK FROM ALL THREATS



The I-70 corridor was analyzed as a series of segments that reflect on and off points to the facility for the traveling public onto CDOT maintained roadways.

ANNUAL RISK BY THREAT TOTAL RISK I-70



All of the relevant threats to the I-70 corridor were included in the study, with annual risks to both CDOT (as owners of the highway facilities) and the traveling public calculated as shown in the above graphic. The most significant physical threats to I-70 include rockfall and flooding. Other potential events that could damage I-70 and impact travel on the corridor include avalanches, landslides, and high-vehicle bridge strikes. Armed with a better understanding of these threats, CDOT will now begin to identify the most cost-effective solutions that can be implemented at specific sites to reduce the risk of damage from future events. Resilience measures could include new roadway/bridge design, identification of a new alternate route, operational plans or improved maintenance.

NEXT STEPS

CDOT is currently analyzing the findings of the Pilot and determining how best to address at-risk locations. This analysis includes an assessment of a range of mitigation measures and includes benefit-cost analysis of potential mitigation measures to identify potential risk reduction and system resilient solutions. Next the agency will determine other corridors to be a part of the risk and resilience process, and how to use the results to inform day-to-day asset management, design, operations and maintenance decisions.

Appendix E Tunnel Analysis

FOR OFFICIAL USE ONLY (FOUO)

Appendix E Improvised Explosive Device (IED)Threat to Tunnels

The eleven tunnel bores in Table E.1 were modeled separately. Each tunnel bore was modeled as three separate subcomponents; i.e., east portal, tunnel, and west portal. Tunnel subsystems are allocated among subcomponents, depending on specific tunnel characteristics; e.g., Eisenhower East Portal has Command & Control, most of the communications, and half of the ventilation fans. Small, medium, and large IEDs were modeled for effect on subcomponent subsystems. For example, it was estimated that small IEDs have very little impact on the Eisenhower East Portal excavation, while the lining and ventilation systems sustain more damage.

The estimation of IED threat to tunnels included the following analysis:

- Terrorist calculus: amount of publicity versus likelihood of detection (from Bier, et al.)
- Terror attack likelihood estimate (from University of Maryland Global Terrorism Database)
- Likelihood of attack in rural Colorado (from Rand/RMS study, 2006)
- Likelihood type of facility (tunnel) will be attacked (from Rand/RMS study, 2006)
- Regional importance of facility (proportion of AADT capacity)
- Vulnerability and Consequence of specific asset and IED attack mode (NCHRP 525, Vol. 12)
- Adjust for likelihood of attack detection and preemption (from Risk Management Solutions, 2008)

Table E.1 Tunnel Bores

Tunnel	Mile Post
Eisenhower	213.7
Johnson	212.7
Hanging Lake EB	125.3
Hanging Lake WB	125.3
Hanging Lake RC	127.1
NoName WB	117.8
NoName EB	117.8
Beaver Tail Mtn WB	50.4
Beaver Tail Mtn EB	50.4
Veterans WB	242.3
Veterans EB	24.3

Tabulations of annual owner risk, user risk, and total risk can be found in the following tables.

Table E.2 Terrorist IED-Tunnel Attack Annual Owner Risk

IED User Risk		East Portal			West Portal			Tunnel			Total			Total
Bore	IED Size	S	M	L	S	M	L	S	M	L	S	M	L	
Eisenhower		$4,898	$4,347	$3,214	$2,556	$2,437	$1,918	$3,926	$4,664	$4,086	$11,380	$11,448	$9,218	$32,047
Johnson		$1,479	$1,412	$1,140	$1,479	$1,412	$1,140	$2,274	$2,701	$2,379	$5,232	$5,524	$4,659	$15,415
Hanging Lake EB		$45	$57	$43	$45	$57	$43	$76	$73	$57	$166	$188	$143	$497
Hanging Lake WB		$45	$57	$43	$45	$57	$43	$76	$73	$57	$166	$188	$143	$497
Hanging Lake RC		$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
NoName WB		$7	$7	$5	$7	$7	$5	$10	$12	$11	$24	$26	$21	$70
NoName EB		$7	$7	$5	$7	$7	$5	$10	$12	$11	$24	$26	$21	$70
Beaver Tail Mtn WB		$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Beaver Tail Mtn EB		$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Veterans WB		$133	$131	$97	$133	$131	$97	$190	$231	$205	$455	$493	$400	$49
Veterans EB		$122	$120	$89	$122	$120	$89	$174	$213	$189	$418	$453	$368	$1,239
TOTAL		$6,735	$6,138	$4,637	$4,393	$4,228	$3,340	$6,736	$7,978	$6,996	$17,865	$18,345	$14,972	$49,883

FOR OFFICIAL USE ONLY

Table E.3 Terrorist IED-Tunnel Attack Annual User Risk

IED User Risk	East Portal			West Portal			Tunnel			Total			Total
Bore / IED Size	S	M	L	S	M	L	S	M	L	S	M	L	
Eisenhower	$290,944	$697,914	$642,516	$170,216	$426,276	$297,041	$170,216	$267,524	$297,041	$631,377	$1,391,714	$1,236,598	**$3,259,689**
Johnson	$170,216	$426,276	$297,041	$170,216	$426,276	$297,041	$153,047	$294,565	$326,014	$493,480	$1,147,117	$920,096	**$2,560,693**
Hanging Lake EB	$130,757	$327,039	$228,522	$130,757	$327,039	$228,522	$220,053	$528,956	$794,503	$481,567	$1,182,034	$1,251,547	**$2,915,148**
Hanging Lake WB	$130,757	$327,039	$228,522	$130,757	$327,039	$228,522	$220,053	$528,956	$794,503	$481,567	$1,182,034	$1,251,547	**$2,915,148**
Hanging Lake RC	$52,575	$126,093	$94,563	$52,575	$126,093	$94,563	$52,575	$126,093	$191,737	$157,724	$378,279	$380,862	**$916,865**
NoName WB	$138,730	$347,107	$242,392	$138,730	$347,107	$242,392	$234,319	$562,181	$845,960	$511,779	$1,256,395	$1,330,744	**$3,098,917**
NoName EB	$138,730	$347,107	$242,392	$138,730	$347,107	$242,392	$234,319	$562,181	$845,960	$511,799	$1,256,395	$1,330,774	**$3,098,917**
Beaver Tail Mtn WB	$89,336	$222,029	$156,784	$89,336	$222,029	$156,784	$141,203	$338,732	$510,238	$319,875	$782,790	$823,806	**$1,926,471**
Beaver Tail Mtn EB	$89,336	$222,029	$156,784	$89,336	$222,029	$156,7784	$141,203	$338,732	$510,238	$319,875	$782,790	$823,806	**$1,926,471**
Veterans WB	$268,342	$657,680	$475,490	$268,342	$657,680	$475,490	$362,881	$870,394	$1,314,684	$899,565	$2,185,753	$2,265,664	**$5,350,982**
Veterans EB	$268,342	$657,680	$475,490	$268,342	$657,680	$475,490	$362,881	$870,394	$1,314,684	$899,565	$2,185,753	$2,265,664	**$5,352,982**
TOTAL	**$1,768,064**	**$4,357,992**	**$3,240,494**	**$1,647,336**	**$4,086,354**	**$2,895,020**	**$2,292,752**	**$5,286,709**	**$7,745,563**	**$5,708,151**	**$13,731,054**	**$13,881,077**	**$33,320,282**

FOR OFFICIAL USE ONLY

Table E.4 Terrorist IED-Tunnel Attack Annual Total Risk

IED User Risk	East Portal			West Portal			Tunnel			Total			Total
Bore / IED Size	S	M	L	S	M	L	S	M	L	S	M	L	
Eisenhower	$295,842	$702,261	$645,730	$172,772	$428,713	$298,959	$174,143	$272,188	$301,128	$642,757	$1,403,162	$1,245,816	**$3,291,735**
Johnson	$171,696	$427,688	$298,181	$171,696	$427,688	$298,181	$155,321	$297,266	$328,393	$498,712	$1,152,641	$924,755	**$2,576,108**
Hanging Lake EB	$130,802	$327,096	$228,564	$130,802	$327,096	$228,564	$220,130	$528,029	$794,561	$481,733	$1,182,222	$1,251,690	**$2,915,645**
Hanging Lake WB	$130,802	$327,096	$228,564	$130,802	$327,096	$228,564	$220,130	$528,029	$794,561	$481,733	$1,182,222	$1,251,690	**$2,915,645**
Hanging Lake RC	$52,575	$126,093	$94,563	$52,575	$126,093	$94,563	$52,575	$126,093	$191,737	$157,724	$378,279	$380,862	**$916,865**
NoName WB	$138,737	$347,113	$242,397	$138,737	$347,113	$242,397	$234,329	$562,193	$845,971	$511,802	$1,256,420	$1,330,764	**$3,098,987**
NoName EB	$138,737	$347,113	$242,397	$138,737	$347,113	$242,397	$234,329	$562,193	$845,971	$511,802	$1,256,420	$1,330,764	**$3,098,987**
Beaver Tail Mtn WB	$89,336	$222,029	$156,784	$89,336	$222,029	$156,784	$141,203	$338,732	$510,238	$319,875	$782,790	$823,806	**$1,926,471**
Beaver Tail Mtn EB	$89,336	$222,029	$156,784	$89,336	$222,029	$156,784	$141,203	$338,732	$510,238	$319,875	$782,790	$823,806	**$1,926,471**
Veterans WB	$268,474	$657,810	$475,587	$268,474	$657,810	$475,587	$363,071	$870,625	$1,314,889	$900,019	$2,186,246	$2,266,064	**$5,352,329**
Veterans EB	$268,464	$657,800	$475,580	$268,464	$657,800	$475,580	$363,056	$870,607	$1,314,873	$899,983	$2,186,206	$2,266,032	**$5,352,2 20**
TOTAL	**$1,774,799**	**$4,364,130**	**$3,245,131**	**$1,651,729**	**$4,090,582**	**$2,898,360**	**$2,299,488**	**$5,294,687**	**$7,752,559**	**$5,726,016**	**$13,749,399**	**$13,896,049**	**$33,371,464**

Table E.5 Terrorist IED-Tunnel Attack Risk

Tunnel	Mile Post	Length (ft)	Owner Risk	User Risk	Total Risk
Eisenhower	213.7	8941	$19,940	$2,028,251	$2,048,191
Johnson	212.7	8941	$9,952	$1,593,320	$1,602,912
Hanging Lake EB	125.3	3658	$696	$1,813,870	$1,814,566
Hanging Lake WB	125.3	3658	$696	$1,813,870	$1,814,566
Hanging Lake RC	127.1	582	$56	$570,494	$570,550
NoName WB	117.8	1045	$105	$1,928,21	$1,928,320
NoName EB	117.8	1045	$105	$1,928,215	$1,928,320
Beaver Tail Mtn WB	50.4	615	$30	$1,198,693	$1,928,723
Beaver Tail Mtn EB	50.4	625	$30	$1,198,693	$1,928,723
Veterans WB	242.3	819	$49	$3,329,500	3,330,173
Veterans EB	24.3	749	$619	$3,329,500	3,330,119
TOTAL			**$31,917**	**$20,732,620**	**$20,765,162**