Chair of Transportation Systems Engineering
Department of Mobility Systems Engineering
TUM School of Engineering and Design
Technical University of Munich

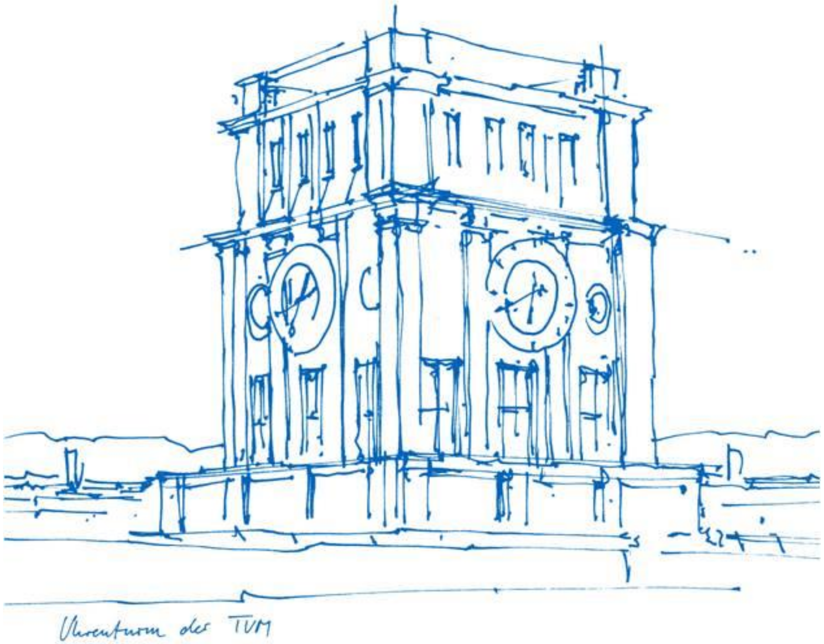
Simulation-based network capacity allocation optimization for traffic resilience via enhanced mixed stochastic approximation

Conference in Emerging Technologies in Transportation Systems (TRC-30)

Qinglong Lu, Yunping Huang, Wenzhe Sun,
Jan-Dirk Schmöcker, Constantinos Antoniou







September 3, 2024

Outline

1. Introduction
2. Traffic resilience definition
3. Network capacity allocation
4. Case study
5. Conclusions

Introduction

Higher capacity means less congestion?

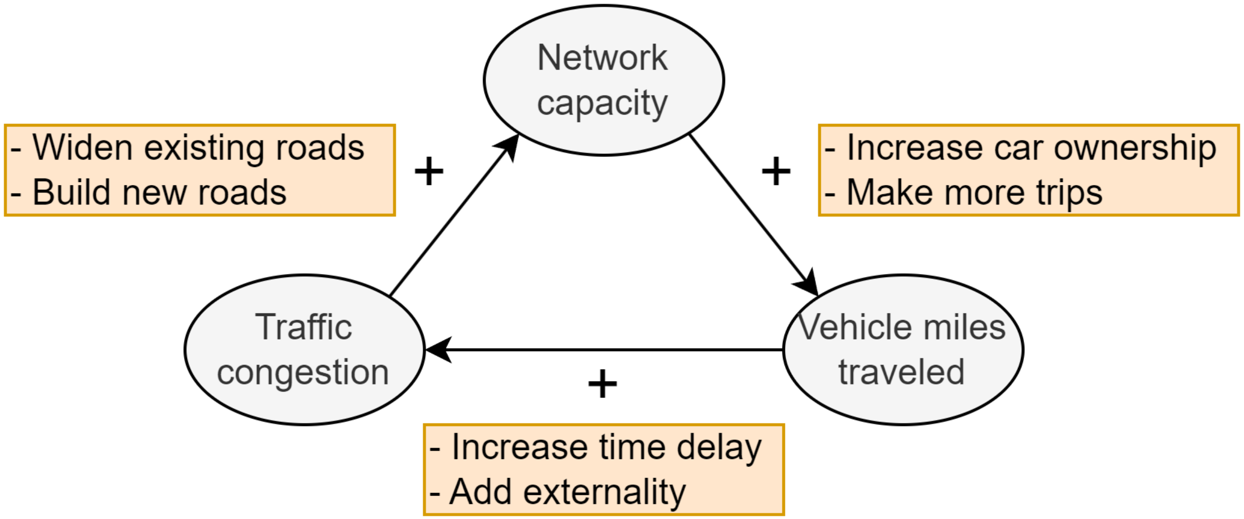
- Increase network capacity:
  - Widening existing roads
  - Building new corridors

Ewing, R., Tian, G., & Lyons, T. (2018). Does compact development increase or reduce traffic congestion?. *Cities*, *72*, 94-101.

- Increased capacity ⇨ additional travel
  - Mode shifts, route shifts
  - Redistribution of trips, new trips

Noland, R. B. (2001). Relationships between highway capacity and induced vehicle travel. *Transportation Research Part A: Policy and Practice*, *35*(1), 47-72.

⇨ Improve network capacity allocation



Urban transportation disruptions

- Triggers: natural disasters, special events, etc.
- Impacts of disruptions
  - Reducing traffic efficiency
  - Increasing travel risk
  - Cascading to other urban subsystems

Significant social and economic losses!

Reuter

Research question

How to optimize network capacity allocation plan to improve traffic resilience?

Strategic network design

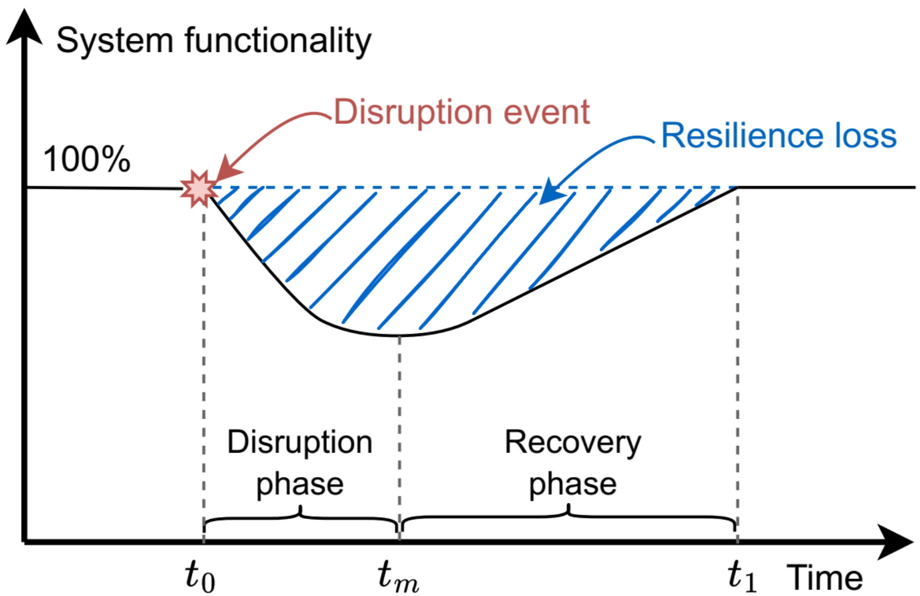
Farahani, R. Z., Miandoabchi, E., Szeto, W. Y., & Rashidi, H. (2013). A review of urban transportation network design problems. *European Journal of Operational Research*, *229*(2), 281–302.

Traffic resilience definition

What is system resilience?

"Resilience represents the ability to prepare for changing conditions and withstand, respond to, and recover rapidly from disruptions."
— Federal Highway Administration (FHWA) of the US

- Different aspects compared to other concepts (e.g., vulnerability, robustness)
  - New equilibrium state
  - Recovery speed



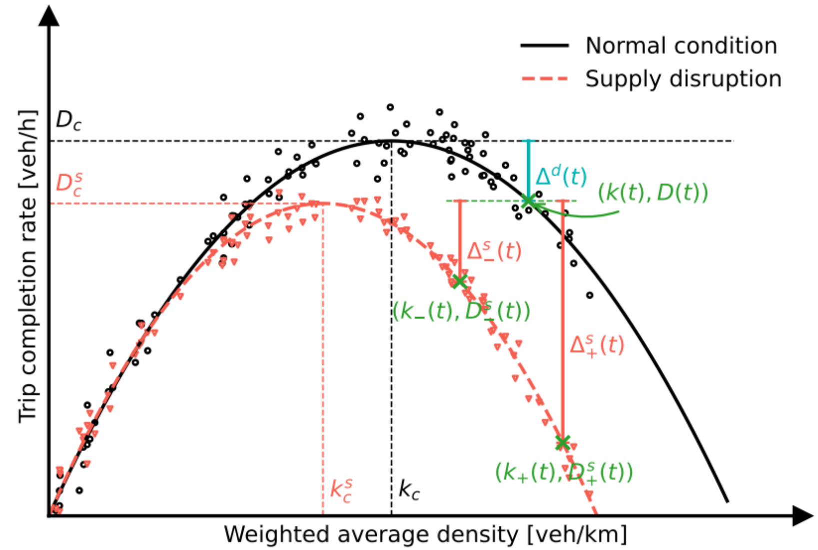
"Resilience Triangle"

$$R = \int_{t_0}^{t_1} \left(100 - Q(t)\right) \mathrm{d}t$$

Bruneau, M., Chang, S. E., Eguchi, R. T., Lee, G. C., O'Rourke, T. D., Reinhorn, A. M., Shinozuka, M., Tierney, K., Wallace, W. A., & Von Winterfeldt, D. (2003). A framework to quantitatively assess and enhance the seismic resilience of communities. *Earthquake Spectra*, *19*(4), 733–752.

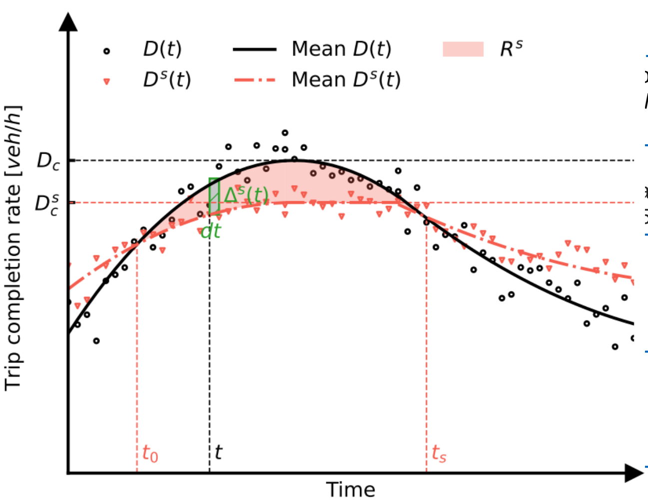
MFD-based resilience indicators

- Macroscopic fundamental diagram (MFD)
  - x-axis: Weighted average density (or Accumulation)
  - y-axis: Trip completion rate (or weighted space-mean flow)

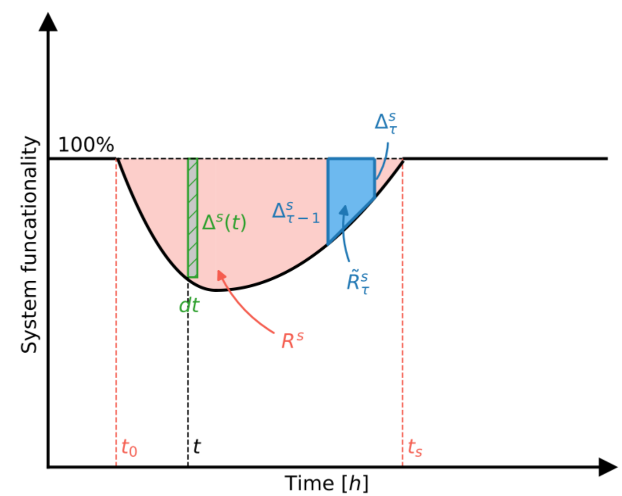


- Transportation systems:
  - Service rate ⇔ Trip completion rate
  - ⇨ MFD-based traffic resilience indicators

Gerolim… fundame… Part B: …
Ji, Y., & … network…
Lu, Q. L… resilienc… analysis… Safety, …
…pic …h
…ation …56.



(a) Trip completion rate deviation

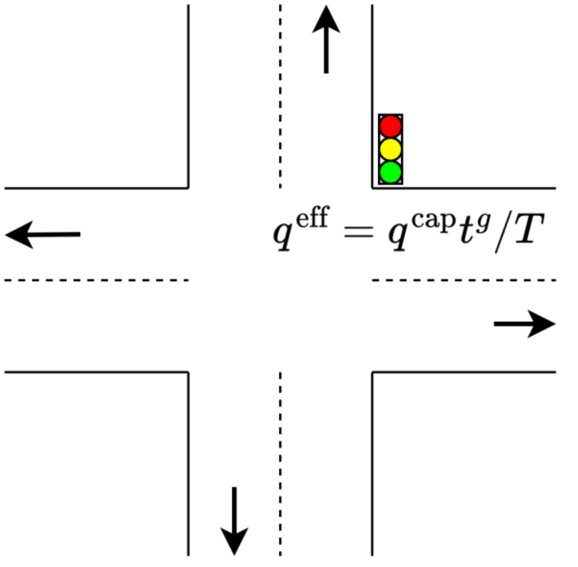


(b) System functionality

Network capacity allocation

Network capacity allocation problem

- Calculation example:
  - Effective capacity of a lane i: $q_i^{\text{eff}} = \frac{q_i^{\text{cap}} t_i^g}{T}$
  - Effective capacity of a link l: $q_l = \sum_{i=1}^{n_l} q_i^{\text{eff}}$



- Network capacity allocation:
  - Lane allocation (discrete)
  - Traffic signal timing (continuous)

  ⇒ Mixed network design problem

Resilient network capacity allocation

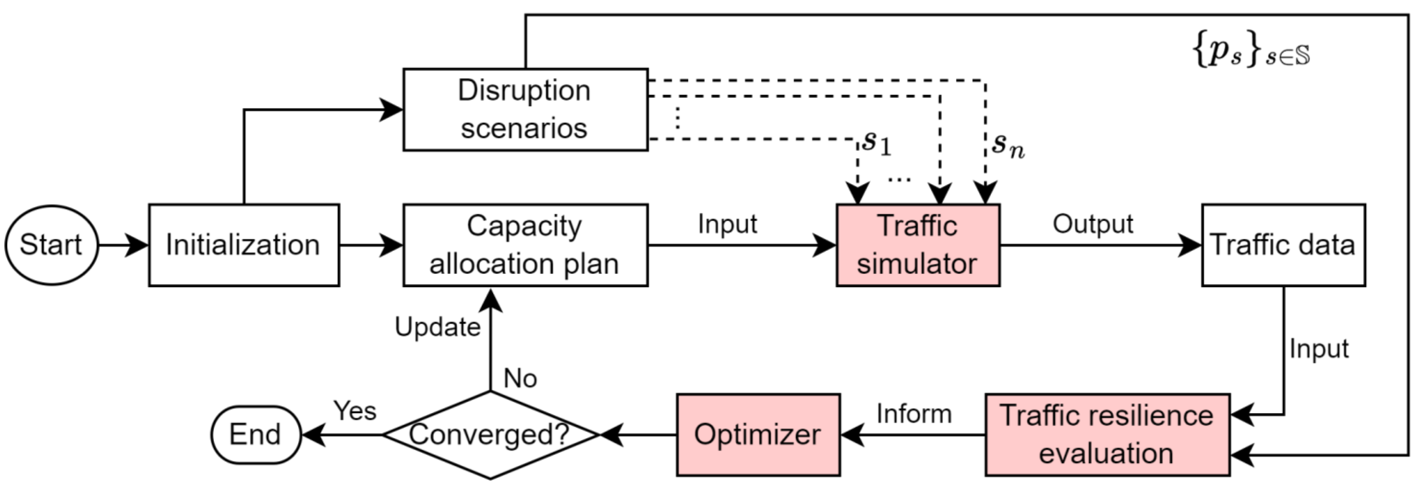
- Multi-objective optimization
  - Disruption scenarios
  - Disruption distribution
- Objective function:

$$y(\boldsymbol{z},\boldsymbol{x},\boldsymbol{\xi}) = -w^n D_c - w^d R^d(\boldsymbol{z},\boldsymbol{x},\boldsymbol{\xi}) - \sum_{\phi\in\mathbb{S}} w_\phi^s R^s(\boldsymbol{z},\boldsymbol{x},\boldsymbol{\xi},\phi)$$

  - Disruption probability
  - Economic losses

$\left.\begin{array}{l}\text{Disruption probability}\\ \text{Economic losses}\end{array}\right\}$ Risk assessment

- Simulation-based optimization



Solution algorithm

- Problem characteristics:
  - High-dimensional
  - Stochastic
  - Expensive-to-evaluate objective
  - Mixed network design

$$
\begin{aligned}
(\text{SOCA}) \min_{\boldsymbol{z},\boldsymbol{x}} \quad & \mathbb{E}_{\boldsymbol{\xi}} = [y(\boldsymbol{z},\boldsymbol{x},\boldsymbol{\xi})] \\
\text{s.t.} \quad & \mathbb{E}_{\boldsymbol{\xi}} = [g(\boldsymbol{z},\boldsymbol{x},\boldsymbol{\xi})] \leq 0 \\
& \boldsymbol{z} + \boldsymbol{z}^{\text{opp}} = \boldsymbol{n} \\
& \boldsymbol{B}\boldsymbol{x} = \boldsymbol{T} \\
& \boldsymbol{z}_l \leq \boldsymbol{z} \leq \boldsymbol{z}_u \\
& \boldsymbol{x}_l \leq \boldsymbol{x} \leq \boldsymbol{x}_u \\
& \boldsymbol{z} \in \mathbb{Z}^d, \boldsymbol{x} \in \mathbb{R}^{p-d}
\end{aligned}
$$

⇨ Enhanced mixed simultaneous perturbation stochastic approximation (SPSA)

SPSA ⇨ { Second-order SPSA (2SPSA); Mixed SPSA (MSPSA) } ⇨ Second-order mixed SPSA (2MSPSA)

$$
\hat{\boldsymbol{\theta}}_{k+1} = \hat{\boldsymbol{\theta}}_k - a_k \boxed{\bar{\bar{\boldsymbol{H}}}_k^{-1}(\hat{\boldsymbol{\theta}}_k)} \boldsymbol{G}_k(\hat{\boldsymbol{\theta}}_k)
$$

Spall, J. C. (2009). Feedback and Weighting Mechanisms for Improving Jacobian Estimates in the Adaptive Simultaneous Perturbation Algorithm. *IEEE Transactions on Automatic Control*, *54*(6), 1216–1229.

Wang, L., Zhu, J., & Spall, J. C. (2018). Mixed Simultaneous Perturbation Stochastic Approximation for Gradient-Free Optimization with Noisy Measurements. *2018 Annual American Control Conference (ACC)*, 3774–3779.

2MSPSA algorithm

$$\hat{\boldsymbol{\theta}}_{k+1} = \hat{\boldsymbol{\theta}}_k - a_k \boxed{\phantom{\bar{\bar{H}}_k^{-1}}}\ \boxed{\boldsymbol{G}_k(\hat{\boldsymbol{\theta}}_k)}$$

$$\boxed{\boldsymbol{G}_k(\hat{\boldsymbol{\theta}}_k) = \frac{y(\hat{\boldsymbol{\theta}}_k^{(+)}) - y(\hat{\boldsymbol{\theta}}_k^{(-)})}{2\boldsymbol{C}_k \circ \boldsymbol{\Delta}_k}}$$

$$\bar{\bar{\boldsymbol{H}}}_k = f_k(\bar{\boldsymbol{H}}_k)$$

$$\bar{\boldsymbol{H}}_k = (1 - w_k)\bar{\boldsymbol{H}}_{k-1} + w_k(\hat{\boldsymbol{H}}_k - \hat{\boldsymbol{\Psi}}_k)$$

$$\hat{\boldsymbol{H}}_k = \frac{1}{2}\left[\frac{\delta \boldsymbol{G}_k}{2}(\boldsymbol{C}_k \circ \boldsymbol{\Delta}_k)^{-\top} + \left(\frac{\delta \boldsymbol{G}_k}{2}(\boldsymbol{C}_k \circ \boldsymbol{\Delta}_k)^{-\top}\right)^{\top}\right]$$

$$\delta \boldsymbol{G}_k = \boldsymbol{G}_k^{(1)}(\hat{\boldsymbol{\theta}}_k^{(+)}) - \boldsymbol{G}_k^{(1)}(\hat{\boldsymbol{\theta}}_k^{(-)})$$

$$\boldsymbol{G}_k^{(1)}(\hat{\boldsymbol{\theta}}_k^{(\pm)}) = \frac{y(\hat{\boldsymbol{\theta}}_k^{(\pm)} + \tilde{\boldsymbol{C}}_k \circ \tilde{\boldsymbol{\Delta}}_k) - y(\hat{\boldsymbol{\theta}}_k^{(\pm)})}{\tilde{\boldsymbol{C}}_k \circ \tilde{\boldsymbol{\Delta}}_k}$$

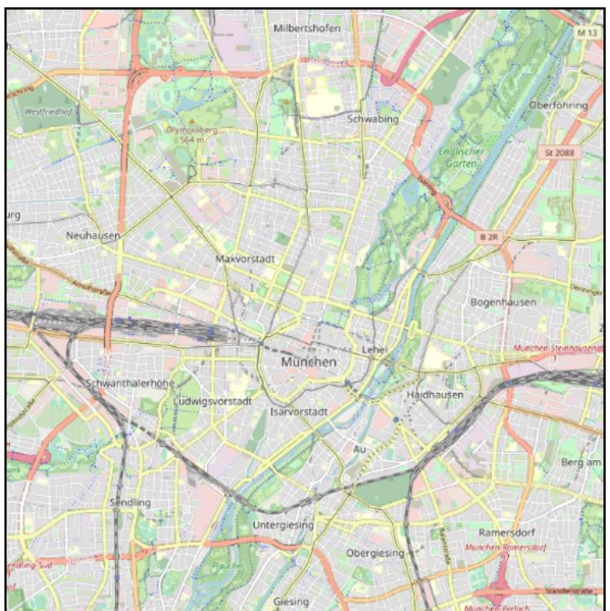
$$\boldsymbol{C}_k = (\underbrace{0.5, \dots, 0.5}_{d \text{ elements}},\ \underbrace{c_k, \dots, c_k}_{p-d \text{ elements}})^{\top}$$

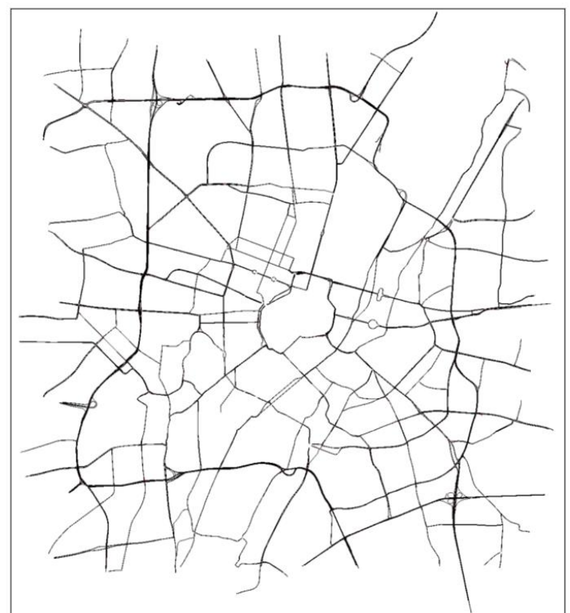
Case study

Case studies: Study areas and disruptions

- Munich city center, Germany: 100 km², 2605 links
- Simulator: SUMO
- Disruption scenarios
  - Daily operation (w^n)
  - Hyper-congestion (w^d)
  - Flooding (w_1^s)

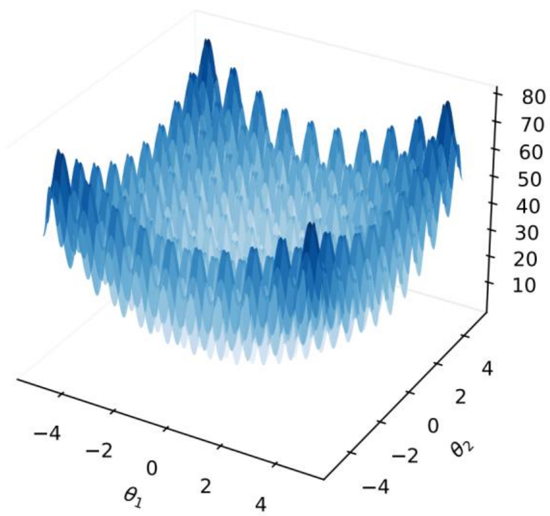
$$y(\boldsymbol{z},\boldsymbol{x},\boldsymbol{\xi}) = -w^n D_c - w^d R^d(\boldsymbol{z},\boldsymbol{x},\boldsymbol{\xi}) - \sum_{\phi\in\mathbb{S}} w_\phi^s R^s(\boldsymbol{z},\boldsymbol{x},\boldsymbol{\xi},\phi)$$





Algorithm evaluation

❑ 2MSPSA vs MSPSA



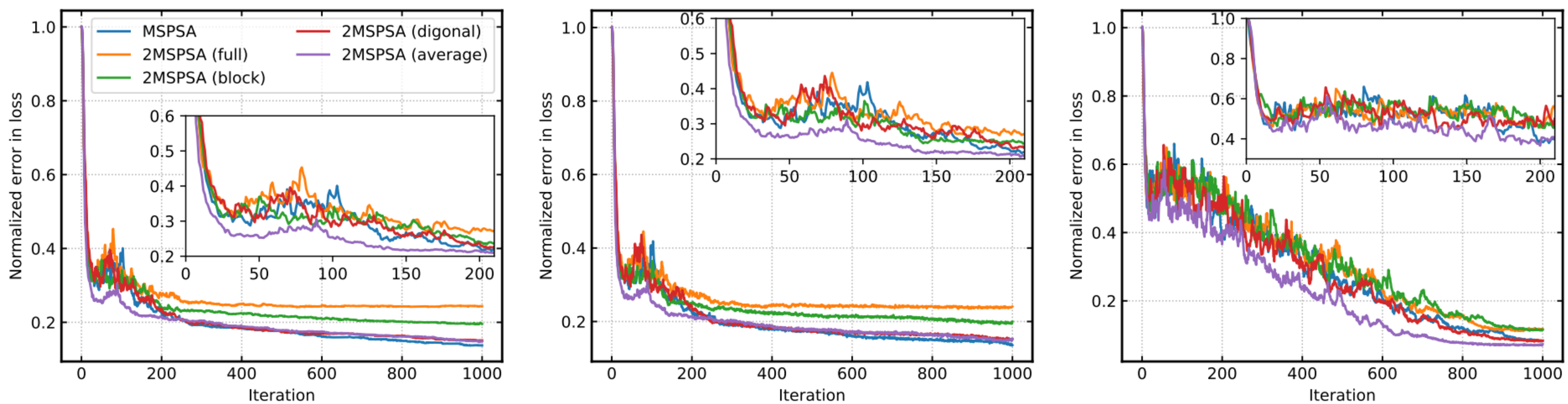
Rastrigin function:

$$L(\boldsymbol{\theta}) = 10p + \sum_{i=1}^{p} [\theta_i - 10\cos(2\pi\theta_i)]$$

$$y(\boldsymbol{\theta}) = L(\boldsymbol{\theta}) + \varepsilon$$

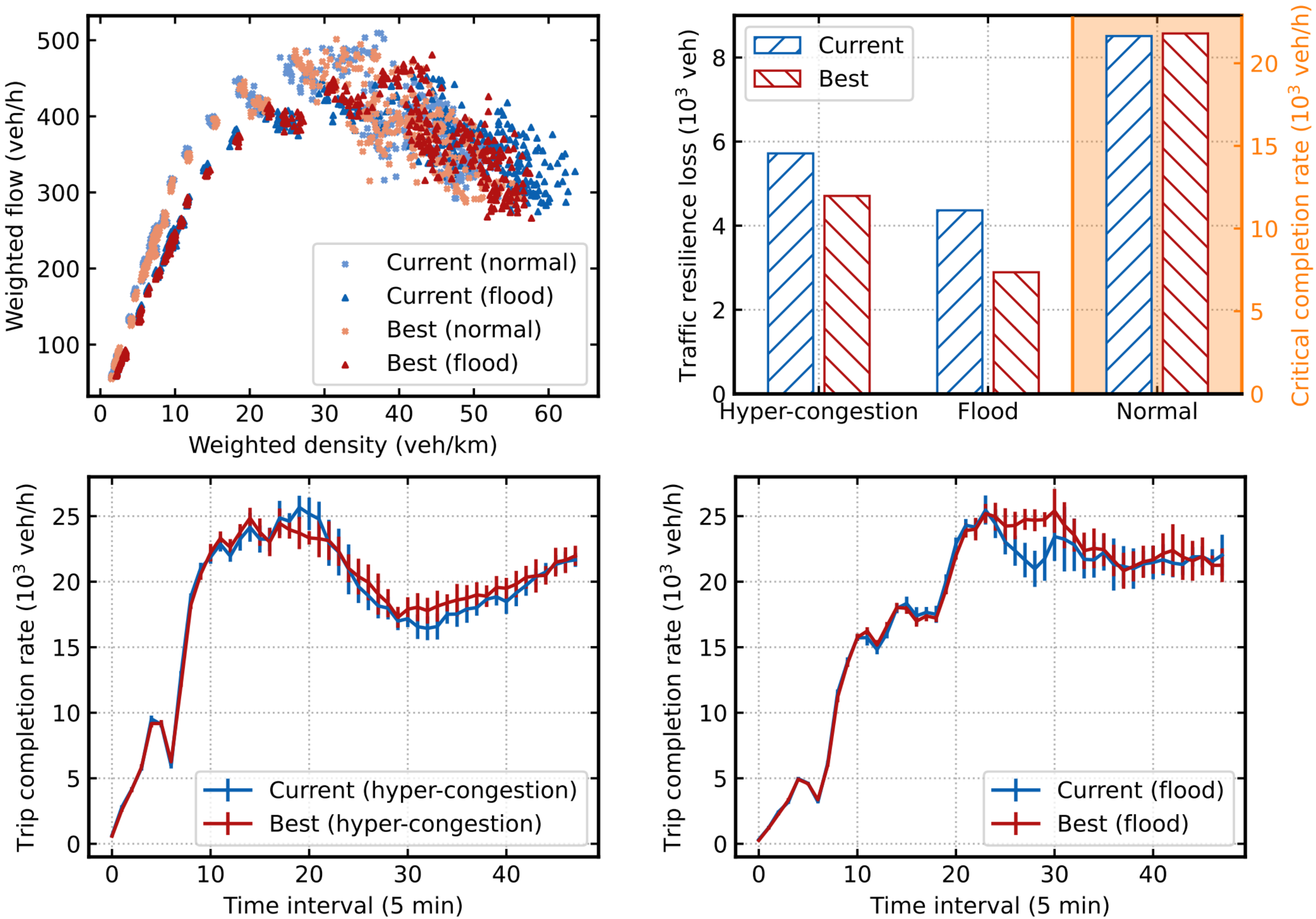
Where p is the number of parameters, among which d variables are discrete, $\varepsilon \sim N(0, \sigma)$.

$$\boxed{\hat{\boldsymbol{\theta}}_{k+1} = \hat{\boldsymbol{\theta}}_k - a_k \bar{\bar{\boldsymbol{H}}}_k^{-1}(\hat{\boldsymbol{\theta}}_k)\boldsymbol{G}_k(\hat{\boldsymbol{\theta}}_k)}$$



(a) $\sigma = 0.1$, $d = 50$ (b) $\sigma = 1$, $d = 50$ (c) $\sigma = 1$, $d = 10$

Traffic dynamics and resilience comparisons



Conclusions

Conclusions

- Formulated the simulation-based network capacity allocation optimization problem
- Developed the second-order mixed SPSA (2MSPSA) algorithm
- Evaluated the 2MSPSA algorithm
- Evaluated the resilient network capacity allocation plan

- Future research:
  - Other disruption scenarios, e.g., cyberattacks
  - Dynamic resilient capacity allocation control

References (a short list)

- Bao, J., Zheng, Y., & Mokbel, M. F. (2012). Location-based and preference-aware recommendation using sparse geo-social networking data. In *Proceedings of the 20th international conference on advances in geographic information systems* (pp. 199-208).
- Bruneau, M., Chang, S. E., Eguchi, R. T., Lee, G. C., O'Rourke, T. D., Reinhorn, A. M., Shinozuka, M., Tierney, K., Wallace, W. A., & Von Winterfeldt, D. (2003). A framework to quantitatively assess and enhance the seismic resilience of communities. *Earthquake Spectra*, *19*(4), 733–752.
- Ewing, R., Tian, G., & Lyons, T. (2018). Does compact development increase or reduce traffic congestion?. Cities, 72, 94-101.
- Farahani, R. Z., Miandoabchi, E., Szeto, W. Y., & Rashidi, H. (2013). A review of urban transportation network design problems. European Journal of Operational Research, 229(2), 281–302.
- Geroliminis, N., & Daganzo, C. F. (2008). Existence of urban-scale macroscopic fundamental diagrams: Some experimental findings. Transportation Research Part B: Methodological, 42(9), 759–770.
- Ji, Y., & Geroliminis, N. (2012). On the spatial partitioning of urban transportation networks. Transportation Research Part B: Methodological, 46(10), 1639-1656.
- Lu, Q. L., Sun, W., Dai, J., Schmöcker, J. D., & Antoniou, C. (2024). Traffic resilience quantification based on macroscopic fundamental diagrams and analysis using topological attributes. Reliability Engineering & System Safety, 247, 110095.
- Noland, R. B. (2001). Relationships between highway capacity and induced vehicle travel. Transportation Research Part A: Policy and Practice, 35(1), 47-72.
- Spall, J. C. (2009). Feedback and Weighting Mechanisms for Improving Jacobian Estimates in the Adaptive Simultaneous Perturbation Algorithm. *IEEE Transactions on Automatic Control*, *54*(6), 1216–1229.
- Wang, L., Zhu, J., & Spall, J. C. (2018). Mixed Simultaneous Perturbation Stochastic Approximation for Gradient-Free Optimization with Noisy Measurements. *2018 Annual American Control Conference (ACC)*, 3774–3779.

Questions?

Contact: Qinglong Lu
Email: qinglong.lu@tum.de

The Technical University of Munich is excited to welcome two prestigious conferences in the coming years!

hEART 2025

13th Symposium of the European Association for Research in Transportation

10th June to 12th June 2025

Short paper submission 31st December 2024

heart2025.eu

ISTTT 2026

26th International Symposium on Transportation and Traffic Theory

20th July to 24th July 2026

Extended abstract submission 9th December 2024

isttt2026.org