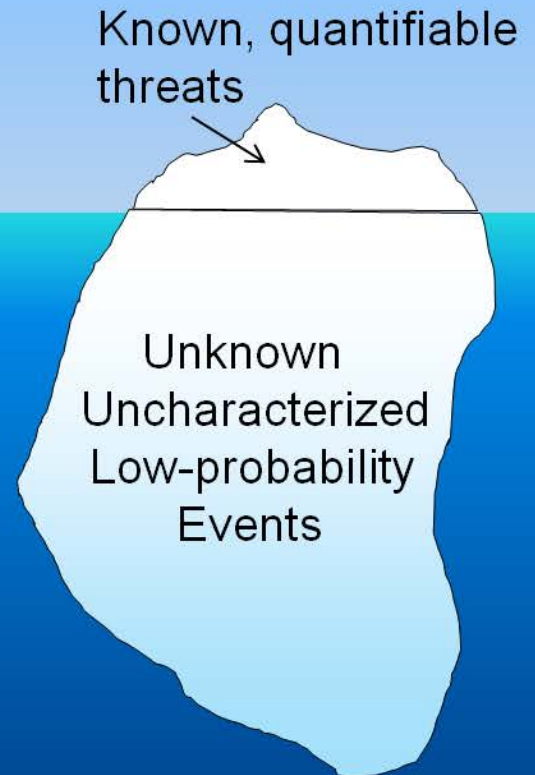


Resilience Assessment and Management in Transportation Networks

Margaret Kurth
Igor Linkov

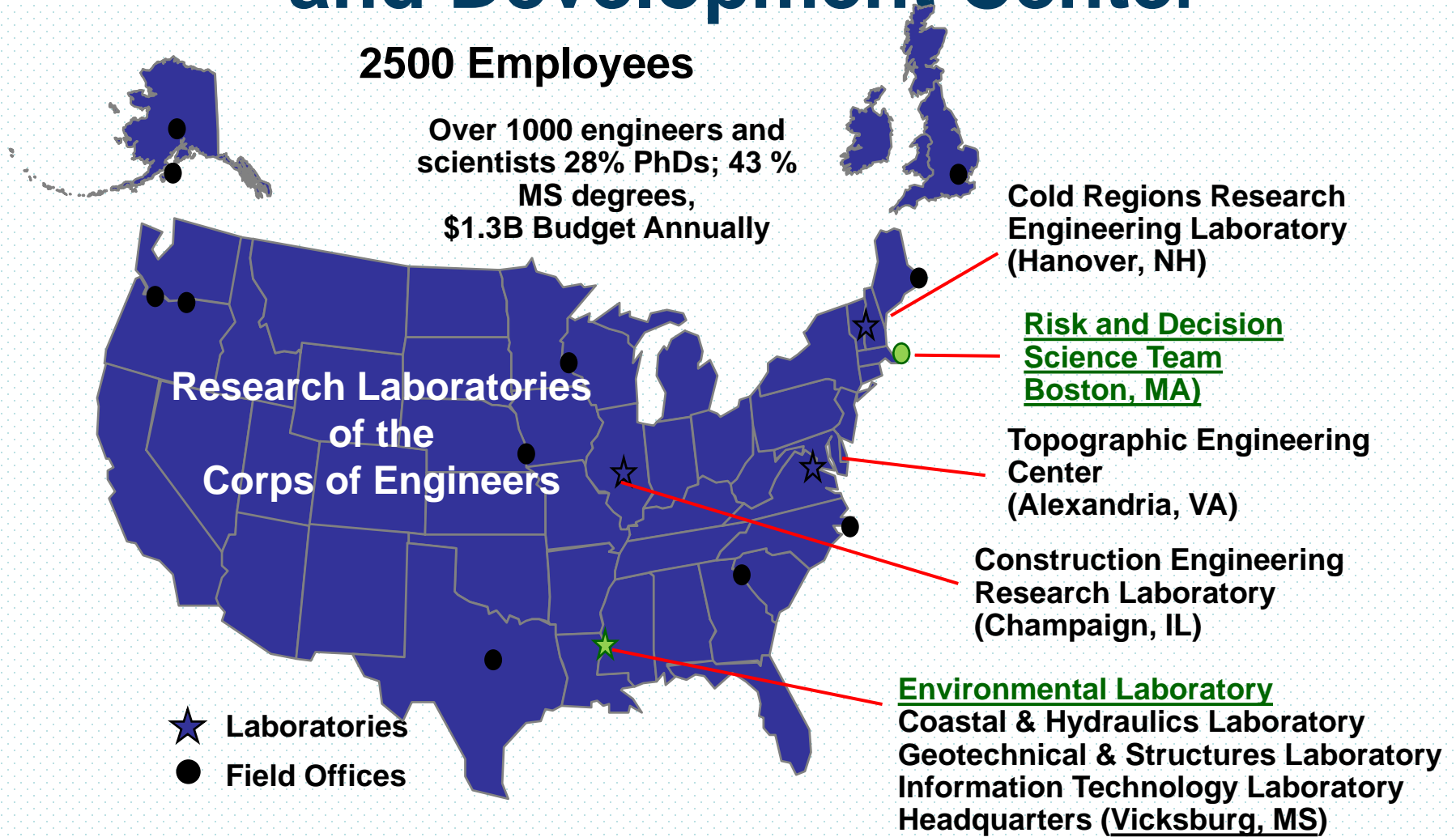
Risk and Decision Sciences Team,
US Army Corps of Engineers
Margaret.Kurth@usace.army.mil
Igor.Linkov@usace.army.mil



US Army Engineer Research and Development Center

2500 Employees

Over 1000 engineers and scientists 28% PhDs; 43 % MS degrees,
\$1.3B Budget Annually



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Risk & Decision Science Team

- **Mission:** to improve decision-making and stakeholder engagement through application and development of risk and decision science techniques.
- **Execution:** through risk assessment, technology-supported stakeholder engagement, decision modeling, portfolio optimization, life cycle assessment, and software development.
- **Results:** help clients to describe relevant risks, identify and compare risk management alternatives, develop consensus among disparate stakeholder groups, and provide repeatable and transparent processes for future decisions.



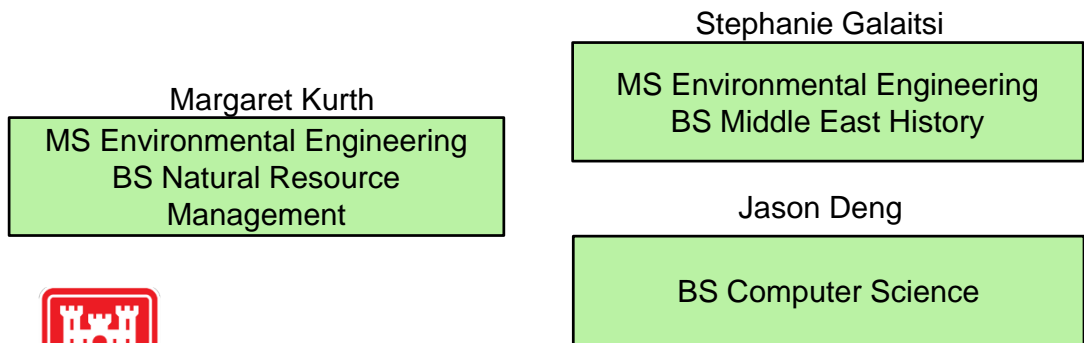
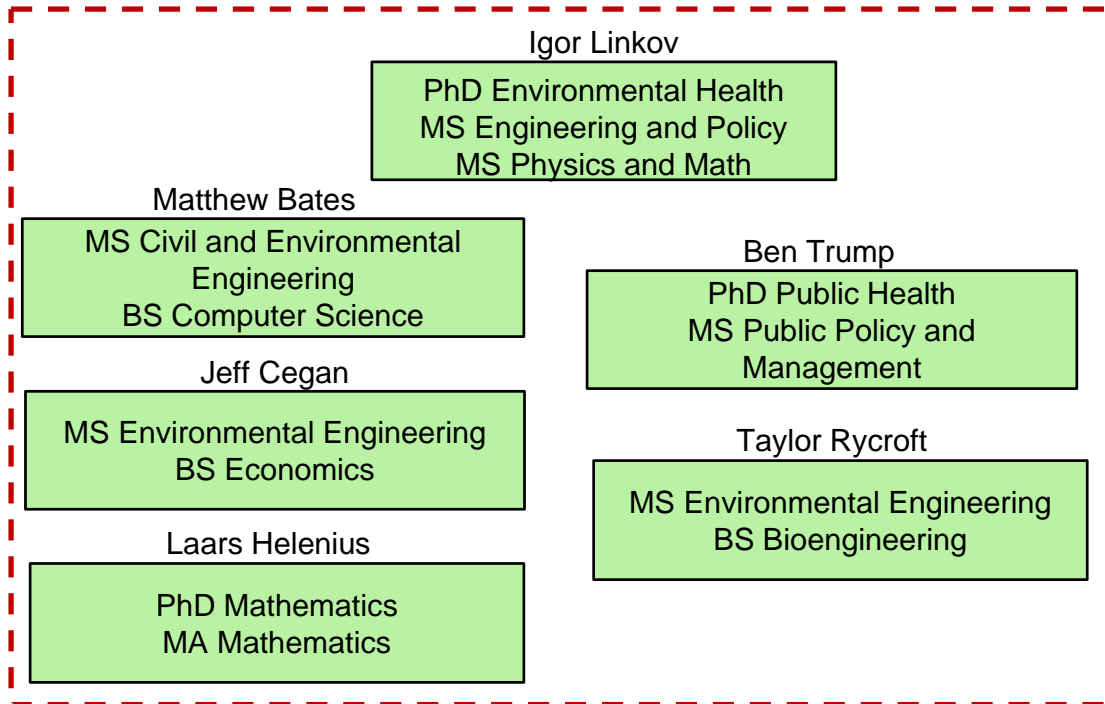
Portfolio of Solution Services

- Decision Support
- Resource Allocation & Optimization
- Risk Assessment
- Resilience & System Analysis
- Stakeholder Engagement

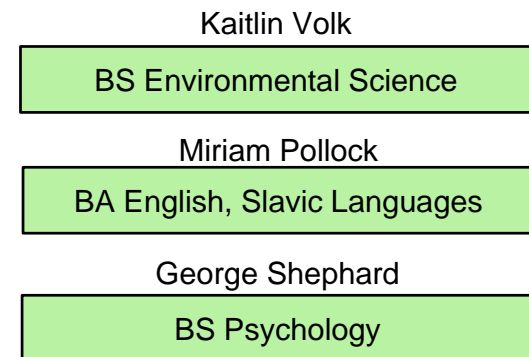
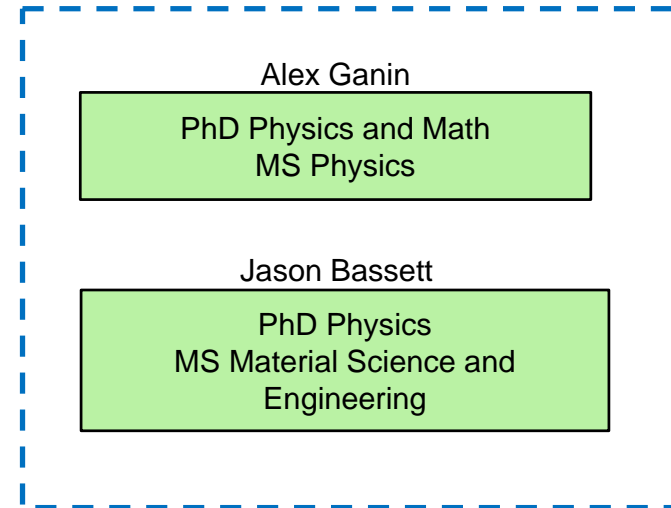


Team Diversity

Federal



Post-Docs

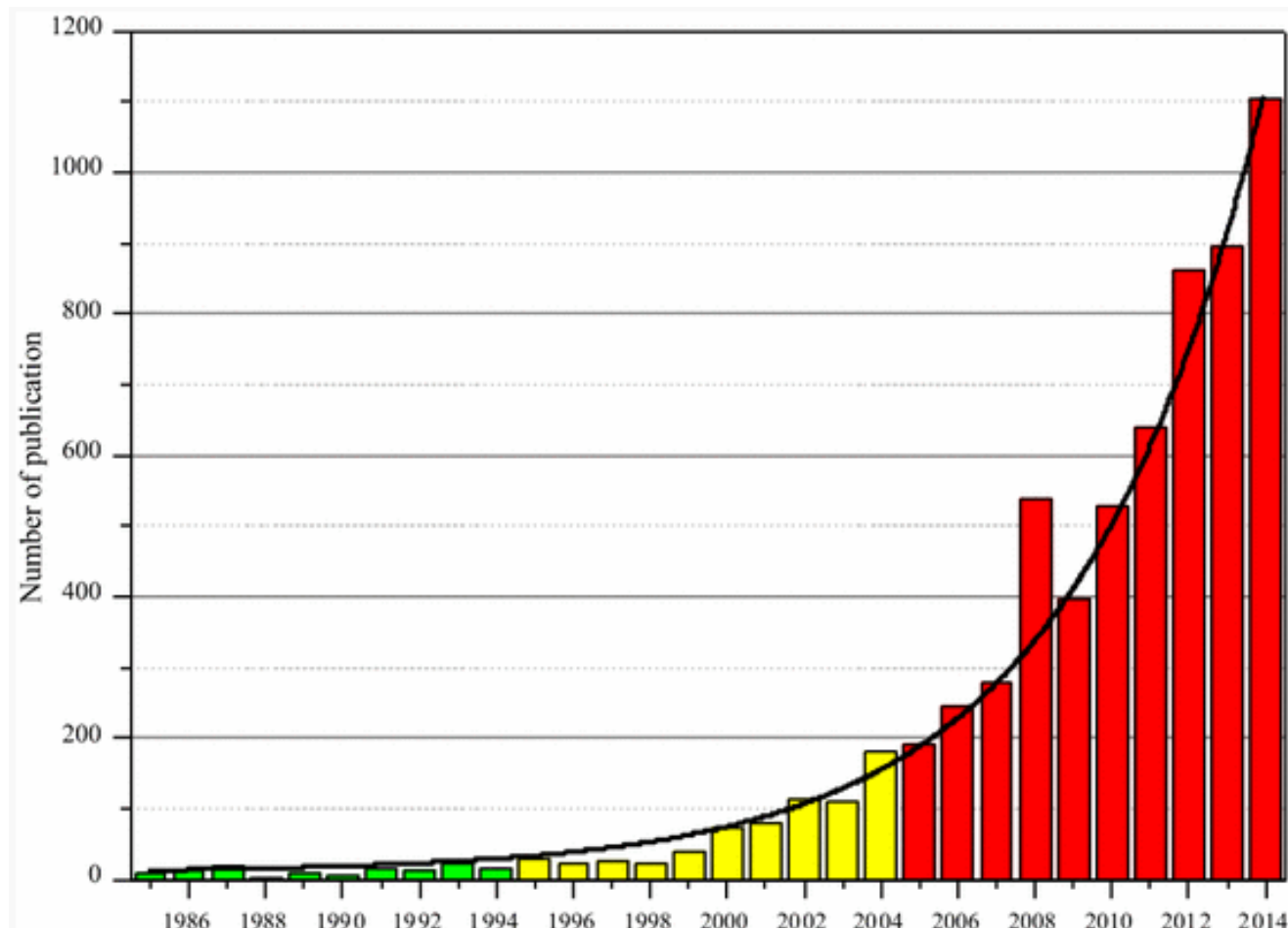


Resilience: Definition

- (National Academy of Science, 2012) - the ability to plan and prepare for, absorb, recover from, and more successfully adapt to disruptive events
- (Lounis & McAllister, 2016) change in a system's performative function and quality over the course of either or both an extreme event or a gradual accumulation of internal or external stress

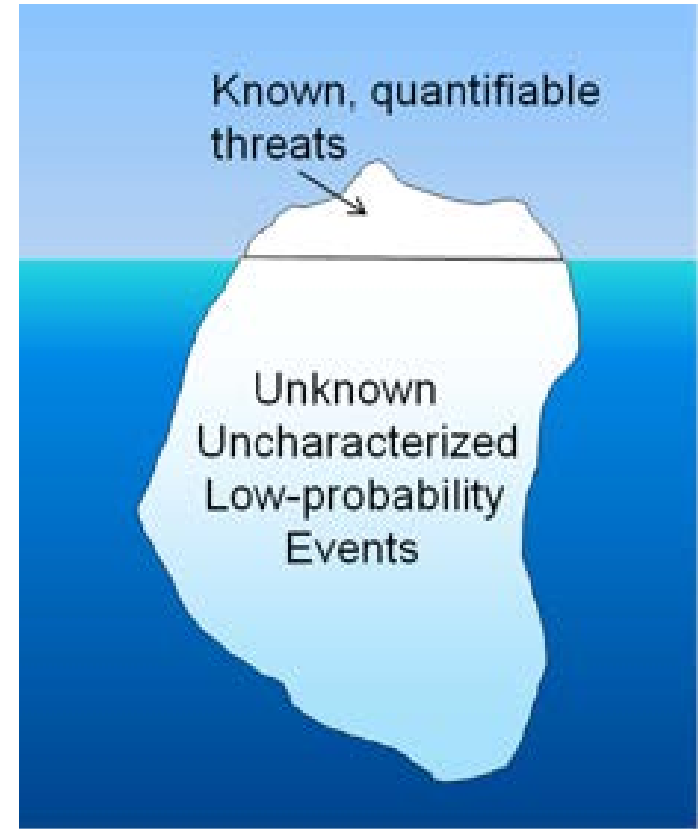
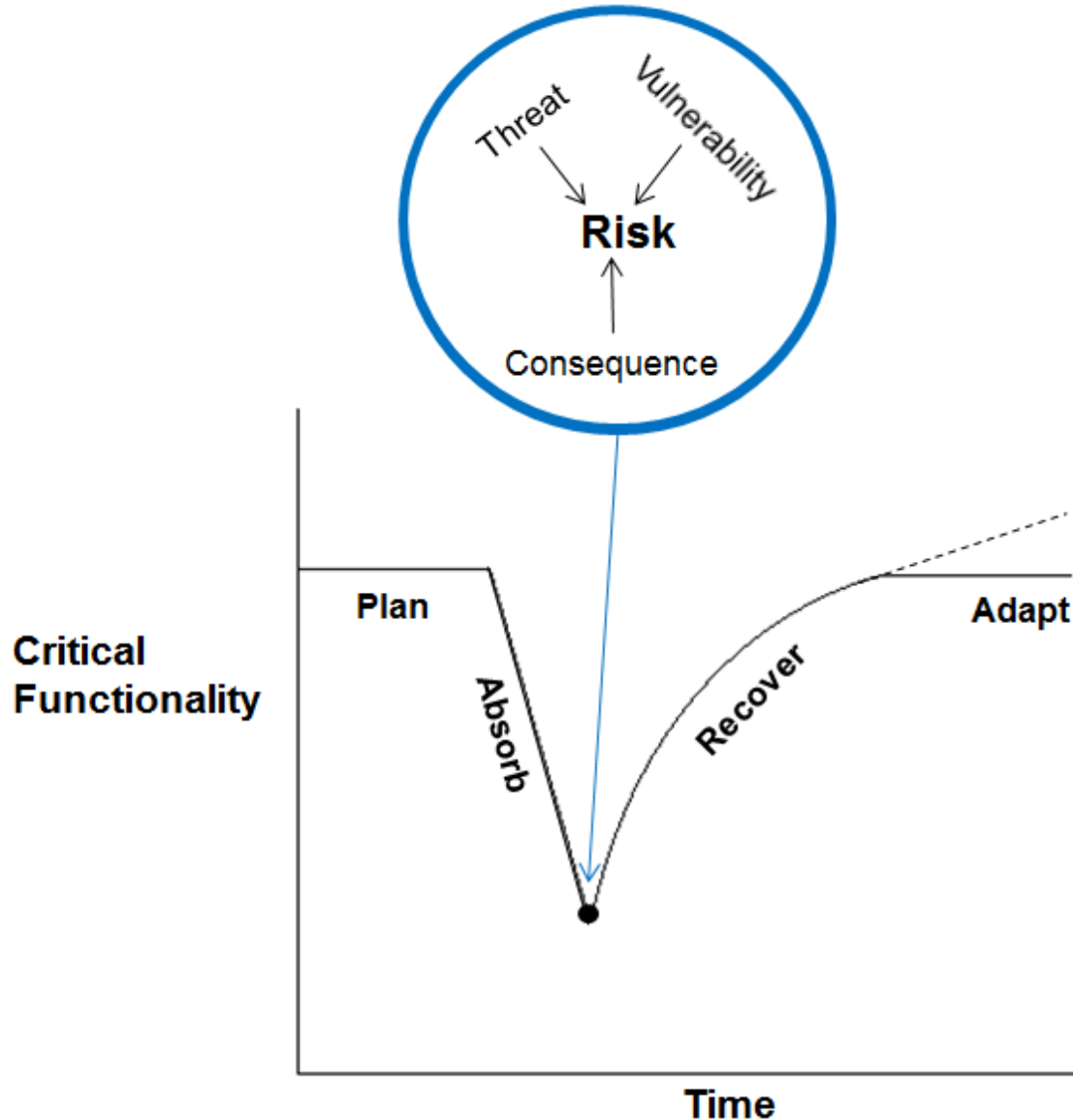


Who is talking about resilience?



From Xue, Wang, Yang (2018) in Natural Hazards - Web of Science, Social Science and Science Citation Indices, "Resilience" in Title

System Functioning under Stress: Risk and Resilience

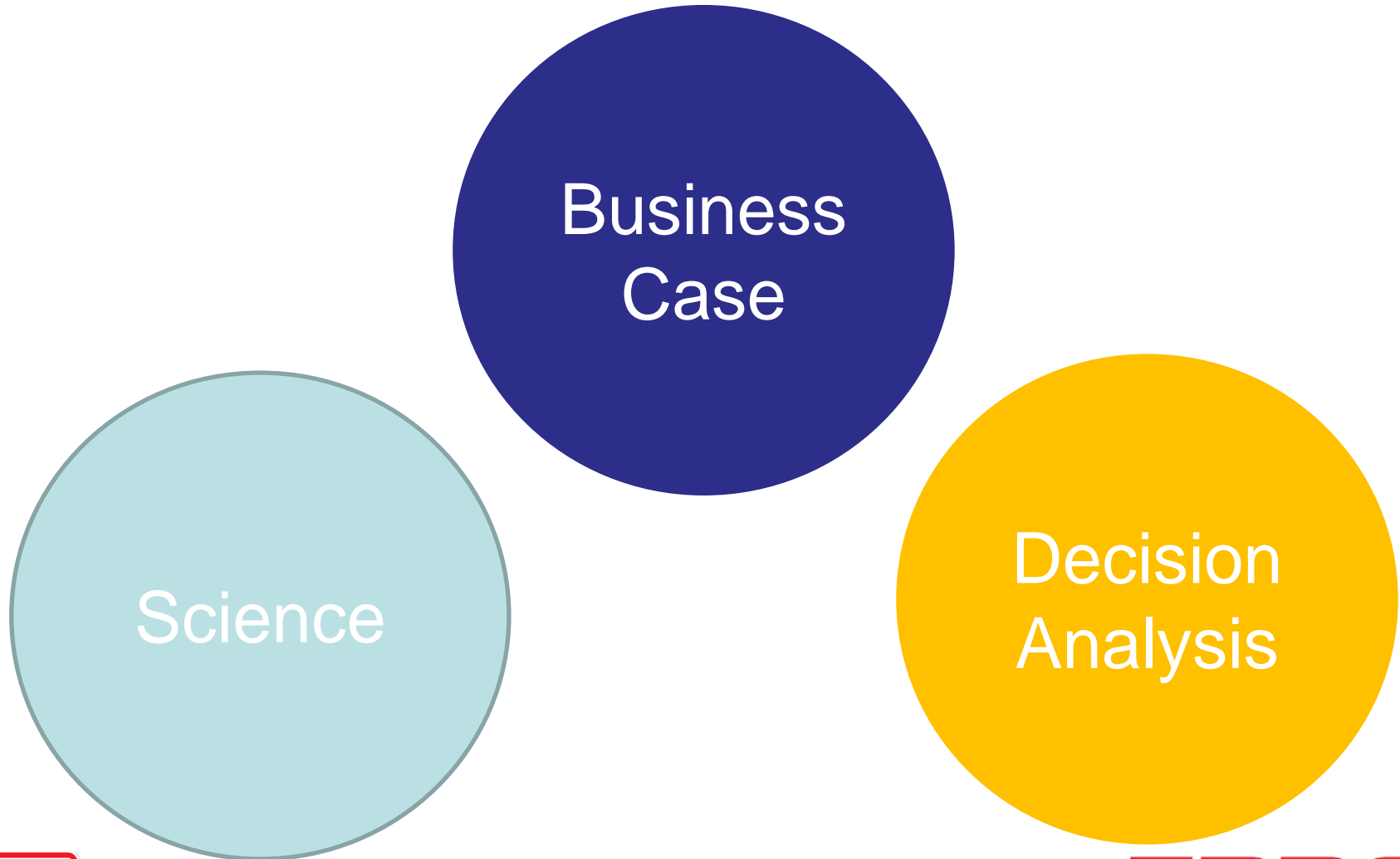


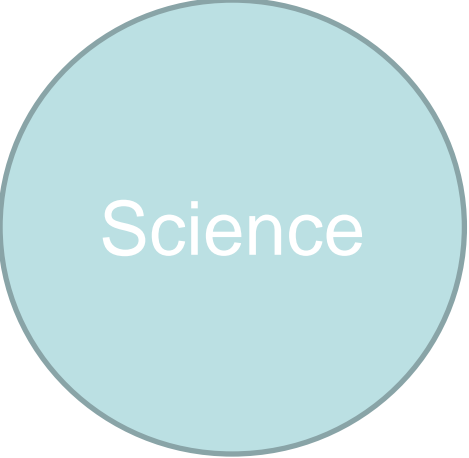
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for a safer, better world

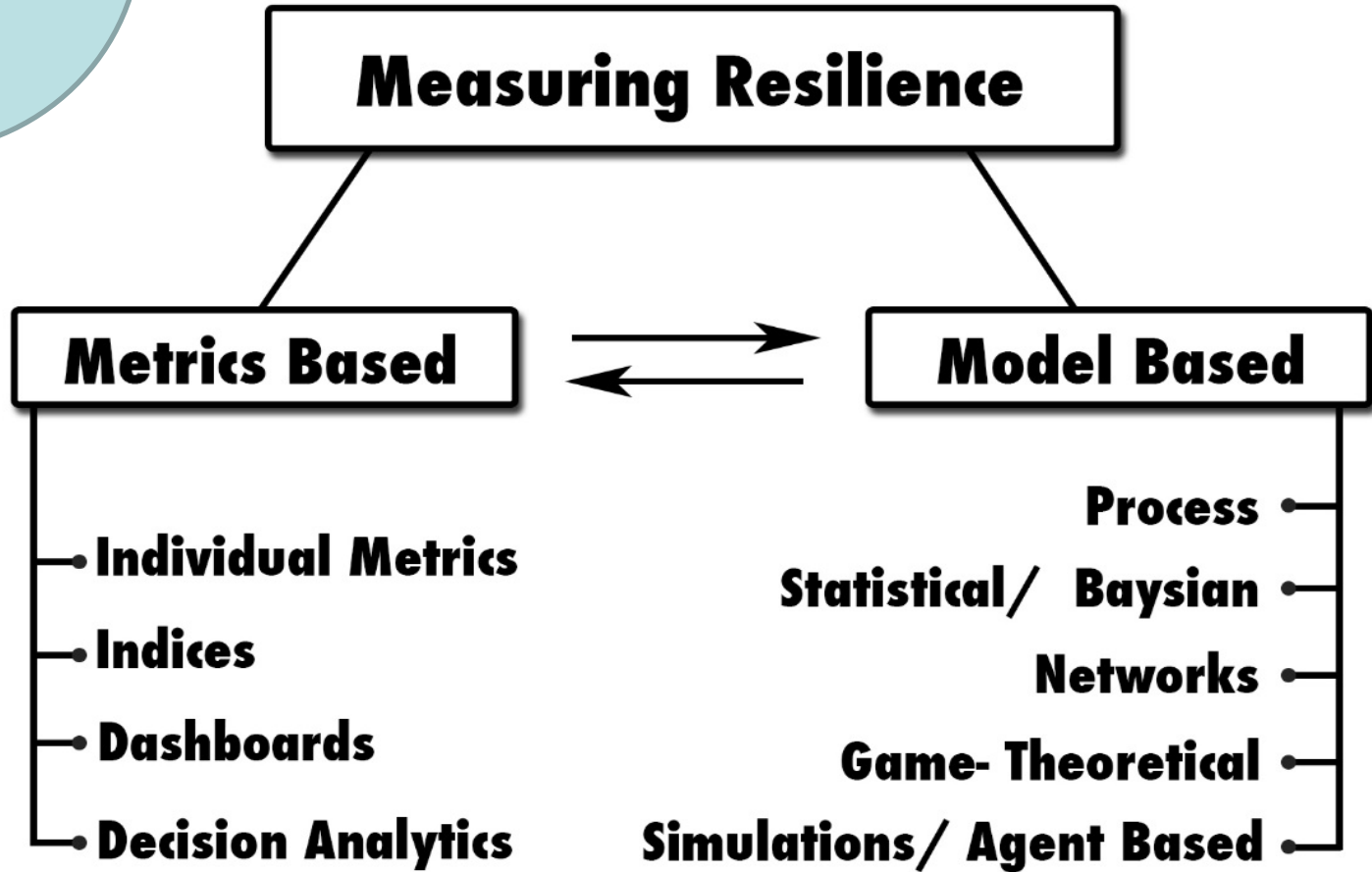
After Linkov et al, Nature Climate Change 2014

State of Practice





Focus is on quantification



After Kott & Linkov book on Cyber Resilience of Systems and Networks (2019)

Science

Issues with Using Metrics-Based Approaches to Measure Resilience

Lack of Causal Model

Changing environments and circumstances may change correlating factors

Changing business and management plans may change how previously causal factors interact

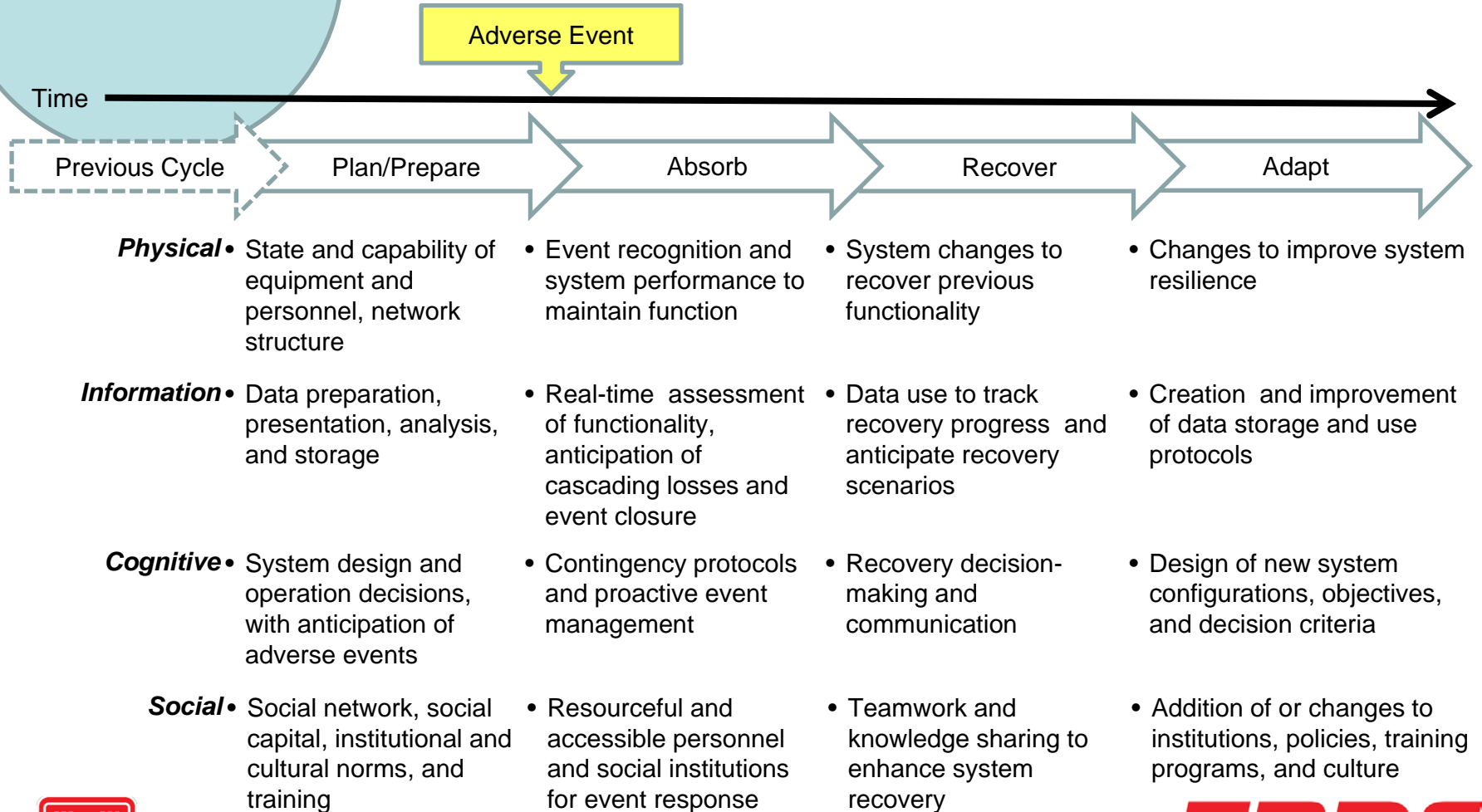
May not work in circumstances different than under those they were designed for

Not everything that counts can be counted, and not everything that can be counted counts.

Albert Einstein

Science

Issues From Whence Does Resilience Come?



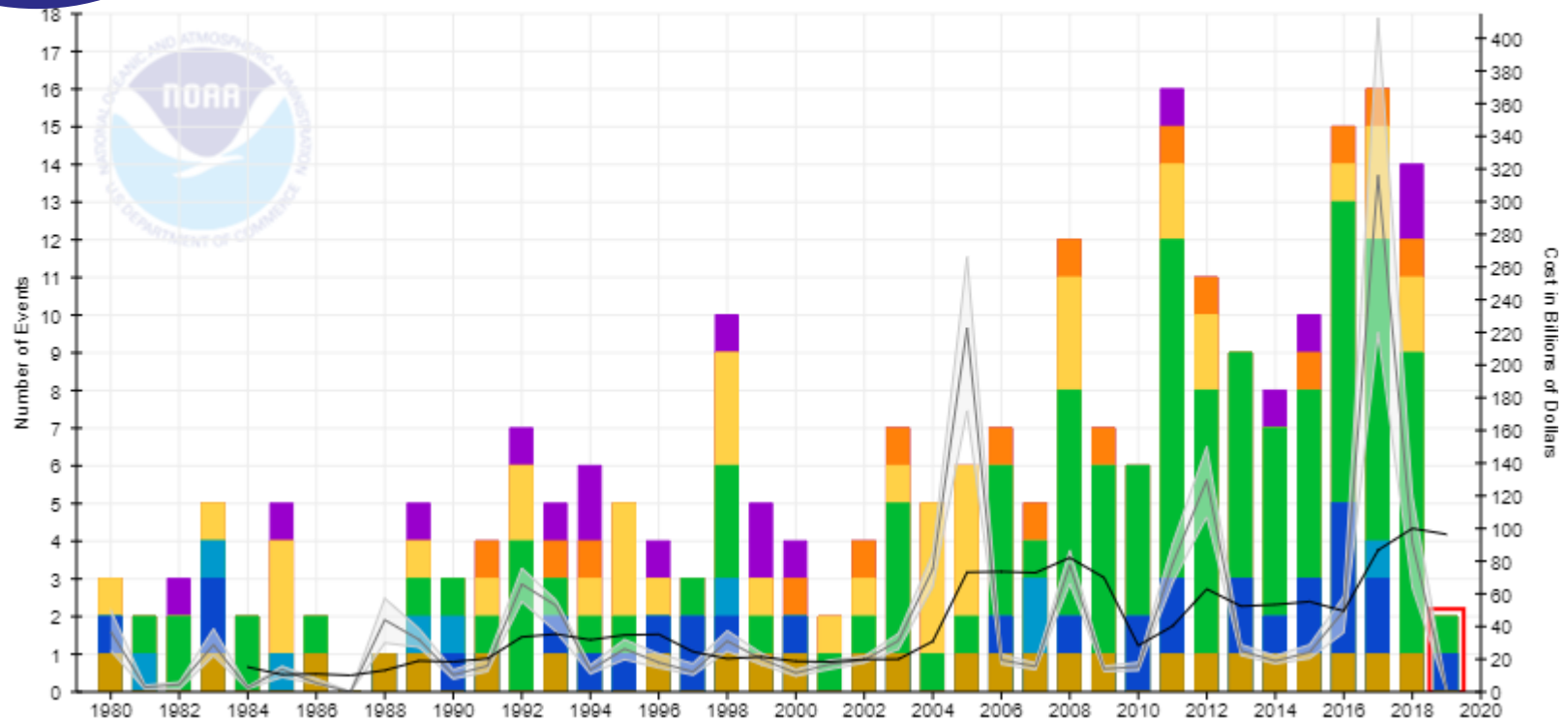
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Business Case

Reacting is More Expensive than Preventing

Billion-Dollar Disaster Event Types by Year (CPI-Adjusted)

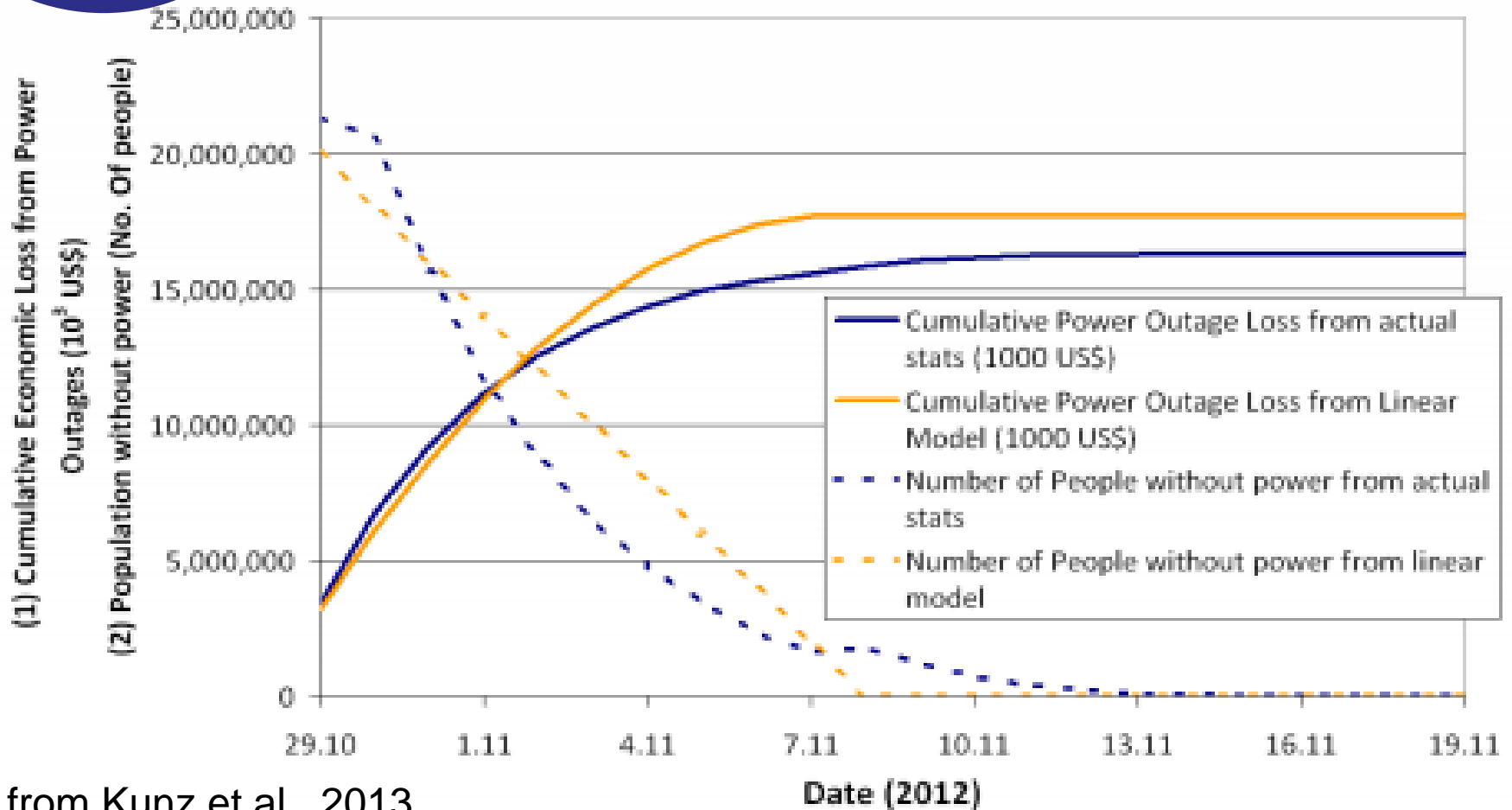
- Winter Storm
- Wildfire
- Trop Cycl
- Severe Storm
- Freeze
- Flooding
- Drought
- Cost w/ 95% CI
- 5-Year Mean



NOAA National Centers for Environmental Information (NCEI) U.S. Billion-Dollar Weather and Climate Disasters (2019). <https://www.ncdc.noaa.gov/billions/>

Business
Case

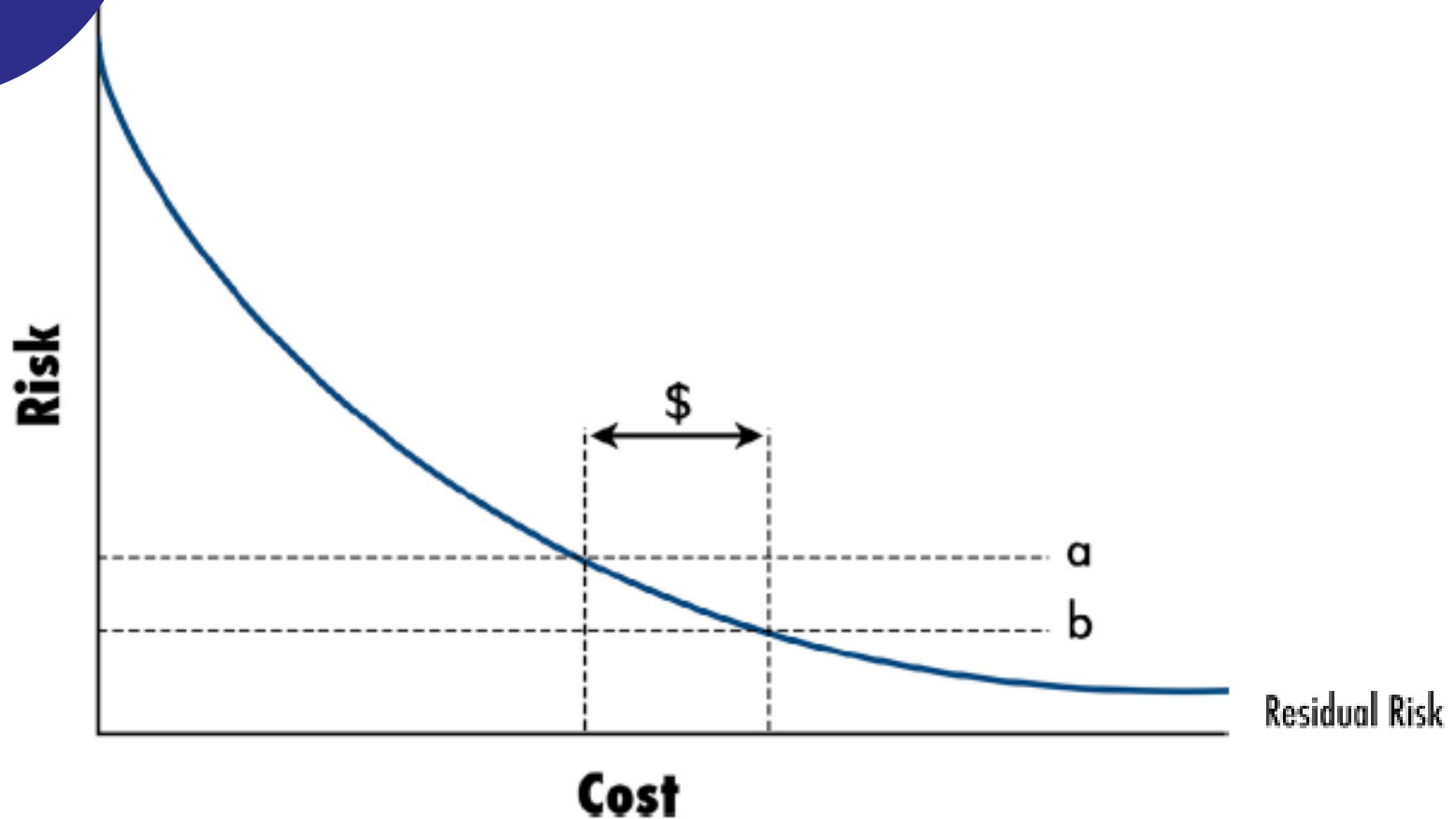
High Indirect Losses



from Kunz et al., 2013

Business
Case

Resilience Can Pick Up Where Risk Mitigation Ends



After Bostick et al. (2018) in Reliability Engineering and System Safety

Decision
Analysis

Formalize Resilience in Decision-Making

Alternative
Management 1

Alternative
Management 2

Alternative
Management 3

Process Model

Resilience
Performance
Metric(s)

Forecasted
Performance

Trade-Off
Analysis

Economic
Analysis



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Case Study: Transportation Network Model

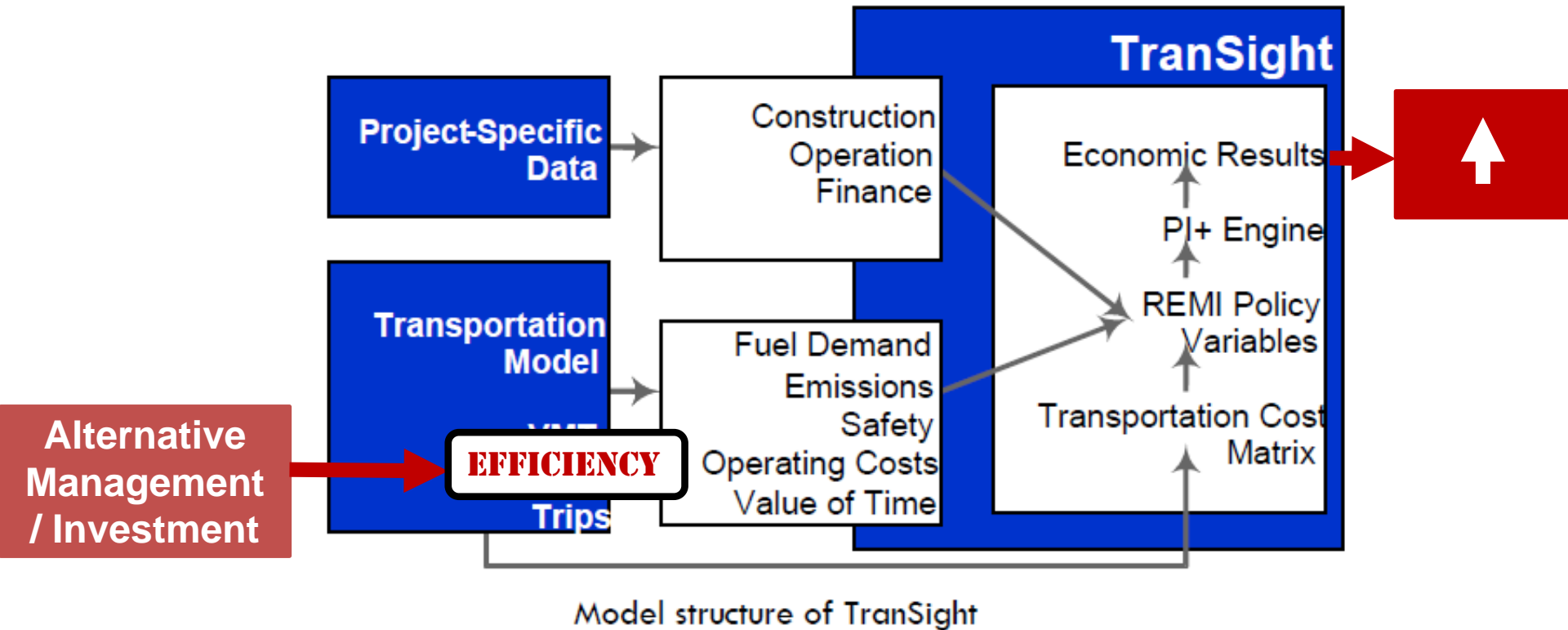
+
REMI

Business
Case

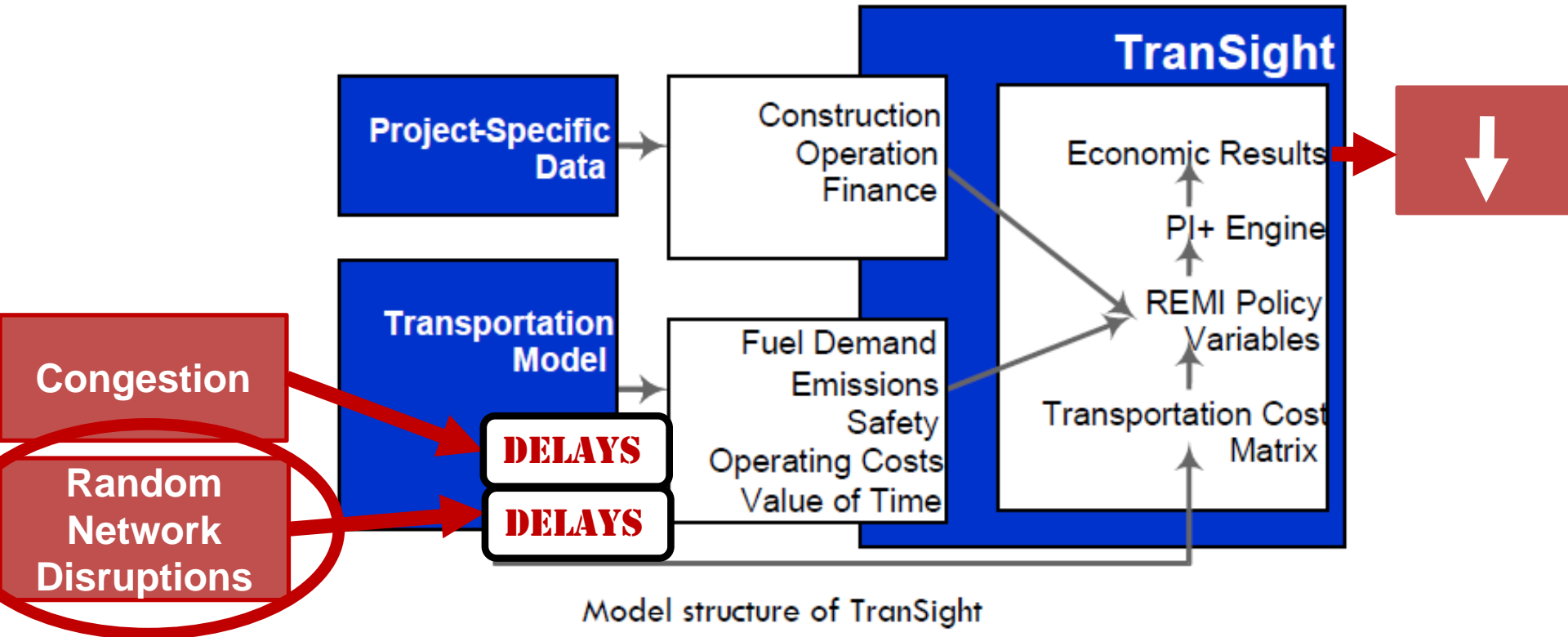
Decision
Analysis



REMI = is a transportation upgrade a “winning proposition” relative to other initiatives?



Repurpose to Study Economic Implications of Resilience (or lack thereof)



Poor Efficiency:

System cannot not accommodate a large volume of commuters driving at the same time.

Traffic congestions are predictable and are typically of moderate level.

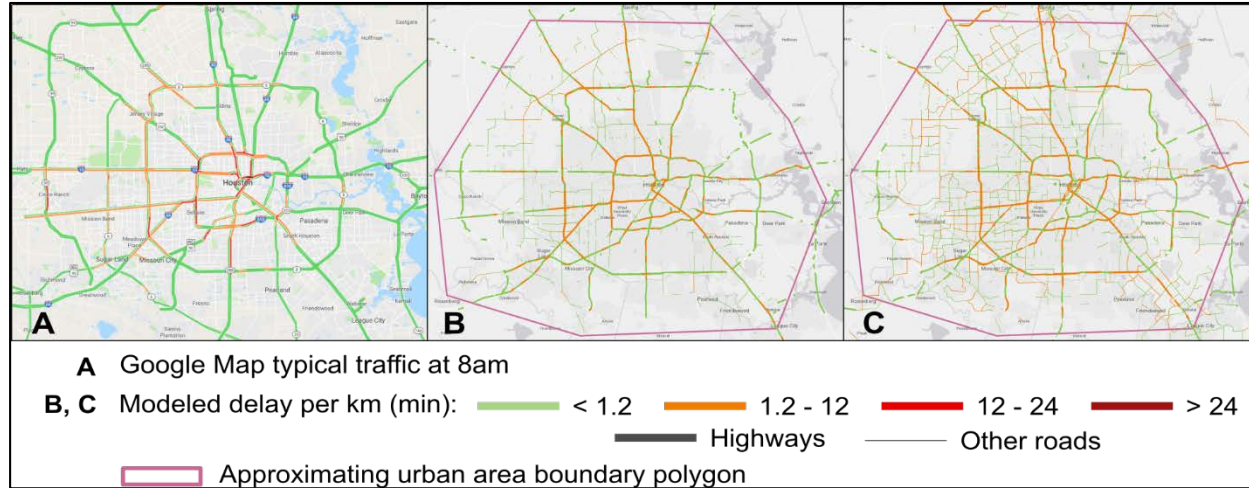


Lack of Resilience:

**System cannot recover from adverse events
(car accidents, natural disasters)**

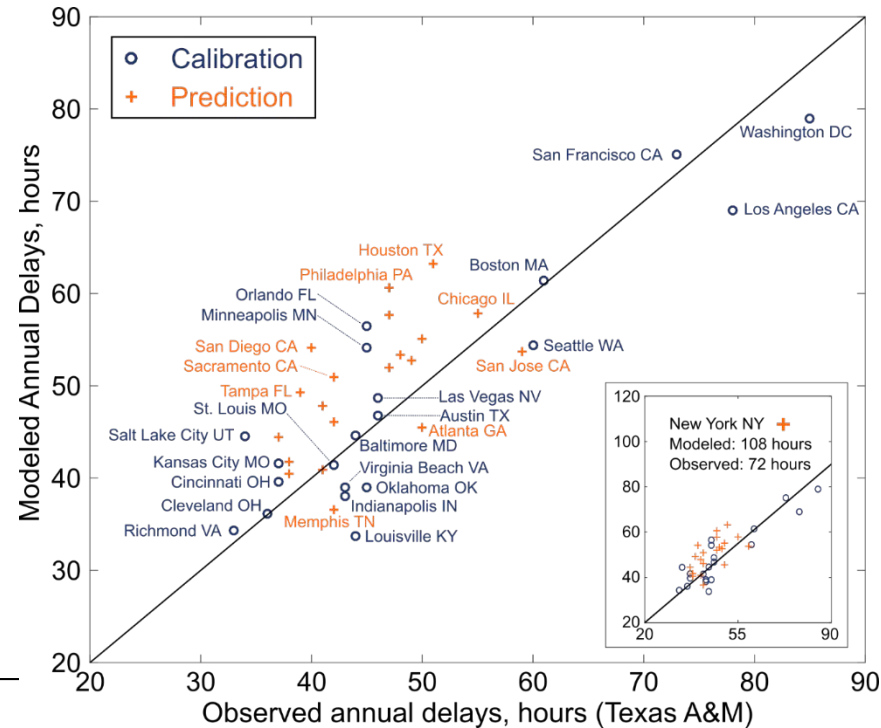
Traffic disruptions are not predictable and of variable scale.

Transportation Network Model:



- 1) Build networks comprise of road links and intersection nodes
- 2) Assign travelers and routes
- 3) Calculate free flow travel times and actual travel times
- 4) Calculate normal delay
- 5) Calibrate model to data

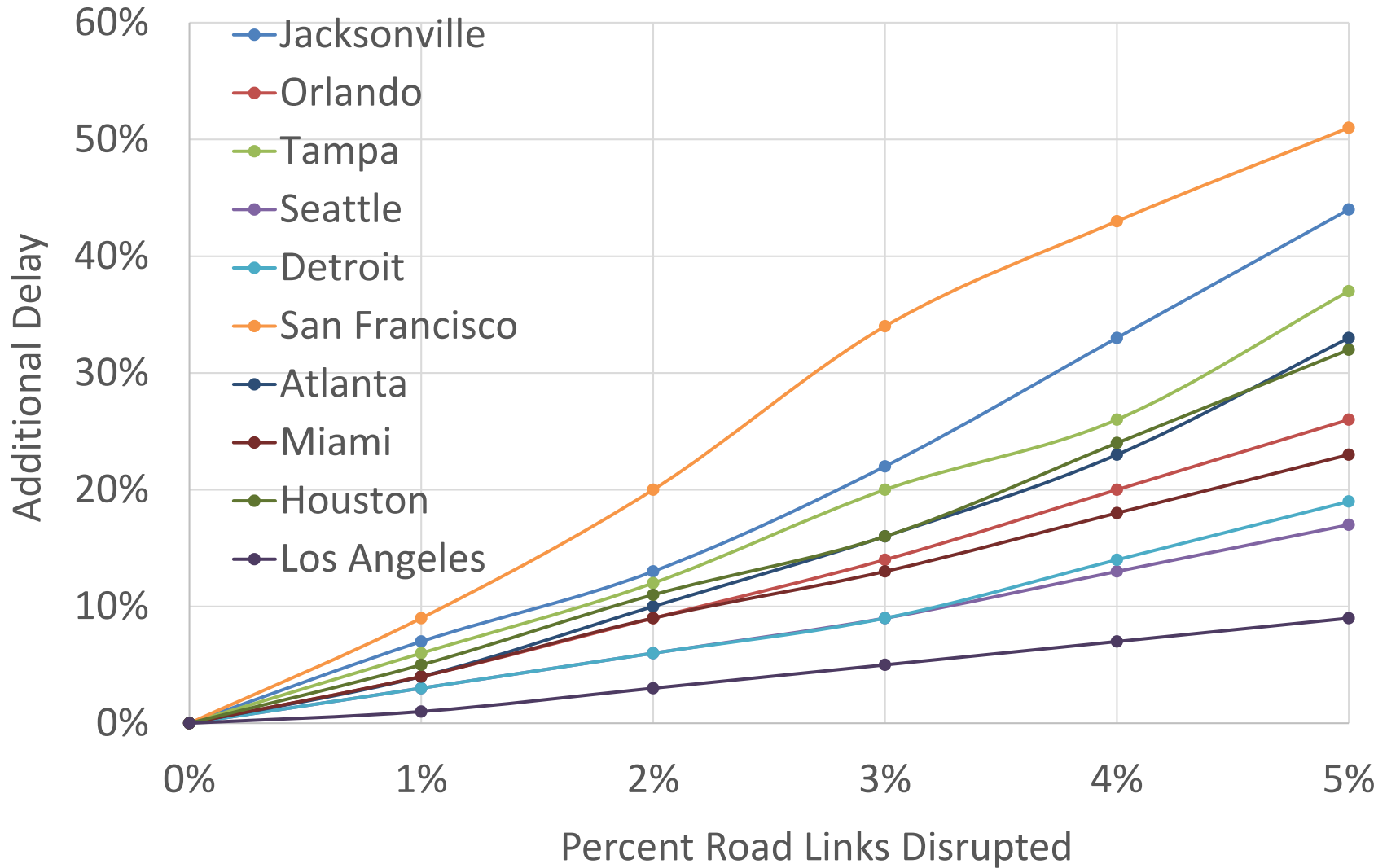
$$\langle \Delta T \rangle = \frac{1}{N_c} \sum_{\{ij\} \in \text{all roads}} L_{ij} l_{ij} \left(\frac{1}{v_{ij}} - \frac{1}{v_{ij}^0} \right)$$



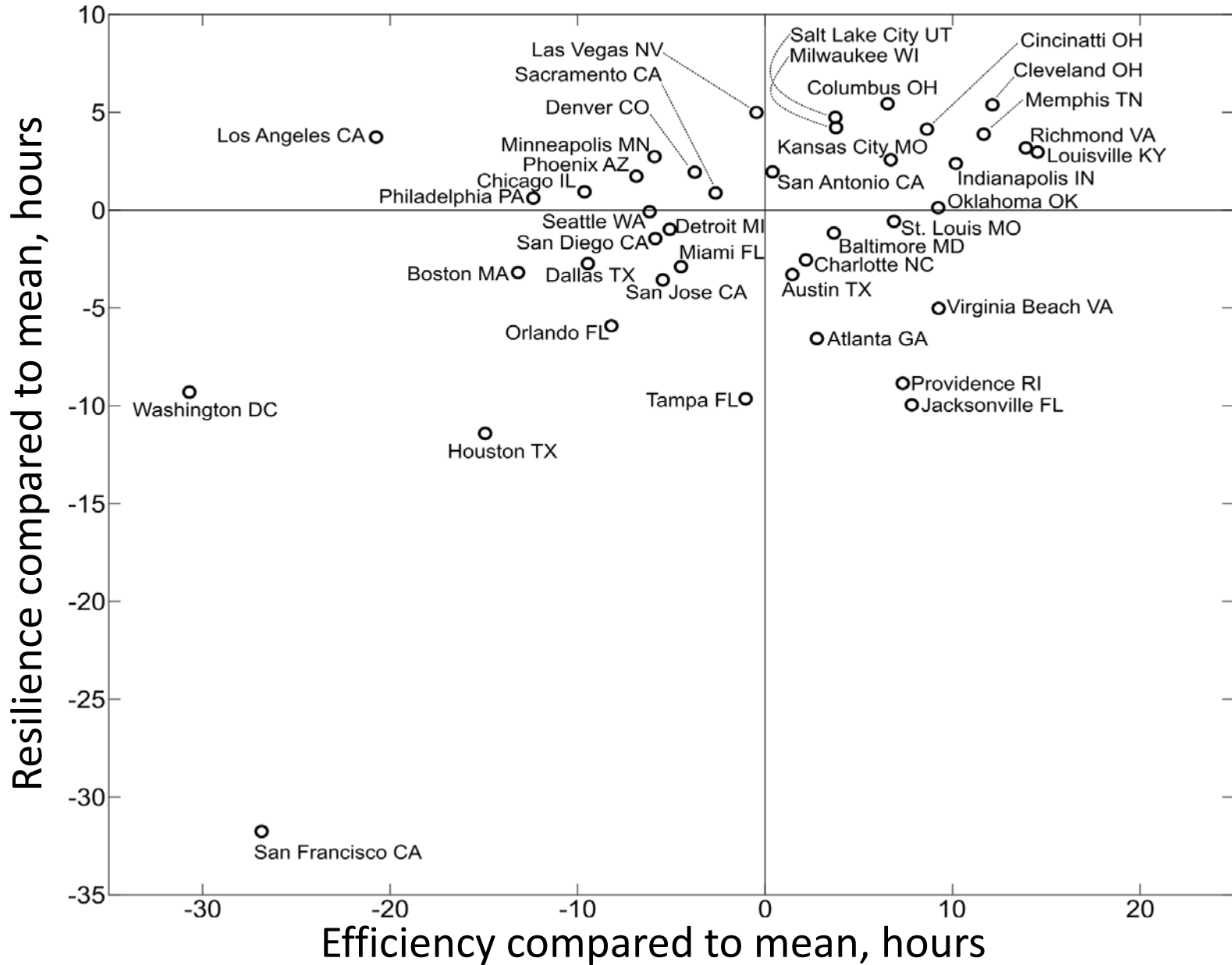
Modeling Disruptions

Case I	Case II	Case III	Case IV
Natural Disasters	Random Disruptions	Attacks Disabling Traffic Control	Attacks Locking Traffic Control
Links (Roadways) Only	Links (Roadways) and Nodes (Intersections)	Nodes (Intersections) Only	
Modeled Fractions of Affected Nodes/Links			
From 5% to 100% with the step of 5%			
Selection of Nodes/Links Affected by a Disruption			
Proportionally to Length at Random	Uniformly at Random Deterministically by Length, Load, and Betweenness		
Disrupted Roads and/or Intersections			
Speeds reduced to 1 km/h		Speeds reduced by 50%	Half of speeds are reduced 80%, the other half is increased 20%

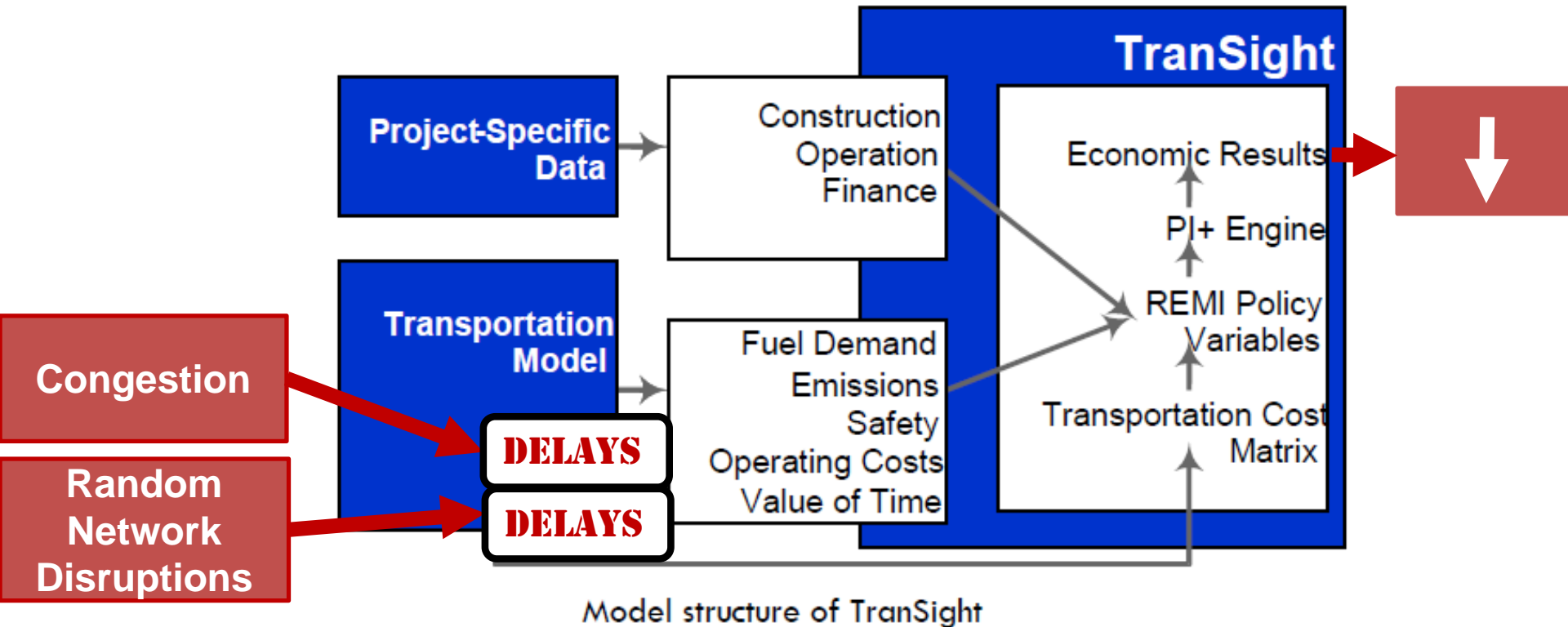
Impact of Transportation Network Disruptions on Travel Time



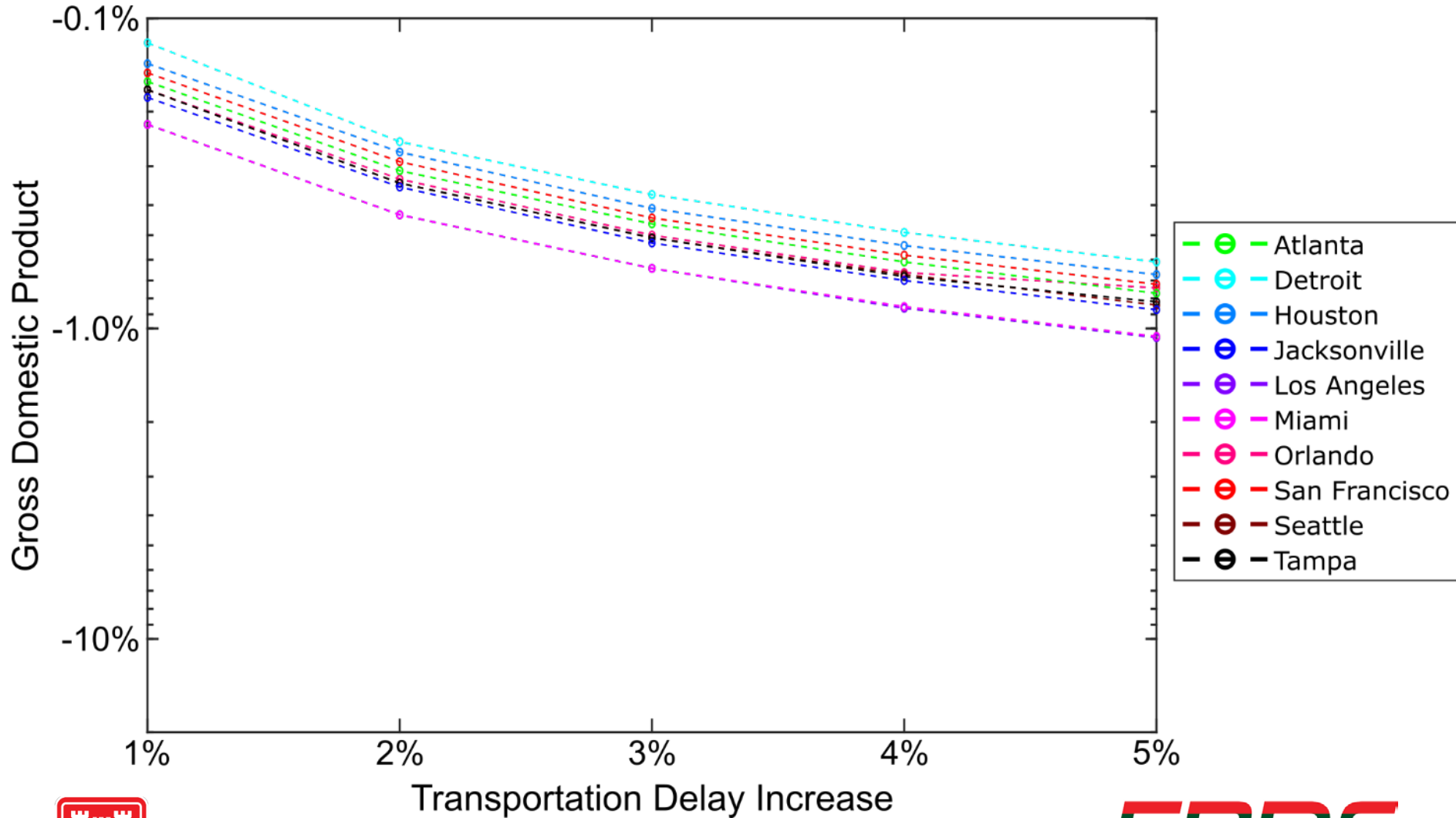
Resilience vs Efficiency at 5% disruption



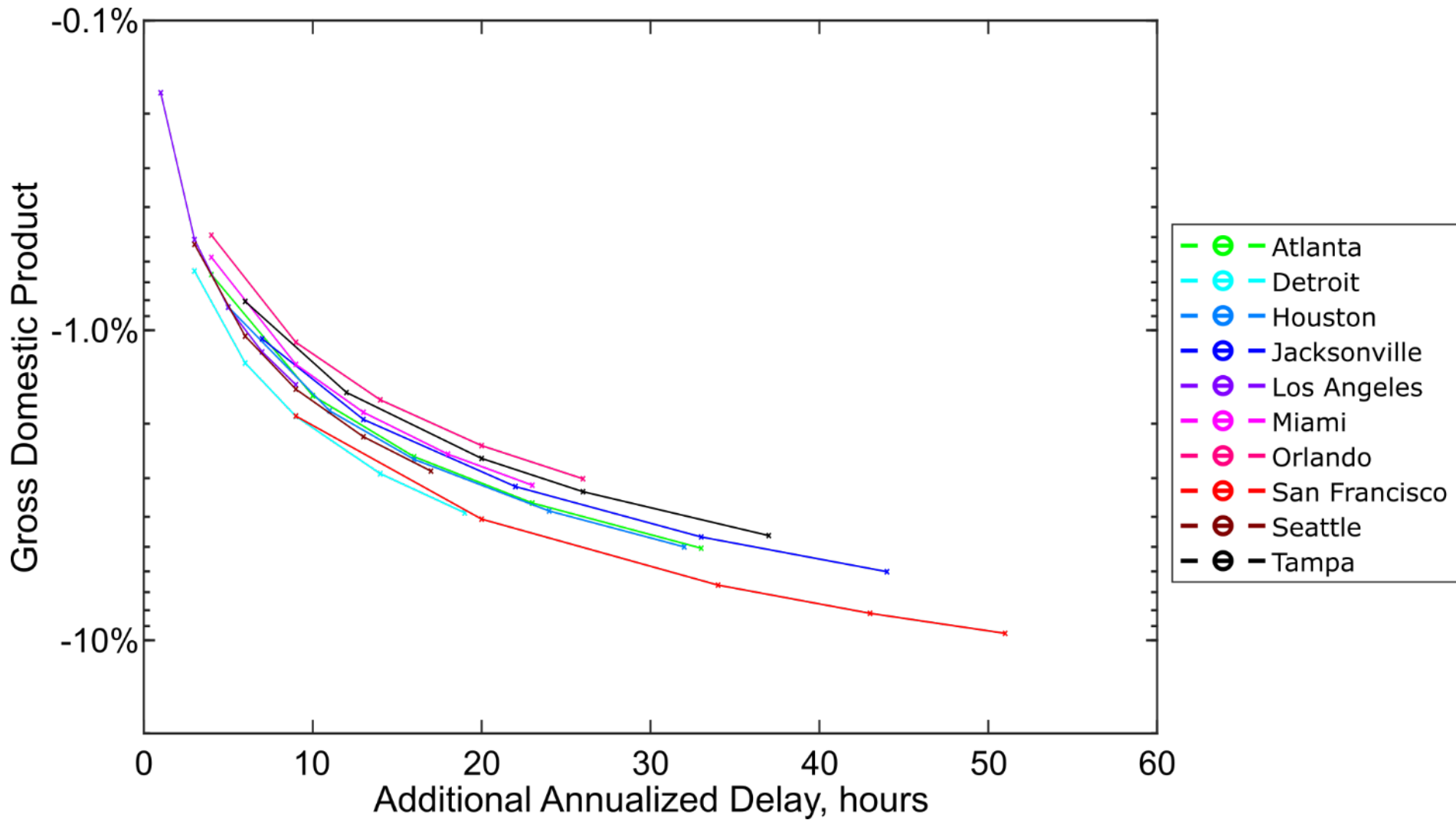
Back to Economic Implications of Resilience (or lack thereof)



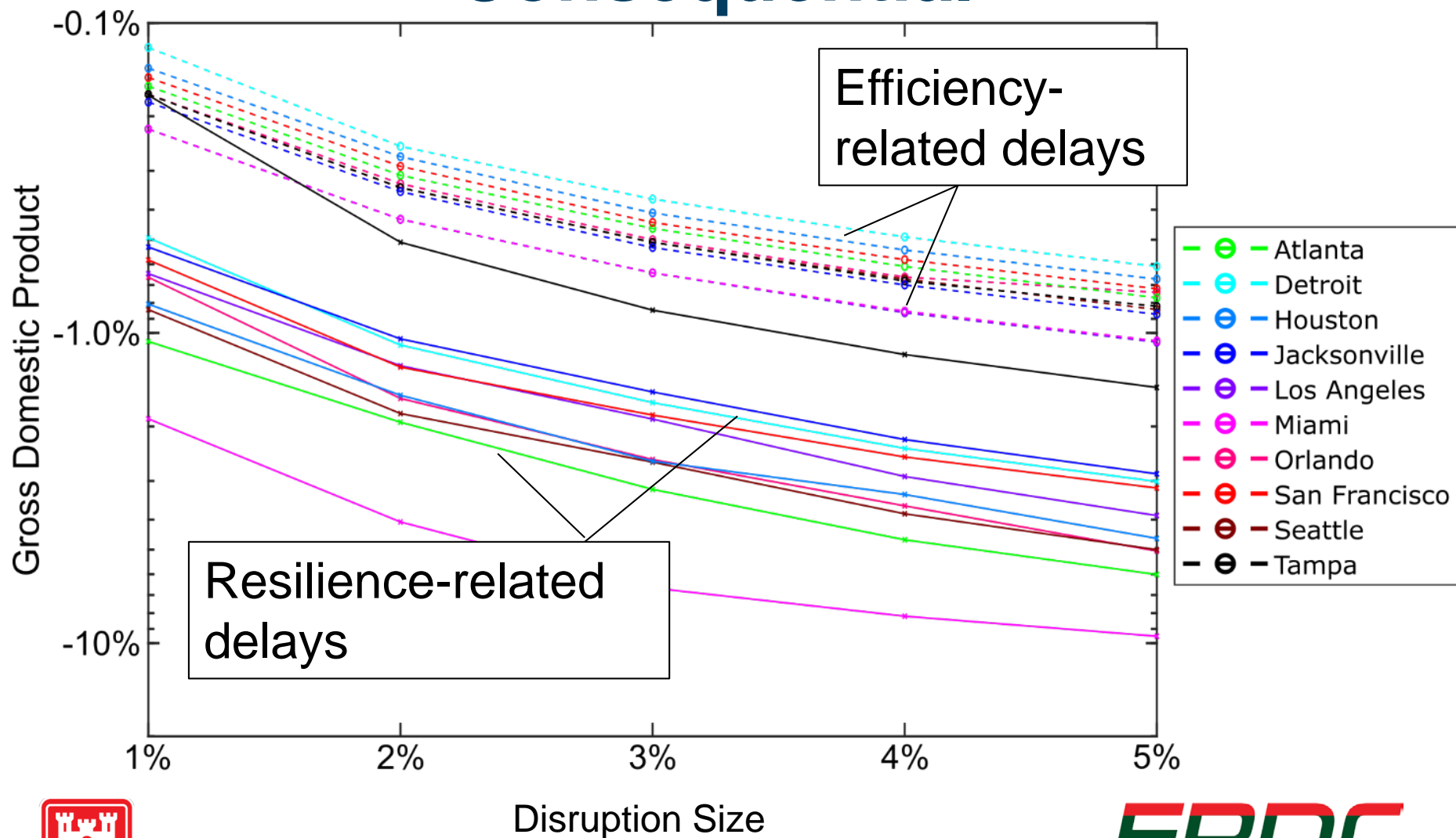
Impact of Efficiency-Related Delays



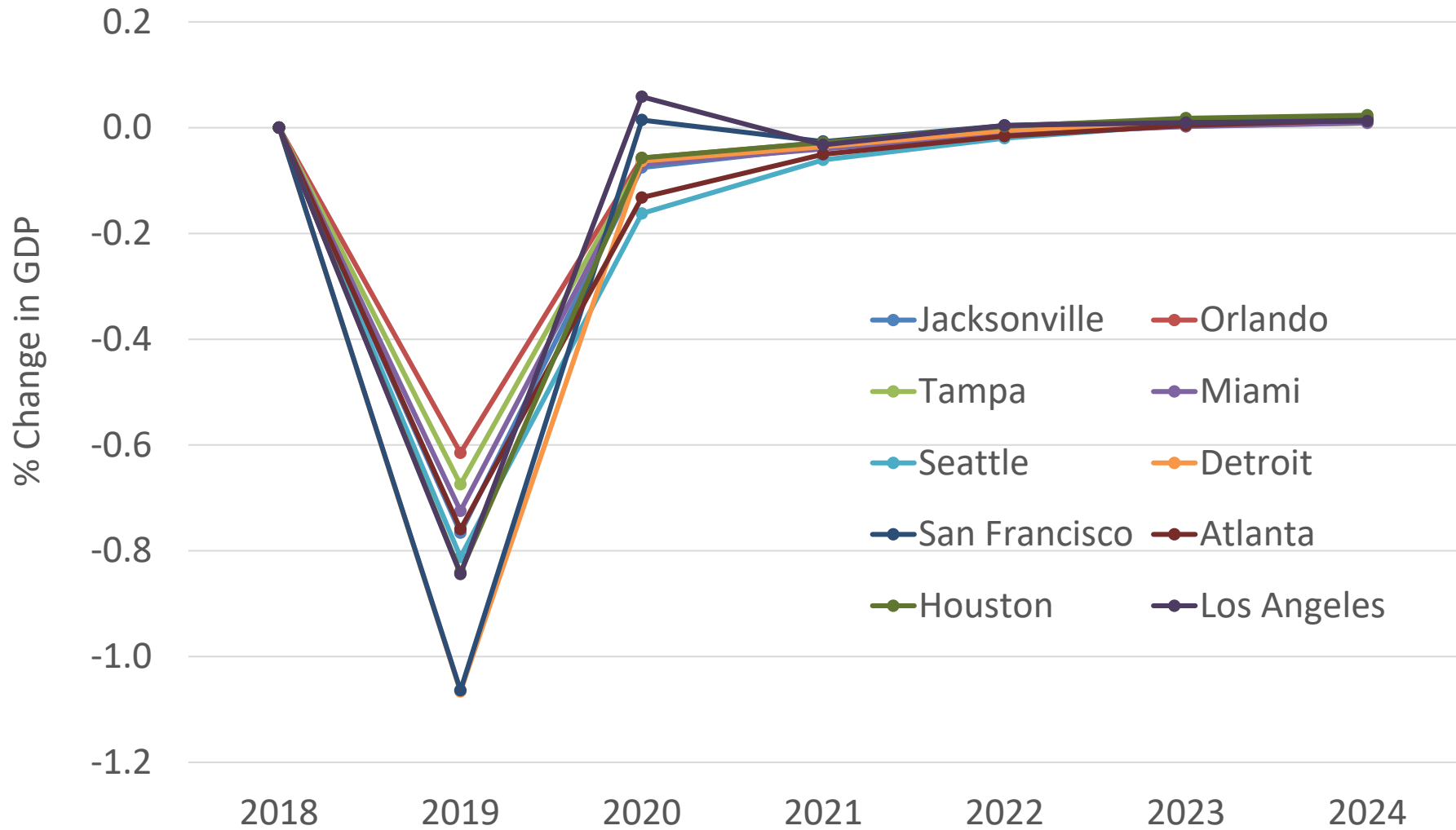
Impact of Resilience-Related Delays



Random Disruptions are Much More Consequential



Temporal Dimension

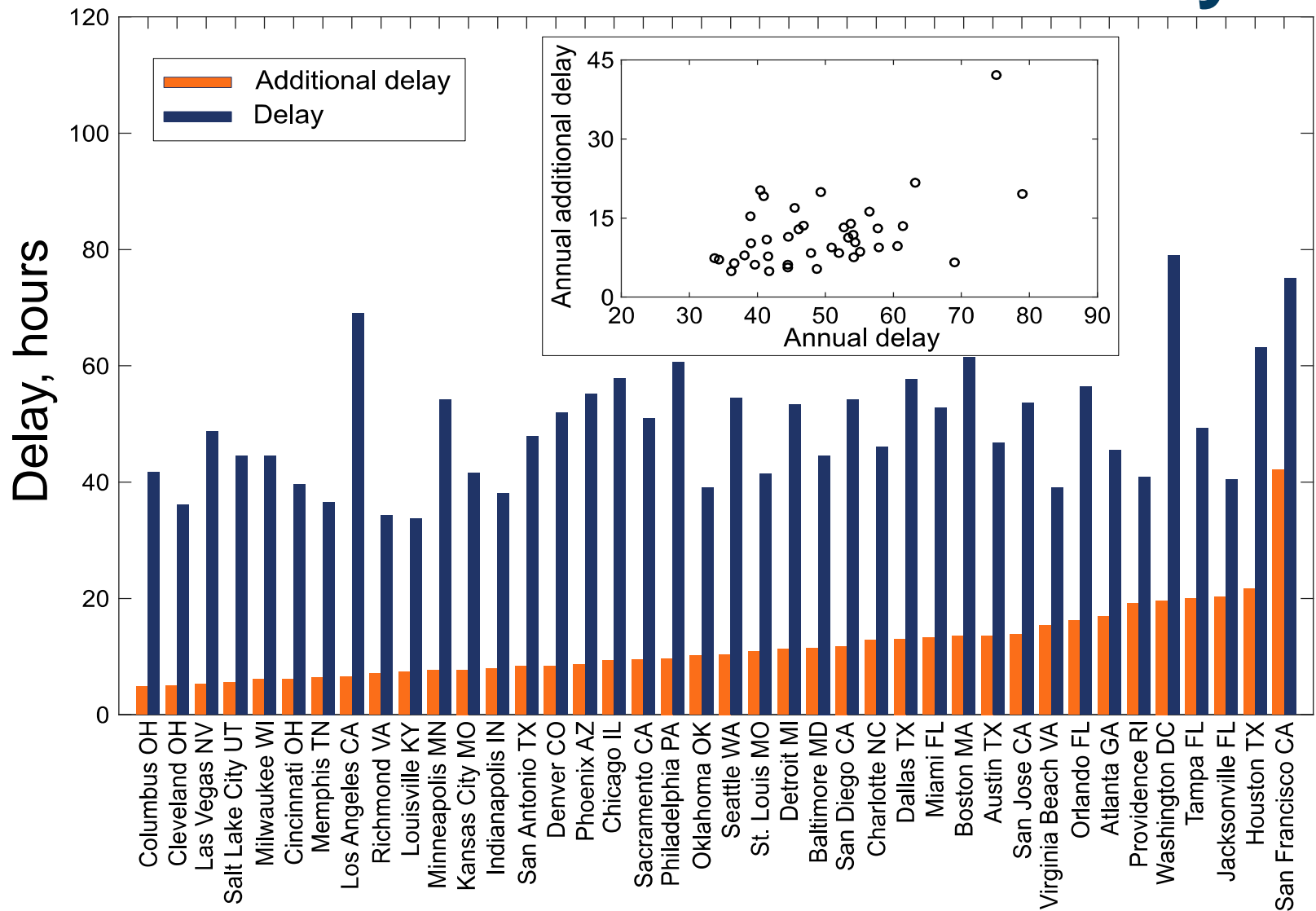


Resilience of What to What?

- Topological resilience of road networks under scenarios of disruptions
- Resilience of the regional economy to road (and other infrastructure) disruption

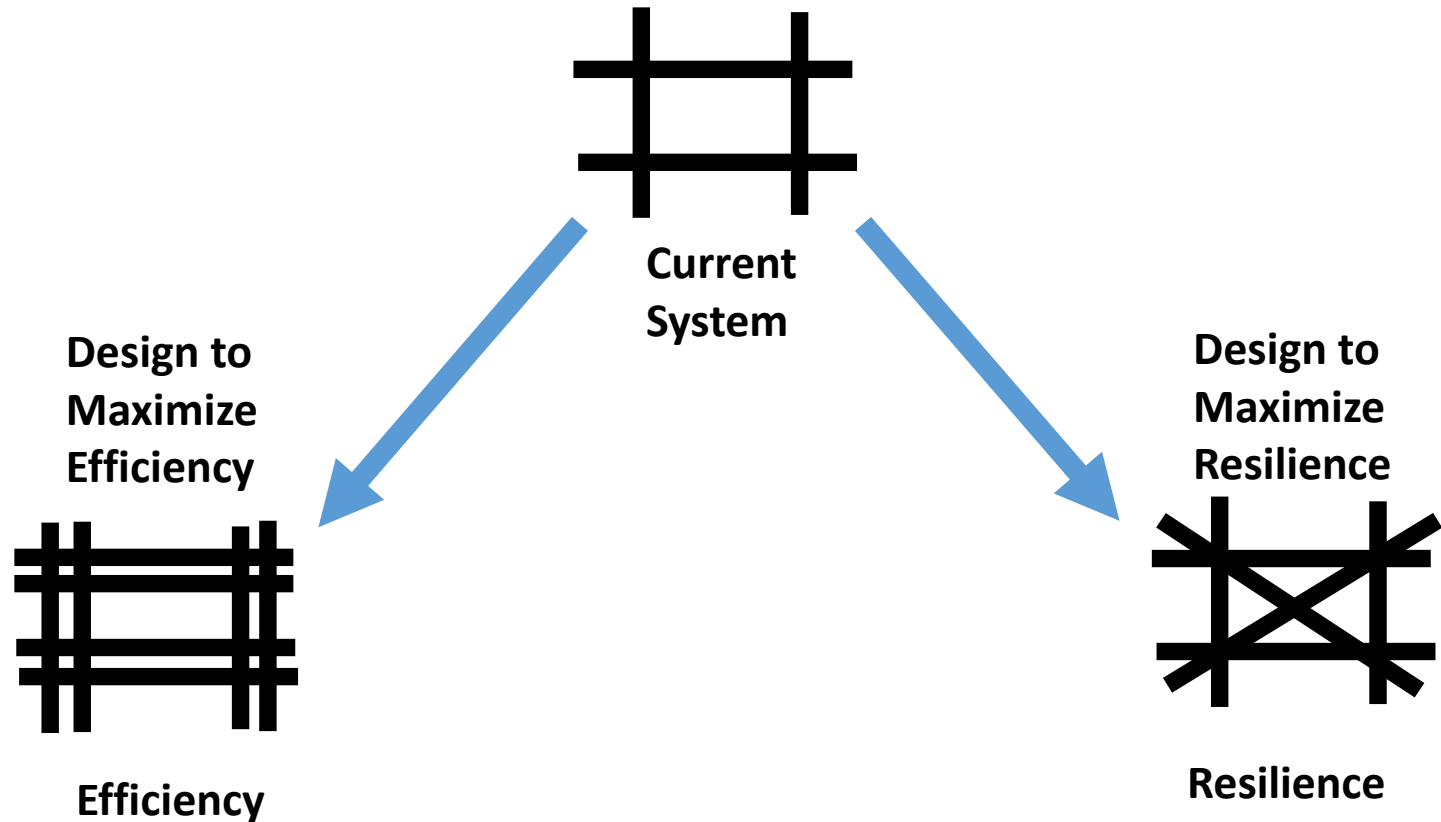


Lack of Resilience to 5% Disruption Adds Variable Additional Delay

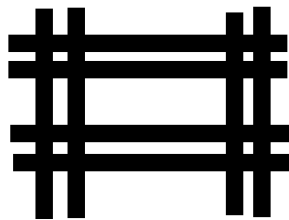


Resilience and efficiency vary greatly from city to city

Managing Resilience is Different than Efficiency

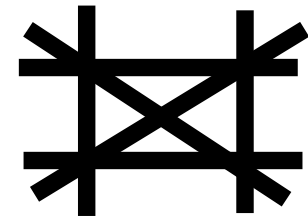


Design to Maximize Efficiency



Efficiency

Design to Maximize Resilience



Resilience

Current System

- the ability to move quickly when the network is functioning as designed
- cost effectively improved by increasing capacity on existing and highly utilized right of ways

- the ability to limit delays from network component failures
- best improved by provide alternative route capacity when failure does occur

Decision
Analysis

Formalize Resilience in Decision-Making

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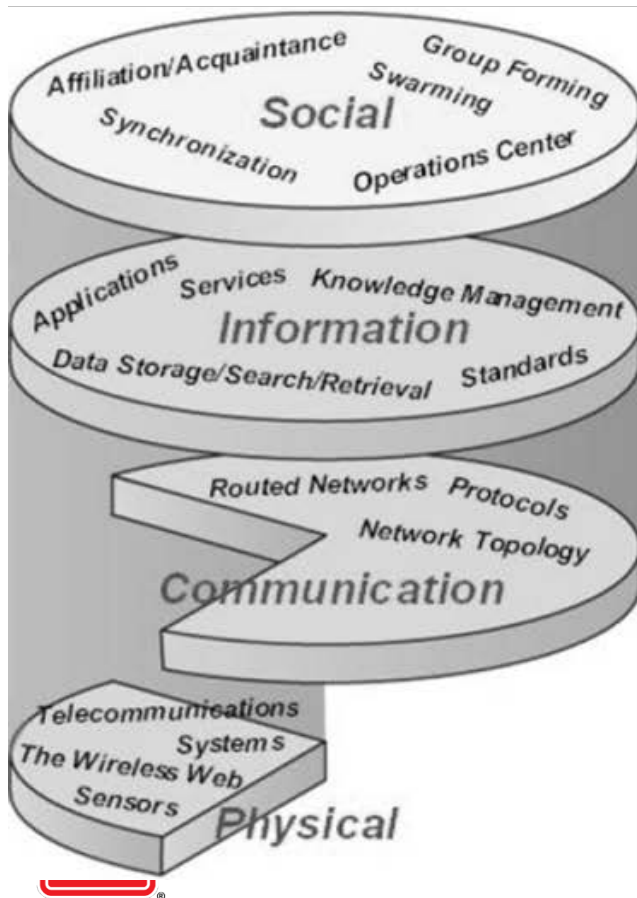
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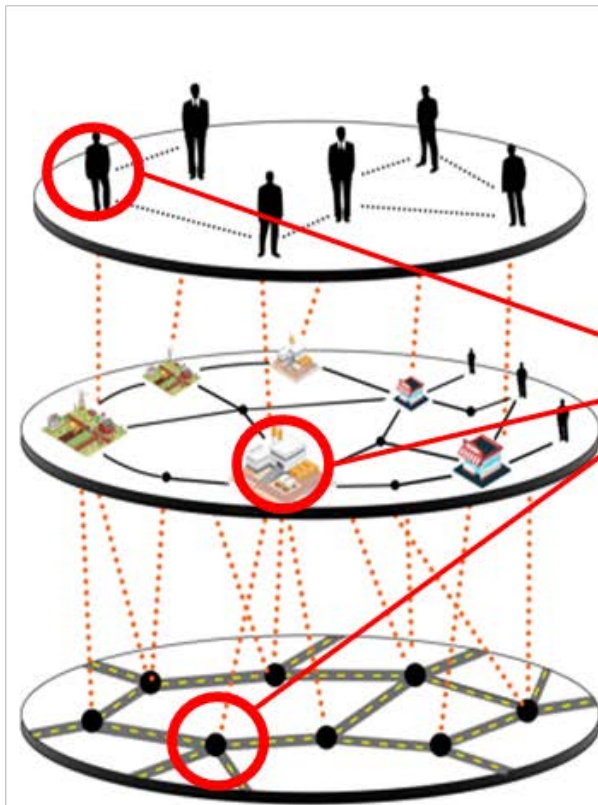
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Vision for Systems Resilience

Real World



Model



Operations

Management Alternatives

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Credits

Transportation Network Modeling

Alex Ganin et al., University of Virginia, Risk & Decision
Science Team

Economic Modeling

William Kozlowski, REMI

Video

Written by Risk and Decision Science Team

Narrated by Ben Trump

Produced by George Siharulidze

With help from EssenceCartoon and Fernando Suarez

