Resiliency Metrics for Transportation Planning

Requested by
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Executive Summary

Background

Resiliency, as defined by the National Academies, is "the ability to prepare and plan for, absorb, recover from, and more successfully adapt to adverse events." One of Caltrans' strategic objectives is to attain a more resilient and integrated transportation system, and this Preliminary Investigation sought information to support that goal.

Caltrans is particularly interested in information to support development of a resiliency score or other metric that the department can use to prioritize projects based on expected resiliency and adaptability to change. Caltrans has a stated initial interest in three types of resiliency: climate, system and financial. The agency is also interested in learning what types of vulnerabilities are addressed in resiliency efforts across the United States and internationally.

Summary of Findings

Consultation with Practitioners and Experts

To better understand developments in resiliency measurement, we spoke and corresponded with practitioners and experts in and beyond California. These conversations helped provide perspective on completed and ongoing research as well as resiliency planning efforts at specific agencies. Among our interviews, we spoke with a New Zealand researcher, a TRB representative, three Caltrans staff and a representative of the Sacramento Area Council of Governments.

Research and Policy

Work is being done at the international, national, regional, state and city levels in the area of resiliency planning and strategy. Below we highlight the resources included in this report that specifically seek to quantify or measure resiliency and are likely to be of greatest interest to Caltrans.

International (see page 12)

- A 2014 United Kingdom report focuses on the resiliency of the transportation network to extreme weather events.
- The New Zealand Transport Agency commissioned the development of a measure of resilience of transportation infrastructure. This 2014 study provides both quantitative and qualitative approaches to measuring resiliency. Table 5.4 (reproduced on page 13 of this Preliminary Investigation) compares the qualitative and quantitative approaches in the areas of flexibility, data requirements, computational requirements, results, ease of implementation, use in targeting resiliency improvement, use in wider assessment and engagement, and use in assessing physical network asset resilience.
- The United Nations Office for Disaster Risk Reduction has developed a Making Cities Resilient campaign.
- A 2013 World Bank report on integrating climate and disaster risk into development gives several international examples of risk data analysis and mapping.

National (see page 15)

- The Volpe Center's risk-based framework for resiliency outlines performance criteria for resiliency: efficiency, sustainability and survivability.
- FHWA has led an ongoing program of climate change resilience pilots.
- The Federal Emergency Management Agency (FEMA) is developing disaster resiliency indicators. The agency is also employing a crowdsourcing tool to canvass for ideas on developing resiliency.
- A recent issue of TRB's *Transportation Research Record* includes more than a dozen papers on resiliency and climate change. This Preliminary Investigation cites several resiliency projects—five of which are in progress—across the range of TRB's cooperative research programs (freight, transit, highways and airports):
    - The 2014 NCHRP report *Climate Change, Extreme Weather Events, and the Highway System* presents a benefit–cost methodology formulated to provide results for a "point of decision" analysis—"in other words, an exercise to determine whether an adaptation strategy or project is worth the additional expense. However, with minor modifications the approach could be used to guide long-range planning decisions."
    - The National Academies report *Disaster Resilience: A National Imperative* addresses in depth:
        - The need for metrics and indicators.
        - Measures of U.S. national resilience.
        - International efforts to measure resilience.

      Noteworthy measurement scales in that report are:
        - The Coastal Resilience Index, which adapts FEMA principles "to the specific needs of coastal hazards and operationalizes them into an ordinal metric" (low, medium and high).
        - The San Francisco Planning and Urban Research Association metrics for measuring the resilience of the Bay Area with respect to earthquakes.

Regional, State and City (see page 25)

- The Building Resilient Regions network at University of California–Berkeley discusses the Resilience Capacity Index, "a single statistic summarizing a region's score on 12 equally weighted indicators—four indicators in each of three dimensions encompassing Regional Economic, Socio-Demographic, and Community Connectivity attributes."
- Arup International Development created a City Resilience Framework that is used by the 100 Resilient Cities program. The framework establishes "four aspects of resilience (health and well-being, economy and society, leadership and strategy, systems and services)" using "twelve indicators by which resilience can be understood."
- Regional activities related to resiliency have been conducted by Transportation for America (addressing resiliency in metropolitan planning organizations) and by the Institute for Sustainable Communities (documenting promising practices in adaptation and resiliency).

- The Sacramento Area Council of Governments (SACOG) climate adaptation plan "includes a base-level analysis of climate impacts to the region's transportation infrastructure, an adaptation policy framework, and [an outline of the] steps necessary to begin implementing the plan." Vulnerabilities include primary effects of climate (extreme temperatures, increased precipitation) and secondary effects (landslides).

- A number of other states and cities are involved in resiliency planning and strategy. Particularly noteworthy are the following:
    - Colorado has developed a Transportation Economic Resilience rating system—a "metric index (rating system) tool to measure the impact of fuel price shocks [based on] an individual's income and compare it across different geographical scales within a region."
    - Mississippi research on measuring resiliency after an event presents a formula to "produce quantitative values for intermodal system measures of resilience with respect to mobility, accessibility, and reliability." These quantifications are post- rather than pre-event, but the methodology may be of interest to Caltrans.
    - New Jersey's resiliency impact assessment details a methodology for the inputs, evaluation and outputs for "redundancy and recovery" and provides an example in the area of network connectivity.
    - Oregon has developed a resilience plan for reducing risk and improving recovery from earthquakes and tsunamis. The plan outlines and describes three thresholds of resilience targets: minimal, functional and operational.

Gaps in Findings

- We did not find much evidence of resiliency efforts to address vulnerabilities beyond the categories that Caltrans is already addressing. Some examples described in this Preliminary Investigation are very specific, such as fuel price shocks (Colorado), which falls under the broader category of "financial stability" noted in Caltrans' strategic plan.
- Many resources with "resiliency" in their titles on closer inspection do not explicitly address resiliency. Resiliency is one aspect of a larger field within transportation planning that includes asset vulnerability, risk, resiliency, recovery, adaptation and sustainability. As discussed with the Caltrans customer team, this Preliminary Investigation sought to focus on resources that address vulnerability in content, not just in title or in broad mission.

Next Steps

- Interest is clearly high in this area, and based on comments from experts and the extent of research in progress, developments in the next few years should be expected. Follow-up contact with SACOG, the Transportation Research Board and AECOM (the firm that developed New Zealand's resiliency measures) in the short- or mid-term may yield new findings.
- The FEMA study in progress is very promising. While it is uncertain what usable input the crowdsourcing effort will yield, that agency's interest in resiliency indexes is very on point. Steps to monitor FEMA's work would be useful for Caltrans.

- At the state and even national level, much work in resiliency is happening beyond transportation departments. Caltrans could consider how efforts at other agencies could be adapted to transportation planning. Resiliency planning work in related areas (such as by natural resource and environmental agencies) may be most easily adapted for DOT use, but even where the connection is less obvious, an examination of underlying methodologies might be fruitful.

Preface

Terminology

While conducting this Preliminary Investigation, we noted that beyond Caltrans, the terms "resiliency" and "resilience" appear to be used interchangeably and with identical meaning.

In the narrative throughout this Preliminary Investigation we use Caltrans' preferred term, "resiliency," which appears in the state's Strategic Management Plan 2015-2020 (see below). However, in citations we quote either "resiliency" or "resilience" depending on the source material.

Beyond Caltrans, it appears that "resiliency" is used with somewhat less frequency than the alternative form, "resilience." During any further follow-up research, Caltrans should note that the keyword "resilience" may provide more search results than "resiliency."

Caltrans Strategic Plan

The Caltrans strategic plan referenced in this Preliminary Investigation is cited below.

Caltrans Strategic Management Plan, 2015-2020
http://www.dot.ca.gov/perf/library/pdf/Caltrans_Strategic_Mgmt_Plan_033015.pdf
The relevant strategic objective is noted on page 21:

> **Strategic Objective**
> Prosperity: Improve economic prosperity of the State and local communities through a resilient and integrated transportation system.
>
> **Performance Measure**
> Resiliency Score for:
>
> - Climate change resiliency (e.g., vulnerability to flood, sea level rise, etc.).
> - System resiliency (e.g., adaptability from emergencies, disasters, etc.).
> - Financial resiliency (e.g., ensure funding considering maintenance, operations, modernization, disasters, financial stability, etc.).
>
> Resiliency Score to be determined considering, e.g., asset management, emergency and risk management, climate change, sea level rise, vulnerability, adaptation, etc.
>
> **Target**
> By December 2017, develop and adopt Caltrans Resiliency Score.

Detailed Findings

Consultation with Practitioners and Experts

Below we summarize our conversations and correspondence with international, national and state experts about resiliency planning and quantification.

International

Contact: James Hughes, Principal Consultant, AECOM New Zealand, +64-9-967-9348, James.Hughes@aecom.com.

We corresponded with Hughes, lead author of the 2014 report *Measuring the Resilience of Transport Infrastructure* for the New Zealand Transport Agency (cited on pages 12-13 of this Preliminary Investigation).

This was among the most promising and on-target resources, and we inquired whether any city, regional or national agency—in New Zealand or elsewhere—had adopted the resiliency measures (or some other scoring method) outlined in the report. Hughes responded:

> In terms of direct adoption of the resiliency measures by utilities or regions here—no, there hasn't been any instances as yet, however—the research is about to be piloted by Auckland University—on a particular section of highway in NZ. The piloting is being undertaken in conjunction with our Auckland University and the Transport Agency (NZTA), with advisory involvement from myself.
>
> LA Metro used the research report as a basis to develop their own approach to resilience. I am unsure where this has got to, but I had some involvement in the development stages.
>
> NZ Treasury has a strong interest in the framework—and has been looking for opportunities to develop it further as well.
>
> "Resilience" is a big topic here at the moment…. Lots of questions, and not so many answers!

National

Contact: Lauren Alexander Augustine, Director of Program on Risk, Resilience and Extreme Events, National Academies of Sciences, Engineering and Medicine, 202-334-2243, laugustine@nas.edu.

We corresponded with Augustine, the staff contact for the National Academies' in-progress project "Increasing National Resilience to Hazards and Disasters," cited on page 23 of this Preliminary Investigation.

Augustine wrote:

> Thank you so much for reaching out to us about integrating resilience into transportation planning. As it turns out, we have recently had a number of discussions about this very topic, and your timing is good.
>
> You may be aware that the Transportation Research Board (TRB) is a big part of the National Academies complex. They are a sibling program unit to the resilience work, and the Resilient America Roundtable works collaboratively with TRB.
>
> I am copying on this message Stephan Parker. Stephan is a friend and he is at TRB, working on a number of risk and resilience issues as they pertain to transportation. Stephan is looking forward to connecting with you, as he thinks that some of his work has relevance to what you are asking. He may reach out to you about your request.
>
> As for the Resilient America work, we are just starting our work to bring closer the transportation planning and the resilience worlds. Stephan and TRB are a great help in this quest, and hopefully, you can join us as we start to till this fertile ground.

Contact: Stephan Parker, Senior Program Officer, TRB, 202-334-2554, saparker@nas.edu.

In our follow-up correspondence with Parker, he mentioned project leadership roles of two Caltrans staff, including Herby Lissade (who is jointly leading this Preliminary Investigation effort).

Parker wrote:

> Herby Lissade and Charlie Fielder are working closely with the National Cooperative Highway Research Program on many projects in the resilience realm.
>
> Charlie is chair of a project that just got under contract, NCHRP 20-101: "Guidelines to Incorporate the Costs and Benefits of Adaptation Measures in Preparation for Extreme Weather Events and Climate Change."
>
> Herby is broadly active and chairs or co-chairs several NCHRP projects:
>
> - 20-59(33), Pre-Event Planning to Support Transportation Infrastructure Recovery.
> - 20-59(36), Managing Catastrophic Transportation Emergencies: A Guide for Transportation Executives.
> - 20-59(51), A Guide to Emergency Response Planning at State Transportation Agencies, Second Edition.
> - 20-59(53), FloodCast: A Framework for Enhanced Flood Event Decision Making for Transportation Resilience.
>
> You might find it useful to scan through the "TRB and Resilience" slide deck update monthly at www.trb.org/securitypubs.

The most relevant resources listed above are cited in full in the "Research and Policy" section of this Preliminary Investigation.

California

Contact: Erik Alm, Senior Transportation Planner, Planning for Operations, Caltrans, 916-653-3874, ealm@dot.ca.gov.

At the customer team's suggestion we corresponded with Alm, who wrote:

> One of the items I brought up during our call is that the American Planning Association is focusing effort on resiliency planning, so I would recommend digging into their resources in addition to the other key research and policy areas identified in the Scope.
>
> In addition to the APA's Planning Advisory Service and its [peer-reviewed journal], the August/September issue of *Planning* is focused on resiliency. From there I learned that the City of Roseville is being held up as a model city for flood preparedness, earning a Class 1 Rating from FEMA's Community Rating System (CRS).

The *Planning* article is cited in the "Research and Policy" section of this Preliminary Investigation.

We searched the American Planning Association's website, http://planning.org, for resources on resiliency. This led to the New York City citation that appears on page 30 of this Preliminary Investigation.

Contact: Matt Carpenter, Director of Transportation Services, Sacramento Area Council of Governments (SACOG), 916-340-6276, mcarpenter@sacog.org.

The customer team suggested we also speak with Carpenter. He wrote:

> The best overview of recent efforts comes from the attached staff report and executive summary for a regional climate adaptation plan our Board adopted in August. The staff report has a link to the full report.
>
> I'm also attaching a Transportation for America report that was released last spring on innovative MPO practices. It highlights SACOG's broader climate change planning work, including resiliency and target setting for reducing greenhouse gas emissions.
>
> It seems like you are launching into an interesting project for Caltrans and we want to be of assistance in moving this work forward.

Both files provided by Carpenter are available online and are cited in detail in the "Research and Policy" section of this Preliminary Investigation.

Contact: Nick Compin, Advanced System Development Branch Chief, Division of Traffic Operations, Caltrans, 916-651-1247, nicholas.compin@dot.ca.gov.

We spoke to and corresponded with Nick Compin to discuss resiliency from the perspective of traffic operations as the customer team suggested. Compin said that Traffic Operations

responds to major "resiliency-related" events according to its traffic incident management plan and as directed by the California Highway Patrol incident commander. He detailed California's pathway to emergency response, which is somewhat complicated considering that it is difficult to pinpoint when and where disaster will strike. He also noted the importance of plans being fairly flexible.

Compin explained what happens in case of a major event (such as the recent mudslides on Interstate 5 and California State Route 58). Caltrans will either on its own or at the request of another agency—such as the Office of Emergency Services or others—establish an emergency operations center to direct and coordinate response.

Compin said that Traffic Operations staff are aware of their roles in staffing such a center. This primarily involves assistance from the Traffic Management Centers though use of changeable message signs, highway advisory radio, and traveler information systems (QuickMap, Caltrans Highway Information Network) to evacuate a major urban area. Traffic Operations and Maintenance staff mobilize to assist in directing traffic out of the area using available routes. Support can also include use of existing and available contra-flow plans or evacuation plans for places like the San Francisco Bay Area.

Compin said that control of making the initial request is either with other agencies, such as the Office of Emergency Services, or other divisions within Caltrans, such as the Division of Maintenance. Traffic Operations does not direct responses once an incident or major event occurs, but it does work with, for example, the California Highway Patrol (CHP) incident commander to respond to an incident on the highway or with CHP and Maintenance to coordinate responses to major weather events and other planned events.

Beyond emergency planning and response, Compin also discussed a new area for Traffic Operations in determining performance impacts for traffic incident management (TIM). Traffic Operations is approaching TIM from a different angle than emergency response (fire/rescue and highway patrol), looking at measuring and improving system performance rather than resolving individual incidents. Improving performance and more quickly restoring traffic flow can reduce secondary accidents. "Forty to 50 percent of congestion is incident-related, and working in this area should give a good cost-benefit," Compin said. Improving traffic movement is a big selling point for integrated corridor management.

Contact: Eric Fredericks, Senior Transportation Planner, Caltrans HQ Division of Transportation Planning, 916-653-0426, eric.fredericks@dot.ca.gov.

We spoke with Fredericks as the customer team suggested. Fredericks described water issues in California's Central Valley near the city of Woodland, providing examples of some of the vulnerabilities faced in California that call for resiliency planning.

- A settling basin for Cache Creek to collect sediment and mercury and prevent passage into the Yolo Bypass has been rising over time with new sediment. This mercury could pose a health risk and a threat to endangered species if released into the environment due to flooding.
- There are concerns about possible Cache Creek levee failures. There is an estimated 20 percent chance each year of a levee failure or overtopping, and some failure modes could lead to flooding of structures as well as a stretch of Interstate 5. The immediate vulnerability is in compromising evacuation routes. In the longer term, this could lead to

the destruction of a section of I-5, leading to months of disruptions of the main artery between Canada and Mexico.

Preventive solutions—such as those that would involve spilling excess water onto farmland—are all costly. Emergency funding for repair and rebuilding of a flooded section of Interstate 5 would likely be forthcoming, but only after the system failure.

Fredericks said he is available to discuss these vulnerability areas in greater detail or could direct those interested to hydraulic engineers with detailed working knowledge of these issues in Yolo County.

Research and Policy

International

United Kingdom

Transport Resilience Review: A Review of the Resilience of the Transport Network to Extreme Weather Events, Department for Transport, 2014.
https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/335115/transport-resilience-review-web.pdf
From the executive summary:

> We ... believe there are a considerable number of lessons that can be learned, to better anticipate the impact of extreme weather events, reduce the vulnerability of our transport networks to them and speed up the restoration of normal services. That is the purpose of this report. ...
>
> Resilience in the context of this review can be described as the ability of the transport network to withstand the impacts of extreme weather, to operate in the face of such weather and to recover promptly from its effects. As such, we take the view that resilience to extreme weather has three layers to it:
>
> - It is about increasing the physical resilience of transport systems to extreme weather, so when extreme weather is experienced, people and goods can continue to move.
> - It would be both very difficult and prohibitively expensive to ensure total physical resilience, so secondly it is equally about ensuring processes and procedures to restore services and routes to normal as quickly as possible after extreme weather events have abated.
> - Thirdly, as part of this, it is essential to ensure clear and effective communications to passengers and transport users so that the impact of disruption on people and businesses is minimized.

The report includes a section on "Planning for Resilience." Section 3.23 (see page 44) states:

> Resilience planning and adaptation planning are fast developing fields, and it is important that best practice and the experience of others is shared. Operators need to learn from each extreme weather event, but often only a subset of them will be impacted by any one event.

However, this report does not describe a specific metric or analytical process for resilience planning.

New Zealand

Measuring the Resilience of Transport Infrastructure, J. F. Hughes and K. Healy, AECOM New Zealand Ltd., New Zealand Transport Agency, 2014.
http://www.nzta.govt.nz/resources/research/reports/546/docs/546.pdf
We discussed this report with author James Hughes. The abstract states:

Internationally there is a growing call to improve the resilience of our critical infrastructure. This is in response to a realization that the services we take for granted may be robust in the face of predictable hazards/failures, but are in fact extremely fragile in the face of unanticipated shocks.

In the context of transport infrastructure, operators strive to ensure that transport assets and services function continually and safely in the face of a range of existing and emerging hazards. This has led to a specific focus on the concept of resilience and how this can be defined, measured and improved across the transport system.

The theory of resilience was researched and a measurement framework has been proposed that broadly covers both technical and organizational dimensions of resilience and breaks these down into specific principles and measures which can be utilized to qualitatively assess resilience.

The measurement of resilience was approached from a view that a risk management approach alone is not sufficient and needs to be complemented by an awareness that resilience requires both consideration of events that fall outside of the realms of predictability and, importantly, that failure is inevitable.

Chapter 5, “How Can We Measure Resilience?” (page 32) is particularly relevant. The report provides both quantitative and qualitative approaches to measuring resiliency, as detailed in the chapter and summarized in Table 5.4 (page 36):

Table 5.4 Summary of qualitative and quantitative measurement approaches

	Qualitative approach	Quantitative approach
Flexibility	Provides a flexible approach that can be adapted to a range of situations, scales and conditions.	Is typically applied only at a smaller geographical scale and at a more detailed level.
Data requirements	Can be applied with complete or incomplete data sets. Relies on subjective assessments in many cases.	Typically requires large, accurate data sets.
Computational requirements	None/minimal.	Requires significant computational effort.
Results	A relative, subjective assessment – often using a ranking scale	Typically delivers a discrete resilience index or measure by way of network modelling or fuzzy logic modelling.
Ease of implementation	Simple	Difficult
Use in targeting resilience improvements	Useful; however, is very much related to the design of the framework, how it is implemented, and subjectivity of the scores given.	Can be accurate for the network analysed.
Useful in wider organisational resilience assessments and engagement	Yes	No
Useful in assessing physical network asset resilience	Yes	Yes

On page 36, the authors state:

> Based on [Table 5.4], we suggest that a broadly qualitative approach would better suit the Transport Agency's requirements for a practical and flexible framework. We note that there may be some quantitative measures within the overall framework; however, generally speaking, we propose a qualitative assessment.
>
> The approach will be based around:
>
> - Dimensions of resilience – technical and organizational.
> - Principles of resilience – robustness, redundancy, safe-to-fail, readiness, continuous management, leadership and culture, networks.

The following summary of the report's main points (page 36) may also be instructive:

> Either an 'all-hazards' or 'hazard-specific' approach could be used for measuring resilience. The latter would be much more detailed and it may be appropriate in certain situations where specific hazards are well understood.
>
> Historically, both qualitative and quantitative approaches have been used for measuring resilience. Quantitative approaches tend to be less flexible, time consuming and appropriate for more narrow assessments of networks and systems. They are data intensive and can be difficult to implement.
>
> Qualitative assessments are, by nature, more subject to interpretation, but are flexible in terms of scale and context, and can provide wider process and organizational benefits due to the necessary involvement of operators and managers.
>
> There are also broadly qualitative frameworks which contain measures that are more quantitative in nature.

International Organizations

Making Cities Resilient, United Nations Office for Disaster Risk Reduction
http://www.unisdr.org/campaign/resilientcities/
This UN campaign presents a 10-point checklist of "Essentials for Making Cities Resilient" (http://www.unisdr.org/campaign/resilientcities/toolkit/essentials). The one most relevant to this Preliminary Investigation is "Essential 3: Maintain up-to-date data on hazards and vulnerabilities, prepare risk assessments and use these as the basis for urban development plans and decisions."

A 2012 publication on this website, *How to Make Cities More Resilient: A Handbook for Local Government Leaders* (http://www.unisdr.org/campaign/resilientcities/toolkit/handbook) includes a chapter on putting these essentials to work ("Chapter 3: How to Implement the Ten Essentials for Making Cities Resilient").

Building Resilience: Integrating Climate and Disaster Risk into Development, The World Bank, 2013.
http://www.worldbank.org/content/dam/Worldbank/document/SDN/Full_Report_Building_Resilience_Integrating_Climate_Disaster_Risk_Development.pdf
From the foreword and introduction:

> This report calls for the international development community to work across disciplines and sectors to build long-term resilience, reduce risk and avoid climbing future costs. ...
>
> Section V, titled "Towards Climate and Disaster Resilient Development" builds upon the processes and instruments developed by the climate resilience and the disaster risk management communities of practice to provide some early lessons learned in this increasingly merging field.
>
> Section VI on "The World Bank Experience" highlights case studies and emerging good practices in climate and disaster resilient development.

Section VI shows several international examples of risk data analysis and mapping.

International Institute for Infrastructure Resilience and Reconstruction
http://www.iiirr.ucalgary.ca/
From the website:

> The International Institute for Infrastructure Resilience and Reconstruction (IIIRR) is a multi-university international consortium which provides overall leadership in research, education, planning, design and implementation for mitigation of the impact of natural disasters and infrastructure renewal and reconstruction projects in tsunami affected or underdeveloped regions.

Among the recent annual conferences listed at http://www.iiirr.ucalgary.ca/conferences, the 2013 conference, "Risk-Informed Disaster Management: Planning for Response, Recovery and Resilience," held in Brisbane, Australia, is most on-topic for this Preliminary Investigation. The conference website is no longer online.

National

United States Federal Government

Infrastructure Resiliency: A Risk-Based Framework, Volpe: The National Transportation Systems Center, U.S. DOT, 2013.
http://www.volpe.dot.gov/sites/volpe.dot.gov/files/docs/Infrastructure%20Resiliency_A%20Risk-Based%20Framework.pdf
Notable risk factors cited in this paper are climate change, accelerated growth on the coasts, growth in the value of assets lost in catastrophic events, and risks of global connectivity. The paper describes a resilient infrastructure as:

- Robust and fault-tolerant.
- Adaptable, aware and resourceful.
- Having functional flexibility and layers of redundant safeguards.
- Having response and recovery capability for mitigation of event consequences.

The section "Resiliency Performance Criteria" (page 5) lists efficiency, sustainability and survivability as the three high-level performance criteria:

By approaching infrastructure asset management in accordance with a systematic process of engineering system resiliency, we are more likely to have a safe, efficient, survivable, and sustainable infrastructure system. The outcome of instituting a resiliency process is that the infrastructure systems that are engineered in accordance with these principles are likely to meet three high-level performance criteria: efficiency, sustainability, and survivability:

- **Efficiency**. This criterion requires that an infrastructure system perform its functions in order to meet its specified functional requirements (technical efficacy) at lowest cost (cost-effectiveness). Metrics for efficiency include the costs of building and maintaining a complex infrastructure system within the constraints of its technical performance, reliability, and service-continuity.
- **Sustainability**. This performance criterion evaluates the extent to which the system uses resources – natural, human, and manufactured – in a sustainable manner. Sustainability is defined as a resource-use pattern that "meets today's needs while protecting resources for future use." To be sustainable, critical infrastructures must be designed and operated within the context of their impacts on the surrounding ecosystems, now and in the future. The metrics for assessing an infrastructure's sustainability include the extent to which transportation construction and operating inputs and resources are used in accordance with the long-term economic and environmental standards developed for the system.
- **Survivability**. A third key performance criterion for resilient infrastructure is the ultimate test of safety, security, and survival of the people, infrastructure assets, and the ecosystem. In accordance with this criterion, an infrastructure meets the resiliency standards if it is capable of withstanding damages with minimal adverse impacts – lost lives, ecological impacts, structural damage – on the people, transportation operations, economy, and the environment.

Draft DOT Strategic Plan, FY 2014-2018
http://www.transportation.gov/policy-initiatives/draft-dot-strategic-plan-fy-2014-2018
This website lists a number of objectives grouped into different categories. One relevant objective appears under the topic "Environmental Sustainability: Advance environmentally sustainable policies and investments that reduce carbon and other harmful emissions from transportation sources." An excerpt:

> Objective: Promote infrastructure resilience and adaptation to extreme weather events and climate change through research, guidance, technical assistance, and direct federal investment.
>
> Discussion: "Climate change research predicts that storms will become stronger, so we need to consider climate change impacts and the incorporation of adaptation strategies into DOT planning, operations, policies, and programs so that taxpayer resources are invested wisely and that transportation infrastructure, services and operations remain effective under extreme climate conditions. We will encourage DOT funding recipients to perform climate change vulnerability assessments for their transportation infrastructure and integrate the results into planning their decision-making."

Section VII of the plan, "Environmental Sustainability" (http://www.transportation.gov/administrations/office-policy/environmental-sustainability-goal-sec-vii), describes "Strategies to Ensure Infrastructure Resilience" (page 69) but does not present resiliency metrics.

FHWA Climate Change Resilience Pilots
https://www.fhwa.dot.gov/environment/climate_change/adaptation/ongoing_and_current_research/vulnerability_assessment_pilots/
From the website:

> FHWA is partnering with State Departments of Transportation (DOTs), Metropolitan Planning Organizations (MPOs), and Federal Land Management Agencies (FLMAs) to pilot approaches to conduct climate change and extreme weather vulnerability assessments of transportation infrastructure and to analyze options for adapting and improving resiliency. This pilot program is being jointly sponsored by the FHWA Office of Environment, Planning and Realty, and the Office of Infrastructure.

A number of state summaries and progress reports appear on this site. Despite the name, they tend to focus on vulnerability and risk rather than resilience.

Disaster Resilience Indicators, Federal Emergency Management Agency (FEMA).
http://fema.ideascale.com/a/ideas/recent/campaigns/60387
This website is a crowdsourcing tool employed by FEMA to canvass for ideas on developing resiliency indicators. The website states:

> FEMA's new 2014-2018 Strategic Plan provides a road map for FEMA's emergency management mission delivery over the next 4 years. The Plan calls for a strategy to build a risk and threat exposure baseline model with indicators to measure community-level and national performance in hazard risk reduction (see Strategy 4.1.2). ...
>
> Strategy 4.1.2 is broken down into the following topical areas for public comment [emphasis added].
>
> - Organizations that have developed or are currently developing resilience indicators or resilience indexing methods and/or tools.
> - Literature or articles after 2012 (post-National Academy Report) that define, discuss or recommend approaches to measuring physical, social, economic and/or environmental resilience at community, regional or national scales.
> - Literature or articles after 2012 that define leading indicators of resilience that are generally applicable at the community level.
> - **Approaches to quantifying (indexing) indicators so that they can be measured and compared (scoring or indexing).**
> - **National performance metrics related to disaster resilience or related topics such as sustainability.**
> - Key hazard vulnerability and threat data sets that FEMA and partners can make more readily available for whole community use.
> - Technology supporting indicators and quantification or indexing approaches
> - Community resilience self-assessment approaches.
> - Communities' current level of awareness of – and use of – resilience indicators – to drive community decisions and investments.

> Please help us shape FEMA's resilience index project by providing your thoughts, ideas or suggestions for strategic goals and objectives related to each topic listed above that could improve the national approach to community disaster resiliency and climate change adaptation.

TRB and National Academies

Climate Change, Extreme Weather Events, and the Highway System, NCHRP Report 750, Strategic Issues Facing Transportation, Volume 2, 2014.
http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_rpt_750v2.pdf
From the foreword:

> This report presents guidance on adaptation strategies to likely impacts of climate change through 2050 in the planning, design, construction, operation, and maintenance of infrastructure assets in the United States (and through 2100 for sea-level rise).

This report ties together the concepts of adaptation and resiliency (page 11):

> Adaptation consists of actions to reduce the vulnerability of natural and human systems or to increase system resiliency in light of expected climate change or extreme weather events.

Most directly applicable to this Preliminary Investigation is Appendix B, "Benefit–Cost Methodology for Climate Adaptation Strategies" (page 103). An excerpt:

> A benefit–cost (B/C) methodology was formulated to provide results for a "point of decision" analysis—in other words, an exercise to determine whether an adaptation strategy or project is worth the additional expense. However, with minor modifications the approach could be used to guide long-range planning decisions. The accompanying CD to this document includes spreadsheets that can be used to conduct simple B/C analyses based on the methodology described in this appendix.

This methodology is a quantitative approach to adaptation (and by extension, resiliency) planning. Calculations include the following steps:

> Step 1. Identify the Highest Risk Infrastructure.
>
> Step 2. Estimate Future Operations and Maintenance Costs.
>
> Step 3. Estimate the Agency Costs of Asset Failure.
>
> Step 4. Estimate the User Costs of Asset Failure.
>
> Step 5. Estimate Likelihood of Asset Failure.
>
> Step 6. Calculate Agency Benefits of the Strategy.
>
> Step 7. Calculate User Benefits of the Strategy.
>
> Step 8. Evaluate Results.

Disaster Resilience: A National Imperative, The National Academies, 2012.
http://www.nap.edu/catalog/13457/disaster-resilience-a-national-imperative
As noted in the summary, "this report confronts the topic of how to increase the nation's resilience to disasters through a vision of the characteristics of a resilient nation in the year 2030."

Three sections of Chapter 4, "Measuring Progress Toward Resilience" (page 91) are most relevant to this Preliminary Investigation:

- The Need for Metrics and Indicators.
- Measures of U.S. National Resilience.
- International Efforts to Measure Resilience.

Two items discussed that may be of particular interest are:

- The Coastal Resilience Index (page 95), which adapts FEMA principles "to the specific needs of coastal hazards and operationalizes them into an ordinal metric" (Low, Medium, and High). An excerpt:

  > Low, Medium, and High categories [are] based on specified ranges—for example, to gain a High rating on critical infrastructure the community must have agreed that 100 percent of its elements would be functioning after a disaster. No weights are applied to each element; rather, the community is asked simply to count. The result is a total of seven metrics (two from Step 1 and one from each of the subsequent steps). The community is advised to treat these as separate indicators and not to attempt to combine them into a single metric.

- The San Francisco Planning and Urban Research Association (SPUR) metrics for measuring the resilience of the Bay Area with respect to earthquakes. As noted on page 100:

  > The process begins with the definition of an "expected earthquake," defined as one "that can reasonably be expected to occur once during the useful life of a structure or system," and in operation is one with a 10 percent probability of occurrence in a 50-year period. In the SPUR methodology, specific recovery objectives are defined in distinct time frames (Table 4.1): hours (3 to 72), days (30 to 60), and months (4 to 36). These target states of recovery and their time frames include those for hospitals, police and fire, the emergency operations center, transportation systems and utilities, airports, and neighborhood retail businesses, offices, and workplaces. Five categories of performance are defined for buildings ranging from A (safe and operational) to E (unsafe).

Systems Resilience and Climate Change, *Transportation Research Record: Journal of the Transportation Research Board,* Volume 2532, 2015.
http://trrjournalonline.trb.org/toc/trr/2532
This edition of TRB's *Transportation Research Record* includes 18 papers that examine resilience and climate change issues related to transportation:

- Roadmaps for Adaptation Measures of Transportation to Climate Change.
- Resilience Versus Risk: Assessing Cost of Climate Change Adaptation to California's Transportation System and the City of Sacramento, California.
- Barriers to Implementation of Climate Adaptation Frameworks by State Departments of Transportation.
- Resilience of Coastal Transportation Networks Faced with Extreme Climatic Events

- Analysis of Transportation Network Vulnerability Under Flooding Disasters
- Vulnerability Evaluation of Logistics Transportation Networks Under Seismic Disasters
- Integrating Stochastic Failure of Road Network and Road Recovery Strategy into Planning of Goods Distribution After a Large-Scale Earthquake
- Multimodal Transit Connectivity for Flexibility in Extreme Events
- Risk and Resilience Analysis for Emergency Projects
- Unmanned Aircraft Systems Used for Disaster Management
- Multimodal Evacuation Simulation and Scenario Analysis in Dense Urban Area: Philadelphia, Pennsylvania, Case Study
- Spatiotemporal Population Distribution Method for Emergency Evacuation: Case Study of New Orleans, Louisiana
- Joint Evacuation and Emergency Traffic Management Model with Consideration of Emergency Response Needs
- Supporting Mobility-Impaired Populations in Emergency Evacuations
- Agent-Based Evacuation Model Considering Field Effects and Government Advice
- Selecting Four-Leg Intersections for Crossing Elimination in Evacuations
- Using Dynamic Flashing Yellow for Traffic Signal Control Under Emergency Evacuation
- Hurricane Evacuation Route Choice of Major Bridges in Miami Beach, Florida

Resilience: Key Products and Projects, TRB, October 2015.
http://www.trb.org/SecurityEmergencies/Blurbs/166648.aspx
Updated monthly, this presentation is a "slideshow summary of the Transportation Research Board's pre- and post-September 11, 2001, transportation security and resilience activities." TRB's Stephan Parker recommended this slideshow as one of the resources available at the TRB security publications page (www.trb.org/securitypubs).

Below we highlight seven TRB projects from the slideshow that are among the most relevant to this Preliminary Investigation. These cross the main areas of TRB inquiry (freight, transit, highways and airports). Five of these research efforts are research in progress.

> **Making U.S. Ports Resilient as Part of Extended Intermodal Supply Chains**, National Cooperative Freight Research Program, Report 30, 2014.
> http://onlinepubs.trb.org/onlinepubs/ncfrp/ncfrp_rpt_030.pdf
> From the foreword:
>
> > How resilient a port is depends on many different factors. From a purely physical processing standpoint, resilience means ensuring that freight gets into, is suitably processed by, and gets out of the port as expeditiously as possible. Given the considerable expense of providing redundant cargo handling capacity, a key to effective disruption response and subsequent recovery is to identify the primary steps in the cargo moving, manifesting, and storage processes involved; who is in charge of each processing step; who and which agencies need to be kept informed of progress; and who will have a decision-making role in changing operating rules and procedures when a disruption occurs.

> Under NCFRP Project 37, the Georgia Institute of Technology was asked to (1) review the literature on past disruption events, with an emphasis on specific actions that helped to limit the extent or duration of a disruption; (2) conduct expert interviews (with seaport operators, truck, rail, and ocean vessel carriers) to obtain their views on current levels of port resiliency, as well as on the most effective means of increasing resiliency and speeding recovery should a disruption occur; (3) conduct two in-depth case studies of recent port disruptions, Superstorm Sandy's impacts on the major East Coast ports and the extended lock closures along the Columbia River System in the Pacific Northwest; and (4) develop high-level guidelines suitable for public-sector decisionmakers who might become involved in a disruption recovery event.

A Pre-Event Recovery Planning Guide for Transportation, NCHRP Report 753, 2013.
http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_rpt_753.pdf
From the overview:

> [This report] is designed to help transportation owners and operators in their efforts to plan for recovery prior to the occurrence of an event that impacts transportation systems. The guide includes tools and resources to assist in both pre-planning for recovery and implementing recovery after an event. *NCHRP Report 753* is intended to provide a single resource for understanding the principles and processes to be used for pre-event recovery planning for transportation infrastructure.

Improving the Resiliency of Transit Systems Threatened by Natural Disasters, Transit Cooperative Research Program, Project A-41, in progress (completion expected February 2017).
http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=3744
Project objective statement:

> The objectives of this research are to develop (1) a handbook with an associated suite of digital presentation materials to address planning principles, guidelines (including metrics), strategies, tools, and techniques to enable public transit systems to become more resilient to natural disasters and climatic events; and (2) a draft recommended practice for public transit resilience to natural disasters and climatic events suitable as input to the APTA Standards Program. The handbook and its associated suite of digital presentation materials should be appropriately designed for use by public transit agency executive staff to plan, budget, and institutionalize effective practices to improve resilience, addressing (a) capital project planning and asset management (including financial planning and risk assessment for natural disasters and climatic events), (b) operations and maintenance, and (c) administration. They should provide sufficient detail to allow users to adapt them to their individual entities.

FloodCast: A Framework for Enhanced Flood Event Decision Making for Transportation Resilience, NCHRP Project 20-59(53), in progress (completion expected March 2016).
http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=3725

Project objective statement:

> The objectives of this research are to develop a strategic framework and a prototype tool for enhanced flood event decision making. The framework and tool should help state DOTs plan, manage risks, mitigate hazards, and respond to flood and flash flood events. The framework and tool should address not only immediate flood impacts, but also cascading, escalating impacts. Given the large amount and diversity of applicable data and tools, the framework design should be flexible and scalable to accommodate the available data sets and allow users to easily share both data and products with other users, thereby fostering collaboration across government organizations and the private sector.

Guidelines to Incorporate the Costs and Benefits of Adaptation Measures in Preparation for Extreme Weather Events and Climate Change, NCHRP Project 20-101, in progress (completion expected April 2017).
http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=3881
Project objective statement:

> The objectives of this research are to develop (a) a stand-alone document providing guidance for practitioners on methods and tools, including illustrative case studies where applicable, to: (i) efficiently mine, manage, and document existing data sources; (ii) acquire and use data from new and innovative sources; and (iii) apply, and communicate the results from, a flexible and scalable framework for analyzing the costs and benefits of adaptation measures in preparation for extreme weather events and climate change conducted by various transportation organizations; (b) a final report that documents the entire research effort and includes the research team's recommendation of research needs and priorities for additional related research; and (c) an updated PowerPoint presentation describing the research and results suitable (upon revision) for posting on the TRB website.

Applying and Adapting Climate Models to Hydraulic Design Procedures, NCHRP Project 15-61, in progress (project statement in development).
http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=4046
Project objective statement:

> The objectives of this research are to: (1) identify the needed levels of precision, accuracy, and confidence for climate models to be compatible with that of the data used in current hydrologic/hydraulic analysis and design techniques, identify downscaling strategies to move climate models closer towards these levels of precision, accuracy, and confidence, and develop science-based strategies and methodologies to advance engineering in extending climate predictions when the limits of downscaling of climate models are reached; (2) identify and quantify resiliency in existing hydraulic design practices due to current safety factors and conservative assumptions/techniques; and (3) identify cost-effective adaptation solutions that extend existing infrastructure to continue to function to the end of its service life despite not having been designed for climate change. An outcome of this research will be a guidance document with a list of available and achievable hydraulic resiliency in design for retrofits.

Integrating Climate Resiliency into Airport Management Systems, Airport Cooperative Research Program, Project 2-74, in progress (project statement in development).
http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=4020
Project objective statement:

> The objective of this research is to develop a handbook incorporating climate adaptation into airport asset, risk, and emergency management systems. Airports need a streamlined method to address climate vulnerability and planning as a part of risk and asset management and a way to align emergency planning with major climate related events. A quantification of risk factors, including airport and regional economic impact, can help inform asset management plans, emergency plans, and capital plans. Research is needed to help airports understand how climate risks add uncertainty to maintenance and capital budgets, and how this exposure can be mitigated and addressed through changes to airport asset management and capital planning.

Increasing National Resilience to Hazards and Disasters, Committee on Science, Engineering and Public Policy, the National Academies of Sciences, Engineering and Medicine, in progress.
http://sites.nationalacademies.org/PGA/COSEPUP/nationalresilience/index.htm
From the website:

> An ad hoc committee will conduct a study and issue a consensus report that integrates information from the natural, physical, technical, economic and social sciences to identify ways in which to increase national resilience to hazards and disasters in the United States.
>
> The ad hoc committee will:
> - Define "national resilience" and frame the primary issues related to increasing national resilience to hazards and disasters in the United States.
> - Provide goals, baseline conditions, or performance metrics for resilience at the U.S. national level.
> - Describe the state of knowledge about resilience to hazards and disasters in the United States.
> - Outline additional information or data and gaps and obstacles to action that need to be addressed in order to increase resilience to hazards and disasters in the United States.
> - Present conclusions and recommendations about what approaches are needed to elevate national resilience to hazards and disasters in the United States.

We corresponded with National Academies staff contact Lauren Augustine Alexander about this effort (see the discussion in the "Consultation with Practitioners and Experts" section of this Preliminary Investigation).

AASHTO

AASHTO Resilient and Sustainable Transportation Systems Technical Excellence Center
http://climatechange.transportation.org
This center's focus is climate resiliency. The "Overview and Purpose" page states:

> AASHTO's Resilient and Sustainable Transportation Systems Technical Assistance Program is designed to assist state DOTs [in understanding] the potential effects of climate change and the range of strategies and options for climate change mitigation and adaptation. The Resilient and Sustainable Transportation Systems Steering Committee and the tasks being implemented by the Technical Assistance Program are helping achieve these goals.

Most recently, topics addressed during the 2013 Extreme Weather Events Symposium (http://climatechange.transportation.org/symposium/) included vulnerability areas, trends/projections, and costs. Breakout groups prepared needs statements about "what data/information/assistance state DOTs need in order to better prepare for and recover from each type of extreme weather: coastal storms, inland floods, winter storms, heat waves/wildfires/droughts."

Institute for Sustainable Communities

Promising Practices in Adaptation and Resilience: A Resource Guide for Local Leaders, Institute for Sustainable Communities, 2010.
http://sustainablecommunitiesleadershipacademy.org/resource_files/documents/Climate-Adaptation-Resource-Guide.pdf
From the Introduction and Overview:

> To better understand the state of climate adaptation practice in cities, and the challenges that cities are facing, ISC's Climate Leadership Academy (CLA) team consulted with several nationally-recognized organizations and nearly 50 practitioners from the 16 U.S. cities participating in the CLA workshop. These practitioners included sustainability directors, energy managers, urban and economic development planners, water resource and public works managers, and public health and safety officials.

The report states that "a science-based risk assessment represents a critical early step in developing an adaptation plan. Typically, risk assessments require access to localized climate projections and they involve a broad stakeholder process in order to evaluate the varied consequences (e.g. safety, health, economic) of predicted climate impacts."

The report addresses challenges that practitioners face in integrating adaptation into planning and operations and in performing economic evaluations of adaptation measures.

Regional, State and City

Resilient Regions

Building Resilient Regions (BRR) network, Institute of Governmental Studies, University of California–Berkeley
http://brr.berkeley.edu
Building Resilient Regions is a network that appears to have ended in 2013; its website remains available as a repository of resources. From the website:

> Metropolitan regions—the collections of cities, suburbs, and rural areas that house two-thirds of America's population—[are] increasingly where transformation takes shape. Leaders at the state, regional, and local levels must now more than ever understand and respond to the demographic, social, and economic changes underway.
>
> To help expand our vision from that of a local city only to metro regions, BRR brings together a group of experts, funded by the MacArthur Foundation, to examine how best to harness the power of metro regions to effect real change.

The key measuring tool used by this program is the **Resilience Capacity Index**, as described at http://brr.berkeley.edu/rci/:

> One way to assess a region's resilience is by its qualities to cope with future challenges, a concept we label resilience capacity. Developed by Kathryn A. Foster, member of the BRR research network and director of the University at Buffalo Regional Institute, the Resilience Capacity Index (RCI) is a single statistic summarizing a region's score on 12 equally weighted indicators—four indicators in each of three dimensions encompassing Regional Economic, Socio-Demographic, and Community Connectivity attributes. As a gauge of a region's foundation for responding effectively to a future stress, the RCI reveals regional strengths and weaknesses, and allows regional leaders to compare their region's capacity profile to that of other metropolitan areas. See Data and Rankings for index scores, ranks, and maps for the overall RCI and its underlying dimensions ("capacity types"). For details on index creation and indicators, see FAQs and Sources and Notes.

We reached out to Kathryn Foster, now president of University of Maine at Farmington, as well Rolf Pendall, the lead researcher for infrastructure, now with the Urban Institute. We were unable to reach either of them.

Resilient Cities

City Resilience Framework, Arup International Development
http://publications.arup.com/Publications/C/City_Resilience_Framework.aspx
From the website:

> The City Resilience Framework establishes:
>
> - An accessible, evidence-based definition of resilience.
> - Four aspects of resilience (health and well-being, economy and society, leadership and strategy, systems and services).
> - Twelve indicators by which resilience can be understood.

> Our research brings together evidence and knowledge from over 150 sources of literature, 14 city case studies and fieldwork in six cities. The fieldwork drew on the input of those in government, businesses and civil society groups in Semarang (Indonesia), New Orleans (USA), Concepción (Chile), Surat (India), Cali (Colombia) and Cape Town (South Africa). This process is documented in three research reports:
>
> - Volume 1: Desk Study.
> - Volume 2: Fieldwork Data Analysis.
> - Volume 3: Urban Measurement.

The measurement framework is detailed in the 2014 report **Volume 3: Urban Measurement Report** (http://publications.arup.com/~/media/Publications/Files/Publications/C/Volume_3_Urban_Measurement_Report.ashx).

This framework appears to be the core measurement tool for the **100 Resilient Cities** (100RC) program (http://www.100resilientcities.org). From the website:

> Cities in the 100RC network are provided with the resources necessary to develop a roadmap to resilience along four main pathways:
>
> - Financial and logistical guidance for establishing an innovative new position in city government, a Chief Resilience Officer, who will lead the city's resilience efforts.
> - Expert support for development of a robust resilience strategy.
> - Access to solutions, service providers, and partners from the private, public and NGO sectors who can help them develop and implement their resilience strategies.
> - Membership of a global network of member cities who can learn from and help each other.

The Innovative MPO: Smart Planning, Strong Communities, Transportation for America, 2014.
http://www.t4america.org/wp-content/uploads/2014/12/The-Innovative-MPO.pdf
SACOG's Matt Carpenter discussed this item in our email correspondence. This guidebook is not focused on resiliency but provides "recommended actions in planning, programming, technical analysis and community partnership" for a range of focus areas. A specific reference to New Jersey is cited below.

Promising Practices in Adaptation and Resilience: A Resource Guide for Local Leaders, Institute for Sustainable Communities, 2010.
http://sustainablecommunitiesleadershipacademy.org/resource_files/documents/Climate-Adaptation-Resource-Guide.pdf
This publication presents several case studies, including "Models for Adaptation Planning" (Chicago, Miami, New York City and Toronto) and "Bolstering Resilience by Integrating Adaptation into Local Planning and Operations" (Seattle, Tucson and New Orleans). These examples may be informative to Caltrans but did not present methodologies directly applicable to this Preliminary Investigation.

California

"Water Warrior," Matt Weiser, *Planning*, August/September 2015.
https://www.planning.org/planning/open/2015/waterwarrior.htm
This citation, suggested by Caltrans' Erik Alm, is part of an issue of *Planning* (a publication of the American Planning Association) dedicated to resilience. The article describes efforts in Roseville, California, to improve resiliency to flooding risks. Noteworthy planning efforts that involved mapping are described in the article:

> Another key early action was that Roseville paid a consultant to prepare its own detailed maps of the floodplain to identify the high-risk areas. Many communities rely on FEMA mapping for this purpose, but FEMA maps may not offer enough detail and they are only updated periodically. Roseville didn't map merely the 100-year floodplain regulated by FEMA, but the estimated 500-year floodplain, which encompasses a much larger footprint. ...
>
> The extra mapping cost about $1 million, a significant bill for a medium-sized city in the late 1980s. But this became a major step toward achieving a high ranking under FEMA's Community Rating System [http://www.fema.gov/community-rating-system]. ...
>
> A basic feature of FEMA regulations is that development must be tightly regulated in the mapped floodplain. Roseville went beyond this rule by setting strict standards for new construction adjacent to the floodplain: Any new structures adjacent to the floodplain must be elevated two feet above the base flood elevation, a significant protective measure.

"Adopt Sacramento Region Transportation Climate Adaptation Plan," Issue, Recommendation and Action paper, Sacramento Area Council of Governments, August 2015.
http://www.sacog.org/calendar/2015/08/board/pdf/8-Adopt%20Sac%20Reg%20Trans%20Climate%20Adoptation%20Plan.pdf
SACOG's Matt Carpenter discussed this item in our email correspondence as well. In this paper, the Transportation Committee of the SACOG Board "unanimously recommends that the SACOG Board of Directors adopt the Sacramento Region Transportation Climate Adaptation Plan."

The document further outlines the scope of the plan:

> Working with Civic Spark members, SACOG authored a transportation climate adaptation plan. The plan includes a base-level analysis of climate impacts to the region's transportation infrastructure, an adaptation policy framework, and outlines steps necessary to begin implementing the plan.
>
> The potential climate change impacts considered in the plan include: extreme temperatures; increased precipitation, runoff and flooding; increased wildfires; and landslides. Although landslides are not a direct result of climate change, these events are expected to increase in frequency due to increased rainfall, runoff, and wildfire.

Colorado

Building a Framework for Transportation Resiliency and Evaluating the Resiliency Benefits of Light Rail Transit in Denver, Colorado, Mountain-Plains Consortium, March 2015.
http://www.mountain-plains.org/pubs/pdf/MPC15-279.pdf
From the abstract:

> This report presents a three-part research program examining transportation resiliency and the ability for a transportation system to maintain or return to a previous level of service after a disruptive, black swan type event.
>
> - The first part of the report examines a regional impact of a drastic fuel price increase.
> - The second part of the report focuses on city-scale resiliency by accounting for active transportation infrastructure in a detailed manner not feasible at the regional scale.
> - The third part of this report develops a Transportation Economic Resilience (TER) rating system to help researchers, planners, and policy makers better understand resiliency and vulnerability across different geographical areas.

Section 15 of the report (page 53) presents the parameters and formula underlying the Transportation Economic Resilience rating system, a "metric index (rating system) tool to measure the impact of fuel price shocks [based on] an individual's income and compare it across different geographical scales within a region. The implementation of this rating system is based on the additional transportation expenditures for home to work tours in the Denver Metropolitan area when the price of fuel doubles from a baseline condition."

The report states that "each geographical area receives a TER score. Higher TER scores (i.e., more resilient) represent lower values of additional percent of income spent on transportation. In contrast, a low TER score represents (i.e., less resilient) higher values of additional income spent on transportation."

A rating was calculated for each of 2,832 transportation analysis zones in the Denver area.

Maryland

Comprehensive Strategy for Reducing Maryland's Vulnerability to Climate Change, Phase II: Building Societal, Economic, and Ecological Resilience, Maryland Commission on Climate Change, Adaptation and Responses and Scientific and Technical Working Groups, 2011.
http://www.dnr.state.md.us/climatechange/climatechange_phase2_adaptation_strategy.pdf
State of Maryland climate change working groups laid out this strategy for addressing climate change vulnerability.

We reached out to Bruce Grey, Deputy Director of Maryland State Highway Administration's Office of Planning and Preliminary Engineering, to learn whether and how these recommendations—or other approaches to resiliency planning—might be implemented by Maryland's transportation agency. We were unable to connect with Grey.

Mississippi

Framework of Calculating the Measures of Resilience (MOR) for Intermodal Transportation Systems, Mississippi DOT, 2010.
http://mdot.ms.gov/documents/research/Reports/Interim%20and%20Final%20Reports/State%20Study%20220%20-%20Framework%20Of%20Calculating%20The%20Measures%20Of%20Resilience%20%28Mor%29%20For%20Intermodal%20Transportatio.pdf
This research presents a formula to "produce quantitative values for intermodal system MOR with respect to mobility, accessibility, and reliability." Formula 8 on page 19 shows that MOR is expressed as a percentage, with lower numbers corresponding to higher resiliency. The main inputs include reliability indicator values before and after a disaster and the time to restore capacity. Although the MOR is a post-event rather than pre-event indicator of resiliency, the data-based scoring methodology may be of use to Caltrans later as a scorecard or performance measure tool.

New Jersey

Performance Results: Assessing the Impacts of Implemented Transportation Projects: Guidebook for Performance Measurement, North Jersey Transportation Planning Authority, 2011.
http://www.camsys.com/pubs/NJTPA_PerformanceResults_FinalGuidebook.pdf
This report is cited in *The Innovative MPO* report above. On page 3.2-1, transportation resilience is listed as a performance measure in the goal area of "repair/maintenance/safety/security."

Transportation resiliency is detailed starting on page 3.2-45. On page 3.2-46, the detailed methodology appears for the inputs, evaluation and outputs for "redundancy and recovery." An example is given involving network connectivity:

> Using results of before-and-after network connectivity analysis, determine extent to which the project improves connectivity in the designated evacuation route system or in the subset of the system consisting of arterials, expressways, and Interstate Highways.

The output measure is the "change in system connectivity for the region's critical and/or most critical transportation assets." The example continues:

> For example, the beta index could change from 1.1 to 1.2 as a result of the project, indicating greater network connectivity and availability of alternative routes in case of a disruption or blockage.

This quantification shows an improvement of a factor (with "beta index" representing connectivity) as a measure of improved resiliency.

New York City

Climate Resilience, Department of City Planning, New York City.
http://www.nyc.gov/html/dcp/html/climate_resilience/index.shtml
From the website:

> As a coastal city, New York City has always faced risks from severe storms and coastal flooding. Hurricane Sandy was as a stark reminder that these climate-related risks exist today. As recognized in Vision 2020, the City's Comprehensive Waterfront Plan, climate change and sea level rise will increase these risks in the future, and it is crucial that the city improve its resilience – the ability of its neighborhoods, buildings and infrastructure to withstand and recover quickly from weather-related events.
>
> The Department of City Planning, in collaboration with other agencies, has undertaken a number of initiatives to build the city's resilience. These studies are focused on identifying and implementing land use and zoning changes as well as other actions needed to support the short-term recovery and long-term vitality of communities affected by Hurricane Sandy and other areas at risk of coastal flooding.

Efforts described in detail on this page are related in varying degrees to transportation infrastructure. These include:

- Resilient retail.
- Retrofitting buildings for flood risk.
- Resilient neighborhoods.

Also described here is New York City's **Flood Resilience Zoning Text Amendment** (summarized at http://www.nyc.gov/html/dcp/html/flood_resiliency/index.shtml; full text at http://www.nyc.gov/html/dcp/pdf/flood_resiliency/final_text.pdf).

The amendment was adopted in October 2013. From the website summary:

> [The amendment] modifies zoning to enable flood-resistant construction. It also introduces regulations to mitigate potential negative effects of flood-resistant construction on the streetscape and public realm. Issues addressed by the text amendment include:
>
> - Measuring building height with respect to the latest FEMA flood elevations.
> - Accommodating building access from grade.
> - Locating mechanical systems above flood levels.
> - Accommodating off-street parking above grade.
> - Accommodating flood zone restrictions on ground floor use.
> - Improving streetscape.

As described on page 12 of the full text, the "flood-resistant construction elevation" is based on New York City Building Code, elevation and flood maps.

Oregon

The Oregon Resilience Plan: Reducing Risk and Improving Recovery for the Next Cascadia Earthquake and Tsunami, Report to the 77th Legislative Assembly, Oregon Seismic Safety Policy Advisory Commission, 2013.
http://www.oregon.gov/OMD/OEM/osspac/docs/Oregon_Resilience_Plan_Final.pdf

Section 5, "Transportation," outlines resilience targets at three levels (page 106):

- **Minimal.** A minimum level of service is restored, primarily for the use of emergency responders, repair crews, and vehicles transporting food and other critical supplies.
- **Functional.** Although service is not yet restored to full capacity, it is sufficient to get the economy moving again—for example, some truck/freight traffic can be accommodated. There may be fewer lanes in use, some weight restrictions, and lower speed limits.
- **Operational.** Restoration is up to 90 percent of capacity: A full level of service has been restored and is sufficient to allow people to commute to school and to work.

Vermont

Planning for Flood Recovery and Long-Term Resilience in Vermont: Smart Growth Approaches for Disaster-Resilient Communities, United States Environmental Protection Agency, 2014.
http://www2.epa.gov/sites/production/files/2014-07/documents/vermont-sgia-final-report.pdf
This report provides detailed options to enhance flood resilience, specifically listing recommendations for transportation agencies. From pages 34 and 35:

Transportation agencies could:

- Incorporate hazard mitigation and flood resilience practices into project design and prioritization procedures. For example, transportation agencies could ensure their designs account for flood hazard vulnerability and the effects of designs on downstream flooding and fluvial erosion, and incorporate those parameters into documents such as the Vermont State Design Standards. The vulnerability criteria used to shape resilient design parameters could be developed in coordination with natural resource agencies and regional planning organizations.
- Review all infrastructure programs, including grant programs for communities, to look for opportunities to create local incentives and prioritize projects and maintenance strategies that reduce the risk of future flood damage in vulnerable areas. Infrastructure resilience features include redundant systems; robustness (inherent strength/resistance); resourcefulness (capacity to mobilize needed resources); and rapidity (speed with which disruptions can be overcome and services restored). An example of a local grant program that can provide incentives for change is Vermont's Flood Resilience Community Program.
- Conduct and maintain an inventory system of federal, state, and local culverts. Once the inventory is complete, the results could be incorporated into the state Hazard Mitigation Plan and linked to the state's strategy for reducing risks from inadequate culverts. Vermont's transportation agency has initiated a state-wide inventory of culverts on state roads. The next step will be to coordinate with towns and regional planning organizations to evaluate town-owned structures. New York and Ohio have manuals for inspecting and inventorying state culverts that could be models for other states.

- Coordinate with environmental and emergency management agencies and local officials to identify appropriate hazard mitigation measures, including those that might be eligible under FEMA's Public Assistance 406 Program and the Hazard Mitigation Grant Program. Measures might include increasing the size of inadequately sized culverts that were damaged during extreme events, limiting upstream development, creating catchment areas, and conducting flood engineering studies that could inform which hazard mitigation measures are appropriate.

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