Integrating Planning and Operations: Insights from Disaster Response Modeling

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Outline

- Disasters: transportation perspective
- Two modeling examples
- Operations: evacuation
- Planning: earthquake response
- Integrated planning and operations
  - Modeling insights
  - Real-world challenges/opportunities
- Concluding comments
In the Real World

- Facing evolving disasters
  - 9/11 (2001)
  - Hurricane Katrina (2005)
  - 3/11 Earthquake, Japan (2011)
  - Tornado season in 2011
  - Hurricane Sandy (2012)
Disaster Impacts

- Transportation perspective

Disaster

- Demand
  - Population in the affected region
  - Individual response to the disaster situations

- Supply
  - Transportation supply in the affected region
  - Individual facility and component condition
System-level Interactions

- Demand-supply-performance interactions

![Diagram showing the relationship between Demand, Supply, Disaster, and Dynamics of network traffic.]

- Level of perceived danger and emergency
- Link/node failure or capacity reduction

Dynamics of network traffic
Two Modeling Examples

- **Operations: evacuation**
  - Dynamics of disaster characteristics
  - Demand, supply, performance dynamics
  - Dynamics of response resources allocation

- **Planning: earthquake response**
  - Investments decisions
  - Identification of critical response routes
  - Coordination among nodal agencies
Operations: Evacuation

- **Similarity**
  
  To manage demand loading and traffic flows over spatial and temporal dimensions for efficiently using the capacity of transportation system.

- **Dissimilarity**
  
  - Disaster impact
  - Characteristics of demand loading and traffic flows
  - Traveler behavior
  - Available management strategies and associated constraints
Emergency Planning Zone (EPZ)

Gaps:

- Notional and simplified consideration of disaster impact
- Behavioral realism in decision-making processes related to the evacuation trip to a safe location
  - Limited resources and capabilities to implement mass evacuation
  - Randomness of the location of disaster occurrence
  - Time-dependent effects of evolving disaster and evacuation network, subsequent interactions

A deployable framework to integrate the aspects of demand, supply and disaster in real-time evacuation operations
Modeling Overview

Start

Stage \( \sigma = 0 \)

- Identifying whom are recommended to evacuate
- Forecasting evacuation demand to be provided with route guidance
- Operation objectives in terms of traffic routing scheme
- Determining route guidance for achieving the objectives
- Deploying information strategies (evacuation recommendation & route guidance)

Risk-based analysis of spatial networks

Evacuee behavior modeling

Dynamic traffic assignment

Evacuee behavior modeling

Is the network cleared?

Disaster characteristics and traffic conditions of evacuation network at \( \sigma \)

Stage update \( \sigma = \sigma + 1 \)

No

Traffic evolution

End

Yes
Evacuation Risk

- Relevant elements for evacuation risk
  - Disaster characteristics
  - Transportation mobility aspects
    (Demand pattern and network supply conditions)

- Definition of evacuation risk for area $a$

$$R_a = - (LT_a - CT_a) \quad << \text{time-unit measure}$$

$LT_a$ : the lead time that area $a$ will be impacted by the disaster
$CT_a$ : the time required to clear the evacuees in area $a$
Advantages of using this perspective:
- Using lead time (disaster characteristics) and clearance time (transportation mobility aspects) can capture the spatiotemporal evolution of the associated components
- Integrating the perspectives of both disaster and traffic management in a single measure
- Allowing seamless incorporation into a stage-based (time-dependent) operational framework
- Using the time-unit measure instead of disaster-specific measures for representing disaster intensity

>> Generalizes to different disaster types
Stage-Based Evacuation Risk Zone

Evacuation risk zone (ERZ), spatially bounded subzone in the affected region, which:

- Encompasses the population currently with the highest evacuation risk
- Reflects the spatio-temporal variability of evacuation risk across the affected region
- Factors the limited resources and operation capabilities for deploying evacuation operation within a stage

- Prioritization and coordination of limited resources and operation capabilities
- Synergistic with information strategies deployment
- Incorporation in phased evacuation operations
Evacuation Risk Zone

- Risk-based spatial zone determination problem to derive stage-based Evacuation Risk Zones (ERZs)
  - Spatial optimization problem to identify the population with higher evacuation risk at each operational stage
  - Factoring the limits of available resources and capabilities for deploying evacuation strategies
  - Techniques and related modeling issues
    - Clearance time estimation: dynamic network flow problem
    - Constraints of contiguity-related requirements for an ERZ

- Applications
  - Coordination of limited resources based on need priority
    (the population with higher evacuation risk)
  - Incorporation into phased evacuation operations
Current approaches with Emergency Planning Zone (EPZ)

Framework with stage-based Evacuation Risk Zones (ERZs)

Implement information-based evacuation strategies:
- Evacuation recommendation
- Evacuation route guidance
Evacuee Behavior Models

Evacuation Decision ($\tau$)

Postpone evacuation decision to ($\tau + 1$)

Evacuation Decision ($\tau$)

Evacuation decision model $H$ (perceived evacuation risk, evacuation recommendation, herding behavior, state dependence)

Evacuee route choice model $F$ (route travel time, freeway bias, link failure along the route, evacuation route guidance, herding behavior, route preference)

Route preference
Route familiarity, training, education, past experiences

Other factors
Time pressure, anxiety, fear
Characteristics

- **Disaster**
  - Intensity
  - Spatiotemporal pattern of impact
  - Effect on transportation networks
  - Predictability

- **Supply (management of transportation systems)**
  - Pre-disaster evacuation plan
  - Operational strategies

- **Demand (responses as evacuation decisions and route choices)**
  - Fear and anxiety
  - Time pressure
  - Preparedness (training, education, and past experiences)
  - Level of social network and behavior of seeking social attachment

(Typhoon Morakot, source: AFP)
Insights

- The effect of disaster is only notionally considered by using just a planning perspective (EPZ) to define evacuation demand:
  - An EPZ cannot be specified \textit{a priori} for disasters with high \textit{randomness}
  - The level of danger can vary spatially across the affected region
  - Effects of demand pattern and network supply conditions
  - Evolution of evacuation networks involves the \textit{dynamics of both disaster and transportation mobility aspects}

- \textbf{Limited resources} and capabilities to implement “optimal” control strategies

- \textbf{Behavioral realism} of demand and traffic management using information-based strategies

- \textbf{Computational efficiency} required for real-time evacuation operations
Planning: Earthquake Response

- In a transportation network, links/nodes may fail after a disaster.
  - e.g. highway structures may be damaged or collapse after a disaster.

- Various post-disaster scenarios arise due to the operational or non-operational state of the links (network realized).

*Collapsed section of I–10 (Santa Monica freeway), West Los Angeles. The freeway had been built across relatively soft soils (drained wetlands), the probable reason for the structural failure. This section of freeway was repaired and made serviceable in three months time. Photograph by Kerry Sieh.*
Disaster Management

Stage 1: Pre-disaster Planning
- Developing Information Systems
- Education and Awareness
- Structural Strengthening

Stage 2: Post-disaster Emergency Response
- Coordination
- Efficient Use of Resources

Stage 3: Post-disaster Reconstruction and Recovery
- Assessment, Construction

Emergency transportation plan, Resource allocation for strengthening, Information Systems, Procedures

Status evaluation, Resource allocation, Deployment
Sequence of Events

Pre-disaster

Investment Plan
(selected links are strengthened)

Disaster

Disaster Scenario Realized

Post-disaster

Network Scenario Realized

Relief Operations
(transportation in realized scenario)
Problem Characteristics

- Make investment decisions
  - in the **pre-disaster planning stage** under uncertainty about the surviving network
  - in order to improve the overall **post-disaster network performance**

- Network performance
  - connectivity (through penalty)
  - performance measures
Strengthening the Network Links

- Vulnerable structures, such as bridges, can be strengthened to reduce their vulnerability.

- The **failure probability of a link** depends on:
  - the disaster scenario that unfolds
  - how the vulnerable components in the link are affected by the disaster

- The link failure probability can be **reduced through investment**:
  - “upgrading cost” of the link
  - a budget limitation on investments for upgrading
Uncertainty in Pre-disaster Planning

Pre-disaster Planning Problem

Disaster Scenario 1

Disaster Scenario 2

Disaster Scenario 3

\( \cdots \)

Disaster Scenario \( k \)

Network Realization 1

Network Realization 2

\( \cdots \)

\( \cdots \)

Network Realization 1

Network Realization 2

\( \cdots \)

\( \cdots \)

Network Realization \( s \)
Investment Decisions

I. Seismic retrofit of bridges in southwest Indiana, USA

None

II. Seismic retrofit of road structures in Istanbul, Turkey

Network realized

III. Investment decisions for Sioux Falls network, USA

Disaster scenario

Network realized
Investment Decisions

Factors considered for analysis

- Population accessibility
- Performance (travel time)

I. Seismic retrofit of bridges in southwest Indiana, USA

II. Seismic retrofit of road structures in Istanbul, Turkey

III. Investment decisions for Sioux Falls network, USA

- Performance (travel time)
- Survivability improvement due to investment

- Survivability improvement due to investment
- Connectivity
Insights

- Link failures are **random** and depend on the **network realized after a disaster**

- The planning problem considers low flow (volume) response only; **actual usage levels** may suggest that it is better to invest in high flow (volume) roads (**systems perspective & capacity considerations**)

- **Retrofitting** of bridges on high volume roads potentially improves **connectivity** in the short- and medium-terms following an earthquake (**operational perspective**)

- **Randomness** in disaster scenario (**operational perspective**)

- **Connectivity** and **flow aspects** need to be better understood (**operational perspective**)
Integrated Planning and Operations: Modeling Insights

- Stochasticity/randomness (need to factor in planning models)
- Dynamics (in focus in operational models)
- Demand-supply interactions (need to factor in both planning and operational models)
- Behavioral heterogeneity (need to factor in both planning and operational models)
- Resource considerations (planning and operational models)
  - Investment decisions and facility location (planning)
  - Dynamic allocation of personnel, equipment, etc.
- Integrated planning and operational models
  - Factoring operational characteristics during planning stage
  - Making planning decisions based on operational performance measures
  - Leveraging planning decisions to enhance operational effectiveness
- Recourse models to respond to emergent scenarios not planned for
Integrated Planning and Operations: Real-world Challenges/Opportunities

- Need for coordination across different transportation divisions
  - Planning, operations, policy, resource allocation, etc.
- Need for coordination across relevant agencies
  - Transportation, security, first responders, emergency response, local administration, schools, large employers, etc.
  - Development of plans and human-in-loop simulations (for example, using agent-based models and/or GIS platforms)
- Data needs and challenges
  - Varied data needs based on models
  - Need for identification of common data needs and standards
  - Lack of data can limit model application
- Public awareness and education of public
- Multidisciplinary needs (involve domain experts at all stages)
- Systems perspective skills
- Need to leverage recent computing and storage technologies
- Need to leverage advances in information and communication technologies
References


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