Resilient Transportation Systems: Moving from Risk to Resilience

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- Cold Regions Research and Engineering Laboratory (CRREL)
- Construction Engineering Research Laboratory (CERL)
- Environmental Laboratory (EL)
- Geospatial Research Laboratory (GRL)
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- Information Technology Laboratory (ITL)

Annual Research Program Exceeding $1.3 Billion

Risk and Decision Science Team Boston, MA

2100 Strong
61% E&S
71% of E&S with Advanced Degrees
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- Blast and Weapons Effects on Structures and Geo-Materials
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All DoD Services
Army, Navy, Air Force, NASA, DHS, FEMA, DIA, NGA

Academia
68 EPAs with top engineering schools

Industry
172 CRADAs

International
14 international agreements with 7 countries
Traditional Approaches: Risk Assessments & Cost-Benefit Analysis

- Identity risks and manage those risks: Threat, vulnerability, consequence

Costs
- Variable/Stochastic
  - Early spoilage/loss of cargo
  - Contingent bottlenecks (e.g., customs delays, fleet failures & maintenance...)
  - Unexpected demand and supply changes (e.g., last-minute order cancellations, shortages...)
  - Etc.

- Intangible
  - Opportunities lost (e.g., sub-optimal processes due to lack of optimisation)

- Estimable

Benefits
- Variable/Stochastic
  - Estimation of reduction in shipments wasted/lost
  - Estimation of reduction in mileage to be covered per delivery
  - Estimation in reduction in customer waiting times
  - Etc.

- Intangible

- Estimable

Cost-Benefit Analysis

Decision

Risk vs Resilience: Definitions

**Risk** -- “a situation involving exposure to danger [threat].”

**Security** -- “the state of being free from danger or threat.”

**Resilience** -- “the capacity to recover quickly from difficulties.”

*Definitions by Oxford Dictionary*
Risk vs Resilience: Definitions

Risk Management Strategy:
- Aim: Predict risks & either:
  - Prevent the from impacting system
  - Planning around them (insurance)
  - Threat*Vulnerability*Consequence

Resilience Strategy:
- We can’t predict all threats a company will face
  - Especially in a dynamic and changing world
  - Reduce severity, time and/or extent of the disruption
  - Prepare, absorb, recover, adapt from disruption

After Galaitsi, Linkov et al, 2022

Risk~ Threat*Vulnerability*Consequence
Risk vs Resilience: Random Disruptions are Much More Consequential

Risk:
- Identity risks and manage those risks
  - Only as good as your risk estimates
  - Doesn’t address system response or un-anticipated disruptions

Resilience:
- Improving system’s ability to:
  - Absorb, Recover, Adapt
- Threat agnostic
  - Addresses both anticipated & unanticipated disruptions
What does it mean to have a resilient transportation network?

**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.
What does it mean to have a resilient transportation network?

Transportation Network Model
Regional Economic Models, Inc.

Lack of resilience in transportation networks: Economic implications

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Network Science
Resilience and efficiency in transportation networks
Alexander A. Ganin, Maksim Kitsak, Dayton Marchese, Jeffrey M. Keisler, Thomas Seager, Igor Linkov
What does it mean to have a resilient transportation network?: Impact of Transportation Network Disruptions on Travel Time

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

$$\langle \Delta T \rangle = \frac{1}{N_c} \sum_{\{v_j \} \in \text{all roads}} L_{ij} \ell_{ij} \left( \frac{1}{v_{ij}^0} - \frac{1}{v_{ij}} \right)$$
ERDC Approach: System-Level Approach to Resilience

What Makes Complex Systems (Communities) Susceptible to Threat?

After Linkov and Trump, 2019
ERDC Vision for System Resilience

The case for value chain resilience

Igor Linkov, Savina Carluccio, Oliver Pritchard, Aine Ni Bhreasail, Stephanie Galiatsi, Joseph Sarkis and Jeffrey M. Keisler

Management Alternatives
System's critical functionality ($K$)

Network topology: nodes ($\mathcal{N}$) and links ($\mathcal{L}$)

Network adaptive algorithms ($\mathcal{C}$) defining how nodes' (links') properties and parameters change with time

A set of possible damages stakeholders want the network to be resilient against ($\mathcal{E}$)

$$R = f(\mathcal{N}, \mathcal{L}, \mathcal{C}, \mathcal{E})$$

After Ganin et al., 2016
ERDC Approach: System-Level Approach to Resilience
ERDC Approach: System-Level Approach to Resilience in Transportation Systems

• Problems that work sought to addressed:
  
  I. General Transportation/Supply Chain Resilience Quantification*
  
  II. Zero-Emission Refueling Station Prioritization

*proposed work
Methodology:
Data Fusion and Optimization Using AI and Resilience Modeling
Methodology: Aggregate GPS

- Tools/Impacts can be understood for:
  - Aggregate Flows
  - Medium vs Heavy Trucks
  - Long Haul
  - CA External Goods:
    - Ports
    - Airports
    - Land Points of Entry

More freight traffic
Less freight traffic
I. Problem 1: Resilience Policy Comparison Tool

- Scenario comparison tool compares new road volumes based on changes to roads
  - **Does not**: Recalculates by assuming cars will divert around the disrupted road
  - **Does**: Re-calculates by defining completely new routes for impacted vehicles
- Finds added congestion and travel time
- Aim: Identify **single points of failure**
II. Problem 2:
Zero Emission Refueling Station

• **Challenge:**
  Minimize the diversion of freight routes caused by fuel conversion (disruption)

• **Solution:**
  Identify gas stations that could be converted to dispensing stations:
  • minimize freight displacement
  • scalable
II. Problem 2: Methodology
Facility Location Problem

- Assigns **Demand** to **Facilities** such that an objective is minimized
  - Objective = **Total Travel Time**

- **Need:**
  - Demand Locations
  - Facility Locations
  - Travel Time between Demand and Facilities
II. Problem 2: Methodology
Facility Location Problem

- Assigns Demand to Facilities such that an objective is minimized
- Objective = Total Travel Time

Need:
- Demand Locations
- Facility Locations
- Travel Time between Demand and Facilities
II. Problem 2: Methodology
Facility Location Problem
II. Problem 2: Methodology

Congestion Aware Travel Time

- **Distances:**
  Mean travel time between tracts from Replica freight trips data

- **Details:**
  - Trip data was used so that travel distances were ‘congestion aware’
  - If no trips existed between blocks, travel time was set to 1 day
II. Problem 2: Optimization Results: Candidate Locations

- **Identified:**
  500 Candidate Census block which, together minimize freight diversion

- **Details:**
  - 500 block were identified based on CTC input
  - Gas and Service stations within census blocks were also identified
II. Problem 2: Optimization Results: Quantifying Location Scalability

Want: Quantify the Scalability of Locations

Solution: Rank solutions by hubness

Hubness:
1. Re-ran for sets of best (1, 2, ..., 500) stations
2. Count of how many sets contain any location
   - High hubness = Scales well as more are added
   - Probably in a good, central location
II. Problem 2: Optimization Results: Quantifying Location Scalability

**Want:** Quantify the Scalability of Locations

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III. Extensions: Multi-Objective Optimization

- **Examined Concerns:**
  Define a set of equity concerns which can be weighed against each other

- **Solution:**
  Preform Multi-Objective Optimization:
  - Gets you a range of answers so decision makers can weight different options

CalEnviroScreen 4.0
Diesel Particulate Matter - Percentage

More Diesel Particulates
Less Diesel Particulates
Where are we? Where do we want to go?

Where we are at:

• Growing call for resilience
• Transportation Systems can be modeled
• A lot of focus is still on risk, not resilience

Challenges:

• Visibility
• Multi-Domain Knowledge
• Validation/Success is Hard to Measure
Where are we? Where do we want to go?

**Costs**
- **Direct** - Investment in new equipment, technologies...
- **Indirect** - Overhead costs for day-to-day operation
- Etc.

**Intangible**
- Opportunities lost (e.g., sub-optimal processes due to lack of optimisation)

**Variable/Stochastic**
- Early spoilage/loss of cargo
- Contingent bottlenecks (e.g., customs delays, fleet failures & maintenance...)
- Unexpected demand and supply changes (e.g., last-minute order cancellations, shortages...)
- Etc.

**Benefits**
- Direct - Savings per reduction in shipment loss
- Indirect - Fuel and CO₂ savings (from reduction in covered mileage per delivery)
- Etc.

**Intangible**
- Higher customer satisfaction (from reduced waiting times)

- Estimation of reduction in shipments wasted/lost
- Estimation of reduction in mileage to be covered per delivery
- Estimation in reduction in customer waiting times
- Etc.

**Cost-Benefit Analysis**
- **Estimable**
- **Variable/Stochastic**

**Decision**

Where are we? Where do we want to go?
Balancing Efficiency and Resilience

- Want to maximize functionality across time over time
- Requires estimating both known and unknown risks
Where are we? Where do we want to go?

Summary:

• Resilience should be prioritized more
• Science emerging but needs to be developed
• We approach through data-driven, system-level modeling
• There are still challenges which need to be addressed:
  • Visibility
  • Multi-Domain Knowledge
  • Validation/Success is Hard to Measure
Questions

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IV. Additional Results: Natural Disaster Overlays

- Overlaying freight volumes with climate change vulnerabilities:
  - Wild Fires - Early 2045

- Result: Near Stockton
  - N/S fright corridors are close
  - Near-term Fire Risk

More freight traffic
Less freight traffic
Overlayed with Caltrans Fire Vulnerability