Traffic resilience based on macroscopic fundamental diagram: Evaluation and the role of network topology

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Introduction

- Transportation system disruption: system not operates with optimal efficiency
- Topological indicators, representing the structural properties of the network, fail to capture traffic dynamics
- Indicators based on direct trip information are sensitive to travel demand levels and patterns
- MFD is an intrinsic property of a homogeneously congested transportation network

Contributions

- Discuss and compare the traffic resilience to congestion and supply-side disruptions
- Case studies on two real networks to evaluate the extent to which topological indicators can explain traffic resilience

Traffic resilience to disruptions

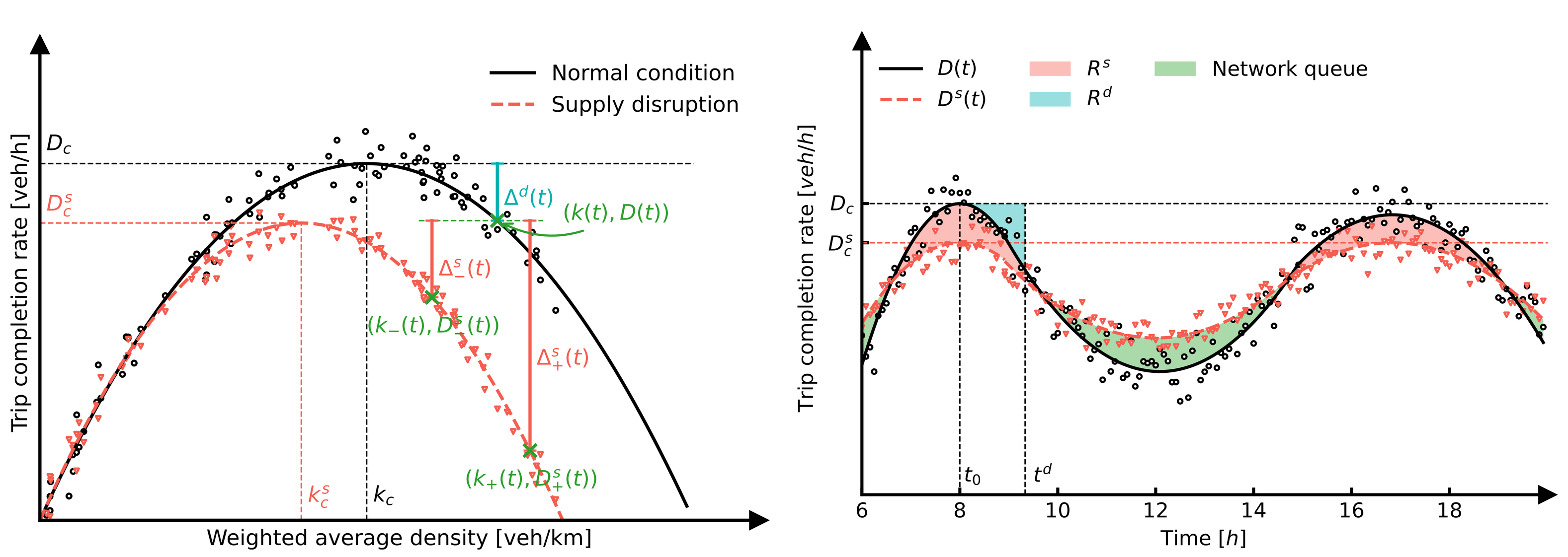
Distinct mechanisms through which congestion and supply disruptions exert influence on the system.

- **To congestion:** Transportation network is unable to efficiently serve vehicles due to the propagation of traffic congestion.

$$R^d = \int_{t_0^d}^{t^d} \left(D(t) - D_c\right) H(k(t) - k_c)\, \mathrm{d}t$$

- **To supply disruptions:** A "shrinkage" of the MFD is anticipated.

$$R^s = \int_{t_0^s}^{t^s} \min\left\{D^s(t) - D(t), 0\right\}\, \mathrm{d}t$$



(a) Trip completion deviation (b) Calculation of traffic resilience

Figure 1. Definition of traffic resilience to disruptions.

Simulation-based synthetic supply disruptions

(1) $p \in [0,1)$: the percentage of links that are blocked due to the disruptive event
(2) With a random seed r, a disruption scenario $\mathbb{S}$ is created by randomly sampling the links to be closed
(3) Topological attributes $\mathbf{x}$ of the damaged network $G(\mathbb{S})$
(4) Run multiple SUMO simulations ($\mathcal{S}$) with $G(\mathbb{S})$ and demand matrix M to generate traffic dynamics $Y(\mathbb{S})$
(5) Estimate the traffic resilience loss $R^s(\mathbb{S})$

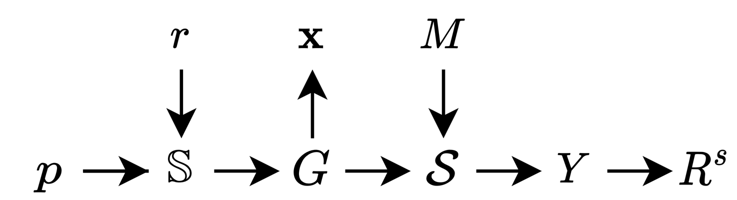
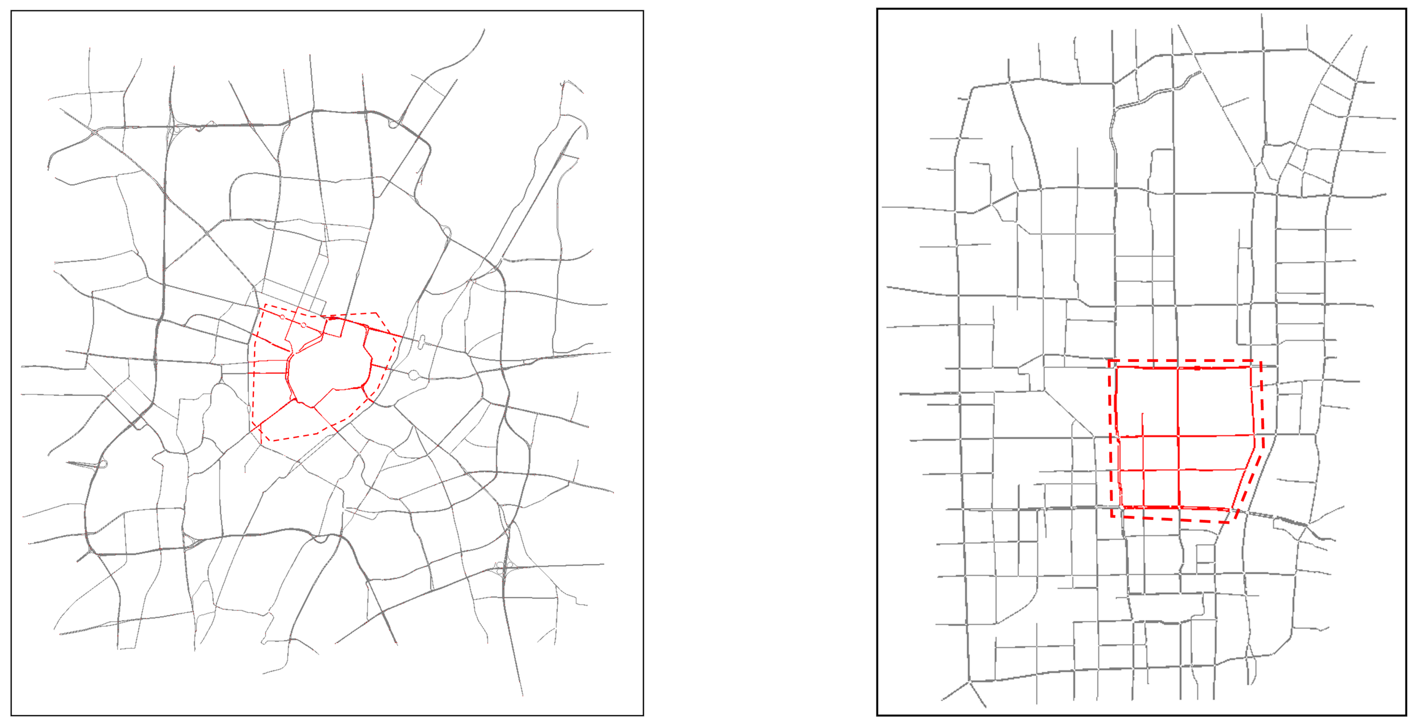


Figure 2. Graphical illustration of generating scenarios for regression analysis.

Case studies

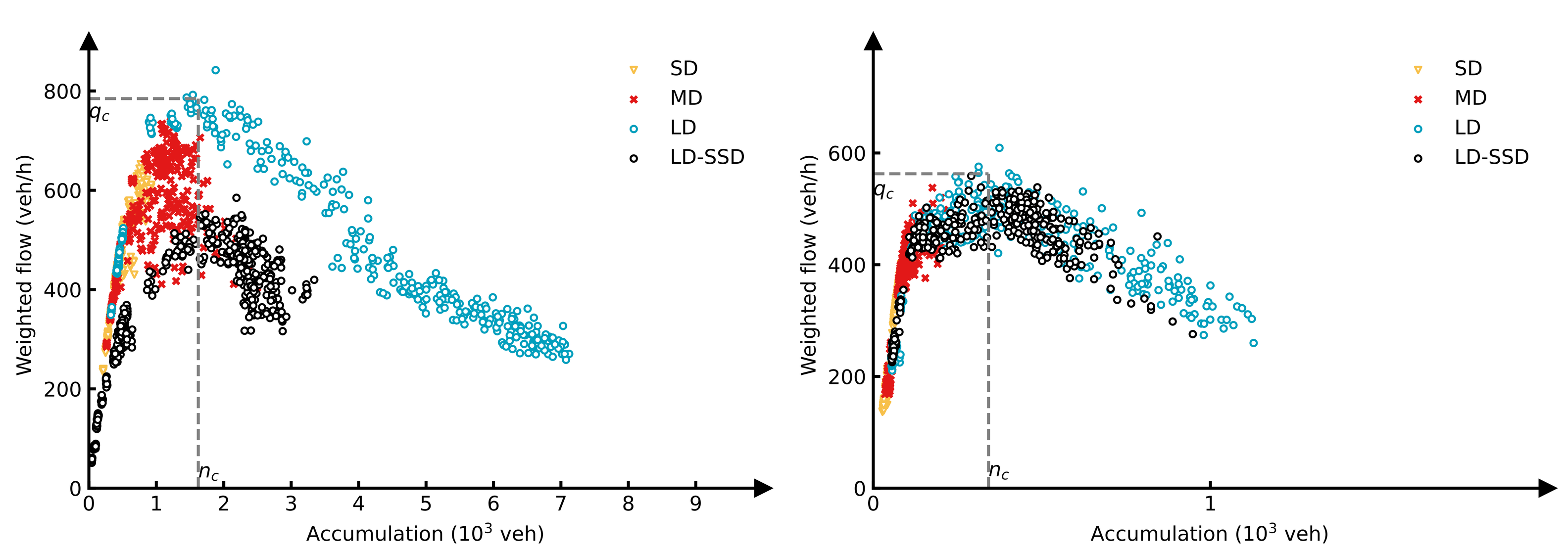
- Munich, Germany: central ring network, 10 km × 10 km, 2605 links
- Kyoto, Japan: grid network, 6 km × 8 km, 1189 links



(a) Munich disruption area (b) Kyoto disruption area

Figure 3. Study areas, networks and locations of detectors.

MFD dynamics analysis

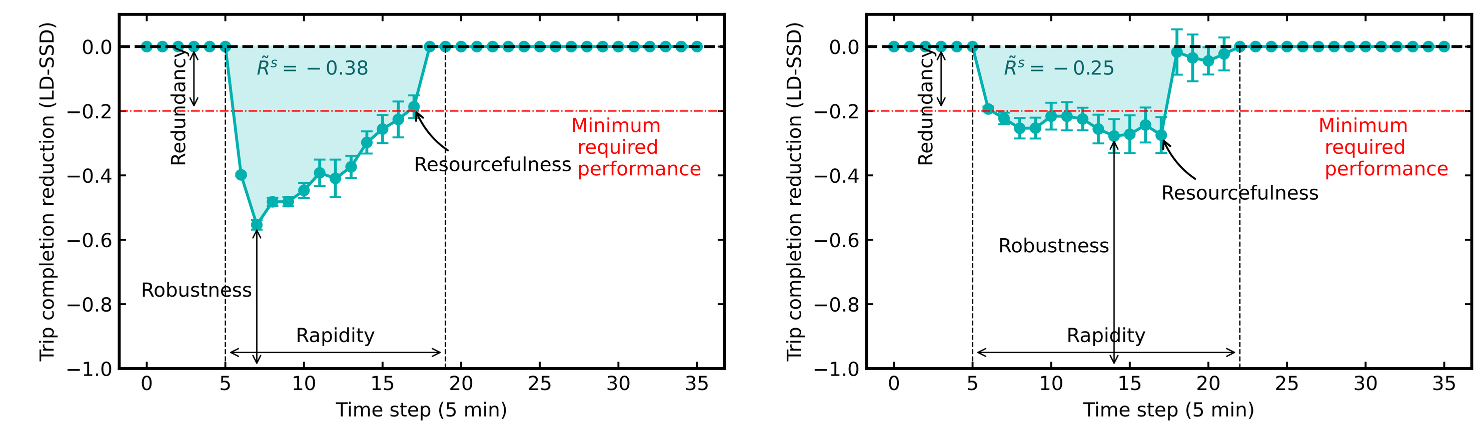


(a) Munich network (b) Kyoto network

Figure 4. MFD dynamics of the scenarios of investigation.

Resilience evaluation under supply disruptions

- Robustness: Kyoto > Munich
- Redundancy: Kyoto > Munich
- Resourcefulness: No quantitative indicator
- Rapidity: Kyoto < Munich
- Traffic resilience: Kyoto > Munich



(a) Munich: Supply-side disruptions (b) Kyoto: Supply-side disruptions

Figure 5. Traffic resilience under supply disruptions (large demand scenario).

Relationship between topology and resilience

Proposed indicators: traffic dynamics + network characteristics

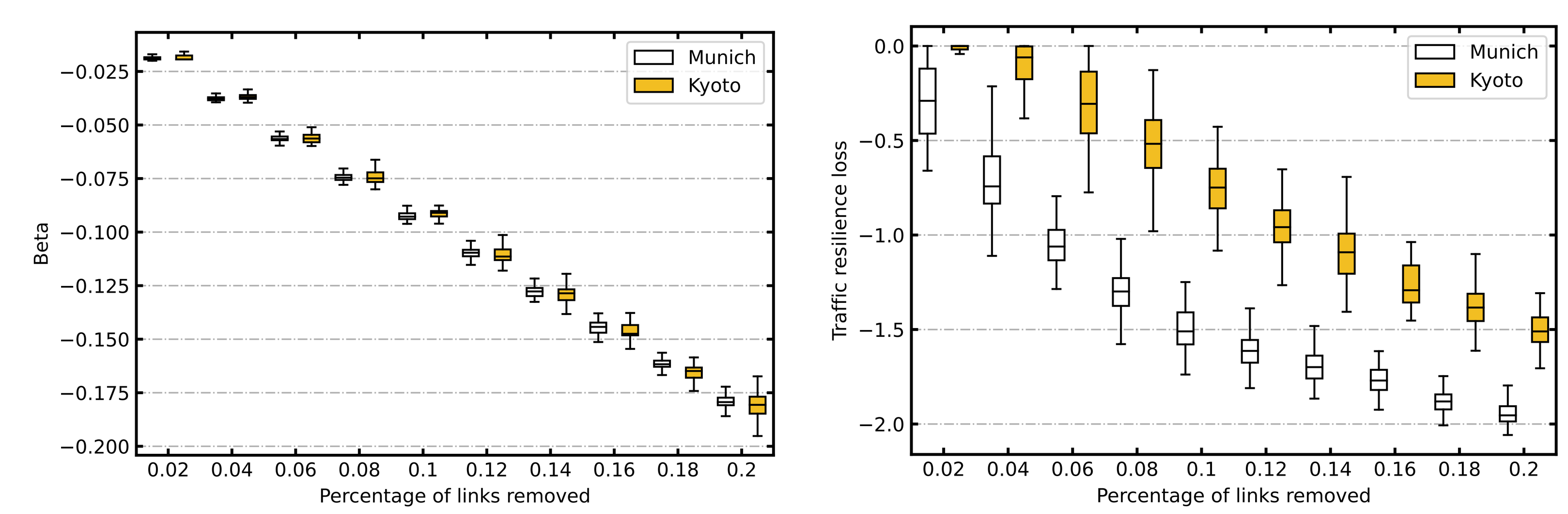


Figure 6. Boxplots for Beta index and traffic resilience.

Variable	Topology Attr.	Coef. [p-value] (Kyoto)	Coef. [p-value] (Munich)
Load centrality	Centrality	-0.1016 [0.25]	-0.9778 [<0.0001]
Beta index	Connectivity	8.1062 [<0.0001]	16.6719 [<0.0001]
Kyoto model		**Munich model**	
# of samples: 925		# of samples: 949	
R-squared: 0.8583		R-squared: 0.7894	

Conclusions

- Different influencing mechanisms of congestion and supply-side disruptions on traffic resilience
- Kyoto's grid-like network demonstrates greater resilience to supply-side disruptions compared to Munich's ring structure
- Network connectivity emerged as the most correlated and significant attribute of traffic resilience