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Infrastructure Resilience: Methodologies and Applications

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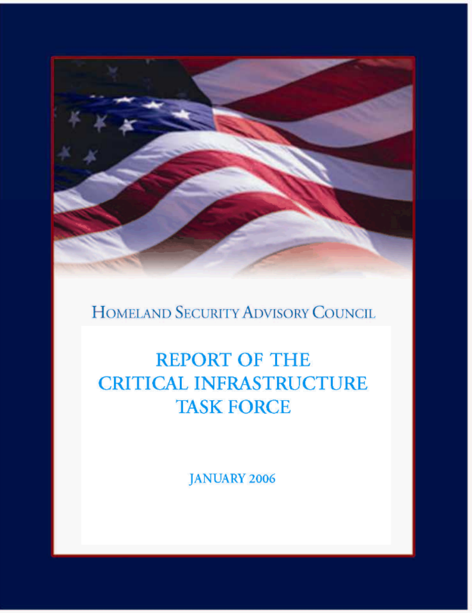
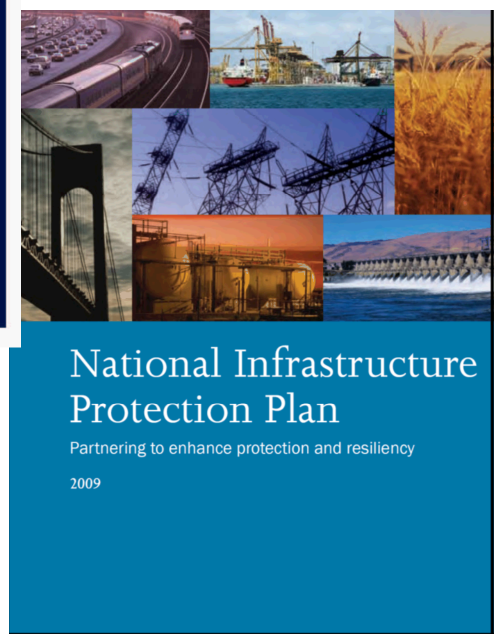
Infrastructure Security is Evolving

- Threats
  - “Bad actors”
  - Natural Disasters
  - Accidents
  - Cyber attacks
- Evolving strategies
  - Physical protection
  - Risk analysis
  - Resilience

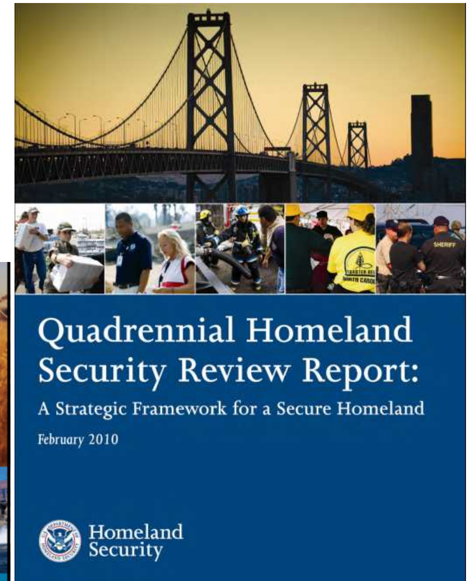
Emergence of Resilience in US Security Policies



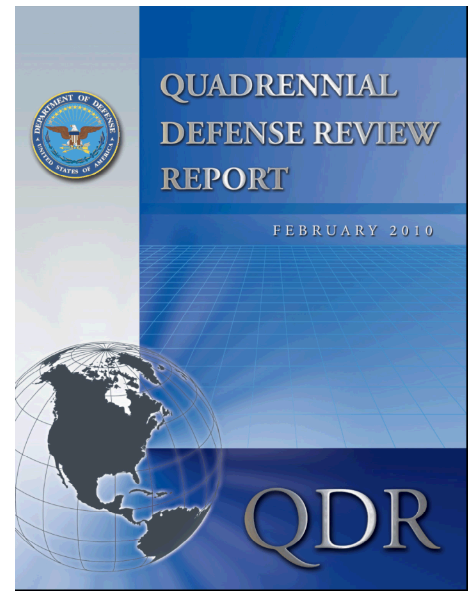
2006: a call for resilience



2009: resilience elevated to same level of importance as protection



2010: Mission 5- "ensuring resilience to disasters"



2010: "Increase the resiliency of U.S. forward posture and base infrastructure"

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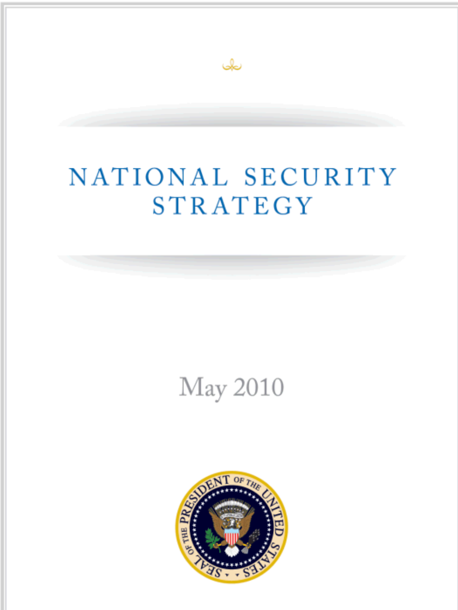
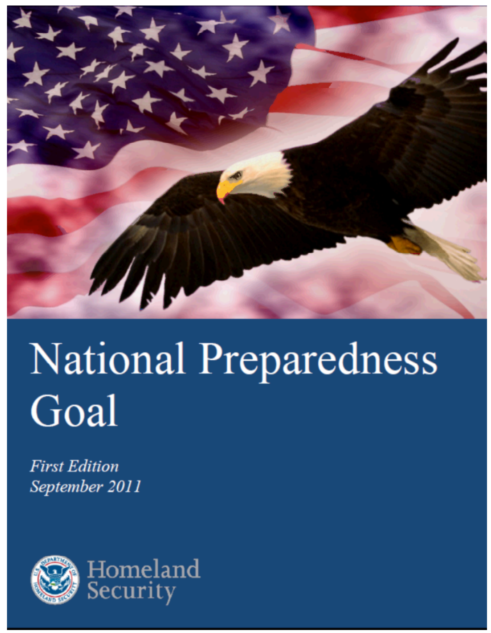
Emergence of Resilience in US Security Policies (2)

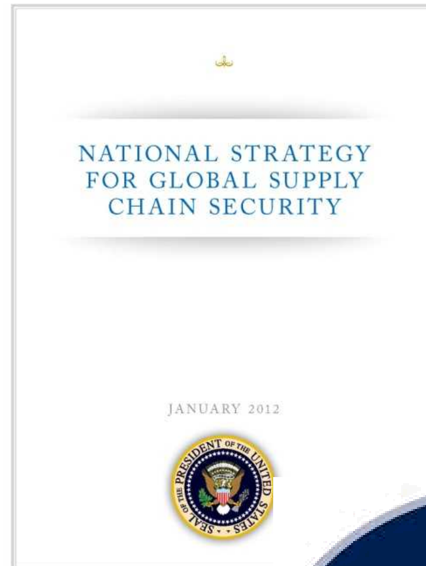


2010: advance US interests by "Strengthen[ing] Security & Resilience at Home"



2011: Definition of success- " a secure and resilient nation…"

Elements of preparedness include prevention, protection, mitigation, response, and recovery



2012: Strategic goal 2 (of 2)- "Foster a resilient supply chain"

PPD-21 Critical Infrastructure Security & Resilience

2013: "advances a national unity of effort to strengthen and maintain secure, functioning, and resilient critical infrastructure"

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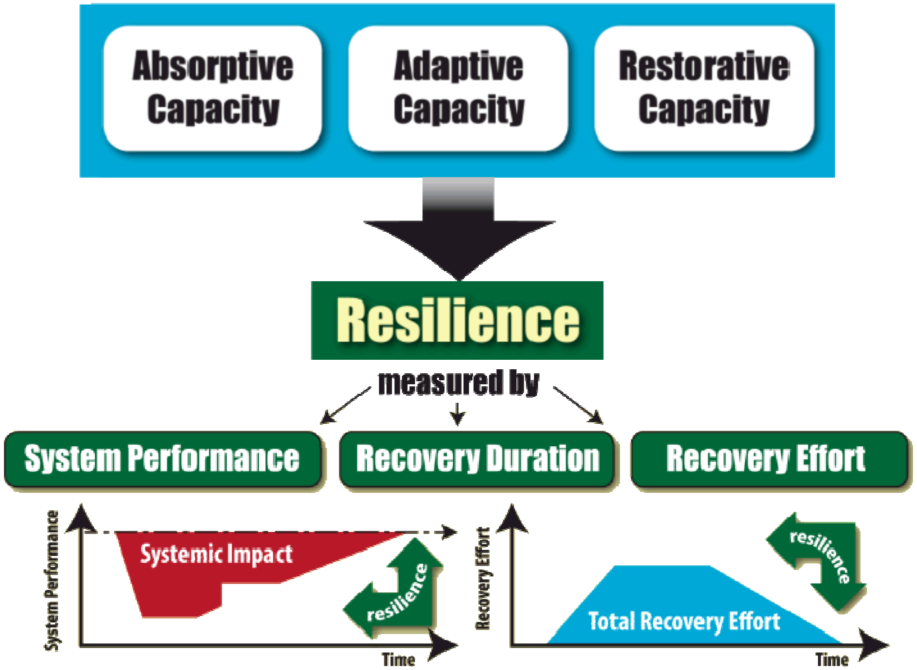
Challenges

- Lack of commonly accepted definitions and methods
- Extent of subjectivity in existing methods
- Disconnect between definitions and metrics
- Resources constraints and costs are often ignored

These challenges are especially important for resilience modeling and analysis.

Infrastructure Resilience Analysis Methodology (IRAM)

- Define
- Measure
- Analyze
- Improve



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Definition: Key Points

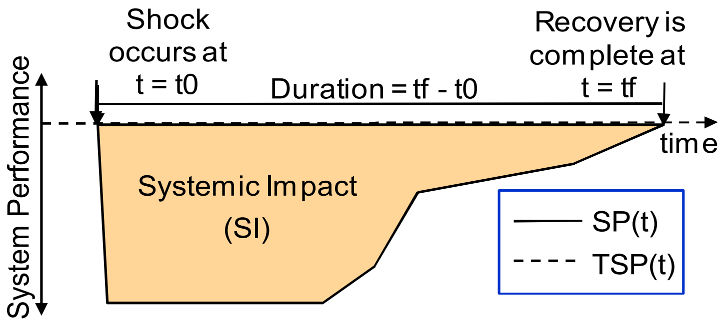
"Given the occurrence of a particular, disruptive event (or set of events), the resilience of a system to that event (or events) is the ability to reduce efficiently both the magnitude and duration of the deviation from targeted system performance levels."

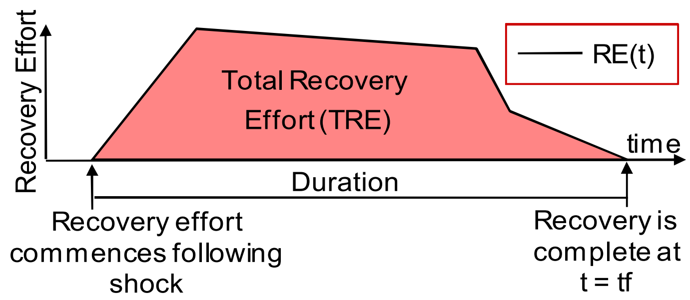
-Vugrin et al., 2010

- Context matters
- Performance
  - Magnitude and duration
  - Target level
- Efficiency is "tip of the hat" to importance of resources

Metrics

- Systemic Impact (SI): cumulative impact of disruption on infrastructure's ability to provide goods and services
- Total Recovery Effort (TRE): cumulative resources expended to attain performance goal
- Feedback between SI and TRE
- Resilience index: linear combination of SI and TRE
  - Comparative analysis
  - Optimal recovery
  - Investment





Attribute Analysis: 3 Capacities

	Absorptive Capacity	Adaptive Capacity	Restorative Capacity
Directly Impacts	Systemic Impact	Primarily Systemic Impact, but also TRE	Total Recovery Effort
Distinguishing features	Automatic manifestation after disruption	Reorganization and change from standard operating procedures	System repair
Temporal Sequencing	First line of defense	Second line of defense	Final line of defense
Post-disruption event required	Automatic/little effort	Increased effort	Greatest effort
Duration of changes	Permanent	Temporary	Permanent
Resilience enhancement feature examples	Stored inventory; robustness; redundancy; segregation	Substitution; rerouting; conservation; reorganization; ingenuity	Advance warning and monitoring systems; pre-positioning; reciprocal aid agreements

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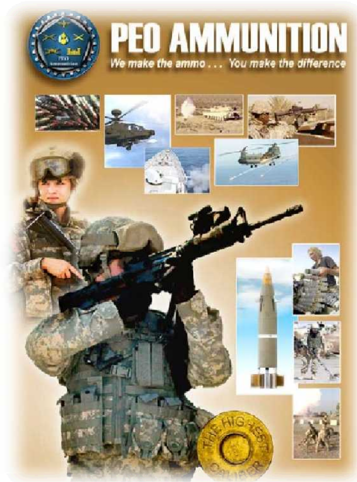
Resilience Studies

Comparative Infrastructures Resilience for a New Madrid Earthquake

Optimize Recovery Strategies for Rail Systems after Mississippi Flooding Events



Evaluate Resilience Enhancement Strategies for Military Supply Chains

Analyze Resilience of Chemical Supply Chains to Hurricanes

Energy Security Assessments for Mission Assurance

Resilience Certification Program

Climate Adaptation

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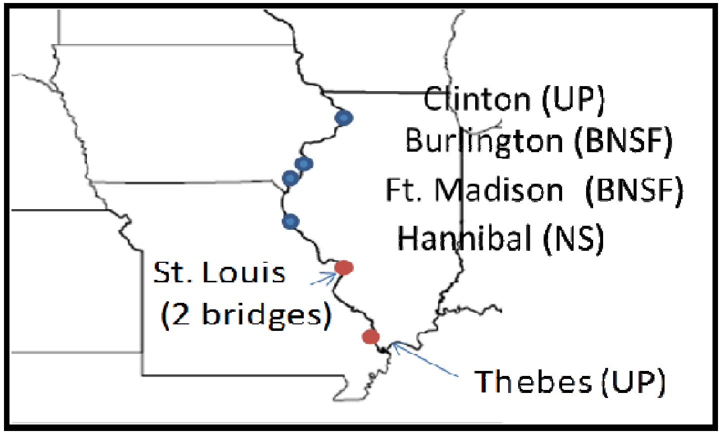
Scenario

- 4 rail bridges on Miss. River out due to flooding
- 3 bridges unaffected

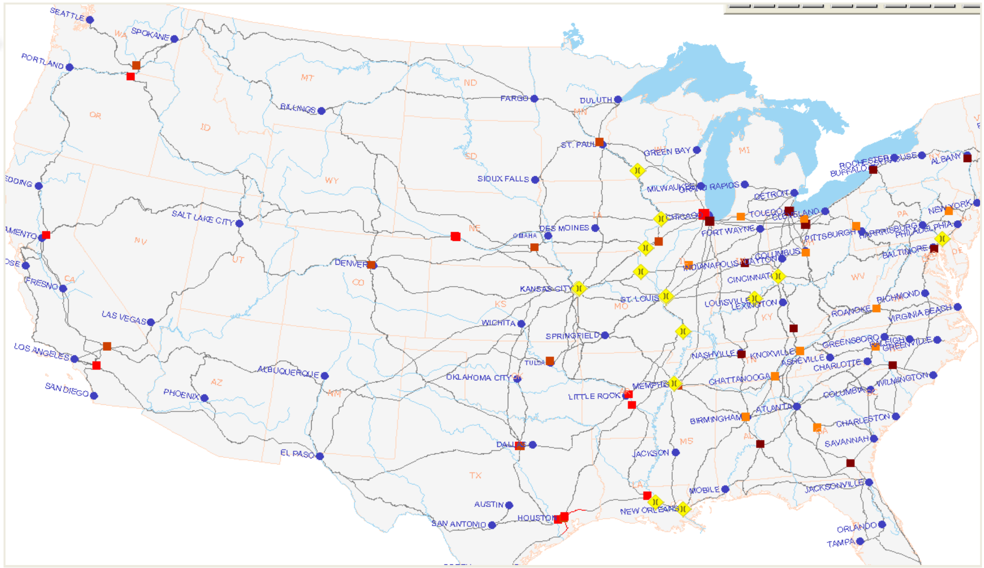


- East-West rail traffic significantly affected
  - Chicago is the largest east-west interchange point
  - Traffic between Chicago and Kansas City, Omaha and Denver expected to be disrupted

Problem Formulation

- Question: what is optimal recovery strategy for maximizing resilience?
- Challenge: keep railcars moving despite <u>limited resources</u>
- Recovery options
  - Recovery sequences: when do we fix a bridge
  - Recovery mode: how do we fix a bridge
  - Resource allocation: how do we split resources

A Freight Rail Network Model



- Rail Network Analysis System (R-NAS)
  - Static, nonlinear optimization model developed by NISAC for consequence analysis
  - R-NAS solves for network flows under the assumption that car-miles are minimized
  - Distances and congestion “delay functions” determine travel times and distances

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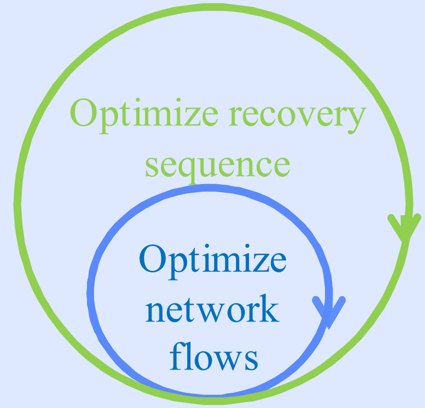
Model Customization for Resilience Analysis

- Model additions: dynamics of recovery
  - Repair modes: nominal, emergency, staged
  - Repair sequences: in what order do we repair
- Parameter additions
  - Repair durations (for each mode)
  - Repair resource requirements (for each mode)
  - Repair costs (for each mode)
  - Costs of “adaptation” (e.g., rerouting) and delays
- Recovery optimization
  - Integrate resilience metrics
  - Bi-level optimization problem
  - Implemented simulated annealing (SA) algorithm “on top” of R-NAS
  - Customized SA algorithm to enhance computational efficiency



Bilevel programming model

Static Results: 4 bridges out

Commodity Group	Additional Car-Miles	% Change	Additional Car-Hours	% Change	Not Moved
Coal	169929	2.9	294479	97.2	58
Grain	-26182	-2	6892	3.2	700
Chemicals	28220	1.6	14234	3.3	819
Intermodal	213801	15.4	31928	48	1146
Motor Veh	45550	3.2	61109	87.1	355
Other	88613	1.6	15616	1	2539
Total	519931	3	424258	15.9	5617

- Daily lost revenue (CNM) = $9.9 M/day
  - # of cars moved decreases by > 1/3
- Daily Add. Car Miles= $830k
- Daily Add. Travel Time= $700k
  - Average additional car-hours increase: 16%
  - Nearly double for coal and motor vehicles

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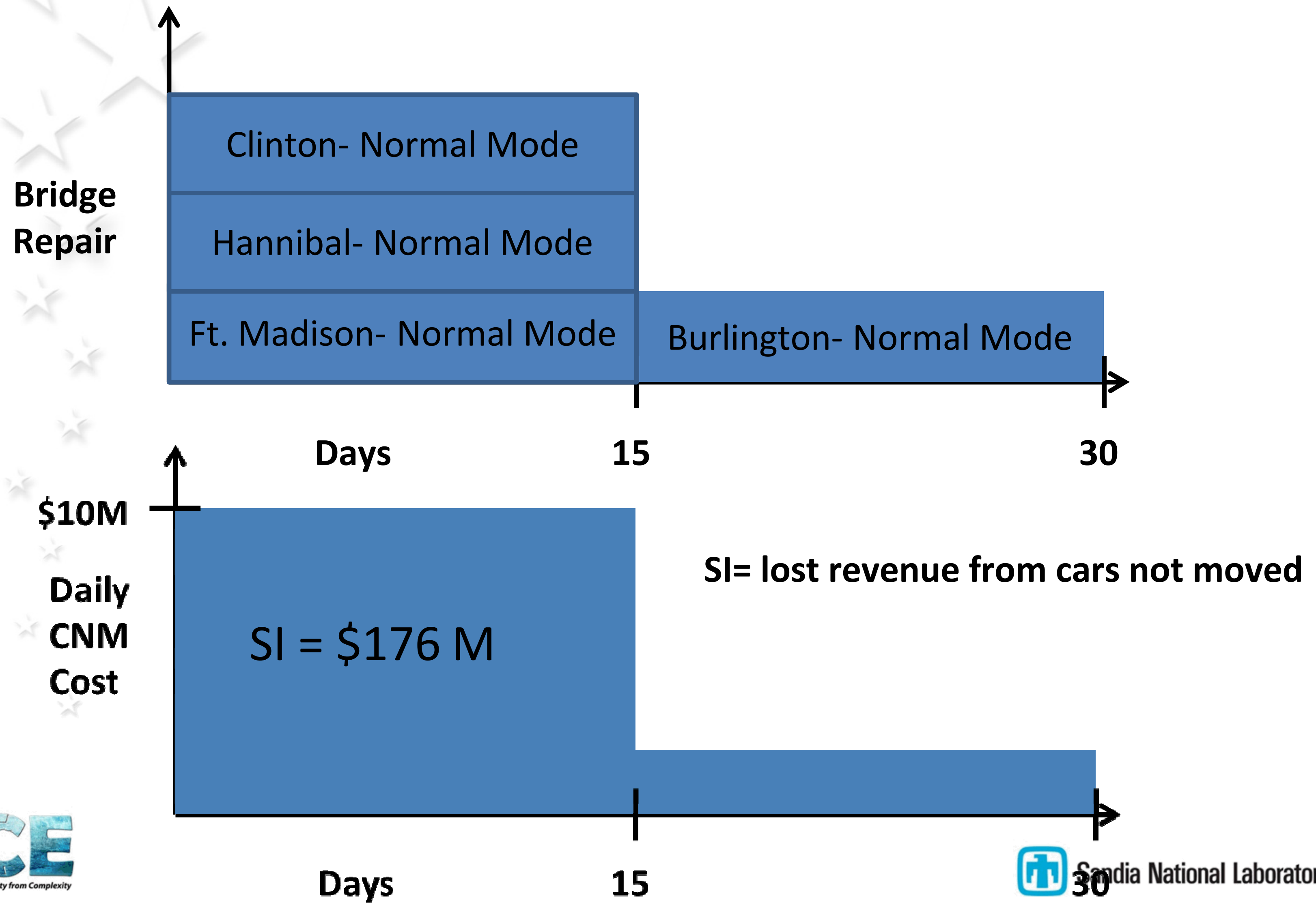
Calculate Resilience Index

Recovery sequence for nominal case, no cooperation



Calculate Resilience Index

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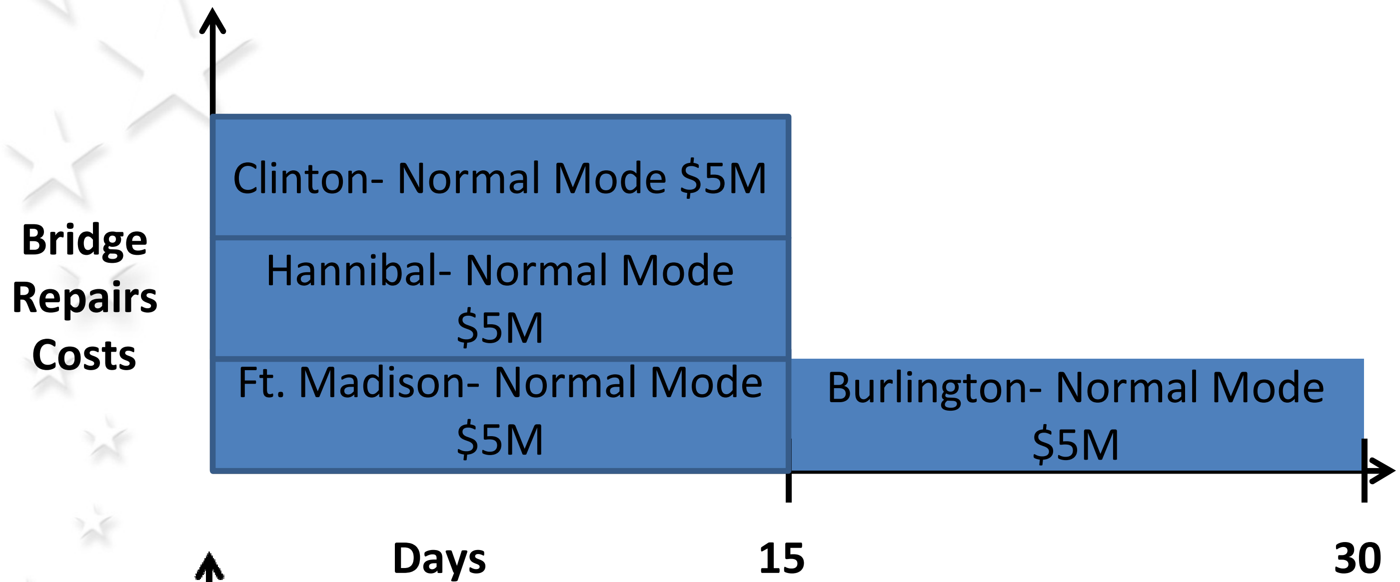
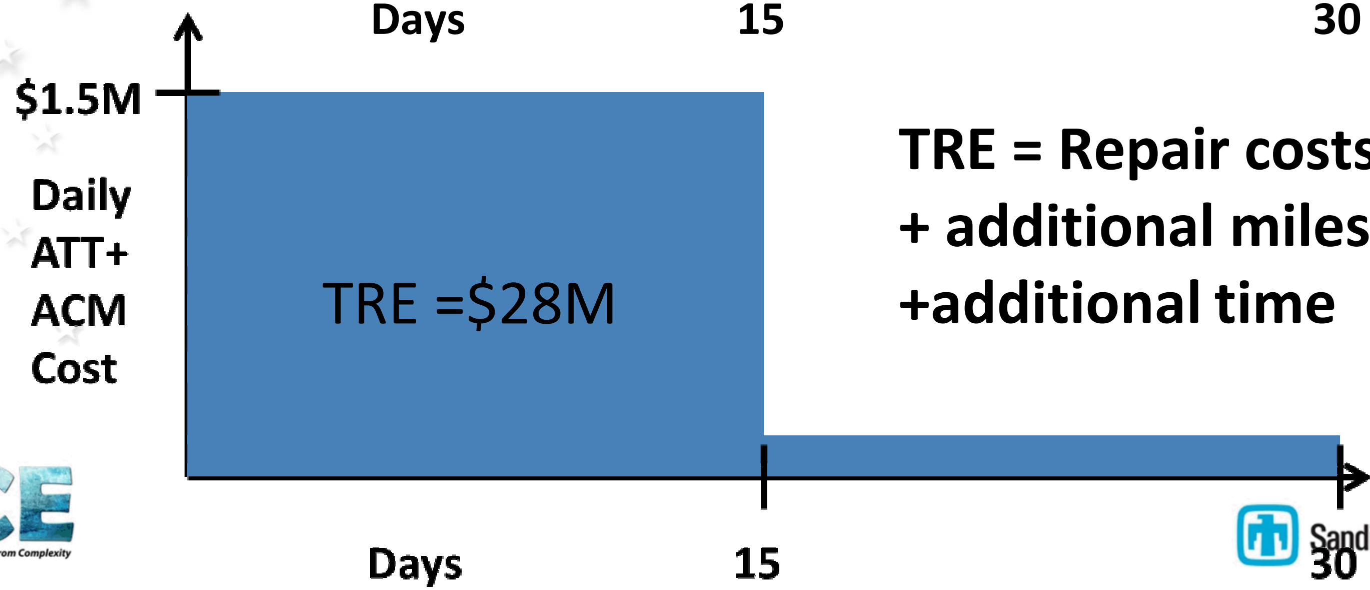
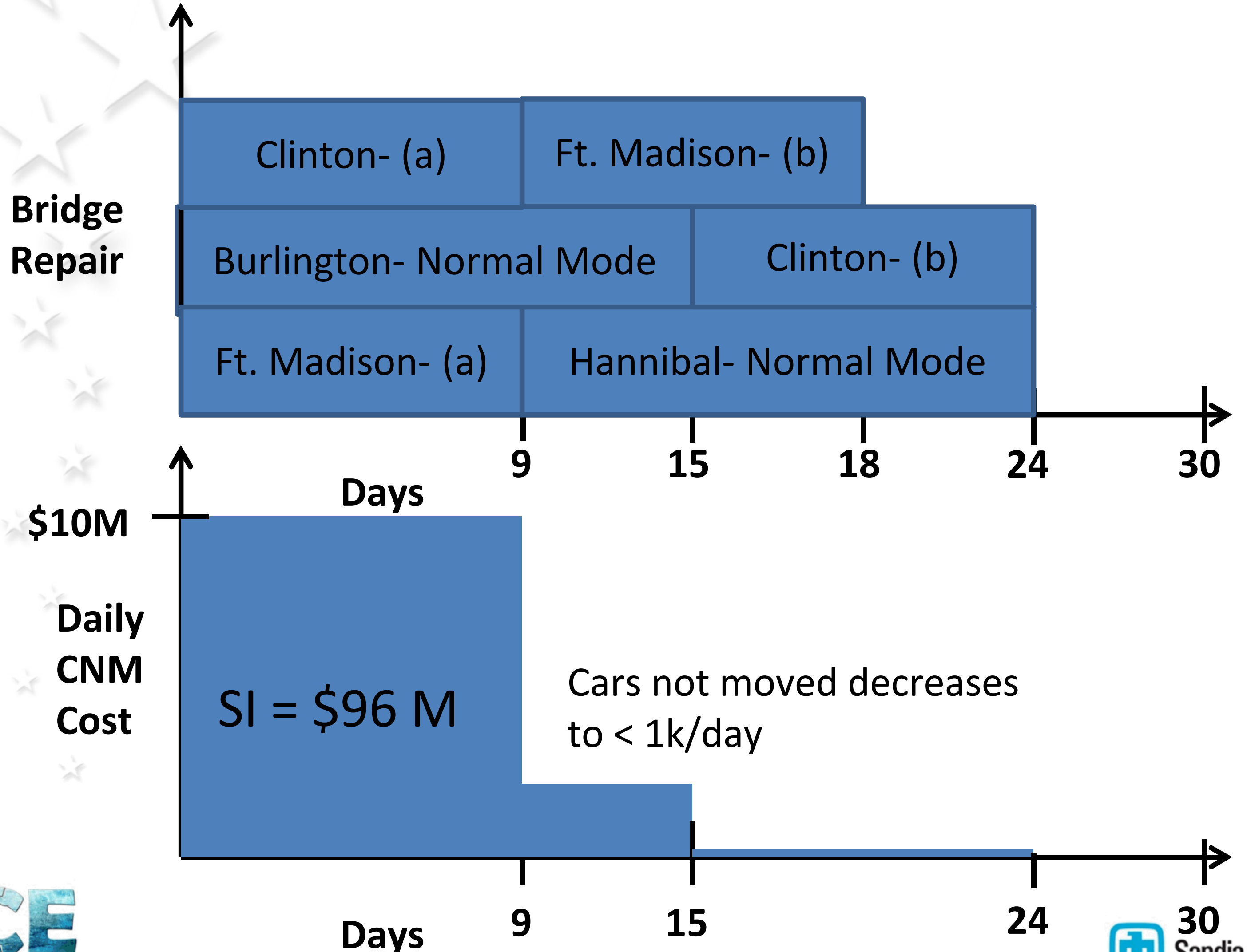




TRE = Repair costs + additional miles +additional time

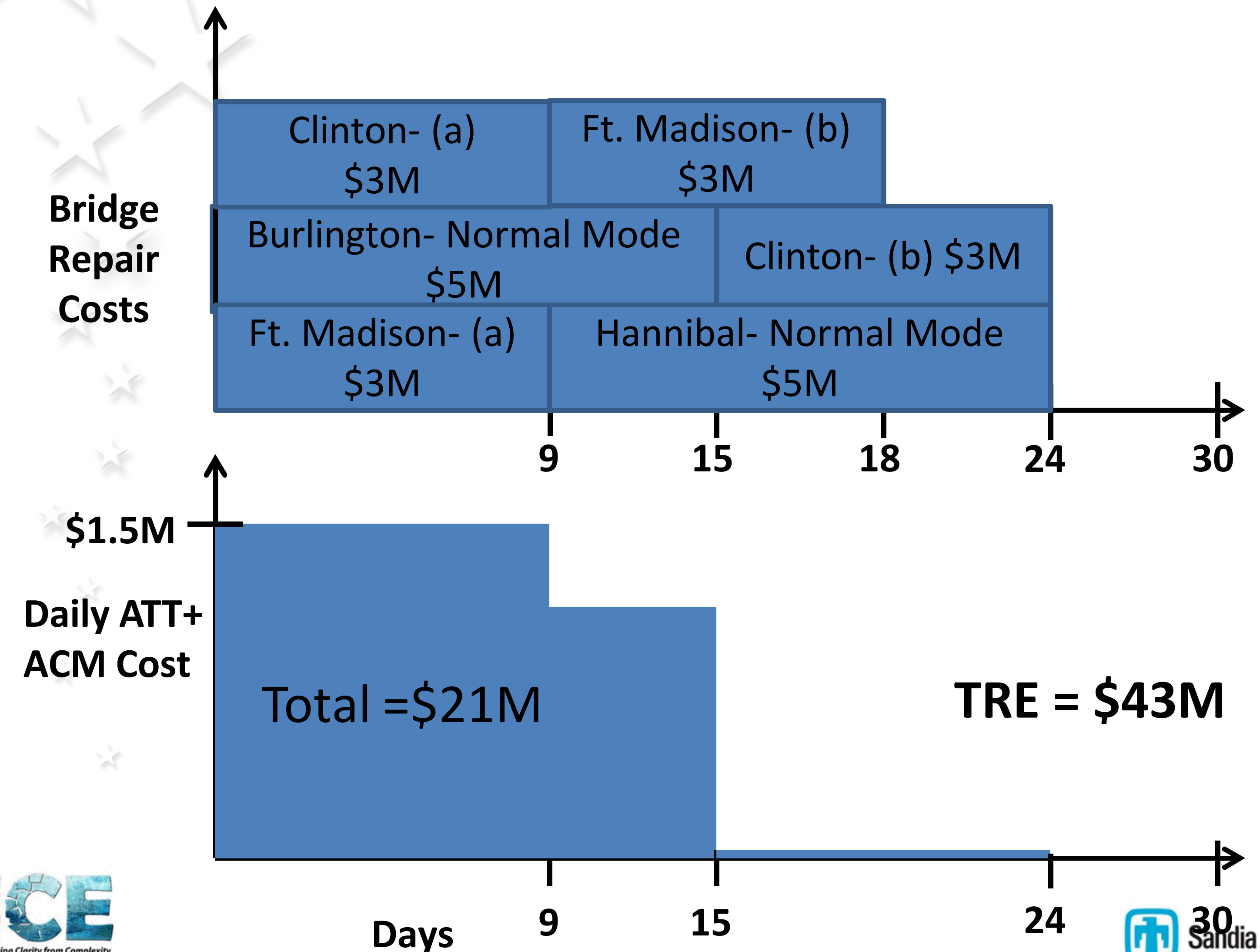
Calculate Resilience Index

Optimal recovery sequence, i.e., pool resources



Calculate Resilience Index

Recovery sequence for nominal case, no cooperation



Comparing Two Strategies

	Days To Complete Recovery	Systemic Impact	Total Recovery Effort
Cooperative Approach	24	$96M	$43m
Non-cooperative Approach	30	$176M	$48M

- **Cooperative approach**
  - Decreases time to recovery by 6 days
  - Decreases SI by $80M (45%)
  - Decreases TRE by $5M (10%)
  - Decreases total resilience costs by $85M (38%)

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Summary

- Resilience analysis complements physical protection focused analysis
- IRAM provides a methodical approach for analyzing, understanding, and enhancing infrastructure resilience
- IRAM's flexible framework allows for straightforward integration with new/existing models
- Resilience analysis presents additional data requirements (compared to consequence analysis)

Backup Slides

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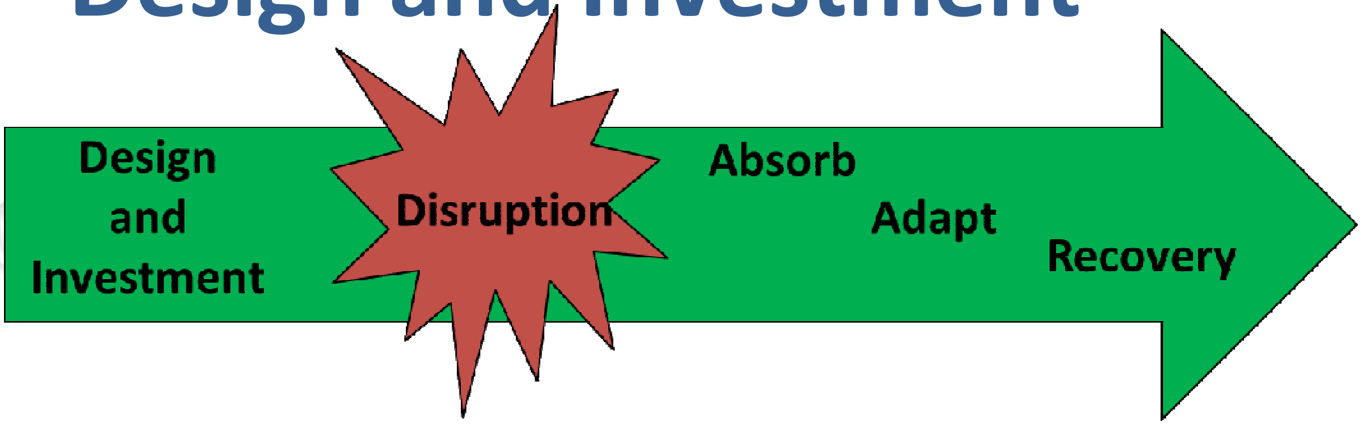
Hurricanes and Chemical Supply Chains

- Objective: compare resilience of chemical supply chains to hurricanes
- Methodology
  - Hurricanes Ike and Gustav
  - Models + historical data
  - SI focused on lost value of production
  - TRE included additional transportation costs, rail repairs, chemical plant repairs, shutdown/start up costs
- Result
  - Petrochemical industry was less resilient to Ike than Gustav
  - Plastics sector was less resilient than organic chemicals
  - Preventative shutdown of plants is costly but decreases time to recovery

Design and Investment



- Objective: develop investment portfolios to optimize resilience across uncertain disruptions
- Approach:
  - Inventory, adaptation, and restoration options
  - 11 uncertain disruption scenarios
  - Optimization + resilience metrics
- Result:
  - Choose excess storage site wisely
  - Investment diversification is often beneficial
  - Great promise for climate change adaptation

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Policy Guidance and Promotion

RESILIENCE STAR

- Objective: assess motivations to participate in first-ever resilience certification program
- Activities:
  - Stakeholder survey
  - Cost/benefit identification and analysis
- Recommendations:
  - Clear message regarding return-on-investment
  - Education for consumers and providers
  - Partnership with key industry partners
  - Piggyback off of sustainability movement