



California Winter (Non-Snow and Ice) Level of Service Strategies

Requested by
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The Caltrans Division of Research, Innovation and System Information (DRISI) receives and evaluates numerous research problem statements for funding every year. DRISI conducts Preliminary Investigations on these problem statements to better scope and prioritize the proposed research in light of existing credible work on the topics nationally and internationally. Online and print sources for Preliminary Investigations include the National Cooperative Highway Research Program (NCHRP) and other Transportation Research Board (TRB) programs, the American Association of State Highway and Transportation Officials (AASHTO), the research and practices of other transportation agencies, and related academic and industry research. The views and conclusions in cited works, while generally peer reviewed or published by authoritative sources, may not be accepted without qualification by all experts in the field. The contents of this document reflect the views of the authors, who are responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the California Department of Transportation, the State of California, or the Federal Highway Administration. This document does not constitute a standard, specification, or regulation. No part of this publication should be construed as an endorsement for a commercial product, manufacturer, contractor, or consultant. Any trade names or photos of commercial products appearing in this publication are for clarity only.

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Executive Summary

Background

Caltrans has well-established procedures for attaining snow and ice level of service (LOS) targets during winter storms. However, winter weather across much of California includes events beyond snow and ice, such as flooding, wildfires, mudslides and strong winds, which can have a major impact on highway infrastructure and require costly maintenance and repair.

Caltrans is seeking to develop strategies to anticipate and manage the impact of such non-snow and ice winter weather events to reduce system disruptions, reduce repair costs and improve system resiliency. To assist Caltrans with this effort, CTC & Associates compiled information about domestic and international practices and research on this topic.

Summary of Findings

After conducting a targeted literature search and corresponding with selected practitioners and experts, we found a number of resources that addressed different aspects of this topic. However, none of these resources matched Caltrans' precise interest in weather-based maintenance operations, planning and LOSs comparable to what is typically done for snow and ice.

Below is a summary of relevant resources we identified in three topic areas:

- Weather event identification, modeling and response.
- Weather resiliency, adaptation and recovery.
- State department of transportation (DOT) level of service and vulnerability screening.

Weather Event Identification, Modeling and Response

Several research studies cite approaches to modeling weather events, resultant hazards and appropriate responses to these events. Most of the citations examine specific types of extreme weather-related emergency maintenance events: floods and landslides. Two citations take a broader approach to modeling road system responses to weather and may be of particular interest to Caltrans: a 2015 journal article about RoadSurf, a Finnish simulation model for predicting road weather and road surface conditions, and a 2014 article that delineates a climatology of adverse and extreme weather events that can be expected to affect European transport systems.

Weather Resiliency, Adaptation and Recovery

Other research developed through national and international efforts addresses weather resiliency, adaptation and recovery. These resources focus first on climate change, but we highlighted those that also address the effects of extreme weather and subsequent maintenance impacts.

Domestic resources include guidance, case studies and pilots developed through the American Association of State Highway and Transportation Officials (AASHTO), the National Cooperative Highway Research Program (NCHRP) and Federal Highway Administration (FHWA) (a multiyear, multiphase effort). For this Preliminary Investigation, we also corresponded with AASHTO and consultants working on AASHTO and NCHRP research.

International citations on weather resiliency and recovery are included from the United Kingdom and New Zealand.

State DOT Level of Service and Vulnerability Screening

We detailed findings from three state DOTs (Mississippi, Utah and Washington State) that have adopted a maintenance LOS system. The discussion includes a summary of their grading systems and ways they might be used in relation to severe weather planning and response.

Also discussed is Tennessee DOT's work to develop extreme weather screening assessment tools. Included with the research citation is an attachment provided by Tennessee DOT that illustrates the screening tool for one of the state's four regions.

Gaps in Findings

While this fact-finding effort yielded elements that are relevant to the topic of this Preliminary Investigation, it did not uncover an existing system for extreme weather maintenance LOS that was precisely what Caltrans was seeking. It appears that entities responsible for maintaining highway infrastructure do not typically budget for non-snow and ice weather maintenance. Instead, planning is more likely to occur for infrastructure improvement to reduce risk. As a result, some of the other features that Caltrans hoped to find through this Preliminary Investigation, such as data collection systems and cost optimization, could not be identified.

Next Steps

Moving forward, Caltrans could consider:

- Reviewing the two citations about road weather modeling (RoadSurf and the extreme weather events affecting the European transport system), which appear to be on target for Caltrans. If these citations are of interest upon deeper examination of methodologies, it may be worthwhile to contact investigators to learn if and how the methodologies have been applied.
- Reviewing the documentation about the Tennessee DOT screening tool. The methodology could be useful for determining a baseline on which assets are more vulnerable to different kinds of extreme weather—and from there, building a response plan based on future weather events. Moreover, Tennessee's regional, rather than statewide, approach may be particularly useful to Caltrans. Revisiting Tennessee in several months could give the state time to make use of these materials and report on its outcomes.
- Examining other states' maintenance LOS system (as well as its own, LOS 2000, detailed in Caltrans' Maintenance Manual) to determine if any aspects of grading or measuring are particularly well-suited to applying to grading extreme weather impacts on infrastructure.

Detailed Findings

While Caltrans has procedures in place for attaining snow and ice level of service (LOS) targets during winter storms, winter weather across much of California includes events beyond snow and ice. Flooding, wildfires, mudslides and strong winds all can significantly impact highway infrastructure, leading to costly maintenance and repair.

Caltrans is interested in developing strategies to anticipate and manage the impact of such non-snow and ice winter weather events to reduce system disruptions, reduce repair costs and improve system resiliency. To assist Caltrans with this effort, CTC & Associates conducted a literature search and corresponded with selected practitioners and experts to gather information about domestic and international practices and research on this topic. We found a number of resources that addressed different aspects of this topic, but none that matched Caltrans' precise interest in weather-based maintenance operations, planning and LOSs comparable to what is typically done for snow and ice.

Below is a summary of relevant resources that we identified in this information-gathering effort. Publications and related resources are organized in three topic areas:

- Weather event identification, modeling and response.
- Weather resiliency, adaptation and recovery.
- State department of transportation (DOT) level of service and vulnerability screening.

Weather Event Identification, Modeling and Response

The research cited below offers various approaches to modeling specific weather events and resultant hazards (flash floods and landslides) and appropriate responses to these events. Two citations take a broader approach to modeling road system responses to weather.

Floods

“Stochastic Modeling of Road System Performance During Multihazard Events: Flash Floods and Earthquakes,” Wisinee Wisetjindawat, Amirhassan Kermanshah, Sybil Derrible and Motohiro Fujita, *Journal of Infrastructure Systems*, Vol. 23, No. 4, December 2017.

Citation at <https://ascelibrary.org/doi/abs/10.1061/%28ASCE%29IS.1943-555X.0000391>

From the abstract: Transport resilience is an important area of research in the global effort to adapt to climate change. This paper introduces and applies a stochastic modeling methodology to assess the impact of multihazard events. Most cities are exposed to multiple types of extreme events, sometimes simultaneously, and focusing on single events may lead to inadequate design recommendations. By assigning failure probabilities of road segments and by estimating road failure through Monte Carlo simulation, roads and areas that are particularly vulnerable to multihazard events can be detected. The performance of the large-scale road network of the Tokai region in Japan (prone to both typhoons and earthquakes) is analyzed by considering three scenarios of hazards: flash flood, earthquake and the combination of both hazards. The model considers two key traffic performance characteristics: postdisaster reduced road capacity and hourly variations in travel demand. Overall, several areas in the region are found to be currently severely at risk, thus providing direct information that can help authorities test the effectiveness of future road infrastructure projects.

“Using Climate Models to Estimate Urban Vulnerability to Flash Floods,” A. Kermanshah, S. Derrible and M. Berkelhammer, *Journal of Applied Meteorology and Climatology*, Vol. 56, pages 2637-2650, September 2017.

<http://journals.ametsoc.org/doi/pdf/10.1175/JAMC-D-17-0083.1>

From the abstract: Climate change will impact urban infrastructure networks by changing precipitation patterns in a region. This study presents a novel vulnerability assessment framework for infrastructure networks against extreme rainfall-induced flash floods, with a specific application to transportation. The framework combines climate models, network science, geographical information systems (GIS) and stochastic modeling to compile a vulnerability surface (VS). Daily precipitation simulations for 2006–2100 from the Community Climate System Model, version 4 (CCSM4), are used to produce a stochastic simulation of extreme flash flood events in five U.S. cities—that is, Boston, Massachusetts; Houston, Texas; Miami, Florida; Oklahoma City, Oklahoma; and Philadelphia, Pennsylvania—under two different climate scenarios (RCP4.5 [representative concentration pathway 4.5] and RCP8.5). To assess the impact of these events, percentage drops in static (i.e., overall properties and robustness topological indicators) and dynamic (i.e., GIS accessibility and travel demand metrics) network properties are measured before and after simulated extreme events. The results of these metrics are inputs on a radar diagram to form a VS. Overall, the results show that changes in flash flood frequency due to climate change can have a significant impact on road networks, as was demonstrated recently in Houston, Texas. The magnitude of these impacts is chiefly associated with the geographic location of the cities and the size of the networks. The proposed framework can be reproduced in any city around the world, and researchers can use the results as guidelines for infrastructure design and planning purposes. Moreover, sensitivity analysis to varying greenhouse gas concentration trajectories can help local and national authorities to prioritize strategies for adaptation to climate change in more vulnerable regions.

“Development of a Post-Flood Road Maintenance Strategy: Case Study Queensland, Australia,” Misbah U. Khan, Mahmoud Mesbah, Luis Ferreira and David J. Williams,

International Journal of Pavement Engineering, Vol. 18, No. 8, pages 702-713, 2017.

Citation at <http://www.tandfonline.com/doi/full/10.1080/10298436.2015.1121781>

From the abstract: Currently, no road authority takes into account flooding in road deterioration (RD) models; as a result, post-flood rehabilitation treatments may be sub-optimal. This paper proposes a new approach to the development of a post-flood maintenance strategy. The recently developed roughness and rutting-based RD models with flooding, by the current authors, are used as input to predict pavement deterioration after a flood (i.e., assuming a flood in year 1). The HDM-4 [Highway Development and Management] model has been used to get the post-flood maintenance strategy with constrained and unconstrained budget, where post-flood rehabilitation starts from year 2. The road groups in state road network of Queensland, Australia, are used as the case study. The unconstrained budget solution aims to keep the network in an excellent condition at a cost of \$49.7bn [billion] with the possible strongest treatments. The constrained budget strategy uses agency cost and pavement performance as constraints in optimization and provides a reasonable solution. This strategy requires about \$26.1bn [billion] in life cycle, which is close to the main road authority of Queensland’s post-flood rehabilitation program. The paper discusses two other strategies [to] maximize economic benefits and budget optimisation. It is expected that a road authority would properly investigate its flood-damaged roads before implementation. The paper shows pavement performances with the post-flood strategy. The need for [an] RD model to predict deterioration after a flood and for post-flood treatment selection is also highlighted.

Landslides

“Exploring Regional Topographic and Rainfall Controls of Landslides on Vancouver Island, British Columbia, Canada,” Jason Goetz, Alexander Brenning and Richard Guthrie, *Landslides and Engineered Slopes: Protecting Society Through Improved Understanding*, CRC Press, 2012.

https://www.researchgate.net/publication/303783991_Exploring_regional_topographic_and_rainfall_controls_of_landslides_on_Vancouver_Island_British_Columbia_Canada

From the abstract: Recent advances in statistical classification methodology have led to new innovative approaches for predictive modeling of landslide susceptibility. These advancements allow us to utilize more flexible modeling techniques. This research focuses on the use of Generalized Additive Models (GAM), a non-parametric regression technique, to explore the relationship of landslides to topography and rainfall on Vancouver Island, British Columbia, Canada. A GAM incorporating only topographic variables and a GAM that also includes rainfall patterns are compared to determine the importance of rainfall to a set of 639 landslides. Rainfall patterns are explored at different temporal scales to examine the relationship between landslides and annual rainfall, seasonal rainfall or rainfall from a specific event known to cause landslides. The most influential rainfall pattern is determined to be annual rainfall, which is determined using a stepwise variable selection method for a GAM. All of the topographic variables are found to contribute significant information for the prediction of landslide susceptibility. In addition, all of the variables, including rainfall, are found to produce the “best” landslide susceptibility model when represented non-linearly.

“Extreme Weather and Landslide Initiation in Coastal British Columbia,” R.H. Guthrie, S.J. Mitchell, N. Lanquaye-Opoku and S.G. Evans, *Quarterly Journal of Engineering Geology and Hydrogeology*, Vol. 43, pages 417-428, November 2010.

Citation at <http://qjgeh.lyellcollection.org/content/43/4/417.short>

From the abstract: More frequent [and] more intense storms predicted by climate models for the Pacific Northwest of North America could increase the regional landslide hazard. The impacts of one such storm are examined on Vancouver Island, British Columbia, during which 626 mapped landslides occurred, encompassing >5 km² total area and generating >1.5 × 10⁶ m³ of sediment. The relationship between rainfall intensity, air temperature and wind speed obtained from mesoscale numerical weather modelling is examined relative to landslide incidence within steep terrain. A critical onset of rainfall intensity between 80 and 100 mm in 24 h that results in a rapid increase in landslides with increasing precipitation is demonstrated. The argument is presented that this result is more useful for landslide management decisions than a minimum threshold. The component of wind-driven rain was calculated, and results indicated that wind caused increased concentrations of rainfall associated with the occurrence of landslides. Approximately half the landslides studied were not related to rainfall alone, but to rain on snow, and we argue that wind played a crucial role. This often neglected component of hydrological analysis remains a major challenge as the role of snow transition zones and a warming climate in coastal mountain watersheds is considered.

“Estimating Temporal Probability for Landslide Initiation Along Transportation Routes Based on Rainfall Thresholds,” Pankaj Jaiswal and Cees J. van Westen, *Geomorphology*, Vol. 112, Nos. 1-2, pages 96-105, November 2009.

Citation at <http://www.sciencedirect.com/science/article/pii/S0169555X09002177>

From the abstract: The estimation of the temporal probability of landslide initiation is an essential component in landslide hazard assessment. In this paper a temporal probability model is presented for the initiation of shallow translational debris slides and debris flows along cut slopes of a railroad sector in southern India, for which an extensive landslide database was

available, covering a time span of 15 years. The model is based on rainfall thresholds and gives the likelihood of occurrence of rainfall that can trigger landslides with a certain density. The temporal probability was calculated as the joint probability of annual exceedance probability of the rainfall threshold, determined using a Poisson probability model and the probability of landslide occurrence once the threshold had been exceeded. The model was tested for a 19-km long railroad alignment in the Nilgiri hills, which was divided into a number of sections on the basis of terrain characteristics. A landslide inventory, containing dates of occurrence, was prepared from historical records for the period 1987 to 2007. Daily rainfall for the same period was collected from 15 rain gauges. Rainfall thresholds were established for the sections based on the relationship between daily and antecedent rainfalls. Four thresholds were defined for rainfall events that can trigger one or more landslides within each section and one threshold that can trigger 15 or more landslides along the entire route. The annual temporal probability varies from 0.27 to 0.49. The model was also found useful in predicting landslides in a nearby road with similar characteristics. The result indicates that more than 60% of the recorded landslides along the road occurred within the sections with high temporal probability values (> 0.40). The temporal probability derived from the model forms the basis for future landslide risk analysis along the transportation routes.

System Modeling

“RoadSurf: A Modelling System for Predicting Road Weather and Road Surface Conditions,” Markku Kangas, Martti Heikinheimo and Marjo Hippel, *Meteorological Applications*, Vol. 22, No. 3, pages 544-553, July 2015.

<http://onlinelibrary.wiley.com/doi/10.1002/met.1486/full>

From the abstract: In Finland, the Finnish Meteorological Institute (FMI) is duty bound to issue warnings of hazardous traffic conditions to the general public. To strengthen these services towards more efficient estimation of rapidly varying conditions of the road surface at a national scale, a simulation model, RoadSurf, has been developed. As input, the model employs numerical weather forecasts, either directly or after modifications made by meteorologists, as well as observations from synoptic or road weather stations and radar precipitation measurement network. As output, the model produces not only road surface temperature, but also road surface condition classification and a traffic index describing the driving conditions in more general terms, as well as road surface friction. The model has been in operational use since 2000. In addition to the original goal of providing road weather forecasts for the national road network, the model has been used in several other applications, for example, in predicting pedestrian sidewalk conditions and in numerous intelligent traffic applications. The present study describes the road weather model RoadSurf and its main applications.

“Severe Weather Affecting European Transport Systems: The Identification, Classification and Frequencies of Events,” Andrea Vajda, Heikki Tuomenvirta, Ilkka Juga, Pertti Nurmi, Pauli Jokinen and Jenni Rauhala, *Natural Hazards*, Vol. 72, No. 1, pages 169-188, 2014.

Citation at <https://link.springer.com/article/10.1007/s11069-013-0895-4>

From the abstract: Severe weather can have serious repercussions in the transport sector as a whole by increasing the number of accidents, injuries and other damage, as well as leading to highly increased travel times. This study, a component of the EU FP7 Project EWENT, delineates a Europe-wide climatology of adverse and extreme weather events that can be expected to affect the transport network. We first define and classify the relevant severe weather events by investigating the effects of hazardous conditions on different transportation modes and the infrastructure. Consideration is given to individual phenomena such as snowfall, heavy precipitation, heat waves, cold spells, wind gusts; a combined phenomenon, the blizzard,

is also considered. The frequency of severe weather events, together with the changes in their spatial extension and intensity, is analyzed based on the E-OBS dataset (1971–2000) and the ERA-Interim reanalysis dataset (1989–2010). Northern Europe and the Alpine region are the areas most impacted by winter extremes, such as snowfall, cold spells and winter storms, the frequency of heavy snowfall. The frequency of hot days is highest in Southern Europe. Severe winds and blizzards are the most common over the Atlantic and along its shores. Although heavy rainfall may affect the whole continent on an annual basis, extreme precipitation events are relative[ly] sparse, affecting particularly the Alps and the Atlantic coastline. A European regionalization covering similar impacts on the transport network is performed.

Weather Resiliency, Adaptation and Recovery

The publications below highlight national and international initiatives in the area of weather resiliency, adaptation and recovery. The central focus of these resources is typically climate and climate change, with unusual or severe weather patterns as outcomes that lead to emergency maintenance needs. We have sought to highlight the maintenance aspects of these resources that are most relevant to Caltrans' interest for this Preliminary Investigation.

Domestic

Research in Progress: Deploying Transportation Resilience Practices in State DOTs, National Cooperative Highway Research Program, NCHRP Project 20-117, project start date: June 2017, expected completion date: June 2019.

<http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=4208>

A major deliverable for this project will be to develop a transportation resilience guide and toolkit. These resources will include resilience model curricula for the topics listed below. Note that maintenance is among the areas to be cover in the curricula:

- Design and engineering.
- Construction.
- Social considerations.
- Economics.
- Prioritization.
- Maintenance.
- A tutorial on funding, with case studies on how funding packages are put together to address transportation systems resilience.

We corresponded with principal investigator Paula Hammond with WSP | Parsons Brinckerhoff, who advised that there aren't yet findings from this project to be shared.

Report in Progress: Resiliency Case Studies: State DOT Lessons Learned, American Association of State Highway and Transportation Officials, expected completion date: 2018.

Program description at <https://rstst.transportation.org/>

This report, which is nearing publication, is being prepared by the AASHTO Resilient and Sustainable Transportation Systems Program, which falls under the Center of Environmental Excellence. It examines recent extreme weather events that have impacted state DOTs and how they have responded to the challenges associated with the events.

Through correspondence with Melissa Savage with AASHTO and Paula Hammond and Michael Flood with WSP (formerly WSP | Parsons Brinckerhoff), the draft report has been acquired for Caltrans' internal use. It will become publicly available from AASHTO after it is finalized.

Maintenance considerations cited in the executive summary of the draft report include:

- Increase the resiliency of infrastructure projects by considering future impacts in all activities (maintenance, emergency response, operations).
- Monitor assets for damage or stress after an extreme event and consider changes in design and maintenance procedures in response, where appropriate.

Resilience Pilots, Federal Highway Administration, 2018.

<https://www.fhwa.dot.gov/environment/sustainability/resilience/pilots/index.cfm>

From the web site:

FHWA has partnered with State Departments of Transportation (DOTs) and Metropolitan Planning Organizations (MPOs) to develop and deploy resilience solutions to current and future extreme weather events, reducing future maintenance costs over the full life-cycle of transportation assets.

2018-2019 Pilot Program: Resilience and Durability to Extreme Weather

FHWA is currently seeking to partner with State Departments of Transportation (State DOTs), Metropolitan Planning Organizations (MPOs), Federal Lands Management Agencies (FLMAs), and Tribes to address one of three areas related to deploying resilience solutions:

1. Integrating resilience and durability into agency practices.
2. Using available tools and resources to assess the vulnerability and risk of transportation projects or systems.
3. Deploying a resilience solution and monitoring performance.

2018-2019 is the fourth phase of the pilot program. The web site also describes the first three phases:

- 2010-2011 Pilot Program: Vulnerability Assessments.
- 2013-2015 Pilot Program: Vulnerability Assessments and Adaptation Options.
- 2016-2017 Pilot Program: Nature-Based Resilience for Coastal Highways.

“Assessing Strategies for Protecting Transportation Infrastructure from an Uncertain Climate Future,” Ali Asadabadi and Elise Miller-Hooks, *Transportation Research Part A: Policy and Practice*, Vol. 105, pages 27-41, November 2017.

Citation at <https://www.sciencedirect.com/science/article/pii/S0965856416309673>

From the abstract: This paper investigates the importance of explicitly considering the stochastic nature of future climate impact predictions and predictive accuracy for optimal investment planning in the protection of coastal and inland transportation infrastructure against climate impacts. Such impacts include sea level rise, coastal and riverine flooding resulting from more frequent and intense precipitation events, storms, storm surges and other extreme events. For this purpose, numerical experiments utilizing stochastic optimization based methodologies were conducted on a case study of the Washington, D.C., Greater Metropolitan area proximate to the Potomac River under varying climatic predictions. Results from the numerical experiments

suggest a 54% reduction in added costs due to the implementation of chosen protective infrastructure investments. They also indicate a reduction in added costs (capital investment and added delays) on the order of 19% when the investments are chosen to hedge against probable future flooding events as compared with planning for the 50th percentile simple linear regression (SLR) prediction with associated weather events. A potential gain of nearly 27% in reduced costs through improved predictive accuracy in climatic forecasts is also noted, suggesting significant value in more accurate forecasts.

“Barriers to Implementation of Climate Adaptation Frameworks by State Departments of Transportation,” Jonathan Dowds and Lisa Aultman-Hall, *Transportation Research Record* 2532, pages 21-28, 2015.

Citation at <http://trrjournalonline.trb.org/doi/abs/10.3141/2532-03>

From the abstract: Disruptive events caused by weather extremes are imposing significant and rising costs on transportation agencies. In response, federal and state transportation agencies and other organizations are exploring adaptation measures to reduce the adverse consequences of these events. Several existing adaptation frameworks are synthesized here into a simplified, core adaptation framework, and the study seeks to delineate the current barriers to the widespread implementation of adaptation programs by state departments of transportation in the United States. From interviews with transportation practitioners and a review of the results from FHWA pilot projects, it is found that uncertainty about future climate conditions, the need for additional vulnerability-modeling tools, conceptual uncertainty about evaluating asset criticality and limited funding all inhibit implementation of adaptation measures.

“Indicator Approach for Assessing Climate Change Vulnerability in Transportation Infrastructure,” Emily Rowan, Cassandra Snow, Anne Choate, Beth Rodehorst, Susan Asam, Robert Hyman, Robert Kafalenos and Aung Gye, *Transportation Research Record* 2459, pages 18-28, 2014.

Citation at <http://trrjournalonline.trb.org/doi/abs/10.3141/2459-03>

From the abstract: From installing culverts with larger safety margins to instituting more frequent training for weather emergencies, transportation agencies around the world are adapting to extreme weather and climate change. An understanding of when and how to adapt (i.e., improve infrastructure preparedness) requires evaluating existing and future vulnerabilities to climate change and prioritizing adaptation efforts. A successful vulnerability assessment lays the groundwork for adaptation by building stakeholder relationships, spurring data collection, and prioritizing needs. One barrier faced by transportation agencies in conducting vulnerability assessments is a lack of financial and staff resources. The process of collecting climate and asset data can be particularly onerous for agencies struggling to meet daily operational needs. Two recent projects piloted a cost-effective screening method for highly vulnerable assets that used indicators developed from data already being collected by many state departments of transportation and metropolitan planning organizations. The indicator that libraries developed during the course of these two studies is described. The results of the data-driven vulnerability screen provide transportation managers with a low-cost starting point toward understanding their system’s vulnerabilities. Future research should focus on testing the indicators to identify and eliminate areas of overlap and on evaluating the prediction accuracy for exposure, sensitivity and adaptive capacity.

Impacts of Extreme Weather on Transportation: National Symposium Summary, Michael D. Meyer and Emily Rowan, American Association of State Highway and Transportation Officials, 2013.

http://www.environment.transportation.org/pdf/2013_symposium/aashto_ewesymposium_2013.pdf

From the introduction:

In recognition of the extreme weather event challenges facing state transportation officials, the American Association of State Highway and Transportation Officials (AASHTO) sponsored a two-day symposium in May of 2013 entitled, National Symposium: Impacts of Extreme Weather Events on Transportation. The first day of the symposium focused on the impacts and costs associated with extreme weather events; the second day examined different ways of managing the events and how transportation officials can incorporate weather concerns into agency decision making. The major findings of the symposium are presented in this document, organized by the six conference session topics [state DOT experiences with recent extreme weather events; extreme weather events—trends, projections and integrating information into decisions; costs of extreme weather; managing extreme weather events (design, operations and maintenance); managing extreme weather (emergency management); and risk assessment and asset management].

Of particular relevance to this Preliminary Investigation is the section titled Managing Extreme Weather (Design Standards, Operations and Maintenance), beginning on page 11 of the report. Following are four key messages in this area:

- **Extreme weather events are affecting the operations and maintenance functions of state DOTs today and will do more so in the future:** State DOTs have responded to extreme weather events for many years, but in many cases the frequency and intensity of the storms being faced today [are] presenting new challenges to state officials. For example, emergency management and response is becoming a more important staff function in many state DOTs.
- **Successful state response in the aftermath of extreme weather events involves coordinated efforts on the part of numerous governmental and emergency response agencies:** Numerous examples of effective state response to the extreme weather events illustrated the importance of having strong partnerships among state DOTs, emergency management agencies, emergency responders, enforcement agencies, public health officials and humanitarian relief organizations.
- **The impacts of extreme weather events could change the way one designs infrastructure:** Design procedures and design standards are based in many cases on the ability of assets to cope with environmental stresses and conditions placed on an asset. The design of storm water drainage systems, roads, bridges, culverts, small dams, detention basins and airport runways all reflect considerations for temperature, precipitation and wind. To the extent that these inputs will be different in the future, designs could change as well.
- **Given the important role that weather-related variables have in determining design parameters, more information is needed on how designers can take likely changes into account:** Engineering design is dependent on inputs relating to the stresses that will likely be placed on assets (e.g., intensity-frequency-duration curves for precipitation). More information and research [are] needed to inform designers on what approaches might be taken for considering changes in such inputs over time.

NCHRP Report 753: A Pre-Event Recovery Planning Guide for Transportation, Patricia Bye, Linda Yu, Shubha Shrivastava and Simon van Leeuwen, National Cooperative Highway Research Program, 2013.

<http://www.trb.org/Publications/Blurbs/169296.aspx>

From the foreword: NCHRP Report 753: A Pre-Event Recovery Planning Guide for Transportation ... provides an overview of what can be done to prepare for the recovery of transportation critical infrastructure. Principles and processes based on federal guidance, effective practices and lessons from case studies are provided to guide transportation owners and operators in their efforts to plan for recovery prior to the occurrence of an event that impacts transportation systems. Tools and resources are included to assist in both pre-planning for recovery and implementing recovery after an event. The Guide is intended to provide a single resource for understanding the principles and processes to be used for pre-event recovery planning for transportation infrastructure. In addition to the principles and processes, the Guide contains checklists, decision support tools, and resources to support pre-event recovery planning. The Guide will be of interest to transportation infrastructure owners/operators, transportation planners and practitioners at the state and local levels.

Adaptation Clearinghouse, Georgetown Climate Center, 2011.

<http://www.adaptationclearinghouse.org/>

The Adaptation Clearinghouse “seeks to assist policymakers, resource managers, academics, and others who are working to help communities adapt to climate change.” The transportation sector page (<http://www.adaptationclearinghouse.org/sectors/transportation/>) states:

Climate change will challenge the ability of transportation agencies to maintain a state of good repair of transportation assets, but many are thinking proactively about how to plan for these impacts and design transportation systems to be more prepared for and resilient to climate change. This page includes resources to help policymakers understand, plan and prepare for the impacts of climate change to transportation systems and assets.

Transportation resources are offered in the following categories:

- Transportation basics.
- Assessments and tools.
- Plans.
- Planning guides.
- Law and policy.
- Case studies.
- Funding.
- Project design.
- Operations and maintenance.
- Organizations.
- Geographic search (access to transportation resources by region or state).

International

United Kingdom

Review of the Resilience of the Transport Network to Extreme Weather Events Expert Panel, Department for Transport (United Kingdom), undated.

<https://www.gov.uk/government/groups/review-of-the-resilience-of-the-transport-network-to-extreme-weather-events-expert-panel>

This effort sought “practical measures to improve the resilience of [the United Kingdom’s] transport network to severe weather events in the short term, [while] giving due consideration to longer term resilience of the nation’s transport infrastructure.” Key findings are noted in the following document:

Transport Resilience Review: A Review of the Resilience of the Transport Network to Extreme Weather Events, Department for Transport (United Kingdom), July 2014.

https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/335115/transport-resilience-review-web.pdf

The following primary weather risks, including associated infrastructure impacts, are discussed beginning on page 24 of the report (page 27 of the PDF):

- Intense rainfall.
- Prolonged rainfall.
- Strong winds.
- Heat waves.
- Coastal storm surges.
- Other weather hazards (fog, crosswinds, hail and lightning).

Among the key recommendations in the executive summary (beginning on page 14 of the report, page 16 of the PDF), the following are particularly relevant to this Preliminary Investigation:

- Item 50 states that protecting all parts of the network against all extreme weather events would be unaffordable and recommends collaboration among transportation, energy and climate change agencies to identify a “critical network” that should be maintained and enhanced to a higher level of resilience.
- Item 52 notes that more work is needed to improve flood forecasting, particularly for complex coastal events.
- Item 53 calls for a complete drainage asset inventory, noting the importance of drainage to resilience.

New Zealand

Measuring the Resilience of Transport Infrastructure, J.F. Hughes and K. Healy, NZ Transport Agency, Research Report 546, February 2014.

<http://www.nzta.govt.nz/assets/resources/research/reports/546/docs/546.pdf>

From the executive summary:

The New Zealand Transport Agency (‘the Transport Agency’) has a key interest in ensuring that transport infrastructure assets and services function continually and safely. This interest

has led to a specific focus on the concept of resilience and how this can be defined, measured and improved across the transport system.

As a result, from late 2012 to mid-2013, the Transport Agency engaged AECOM to develop a framework to measure the resilience of the New Zealand transport system.

The project involved initial research and scoping to determine the project boundaries and definitions, and following this, the development of a practical framework and assessment tool.

The framework is applicable to the broad land transport system (road and rail) and allows consideration of various scales (asset/network/region).

Table 2.1 (pages 14-15 of the report) defines the perspective of the operator and maintainer in terms of resilience: “Operators need to deliver resilience which does not adversely raise the cost of maintenance and operational expenditure. They have a key interest in interdependencies and potential cascade failure.”

Figure 6.2 (page 43 of the report) presents a measure of robustness for maintenance:

Measurement:

Processes exist to maintain critical infrastructure and ensure integrity and operability—as per documented standards, policies and asset management plans (e.g., roads maintained, flood banks maintained, stormwater systems are not blocked). Should prioritize critical assets as identified.

Measurement scale:

- 4 Audited annual inspection process for critical assets and corrective maintenance completed when required.
- 3 Non-audited annual inspection process for critical assets and corrective maintenance completed when required.
- 2 Ad hoc inspections or corrective maintenance completed, but with delays/backlog.
- 1 No inspections or corrective maintenance not completed.

Table 8.1 (beginning on page 48 of the report) provides an example of a regional all-hazard assessment.

State DOT Level of Service and Vulnerability Screening

The citations below highlight three state DOTs (Mississippi, Utah and Washington State) that have adopted a maintenance LOS system. We have emphasized aspects that may be relevant to extreme weather response. Included among these is a summary of our discussion with a representative from Washington State DOT.

In addition, we corresponded with Tennessee DOT and researchers at Vanderbilt University to learn more about efforts in Tennessee to develop extreme weather screening assessment tools. Included with the research citation is an attachment that illustrates the screening tool for one of Tennessee's four regions.

Maintenance Level of Service

Mississippi

Maintenance Summary—Fiscal Year 2014, Mississippi Department of Transportation, 2014 (included in Summer Maintenance Operations Reporting: A Survey of State and National Practice, Minnesota Department of Transportation, February 2015).

<https://www.dot.state.mn.us/research/TRS/2015/TRS1504.pdf>

Mississippi's maintenance LOS measures appear on pages 211-213 of the PDF. Those related to drainage and roadside may be relevant to this Preliminary Investigation. Mississippi defines an LOS grading class A through F for each measure.

Utah

Maintenance Management Quality Assurance Plus (MMQA+) Inspection Manual, Utah Department of Transportation, July 2012.

<http://www.wistrans.org/mrutc/files/MMQA-Manual-Revision-07-01-2012-Final.pdf>

From page 4 of the report (page 6 of the PDF):

Maintenance performance is measured and reported in terms of a Level of Maintenance (LOM), expressed as a letter grade A, B, C, D or F. At the statewide level, a target LOM (A through C) is established for each of the MMQA+ activities. Each maintenance station divides each of its routes into one or more segments. Following the guidelines in this manual, station personnel conduct inspections of each route segment, and record both the total number of features to be maintained within the activity subgroup on the segment, and the total number of deficient features. The inspection data are entered into the MMQA+ software (part of OMS), which calculates a LOM (A through F). Once the data are entered, the software can be used to print reports that help maintenance managers at all levels to effectively manage the resources at their disposal.

For each item to be measured, the manual presents both a desired condition and a deficient condition. Measurement frequency (by event, monthly or semiannually) is discussed on page 7 of the report (page 9 of the PDF).

Washington

Maintenance Manual, Washington State Department of Transportation, June 2017.
<http://www.wsdot.wa.gov/publications/manuals/fulltext/M51-01/M51-01.07Revision.pdf>

From the foreword:

Providing for safe movement on our highway system while performing a variety of maintenance activities in a safe manner is a priority for our Maintenance Operations family.

Chapters in this publication are:

1. Emergency Procedures
2. Work Zone Traffic Control and Safety
3. Pavement Patching and Repair
4. Drainage
5. Maintenance of Structures
6. Roadside Maintenance
7. Snow and Ice Control
8. Traffic Services
9. Electrical System Maintenance
10. Miscellaneous

As the weather primarily addressed in this manual is snow and ice, we spoke with John Himmel, Washington State DOT's emergency and security program manager, for more information.

Himmel advised that Washington State watches the National Weather Service closely (Washington State DOT staff includes an in-house forecaster) and relies on the expertise of highly experienced field staff to know where road flooding is most likely to occur. Slides are harder to predict, though sites where slides occur regularly are known.

Unlike snow and ice maintenance, there is no pre-existing budget for extreme weather disaster maintenance because it's so hard to predict. Himmel also mentioned factors beyond the agency's control, such as a slide-prone area affected by land beyond the limit of Washington State DOT's right of way that may be destabilized by fire.

Himmel directed us to Washington State DOT's Maintenance Accountability Process (MAP) Manual (see Related Resource below), which details the agency's outcome-based performance measures for the maintenance program. This system helps the maintenance office justify its funding needs based on quantifiable metrics.

Related Resource:

Maintenance Accountability Process (MAP) Manual, Washington State Department of Transportation, June 2017.

<https://www.wsdot.wa.gov/NR/rdonlyres/97DD3129-E385-4C53-A51A-1F081ED1AEA4/0/MAPManuaFull.pdf>

Washington State DOT's performance measures of asset management and task completion are defined on page 1-2 (page 4 of the PDF).

Maintenance service levels A-F are presented beginning on page 5-1 (page 45 of the PDF):

Service Level A (Best)

This is a very high service level in which the roadway and associated features are in excellent condition. All systems are operational and users experience no delays. ...

Service Level B

This is a high maintenance service level in which the roadway and associated features are in good condition. All systems are operational. Users may experience occasional delays. ...

Service Level C

This is a medium maintenance service level in which the roadway and associated features are in fair condition. Systems may occasionally be inoperable and not available to users. Short term delays may be experienced when repairs are being made, but would not be excessive. ...

Service Level D

This is a low maintenance service level in which the roadway and associated features are kept in generally poor condition. Systems failures occur regularly because it is impossible to react in a timely manner to all problems. Occasionally delays may be significant. ...

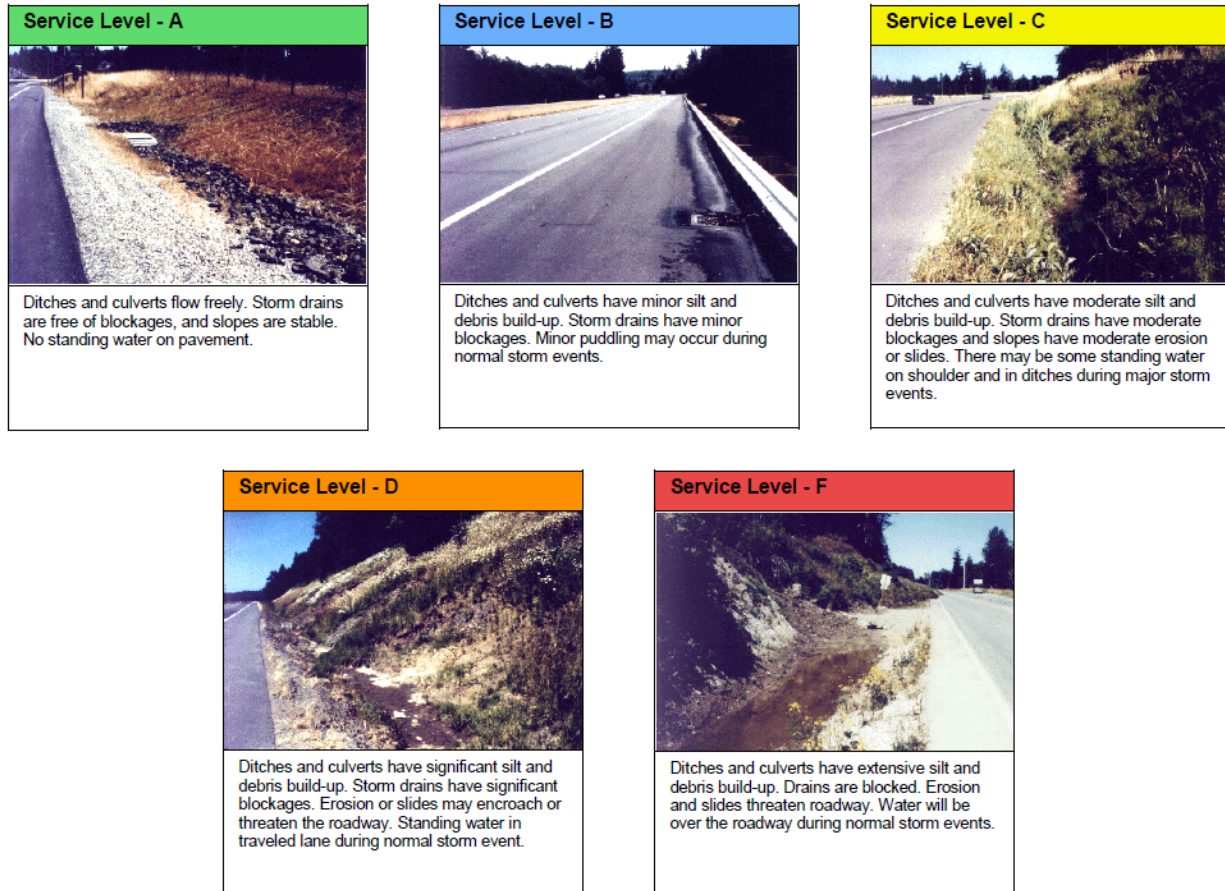
Service Level F (Worst)

This is a very low service level in which the roadway and associated features are kept in poor and failing condition. A backlog of systems failures would occur because it is impossible to react in a timely manner to all problems. Significant delays occur on a regular basis. ...

The chart on the following page gives a pictorial view of the relationship between the level of investment, level of delivery and service level outcome. ... Following the chart, pictures and narration provide examples of service levels for each group of activities.

Among the examples provided is one for drainage maintenance and slope repair (below and on page 5-5 of the report, page 49 of the PDF), which would be relevant to Caltrans' interest in the impact of extreme rain during the winter season. This example illustrates service levels A through F.

GROUP 2 – Drainage Maintenance and Slope Repair



Emergency response is among the full list of performance measures listed in the manual (page 4-18 of the report, page 42 of the PDF). However, the performance indicator, outcome measure and outcome thresholds A through F are not defined for emergency response.

Landslide Mitigation Action Plan, Washington State Department of Transportation, 2014.
<https://www.wsdot.wa.gov/NR/rdonlyres/8B3B653E-5C50-4E2B-977E-AE5AB36751B7/0/LandslideMitigationActionPlan.pdf>

Additional Washington State DOT guidance, specifically focused on rail and transit issues, is found in the state's Landslide Mitigation Action Plan. Sections relevant to this Preliminary Investigation are:

- Maintenance and Monitoring.
- Proactive Versus Reactive Mitigation Strategies.
- Strategies to Reduce Landslide-Related Interruptions and Impacts.
- Complicating Factors for Landslide Reduction.

Two of these sections— Maintenance and Monitoring, and Proactive Versus Reactive Mitigation Strategies—are provided below:

Maintenance and Monitoring

Maintenance and monitoring measures may involve proactive cleanout of available catchment areas, routine observation and assessment of slope conditions, landslide-warning (slide) fences, monitoring slope and weather instrumentation and preemptive closures. Generally, these measures are relatively low cost and can be highly effective in reducing public exposure to slide risk. With the exception of cleaning existing catchment areas, these measures do not reduce the likelihood of a landslide event or the potential of landslide debris reaching the tracks. Slide fences are used extensively through the corridor to warn of the potential for debris on the tracks (top of the wall in Figure 8). Another measure employed by BNSF [Railway Company] is the passenger rail moratorium imposed for 48 hours following a blocking event due to a landslide.

Selection of the most appropriate mitigation strategies is influenced by many factors that often have little relationship to the factors contributing to the landslide. Some of these include available funds, right-of-way/property ownership, required permits, access constraints, environmental effects and service interruption during construction.

Proactive Versus Reactive Mitigation Strategies

The mitigation strategies above can be implemented reactively or proactively. Reactive responses are instituted at the time of failure with little to no advanced planning. Expenditures are made when necessary, and are tailored to address actual conditions. No unnecessary expenditures are made on slopes that might not otherwise fail and impact the facility within a reasonable timeframe. However, reactive responses are often required at inconvenient times and locations, and are generally more costly to construct than when the same work is performed proactively at a more opportune time. Also, there are often more barriers to designing and constructing what is most effective and best suited for the site under emergent conditions. Further, direct and indirect costs/impacts—especially those indirect—are more difficult to manage by relying solely on reactive responses. Problems with a reactive management approach for unstable slope impacts to transportation facilities include high public expectations of the reliability, convenience and safety of the system (Lowell and Norrish, 2013).

Proactive responses, on the other hand, require considerable planning, especially when having to choose among hundreds of landslide-prone slopes. Some of the benefits of a proactive response generally include lower costs, better conditions to design and build under, and higher reliability. With the responsibility of managing many unstable slopes along transportation facilities, several public transportation departments (including WSDOT) instituted management systems for proactively identifying, prioritizing, programming, funding and ultimately mitigating these hazards. It is important to stress that implementation of a proactive management system to address large numbers of landslide-prone slopes does not relieve the need for reactive responses or eliminate the potential of further closures. When managing numerous unstable slopes, it is not possible to predict which slope will fail first or when it will fail. In addition, program implementation requires long-term commitments, since it can take many years to make necessary improvements to significantly reduce landslide-related closures on such a landslide-prone corridor. As an example, in 1974 a rock slope maintenance program was implemented along a rail corridor in British Columbia involving 750 rock fall sites. In the opinion of the geotechnical specialist involved since program inception, it took nearly three decades for the program benefits to become clearly recognizable (WSDOT, 2006).

Vulnerability Screening

Tennessee

“Using Climate and Weather Data to Support Regional Vulnerability Screening Assessments of Transportation Infrastructure,” Leah A. Dundon, Katherine S. Nelson, Janey Camp, Mark Abkowitz and Alan Jones, *Risks*, Vol. 4, No. 28, pages 1-24, 2016.
www.mdpi.com/2227-9091/4/3/28/pdf

From the abstract:

This paper describes a methodology for using extreme weather and climate data to identify climate-related risks and to quantify the potential impact of extreme weather events on certain types of transportation infrastructure as part of a vulnerability screening assessment. This screening assessment can be especially useful when a large number of assets or large geographical areas are being studied, with the results enabling planners and asset managers to undertake a more detailed assessment of vulnerability on a more targeted number of assets or locations. The methodology combines climate, weather and impact data to identify vulnerabilities to a range of weather and climate related risks over a multi-decadal planning period. The paper applies the methodology to perform an extreme weather and climate change vulnerability screening assessment on transportation infrastructure assets for the State of Tennessee. This paper represents the results of one of the first efforts at spatial vulnerability assessments of transportation infrastructure and provides important insights for any organization considering the impact of climate and weather events on transportation or other critical infrastructure systems.

We corresponded with report co-author Leah Dundon from Vanderbilt University for more information about this effort. Dundon wrote:

I would say that the tools are being considered, but we are still in a discovery phase. We took the work from the vulnerability study and just recently completed a set of briefing books more tailored to each of the four TDOT regions in the state. Our next work is looking at drilling down in a bit more detail to specific assets and looking at potential adaptation measures.

At Dundon’s suggestion, we subsequently corresponded with and spoke with report co-author Alan Jones of Tennessee DOT. Jones wrote:

I have attached the four briefing books. Our intent was to provide the information to TDOT’s four regions in a more user-friendly format than our statewide extreme weather vulnerability assessment. TDOT’s regions and districts are where a lot of our fieldwork, including maintenance, is planned and managed.

The four books are similar in scope and layout. The briefing book for Tennessee Region 1 is provided as [Attachment A](#) as an example.

Related Resources:

Assessing the Vulnerability of Tennessee Transportation Assets to Extreme Weather, TDOT Region 1 Briefing Book, Mark Abkowitz, Janey Camp and Leah Dundon, Tennessee Department of Transportation, Federal Highway Administration, November 2017. See [Attachment A](#).

This briefing book illustrates the screening tool developed to assess extreme weather events in one of four regions in Tennessee.

Assessing the Vulnerability of Tennessee Transportation Assets to Extreme Weather, Final Report, Mark Abkowitz, Janey Camp and Leah Dundon, Tennessee Department of Transportation, Federal Highway Administration, February 2015.
https://environment.transportation.org/pdf/infrastructure_resilience/tdot_extreme_weather_vulnerability-final_report_complete_opt.pdf

This is the final report for the project described in the 2016 journal article. Researchers used the results of an online survey that received responses from 220 stakeholders considered knowledgeable about various transportation assets. The survey asked respondents to assess “the potential impacts (asset damage and system disruption) to each asset type when exposed to specific extreme weather scenarios.” *From the introduction:*

A vulnerability score (annual frequency of a given weather event multiplied by the impact score for an exposed asset type) was derived for each unique weather/asset combination and mapped for every county in Tennessee. The inventory of critical assets was superimposed on the vulnerability maps in order to determine the locations where certain asset types appear to have the greatest potential vulnerability.

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CTC & Associates contacted the individuals below to gather information for this investigation.

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