PhD in Information Technology and Electrical Engineering

Università degli Studi di Napoli Federico II

PhD Student: Manfredi Napolitano

Cycle: XXXIX

Training and Research Activities Report

Academic year: 2025-26 - PhD Year: Second

Manfredi Napolitano

Tutor: prof. Nicola Mazzocca *__tutor signature_*

Date: December 28, 2025

1. Information:

- **PhD student: Manfredi Napolitano** **PhD Cycle: XXXIX**
- **DR number: DR997199**
- **Date of birth: 07/09/1996**
- **Master Science degree: Computer Engineering** **University: Università degli Studi di Napoli Federico II**
- **Scholarship type: PNRR - DM 118/2023 Mis.: I.3.4 Dottorati Transizione Digitale**
- **Tutor: Nicola Mazzocca**
- **Period abroad:** ***list research institutions, public administrations and/or companies and number of months spent/to be spent there***

2. Study and training activities:

Activity	Type[1]	Hours	Credits	Dates	Organizer	Certificate[2]
Il computer quantistico a piattaforma superconduttiva a Federico II e il suo ecosistema	Seminar	1	0.2	06/02/2025	Prof. Fabio Villone	Y
Imprenditorialità e proprietà intellettuale	Seminar	2	0.4	06/02/2025	Prof. Fabio Villone	Y
Dynamic Risk Assessment in Industrial Applications: Leveraging Bayesian Inference for Enhanced Decision-Making	Seminar	1	0.2	04/03/2025	Dr. Francesco Vitale	Y
5G & DIGITAL TRANSFORMATION: A VIEW FROM AN UNCONVENTIONAL PERSPECTIVE	Seminar	4	0.8	14/03/2025	5G Academy	Y
Cybersecurity at Italdesign	Seminar	2	0.4	26/11/2025	Prof.ssa Valentina Casola	Y

Namirial technologies: Public Key Infrastructure and Digital Wallet	Seminar	2	0.4	11/12/2025	Prof.ssa Valentina Casola	Y
20th TAROT Summer School on Software Testing, Verification & Validation	Doctoral School	24	5	From 30/06 to 04/07	Prof.ssa Valentina Casola	Y
How to boost your PhD	Course	18	5	8-15-22-29/01/25 and 5-12/02/2025	Prof.ssa Antigone Marino	Y

1) Courses, Seminar, Doctoral School, Research, Tutorship
2) Choose: Y or N

2.1. Study and training activities - credits earned

	Courses	Seminars	Research	Tutorship	Total
Bimonth 1	5	0.6	5	0	10.6
Bimonth 2	0	1	9	0	10
Bimonth 3	0	0	10	0	10
Bimonth 4	5	0	5	0	10
Bimonth 5	0	0	10	0	10
Bimonth 6	0	0.8	8	0	8.8
Total	**10**	**2.4**	**47**	**0**	**59.4**
Expected (2nd year)	**10 - 20**	**5 - 10**	**30 - 45**	**0 – 1.6**	
Expected	**30 - 70**	**10 - 30**	**80 - 140**	**0 – 4.8**	

3. Research activity:

During the second year, my research focused on advancing the design and implementation of a Mobility Digital Twin (MoDT) system aimed at modeling and monitoring urban traffic flows in a realistic and interpretable way. The research effort concentrated on developing methodologies and tools capable of reproducing the dynamics of vehicular traffic while maintaining consistency with real-world measurements. The city of Bologna was adopted as a case study, leveraging real traffic flow data collected by induction loop detectors and publicly available through the Bologna Open Data portal.

The starting point was the observation that existing traffic monitoring MoDTs rely primarily on macroscopic measurements which, while useful, are often insufficient to capture the underlying vehicle interactions that shape real traffic dynamics [1] [2]. This lack of coherence between measured and simulated conditions limits the effectiveness of current DT solutions, reducing their interpretability and their ability to support data-driven monitoring. In this context, the research set out to investigate how real traffic data could be used to model complex traffic dynamics in a realistic and interpretable way, and how this modeling could be integrated into a digital twin capable of continuously following measurements collected on the field.

The core methodological objective was to ensure that the simulated traffic behavior faithfully mirrored the real, heterogeneous conditions observed in the city. To achieve this, I designed and implemented a driver behavior calibration process based on the tuning of microscopic car-following models, enabling the MoDT to realistically reproduce traffic flow patterns derived from the real-world measurements. This calibration process combined macroscopic traffic flow models—used to estimate aggregate quantities such as speed and density—with microscopic models describing the interactions among individual vehicles [3] [4]. The integration of these two modeling levels allowed the system to follow the evolution of observed flows, enhancing its interpretability and suitability for continuous traffic monitoring under diverse conditions.

The outcome of this work was the development of **FlowTwin**, a comprehensive methodology and software framework for the engineering of Mobility Digital Twins for traffic flow monitoring. FlowTwin introduces a two-phase methodology designed to integrate macroscopic and microscopic flow models into a coherent MoDT architecture:

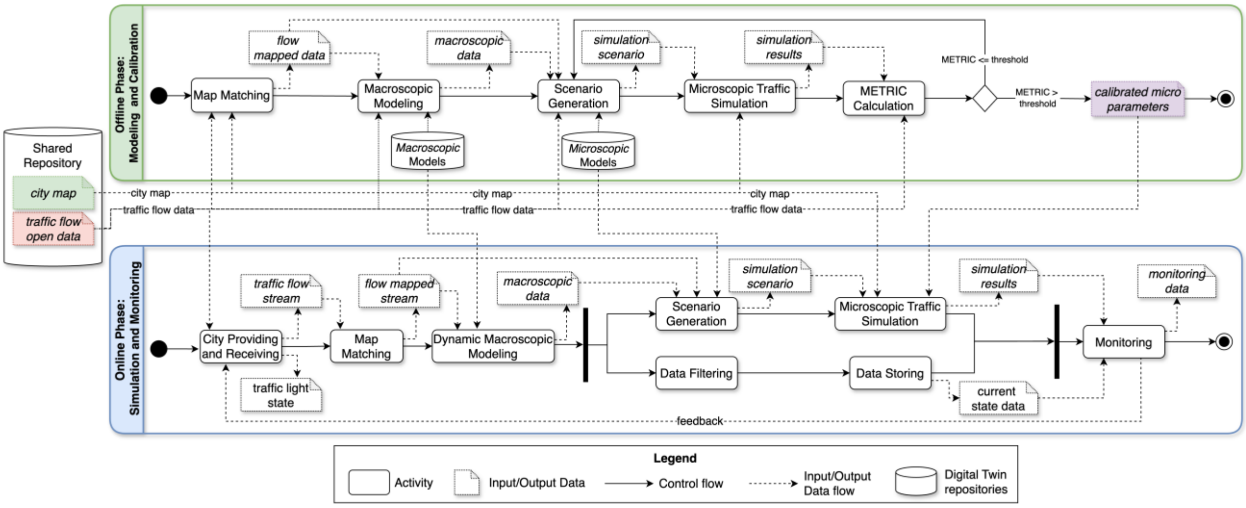

Figure 1: FlowTwin Methodology

In the *offline phase*, real-world traffic flow data are first mapped to the digital road network through a map matching process, ensuring spatial correspondence between sensors and the virtual model. The macroscopic modeling computes aggregated traffic quantities as density and speed using well adopted fundamental traffic diagram, which establish a baseline for the calibration process. The scenario generation process combines the selected macroscopic model with a microscopic car-following model along with its parameter configuration, defining different simulation setups capturing diverse driver behaviors and flow conditions. Each scenario is then executed in the microscopic simulation stage using the SUMO engine, which reproduces detailed vehicle interactions and emergent flow dynamics. The simulation outcomes are compared with the macroscopic estimates in the metric calculation stage, where quantitative indicators are computed to assess the consistency between modeled and observed conditions. These metrics support the iterative calibration of the microscopic parameters until the simulation behavior closely reflects real-world traffic.
The *online phase* establishes a continuous loop between the physical city and its digital counterpart. Real-time city data ingestion is performed through FIWARE components, followed by map matching to harmonize incoming streams with the road network. The updated flows feed into a dynamic macroscopic modeling process, which generates aggregate indicators that both support monitoring and form the basis for scenario generation. Calibrated microscopic models are then deployed to run microscopic traffic simulations,

producing detailed indicators such as queue lengths, delays, and vehicle trajectories. Meanwhile, data filtering and storing ensure that traffic information is incrementally maintained in a high-resolution state database, preserving an accurate and evolving snapshot of network conditions. The resulting indicators are finally integrated into monitoring dashboards, supporting real-time observation and, in perspective, adaptive traffic management through actuation modules.

Building upon this methodology, the research led to the development of a modular and extensible software framework designed for the engineering of Mobility Digital Twins for traffic flow monitoring. The framework adopts a layered architecture aligned with the Digital Twin **Capabilities Periodic Table** (CPT), ensuring the inclusion of all key functional dimensions, from data management and model orchestration to visualization and user interaction [5].

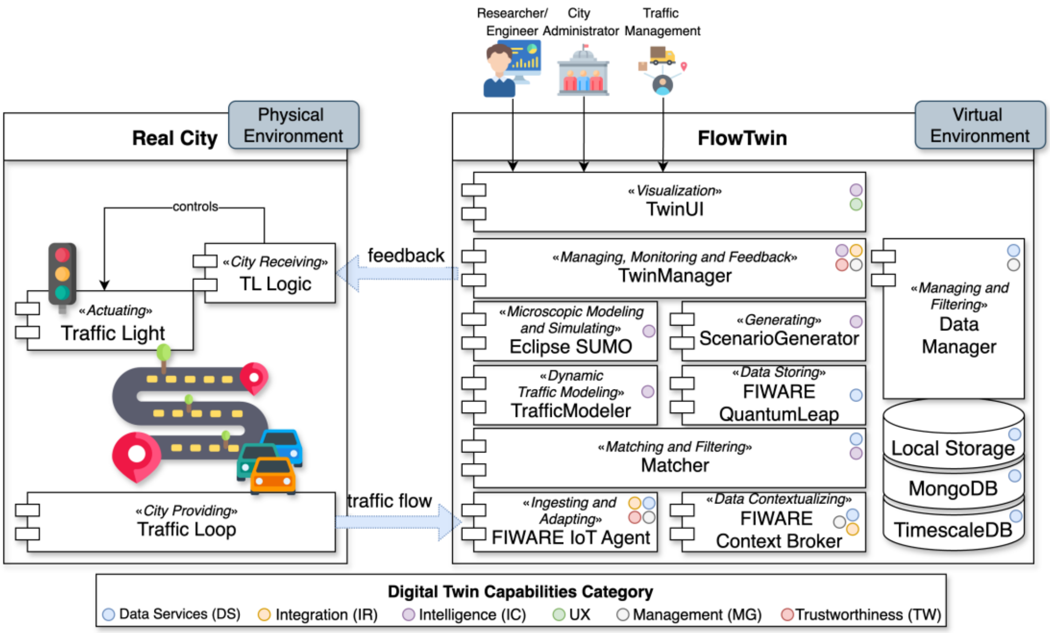

Figure 2: FlowTwin Framework

At the foundation, **FIWARE** provides the infrastructure for data ingestion, contextualization, and storage through its key components: the *IoT Agent* for collecting sensor data, the *Context Broker* for managing data streams and context entities, and *QuantumLeap* for time-series persistence and retrieval. These components ensure interoperability with heterogeneous data sources and enable continuous data flow between the real city and its digital replica.

Once the data are available, the *Matcher* module performs the necessary pre-processing operations, including filtering, reshaping, and the *map-matching* of incoming data with the digital road network. This ensures full spatial consistency between real-world traffic measurements and their virtual representation. The processed and aligned data are then handled by the *Traffic Modeler*, which implements the *macroscopic modeling layer*. This component dynamically selects and applies the most suitable macroscopic traffic model, such as *Greenshields*, *Underwood*, or *Van Aerde*, based on current traffic conditions, computing high-level indicators like flow, speed, and density that summarize the overall state of the network.

The resulting macroscopic indicators are passed to the *Scenario Generator*, which bridges the macroscopic and microscopic modeling layers. This module combines the aggregated traffic conditions with a selected microscopic car-following model (e.g., *Krauss*, *IDM*, *Wiedemann-99*) and its parameter configuration, generating complete simulation-ready scenarios. These scenarios can either be used for parameter calibration during the offline phase or executed directly during online monitoring. Through this mechanism, macroscopic results define the boundary conditions for microscopic simulations, while microscopic outcomes (e.g., speed distributions, headways, or queue lengths) can be aggregated to refine macroscopic parameters or provide additional insights for traffic analysis.
The *Twin Manager* acts as the orchestrator of the entire system, coordinating data flow, simulation execution, and synchronization between the physical and virtual environments. It also interacts with the *TwinUI*, a web-based dashboard that provides real-time visualization of observed and simulated traffic conditions, enabling users to explore the evolution of the network and assess system performance.

The feasibility and effectiveness of the proposed methodology were demonstrated through its application to the Bologna metropolitan area, resulting in the **Bologna Mobility Digital Twin** (BoMoDT). BoMoDT operationalizes the FlowTwin framework by integrating real traffic data into a simulation-driven monitoring pipeline, supported by a dedicated City Emulator that reproduces sensing and actuation processes based on the data made available by Bologna's Open Data portal. The calibration of the system ensured consistency between the measured and simulated traffic dynamics across different model configurations, confirming the ability of FlowTwin to reproduce realistic traffic conditions and support data-driven monitoring at the city scale.

Building on this foundation, a subsequent line of research explored the integration of Reinforcement Learning (RL) within the FlowTwin architecture to enable adaptive traffic management. This ongoing work, presented in a dedicated extended abstract, investigates a hierarchical RL model capable of coordinating multiple control agents across different *Traffic Analysis Zones* (TAZ), establishing a closed feedback loop between live data, simulation, and decision-making [6]. Such integration represents a step toward fully adaptive, self-optimizing Mobility Digital Twins that couple high-fidelity modeling with real-time control and planning capabilities.

3.1.References:

[1] Z. Wang, R. Gupta, K. Han, H. Wang, A. Ganlath and N. Ammar, "Mobility Digital Twin: Concept, Architecture, Case Study, and Future Challenges," *IEEE Internet of Things Journal,* vol. 9, no. 18, pp. 17452-17467, 2022.

[2] C. Weil, S. E. Babri, R. Longchamp, F. Golay and A. Alahi, "Urban Digital Twin Challenges: A Systematic Review and Perspectives for Sustainable Smart Cities," *Sustainable Cities and Society,* vol. 99, 2023.

[3] F. Kessels, Traffic Flow Modelling, Springer, 2019.

[4] H. Rakha and B. Crowther, "Comparison of Greenshields, Pipes, and Van Aerde Car-Following and Traffic

Stream Models," *Transportation Research Records,* 2002.

[5] P. Van Schalkwyk, "Digital Twin capabilities periodic table," *Digital Twin Consortium,* 2022.

[6] J. Cao, L. Dong, X. Yuan, Y. Wang and C. Sun, "Hierarchical multi-agent reinforcement learning for cooperative tasks with sparse rewards in continuous domain," *Neural Computing and Applications,* 2023.

4. Research products:

J1. Napolitano, M., Somma, A., De Benedictis, A., Mazzocca, N., “FlowTwin: A Digital Twin for Traffic Flow Monitoring”, *IEEE Open Journal of Intelligent Transportation Systems* (OJ-ITS), Status: Published on November 26, 2025.

C1. Napolitano, M., “A Reinforcement Learning Approach for Urban Traffic Management with Digital Twins”, *41st ACM/SIGAPP Symposium On Applied Computing - Student Research Competition*, Status: Accepted, to be presented.

5. Conferences and seminars attended

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6. Periods in a company

From May 12th to November 12th 2025, I carried out a six-month research period hosted by **Hitachi Rail STS S.p.A.** as part of my PhD fellowship. The activity was conducted in collaboration with **Carnegie Mellon University (CMU)**, based in Pittsburgh, Pennsylvania (USA), within the framework of an ongoing scientific cooperation between Hitachi Rail and CMU on advanced traffic simulation systems.
The work focused on the extension the *Mobility Data Analytics Center – Prediction, Optimization, and Simulation toolkit for Transportation Systems* (**MAC-POSTS**), originally developed at CMU. The collaboration aimed to broaden the tool’s capabilities for multimodal public transport systems (including metro and bus modes) and to introduce new traffic assignment optimization methods based on trip-level criteria rather than traditional travel-time minimization.
My contribution mainly involved the design and execution of a **sensitivity analysis** on the extended version of the MAC-POSTS.
The sensitivity analysis specifically targeted the *MultiModal Origin–Destination Estimation* (**MMDODE**) component, evaluating how variations in key parameters, such as demand scaling factors, mode-choice weights, and estimation constraints impacted the stability, robustness, and accuracy of the multimodal OD estimation process. This assessment made it possible to identify the operational range, performance boundaries, and potential limitations of the updated Dynamic Traffic Assignment and MMDODE framework.

This research period strengthened the methodological integration between dynamic simulation and data-driven model evaluation, supporting future extensions of the Mobility Digital Twin research line within my PhD project.

Company	Supervisor	Starting date	End date
Hitachi Rail STS S.p.A	Paolo Sannino	12/05/2025	12/11/2025

7. Tutorship

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8. Plan for year three

The third year of the PhD will continue and expand the research line on Mobility Digital Twins (MoDTs), with the aim of extending the capabilities developed so far and exploring new functionalities to support advanced traffic modeling and monitoring. Building on the methodological and technological foundations established with FlowTwin, the upcoming work will focus on enhancing the expressive power of the DT by incorporating new forms of vehicle behavior, additional mobility modes, and mechanisms that better capture the complexity of real urban traffic. These extensions are intended to broaden the applicability of the MoDT framework and to enable more comprehensive analyses of traffic dynamics in realistic operational settings.

A major research direction for the upcoming year will concern the **integration of Autonomous Vehicles (AVs) and Electric Autonomous Vehicles (E-AVs)** into the MoDT framework. The presence of AVs introduces new decision layers and operational constraints, especially when electric propulsion and battery management are considered. The third-year activities will therefore explore how MoDTs can represent AV/E-AV behavior and evaluate their impact on urban traffic systems, enabling scenario analyses that consider adoption levels, interactions with human-driven traffic, and implications for sustainability and energy efficiency. This line of research naturally extends FlowTwin toward a new generation of DT systems capable not only of reproducing traffic behavior, but also of assessing the sustainability implications of emerging mobility technologies.

The research activity will follow a combined methodological and experimental approach. Methodologically, the work will focus on extending the modeling capabilities of the digital twin to integrate AV/E-AV behavioral features, energy-aware mobility models, and emission-related indicators where appropriate. Experimentally, the objective is to design and evaluate simulation-driven scenarios involving mixed traffic conditions, using the DT as a controlled environment for exploring energy and sustainability implications of different configurations and mobility strategies. Rather than predefining a fixed set of tasks, the work will focus on progressively refining the models, integrating relevant features, and assessing their impact through data-driven experiments consistent with the evolving research questions.

Part of this research will be conducted abroad through a collaboration with **Technische Universität München (TUM)** and **Fortiss GmbH**, institutions with strong research expertise in automotive systems, autonomous vehicles, and smart mobility. This collaboration will be supervised by Dr Andrea Stocco. The planned period abroad is expected to take place from **mid-January to mid-July 2026 (6 months)**, and will support the development of energy-aware simulation experiments, AV/E-AV integration methods, and sustainability-oriented decision models within the Mobility Digital Twin.

A preliminary working title for the PhD thesis is:

"**Data-Driven Mobility Digital Twins for Urban Traffic Modeling and Monitoring**"