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Climate-induced delay propagation in rail networks as a non-Markovian process

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COMPLEX MULTILAYER NETWORKS

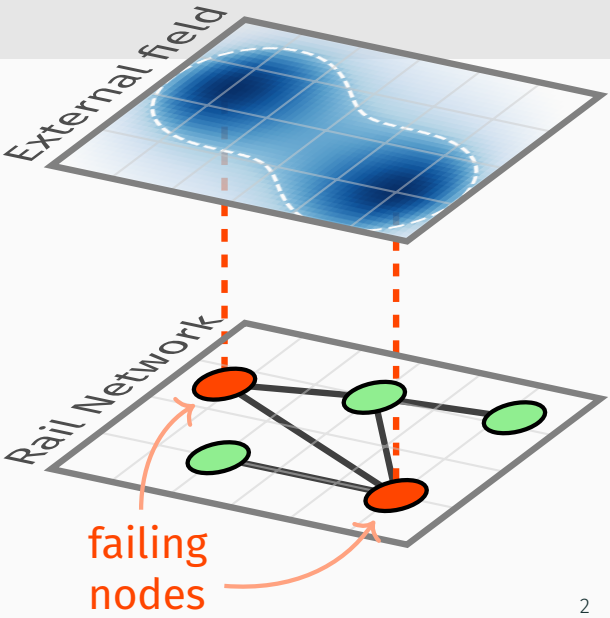
Framework

3 ingredients for this soup:

- Infrastructure: complex topology embedded in space
- Dynamical model
- External climate stressors

Research Question

Interaction between human-made systems and natural external stressors.



Model the system perturbations

Model

Non-Markovian ***propagation*** model with ***generation*** and ***absorption*** processes

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

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

Real world application:

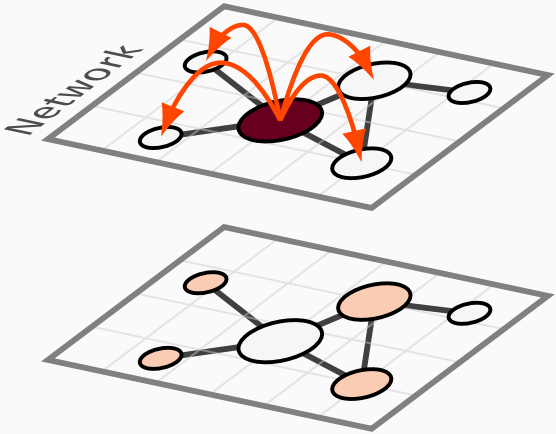
- ***Delay propagation on a***
- ***railway system influenced by***
- ***rainfalls***

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



Model — Generation process

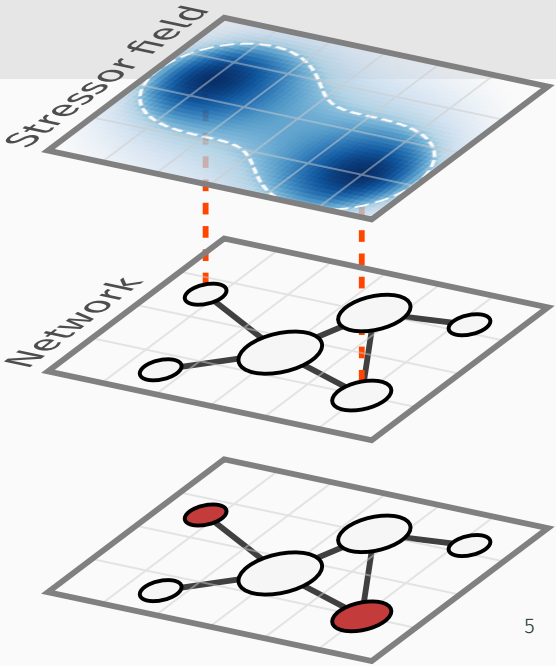
The generation process ruled by the **external stressor field** (rain)

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

β generation rate

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

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



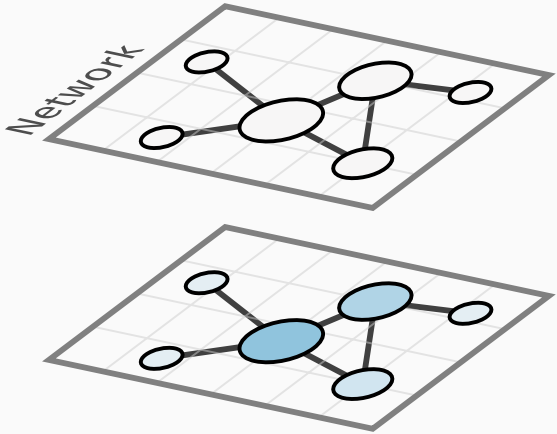
Model – Absorption process

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

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

γ absorption rate

$\mathbf{c}$ station capacity

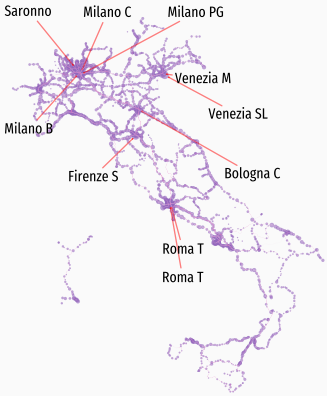



DATA

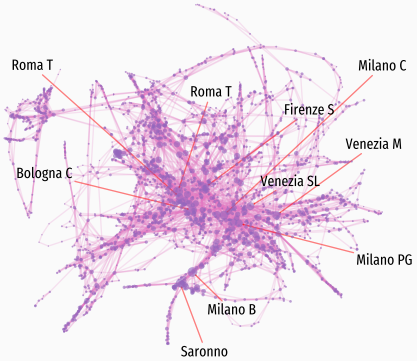
Data — Network

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

Network embedded



Hairball

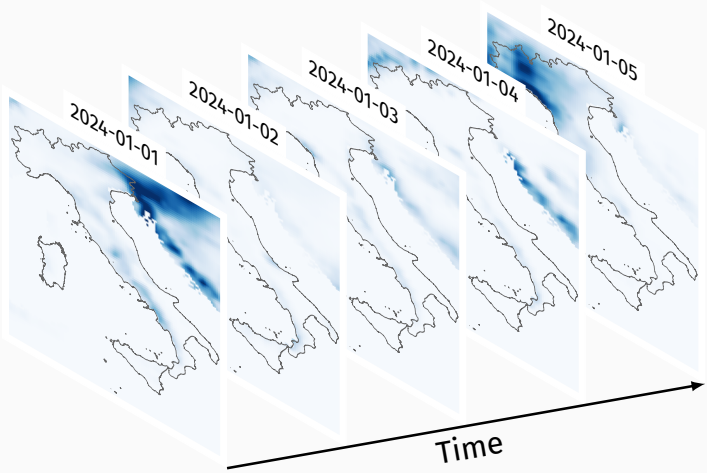


Not a Ridiculogram since not published in ***Nature*** nor ***Science***

Data – Stressor

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

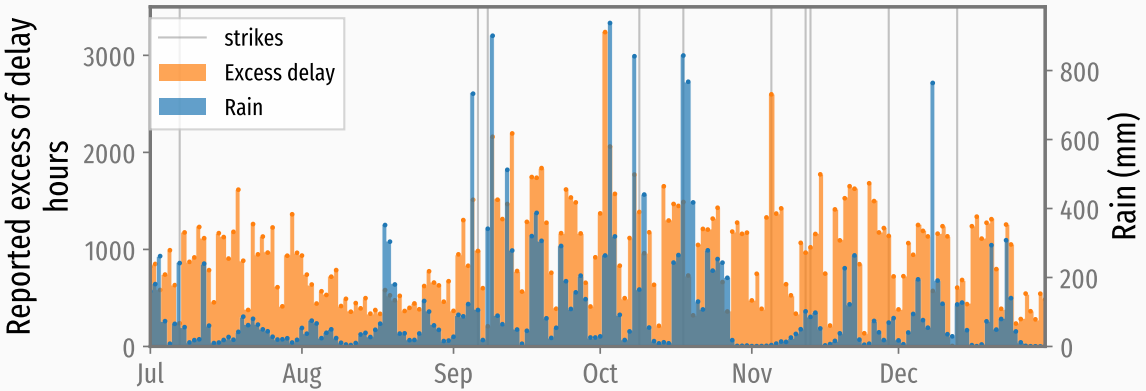
`total_precipitation_land`



Data — Real world

- All trains (2020-2024) from the major Italian railway operator
- Arrival/departure scheduled and real time

Delays originate from multiple sources



Cumulated daily delay vs. rainfalls → multiple sources of delay

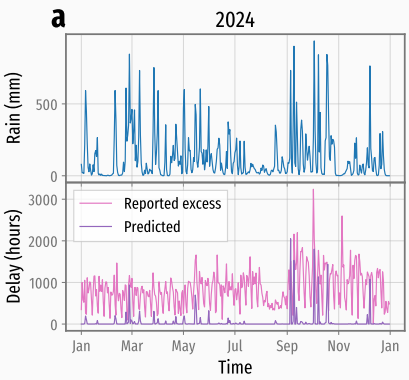
Results

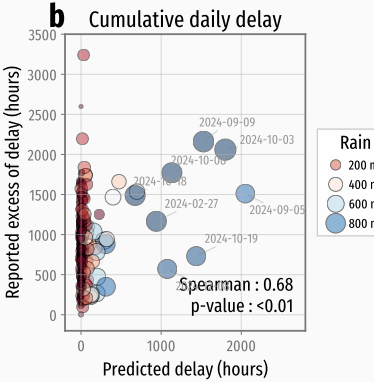
Parameter inference

- Learning set: 2021-2023.
- Validation set: 2024

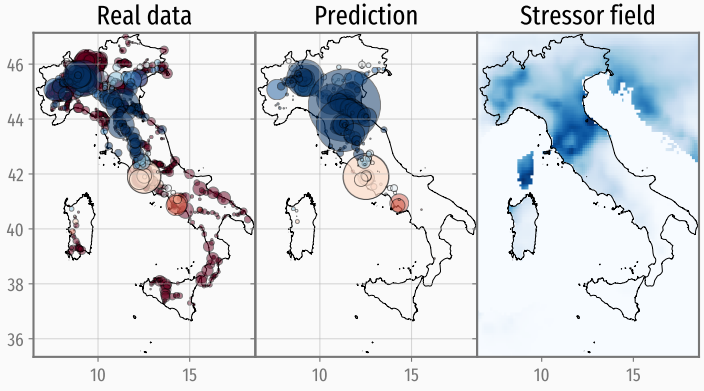
We can predict delay distribution in rainy (blue) days.

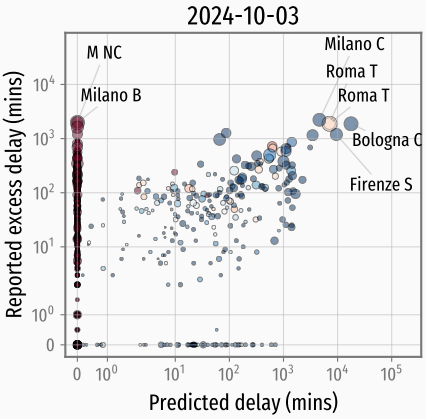
Spearman: 0.68



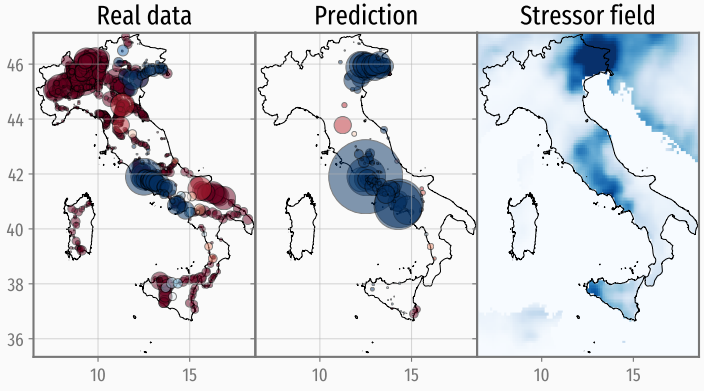


2024-10-03


Real data
Prediction
Stressor field
46
44
42
40
38
36
10
15


2024-10-03
M NC
Milano B
Milano C
Roma T
Roma T
Bologna C
Firenze S
Reported excess delay (mins)
Predicted delay (mins)

2024-09-09


Real data
Prediction
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46
44
42
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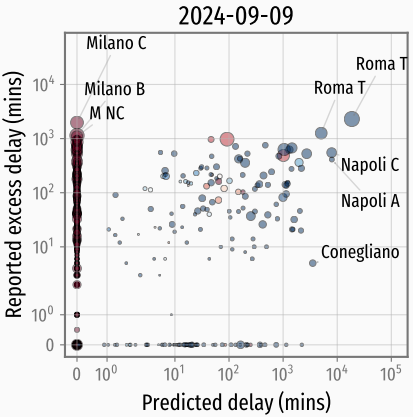
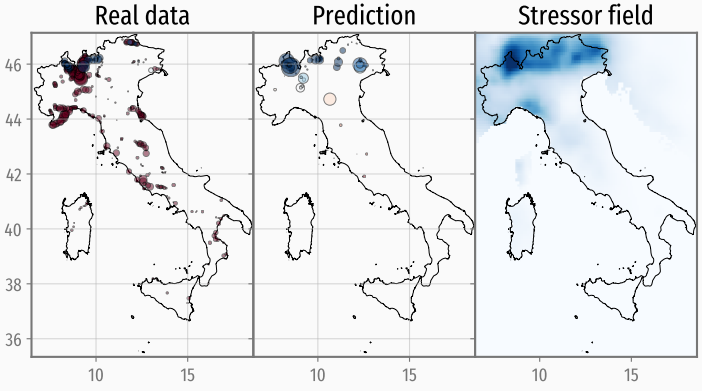
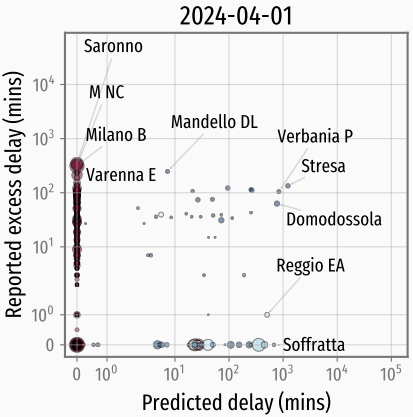
10
15
10
15
10
15


2024-09-09
Milano C
Milano B
M NC
Roma T
Roma T
Napoli C
Napoli A
Conegliano
Reported excess delay (mins)
Predicted delay (mins)
0
10^0
10^1
10^2
10^3
10^4
10^5

2024-04-01

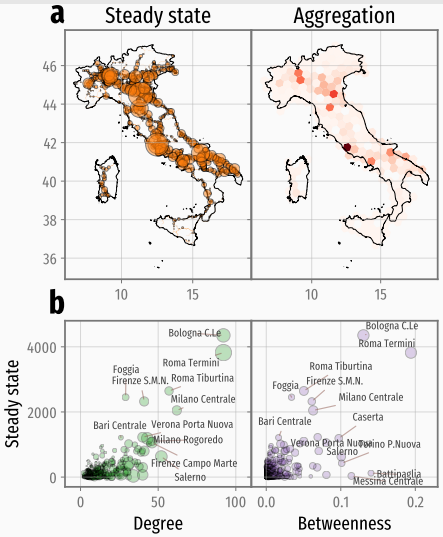

Real data
Prediction
Stressor field
46
44
42
40
38
36
10
15

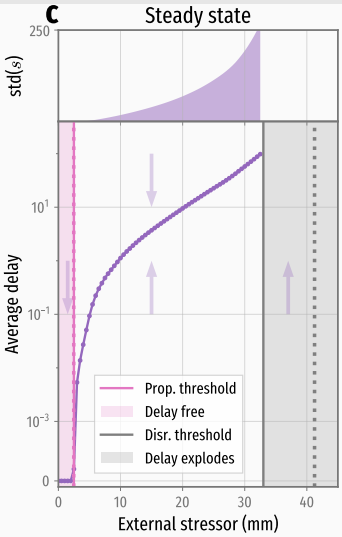

2024-04-01
Saronno
M NC
Milano B
Mandello DL
Varenna E
Verbania P
Stresa
Domodossola
Reggio EA
Soffratta
Reported excess delay (mins)
Predicted delay (mins)
0
10^0
10^1
10^2
10^3
10^4
10^5

Phase space – System resilience

System response from a continuous external stressor field.

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



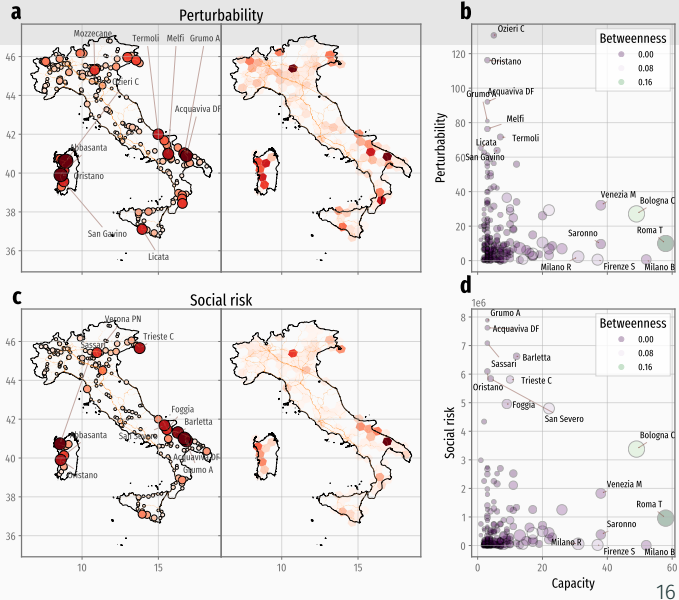


Perturbability and Social risk

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?

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Joint work with:

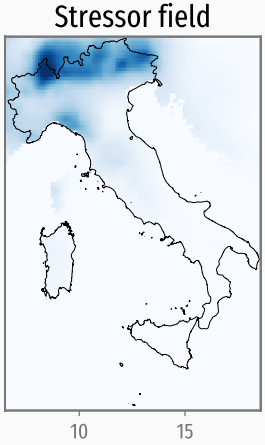
Tomas Scagliarini

Manlio De Domenico

- 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).

Perturbability and Social risk



What happened in 2024-04-01 🐟?

Stressor field ***perpendicular*** to the ***system perturbability***.