Risk-Based Transportation Asset Management:

Building Resilience into Transportation Assets

REPORT 5: MANAGING EXTERNAL THREATS THROUGH RISK-BASED ASSET MANAGEMENT

U.S. Department of Transportation
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NOTE FROM THE DIRECTOR

The Federal Highway Administration (FHWA) continuously seeks innovative ways to improve the management of the nation's highway infrastructure. The Office of Asset Management offers this series of reports on risk management as another means by which transportation agencies can better understand and manage their highway assets.

The use of risk management among U.S. transportation agencies largely is limited to managing risk at the project level generally focused during construction. Risk management at the project level helps to identify threats and opportunities to projects' cost, scope and schedule. However, we at the FHWA along with our partners at state and local transportation agencies recognize the growing need for a better understanding of risk management at program and organizational levels.

Today, the leading international transportation, banking and insurance organizations have explored the benefits of risk management at the program and enterprise level and use it as a tool to protect their investments. Based on those practices, the Office of Asset Management is offering this series of reports on how risk management can be scaled up to asset management programs, and to the entire enterprise of a transportation agency.

It's important for highway agency officials to consider incorporating risk management in the decision-making process for several reasons. First, they have seen the benefits of risk management at the project level. Second, they have heard from their international colleagues that risk management can pay dividends when used at the broader program and enterprise level, particularly when agencies don't have enough funding to address their priorities. Third, managing risk is an integral step in following a comprehensive asset management framework as described in the *AASHTO Asset Management Guide—A Focus on Implementation.* Finally, the U.S. Congress has proposed that states develop “risk-based transportation asset management plans.” These factors convinced the Office of Asset Management to offer this series of reports.

We believe you will find these reports helpful as you develop your asset management program and make investment decisions. This series of reports will help the transportation agencies to meet the increasingly complex challenges involved in making decisions and communicating them effectively to the public.

Sincerely,

Butch Wlaschin
Director of the Office of Asset Management

Contents

Introduction

This is the fifth of five reports examining how risk management complements asset management. This last report examines how physical, climatic, seismic and other external threats can be addressed in risk-based asset management programs. The first four reports and the literature review emphasized the definition of risk as the positive or negative effect of uncertainty or variability upon agency objectives. Those reports emphasized that risks could be positive in that some types of uncertainty can create opportunities. However, this report will focus more on negative risks, or threats. These risks generally are external, and while highly probable over a long period of time, are difficult to predict in the short term. Randomness and variability complicate planning for them.

The wrenching impacts of major external threats create havoc with the methodical, well-planned and tightly forecast scenarios adopted in transportation asset management plans (TAMPS). These plans rely upon gradual, predictable deterioration curves based upon the past performance of asset inventories. They rely on assuming gradual, incremental change in revenues. They forecast marginal rates of change, both in terms of deterioration rates and improvement effects, based upon past experience. However, major external threats such as earthquakes and hurricanes are the opposite of incremental. They are erratic, abrupt and almost always negative.

In August 2011, Hurricane Irene reached one of the nation's most northern states, Vermont, and damaged 480 bridges out of a total network of 2717 bridges.[i] In one day, more bridge deterioration occurred than normally would occur over many years. Accurate prediction of such events is nearly impossible. Such a significant storm had not struck Vermont for 83 years.[ii]

Yet the next year, Hurricane Sandy struck New Jersey, New York, Connecticut and Rhode Island creating similar damage.

Climate change projections warn that storm severity is likely to increase. Federal emergency management experts warn that these and other events have increasing impacts because urban areas are more highly populated, supply chains are more tightly strung and the economy is more highly integrated. The effects of events such as hurricanes, earthquakes or terrorist attacks are greater today than they could have been 50 years ago in a less urbanized and connected society.

Therefore, asset management practitioners face the dual task of refining the predictability of asset performance while preparing for the unpredictable impacts of major external threats. The modern asset management practitioner is likely to be focused upon marginal improvements to the accuracy of forecasting models based on known variables and marginally improving the assessment of current asset conditions. At the same, in a world of increasing threats he or she needs also to be prepared for the Irenes, Sandys, earthquakes, terrorist attacks, and even economic threats that interrupt carefully developed forecasts.

The earlier reports emphasized the Five Ts of risk management. When a risk is identified, officials can decide to treat, tolerate, transfer, terminate or take advantage of the risk. The Five Ts recognize the possible opportunities in many risks that may cause agencies to embrace reasonable risks to achieve greater rewards.

In the subset of risks that include threats, few rewards are possible. Hurricanes, floods, earthquakes or terrorist attacks are unlikely to create opportunities. Their impacts must be minimized as they cannot be prevented, at least by the asset management practitioner.

In managing risks to assets from external threats, this report emphasizes the Three Rs, which are Redundancy, Robustness and Resiliency. These will be defined, described and illustrated through several agency examples. Asset management plays a critical role in each, particularly Robustness and Resiliency. Including the Three Rs in asset planning efforts can better prepare agencies to cope with an increasingly unpredictable world.

Black Swans and White Knights

A popular economic and sociology book [iii] calls unexpected, scenario-changing events “Black Swans.” Europeans were convinced all swans were white until explorers reached Australia and found that the totally unexpected can occur. Black swans were common. The premise of black swan thinking is that the large majority of planning is based upon norms. Bell curves, linear forecasts and regression analysis assure planners that they can reasonably predict the future

As these earlier reports have defined, risk is the positive or negative effects of uncertainty or variability upon agency objectives. This internationally recognized definition broadens the consideration of risk to be more than only threats. The implications of this broader definition is that risk management can be applied not only to threats but also to opportunities created by uncertainty, variability or change as they relate to the achievement of all organizational objectives.

Building from this broad definition of risk, these reports use as the definition of risk management the one adopted by the New Zealand transport agency. Risk management is the cultures, processes and structures that are directed towards the effective management of potential opportunities and threats.

based on past events. However, black swan thinking says that history jumps and lurches in unpredictable ways, it does not incrementally and predictably crawl forward.

Black swan thinking emphasizes that unpredictable, abrupt and non-linear events have a much greater impact on society than most planners acknowledge. Few predicted the epoch-changing events that led to World Wars I and II, the Great Depression, the 2000 technology-bubble stock crash, the Sept. 11 terrorist attacks or the economic downturn of 2008 caused by real estate and banking meltdowns. A black swan advocate would contend that the unpredictable is the norm and that over-reliance on normative models provides false confidence. "Although unpredictable large deviations are rare, they cannot be dismissed as outliers because cumulatively, their impact is so dramatic."[iv]

Figure 1. *Roadway damage caused by increased flooding is a predicted outcome of climate change.*

For the Vermont DOT, for 82 out of 83 years flooding as severe as it experienced in 1927 did not occur. Then in 2011, it returned. This illustrates the dilemma of the low probability but high impact Black Swans. Further complicating the planning for asset managers is the varying nature of potential threats. If they prepare for a flood, the next threat may be a terrorist attack, or a seismic event or even a major economic downturn that reduces resources. Preparing continually for every eventuality of low-probability but high impact threats would consume needed resources required for immediate needs, not only for potential future ones.

Although predicting which disaster will strike where is difficult, panels that study disaster preparation warn that the frequency and severity of events is increasing given the more populous planet and more changeable climate. One report [v] notes the steady increase in federal outlays related to increasingly severe events. The 1994 Northridge California earthquake resulted in $11.6 billion in federal disaster recovery expenditures, while the 2001 World Trade Center attacks totaled $13.6 billion, 2005's Hurricane Katrina led to $48.7 billion in federal outlays and Hurricane Sandy led to a recent $50 billion Congressional appropriation. To put those amounts in perspective, the Federal Fiscal Year 2014 highway apportionments in MAP-21 total $37.8 billion.

Asset Management is not a complete answer to addressing the threats to physical transportation assets but it can serve as an important component of the Three Rs, particularly in making assets robust and agencies' asset-repair practices resilient in times of crisis. An agency may not be able to plan for every threat. However, by creating a transportation network and a transportation agency that includes redundancy, robustness and resiliency, it possesses the tools to more ably cope with a wide and unpredictable range of threats. This general preparedness has been called an "all hazards" approach that suggests that planning for one kind of hazard or threat can increase an agency's or a community's ability to deal with others.[vi]

Redundancy can be defined as duplicative or excess capacity that can be used in times of emergency. Adding redundant highway capacity generally falls outside the practice of asset management. However, sound management of the assets on detour and emergency evacuation routes increases a highway system's redundancy.

Robustness can be defined as the capacity to cope with stress or uncertainty. Asset management focuses upon optimizing the conditions of assets with available revenues. Well-maintained assets generally are better able to withstand the stresses of storm events and other disasters better than weakened and poorly maintained ones.

Resiliency has been defined[vii] as the ability to prepare and plan for, absorb, recover from, and more successfully adapt to adverse events. Enhanced resilience allows better anticipation of disasters, better planning to reduce disaster losses and faster recovery after an event.

A risk-based asset management program contributes strongly to all three, particularly robustness and resiliency.

1. Providing accurate inventories of assets and their condition assists with identifying which assets are at risk for given types of events such as floods, hurricanes, or earthquakes.
2. Sound maintenance practices within an asset management regime "hardens" assets. Well maintained drainage structures are better able to withstand floods. Sound high-mast lights and overhead signs are more wind-resistant. Bridges with well-maintained wing walls, bank protection and scour protection are more robust during high water. Pavements with cleaned under drains and catch basins drain more quickly and perform longer.
3. The hierarchal prioritization of critical assets conducted in a risk-based asset management program provides priorities for asset repair after events.
4. Asset management staffs become competent at asset management scenario planning, which is critical when developing a post-event recovery plan.
5. Sound asset inventories and good unit-cost data assist with estimating recovery costs.
6. Asset mapping and GIS capability assists with identifying assets and prioritizing their coordination with evacuation planning.
7. Complete and accurate inventories of traffic control devices, signs, guardrail and culverts allows the faster development of contract plans immediately after a flood or hurricane. Contractors can be instructed to restore the assets that existed before the event.
8. Risk-management capability provides not only critical before-event prioritization but also is useful in post-event recovery allocation of resources.

A study of the New York City area after Super Storm or Hurricane Sandy emphasized the need for resilient infrastructure. It describes resilience as the ability of a system to withstand shocks and stresses, to not be "brittle" or stretched to capacity and possessing low diversity.[viii] Systems that are resilient are flexible and responsive, they limit failure so that when one asset fails it does not create a "domino effect." The system can rebound swiftly and it allows for constant learning from past events.

Asset Management and Risk Management serve dual and complementary roles in relation to resilience. Although the type, nature and impacts of any given external threat are difficult to accurately predict, the resiliency created by sound asset management and risk management programs better prepares an agency to deal with a wide array of physical threats, and more quickly recover from them if they occur. Risk management can help identify, quantify and mitigate the threats to physical assets. Likewise, a sound asset management program increases infrastructure resiliency and robustness that reduces impacts caused by storms, floods or seismic events.

When an agency is competent in the tools of risk management, it can logically recalculate its priorities after an event. A risk-based disaster preparedness plan for highway assets is likely to include at least:

- An assessment of the greatest threats based on a probability and impact assessment;
- Ongoing mitigation programs for the greatest threats such as seismic retrofit programs, stream monitoring systems, hurricane evacuation and preparedness programs, redundant communication systems and recovery protocols;
- Business continuity plans;
- A rank order of priority for restoring asset functionality;
- Emergency-response contracts for rapid mobilization;

- Existing prioritization protocols for making tradeoffs as to which new level of asset condition to accept after events.

In addition to these tangible benefits, a risk-based asset management program contributes to what has been called a necessary "culture of resiliency."[ix] Various reports[x. xi. xii] address how successful risk management and asset management programs create an organizational culture that actively pursues sound assets and actively manages risks. Similarly, among the most important elements for disaster preparedness is a culture of resiliency[xiii]. Therefore, risk-based asset management programs serve to both prepare physical assets to withstand disasters they also complement a larger governmental and societal perspective that prepares agencies to anticipate and respond to threats.

Climate Change and Extreme Weather Risks

If risk is the effect of uncertainty upon objectives, than climate change is one of the largest risks facing asset management objectives. Climate change forecasts emphasize uncertainty and greater variability. Climate change scenarios predict that storm events will increase, both in frequency and intensity.[xiv] This can bring increased flooding but also increased soil saturation that could increase rock falls and slope failure. Higher temperatures and changing weather patterns can lead to droughts that bring increased numbers of wildfires that damage infrastructure, higher temperatures that cause pavements to rut, crack or shove. Less snowfall and greater rainfall change mountainous hydraulic patterns with effects upon culverts and ditches. Rising sea levels will affect coastal storm surges, drainage outflows and even the inundation of low-lying roads. Climate change, therefore, creates substantial risk to asset management objectives.

The impact of severe weather events upon assets is likely to become increasingly common and will be a threat for asset managers to consider.

Integrating Climate Risks into Policies

A recent paper on integrating extreme weather events into asset management practices[xv] suggests that asset managers may want to establish among their goals and objectives for TAM programs the ability to address extreme weather risks to assets. The risk-based asset management approach could include identifying those assets most at risk from weather events, such as low-lying flood-prone routes. Or, the agency may establish different condition or resiliency levels for higher functional classes or for critical assets most at risk. The intent is to ingrain preparation for extreme weather events as a basic goal or objective of asset management programs.

Similarly, the first step in risk management is to establish the agency context. This context includes the agency goals and objectives, against which all potential threats and opportunities are considered. As such, the inclusion of climate-based extreme weather events is likely to be a common element in the initial context-setting phase of risk management. The inclusion of extreme weather events ingrains consideration of them as a basic goal or objective of both risk programs, as well as asset management programs.

Integrating the extreme variability caused by climate-change-driven weather events requires a new perspective from transportation planners and engineers who typically extrapolate from historical trends to forecast future needs and conditions that influence their investment choices and operating plans.[xvi] The extreme events that in past years were considered to be outliers may become more common. The bell curve of weather events may well flatten with much more deviation from the traditional mean of events. Floods are likely to be more severe, wind events more extreme, hurricanes more frequent, and even droughts and high temperatures much more common. As such, the asset managers may need to establish as a basic goal for their programs considerations of extreme weather variability.

NCHRP Special Report 290[xvii] says that climate change is not a future issue, but rather a current one for climate change policy makers and for transportation asset managers. Past benchmarks for predicting 100 year floods when designing hydraulic structures or for estimating thermal effects upon pavements may no longer be valid. Greater extremes and more frequent events prudently could be assumed. Higher flooding and more frequent storm events should be assumed for coastal areas, particularly in the eastern seaboard. These more severe floods and storm surges should prompt the inventorying of at-risk coastal assets and the risk-assessment of their vulnerability. The mapping and assessment of these

Figure 2. *Incorportating climate-change induced risks into asset management planning is likely to become more common.*

assets can clarify which storm scenarios require the greatest analysis, which provides an informative feedback loop for climate forecasters. Understanding how these at-risk assets may be affected can influence long-range asset maintenance, repair and replacement strategies in an asset management plan. Some assets possibly could be hardened, some relocated to less-vulnerable areas when their economic lifecycle ends and others may need to be abandoned.

The Intergovernmental Panel on Climate Change[xviii] (IPCC) notes that climate-change impact approaches are shifting from a disaster-response-focused approach to a risk-management approach.[ixx] Risk-based approaches seek to build resistance to climate-induced impacts through making systems more robust and more resilient. Risk management and climate adaption become linked as risk-based strategies to increase infrastructure's resilience also serve to mitigate the effect of severe climate events.

The IPCC says that an idealized risk-based approach to protecting assets from climate change threats would be probabilistic. It would create common denominators between possible actions by multiplying the probability of an event by its consequences. A wide number of possible events could be calculated and compared for prioritizing risk-mitigation actions. This type of standard calculation is seen in most risk registers.

However, the ability to produce a purely probabilistic analysis is greatly complicated by the wide variability in calculating a threat to a given asset within a given time period.[xx] Although a flood is likely to occur over a 100 year period at a given location, an agency with a 20-year planning horizon may not be able to justify the higher cost to protect against such an event. Also, reliable estimates of the cost of an event is speculative and may not be firm enough to withstand a benefit/cost analysis with a short time horizon. A simple approach would be to design every facility for a 500 year storm event, but the costs are prohibitive and unrealistic.

The difficulty in prioritizing all risk-response actions based on probabilities leads the IPCC to recommend that agencies consider a set of "no regrets" mitigation steps to address

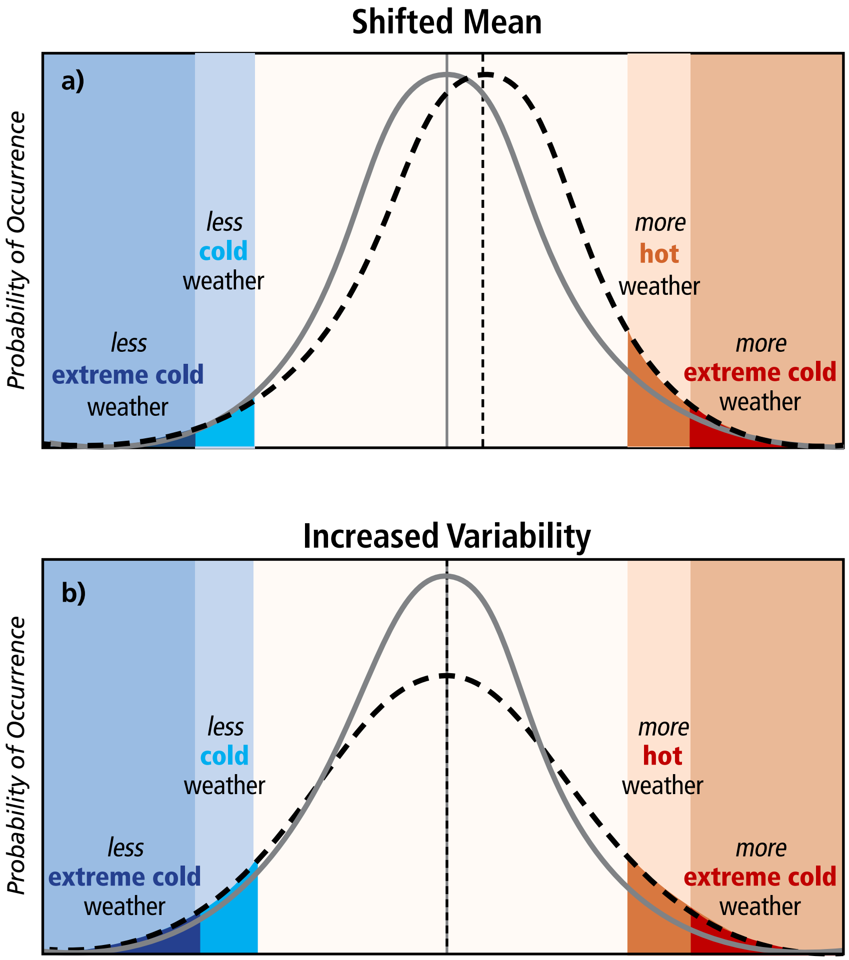

Figure 3. *The IPCC forecasts that overall temperatures will rise with the mean average temperature shifting right toward hotter temperatures and greater variability.*

climate change threats. These are steps or expenditures likely to produce both climate- change-mitigation benefits and other benefits, thereby warranting their investment even if severe events don't occur by a given planning horizon. For infrastructure, "no regrets" investments could include:

- Updated design standards or design inputs that take greater storm frequency and severity into consideration;
- Improved event forecasting systems such as stream gauges and hydrological forecasting tools to better predict hydrological events and understand their effects upon assets;
- Increased inspection protocols to more promptly identify the effects of events upon at-risk assets;
- Coordination with land use agencies to discourage development in vulnerable areas where impacts could exacerbate at-risk infrastructure;
- Improved "downscaling" or the localizing of climate change projections to better understand the likelihood of extreme events;
- Improved asset inventory data including more accurate elevations to understand more precisely the potential effects of flooding or storm surges;
- The identification of at-risk slopes, routes, structures and other assets;
- Qualitative and simple probabilistic analyses to identify and prioritize storm event risks to assets.

The IPCC notes these types of risk-mitigation strategies are more incremental and lower cost than hardening or expanding all assets to withstand the most severe climate event possible.

Risk-Based Asset Management as a Climate-Change Adaptation Strategy

Risk-based transportation asset management easily can be added to the portfolio of activities helping societies adapt to climate change. The IPCC notes that effective adaptation strategies include risk-base activities that help to make physical infrastructure more resilient, that allow better understanding of the potential effects of storms and that help societies recover after events.[xxi]

Risk-based adaptation strategies seek to reduce the exposure and vulnerability of critical societal assets, be they economic, human or physical. The IPCC notes that the fields of climate change adaptation and risk-based disaster management are becoming more similar. As with asset management, both seek to improve decision-making so that infrastructure better resists the intensity of increasing storm events.

The linkage of asset management and climate-change adaptation was emphasized in an assessment of climate change vulnerability conducted by the Washington State Department of Transportation [xxii] "Like other risks we plan for, such as retrofitting bridges against earthquakes, we plan to take action, including updating planning and design policies, to protect our transportation infrastructure from climate impacts. This is responsible asset management. We build highways, bridges, and state ferries to last decades, so the need to improve structure resiliency to better adapt to weather extremes is essential to reducing risk," the WSDOT report summarizes.

Among its asset management activities that adapt to a changing climate include:

- Emergency response planning and preparedness;
- Maintenance accountability and risk management;
- Improvement programs targeting areas of concern such as unstable slopes, bridge scour, storm water retrofit, chronic environmental deficiencies and repeat flooding.[xxiii]

The department's assessment was complicated by an issue that was common in three other pilot climate-change risk assessments—comparable asset inventories. It assessed airports, ferries, rail lines, highways, roadsides, mitigation sites and buildings. Even within one mode, common information was a challenge. Seen in the WSDOT and other assessment exercises was the need to improve asset inventories to be more complete, easily located and inclusive of important information such as elevations and contained in compatible geo-databases and GIS formats.

The department relied on a qualitative analysis to determine vulnerability of assets. It organized workshops with the field staff knowledgeable of local assets and their performance in past storm events. Workshop participants were provided an overview of the "down-scaled" climate forecasts for Washington State, which predict increases in annual temperatures with increasing likelihood of extreme heat events, enhanced seasonal precipitation patterns, declining snowpack, seasonal changes in stream flows, sea level rises and increased wave heights. The department used its experience with risk-assessment workshops to qualitatively evaluate the climate change vulnerability of its assets. Workshop participants evaluated the criticality of assets and the potential impacts under the climate change scenarios.

The department provided a frame of reference for participants. It asked them to describe impacts on 1-10 scale with the group reaching consensus that consolidated each individual's assessment. The department also provided a framework of vulnerability from complete failure of the asset, temporary operational failure and reduced capacity of the assets. Reflecting the cross-cutting nature of threats and impacts, the workshops included subject matter experts in materials, hydrology, geology, and area maintenance superintendents. In addition to the relatively straight-forward ranking process, they were asked simple but catalytic questions regarding potential climate impacts such as, "What keeps you up at night." Based upon already observable increased events of recent years, the participants could note climate-change-induced impacts that already had affected transportation assets.

The assessment concludes that the Washington DOT already is seeing the effects of extreme weather and climate change and that its risk management, and asset management practices are reducing vulnerabilities. It already has seen increased sea levels of 8 inches over the past century, its glaciers are melting which increases sediment loads in streams and creates lateral instability in channels. However, the majority of its assets are resistant to climate change because of existing "no regrets" asset management practices such as:

- Seismic retrofit efforts, improved fish passages, culvert replacements and drilled bridge shafts on new structures have made those assets more resistant to events;
- Climate change may exacerbate existing conditions such as unstable slopes, flooding and coastal erosion;
- Areas that already are experiencing problems are on watch lists such as scour critical bridges, or low-lying areas subject to flooding or sea-level rise.

WSDOT determined that its greatest vulnerabilities are in the mountains, above or below steep slopes, in low-lying areas, along rivers with grade changes caused by increased sediment loads and in low-lying areas long the coasts. Among its internal recommendations, are to incorporate the vulnerability assessment into investment decisions, into long-term plans for key routes and to integrate climate change projections into planning, design, and operational programming.

The criticality of sound asset data was emphasized in a second climate change vulnerability case study supported by the FHWA. The Climate Change Vulnerability and Risk Assessment of New Jersey's Transportation Infrastructure[xxiv] was performed by merging and superimposing over the transportation asset data sets a series of different climate change scenarios. Those scenarios examined sea level rise, storm surge and increased flooding events under two different time periods, 2050 and 2100. The study also examined changes in temperature but those impacts were more systemic and less localized to specific low-lying facilities. Generally, the forecasts predicted a hotter, wetter New Jersey, with notable increases in annual rainfall coupled with increases in average temperatures.

Digital elevations were used to determine the roadway and rail segments and facilities where inundation may occur based upon the elevation of the facility compared to projected elevations of flood depths or storm surges.

The analysis provided substantial information on the potential risks to critical assets in 2050 and later in 2100 given possible climate change scenarios. It illustrated the roadways, bridges, rail lines, and transit facilities at increased risk and which could be highlighted for adaptation to ensure their continued functionality. The analysis did not specifically examine asset management impacts but focused more

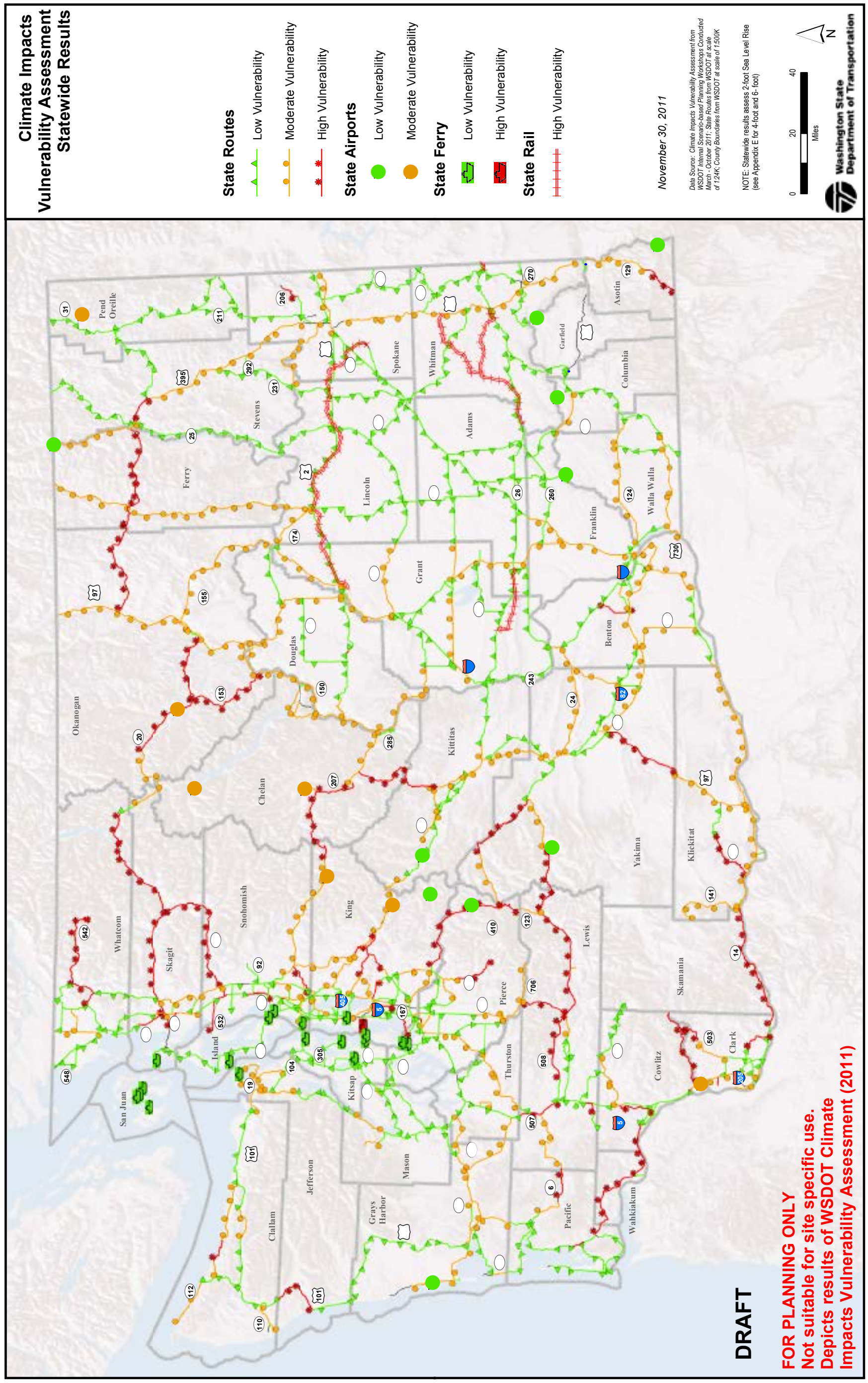

Figure 4. *At a planning-level, WSDOT identified assets potentially vulnerable to climate change.*

on connectivity and mobility impacts if storms seriously damage or temporarily impede critical facilities. It found that the mid-range inland flooding scenario in 2100 could have devastating effects on transportation infrastructure. Almost 81 miles of roadways could be affected, nearly 59 of which are major. Over 138 rail miles could be impacted, almost 21 miles of which are major freight lines, and 11.7 of which are on Amtrak's system. Such impacts would be crippling today but would be even more so given the expected population growth of between 7 percent and 126 percent per county by 2100.

A lack of readily available asset data, combined with a lack of spatial data such as road and bridge elevations and adjoining slopes, limited the analysis of the 1,000 square mile areas to a sketch planning level analysis that could be used to pinpoint more specific areas for in-depth analysis. That would include collecting actual roadway and bridge elevations, watershed elevations, ground-cover data, bridge and culvert-capacity data so that actual inundation analyses could be calculated for individual assets or segments. Critical factors such as localized drainage structures or the slope and ground-cover data needed to calculate runoff were not available at the scale of the study area. The absence of consistent bridge elevation and under-clearance data caused the potential overstatement of vulnerability. Some areas represented as "inundated" may in fact be spanned by bridges although the bridge approaches may still be vulnerable. Culvert information also was incomplete over a large area with multiple jurisdictions.

The Post-Sandy analysis of New York resilience reported that not only must asset and elevation data be more robust but the data itself needs to be stored in a way that is resilient, redundant and accessible.[xxv] The NSA 2100 report recommended that improved future mapping resources be stored in the "cloud" where it can be accessed by multiple agencies,

in real-time, from multiple locations in case some critical agencies are knocked out of commission. It notes that essential systems should be backed up and redundant with remote storage to ensure redundancy and resilience. It recommends social media interaction options so that citizens can text or email in locations of downed power lines or other emergency situations. In short, the data itself should be resilient and offer redundant paths for access.

The New Jersey assessment and another in the Hampton Roads area of Virginia[xxvi] emphasize how these analyses can influence a region's short and long-range planning, not only for new capacity projects but also for the long-term rehabilitation and replacement of existing assets. The routes and facilities examined in the Hampton Roads and New Jersey studies represent critical assets essential for the regional, and sometimes national, movement of goods and people. The IPCC and the New Jersey and Hampton Roads reports emphasize that transportation planners and asset managers can use these scenarios to engage with land-use planners, local governments, federal officials, and even the home-building and insurance industries, to urge the long-term consideration of climate-induced events upon transportation assets. If residential and commercial construction continues in flood-prone areas, the increased runoff will exacerbate flood impacts upon low-lying transportation facilities. Conversely, the damage to transportation facilities caused by storms makes the new residential and commercial developments more susceptible to being isolated when storms occur. The Hampton Roads analysis specifically considered how the projects in the region's long-range transportation plan could be affected by long-range climate-change-induced floods, tides, storm surges and hurricanes. It found that the 2010 long-range plan made no mention of climate change and had not evaluated how the proposed transportation program may be influenced by future storm events.

These analyses illustrate the need for close coordination between asset managers, transportation planners, designers and local governments. Existing highway assets are continually in a state of long-term change with an eventual need for major rehabilitation or replacement. The climate-change scenarios used in New Jersey of 2050 and 2100 represent several generations of life spans for highway assets such as new pavements, bridges, culverts and appurtenances such as traffic control devices. Replacement in kind for existing assets frequently may not advisable because of higher coastal storm surges or greater inland flooding. Major rehabilitation or replacement of assets will necessitate an evaluation of the long-term climate-induced scenarios that affect drainage structures, roadway elevations or bridge clearances.

The New Jersey and Washington DOT analyses also illustrate how "down-scaled" climate-scenario data becomes another important data set for asset managers performing risk-based asset management. The external influences of floods, storm surges, greater precipitation, increased temperature extremes, or even droughts, create greater stresses upon assets than in the past. The New Jersey assessment noted that the overarching limitation of all climate change information is uncertainty, particularly for estimates after 2050.

FHWA's Vulnerability Assessment Model

The Washington State, New Jersey and Hampton Roads analyses were conducted as pilots to test a draft version of the FHWA's Climate Change & Extreme Weather Vulnerability Assessment Framework.[xxvii] The updated framework completed in December 2012 consists of three fundamental steps which are to:

- **Define the study objectives:** For a risk-based asset management assessment, a likely objective could be to identify which assets are most at risk and what range of adaptation strategies would be most effective at reducing that risk.
- **Assessing the vulnerabilities of the assets that are being considered:** For a risk-based asset management assessment this could include assessing how temperature changes, rainfall variation, higher water levels or even greater periods of drought will create new stresses upon asset condition.
- **Incorporating the results into the decision-making process:** For asset managers, this could include adjusting deterioration curves, modifying unit costs to reflect more expensive future drainage facilities, lowering lifecycle performance for assets subject to extreme environmental conditions and assisting with new design standards to harden new assets to withstand future climatic extremes.

Strategic Objective Considerations

Earlier reports emphasized that the underlying intent of both risk management and asset management is to allow organizations to achieve critical strategic objectives. Similarly, a risk-based analysis of climate-change effects upon assets begins with an assessment of key policy objectives to be considered. The FHWA framework emphasizes as a first step the identification of the key policy objectives most important to the agency. These could include keeping robust the assets on critical corridors, or ensuring the functionality of high-risk assets, or achieving the lowest-lifecycle costs for assets that may now be subject to new climate stresses. The climate change assessment of asset impacts begins with the same policy-foundation focus as do risk management and asset management themselves.

These policy objectives could extend to areas beyond only mobility. The Washington DOT analysis included fish passages that it built for enhancement of endangered fish species. Agency-built wetlands or retention ponds also could be considered to be assets critical to agency environmental objectives that may be seriously affected by changed weather. Not only floods, but also drought, could be influences upon such assets and would require monitoring to ensure agency environmental objectives and commitments are met.

Time-Horizon Considerations

Because risk-based asset management involves many different assets, a key consideration for a risk-based analysis of assets affected by climate change is the time horizon of the various asset classes in part because certainty of future conditions is less clear as time progresses.

Long-term changes in future flooding events predicted for the next 50 years may not have any bearing on short-term but important asset treatments such as crack sealing or chip sealing, or how signs or bridge expansion joints are maintained. However, higher temperatures or more frequent storm events may influence these treatments. Higher temperatures for longer periods may require evaluation of chip sealing and crack sealing products. More frequent and extensive thermal expansion places an even great importance on properly cleaned and functioning bridge expansion joints. Overhead signs are vulnerable to increased winds and may require more frequent inspection and repair as a result of more frequent storms and higher winds. Although it may not be practical to harden all roadside signs to withstand hurricanes, New York State DOT officials said that more accurate sign inventories would have been very helpful after

hurricane Sandy. They had more than 100 miles of key roadway in which all the signs were knocked down. An accurate inventory of all signs, and which met current standards, would have accelerated repair contracts. The sign inventory could have produced a work order for a contractor to replace all the signs in accordance with the inventory, while correcting any that had not met current standards.

When asset managers analyze the impacts of climate change on long-lived assets, their adaptation strategies and impact considerations will be different from the consideration of short-cycle assets. In areas of slope instability aggravated by more saturated soils, more extensive geotechnical treatments may be required when roadway sections or bridges are replaced. Culverts may need to be resized, bridge under-clearances raised and catch basins and other drainage structures enlarged compared to current, as-built structures. Even more extensively, the projects in the long-range plan may need evaluated for climate-change considerations, such as was suggested in Hampton Roads. Considerations of climate change resilience will vary by asset, and by each asset class' time horizon.

Regional Climate Change Scenarios

In addition, the climate change framework FHWA provides includes a summary of how climate-change scenarios can be generated that can be helpful in preparing for a climate-change risk assessment to assets. In the framework, it discusses "downscaling" or how climate change scientists can generate more localized climate change scenarios, relevant to a city or small section of a state, from the broader, regional projections generated by climate models. The complexities of climate prevent the precise forecasting of rainfall or temperature events but the downscaling can provide local scenarios that indicate which climate impacts are most likely to change, by what degree over given time horizons.

A general summary of common regional projections includes:

- The Northeast is projected to become substantially warmer with an annual average temperature increase of 4 to 5 degrees Fahrenheit (F) and become wetter, particularly during the winter months. The duration of heavy rains of more than more than 2 inches per day is projected to increase.
- The Southeast is projected to undergo a 3.2 to 4.0 degrees increase in annual average temperature, with greater warming and reduced precipitation during the summer and fall months.
- The Midwest is projected to experience an annual average temperature increase of 4 to 5 degrees, with much wetter winters and springs and drier summers.
- The Great Plains' annual average temperature is projected to increase by 3.8 to 4.7 degrees, with wetter winters and drier summers.
- The Southwest is projected to experience an annual average warming of 3.6 to 4.5 degrees, with summers and falls experiencing the greatest increases. The Southwest's winters are projected to be somewhat wetter, while the spring months, in particular, are projected to be substantially drier.
- The Pacific Northwest is projected to experience an annual average temperature increase of 3.6 to 4.3 degrees, with the greatest warming and greatest reductions in precipitation projected for the summer months.
- Alaska is projected to experience the greatest warming of any U.S. region, with increases in annual mean temperature of 4.3 degrees, and the greatest warming expected during the winter months. Precipitation increases are projected year round, ranging from 9 percent to 17 percent, depending on the season.
- Annual mean temperature on the Hawaiian Islands is projected to increase by 2.7 to 3.3 degrees. Hawaii's precipitation is projected to increase during the fall months while the other seasons are projected to experience a decrease.

In addition to more droughts and heat effects, higher temperatures can contribute to more severe hurricanes that threaten much of the southeast and eastern coastal states. Increased intensity and frequency of storms generally is predicted in climate change forecasts.

Building Resilience Through Asset Management

In an article entitled, "Brittle Infrastructure, Community Resilience, and National Security," the authors[xxviii] contend that natural disasters and large-scale accidents are more common than community or political leaders often assume. Normalcy is regularly punctuated with dramatic episodes that tax a community's infrastructure or threaten its population. They contend that the impacts of an event are inversely proportional to the degree of preparedness or resilience that a community possesses. Similarly, a report to Congress by the Multi-Hazard Mitigation Council concluded that for each $1 spent on hazard mitigation by the Federal Emergency Management Agency (FEMA) produced $4 in future benefits.[xxix] Extrapolating such studies that address a broad range of impacts such as those upon housing, businesses and public safety to highway infrastructure may not be comparable. However, anecdotal evidence and the results of the three pilot studies indicate that sound asset management practices and the results of risk-based scenario planning better prepare an organization to anticipate events and be ready with an “all hazards” mindset that allows them to respond when an event occurs. Risk-based asset management also can identify “no regrets” strategies that complement both sound assets and disaster preparedness.

The New York State DOT officials reported a continuous learning and improvement process related to managing risks and assets as a result of hurricanes Lee and Irene in 2011 and Sandy in 2012. With each event, the department refined its emergency responses and incorporated lessons learned into many practices, from maintenance management, programming, project selection and managing assets. They noted that the maintenance management system was a key element that allowed the department to record damages, issue work orders and capture costs for later federal emergency reimbursement. They have developed a storm-response pattern in which they pre-position maintenance forces before a storm if possible. The crews spend between two and three weeks on repair and clean-up while the emergency contracting process prepares to bring contractors on board so that crews can return to their normal maintenance activities. While many of the costs of the damages may be reimbursed, the lost maintenance activities caused by the necessary diversion of maintenance crews cannot be. As a result of the repeated storms, the department has learned to use its management systems to quickly assess damages and has streamlined emergency-response contracts to quickly engage contractors so that maintenance forces can return to important, regular duties.

The storms provided resilience lessons such as the benefits of improved asset inventories, the need to acquire emergency lighting and the need to make resilient critical emergency assets such as traffic management centers. Investing in generators, redundant communication systems and other assets can increase the resilience of TMCs, which are critical before, during and after emergencies. The storm lessons also reiterated the continued importance of current practices such as the “bridge watch” systems. Observers pre-stage at critical bridges before floods and observe the structures during the event and inspect them for damage afterwards. This type of asset-monitoring effort pays off during repeated storm events.

The need to strengthen redundant assets also became more apparent. A portion of the New York State Thruway is subject to flooding but extremely expensive to improve. However, the department realized that a relatively minor investment of $1 million on parallel U.S. 20 near Utica could substantially reduce flooding on the parallel route and provide an important redundant alternative to the Thruway. Such risk-based investments are emphasized as the department prioritizes asset investments in three tiers to make New York’s highway infrastructure more sustainable. The top tier includes the National Highway System, Interstate Highways and major arterials. The bottom tier includes low-volume routes with the remaining facilities in the middle tier. The need for redundancy and resiliency of the higher tiers is given priority in programming investments.

The steps taken by the New York State DOT presage the findings of a report issued by a state commission following Hurricane Sandy. In November 2012 New York Governor Andrew Cuomo organized the NYS 2100 Commission to examine lessons learned from Sandy and other recent storms and to set forth recommendations on how to make the state more resilient. The report emphasizes that risks to assets are increasing and preparing for those risks must become a competency of government, the private sector and communities.

The report says in part, “As New York continues to recover, we must also turn our attention to the future. We live in a world of increasing volatility, where natural disasters that were once anticipated to occur every century now strike with alarming regularity. Our response capabilities to this new level of instability and the ability to bounce back stronger must be developed and strengthened. Our efforts must be rooted in robust structural underpinnings as well as expanded operational capacities. Superstorm Sandy made the urgency of this undertaking painfully clear. We also now possess a vastly deeper understanding of our current vulnerabilities. We cannot just restore what was there before—we have to build back better and smarter.”

The commission focused extensively on transportation. While ensuring mobility in times of crisis was a major concern, concurrently the commission also emphasized the importance of integrating climate considerations into the management of critical transportation assets.

Its key recommendations for the transportation sector were to:

Develop a Risk Assessment of the State’s Transportation Infrastructure

- Identify those assets that are vulnerable to extreme weather events, storm surge, sea level rise and seismic events, and to prioritize future investment through the use of a lifeline network that defines critical facilities, corridors, systems, or routes that must remain functional during a crisis or be restored most rapidly.

Strengthen Existing Transportation Networks

- Improve the State’s existing infrastructure with an emphasis on key bridges, roads, tunnels, transit, rail, airports, marine facilities, and transportation communication infrastructure. Focus on improved repair, as well as protecting against multiple hazards including flooding, seismic impact and extreme weather.

Protect transit systems and tunnels against severe flooding

- Invest in upgrades to bridges, tunnels, roads, transit and railroads for all hazards
- Strengthen vulnerable highway and rail bridges
- Protect waterway movements
- Safeguard airport operations

Strategically expand transportation networks in order to create redundancies

- Make the system more flexible and adaptive
- Encourage alternate modes of transportation
- Modernize signal and communications systems

Build for a resilient future with enhanced guidelines, standards, policies, and procedures

- Change the way we plan, design, build, manage, maintain our transportation network in light of increased events.
- Review design guidelines
- Improve long-term planning and fund allocation
- Improve interagency and interstate planning
- Seek expedited environmental review and permitting on major mitigation investments

NYS 2100 Post-Sandy Resilience Report

The following is an excerpt from the NYS 2100 report, a comprehensive examination of lessons learned in New York from Hurricane Sandy.

> *After the damage inflicted by recent extreme storms, it is clear that New York State must prepare for a new normal. Planning for the future will never again mean the same thing. The recent storms are not anomalies. They represent further evidence in a developing pattern: an increased frequency and intensity of severe weather attributable to climate change*
>
> - *Subway tunnels and depots for both subway cars and buses in New York City lack sufficient protections against flooding and capacity to pump out water that not only stops mass transit service but also damages communications and other aging systems.*
> - *Bridges, culverts, roads, and certain rail infrastructure are all susceptible to the threat of "scour," caused by flooding that erodes the foundations of structures and, if not addressed, undermines the structural integrity of critical transportation links.*
> - *Flooding poses a major threat to airport runways, terminals, and other systems, especially at airports like LaGuardia and JFK that are adjacent to water.*
> - *Vulnerabilities to marine transportation (ports, rivers, canals) vary in nature, but include insufficient tidal gates, electrical power lines vulnerable to damage, and insufficient embankments to protect against flooding and severe winds.*

Beginning a Risk-Based Approach to Protecting Assets

Comprehensive risk-based asset management programs that systematically focus upon evaluating and reducing hazards to transportation assets are, in some ways, new and untried by many agencies. However, in many ways there are clear analogs already under way in transportation agencies that provide templates that can be adapted to managing risks to transportation assets. These analogs include highway safety programs, rock fall and geologic hazard programs, scour-risk programs and seismic retrofit programs.

Analogy of Safety Programs

The approaches used in highway safety programs provide analogies that could be adapted for risk-based management of threats to physical highway assets. Safety programs involve the collection of risk data, only the risks are exhibited as highway crashes as opposed to infrastructure failure. The risks or threats (crashes) are described and categorized for easier analysis. The number of crashes (or threat probability) are overlaid upon mapping of the highway network and correlations are sought between elements of the highway network that could be causative factors in contributing to crashes (threats.) Then, mitigation steps are taken to reduce the causative factors that contribute to the crash risks. Sometimes, the mitigation steps or corrective actions involve localized physical changes to the highway networks, such as when an intersection is channelized, or a sight-distance deficiency corrected. Other times, risk-impacts are high but crash probabilities are low, such as with rural, roadway departure crashes. These crashes, or the risks of them, tend not to cluster but are widely dispersed. In these cases, mitigation often consists of system-wide or programmatic approaches that are relatively low cost at any given location. These could include on two-lane roads safety edges, centerline and edge rumble strips, enhanced lane delineation or improved pavement friction. On multi-lane routes, they could include cable median barrier, or dynamic speed signs or increased enforcement. The decisions on which strategies to deploy are often based on probabilistic analysis, such as those that produced standardized crash-reduction factors. Risk-treatment decisions often are supported by standardized cost/benefit analyses. In addition, they are augmented by engineering judgment and the observations of knowledgeable experts such as local maintenance engineers or law enforcement officials.

The safety programs illustrate that strategies to reduce risks can include localized roadway improvements, system-wide or programmatic improvements or operational strategies such as stepped-up enforcement. Safety programs also illustrate the utility of both quantitative tools such as cost/benefit analysis and probabilistic crash-reduction factors and the benefits of qualitative judgment such as the experience of local experts. Both play important roles.

Although statewide hazard-risk programs may not be common, they can be based on the logic used in highway safety programs. Beginning from that perspective, the approach to starting a statewide risk-assessment program to assets becomes easier to conceptualize.

Geologic Hazard Programs

At least seven states have rock fall hazard rating systems that also provide existing templates for systematic threat assessments. These rock fall programs include evaluation of risks of various types of slope failures or subsidence in addition to risks of falling rocks.[xxx, xxxi] Most use an explicit risk-rating system and some differentiate between "risks" and "hazards." A Scottish rock fall analysis process considers "hazards" to be the potential for harm from falling rocks or failing slopes while "risk" is the "hazard" converted to a weight and multiplied by the exposure. As a result, high-volume routes that are dense with traffic create greater exposure to the hazard of a falling rock or failing slope than would a lightly travelled road. Hence, the greater risk caused by higher traffic elevates the site's priority.

Figure 5. *Rock fall programs provide templates for risk-based asset management planning.*

Most of the rock fall hazard programs derive from the Oregon Rockfall Hazard Rating System that was begun in 1984 and was further refined in 1991.[xxxii] It still serves as a model for rock fall hazard systems and as a model for other types of risk-based analyses of risks to assets.

It includes six main features:

1. A uniform inventory of slopes
2. A preliminary rating of the slopes

3. A detailed rating of the hazardous slopes
4. A preliminary design and cost estimate for the most serious sections
5. Project identification and development
6. Annual review and evaluation.

The first two steps result in all slopes categorized into an A, B, or C rating. Slopes in the A category are prioritized for further analysis, the B's analyzed as resources permit and the C slopes are deemed to be of low risk and not included in the data base or subject to further analysis.

An objective, risk assessment is then conducted on the A slopes. The B slopes are analyzed as resources permit. The objective assessment categorizes the slopes by risk factors including:

- Slope height
- Ditch effectiveness which assesses its ability to prevent a falling rock from traversing the ditch and reaching the roadway
- Average vehicle risk which is a measure of the percentage of time that vehicles are present in the rockfall zone
- The percent sight distance determines the length of roadway a driver has to avoid a sudden hazard
- The roadway width which is a function of the maneuvering room a driver has
- The geologic character of the slope reflects its proclivity to fail or produce falling rocks

- Block or rock size prone to falling
- Presence of water or other climatic factors
- Rockfall history

The points assigned to each factor range from a low of three to a high of 81, which leads to substantial risk-assessment differences between the lowest-and-highest-risk sites.

The 1991 Oregon process has been refined and updated by Oregon and adapted by other states using additional criteria and data-collection methods. However, the original risk-assessment process is cited here to make the point that analogs for risk-based asset management are long-established, their concepts can be adapted to other assets and their utility has been repeatedly validated. For instance, with the six steps cited above, the word "slopes" could be replaced with "culvert," or "bridge" or "lifeline route" and the six steps would still be useful for a basic risk-based asset analysis.

Current asset managers have the advantages of improved data-collection and streamlined analytic tools not available in 1991. The Missouri Rock Fall Hazard Rating System demonstrated how mobile digital video logging could be used for the initial screening of hazardous locations.[xxxiii] An outfitted vehicle was used to drive the roads, video log slopes and record their position through global positioning system (GPS) technology. The video logging can be used to calculate important risk factors such as slope height, lengths, angles, ditch widths and depths and mass volumes. Trained geologists review the video data for initial assessments of slope or rock stability. The initial prioritization can be used to direct field evaluations of the highest-risk locations. Twenty-three factors which are similar to the original Oregon factors are then inputted into a risk-andconsequence assessment software. Risks such as slope stability and slope geology are multiplied by factors such as average daily traffic or ditch effectiveness to determine the potential consequences from the risks. Being a digital system, the risk locations can be mapped and plotted for easier inclusion into on-going monitoring, planning and programming activities. Although the system is not commonly used by the Missouri DOT, the project did demonstration how technology could accelerate the assessment of rockfall hazards.

In the early 1990's, the Washington State DOT developed a risk-based programming application that includes a numerical rating system that relies upon easily measured and quantifiable factors to evaluate risk of an unstable slope impacting the highway facility. This numerical rating system assigns points to eleven risk categories using an exponential scoring system that quickly distinguishes increasing hazard and risk potential. The rating system addresses the type and severity of a slope hazard in only one rating category, while the remaining categories are dedicated to establishing risk factors to the highway facility. Generally, the higher the total point value for an individual slope, the higher the overall risk to the highway facility. In addition to numerically rating the slopes, a cost-benefit analysis is conducted on potential projects that considers the anticipated cost of traffic impacts resulting from a slope failure with the annual maintenance costs over 20 years versus the cost of mitigating the slope hazard. To select slopes for programming, WSDOT initially concentrated on slopes along high volume corridors with higher ratings, positive cost-benefit ratios, and higher average daily traffic values (ADT). It has more recently moved on to slopes with lower ratings, positive cost-benefit ratios, and lower ADT. Since 1995, WSDOT has mitigated approximately 250 (8%) of its known (≈3000) unstable slopes and about 35% of its highest risk slopes for an approximate cost of $180 million.

Scour Hazard Programs

Another methodology that provides a conceptual approach for expanding risk-based asset management mitigation programs is the HYRISK program.[xxxiv] It provides a rational strategy for assessing relative risk of scour failure for bridges with unknown or scour-prone foundations. It provides estimates of the annual probability of failure based on known variables such as the annual probability of a 100-year flood and known percentages of failure out of the total population of scour-critical bridges. The probability can be multiplied by the cost of failure. The cost of failure includes not only the bridge-replacement costs but the economic value of loss of life and the detour costs, which are based on vehicle volumes, vehicle mix, detour length and detour duration. Once the probability of failure and the cost of failure associated with a specific hazard are known (or estimated), the risk of failure is computed as the product of these two quantities. For example, if the annual probability of hazard-induced bridge failure is multiplied by the cost of bridge failure, then the risk of hazard-induced bridge failure can be expressed as dollars per year of impact. From that cost, the cost/benefits of mitigation strategies can be estimated.

Probabilistic Seismic Retrofit Programs.

Another set of risk-based, probabilistic hazard-reduction programs are the seismic retrofit programs used by Caltrans and Washington State DOT to identify at-risk structures and prioritize retro-fit investments.

A paper written by long-time Caltrans bridge engineers [xxxv] tracks this history of the bridge seismic retrofit program in the state. They noted that 65 years passed between the great 1906 San Francisco earthquake and the 1971 San Fernando quake, the first major quake of the recent era. During those decades, little was done to protect bridges from seismic damage. The 1971 event did not precipitate a major statewide retrofit program but subsequent quakes in 1987 and 1989 convinced policy makers of the need for an aggressive bridge retrofit program. In an example of how a risk can create opportunity, the 1987 Whittier earthquake did not create extensive damage but it provided the department valuable lessons regarding bridge vulnerabilities and further convinced the public of the need for a retrofit program. Then, the damaging 1989 Loma Prieta earthquake accelerated the legislative support for an aggressive retrofit program.

Caltrans engineers developed a risk-based process for prioritizing the state's 24,000 bridges. The objective was to prevent loss of life not the more expensive objective of preventing all damage to bridges. The department engineers developed a risk-based algorithm for three categories: site hazard, structure vulnerability and system impact as seen in Table 1. By applying the algorithm to all bridges, a risk-based prioritization was possible.

In 2003, a state seismic advisory board issued a report that recommended that the comprehensive, risk-based process continue with continuous-improvement and continuous-monitoring processes incorporated. The recommended steps included:

- The state adopt as official policy Caltrans' policy of building, maintaining and rehabilitating bridges to provide an acceptable level of earthquake safety;
- Caltrans should maintain its construction standards to provide safety and functionality of lifeline bridges and continue its current practice of independent reviews to ensure compliance with those design standards;
- Caltrans should regularly reassess seismic performance to ensure that the design standards are adequate as additional seismic events and research provide new information;
- Caltrans should continue its commitment to seismic research;
- Caltrans should maintain its rapid response capability to evaluate, repair and restore damaged bridges.

Table 1. *The Caltrans seismic rating algorithm.*

Category/Characteristic	Characteristic Weight, %
Site Hazard (Hf)	
Soil conditions	33%
Peak rock acceleration	38%
Duration	29%
Structure Vulnerability (Vf)	
Year designed	25%
Outriggers or shared columns	22%
Abutment type	8%
Skewness	12%
Drop type failure	16.5%
Bent redundancy	16.5%
System Impact (If)	
Average Daily Traffic (ADT)	28%
Leased air space (residential, office)	15%
Leased air space (parking, storage facility)	7%
ADT under/over structure	12%
Facility crossed	7%
Route type on bridge	7%
Detour length	14%
Critical utility	10%

Although the advisory board did refer to the concept of "resiliency," its recommendations incorporate the elements of a risk-based, continuously improving resiliency program for seismic retrofit of bridges.

The Washington State DOT likewise developed an objective, risk-based program for prioritizing its seismic retrofit program. The risk elements include the structural redundancy of a bridge, the seismicity of its location, the route recovery time and the average daily traffic. The structural redundancy focused upon each bridge's number of columns, as non-redundant one-column bridges are at higher risk than structures with multiple columns. The seismicity was based upon U.S. Geological Service maps which rate the 1000 year seismic risks of sites. State routes were given higher priority than non-state routes, and priority was given for structures carrying higher traffic volumes. With this criteria, the department could prioritize for retrofit its bridges facing the highest risks.

Summary and Conclusions

This report and the four that precede it emphasize that risk management and asset management are complementary disciplines that help agencies achieve their strategic objectives for managing infrastructure. Asset management assists agencies to sustain desired infrastructure conditions for the lowest cost over a number of decades. While asset management seeks to achieve reliable, predictable highway system conditions, risk management seeks to identify and mitigate the unpredictable threats to infrastructure, while identifying opportunities created by uncertainty or new opportunities. Climate change, increased flooding, terrorist attacks, earthquakes and other unpredictable events clearly create risks to infrastructure. Many of these risks are negative but some could be positive such as warmer winter temperatures or the lessons learned from minor seismic events. A risk-based asset management program includes a "learning function" in which risks such as these are identified, evaluated, and categorized. They can be rationally treated, tolerated, transferred, terminated or taken advantage of depending upon the risk analysis.

This report concludes the series by emphasizing that risk-based asset management serves a dual function in an uncertain and risky world. It not only helps agencies anticipate and mitigate risks to assets but it also helps agencies recover more quickly if disasters occur. As such, asset management becomes a key component of a resilient agency by creating robust infrastructure, complete asset inventories and prioritization processes that allow agencies to quickly respond to changed conditions. An agency with a mature asset management program not only has stronger physical assets, it also will have better information systems and is more likely to have a culture of resiliency that will serve it well in times of crisis.

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