Dan & Eva Roos Thesis Prize

2021-23 Call Winner Presentations
About the Prize

- Thank Dan & Eva Roos for their generosity
- This is the 3rd edition of the Prize hosted by MMI
- The Thesis Prize is awarded to an outstanding MIT PhD dissertation in the field of transportation/mobility, submitted between Sep 2021 - Jun 2023
- Mobility is broadly defined and the thesis can be submitted to any department or PhD-granting program at MIT, and can address any aspect of transportation systems, such as:
  - research related to any mode of transport
  - passenger or freight transportation
  - theoretical or applied problems in transportation
  - technological, economic, planning or policy analysis in transportation and mobility
- [https://www.mmi.mit.edu/roosaward](https://www.mmi.mit.edu/roosaward)
Previous Year Winners

2021 Winner: Dr. Shenhao Wang, Deep Neural Networks for Choice Analysis

Honorary Mentions:
Dr. Arthur Delarue: Optimizing School Operations
Dr. Wilko Schwarting: Learning and Control for Interactions in Mixed Human-Robot Environments

Prize Selection Committee: Yossi Sheffi, Cindy Barnhart, Alexandre Jacquillat, Jinhua Zhao (Chair)

2018 Winner: Dr. Gabriel Kreindler "Essays on the Economics of Urban Transportation (Extended Abstract | Full Thesis"

Prize Selection Committee: Ali Jadbabaie, CEE and IDSS, Yossi Sheffi, CTL and CEE, Hamsa Balakrishnan, Co-Chair, AeroAstro, Jinhua Zhao, Co-Chair, DUSP
2023 Prize

Selection Committee:

- Prof. Amedeo Odoni
- Prof. Alexandre Jacquillat
- Prof. Jinhua Zhao (Chair)

Shortlisted:

- Angela Acocella: Alternative Freight Contracts: Data-driven Design Under Uncertainty
- Hanzhang Qin: Stochastic Control Through a Modern Lens: Applications in Supply Chain Analytics and Logistical Systems
- Baichuan Mo - Toward a Resilient Public Transportation System: Effective Monitoring and Control under Service Disruptions
- Rounaq Basu - Planning sustainable cities: Coordinating accessibility improvements with housing policies
- Karthik Gopalakrishnan - Modeling and Control of Networked Systems: Applications to Air Transportation
2023 Prize

Winner:

- Baichuan Mo - Toward a Resilient Public Transportation System: Effective Monitoring and Control under Service Disruptions

Honorable Mentions

- Rounaq Basu - Planning sustainable cities: Coordinating accessibility improvements with housing policies
- Karthik Gopalakrishnan - Modeling and Control of Networked Systems: Applications to Air Transportation
Toward a Resilient Transportation System: Applications to Public Transit

Baichuan Mo
Ph.D. @ MIT
Senior Research Scientist @ Lyft Inc.

Dec 08, 2023
A shift of transportation research paradigm

“Uncertainty is the only certainty there is.”
——John Allen Paulos, Professor in Mathematics

- The world never works as expected. Various unpredictable incidents and disturbances happen everyday.
- However, most of previous studies usually assume “normal situations” for prediction, planning, operation, and control in a transportation system.

“Abnormal” is the “actual normal” of the world.

Shift of Research Paradigm: Certain, Normal ➔ Uncertain, Abnormal
Resilience

● **Definition:** The ability of a system to cope with unplanned incidents and disruptions

● **Motivation:** Building a resilient transportation system is a way to embrace uncertainties and protect the system’s functionality under these incidents.

● This dissertation focuses on two import tasks to develop a resilient public transit (PT) system: Monitoring and Control.

   ● 1) Understand the impact of unplanned incidents on PT systems (i.e., Monitoring)

   ● 2) Design mitigating strategies to relieve incident impacts (i.e., Control)
Understand the Impact: Long-term incidents

Empirical analysis

1. **Number of taps per 10 min**
   - Normal day (mean)
   - Incident day
   - Incident period

2. **Number of taps per 10 min**
   - Normal day (mean)
   - Incident day
   - Incident period

3. **Number of taps per 10 min**
   - Normal day (mean)
   - Incident day
   - Incident period

(a) Brown Line (blocked)  
(b) Purple Line (blocked)  
(c) Red Line (open)

Response inference

- **Possible reason 1:** He/she needs to transfer to a bus for normal commute
- **Possible reason 2:** He/she transfers to an alternative route due to the incident

(Suppose $S_i$ is the set of passengers who transfer to a bus stop due to incident, $N_i = |S_i|$)

- $P(p \in S_i) = P(\text{"Passenger p's transfer is an atypical behavior"})$
- # days passenger p transfers to bus
- # days passenger p with travel

$$E(N_i) = \sum_p P(p \in S_i)$$
$$\text{Var}(N_i) = \sum_p (1 - P(p \in S_i)) \times P(p \in S_i)$$
(By def. of Bernoulli variable)

Impact of unplanned long-term service disruptions on urban public transit systems, B Mo et al., IEEE Open Journal of Intelligent Transportation Systems, 2022, 3, 551-569

Understand the Impact: Short-term incidents

Theoretical queuing analysis

- higher rate of incidents (gamma) and higher duration of incidents \((1/\theta)\) make the system more likely to be unstable.
- The closed-form formulation can be used to calculate queue length and waiting time efficiently considering short-term perturbations.
- Public transit design diagnose (e.g., headways and vehicle capacity)

**Proposition 12.** Under the setting of this study, the bulk-service queuing system at station \(n\) is stable if and only if

\[
\rho^{(n)} = \frac{\bar{Y}^{(n)}}{S^{(n)}} = \frac{\lambda^{(n)} \cdot \mathbb{E}[\hat{H}_{\text{Normal}}^{(n)}]}{\sum_{u=0}^{C} s_u^{(n)} u} < 1 \quad (2.59)
\]
Control under disruptions: Path recommendation

Individual-based with behavior uncertainty

System recommendation ($r'$)

<table>
<thead>
<tr>
<th>Path 1</th>
<th>Path 2</th>
<th>Path 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.7</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>0.2</td>
<td>0.8</td>
<td>0.3</td>
</tr>
<tr>
<td>0.1</td>
<td>0.1</td>
<td>0.6</td>
</tr>
</tbody>
</table>

User $p$ choices ($r$)

Matrix of $\pi^r_{p,r'}$
Control under disruptions: Path recommendation

New solving methods and with solution-quality bounds

- **Challenges**: Randomness in passenger behavior makes the decision variables (passenger flow) become random variables.

- **Ideas**: Treat the passenger flow (decision variables) as realizations (deterministic), but add constraints to it ($\varepsilon$-feasibility and $\Gamma$-concentration).

- **Solution-quality bound**: The optimal system travel time (STT) in the new formulation is close to the expected STT without approximation (true system performance indicator) if $\varepsilon$ and $\Gamma$ are small enough.

\[
|E_{Q|\text{x}^*}[\text{STT}(Q|\text{x}^*)] - \text{STT}(q^*)| \leq 2L \cdot \|\varepsilon\|_1 + L \cdot \left( \|E[Q|\text{x}^*]\|_1 + \|q^{\text{Max}}\|_1 + 2\|\varepsilon\|_1 \right) \cdot \|\Gamma\|_2
\]
### Chicago public transit case study

<table>
<thead>
<tr>
<th>Models</th>
<th>Average travel time (all passengers)</th>
<th>Average travel time (incident line passengers)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean (min)</td>
<td>Std. (min)</td>
</tr>
<tr>
<td>Status quo</td>
<td>28.318</td>
<td>N.A.</td>
</tr>
<tr>
<td>Capacity-based</td>
<td>27.609 (-2.5%)</td>
<td>0.033</td>
</tr>
<tr>
<td>IPR model</td>
<td><strong>26.457 (-6.6%)</strong></td>
<td>0.018</td>
</tr>
</tbody>
</table>

Numbers in parentheses represent percentage travel time reduction compared to the status quo.
Implementation: Incident management system
A unified framework and extensions

Degree of behavior and operational changes

Normal scenario
- Network performance model

Short-term and non-severe incidents
- Bulk-service queueing model
- Real-time re-routing, vehicle control
- Robust frequency design

Long-term and severe incidents
- Empirical analysis
- Path recommendation
- Pre-trained machine learning models

Monitoring
- Inflow demand control

Planning
- Timetable design, Promotion design

: Previous research  : Future research
Planning sustainable cities

Coordinating accessibility improvements with housing policies

Rounaq Basu

Postdoctoral Associate, MIT
Manager of Multimodal Planning and Design, Boston Region MPO

December 8, 2023
The challenges of auto-dependence

GHG emissions

- Transportation (29%)
- Industry (22%)
- Electricity (28%)
- Agriculture (9%)
- Commercial & Residential (12%)

Light-Duty Vehicles

Road fatalities
(per million people)

Countries included: Portugal, Other OECD countries, UK, US
Car-lite programs

**GOAL:** Reduce private vehicle ownership, use, and emissions without reducing mobility and accessibility

- Improve accessibility from non-auto modes
- Make owning and using a car less attractive
Neighborhood change

Improvements in non-auto accessibility

Net Effect

Rounaq Basu | Planning sustainable cities | MIT Mobility Initiative
Car-lite policy scenarios

● Blanket ban on private vehicles

● Non-auto accessibility improvements
  ○ Non-auto accessibility = Auto accessibility (on average)

● Non-auto accessibility improvements + Housing policies
  ○ Upzoning (Increased housing supply)
  ○ Parking minimum reductions (Reduced vehicle ownership opportunities in new housing supply)
Integrated Urban Modeling

SimMobility

A land use-transport interaction (LUTI) model

Rounaq Basu | Planning sustainable cities | MIT Mobility Initiative
Blanket ban on private vehicles

Change in accessibility (%)

![Change in accessibility graph]

Change in consumer surplus (million SGD)

![Change in consumer surplus graph]
Non-auto accessibility improvements

Lower-income and more vehicle-free neighborhoods are more susceptible to accessibility-induced gentrification (!)

Rounaq Basu | Planning sustainable cities | MIT Mobility Initiative
Coordinated housing-mobility policies

**GOAL:** Mitigating undesired consequences while maximizing benefits of accessibility improvements

- No ‘one size fits all’ housing policy!
- Certain policy combinations can result in worse outcomes compared to ‘baseline’ or ‘no-coordination’ scenarios
Planning sustainable cities requires careful attention to **both transportation and housing** impacts of accessibility improvements.
How can we accelerate sustainable mobility outcomes?

- Improve accessibility from non-auto modes
- Make owning and using a car less attractive
Modeling and Control of Networked Systems

Applications to Air Transportation

Karthik Gopalakrishnan
Systems Engineer at Tesla

PhD in Aeronautics and Astronautics, 2021
Advisor: Prof. Hamsa Balakrishnan
Air travel connects the world...

4.5 billion pax, $6.7 trillion worth goods, 22k city pairs, 39 million scheduled flights
but the system is far from perfect. 

In the US, almost 20% of flights are delayed and 2% of flights are cancelled. This costs $30-40 billion a year (approx $300 / min of delay / flight).
What causes flight delays?

Cause of flight delays in the US

- Extreme weather: 5%
- National Aviation System delay: 24%
- Air carrier delay: 31%
- Later arrival of incoming aircraft: 40%

“Your flight is delayed because the incoming flight is delayed”

How do we model, predict, and reduce the spread of flight delays?

- Data-driven methods: Accurate but not interpretable
- Network model: Interpretable but not accurate

[Data: FAA]
Features of our new delay propagation model

Airport delays don’t change abruptly

\[ d_{in}^i(t + 1) = \alpha_{in}^i d_{in}^i(t) + \sum_j \beta_{in}^{ji} a_{ji}(t) d_{out}^j(t) \]

\( \alpha \): Persistence coefficient
\( \beta \): Network-effect coefficient

Airport delays experience network effects

Time-varying network topology

[Images: SITA, Wikipedia]
The Markov Jump Linear System (MJLS) model

The model combines interpretability and accuracy
- Network modes and their transitions are interpretable
- Network modes, model coefficients, and transition probabilities are learnt from data
The MJLS model performs well...

... qualitatively and quantitatively
The model suggests strategies to minimize delays.

We solve an optimal control problem to identify the ideal airports and network modes that can help minimize the spread of delays in the entire country.

Target airports to reduce delays: Atlanta, Chicago, San Francisco, Los Angeles.

Ideal time to reduce delays: 10 AM to 2 PM Eastern.
Data-driven network models offer a powerful paradigm to study large-scale transportation systems

UAM/AAM traffic management

Road traffic prediction & control

[Images: NASA, Google]
Q&A