Systemic collapse of Transportation networks

Induced by extreme weather

Mauro Faccin, *Tomas Scagliarini*, *Manlio De Domenico*

INFN and DFA @ University of Padova (Italy)

mauro.fccn@gmail.com

Università degli Studi di Padova

INFN

CoMuNe lab
COMPLEX MULTILAYER NETWORKS

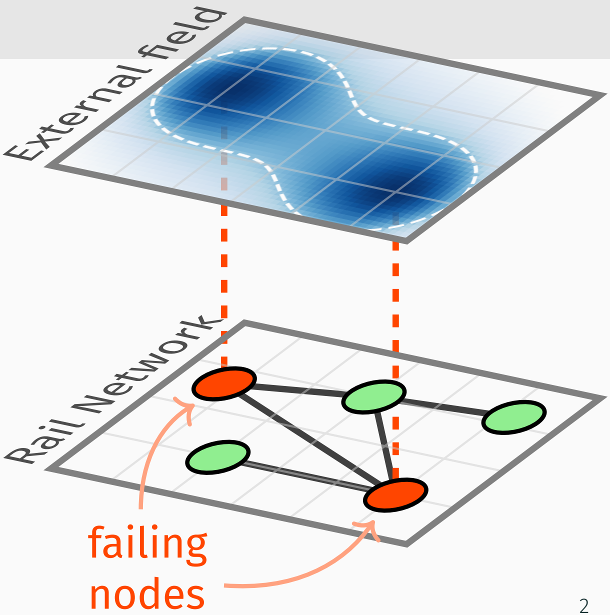
INSTR'26
Lyon, France
July 15–17

Framework

Ingredients

Interaction between human-made systems and natural external stressors.

- *Infrastructure:* complex topology embedded in space
- External ***climate stressor***
- ***Perturbation dynamics*** (functionality reduction)



Modeling perturbation

Model

Propagation model with *generation* and *absorption* processes

$$\mathbf{s}(\mathbf{t}+1) = \mathcal{T}(\mathbf{t})\mathbf{s}(\mathbf{t}) + \beta\mathbf{g} - \gamma\mathbf{c}$$

$\mathbf{s}(\mathbf{t}) \longrightarrow$ *perturbation state* vector defined at each node/edge

Real world application:

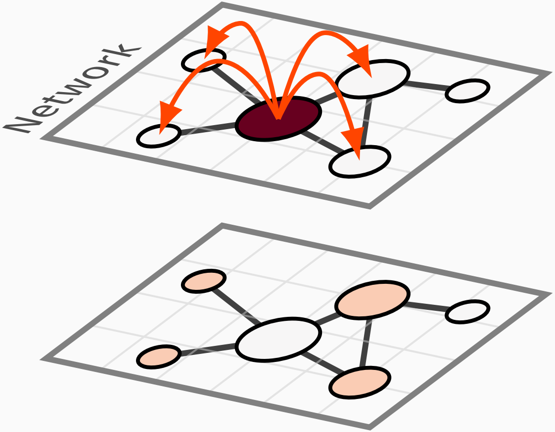
- *Delay propagation on*
- *railway systems influenced by*
- *rainfalls*

Model — Diffusion process

The diffusion process ruled by the **network topology**

$$\mathbf{s}(\mathbf{t}+\mathbf{1}) = \mathcal{T}(\mathbf{t})\mathbf{s}(\mathbf{t}) + \beta\mathbf{g} - \gamma\mathbf{c}$$

$\mathcal{T}(\mathbf{t})$ transfer probability



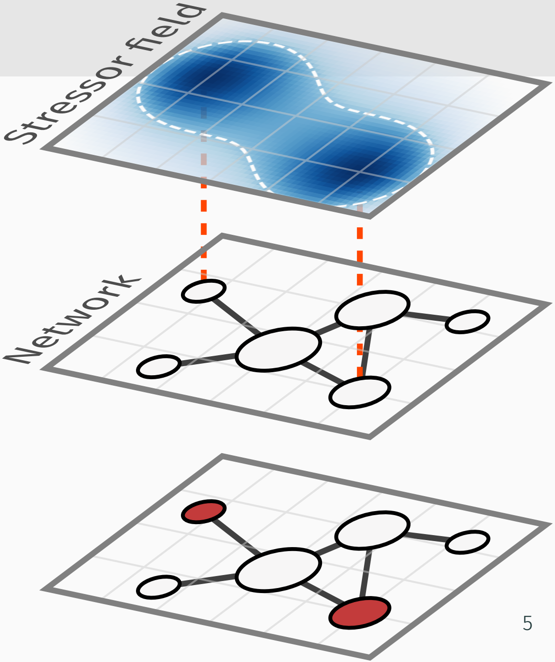
The generation process ruled by the **external stressor field** (rain)

$$\mathbf{s}(t+1) = \mathcal{T}(t)\mathbf{s}(t) + \beta\mathbf{g} - \gamma\mathbf{c}$$
$$\mathbf{g} = (\mathcal{W}(t) \odot \mathcal{S}(t))\mathbf{1}$$

β generation rate

$\mathcal{W}(t)$ e.g. trains traversing each link

$\mathcal{S}(t)$ e.g. amount of rain experienced at each link



Model — Absorption process

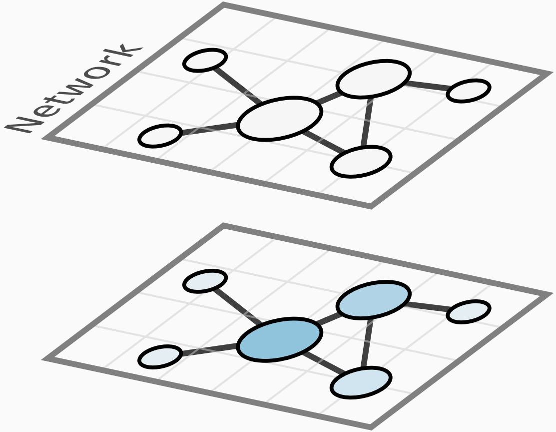
The absorption process ruled by the **local capacity** to absorb delays

$$\mathbf{s}(t+1) = \mathcal{T}(t)\mathbf{s}(t) + \beta\mathbf{g} - \gamma\mathbf{c}$$

γ absorption rate

$\mathbf{c}$ station capacity

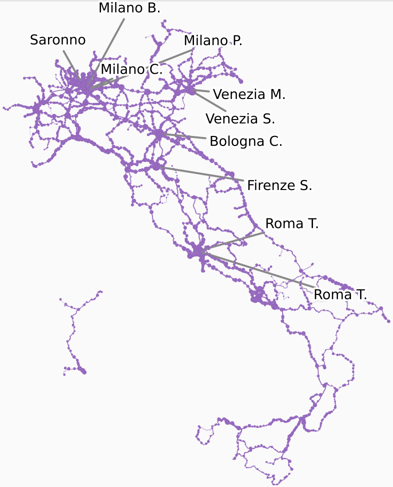
Capacity proportional to max station throughput.



Data

Data — Network

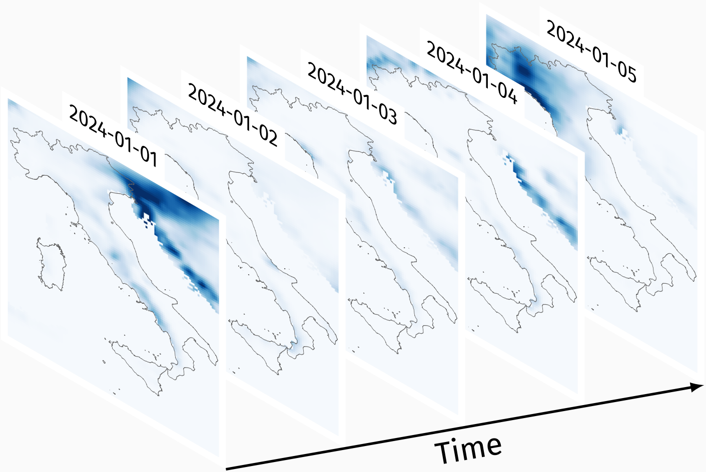
- Network of stations connected by direct trains.
- Shapes and locations from OpenStreetMap



Data — Stressor

Historical weather variables
(*hourly*; ERA5@Copernicus)

`total_precipitation_land`

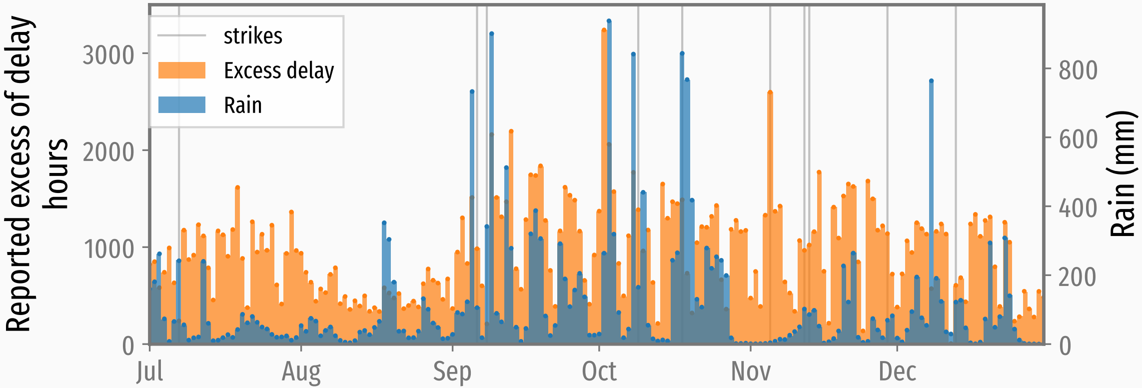


ERA5: Fifth generation ECMWF reanalysis for the global climate and weather

Data – Perturbation

- All trains from the major Italian railway operator and high-speed Chinese trains
- Train delay at each station

Delays originate from multiple sources



Cumulated daily delay vs. rainfalls ⟶ multiple sources of delay (Italy)

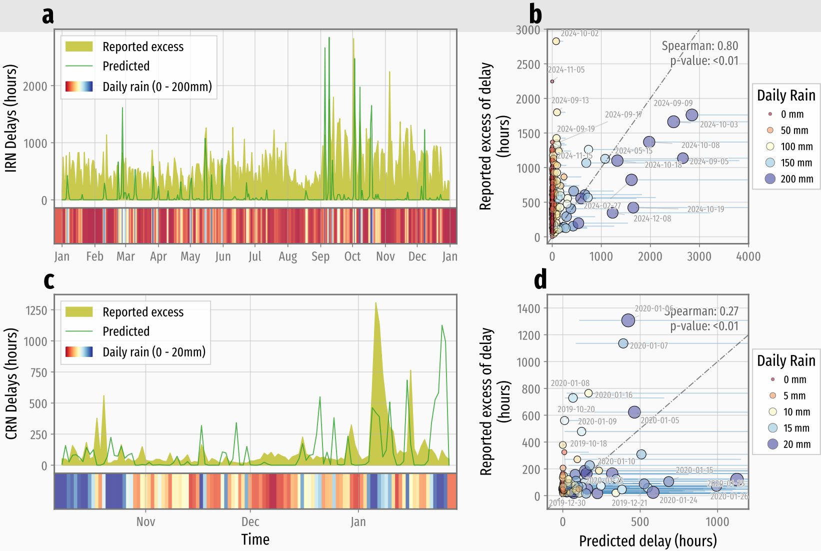
Results

Parameter inference

Fit the model parameters with a **k**-fold cross-correlation.

We can predict delay distribution in ***rainy*** (blue) days.

CRN have lower rain intensity and smaller dataset.

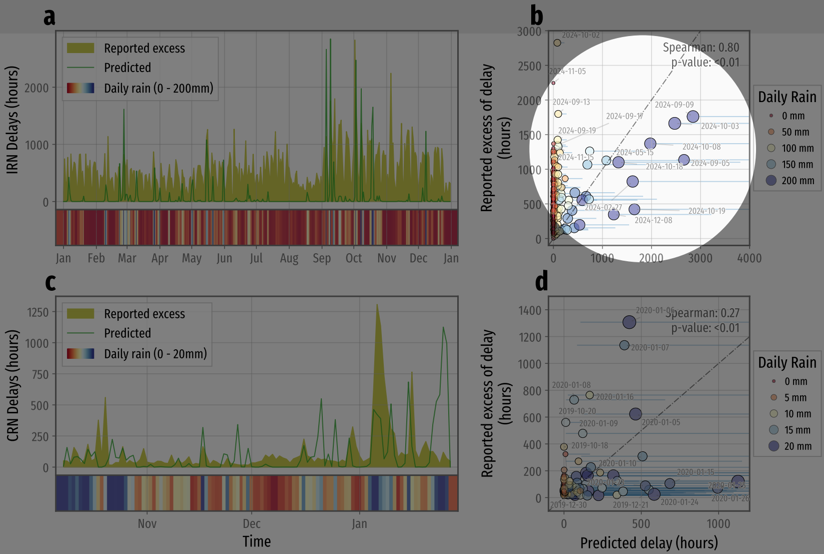


Parameter inference

Fit the model parameters with a **k**-fold cross-correlation.

We can predict delay distribution in *rainy* (blue) days.

CRN have lower rain intensity and smaller dataset.

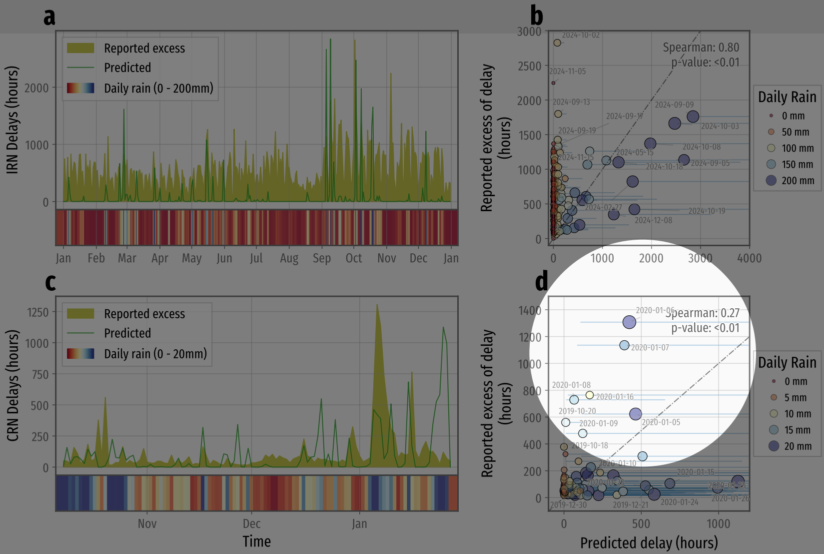


Parameter inference

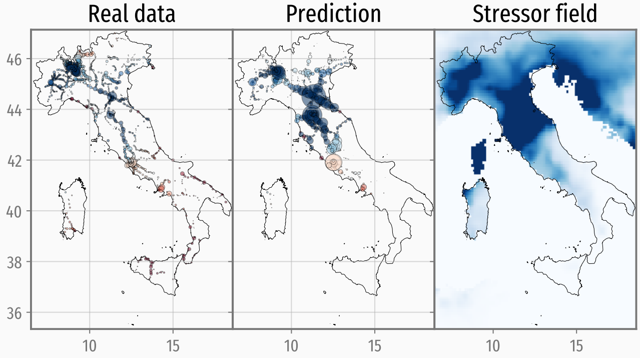
Fit the model parameters with a **k**-fold cross-correlation.

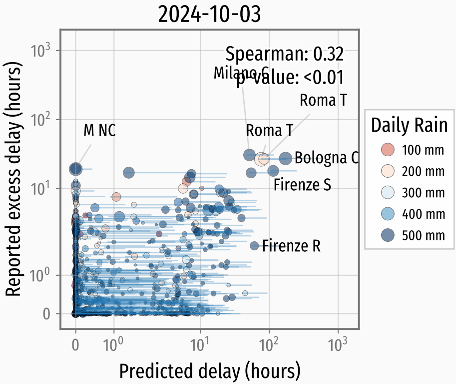
We can predict delay distribution in *rainy* (blue) days.

CRN have lower rain intensity and smaller dataset.

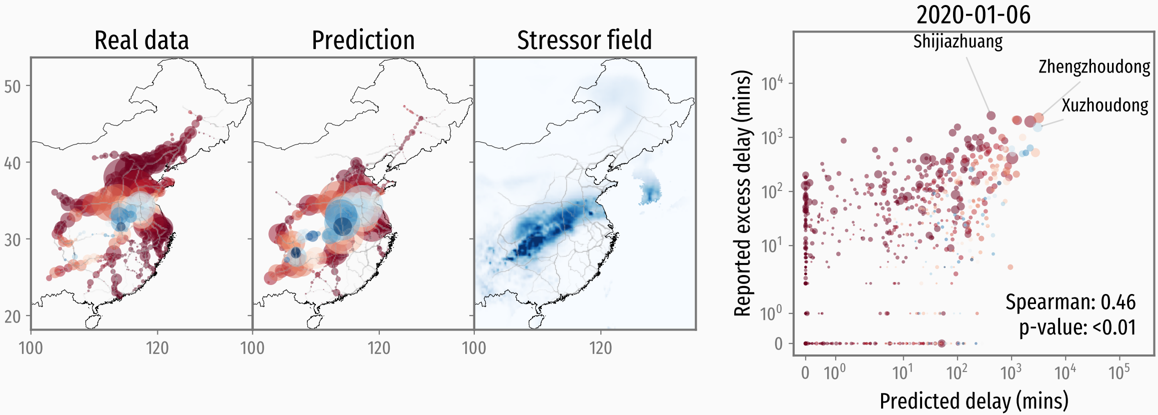


ITA 2024-10-03

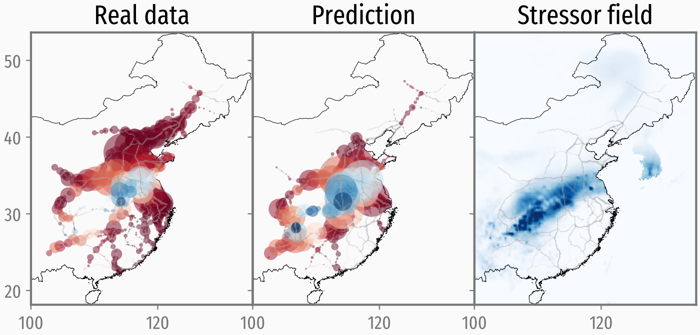




CN 2020-01-06


Real data
Prediction
Stressor field
50
40
30
20
100
120
100
120
100
120
2020-01-06
Shijiazhuang
Zhengzhoudong
Xuzhoudong
Reported excess delay (mins)
Spearman: 0.46
p-value: <0.01
Predicted delay (mins)

CN 2020-01-06



Flight Are Canceled, High-Speed Trains Delayed as Beijing Gets First Snow of 2020

LIAO SHUMIN
DATE: JAN 07 2020 / SOURCE: YICAI

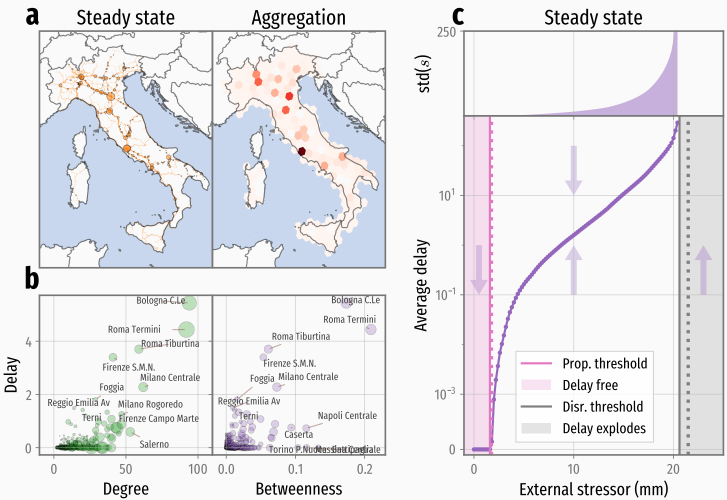
Flight Are Canceled, High-Speed Trains Delayed as Beijing Gets First Snow of 2020

(Yicai Global) Jan. 6 -- Flights have been canceled and high-speed trains delayed after snow fell on Beijing for the first time this year.

System resilience

System response from a continuous external stressor field.

- *Delay absorbed below a* **propagation threshold** $\beta \mathbf{g}_\mathbf{i} < \gamma \mathbf{c}_\mathbf{i}\ \forall \mathbf{i}$
- *System collapse above a* **disruption threshold** $\langle \beta \mathbf{g} \rangle > \langle \gamma \mathbf{c} \rangle$
- ***Endemic delay*** in-between (dynamical equilibrium)

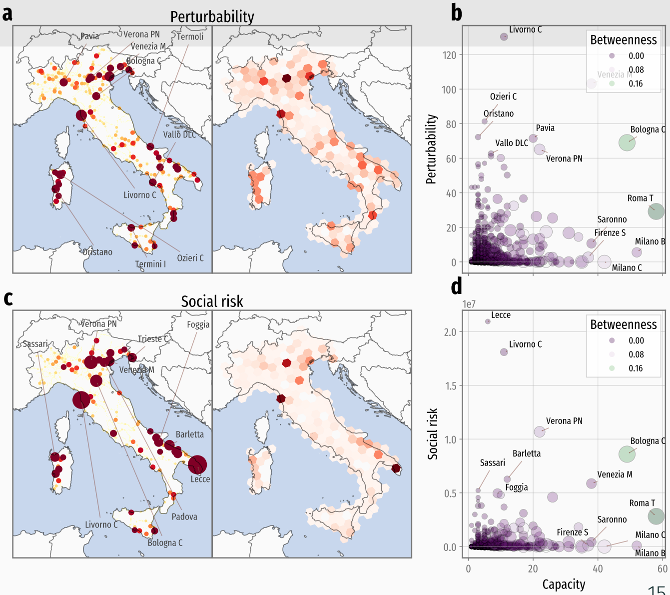


Perturbability and Social risk

Perturbability: station ability to influence the network

Total delay experienced by the network after initial stress around a station.

Social risk: perturbability weighted by the *social cost* (population affected)



Questions?

https://maurofaccin.github.io
mauro.fccn@gmail.com
@CoMuNeLab, @UNIPD, @INFN

Joint work with:

Tomas Scagliarini

Manlio De Domenico

Università degli Studi di Padova — INFN — CoMuNe lab COMPLEX MULTILAYER NETWORKS

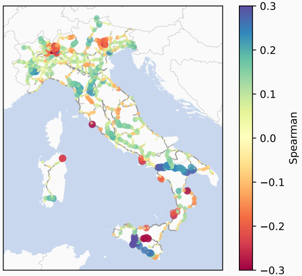
- Model of ***propagation+generation+absorption*** of perturbations
- Interaction between external stressor (e.g. climate variables) and dynamics
- Prediction of ***complete system failure*** at high values of the external stressor
- ***Perturbability centrality*** and ***social risk***

Aknowledgements: FIS project no. FIS00000158 (CUP C53C23000660001). INFN (LINCOLN).

Backup1: Sensibility to rain

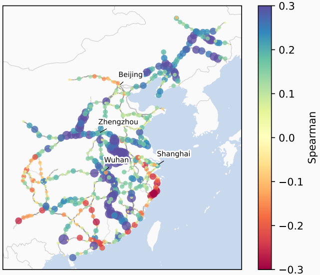
Comparison ITA vs CN
Correlation between delays and rains at each station.

Italy



Homogeneous distribution

China



Coast/Inland heterogeneity

Backup2: Perturbability

Comparison ITA vs CN Perturbability:

ITA: geographic concentration

CN: correlated to high capacity stations