Towards an Urban Digital Twin: A use case for the optimization of urban traffic

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Abstract

The concept of **Digital Twin** has been recently explored in the context of urban planning, to address problems with a degree of complexity otherwise difficult to manage. As a result, a noticeable amount of cities around the world are trying to bring this concept to reality, i.e. developing a Digital Twin of their entire urban area. Given that reproducing in detail the entities and the connections of an entire city is rather demanding, the goal of our research is **to find the optimal level of detail** (LOD) to build the Digital Twin of a city. Following some insights and results from complex systems physics, we argue that the effectiveness of such a project is not a linear function of the LOD, indeed having too many details (or parameters) can lead to overfitting, high parameter sensitivity and no added value. The LOD of a simulation is rather something to determine depending on the specific problems one want to address, especially when dealing with a Digital Twin, and retroaction enters the picture.

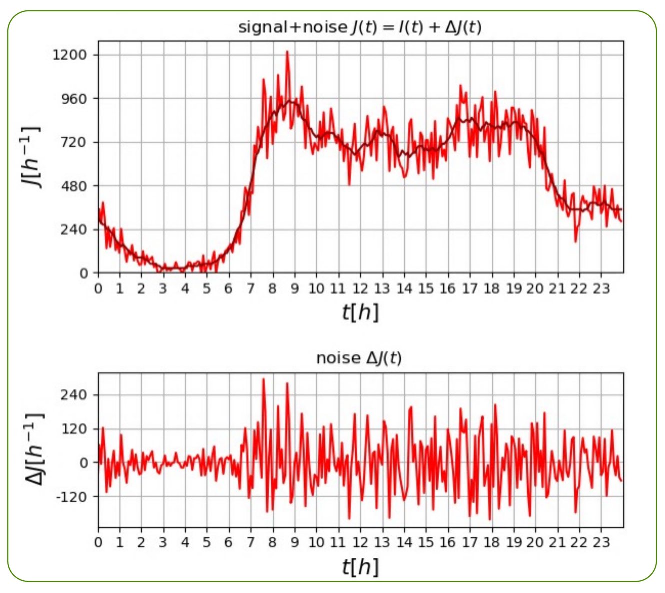
Starting from the development of a **mesoscopic traffic simulation**, we explicitly consider application to the Bologna road network using the traffic flow data available from magnetic coils to infer the traffic load, and a GPS data set on mobile phone positions that allows to reconstruct individual mobility paths and get information on the road network weights. We then built a Digital Twin use case by crafting a dynamic algorithm to **optimize traffic light phases using real time data**.

The implementation of an Urban Digital Twin use case poses several **challenges:**

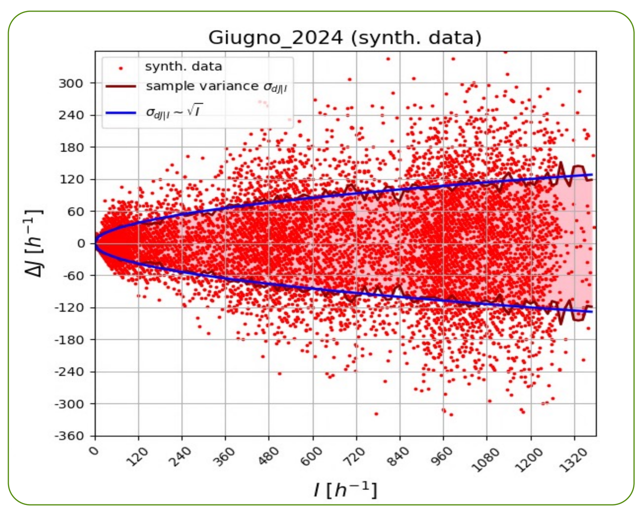
- How to process traffic and geometric data in order to set the appropriate scale? — Road network from OSM: messy, too many segments, too many streets. Traffic sensors: malfunctions, outliers, noise
- How to reconstruct the dynamics, patterns and complex behaviours of urban traffic? — Agent base modelling: find the scale, the base rules, the complexity; reach optimization, validation and portability
- How to exploit the value of a digital twin solution? — Real time monitoring, control over physical reality, enhancement of the system

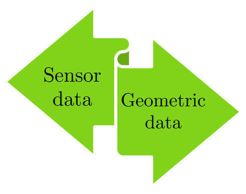
How to process traffic and geometric data in order to set the appropriate scale?

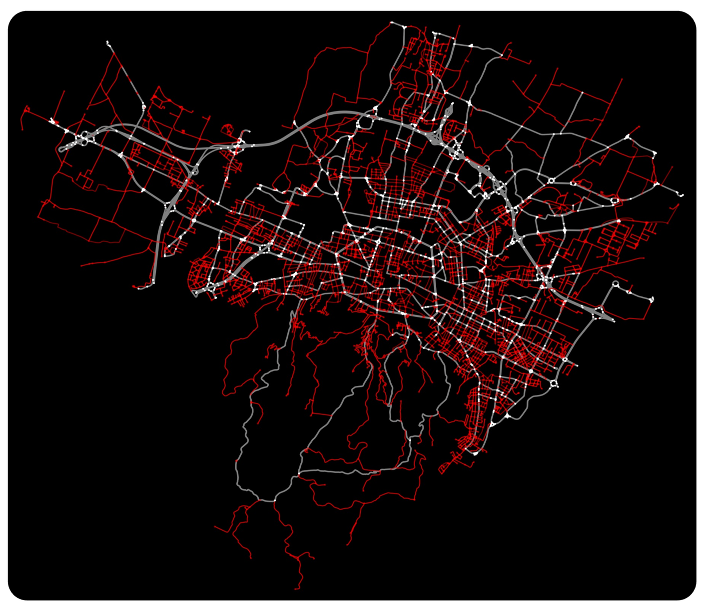
Centred moving average (CMA) to filter out the fluctuations



What is the real traffic demand? Can we isolate the noise coming from traffic light dynamics (TLD)?



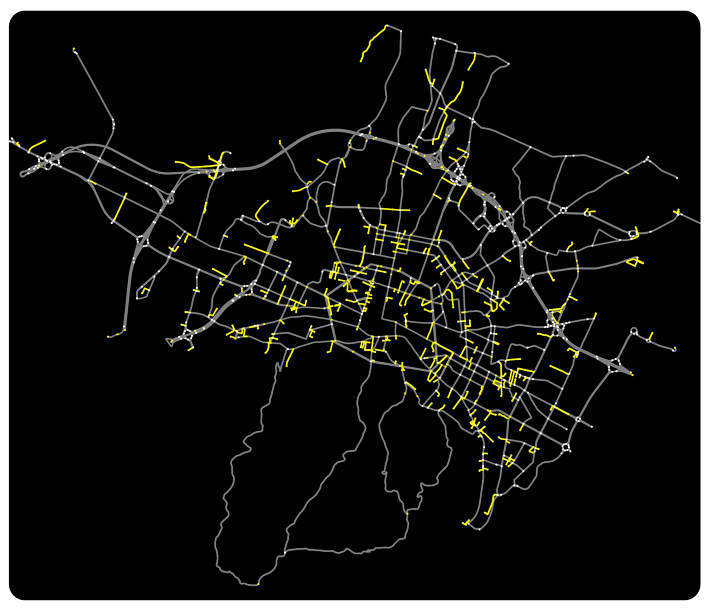




For the sake of our study, the Bologna network is considered. The full network has 2444 nodes and 4271 edges, too much dense, not enough data.

Get the primary network
- Keeping the primary roads for the main network, discarding residential streets
- Consolidate the network: merging small segments, clusters of nearby nodes

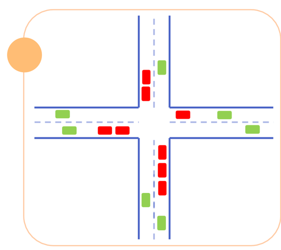
Add sources and destinations
- Need of reservoirs for agents
- From residential streets, add only segments attached to the primary network as input/output
- betweenness centrality score for remaining inputs/outputs



The filtered network used for the simulation has now 1031 nodes and 1925 edges. The yellow segments are used as I/O markers, with a fraction of them linked to the sensors.

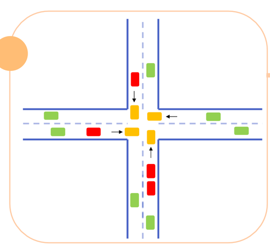
How to reconstruct the dynamics, patterns and complex behaviours of urban traffic?

Agent-based traffic model on a **directed graph**. Nodes correspond to junctions and edges correspond to streets. The agents (vehicles) are moving following an **origin-destination** path computed using the Dijkstra algorithm **weighted on the distance** and **flow scores from GPS data.** We distributed origins and destinations using traffic sensor data.

1 

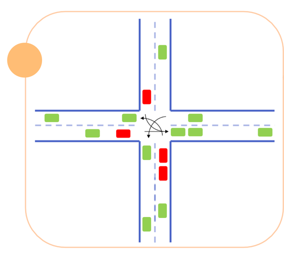
Agents queuing at the end of the streets

Every street has a maximum speed limit and a maximum capacity, depending on the number of lanes, the length, the number of agents. The number of output queues is equal to the number of lanes.

2 

The first n agents are inserted in the node

The number n of agents entering the nodes at each timestep depends on the street's (and nodes) capacities, the agents in the queue, the traffic light phase.

3 

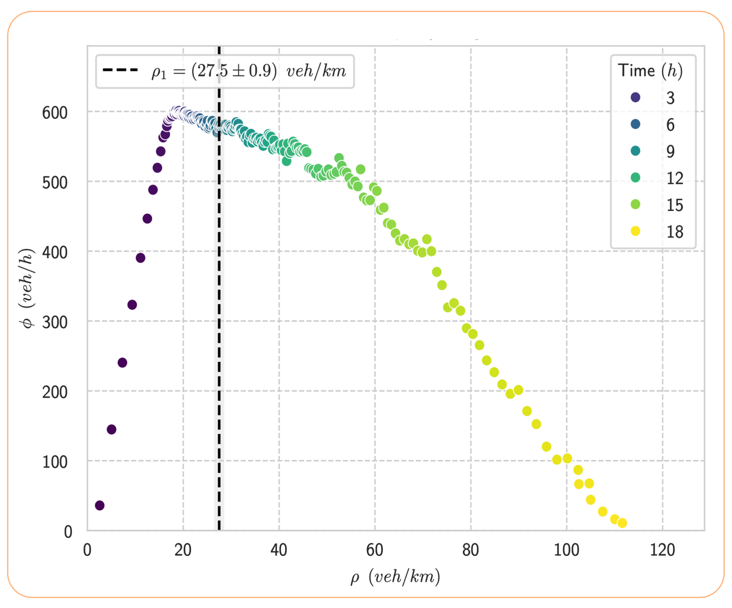
Agents are inserted on their destination streets

Depending on their paths, the agents are inserted into the streets (if they're not saturated), and assigned a velocity that depends on the speed limit and the street's density [1].

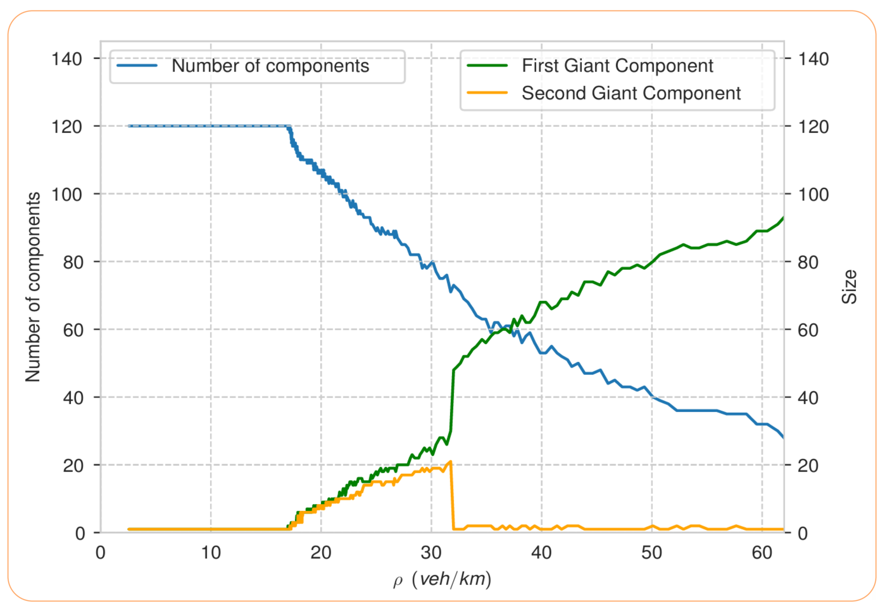
$$v(\rho) = v_0(1 - \alpha\rho)$$

We used aggregated GPS data from mobile phones (MDT Tim dataset) to recalibrate the weights of the streets, and data from the traffic sensors (the ones on the primary roads) to validate the simulation.

Some of the typical features of a network congestion [2][3] have been studied and reproduced successfully.



The macroscopic fundamental diagram, obtained on a simulation over Bologna's network.



Evolution of congested clusters ($\rho_{street}/\rho_{max} \geq 0.7$). The green and yellow lines show the size of the first and second giant components (right axis).

How to exploit the value of a digital twin solution?

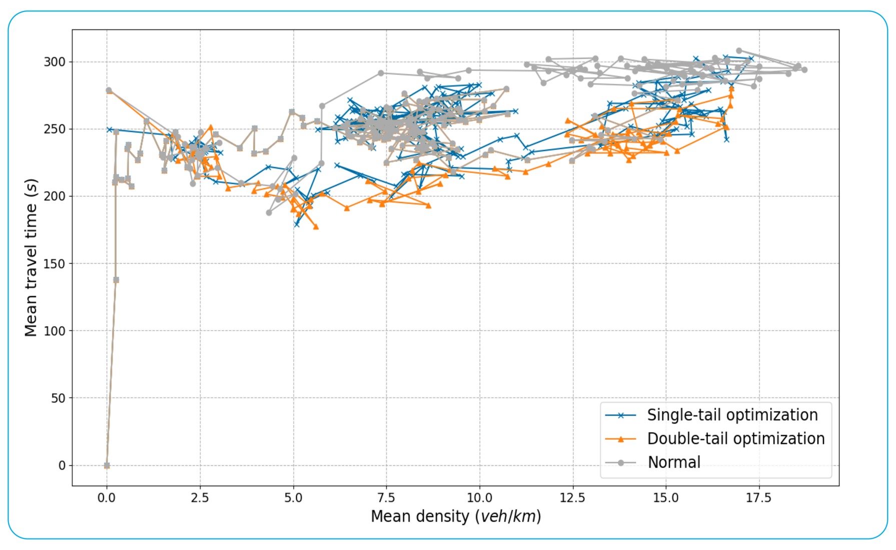
The core principle of a digital twin is its ability to mirror and interact with physical reality, to actuate the optimization inferred by the model, i.e. the "retroaction", or feedback control. More automated that is, the better it is. Bologna's road network is highly susceptible to congestion during rush hours (7:00 to 9:00 and 17:00 to 19:00). Could it be made more resilient?

Control over the network:
- Traffic demand
- Network morphology
- Traffic regulators

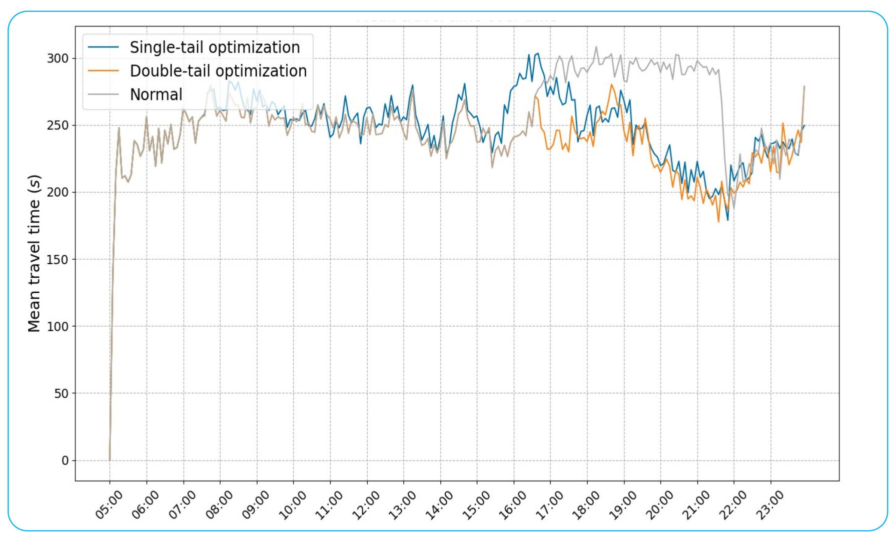
The traffic of the city of Bologna is mainly regulated by traffic lights, especially in the old town: A dynamic algorithm to control TL phases

1. Check if there's unbalance between ingoing queues
2. Check if the density of the outgoing street is less than the average density of the network
3. If so, modify red and green times favouring those with accumulated cars
4. If the balance is restored, reset the traffic light cycle

The results are promising! The road network shows **improved density-flow scores**, as well as **reduced travel time.**



The evolution of network's mean travel time over the mean density, significantly lower when the dynamic algorithm is active (orange line).



The evolution of network's mean travel time during the day.

Conclusions

We showed how mesoscopic traffic modelling, combined with real-world data from magnetic induction loops and GPS-based mobility tracking, can effectively capture urban mobility dynamics features like congestions. Furthermore, our dynamic traffic light optimization use case highlights the potential of Digital Twin frameworks in enhancing real-time traffic management. Future research should explore a more complete validation of the solution in the real word (e.g., considering latency time or accidental formation of gridlocks), study compatibility with Bologna's traffic signal priority system for buses.

Acknowledgements

[1] E. Andreotti, A. Bazzani, S. Rambaldi, N. Guglielmi, and P. Freguglia, *"Modeling traffic fluctuations and congestion on a road network"*, Advances in Complex Systems, vol. 18 (2015), no. 03n04, p. 1550009, https://doi.org/10.1142/S0219525915500095

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[3] Ambühl, L., Menendez, M. & González, M.C. *"Understanding congestion propagation by combining percolation theory with the macroscopic fundamental diagram"*. Commun Phys 6, 26 (2023). https://doi.org/10.1038/s42005-023-01144-w

[4] U. Beuck, K. Nagel, M. Rieser, D. Strippgen, M. Balmer, *"Preliminary Results of a Multi-Agent Traffic Simulation for Berlin"*. Advances in Complex Systems (ACS). 10. 289-307. 10.1142/S0219525907001367.

Dynamical Systems Framework

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