

AMERICAN ASSOCIATION
OF STATE HIGHWAY AND
TRANSPORTATION OFFICIALS

AASHTO

Resiliency Case Studies: *State DOT Lessons Learned*

May 2018

For the AASHTO Resilient and
Sustainable Transportation Systems
Program (which falls under the Center
of Environmental Excellence)

Formerly
WSP | PARSONS BRINCKERHOFF

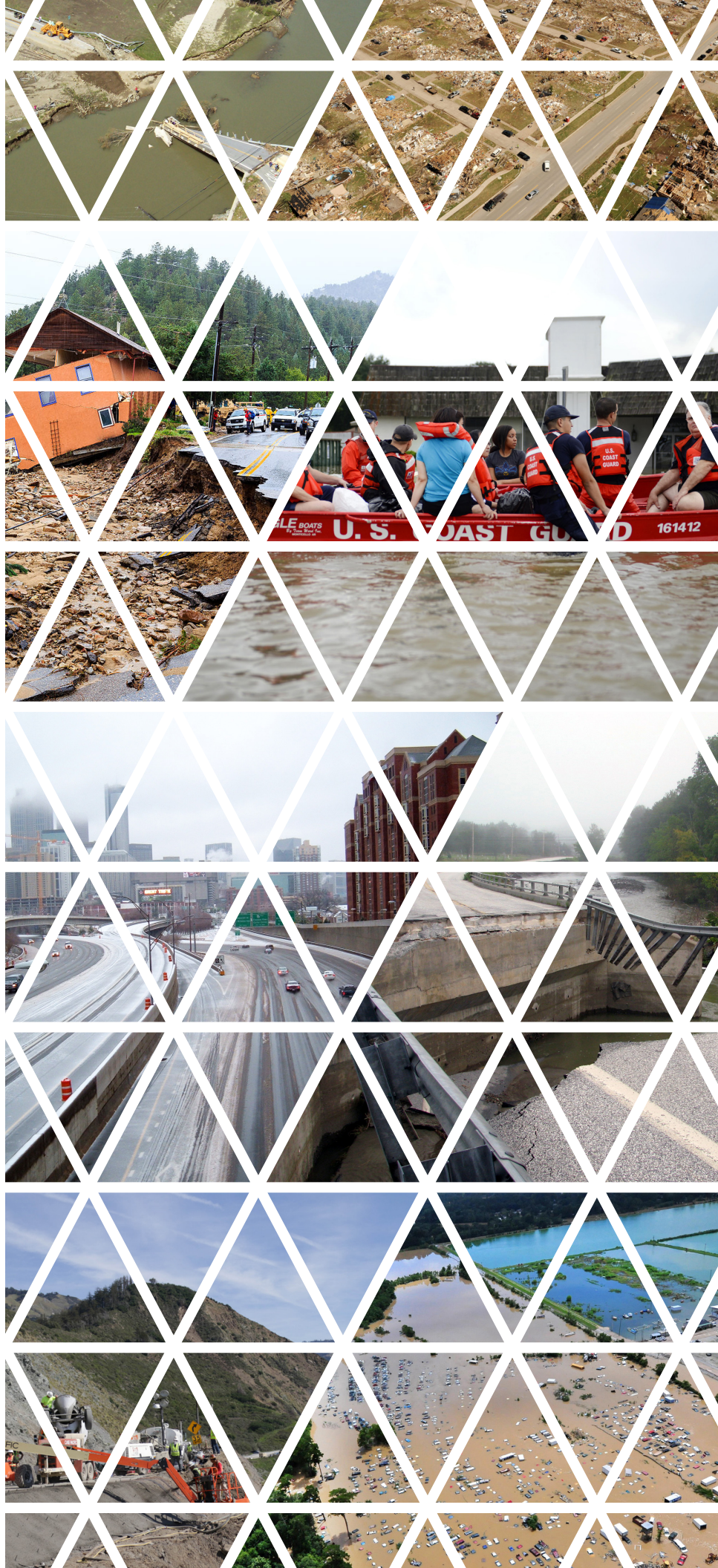


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ACRONYMS

AASHTO: American Association of State Highway and Transportation Officials

Caltrans: California Department of Transportation

CDOT: Colorado Department of Transportation

DOT: Department of Transportation

DOTD: Louisiana Department of Transportation and Development

FDOT: Florida Department of Transportation

FEMA: Federal Emergency Management Agency

GDOT: Georgia Department of Transportation

GIS: Geographic Information System

GPS: Global Positioning System

ICS: Incident Command System

MOA: Memorandum of Agreement

NCDOT: North Carolina Department of Transportation

NCHRP: National Cooperative Highway Research Program

RAMCAP: Risk Analysis and Management for Critical Asset Program

VTrans: Vermont Agency of Transportation

AASHTO's Resilient and Sustainable Transportation Systems (RSTS) Technical Services Program is a voluntary pooled-fund program designed to help AASHTO members understand the potential effects of extreme weather and sea level rise and the range of strategies and options to address these challenges. RSTS provides timely information, tools, technical assistance and other products including case studies, reports, and peer exchanges.

EXECUTIVE SUMMARY

This report presents the results of an examination of recent extreme weather events that have impacted state Departments of Transportation (DOTs) and describes how the state DOTs responded to the challenges associated with the events. The project study team, consisting of American Association of State Highway and Transportation Officials (AASHTO) and WSP staff, interviewed state DOT representatives to obtain the lessons learned from each event, namely, what went well and what went wrong? And, what actions were taken in response that would create a more resilient DOT because of these events?

Highways remain a critical element of community and social resiliency and represent one of the most important factors in effective emergency response and event recovery. As communities grow and highway use continues to increase, the importance of the system as a part of the economic and social resilience for regions grows as well, but is often misunderstood as a concern or understated in governmental or agency policies. Recent events have shown that impacts to highways often results in a multiplier effect on costs to communities from extreme events and therefore they represent a critical concern for every agency in the country. Determining how best to increase the resiliency of the highway system to major shocks from extreme weather events should be a focus of DOT and state leadership.

The individual state case study findings are compared with each other and cross-cutting (overlapping or similar), lessons learned are identified. **The goal of this report is to disseminate the DOT lessons learned from the most impactful extreme weather events of the last six years and identify how DOTs can become more resilient in anticipating and responding to future events, especially given the realities of a changing climate and the potential for changing storm patterns.**

Representatives from eight DOTs were interviewed about recent extreme weather events affecting their state. The case studies and the extreme weather events highlighted are:

- Vermont – Tropical Storm Irene, 2011
- Louisiana – 500 and 1,000-Year Flooding Events, 2016
- Colorado – Flooding and Rock Falls, 2013/2016
- North Carolina – Hurricane Matthew, 2016
- Georgia – Atlanta Ice Storm, 2014
- Oklahoma – Moore Tornado, 2013
- California – Coastal Landslides, 2017
- Florida – Hurricanes Hermine and Matthew, 2016

Interview findings from these eight state DOTs and the summarized cross-cutting lessons learned are categorized into three subject areas: **planning and design, policies and regulations, and emergency response**. These subject areas naturally developed after conducting the interviews. Interview findings revealed how a state DOT can improve or increase resiliency associated with these three subject areas. For example, findings from the Florida DOT showed that a successful emergency response was

strengthened through annual regional coordination and training exercises. This lesson learned for FDOT was categorized under “policies and regulations” as it reflects a policy decision by FDOT to prepare for an emergency event every year, and demonstrates a lesson that can be applied for other DOTs. After finding that other state DOTs had come to similar conclusions regarding their own emergency response, FDOT’s experience was summarized in the following lessons learned:

- Organize contracts and collaborate with other states, counties, DOTs, agencies, etc. who may aid in an emergency before it occurs
- Encourage regional coordination and emergency response preparations wherever possible

The full collection of cross-cutting lessons learned can be found in the Cross-Cutting Lessons section, but are summarized on the next page for a quick reference.

PLANNING AND DESIGN

- Improve intelligent transportation system (ITS) highway user messaging.
- Integrate considerations of changing climatic conditions and extreme weather into state DOT planning and design actions to reduce the potential impact of future events.
- Increase the resiliency of infrastructure projects by considering future impacts in all activities (maintenance, emergency response, operations).
- Update design manuals and strategic plans to reflect climate change, existing and future uncertainties in data and the need to increase resiliency.
- Monitor assets for damage or stress after an extreme event and consider changes in design and maintenance procedures in response, where appropriate.
- Identify vulnerable roadways and assets and understand the full range of hazards they may be exposed to before a disaster strikes.
- When important information does not exist for decision making (risk data, etc.), create it and reprioritize funding to do so.

POLICIES AND REGULATIONS

- Update agency policies and approaches when new information is available, especially related to lessons learned from recent events that could lead to change.
- Understand the risks to assets and rank the most vulnerable in terms of potential impacts to the system and its users to establish future project priorities.
- Achieve support from leadership and executive staff in adopting and implementing resiliency goals.
- Establish regional coordination and emergency response preparation coordination efforts wherever possible.

EMERGENCY RESPONSE

- Establish repair/response contracts and collaborate in advance with other states, counties, DOTs, agencies and key officials who might aid in an emergency event, before it occurs.
- Use social media to disseminate DOT information directly to the public to avoid confusion.
- Make sure emergency protocols for financial accounting are in place for effective use of relief funds, to maximize federal reimbursements.
- Consider the use of one state emergency management center, which has been shown to be important for coordinating the emergency response.
- Partner with GPS and mapping applications to better disseminate information on road closures and/or detours to maximize effectiveness.
- Prioritize public safety above all other issues when deciding on actions.

INTRODUCTION

State DOTs have had to anticipate, design for and respond to extreme weather events ever since the first state transportation agency was created. Whether designing drainage systems to handle high levels of rainfall, or removing debris after storms with heavy winds, DOTs have incorporated a consideration for extreme weather conditions into their standard operating procedures. Over the past 15 years, however, the transportation community has become increasingly concerned about the impact of extreme weather events on DOT transportation infrastructure and services. Partly in response to: major natural disasters such as Hurricanes Sandy, Katrina, and Irene, massive flooding in the Midwest, large forest fires and landslides in the West, and an awareness of the potential threats of climate change described in research and policy studies, a growing number of state transportation agencies are interested in understanding the risks associated with extreme weather.

Much of the climate science literature, national climate assessments, and national monitoring of weather-related disasters suggest that extreme weather events are likely to become more commonplace in future years as temperatures warm and extreme weather events become more likely. Such events will likely represent even greater challenges to state DOTs and the expectation is that many of these events will cause widespread damage. **The purpose of this report is to examine some extreme weather experiences of selected state DOTs and identify lessons learned from those experiences that could be valuable to other state DOTs.** The focus of these lessons learned is to inform state DOT planning, design, regulation and policy efforts to meet the challenges represented by extreme weather events and climate change. Other state DOT lessons learned focus on emergency response efforts following extreme weather events.

POTENTIAL IMPACTS AND CONSEQUENCES TO STATE DOTs OF CLIMATE CHANGE

A research report for the National Cooperative Highway Research Program (NCHRP) summarized some of the likely consequences of future climatic and extreme weather conditions to DOTs.¹ It noted that over time, sea level rise threatens to permanently inundate low-lying communities and their transportation facilities such as coastal highways and ports. Increased risk of coastal flooding in conjunction with sea level rise, however, may pose a more serious risk than inundation alone. The intensity of storms, particularly the most powerful hurricanes, will likely increase in the future. This means stronger winds and higher storm surges – on top of higher sea levels – which will put even more land and transportation facilities at risk from the damaging effects of surging ocean water and waves. Very high temperatures can cause concrete pavements to buckle and can soften asphalt roads, leading to greater degrees of rutting and subsidence, and higher costs to the DOT for repair/maintenance. High temperatures will cause more precipitation to fall as rain rather than snow, which could increase the likelihood of flash flooding and drainage problems, increasing damage to bridges and culverts. The melting of the permafrost will create significant challenges to road design and maintenance (as is happening in Alaska), increasing the costs for maintaining a viable system. Increased frequency of freeze and thaw cycles could significantly affect pavement, increasing damage. Precipitation patterns and intensity could change dramatically, affecting transportation networks and

¹National Cooperative Highway Research Program. 2014. *Strategic Issues Facing Transportation Volume 2: Climate Change, Extreme Weather Events, and the Highway System: Practitioner's Guide and Research Report*, NCHRP Report 750, Vol. 2, Washington DC.

facility operations through flooding and damage. Some areas may face increased precipitation and increased flooding. For example, climate models tend to project increased winter precipitation in the Midwest and Northeast, increasing the risk of early spring flooding as snow packs melt and are combined with spring rainfall events. Precipitation intensity is projected to become more severe in the future, increasing the risk of flooding, particularly from convective thunderstorms in the summer.

As noted by the NCHRP report, “Adapting infrastructure to better withstand these impacts could allow infrastructure to remain operational through extreme weather events that otherwise would result in failure. Adaptations may also help to reduce operations and maintenance costs, improve safety for travelers, and protect the large investments made in transportation system infrastructure.”

WHY STATE DOTs ARE CONCERNED

DOT officials have observed the extreme weather impacts in their states or in states with similar experiences, and are concerned about the readiness of their agency to respond quickly and effectively to the range of threats that may plausibly disrupt the transportation system and services for which they are responsible. They are likely uncertain as to the location of assets that may be at risk from extreme weather events, often leading to a reactive response rather than proactive planning.

They are concerned about their ability to gain a timely and reliable assessment of the damage, and what it would take to get the affected or alternative transportation facilities into operation as quickly as possible and reduce safety concerns and/or bring critical service back to customers. They are concerned about their readiness to respond to the need for information and communication with the Governor’s Office; other elected officials; partner federal, state and local agencies such as law enforcement, fire and rescue, emergency coordinators; other transportation agencies; the media (traditional as well as through social media) and with individuals and groups of citizens whose homes and businesses may be affected.

Concerns also include an ability to restore stopgap service, pulling out all stops to speed up the process of returning the transportation system to functional operations. Officials are also naturally concerned about the safety and well-being of their department staff and their capacity to recommend immediate as well as longer-term actions to relieve and ultimately resolve the disruptions caused by the emergency. Many DOT officials would likely become personally engaged in the process of working with other agencies in formulating and directing the implementation of short- and long-term recovery strategies to reestablish and sustain the viability and function of the affected network.

Since not all risks and potential impacts occur suddenly and without much advanced warning, state DOTs will want to be able to demonstrate that predictable, long-term threats (such as sea level rise) are being planned for in a strategic way, that is, from a perspective of eliminating, or at least minimizing, potential adverse impacts through the judicious long-term planning, design, deployment and operational management of transportation facilities.

ORGANIZATION OF THE REPORT

The following section presents case studies of extreme weather events and state DOT activities in preparing for and responding to the challenges associated with the weather emergency. Next, the report presents the cross-cutting lessons learned from these case studies, and the implications for DOT planning and design, policies and regulations, and emergency response. The report concludes by

discussing how state DOTs can consider changing climate conditions in planning and decision-making processes.

EXTREME WEATHER EVENT CASE STUDIES

The study focused on eight case study states for examples of extreme weather events. The events highlighted occurred in the last six years, ranged across the continental U.S., varied by event type, were notable in the media, had severe impacts for the public and affected the operations and other activities of each respective DOT. The eight case study states, as well as the nature of each event and year of occurrence, are shown in Figure 1.

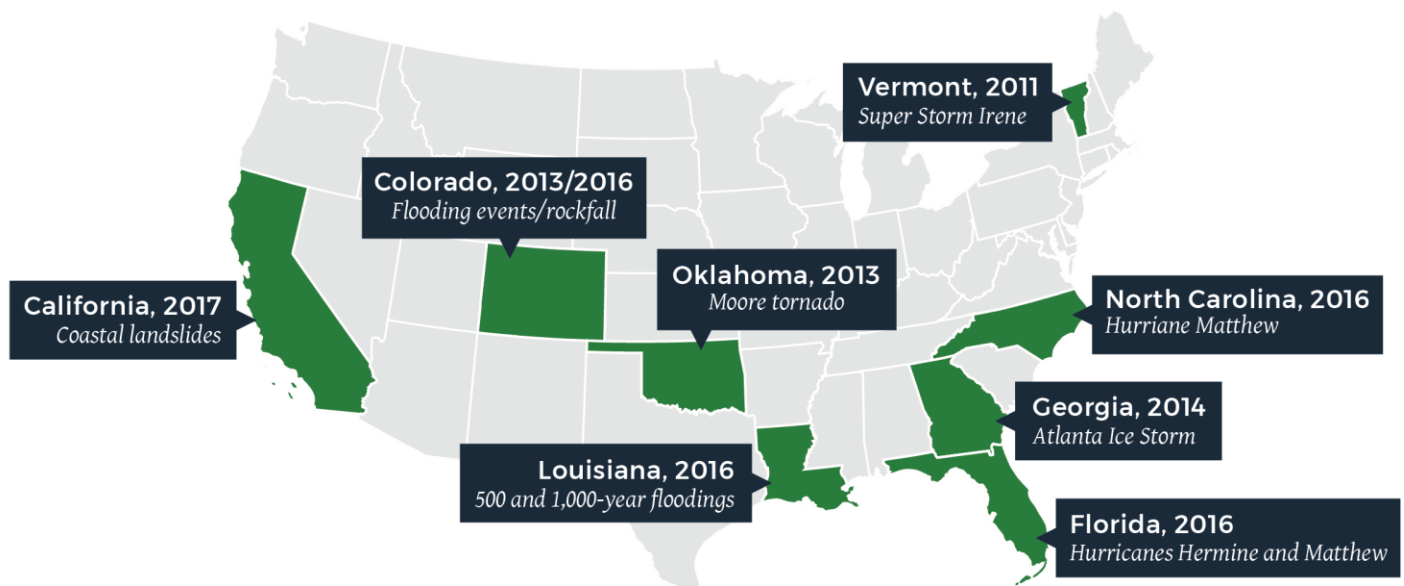


Figure 1 – States and extreme weather events highlighted for case studies

Each of the case studies provides details on the extreme weather event, as well as interview findings from each state DOT. Interviews with DOT staff focused on understanding the emergency response effort including what worked, and how the DOTs actions could have been better. Questions were also asked on what changes the DOT have made or would recommend making to planning, design, policies, and/or regulations to become more resilient to similar events in the future. From the state DOT responses, the following three categories of prospective action were identified and used to present the study results:

- Planning and design
- Policies and regulations
- Emergency response

This report highlights the findings that focused on making changes to state DOT efforts that would increase the overall resiliency of DOT infrastructure, response efforts, communications, finances, and internal DOT practices. At the end of this report, findings are assessed and grouped into cross-cutting lessons learned for the categories listed above. The lessons learned can act as a quick reference for DOT staff to see what other DOTs learned during recent extreme weather events and their suggestions for moving forward for creating a more resilient DOT.



VERMONT – 2011 TROPICAL STORM IRENE

In 2011, Vermont was hit by Tropical Storm Irene, which poured as much as 11 inches of rain in some areas and caused about \$733 million in total damages.² The heavy downpour caused flooding events around the state and washouts of buildings, roads, and bridges/culverts. Before the flood, rivers and streams in some areas had been straightened to accommodate surrounding development, which essentially channeled runoff into fast-moving waterways. When the water eventually breached river channels it did not just flood nearby areas, it swept them away.³ This damage to the infrastructure had left 11 communities stranded.⁴ When the storm was over, the Vermont Agency of Transportation (VTrans) was responsible for coordinating with key partners to streamline infrastructure recovery.

Key Points

More than **2,400 roads, 800 homes and businesses, 300 bridges, and a half dozen railroad lines** were destroyed or damaged.

Statewide impacts caused **\$733 million** in total damages.

Tropical Storm Irene was considered a **1-in-1,000-year** event given the averages of the 20th century.

Immediately after the event, 700 VTrans workers, combined with members of the National Guard, volunteers, private sector employees, and transportation workers from other states, began rebuilding washed out roadways. At the same time, VTrans began a public communication campaign using a 20-line call center, email, and social media. The goal was to keep the public updated on the status of roads and bridges. The speedy response was due largely to the creation of an Incident Command System (ICS), which allowed VTrans to respond to and recover from the emergency efficiently.

² Kendra Pierra-Louis, “Five Years After Hurricane Irene, Vermont Still Striving for Resilience,” *Inside Climate News*, September 1, 2016, <https://insideclimatenews.org/news/31082016/five-years-after-hurricane-irene-2011-effects-flooding-vermont-damage-resilience-climate-change>

³ Ibid.

⁴ Vermont Agency of Transportation, “Irene Innovation Task Force,” March 2012, http://54.172.27.91/EM/VTrans_IreneInnovationTaskTeam_201203.pdf

VTrans created an Irene Innovation Task Force after the event to identify what went well during the event and what needed to be improved. The general sense was that during Tropical Storm Irene, VTrans was innovative and inventive, with an effective, streamlined emergency response. For example, most of the damaged roadways were addressed within a month of Irene and all roadways were fixed within four months. The agency focused on what had gone well during the event and tried to identify best practices.

In addition to general ideas to boost innovation, the recommendations that came out of the Task Force included those to improve: integration, communications, informational technology, and operations. Many recommendations were focused on preventative measures that would increase transportation resiliency for another event such as Irene. The recommendations included the promotion of streambed stabilization, updating bridge design criteria to include the ability to withstand flooding, and to revisit riverbank design methodology, among other items.

Interview Findings

The VTrans Policy, Planning, and Research Bureau Director was interviewed regarding Tropical Storm Irene and the key findings made by the DOT in the period following the event. The Director's responsibilities include an ongoing resiliency project that aims to identify critical culverts, bridges, and road embankments and measure their level of risk from different storm events. The Director noted that, overall, VTrans reacted well to Tropical Storm Irene and there are best practices that can be applied by other DOTs. VTrans was successful during and after the event primarily through implementing ICS and collaborating with key partners. The existence of a centralized command and control capability during the event was considered a key element of the overall success.

Examples of changes being made to address resiliency within the DOT after the event has included updates to the Hydraulics Manual and Strategic Plan, as well as plans to support streambed stabilization and more resilient design. Key lessons learned from Tropical Storm Irene are categorized and outlined below. The findings are a mix of best practices that other DOTs could adopt during similar events, and as well represent challenges that other DOTs can learn from.



Figure 3 - Bridge 25 along VT 12 after Tropical Storm Irene



Figure 2 - Bridge 6 in Braintree after Tropical Storm Irene

PLANNING AND DESIGN

- The VTrans Hydraulics Manual was updated to be brought up to date with the current VTrans bridge manual and include considerations of bridge abilities to withstand flooding
- Fiscal resilience is an important consideration in managing a state's recovery. Pre-organized emergency protocols had been put in place to ensure timely drawdown of Federal relief funds.
- River channeling had a direct influence on the severity of the event, which was outside of VTrans's control. Moving forward, VTrans is supporting streambed stabilization as part of its design procedures, by increasing use of rip rap and other river stabilization design options.
- An Accelerated Bridge Program is now well-established and adopted by VTrans and the industry, making Vermont even better prepared for rapid bridge replacements.
- VTrans, in partnership with the River Program in the VT Agency of Natural Resources has developed a three-tiered Rivers and Roads Training Program.⁵

POLICIES AND REGULATIONS

- The ICS was an integral part of the emergency response and VTrans now holds mandatory ICS training to prepare for future events.
- Contracts and audit trails need to be available so that when an event strikes, funding from FEMA and other sources can be gathered quickly.
- VTrans brainstormed with Vermont government about changes that needed to be made to state policies, and are now updating the state hazard mitigation plan following these discussions.
- VTrans worked with FEMA to develop standards that would ensure structures such as culverts are built wide enough to handle debris.
- The VTrans Strategic Plan has been updated to include language about resiliency and preparedness for future events.
- VTrans officials believe resiliency should be incorporated into everything VTrans does, and including resilience as factor in its project selection and prioritization process.

EMERGENCY RESPONSE

- Partnerships were crucial to the response effort; VTrans partnered with Google to create a map showing closures and detours.
- Planning in anticipation of an extreme weather event is vital to the effectiveness of the response effort; VTrans was not prepared for Tropical Storm Irene and hurried to set up ICS centers.
- Knowing where vulnerabilities may arise in the transportation system allows DOTs to have an idea of where resources will need to be allocated in the event of an emergency and VTrans would like to identify these areas in the future.
- Practicing and running drills is important for a successful emergency response.

⁵ Rivers and Roads Flyer, VTrans, http://dec.vermont.gov/sites/dec/files/wsm/rivers/docs/Rivers_and_Roads_Flyer_2016-08-29.pdf



LOUISIANA – 2016 500 AND 1,000-YEAR FLOODING EVENTS

In 2016, two major flooding events in Louisiana caused 58 out of the state's 64 parishes (counties) to be declared as disaster areas. The first of the two was a 500-year storm that hit in March 2016 and the second was a 1,000-year storm that lasted for three days in August. The events caused rivers throughout the state to reach record levels as rainfall exceeded two to three inches per hour and nearly two feet in total in some areas. The impacts of which were: road washouts, bridge failures, and bridge scour, made worse in some areas when debris carried by flood waters jammed underneath bridge abutments.

The Louisiana Department of Transportation and Development (DOTD) was involved in the response effort for both events. DOTD piped water out of Interstate corridors, redirected traffic, staffed traffic management, contributed to rescue operations, and was involved in coordinating an information exchange with the State Police and public. The DOTD used geospatial mapping to map flooded areas and coordinate with 511 to get the word out on these locations. DOTD also used social media to communicate with the public regarding closures.

However, there were multiple challenges associated with the response effort. At one point, DOTD had used all the barricades available, keeping unsafe roadways open to the public. Even in areas where there were barriers, DOTD found that sometimes people drove around them into flooded areas. Another challenge was that many of the DOTD staff had personal emergencies during the events, which strained their capacity to respond.

After the events, 200 bridges were inspected and found to be “scour crucial” from debris such as floating docks. Bridges failed, debris and timber clogged waterways, and there were several washouts. Louisiana DOTD was responsible for roadway and bridge repair/reconstruction following the floods.

Key Points

The August 2016 flood caused widespread devastation across central Louisiana and **killed 12.***

More than **25 inches** of rain fell in the Baton Rouge area over **three days** in August.*

Considered the **worst natural disaster** to strike the U.S. since Hurricane Sandy.**

Roadways took about four to six weeks to repair and bridge replacements took about 12 to 16 months, and some assets are still out of service.

DOTD is considering how assets can become more resilient in preparation for future flooding events and is considering stronger designs for bridges, as well as closer coordination with parishes on bridge inspections. DOTD is also considering policy changes to better prepare for similar emergencies, including better watershed management practices, and flooding mitigation.

Mitigating for future flooding is not only a responsibility of DOTD, but for state government and other stakeholders as well. Several items that need to be addressed statewide include: providing better real-time information during emergency events, avoiding building in Special Flood Hazard Areas, increasing flood protection, and addressing design standards to increase resiliency.⁶

Interview Findings

Those interviewed included the Chief of Staff who has contributed to Hurricanes Katrina, Gustav, Ike, and other response efforts; the Confidential Assistant to the Secretary, and the Director of Emergency Operations. All three recounted the challenges to the state DOT of both floods, the impacts they had on the traveling public and the State Highway System, and steps being considered to increase resiliency.

During the emergency response, communication with the public, other stakeholders, as well as internal to the state DOT, was considered crucial to the effort; and the DOT officials felt that better communication could have made things run more smoothly. Since the events, DOTD has been taking steps to address resiliency through flood mitigation, mapping watersheds and waterways, and designing more durable infrastructure. The DOTD observations and findings concerning these events are listed below.



Figure 4 - Coast Guard conducting evacuations

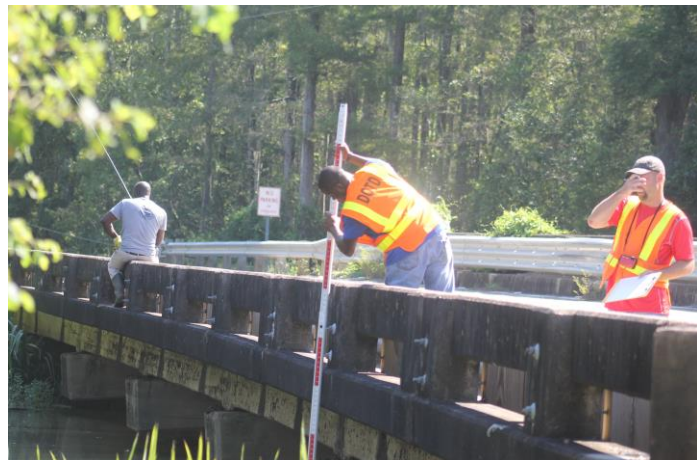


Figure 5 - DOTD inspects a bridge in Livingston Parish

*Michael Martinez, Ed Payne; and Dave Alsup, "Flooding Spreads across Southern Louisiana and Mississippi," *CNN*, March 12, 2016, <http://www.cnn.com/2016/03/12/us/southeast-weather/index.html>.

** Holly Yann, Rosa Flores, "Louisiana Flood: Worst US Disaster since Hurricane Sandy, Red Cross says," *CNN*, August 19, 2016, <http://www.cnn.com/2016/08/18/us/louisiana-flooding/index.html>.

⁶ Laura Bliss, "What we can and can't Learn from the Floods in Baton Rouge," *CityLab*, August 17, 2016, <https://www.citylab.com/design/2016/08/baton-rouge-floods-planning-resiliency/496172/>.

PLANNING AND DESIGN

- In response to the flooding events, DOTD has prioritized efforts to better map waterways and watersheds, to more accurately map flood prone areas and better information to support decision making.
- DOTD found that the current values for storms per “500-year” or “1,000-year” events seem problematic and is not helpful for planning; these probabilities and the methods behind identifying them need to be revisited.
- Louisiana DOTD would like to design for more resilient, stronger infrastructure, but is not planning to build roadways or bridges higher due to cost concerns.
- The events have caused DOTD to reprioritize funding and concentrate on data modeling to better understand areas of risk.

POLICIES AND REGULATIONS

- DOTD is changing its policies regarding watershed management and is trying to fund governance within the geography of a watershed rather than by locality (by town or parish).
- Louisiana DOTD is encouraging regional coordination on flooding mitigation efforts.
- FEMA Hazard mitigation funds are being considered for resiliency-focused projects.
- The DOTD is interested in utilizing a FEMA resiliency model focused on transportation.

EMERGENCY RESPONSE

- Communicating with the public through social media was much more effective than through previous methods used, such as radio announcements.
- Enforcing barricades was a challenge and there were an inadequate number of staff available to monitor public compliance, contributing to concerns.
- Accounting for personal staff needs during emergency response is important, as this limited the number of people available to help guide the response.
- Strong relationships with Federal agencies in advance of events are crucial for disaster planning and response.
- Not declaring the events as “hurricanes” may have influenced public perception of the damage potential of these events.



COLORADO – 2013 FLOODING AND 2016 ROCK FALLS

Key Points

1000-year rainfall event and a **100-year flood**.

Almost **\$4 billion in damages** and disaster declared in 17 counties, with **24 counties affected** total.

CDOT spent over **\$700 million** to rebuild and repair roads.*

The 2016 rockfall **closed I-70 for a week**, causing delays which affected the tourism industry.

In 2013, 17.6 inches of rain fell over eight days in northeastern Colorado. The event affected 24 counties and caused almost \$4 billion in damage.⁷ Mudslides tore houses apart; rivers dragged trees down mountainsides and agricultural land was submerged. The storm poured on the Rocky Mountains: swelling reservoirs, lakes, and rivers. This caused water to surge down three canyons, tearing down roads and bridges, and leaving ten dead in its wake. When the storm finally ended, the Colorado Department of Transportation (CDOT) owned 30 destroyed bridges and over 486 lanes miles of road needing to be repaired or replaced.⁸

During the flood, CDOT closed over 200 lane-miles and 102 bridges for detours.⁹ The agency worked closely

with the state's Office of Emergency Management to respond to the event as well as continue monitoring roads and bridges in the flood area. Rebuilding and repairing the state highways cost over \$400 million.¹⁰ Major highways US-36 and US-34 suffered significant damage through the canyons and out to the eastern plains of Colorado (see the Appendix for US-34 photos). It was noted that these highways must be moved away from the rivers to avoid future disruption and damage, posing a technical and expensive challenge to the DOT.

⁷ J Aguilar, "Two Years Later, 2013 Colorado Floods Remain a 'Nightmare' for Some," *The Denver Post*, July 14, 2015, https://issuu.com/pdettmann/docs/july_13_full_edition.

⁸ M Whaley, "Colorado Flood-Damaged Road Repairs now Estimated at \$590 Million," *The Denver Post*, April 25, 2016, <http://www.denverpost.com/2015/03/28/colorado-flood-damaged-road-repairs-now-estimated-at-590-million/>.

⁹ Colorado Department of Transportation, PowerPoint, October 8, 2013, <https://www.codot.gov/about/governmentrelations/state-government-liaison/cdot-presentation-to-the-tlrc-october-2013.pdf>.

¹⁰ Ibid.

Another significant event that CDOT recently responded to was a massive rockfall in 2016 that closed I-70 for a week and required the repair of a section of bridge deck that cost \$5 million. These rockfall events occur on this section of I-70 approximately every five years, with other major rockfalls occurring in 2004 and 2010. So far there have been no associated fatalities, but there have been significant damages to the Interstate during each event.

Interview Findings

Those interviewed included the CDOT Environmental Liaison, the CDOT Flood Recovery Program Manager and the Director of the Geohazards Division. The questions focused on the DOT's response to the flooding and rockfall events, and how the agency is planning to address resiliency.

Following the 2013 flood and the 2016 I-70 rock fall, the Governor introduced the "Colorado Resiliency Framework."¹¹ The plan encourages state agencies to explore resiliency and plan for the State's next emergency event. CDOT took up the challenge and began exploring ways to identify risks to assets, and potential costs if there was another disaster. Of significant concern are rock slides and rock falls, which occur along corridors that snake through the Rocky Mountains. CDOT began analyzing the state's roads for potential threats such as avalanches, floods, fires, and rockslides. The DOT decided to conduct a pilot project on a section of I-70 West for the Resiliency Framework. The pilot project aims to collect data and study what resiliency measures will be needed to protect public health and safety, as well as minimize infrastructure damage.

The pilot project will also help CDOT understand where impacts will occur along I-70 West and consider how adaptation methods score on a cost-benefit analysis. It is also an effort to begin to understand how resiliency principles can be incorporated into CDOT's asset management planning and understand what the greatest risks are to this section of I-70. Ultimately, CDOT would like to expand the pilot to other vulnerable roadways and develop adaptation responses that are financially feasible.



Figure 6 - SH71 flood damage, CO



Figure 7 - SH71 flooding, CO

¹¹ State of Colorado, "Gov. Hickenlooper Adopts Colorado Resiliency Framework," June 1, 2015, <https://www.colorado.gov/governor/news/gov-hickenlooper-adopts-colorado-resiliency-framework>.

PLANNING AND DESIGN

- In response to the flood, CDOT made identifying vulnerable roadways statewide a priority.
- CDOT did not rebuild in-kind, but rebuilt roadways to accommodate higher flows.
- CDOT is currently executing a pilot project designed to help the department gather data that will encourage resiliency in future projects.
- Increasing the resilience of CDOT projects can be expensive; part of the I-70 pilot project is aimed at understanding the benefit-cost of adaptation by measuring the impacts to the traveling public.
- CDOT is using the I-70 pilot project to consider an all hazards approach to the roadway section and understand how this can be incorporated into everyday actions at the DOT.

POLICIES AND REGULATIONS

- CDOT developed a risk-based asset management plan using a risk and resiliency analysis to rank the most exposed assets.
- Using Risk Analysis and Management for Critical Asset Program (RAMCAP) metric to rank the most critical corridors was beneficial; this accounted for social vulnerability, tourism value, and redundancy, amongst other factors.
- Staff found that the pilot project was delayed due to spending too much time on identifying critical routes; need to build in this time.
- CDOT found that buy-in from executive level staff was very important to driving the pilot project.

EMERGENCY RESPONSE

- CDOT sponsored a peer exchange with other state DOTs to explore best practices from other states as a part of their internal effort, which proved critical to response.
- Emergency Relief funding impacted how the infrastructure could be repaired or reconstructed. It doesn't always allow roadways and bridges to be built "bigger and better", traditionally these funds are replace in kind.
- CDOT found that working more closely with federal agencies impacted by the event, such as the Forest Service, is important in defining mutual concerns and response strategies.
- CDOT found that they could have saved money through bidding instead of force accounting, but did not take the time to consider it given the need to respond quickly.



NORTH CAROLINA – 2016 HURRICANE MATTHEW

In October 2016, North Carolina was hit by Category 5 Hurricane Matthew, resulting in flooding that caused \$1.5 billion in damages. The hurricane dropped more than a foot of rain 100 miles inland, with flooding affecting the eastern part of the state. Towns predominantly affected included Princeville, Lumberton, and Fair Bluff. There were 26 fatalities in the state, most of which involved citizens bypassing road closure signs in areas where there were inundated roads, resulting in accidental drowning.¹² Millions of farm animals also died, including an estimated 5 million chickens, which caused additional environmental contamination concerns and was a concern for clean-up.¹³

Key Points

Hurricane Matthew was classified a **1,000-year event** by NCDOT.

600 roads were closed across the state and it was impossible to deploy police at each location.

Drivers **surpassed detours**, resulting in multiple casualties.

Hurricane Matthew was expected to be a coastal wind event, rather than an inland flooding event, affecting the eastern as well as southern parts of the state. Hurricane Matthew filled many streams and rivers, and five river basins in the eastern part of the state were close to exceeding record water lines. Pond and lake levels were so high that there was a significant concern about dam failure and many associated spillways experienced significant erosion. Approximately 1,600 sections of roadway were underwater.

The North Carolina Department of Transportation (NCDOT) responded immediately to this event with road closures, detours, and some emergency and temporary maintenance. NCDOT brought in personnel and material from the western, less affected, part of the state to address flooding in the impacted area. This coordinated effort occurred later than was anticipated since the hurricane was expected to hit the coast and be primarily a wind event, and the severity of the event caught NCDOT leadership off guard. As the event was ongoing, resources were spread thin, and barricades and signs were soon out of stock.

¹² "Hurricane Matthew Floods Caused \$1.5B Damage in North Carolina," *Daily News*, October 16, 2016, <http://www.nydailynews.com/news/national/hurricane-matthew-floods-1-5b-damage-north-carolina-article-1.2832916>.

¹³ Ibid.

Some roadways were ultimately inundated for two weeks and pipes were damaged, constricting flow and in some cases causing blow outs. Over 700 pipes were analyzed and many replacements were needed. Debris caused several million dollars in damages to structures, bridge foundations and piers absorbed scour damage, and some box culverts were damaged beyond repair. NCDOT led a comprehensive repair effort to get most roads reopened in 30 days, putting in temporary infrastructure where necessary.

NCDOT also coordinated with the U.S. Department of Health and Human Services to determine how to keep drivers from trying to go around or through closed roads. They began utilizing the signage of “Turn around, don’t drown” at road blocks across the state. However, older car-based GPS programs did not immediately update the positioning of road blocks and detours, and it was difficult for drivers to use those systems to navigate and find new routes. Newer programs like Waze and Google Maps were noted as successfully incorporating closures. The number of barricades was also found to be insufficient by the DOT. NCDOT staff think twice as many could have been utilized during the event to cover the needs, and should have been sent out earlier – but the extent of the event was unanticipated.

Interview Findings

Those interviewed included the Chief Engineer, the State Maintenance and Operations Engineer, and the Disaster Recovery Engineer. They provided feedback on the overall successes and challenges of the NCDOT response effort, as well as any next steps NCDOT is taking to mitigate for future events through planning, design, or agency policies (see summarized findings below).

The main takeaway from Hurricane Matthew was that driver safety during major storm events needs to become an even higher priority, and NCDOT needs to expand what they are already doing to keep drivers off dangerous roadways. In many cases detour routes for flooded roads were also flooded, contributing to the logistical challenge of providing system users with alternate routes.

The NCDOT officials also thought that more barricades are needed during events, they need to be deployed sooner, and the process of updating GPS units in cars needs to be reassessed to identify how best to immediately update drivers on roadblocks or detours. They also suggested setting up a phone line for the public to find alternative routes, rather than relying upon GPS as it often was problematic. It is important to have several reliable sources available for drivers to find out more information during extreme weather events with an extent like that noted in North Carolina, including: GPS and mapping applications, roadway signage, phone lines, online updates, and social media.



Figure 8 - I - 95 flooding



Figure 9 - Fayetteville road damage

PLANNING AND DESIGN

- Evaluating the current locations of fixed Variable Message Boards prior to events is important to ensure enough are situated at critical junctions.
- NCDOT recognized after the event that they need around twice as many barricades for major emergencies such as this one.
- NCDOT is considering including the effects of sea level rise and more intense storms in its hydraulics manual to address long term risks.

POLICIES AND REGULATIONS

- Financial recovery training was held just prior to the event and helped prepare NCDOT to handle the contracts, permits, and back-up documentation for reimbursement.
- Memorandums of Agreement (MOA) should be issued with counties for debris removal in advance of events.
- MOAs should be set up with nearby states to assist in providing service/equipment in case assistance is needed.
- Driver safety during an event needs to be held as a high priority and precautions need to be made on behalf of the traveling public.

EMERGENCY RESPONSE

- NCDOT created paired divisions who supported each other during and after the event, which was key to the response effort.
- Disaster liaisons were assigned in each division of the DOT, who were helpful in moving people and equipment.
- Automated financial accounting systems were key tools for maintenance and repair, as well as the ability to access on-call contracts and waive requirements.
- A state emergency management center was critical for coordination for an event of this magnitude.



GEORGIA - 2014 ATLANTA ICE STORM

On January 29, 2014, thousands of cars and trucks were stuck on ice-coated highways in the greater Atlanta area. Everyone was trying to reach their destinations during and in the aftermath of an ice storm that hit the city. Students spent the night in schools, shoppers waited out the storm in grocery stores and many abandoned their vehicles to walk to nearby hotels until their vehicles could be retrieved. Some motorists were stuck in their cars for 24 hours as they slowly inched towards home. The National Weather Service had difficulty pinpointing exactly where the storm was going to hit and

Key Points

Three to five inches of ice deposited on roads throughout the Atlanta highway network.

Rapid changes in storm dynamics **did not allow accurate predictions** of where the most severe impacts would be.

Massive and **two- to four-day traffic tie-ups** resulted.

GDOT **response was significantly affected** due to clogged roads.

GDOT was responsible for towing over **10,000 cars** that were stranded or abandoned.

A series of **post-mortem strategies** developed through analysis of the response were implemented.

state agencies scrambled to prepare the roads for the severe weather. Once it was clear where the storm was going to have its greatest impact, roads and highways were so clogged that salt trucks were unable to treat the roadways.

Perhaps the most important factor that contributed to the resulting congestion on the region's roads was that both state and city governments released their employees to "get home before the storm hits" exactly at the time when the storm would be at its most dangerous.

The political backlash was swift. Georgians blamed the government for a poorly executed emergency response; city and local politicians pointed fingers at one another; a national blame game between state agencies and the National Weather Service played out on national TV; and the media disseminated story after story about how

unprepared the government was to respond to such situations. After the storm was over, the Georgia Department of Transportation (GDOT) recognized that they needed to have a better plan in place for the next severe storm. Very little physical damage had been done to the roadways, but the near total collapse of the region's major highway network was an outcome the GDOT was not willing to face again.

Interview Findings

The public safety implications of the storm's consequences, and frankly the perspective on the disaster as portrayed in the national press, caused state government and GDOT to re-examine its policies, strategies and institutional structures to respond to such events in the future. The Governor, for example, gave GDOT \$15 million to put in place a strategy to make sure "it will never happen again."

Much has changed since the ice storm. In the post-mortem of the event, the Chief Engineer identified many issues that needed to be addressed to avoid future traffic bottlenecks and network collapse, as had occurred during this storm (see list below). However, some challenges remain. When asked what the most pressing issue still facing GDOT was when dealing with emergencies such as the ice storm, GDOT officials said that coordinating with local governments during and after an event is still a major challenge. For example, after a recent hurricane, local governments were putting pressure on GDOT to let people back into their affected neighborhoods over

roads and bridges that had not been inspected for damage to assure safe travel. Several confrontations occurred between GDOT and local officials (including one between a sheriff and GDOT employees) because of this basic difference in perspective of when is it safe to return. As noted by GDOT officials, there remains a lot of "friction" between GDOT, local emergency management officials and sheriffs. GDOT has begun speaking at sheriff association meetings to explain why it has adopted the policy it has, to bolster more communication.



Figure 10 - Atlanta, parking lot during ice storm



Figure 11 - Atlanta, roadway during ice storm

PLANNING AND DESIGN

- GDOT has since expanded its connection to the National Weather Service for improved advanced warning.
- Road sensors have been put in place to get a better handle on what is happening with respect to traffic conditions on the road network.
- GDOT formed “strike teams” covering every section of Interstate that will respond to disasters having responsibilities for assessing initial damage and organizing DOT response to open the roadway as soon as possible.
- GDOT has engaged in many advanced planning efforts for possible disruptions, including with major tow truck operators who had a critical role to play in the ice storm.
- Efforts have been made to better coordinate release of employees among government agencies in anticipation of serious weather.

POLICIES AND REGULATIONS

- Governor gave GDOT \$15 million to make changes so that “it would never happen again.” Funds were focused on improved planning for emergency response and coordinated agency action.
- Prior to the storm, the State Maintenance Engineer was responsible for response; a new position in Operations called Director of Emergency Operations was created. GDOT changed the responsibility of responses to the Director of Emergency Operations. New procedures and approaches, such as putting brine on Interstates in anticipation of ice, pretreating roads and using agriculture vendors for salt supply have been adopted.
- A new GDOT coordinated effort was established to not send GDOT teams into a disaster area without the state patrol accompanying them.

EMERGENCY RESPONSE

- GDOT added a dedicated radio service to its and other agency communications that allowed all the agencies involved in the response to communicate and listen to what others were doing.
- GDOT’s system of emergency response has become the foundation for a web-based emergency response system for all state agencies.
- A better tie in to the Navigator System (a traffic information public outreach effort) was established to expand the information available to highway users.
- An expansion of the Navigator System is moving forward to offer more highway coverage.



OKLAHOMA – 2013 MOORE TORNADO

On the afternoon of May 20, 2013, a tornado followed a 17-mile destructive path¹⁴ through Moore, Oklahoma, a suburb of Oklahoma City, leveling houses, schools and other buildings in its wake. In just 37 minutes, 200 mph winds caused over \$2 billion in damage and took 24 lives.¹⁵ The tornado was the worst natural disaster in Oklahoma’s history. The tornado was classified by the National Oceanic and Atmospheric Administration (NOAA) as an EF5 on the Fujita Damage Scale. This rating is the highest possible on the scale and defined by extremely high winds and “incredible damage.”¹⁶ Unfortunately, the 2013 tornado followed a similar path to a previous, even deadlier 1999 tornado, destroying many buildings that had only recently been rebuilt. When forecasters predicted the storm, the Department of Emergency Management (DEMA) called each agency’s “emergency” liaison to the DEMA command center. As found in most states, emergency response was coordinated from this center.

After the storm, the Oklahoma Department of Transportation (ODOT) assessed the damage to state highways in the affected area. Except for light poles and roads signs that had been torn from their supports, very little damage had occurred to its infrastructure. Given little damage to ODOT assets, the Department focused on communication and information efforts with the public as well as clearing State Highways of debris for emergency response vehicles to pass through. It also provided support to local government through removing debris from “off-state-network” roads, which were primarily in residential areas.

Key Points

The tornado was the **worst natural disaster** in Oklahoma history.

24 fatalities and over **1,000 buildings** destroyed.

Many of the buildings destroyed **had been previously rebuilt** following the 1999 Moore tornado.

¹⁴ Ben Brumfield, “Moore Oklahoma, Looks Back on Tornado that Killed 24 One Year Ago,” *CNN*, May 20th, 2014, <http://www.cnn.com/2014/05/20/us/oklahoma-moore-tornado-anniversary/index.html>.

¹⁵ Ibid.

¹⁶ Fujita, Theodore, Fujita Tornado Damage Scale, 1971, <http://www.spc.noaa.gov/faq/tornado/f-scale.html>.

Overall, the largest challenge ODOT faced was debris removal, which included clearing dead livestock. The Department helped local governments remove major debris in the early days of the recovery, but soon this effort was overwhelmed by the sheer volume of rubble and the complications involved with clearing debris on weekends, when family members came out to clean up as well, which presented a safety hazard. At that point, contractors with specialized equipment were brought in by ODOT and over two weeks, debris was removed from the disaster area.

In the wake of the disaster, ODOT officials examined how they could improve ODOT's response to the next severe storm. Tornadoes, quite common in Oklahoma, typically occur in rural areas and cause little damage. The Moore tornado, however, was devastating because it occurred in a suburban area. In response, ODOT's social media presence has increased, and Intelligent Transportation Systems (ITS) applications have been improved; highway message signs, for example, now give motorists warnings much more quickly in anticipation of extreme storms.

Interview Findings

The ODOT Maintenance Division Engineer was interviewed about the DOT's experience during and after the Moore tornado, and how incorporating resiliency principles may be considered following the event. He noted that a changing climate could be a significant factor in the frequency of tornado events in the future and this should be addressed by state officials.

Unlike some other cases in this study, the Moore tornado case study does not illustrate significant changes to DOT operating procedures or new policies for handling emergency response. However, it does represent a common experience for many state DOTs in disaster response, in that the agency provided important support resources to communities struggling to recover from the major disruption caused by a natural disaster such as the 2013 Moore tornado. For example, the ODOT official noted that

ODOT is more flexible in using its resources "off-system" where it does not have legislated authority when the action is in response to the Governor's declaration of an emergency. Some other ODOT response actions included placing more emphasis on communications via social media outlets, upgrading ITS messaging for highway users, and using contracts with debris removal firms that have specialized equipment to handle this important aspect of disaster recovery.



Figure 12 - Moore, aerial of tornado damage



Figure 13 - Moore, damaged homes in tornado path

PLANNING AND DESIGN

- ODOT is improving its ITS highway user messaging capability to improve warnings to drivers prior to and during severe storm events.
- Climate change and extreme weather should become an integrated consideration for state DOT actions with the consideration of the potential for more storms of this type.

POLICIES AND REGULATIONS

- Debris cleanup on the weekend proved to be a challenge and inefficient. Moving forward, ODOT will try to schedule its activities for debris removal around weekends.
- ODOT is internally considering how they can best prepare for and limit damage from future tornado events across its assets.

EMERGENCY RESPONSE

- ODOT is considering entering on-call contracts with firms that specialize in debris removal to augment its own capabilities during emergencies.
- In the future, ODOT will expand its use of social media to disseminate public information on storm tracks and appropriate public action.



CALIFORNIA- 2017 COASTAL LANDSLIDES

After five years of drought, California's water supply was finally replenished in 2017 by a tremendously wet winter. While storms at the start of 2017 came as a huge relief at first, the state soon reached around double its average rainfall, rivers began to swell, land gave way and ultimately the State Highway System saw significant damage. Flash flooding, coastal erosion, and landslides damaged and destroyed roadways, and the California Department of Transportation (Caltrans) ended up with an approximate \$860 million repair bill.¹⁷ Some of the most dramatic damage occurred in Caltrans District 5, which lies south of the San Francisco Bay Area, from Santa Cruz southward along the coast to Santa Barbara. Three of the most noteworthy events in District 5 were landslides, which occurred at Pfeiffer Canyon Bridge, Paul's Slide, and Mud Creek

Pfeiffer Canyon Bridge was a three-span bridge on State Route 1 in Monterey County. A column was displaced by an active mudslide in mid-February, moving eight inches in one night and destabilizing the bridge. Caltrans closed the bridge to all traffic and determined it was beyond repair. Caltrans has since demolished the bridge and constructed a new Pfeiffer Canyon Bridge, which was opened to the traveling public on October 13, 2017.

Paul's Slide was a landslide event in March of 2017, which had been active in previous years. In this occasion, the slide covered a portion of State Route 1, preserving only 11 feet of roadway at its narrowest. The roadway was closed to all traffic and the slide was assessed to see if it could be stabilized. After reaching limited stabilization, Caltrans officials began to let supply trucks and residents through at specific times of day. There were approximately 435 residents caught in-between the Pfeiffer Canyon Bridge and Paul's Slide closure.¹⁸

Key Points

Heavy rain events caused damages all over District 5 and **led to one Caltrans fatality** during road repair.

Multiple landslide events **closed traffic** on a 50 mile stretch of State Route 1.

The **last slide of this magnitude** was in 1998.

¹⁷ Joseph Serna, "California Faces \$860-million Repair Bill for Roads Battered by Record Winter Storms," *Los Angeles Times*, April 3, 2017, <http://www.latimes.com/local/lanow/la-me-ln-caltrans-storm-damage-assessment-20170403-story.html>.

¹⁸ Lizzie Johnson, "Bridge Failure Severs Big Sur's Ties to Outside World," *San Francisco Chronicle*, February 25, 2017, <http://www.sfchronicle.com/bayarea/article/Bridge-failure-severs-Big-Sur-s-ties-to-outside-10958200.php#photo-12444874>.

The Mud Creek slide received national and international attention and was the largest landslide seen on Route 1, creating 15 acres of new coastline and displacing four million tons of debris. Caltrans was able to detect the instability of the hillside before the slide occurred in May, and successfully blocked off the area to traffic beforehand. The slide is still active and no traffic can pass through the area, however, Caltrans staff are collecting information to determine how best to move forward and remedy the situation.



Figure 14 - Paul's Slide clean up

Interview Findings

The landslides on State Route 1 have effectively cut off part of the coast on one of the most scenic routes in the U.S., affecting locals, businesses, and the tourism industry. While Caltrans typically must battle landslides in this area, the DOT has never had to deal with anything approaching the number and scale of these slides. However, DOT staff worked on tackling the conditions and sought resilient solutions in a timely fashion.



Figure 15 - Mud creek active landslide

The Caltrans District 5 Director was interviewed to understand what Caltrans is doing to respond to these events and what changes in policy, planning or design might occur to increase the resiliency of Route 1. For the Pfeiffer Canyon Bridge, the new design is a steel girder, single span bridge, which allows Caltrans to span the canyon without a column vulnerable to the same event occurring again in the future. During the demolition and reconstruction phases, Caltrans worked with the local community to identify a mile footpath that residents used to go to school or work.

Paul's Slide is still being cleared by Caltrans staff, which is made more difficult because the slide is in a designated marine wildlife area. This means that Caltrans needs to clear the roadway without any debris being pushed into the ocean. Their current strategy is to excavate above the slide and use that fill to reinforce the area below the slide. As for the Mud Creek slide, the sheer magnitude of the active slide limits Caltrans options and complicates the response. The current strategy is to collect more information on the slide using drones, photogrammetry, LiDAR, and on-the-ground staff to map slide features and use that information to develop a strategy.

PLANNING AND DESIGN

- Assets should be assessed so that they are not replaced in-kind if facing similar environmental risks; the new design for the Pfeiffer Canyon Bridge is more resilient to landslides than the previous design.
- Repair at the Paul's Slide location is also using strategies to make the area less landslide prone (see above for more detail) and more resilient.
- Caltrans is assessing the Mud Creek area to understand how to best get Route 1 accessible again and develop a long-term solution.

POLICIES AND REGULATIONS

- Caltrans is working with Waze to create an app that shows road work locations, to make detours easier to find and reduce backups at these locations.
- Communication is key to communicating work and progress: weekly meetings are held with local stakeholders.
- Safety policies are critical for known risk areas and responding to onsite accidents is important; processes for assessing site safety will prevent injuries/fatalities.

EMERGENCY RESPONSE

- Each landslide was caught early through stability monitoring and responding to calls from the public.
- Finding detours and allowing public walking access has been a huge challenge as detour routes are very limited/unavailable. Caltrans has worked with local communities to identify footpaths where they can pass through and/or specific times where the public can drive through.



FLORIDA – 2016 HURRICANES HERMINE AND MATTHEW

In the late summer and early fall of 2016, Florida was struck by two hurricanes, Hermine (Category 1), and Matthew (Category 5). Hurricane Hermine was the first hurricane to make landfall in Florida in 11 years. Hermine came ashore near the Gulf shore town of St. Marks, Florida, which lies 20 miles south of the capital of Tallahassee. The hurricane arrived packing winds of 80 mph and churning up a devastating storm surge in coastal areas. Heavy downpours and high surf left parts of some communities underwater and mandatory evacuations were ordered in parts of five northwestern Florida counties.¹⁹

Key Points

Hurricane Hermine was the **first hurricane to make landfall** in 11 years.

Matthew was **unique** in that hurricanes do not often track along the east coast of Florida; they are more common along the panhandle like Hermine.

More than **1.5 million people** were **evacuated** when Matthew hit.

On October 7, 2016, Hurricane Matthew brushed the eastern coast of Florida before making its final landfall in South Carolina. Although Florida escaped a direct hit, numerous counties were impacted by Matthew's high winds and storm surge. Eighteen counties between Broward County and Nassau County were declared by the President of the United States as major disaster area DR-4283, under the Governor's request for Individual Assistance and Public Assistance. Over 1.5 million people were under evacuation orders along the coastline and more than one million lost power.²⁰ On January 31, 2017 upon proposing a budget investing \$437 million in the Florida Division of Emergency Management, the Governor said in a press release, "With a steadily increasing number of individuals who call the Sunshine State their home, public safety and preparedness are critical priorities. Last year, our state was impacted by two hurricanes and a tropical storm and we saw the incredible importance of being

¹⁹ Letitia Stein, "Hurricane Hermine Slams into Florida, Leaving Thousands without Power," *Huffington Post*, September 2, 2016, [HTTP://WWW.HUFFINGTONPOST.COM/ENTRY/HURRICANE-HERMINE-FLORIDA_US_57C910C5E4B0E60D31DEA11E](http://www.huffingtonpost.com/entry/hurricane-hermine-florida_us_57c910c5e4b0e60d31dea11e).

²⁰ Florida Division of Emergency Management "Loss Avoidance Assessment – Hurricane Matthew," April 2017, http://www.floridadisaster.org/Mitigation/SMF/documents/DR-4283-Matthew/01_DR-4283%20Loss%20Avoidance%20Report.pdf.

prepared before severe weather strikes. These investments ensure that Floridians will continue to have everything they need to keep their loved ones and businesses safe during any potential disaster.”

During the aftermath of Hurricane Hermine, FDOT primarily grappled with massive amounts of debris and downed powerlines. Typically, FDOT does not deal with power lines, but after Hurricane Hermine they had to have power lines moved to get to other debris. This made coordinated efforts with the utility companies a critical component of the emergency response. Hurricane Matthew delivered the same challenges with debris as well as washouts to roadways and around bridges. Repairs to damaged areas required armouring of roadway sideslopes and in some cases sheet and soldier piling.

Interview Findings

The Florida DOT response teams along with sister agencies were well drilled and prepared for both events, having a long history of responding to hurricanes. The early response effort began once winds were down to 40 mph. Staff were deployed to make assessments where roads needed to be closed and barricades installed to keep travelers away from the damage. Sometimes law enforcement were posted in areas that could be dangerous to the public. Portions of Route A1A were washed out requiring both temporary and permanent repairs. In one area, up to a mile of highway was washed away, but FDOT had the area repaired and traffic restored in 14 days. People wanted to get back to their homes, which they had evacuated on the barrier islands, and FDOT responded by conducting bridge inspections right away.

Those interviewed for this study included the Assistant Secretary/Engineering & Operations, the FDOT Chief Engineer, and the FDOT District Secretary for District Three. All three played a role in the response and recovery efforts for both hurricanes. They articulated how experienced and well trained FDOT responders are and that they drill annually for weather events just like these. It has been helpful to the entire effort that government leaders from the Governor down were very engaged and supportive across all agencies. The culture across Florida, in large part due to the constant awareness of the threats, is that everyone understands the emergency response effort and everyone gets involved in preparations ahead of time.



Figure 16 - FDOT District 5 response following Matthew



Figure 17 - FDOT in District 4 during Matthew response

PLANNING AND DESIGN

- FDOT's signs and signals are designed with mast arms along the coastal areas instead of strain poles, to be more resilient and withstand hurricane wind loads.
- FDOT is strengthening areas with sea walls and elevating roads where possible to mitigate flooding.
- The FDOT drainage systems design is being adjusted along the coastline to allow for more efficient water flow out of flooded areas.

POLICIES AND REGULATIONS

- The Governor is very engaged in emergency response, and everyone understands that the transportation system must be up and running as soon as possible after an event.
- The Florida Division of Emergency Management runs trainings and exercises every year with applicable agencies and the division acts as mission control during an emergency, increasing efficiency and collaboration.
- FDOT recently adopted the plan to use shoulders on interstates rather than turning roads into one-way evacuation routes.

EMERGENCY RESPONSE

- FDOT and the State of Florida has a very robust statewide comprehensive management plan that can be a resource to other state DOTs.
- FDOT, with its state and Federal partners, rehearses emergency response plans annually, with a foundation based on a long history of hurricanes. This well-rehearsed plan helped FDOT respond to Hermine and Matthew efficiently.
- Contingency plans are in place for “just about everything” that can occur and are a part of emergency planning.
- After Hermine FDOT is teaming up with utility companies prior to hurricane impacts to better coordinate recovery efforts during debris removal.
- Coordination with utility companies during debris removal activities was critical to the success of bringing the system back on line.

CROSS-CUTTING LESSONS

Many key lessons can be garnered from the DOT case studies. These lessons include plans that went well during an event to those that went awry. The following lessons were supported by more than one DOT case study. The lessons have been categorized by the cross-cutting findings identified earlier as: planning and design, policies and regulations, and emergency response.

Note: Each DOT may agree with ALL cross-cutting lessons, but DOTs are only listed under a lesson if it was specifically discussed in their case study interview.

PLANNING AND DESIGN

		State DOT							
		VT	LA	CO	NC	GA	OK	CA	FL
Lesson	Improve ITS user messaging for drivers				✓	✓	✓		
	Integrate climate change into DOT actions	✓	✓	✓			✓	✓	
	Increase infrastructure resiliency now (HOW?)	✓	✓	✓				✓	✓
	Update design manuals and strategic plans	✓			✓				✓
	Monitor assets for damage or stress before disasters					✓		✓	
	Identify vulnerabilities before disaster strikes	✓		✓					
	When needed information or data does not exist, create it	✓	✓						
	Mitigate for future disasters in advance where possible					✓		✓	

Improve ITS highway user messaging

ODOT is planning to improve its ITS user messaging capabilities; NCDOT is evaluating the current locations of messaging boards to ensure they are situated at critical junctions; and GDOT has since established a better public outreach element to its Georgia Navigator system. NCDOT also implemented a messaging campaign used by the National Weather Service during Hurricane Matthew, which encouraged drivers to “Turn Around, Don’t Drown” in response to drivers passing road barricades.

Integrate considerations of climate change and extreme weather into DOT actions

Several interviewees mentioned the need for DOTs to integrate climate change and extreme weather concerns into all internal processes, recognizing how extreme weather effects may change over time. Resiliency and changes in climate should be considered just as safety is addressed in all DOT actions. It was the belief of multiple DOTs that this would increase efficiency in implementing resilient practices, ensuring that extreme weather/climate change-related risks are on people’s minds at each DOT. ODOT, CDOT, VTrans, DOTD, and Caltrans all expressed interest in changing climate conditions and extreme weather being considered in DOT policies. CDOT is getting a start on integrating a concern for a changing climate into DOT actions through its I-70 pilot project, which is helping the DOT gather data that will be used to prioritize future projects and encourage resilient practices. Similarly, VTrans is interested in knowing where vulnerabilities to extreme weather-related events exist in its road network, to understand how to prioritize projects and allocate resources. Caltrans has been effective in replacing damaged assets with ones that are more resilient, and would like to improve the consideration of future climate conditions in design.

Increase the resiliency of infrastructure projects on all actions

While this lesson is like those above, the difference is that resilient infrastructure does not need to necessarily consider future climate conditions. Some DOTs have already made efforts to develop more resilient infrastructure, based upon these recent extreme weather events and historic data. As an example, FDOT has taken steps to strengthen its infrastructure such as: designing signs and signals to withstand hurricane wind loads based upon past events, protecting roads from flooding via sea walls or elevated roadways, and increasing the capacity of drainage systems for hurricane events.

Update design manuals and strategic plans to reflect climate change and the need to increase resiliency

Another strategy to incorporate climate change, extreme weather and resiliency into design considerations is to update design manuals and strategic plans to reflect these needs. VTrans updated its Hydraulics Manual and Strategic Plan because of Tropical Storm Irene, and NCDOT is also considering updating its own Hydraulics Manual to consider the effects of sea level rise. FDOT has altered its designs in consideration of past hurricane events, including changing the standard for signs and signals to mast arms, rather than strain poles, in hurricane prone areas. Changing climate conditions and increased resiliency require a consideration of the implications of damage and how to invest to ensure that any investments are cost effective when considering a larger definition of risk (economic and social impacts, etc.)

Monitor assets for damage or stress

To identify issues, prevent dangerous situations, and coordinate a timely response, it is important to monitor existing assets for damage from extreme weather. GDOT set up a road monitoring system following the 2014 Atlanta ice storm to identify when roadways begin to freeze and prevent a serious situation as seen in the ice storm. Caltrans was able to recognize two extremely dangerous situations before they had caused any noticeable impacts: the Pfeiffer Canyon Bridge and Mud Creek slides. Caltrans closed off the Pfeiffer Canyon Bridge before it became unsafe to cross, due to a tip from someone walking near the bridge, who recognized that damage was already happening. The Mud Creek area was also determined to be unstable and closed off before the major slide, due to monitoring by Caltrans. Monitoring for other potential effects (precipitation and storm surge) could also reduce impacts on system assets.

Identify vulnerable roadways and assets before a disaster strikes and understand the full range of hazards it may be exposed to

Both CDOT and VTrans are taking steps to identify vulnerable assets and rank the risk to each of these. Considering these vulnerabilities ahead of time can allow DOTs to understand where there are weak points in their systems and respond to these areas first during an extreme weather event. NCDOT has a program in place that allows the DOT to identify at risk assets for various precipitation levels. Knowing the range of hazards that these areas are exposed to may also inform future projects to mitigate for impacts at these locations.

When important information does not exist, create it and reprioritize funding to do so

Informed decisions cannot be made without the data to support them. That is why DOTD and VTrans are undertaking efforts to develop the information they need. DOTD has reprioritized funding to concentrate on data modeling following the 2016 flooding events in Louisiana. VTrans worked with FEMA following Tropical Storm Irene to understand flooding conditions and develop new standards that would ensure structures like culverts are wide enough to accept debris. Data specific to resiliency, from asset data to identifying areas of concern for various stressors (precipitation, storm surge, etc.) will require a new focus for DOTs.

Mitigate for future, similar disasters where possible

GDOT has taken numerous steps to mitigate the impacts of future ice storms following the 2014 Atlanta ice storm. Road sensors have been put into place to better understand road conditions and new procedures have been adopted to pretreat roads in anticipation of ice storms. GDOT has begun adding agricultural vendors to its list of salt suppliers, to prevent another shortage in the future. Caltrans has also taken steps to mitigate for landslide events on State Route 1, due to the historically high-risk location. When assets have been identified as “at-risk,” actions should be taken to mitigate such risks where possible.

POLICIES AND REGULATIONS

		State DOT							
		VT	LA	CO	NC	GA	OK	CA	FL
Lesson	Update policies and approaches when new info is available					✓		✓	
	Understand the risks to assets and rank vulnerabilities	✓		✓					
	Achieve support from leadership staff surrounding resiliency goals			✓				✓	
	Encourage regional coordination wherever possible	✓	✓	✓	✓	✓	✓	✓	✓

Update policies and approaches when new information is available

Caltrans and GDOT staff mentioned that policies and standard operating procedures need to be updated periodically when new information is available or as policies are developed. At present, Caltrans is assessing the Mud Creek landslide to collect more data and perspective on the situation. It will not decide upon an approach until a better understanding of the slide is obtained and the slope conditions better understood. GDOT has also updated its policies to pretreat roadways and procure salt needed before ice storms, after assessing the challenges associated with the 2014 Atlanta event.

Understand the risks to assets and rank the most vulnerable to prioritize future projects

CDOT and VTrans are both taking steps to rank their most vulnerable assets to incorporate into risk-based decision making. CDOT specifically would like to develop a risk-based asset management plan by identifying the most exposed assets and developing strategies which address them. The understanding of exposed assets can be used to prioritize future projects or resource allocation.

Achieve support from leadership staff surrounding resiliency goals

A few DOTs specifically mentioned that top leadership support was critical in achieving the agency's resiliency goals. FDOT found that the Governor's involvement and understanding of extreme weather event's effects on the transportation system has been helpful to their emergency response planning and execution. CDOT also found that buy-in from executive level staff has been critical to conducting its I-70 pilot project. Caltrans has found that the Governor and other state agencies have been supportive in allocating resources to address the impacts of the 2017 coastal landslides and other precipitation impacts across the state.

Encourage regional coordination and preparations wherever possible

Every interviewee discussed the importance of regional coordination and preparations before an extreme weather event occurs. For example, FDOT had a very successful response to the 2016 Hurricanes Hermine and Matthew in large part due to the extensive regional collaboration and preparation it conducted before as part of the State Emergency Response Team. Hurricanes are commonplace in Florida, occurring around one every ten years, and therefore state agencies and organizations are very effective in coordinating efficiently and frequently. FDOT found this system to be a key component to its successful response to Hermine and Matthew. To find out more about Florida response preparations and agency coordination, visit Floridadisaster.org.

The screenshot displays the FloridaDisaster.org website. At the top, there is a navigation bar with links for Contact, FAQs, Search, Site Index, and flags for the United States, Florida, and other regions. The main header features the FloridaDisaster.org logo and the text "Florida Division of Emergency Management". Below this is a secondary navigation bar with links for Public, Business, EM Community, Organization, News Media, and Kids.

The central content area is titled "Current Situation and Weather Update" and includes a "Current Weather" section for Friday, July 21, 2017. The update text reads: "...Typical Summertime Day in Florida...Isolated to Scattered Showers and Thunderstorms Statewide Today...Gusty Winds, Frequent Lightning, Heavy Downpours Possible With Any Storms...Moderate Risk for Rip Currents for Many East Coast Beaches...No New Tropical Cyclone Activity Expected Over the Next 48 Hours...". It is dated "Updated 9:45 A.M. EDT Thursday". Below the text is a small weather icon and a paragraph describing the current weather conditions.

To the left of the main content, there is a sidebar with a "GET A PLAN!" section, a "FloridaDisaster.org" logo, and links to "Get A Family/Business Plan!" and "Get A Plan! Mobile App". Below this is an "About Us" section with a list of links: About the Division, Director's Office, Policy & Finance, Preparedness, Response, Recovery, Mitigation, and Internship Opportunities. At the bottom of the sidebar is a "Severe Weather Awareness Guide" link.

To the right of the main content, there is a sidebar with a "my" logo, a "Level 3 EOC" status, and a "Shelters" link. Below this are social media icons for Facebook, Twitter, and RSS. Further down are "ALERT FLORIDA" and "HURRICANE MATTHEW" and "HURRICANE HERMINE" sections, each with a "Recovery" link. At the bottom of the sidebar are "511 Travel Info" and "Road Closure Information" links, followed by a "Media" section with "Videos" and "Press Releases" links.

At the bottom of the main content area, there is a section titled "Latest Information on Road Closures, Please Visit the Following" with links to "Florida 511" and "Florida Highway Patrol".

Figure 18 - Screen capture of Florida Disaster website, showing weather and contact information

EMERGENCY RESPONSE

		State DOT							
		VT	LA	CO	NC	GA	OK	CA	FL
Lesson	Organize contracts and collaborate with those who may provide aid, beforehand	✓	✓	✓	✓		✓		✓
	Use social media to provide info to the public		✓				✓		
	Emergency protocols need to be put in place for relief funds	✓		✓	✓				
	Have one emergency mgmt. center to coordinate response	✓			✓				✓
	Partner with GPS and mapping applications to disseminate info to public	✓						✓	
	Public safety should always be the top priority during response	✓	✓	✓	✓	✓	✓	✓	✓

Organize contracts and collaborate with other states, counties, DOTs, agencies, etc. who may aid in an emergency, before it occurs

Emergency response needs to be conducted quickly and efficiently. One way that the case study DOTs could mobilize their response in a timely fashion was due to having contracts and MOAs set up before an emergency. On occasions where these were not set up beforehand, some DOTs had to scramble to set them up during the event. ODOT noted that it would have been helpful to have contractors who specialize in debris removal available after a tornado, and is planning to set up these contracts ahead of time to augment its own debris removal. NCDOT also found that having MOAs issued with counties before an event is helpful to mobilize debris removal. MOAs can also be set up with nearby states in case of a disaster and CDOT found collaboration with other states to be crucial to its own flooding response effort. Considering these agreements before an emergency can save time, increase DOT efficiency, and decrease stress during the event.

Use social media to disseminate information to the public

As methods of communicating change, DOTs should also change how they communicate information to the public and begin to use a mix of mediums. Previous methods such as radio or signage may be effective for certain audiences, but not everyone and may be dated given current technologies. Social media can be a useful way to get the word out about storm events, detours, and road closures to keep the public safe when traveling. Both DOTD and ODOT are hoping to increase their use of social media.

Emergency protocols need to be put in place for effective use of relief funds

Another critical aspect of an emergency response is having systems in place for drawdown of relief funds. NCDOT found that automated financial accounting systems were helpful for maintenance and repair. VTrans also found that fiscal resilience was important for the response effort and noted that pre-organized protocols eased the stress during the recovery stages. CDOT encountered some monetary challenges during the 2013 flood response and realized they could have saved funds through bidding instead of force accounting. Having a plan for managing recovery funds before an emergency can streamline the process during and after an extreme weather event.

An emergency management center is critical for coordinating the response

Multiple DOTs noted that having one emergency management center streamlines emergency response. Florida has a Division of Emergency Management, which acts as “mission control” during emergency response efforts. VTrans implemented ICS after Tropical Storm Irene, which was considered very successful, but the ICS was organized during the Storm, with little advance training undertaken on how it should work. Since Tropical Storm Irene, VTrans has held mandatory ICS training to have a plan for future emergency events. One emergency center allows for a central hub to simplify communication and coordination during response.

Partner with GPS and mapping applications to better disseminate information on road closures or detours

Spreading the word about road closures and detours is important to protect anyone who may need to travel at the time of or after an emergency. A frequent challenge reflected in the state case studies and DOT interviews is that the traveling public may not know where to find detour routes or may even go around barricades. North Carolina and VTrans faced this challenge, with both states dealing with multiple route closures due to events or damage. VTrans attempted to address this issue by partnering with Google to create a map showing all closures and detours. Caltrans worked with Waze to create a free app called Quickmap that shows road work locations to reduce backups, among other road conditions.

Public safety should always be a top priority

This was a top priority, mentioned in some way by all DOTs. The public was affected by each of the extreme weather events represented in the case studies above and in some cases, there were even public fatalities. Wherever they can, DOTs should act to protect public safety during extreme weather events. This is especially necessary given that extreme weather events may become more frequent as the climate continues to change.

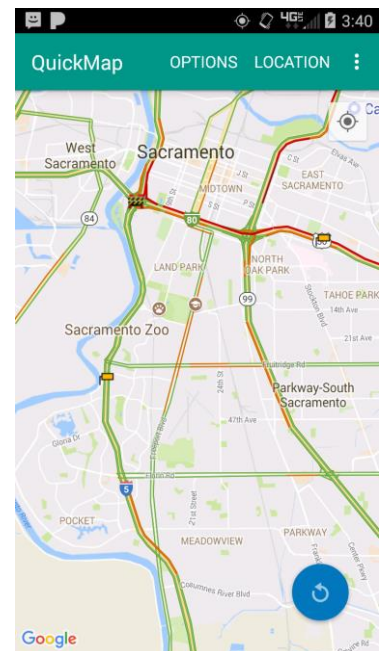


Figure 19 - Caltrans QuickMap screenshot showing traffic, road closures,

CONSIDERING A CHANGING CLIMATE

A recent report by the Federal Highway Administration (FHWA), entitled “Synthesis of Approaches for Addressing Resilience in Project Development,” provides examples of how climate considerations can be integrated into a range of transportation engineering design projects.²¹ As noted in the report, the study provided, 1) information on why, where, and how to integrate climate considerations into the project development process, 2) basic, how-to information in related disciplines such as climate science and economics, and 3) lessons learned, climate sensitivities, FHWA guidance, adaptation options, and knowledge gaps for various engineering disciplines from project-level case studies. The basic premise of this study was that it will be difficult to make assumptions about future temperatures, rainfall, flood levels, and other climate stressors given non-stationarity in future climatic conditions.

Integrating Climate Considerations into the Transportation Project Development Process – As noted in the report, “it is important to consider changing climate impacts and adaptation early in the project development process to ensure that climate resilience is incorporated into the project design to the extent possible and appropriate. It is during the first three stages—planning, scoping, and preliminary design/engineering—that engineering-informed adaptation studies can have the greatest impact on the design features of the project.” As shown in Figure 20, this early consideration should occur primarily in the planning, scoping and preliminary design/engineering phases of project development.

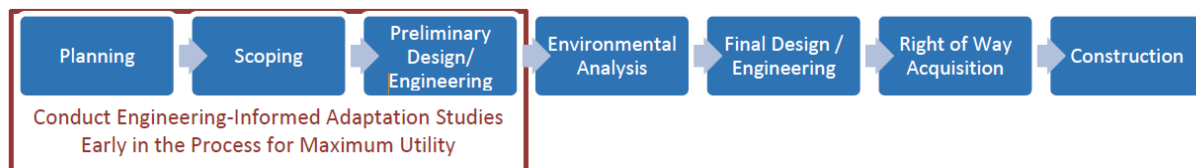


Figure 20 - Primary Focus of Climate Considerations in the Project Development Process

The report then presents information on the five major steps in an engineering-informed adaptation study: using climate information, completing engineering assessments and design, conducting economic analyses, evaluating additional considerations and monitoring and revisiting as needed.

Using Climate Information: Adaptation studies explicitly recognize that future climate conditions, and thus the future environmental conditions for an asset or facility, will likely be very different from what has occurred historically. In the current state-of-practice, engineers draw from long records of historical data to make assumptions about the type of climate an asset will be exposed to over its lifetime. With uncertain future climatic conditions, while the current design standards and engineering methods may still apply, it is more difficult to determine what the future temperature, rainfall, flood levels, and other climate stressors might be. To assess local, weather-related environmental impacts at the asset level, it is necessary to look at locally specific climate projections, which involves considering: 1) future climate scenarios, (2) climate models, and (3) downscaling of model projections, which are at a more aggregate level, and thus a process is needed to refine the resolution of climate projections so

²¹ Federal Highway Administration. 2017. Synthesis of Approaches for Addressing Resilience in Project Development, FHWA-HEP-17-082, Washington DC. July, Accessed August 28, 2017 from, https://www.fhwa.dot.gov/environment/sustainability/resilience/ongoing_and_current_research/teacr/synthesis/fhwahep17082.pdf

that they better reflect expected future local conditions. Importantly, most assets will consist of many different types of components that could be affected differently by future climatic conditions. Table 1, for example, shows the different types of future climate stressors and whether they will likely affect different types of assets. For those critical assets being studied, different climate projections, tools and databases might be necessary to determine likely impacts on the different asset component.

Asset	Climate Change Stressor							
	Extreme Temperature	Inland Flooding/ Precipitation	Sea Level Rise	Storm Surge	Wind	Drought	Changes in Freeze /Thaw	Permafrost Thaw
Pavements	✓	✓	✓	✓	✗	✓	✓	✓
Bridges	✓	✓	✓	✓	✓		✓	✓
Culverts		✓	✓	✓				
Slopes and Soils	✓	✓		✓				✓
Mechanical/ Electrical Equipment	✓	✓		✓	✓			

Note: In the table, check marks indicate where there is a documented relationship between the asset type and the climate change stressor, X's indicate where it is very unlikely that there is a relationship between the asset type and the stressor, and blanks indicate where there is little or no research on the topic.

Table 1- Climate Stressors That Could Affect Asset Categories, Per the FHWA Sensitivity Matrix²²

Develop, Evaluate, and Select Adaptation Measures: This section of the report describes how transportation professionals can identify, evaluate and select the most appropriate and cost-effective adaptation strategies for different assets facing different types of climate stressors. The discussion is divided into two areas, 1) completing engineering assessments and design, and 2) conducting economic analyses.

Completing Engineering Assessments and Design: The study examines many different types of adaptation designs for different assets, including those located in coastal and riverine environments, and for design components such as pavements, soil foundations, and mechanical and electrical systems. For each area, the sensitivities of that design component to changes in local, climate-related environmental conditions, different types of adaptation strategies, existing research on climate impacts, the lessons learned from the study's case studies and knowledge gaps are presented. This information is too extensive to repeat here, but as an example, the lessons learned for pavement and soils are shown in Table 2.

²² FHWA Sensitivity Matrix is available at:

https://www.fhwa.dot.gov/environment/sustainability/resilience/ongoing_and_current_research/gulf_coast_study/phase2_tas2/sensitivity_matrix/

Lesson Category	Lessons
Impacts on Pavement	Changes in temperature and precipitation could have widespread impacts on pavement performance, resulting in significant adaptation costs.
	Temperature and moisture changes affect the entire pavement system.
	Pavement designers will likely have to account for climate uncertainty when assessing existing pavement systems and developing pavement mix designs.
	Changes in climate could affect seasonal truckload restriction policies.
	Although the current state of climate model data is not “plug-and-play” with current pavement design and analysis tools, practitioners can frequently develop workarounds.
Impacts on Landslides and Rock Falls	Detailed climate data are not necessary for an initial, general assessment of changing climate impacts on soil stability.
	To determine if changing climatic conditions could increase weathering, practitioners should consider projections of freeze-thaw cycle frequency, temperatures, and precipitation amount, as well as the relative timing of these events.
Impacts on Permafrost Thaw	Location-specific permafrost and soil data are critical.
	The warming associated with a changing climate may be too great to enable long-term prevention of permafrost thaw underneath a roadway.

Table 2 - Lessons Learned from Pavement and Soils Engineering Adaptation Assessments

Conducting Economic Analyses: Given that most agencies have a limited amount of resources for their investment programs, some form of analysis needs to be conducted to determine the relative benefits and costs associated with the alternatives under consideration. An economic analysis focuses on the comparative costs and benefits of alternatives and serves as the return-on-investment analysis for public agencies. In the context of climate-related adaptation measures, economic analyses quantify costs and benefits of different project options under each climate scenario. The report discusses both benefit/cost, net present value and life cycle cost analysis (LCCA) approaches to conducting economic analyses for climate adaptation decisions. As noted in the report, traditional approaches to economic analyses need to be modified when considering the benefits and costs associated with climate change adaptation strategies. For example, LCCAs in transportation projects have not traditionally considered damage repair and socioeconomic costs due to extreme weather events and changing climatic conditions (e.g., increased travel delay costs, disruptions to the regional economy). Not including these climate-related costs may underestimate the benefits of avoided climate change-related impacts.

Other differences in a climate-sensitive economic analysis could be incorporated into the scope of such an analysis effort. For example, an appropriate scope and complexity of an economic analysis of an adaptation measure can depend on the following factors:

- *“Resources available.* Economic analyses may be demanding, in terms of time, data, and expertise. Some economic analysis approaches are more resource-intensive than others and the approach practitioners decide on may depend on the amount of resources available.
- *Relative cost of implementing the adaptation measures(s).* If the adaptation measure is inexpensive, it may not make sense to do a detailed economic analysis. If the adaptation measure involves a significant investment, a detailed analysis might be warranted to help select the most appropriate course of action.
- *Cost of the facility.* Generally, analyses of lower cost facilities might entail greater use of assumptions regarding various economic parameters under future climate conditions, whereas more expensive facilities may warrant better estimates. For higher cost facilities, more money is at stake, so it may be worth a higher investment in the economic analysis to make sure the most appropriate adaptation measure is selected.
- *Consideration of the broader system.* An economic analysis with a wide scope that includes the broader system may be informative about the economic impact of the adaptation measure on the network. A large project will likely have impacts on the broader system. In some cases, discrete decisions across a network may have a greater effect than a decision pertaining to one big project. For example, decisions at lower cost facilities repeated throughout a network can have a large impact.
- *Risk tolerance.* If an agency has low risk tolerance for failure of an asset, adaptation measures could be put in place regardless of the costs. Economic analyses should still be conducted to select the most cost-effective alternative. Additionally, an agency’s risk tolerance can also relate to overinvesting. If there is low risk tolerance for potentially overinvesting, then it may make sense to do a more detailed economic analysis.
- *Timeframe.* It is best to conduct the analysis to cover the expected service life of the asset to enable a full LCCA and fully capture the costs and benefits of the design alternatives under a long-time change in climate. A longer analysis period is preferred, especially for adaptation measures with large upfront costs and benefits that may not actualize for many years. It is also important to consider consistent analysis periods between multiple adaptation measures for a comparative analysis.
- *Geographic scope.* It is important to consider the appropriate geographic bounds for the economic analysis. For instance, while economic activity in an area with a road closure due to climate impacts may be stifled, activity may increase in neighboring communities. Consider whether the neighboring communities would be included in the analysis.”

The study examines the advantages and disadvantages of different approaches in defining benefits and costs and accounting for uncertainty in estimating both for future climate scenarios.

Evaluating Additional Considerations: Transportation investment decisions are influenced by a range of concerns and external (to the agency) factors. The report observes that such factors can include those relating to: additional environmental issues, impacts on the local economy, societal goals, governance structures, conflicting agency priorities and systematic considerations, such as changes in environmental conditions, traffic composition and levels and the role that an asset plays in the transportation system.

Monitoring and Revisiting as Needed: This step in the adaptation study effort constitutes the “feedback loop” into agency decision making in that it provides the capability of monitoring asset performance over time to gauge how it is performing, considering changing environmental conditions. The report suggests several ways an agency can provide this monitoring effort.

- A facility management plan can be developed to determine when to implement adaptation measures and ensure the project continues to perform as designed under changing climate conditions.
- The agency can encourage and adopt an *adaptive management* approach to asset design that provides for future flexibility in modifying assets when needed, especially in light of uncertainty in future climate change projections.
- Phased adaptation strategies can be incorporated into an overall asset management strategy. Incorporating adaptation planning into asset management helps to ensure that adaptation is considered in a systematic manner alongside other needs for maintenance and repair.
- Monitoring the performance of a facility and regional climate trends after a project is constructed allows a periodic assessment to determine if an asset’s design standards are being exceeded.
- Monitoring land use or demographic changes provides the ability to assess any changes in the functional use of the asset.
- Assumptions about how the asset will be exposed to climate change stressors could change as information improves over time. Thus, agencies should periodically revisit the assumptions made in the original adaptation study.
- Advancements in engineering may make new adaptation measures feasible or lower the costs of others. An agency should develop an internal procedure for monitoring relative cost-effectiveness of potential adaptation solutions.

One of the most useful contributions of this study is the list of overarching lessons learned from the study’s case studies. See the appendix, which lists these lessons.

CONCLUSIONS AND NEXT STEPS

This study has shown that state DOTs have been responding to a variety of extreme weather events with varying levels of success, while at the same time learning and adapting about how to make improvements to how the agency will respond in the future. As noted at the beginning, state DOTs have been considering weather conditions in project design at some level from the very early years of road building. However, what is different in today's world, and even more likely in the future, is that the frequency and intensity of this extreme weather may be much worse or more frequent, and given the development and urbanization patterns over the past 50 years, more Americans are likely to be impacted by the consequences of such storms. Many states have recognized this and have undertaken, or are currently undertaking, efforts to identify assets that are vulnerable to extreme weather conditions, and are considering approaches to planning, design, operations and maintenance that reflect these vulnerabilities. The case studies in this study indicate that state DOTs do learn and evolve in response to their experiences with extreme weather events. The movement toward better preparing for future events is motivated not only by a desire to protect state investment in its transportation infrastructure, but also by a concern for the economic and social impacts associated with an impacted transportation system.

The previous section summarized the key lessons learned from the case studies. These lessons also lead to identifying some next steps for how planning and design, policy and regulation and emergency response can be better prepared for the next extreme event.

Planning and Design: Given the potential disastrous consequences of extreme weather events, it makes sense to think strategically how the transportation system can be made more resilient to the stresses that come from such events. The more successful state DOTs in emergency response and recovery are those that anticipate potential pitfalls, and that put in place the institutional structure, resources and partnerships needed to react and respond to natural disasters. In addition, those states that systematically identify asset vulnerabilities provide an important piece of information for efforts to minimize the damage and disruption associated with these events. In other words, those state DOTs that plan ahead, will be in the best position to reduce the consequences of climate change and extreme weather. Such planning could include identifying system vulnerabilities, associated risks, endangered populations, potential strategies for reducing risks, and creating the institutional structures for managing effectively the state DOT response to an extreme event.

From the design perspective, one of the ways of avoiding or at least minimizing damage to transportation assets is to use designs that are flexible enough to withstand extreme stresses. The FHWA is currently conducting a study that is examining such flexible designs, and several state DOTs that have faced extreme weather events (such as FDOT) examine the effectiveness of designs considering the changing environmental conditions. It seems likely that some form of risk-minimizing design process will be an important tool for state DOTs in designing facilities and other assets in areas that are highly vulnerable to extreme weather events.

Policy and Regulation: Most of the state DOT officials interviewed stressed the importance of top agency leadership support in implementing actions to improve the resilience of the transportation system and of the agency itself. One of the ways of doing this is to adopt policies and directives that guide agency staff on how resiliency should be considered in different functions in the agency. It is no

accident that Vermont, one of the hardest hit states from a national disaster, updated the DOT's strategic plan to include new ways of looking at transportation planning and design given the lessons of Tropical Storm Irene. It is important that the policy documents, operating procedures and regulations that guide agency staff clearly articulate the importance of resiliency in the agency's activities. As one state DOT official interviewed for this study stated, "resiliency should be found throughout my agency's efforts just as much as safety is."

Emergency Response: The experiences of the case study DOTs indicate that there are two important perspectives in considering efforts to improve emergency response. The first focuses on the state DOT's actions themselves, and how effective they are and how they can be improved given new technologies and applications. Examples in the cases studies include the use of ITS technologies to provide better information to highway users to partnering with Google and other providers in providing better information on detours and road closures. The use of social media has also been an important step adopted by many of the case study DOTs in improving their outreach to the public. Improving an agency's response can occur by doing a post event assessment of what could be done better next time (as many of the case study DOTs did) or by looking at what others have done to identify strategies that could be adopted in their own agency.

The second perspective on emergency response is that successful efforts involve more than just the DOT. Partnerships with state police, other state agencies, federal agencies, local agencies, tow truck operators, media outlets, and a host of other agencies and groups are essential to respond to extreme weather emergencies. This often entails establishing an institutional arrangement of responsibility and command/control during the event itself, as well as identifying responsibilities post event. Several of the case study DOTs, for example, noted that one of the key challenges post event was clearing the debris, and often the need to help clear the roads off the state highway network. In other cases, conflicts between state DOT responsibility for declaring state highways safe has conflicted with local officials desires to have residents return as soon as possible to their neighborhoods. In many instances, it has been the strength (or lack thereof) of the institutional framework for emergency response that has been a key determinant in how people viewed the effectiveness of the governmental response. Establishing clear lines of responsibility, communication and authority, combined with training in simulated emergencies, is a critical factor for the success in state DOT response to extreme weather events.

APPENDIX

Lesson Category	Lessons Learned
Scoping Asset-Level Adaptation Assessments	Flexible approaches are best.
	Focus data collection on the most critical elements, utilizing readily available data.
Applying Climate Science and Managing Uncertainty	While engineers should alter the inputs to engineering analyses due to climate change, the applicable design standards should not be altered.
	The use of historic climate data in lieu of climate projections is sometimes appropriate, but historic data should always be as up to date as possible.
	Maintenance records from extreme weather events can help practitioners understand the likelihood of future infrastructure damage.
	Historical climate data may be useful for a first-cut assessment of relative vulnerability and to narrow the number of assets that require detailed analysis, but to incorporate non-stationarity into a design, climate modeling projections should be used.
	Climate projections developed specifically for the study region by qualified climate scientists/modelers can help account for unique considerations.
	Existing tools can translate climate model outputs into variables that are appropriate for engineering design.
	Practitioners can compare climate projections to historical/observed climate values to increase integrity of results.
	The range of possible future emissions and climate scenarios should be considered, rather than focusing on just one projected scenario.
	Increases in the frequency of smaller, nuisance events should be considered in addition to extreme weather events.
	Given climate uncertainty, taking an incremental approach to adaptation may help reduce the risk of overspending while still increasing resilience.
Integrating Climate and Weather Risks into Asset Management	To avoid misinterpretation, engineers need to understand differences in conflicting future precipitation climate narratives that may be generated by groups of various climate models.
	Feeding information gathered and produced through engineering-informed adaptation studies into asset management programs may assist with more robust decision-making.
	Data generated from asset management systems may be leveraged to augment engineering-informed adaptation studies.
	Climate change and extreme weather event risks should be considered alongside other risks and agency priorities in asset management plans.

Lesson Category	Lessons Learned
	Practitioners may want to consider the impact of future environmental conditions on deterioration rates when conducting lifecycle planning.
Breaking Down Silos	Coordination among agencies with a vested interest in infrastructure resilience limits incompatible initiatives.
	Dialogue and communication across disciplines helps discourage barriers when undertaking climate change studies.
Selecting and Implementing Adaptation Measures	It may be helpful to define failure and how it could occur before selecting an adaptation strategy.
	Existing infrastructure designed using current or older climate data sets may still have a level of resiliency under future climate conditions.
	Many climate adaptation measures will be amplified forms of countermeasures currently installed to manage risks associated with today's environmental conditions.
	When selecting adaptation measures, the remaining life of the facility is important to consider.
	An adaptation portfolio approach to risk mitigation is likely to result in a suite of potentially viable options.
	When conducting analyses and selecting adaptation measures, policy-makers should provide guidance on risk tolerance across assets.
	Ecosystem-based adaptation and non-structural solutions may provide similar protection but broader project benefits.
Understanding Conservatism in Design Assumptions	Long-term strategic land use planning can be an alternative to modifying the transportation asset.
	Multiple conservative assumptions can compound to produce an overly conservative result.
Considering the Bigger Picture	Additional criteria routinely applied in designs may provide additional conservatism.
	Regional or corridor-scale vulnerability and criticality screens bring focus to asset-level studies.
	Sometimes the most appropriate adaptation measure can only be identified when considering the bigger picture.
	Avoid creating stranded assets or "adaptation islands."
	An adaptation strategy at a broader geographic scale may be appropriate.
	When evaluating adaptation strategies, it is important to consider potential secondary impacts or cascading consequences of a failed asset.
	Potential impacts on adjacent property due to proposed construction conditions should be addressed when designing for adaptation in urbanized areas.
	Post-event assessments of damage mechanisms can provide information for enhancing resilience to extreme events.
	Marine vessels have lower adaptive capacity than road users to disruptions at coastal bridges.

Table 1 - FHWA lessons learned for transportation engineering design projects

Additional event photos provided by state DOTs :

Courtesy of VTrans

Additional photos of Super Storm Irene as well as other VTrans photos can be viewed here:

<https://www.flickr.com/photos/vtrans/albums/with/72157637841859396>

Courtesy of CDOT



Figure 1 - US 34 East of Greeley washout



Figure 2 - US 34 East of Greeley, replacement of roadway with bridge to pass future flows in the area



Figure 3 - US 34 East of Greeley, bridge in 2015 allowing water flow beneath it

Courtesy of NCDOT



Figure 4 - Damages in Fayetteville, NC



Figure 5 - Further damage to roadways in Fayetteville, NC

Courtesy of Caltrans



Figure 6 - Damaged Pfeiffer Canyon Bridge



Figure 7 - Damaged Pfeiffer Canyon Bridge



Figure 8 - Pfeiffer Canyon Bridge rebuild

Courtesy of FDOT

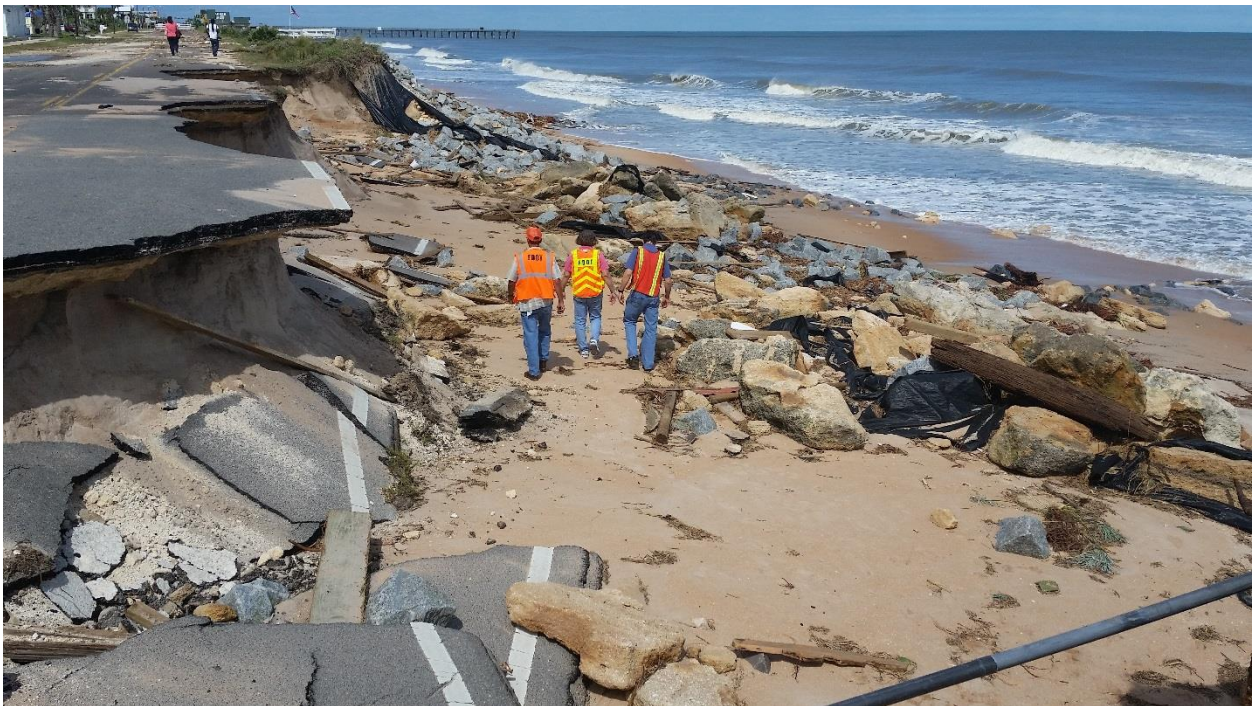


Figure 9 - A1A damage assessment



Figure 10 - A1A repairs begin



Figure 11 - Governor re-opens A1A



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