

An extensible framework for urban mobility digital shadows

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Abstract—Urban mobility systems require continuous monitoring and optimization to address increasing complexity and sustainability demands. This paper introduces UM-DS (Urban Mobility–Digital Shadow), a modular framework that integrates heterogeneous real-time and historical data, such as traffic intensity, incidents, weather, and public transport, into a unified model of urban mobility. UM-DS enables visualization, simulation, and analysis through an extensible dashboard connected to the SUMO simulation engine. Validated in the city of Malaga, the framework supports real-time exploration and temporal playback of traffic conditions, facilitating the development of AI-based forecasting models and multi-agent simulations. Its flexible, city-agnostic architecture allows adaptation to diverse urban contexts, bridging the gap between raw data and intelligent decision making. UM-DS provides a replicable foundation for next-generation smart-city mobility systems, fostering informed, data-driven strategies for sustainable urban transport.

Urban mobility management increasingly relies on heterogeneous data streams, including traffic conditions, road incidents, weather, and public transport activity. In practice, these data are often fragmented across independent platforms, making it difficult for city stakeholders to obtain a unified, street-level view of current conditions, to reproduce past traffic states, or to couple real-time monitoring with simulation and predictive analysis. This fragmentation limits informed decision making, especially when evaluating traffic strategies or testing interventions before deployment. In this context, digital twins (DTs) provide a means to continuously monitor, simulate, and evaluate urban processes in ways that traditional models cannot do [1], [2]. While DT concepts have been critically discussed in logistics planning and policy contexts [3], and frameworks for formalizing sustainable mobility management have been proposed [4], few existing

systems integrate heterogeneous data streams, real-time updates, and historical playback within a unified operational architecture. The term digital shadow (DS) is often used as a synonym for DT [5], however, in DSs, data exchange is restricted to a unidirectional real-time connection from the physical twin to the DT.

The UM-DS (Urban Mobility-Digital Shadow) framework is modular and extensible. It fuses heterogeneous urban data into a cohesive digital representation. The framework is designed to support the development and deployment of urban DSs, and integrates real-time and historical mobility data, including traffic rules, infrastructures, and level intensity, road incidents and weather conditions. Those data are combined with static contextual layers such as public transport networks, and urban points of interest. Unlike traditional dashboards or isolated simulations, UM-DS offers a flexible architecture that supports both visual analysis and integration with external traffic simulation systems such as SUMO (Simulation of Urban MOBility) [6].

Furthermore, UM-DS serves as a launchpad for

XXXX-XXX © Year IEEE
Digital Object Identifier 10.1109/XXX.0000.0000000

advanced modeling efforts. Thanks to the scraping of the previously mentioned heterogeneous data, the DS provides a solid basis for forecasting traffic intensity and running simulations. These capabilities facilitate the development of deep-learning models for traffic prediction and multi-agent systems for simulating and evaluating new traffic and mobility strategies. Such simulations allow potential interventions to be tested before they are implemented in the real world, thus supporting more informed decision making and reducing risks in urban planning.

The main contributions of this work can be summarized as follows:

- UM-DS provides a flexible, modular framework that integrates heterogeneous mobility-related data into a unified representation.
- UM-DS enables real-time visualization of traffic levels at configurable temporal resolutions, integrating incident reports, congestion metrics, and contextual layers into a single dashboard.
- UM-DS supports temporal exploration and playback of past traffic conditions, enabling detailed analysis and validation of urban mobility strategies and predictive models.
- The platform integrates traffic simulation engines, enabling the testing of mobility strategies under realistic and data-driven conditions.
- The data acquisition engines periodically collect data from multiple heterogeneous sources to characterize traffic periodicity and keep mobility-related layers up to date, including optional context such as weather, additional signals, or domain-specific geospatial features.
- UM-DS provides a solid foundation for AI-based models and intelligent simulation systems by generating rich, high-resolution temporal datasets tailored to each city.
- The platform is designed to be city-agnostic, allowing adaptation to diverse urban context through configurable data ingestion layers and traffic parameters.

Framework Description

To manage heterogeneous data formats and sources, UM-DS uses a MongoDB database, which allows flexible and scalable storage. Traffic regulations and street-level topology are modeled using a GraphML-based graph structure, enabling efficient spatial reasoning and network analysis. The framework is composed of the following five complementary subsystems (Figure 1):

- **DS Core:** An interactive dashboard that acts as the central control panel of the framework. It integrates, visualizes real-time and historical data on urban mobility and traffic conditions. Through this interface, users can explore spatial and temporal mobility patterns, compare different scenarios, and test potential interventions in specific areas of the city. The dashboard supports multi-layered data analysis and manual or automated playback of historical traffic.
- **Data Acquisition Engine:** This subsystem feeds the core with high-frequency data from sources such as traffic levels, incidents, and weather conditions. New extractors can be added as required by the city's monitoring needs. All incoming data are integrated and stored in a centralized database, supporting both real-time monitoring and long-term analysis.
- **Road Network Layer:** This layer provides the structural backbone of UM-DS by modeling the street network and traffic rules of the area of interest. It is built from OpenStreetMap(OSM) ¹ data and stored in GraphML format ², which encodes variables such as road topology, directions, speed limits, and street type. This component supports the mapping of dynamic data acquired by the data acquisition engine layer (e.g., linking traffic levels to street segments), and enables spatial reasoning and visualization in the DS Core, including graph rendering and simulation setup. Its modular design allows multiple GraphMLs to co-exist, one per area of interest, facilitating city- or district-level deployments.
- **Dynamic Data Layers:** These layers contain the real-time and periodically updated information collected by the Data Acquisition Engine. They include dynamic data such as traffic intensity levels, road incidents, and weather conditions. All dynamic layers are stored in MongoDB, ensuring consistent integration with the Road Network Layer and the DS Core.
- **Static Contextual Layers:** They are a curated set of georeferenced urban features that enrich the DS with valuable background information. These layers include relatively stable elements such as public establishments, bicycle parking stations, Electric Vehicle charging points, and public defibrillators. Although not updated in real time, they provide an essential spatial context

¹<https://www.openstreetmap.org>

²<http://graphml.graphdrawing.org>

for interpreting dynamic mobility data and help tailor the analysis to the specific characteristics of each urban area.

Deploying UM-DS in a Specific Urban Area

The flexibility of UM-DS allows it to be adapted to new geographic regions by reconfiguring data sources and contextual parameters, without modifying the core components of the architecture. The deployment process consists of the following practical steps:

- 1) *Defining the Area of Interest and Preparing the Base Context.* The first step is to define the geographic boundaries of the area to be monitored or simulated and obtain the corresponding road network in GraphML format. This street network underpins traffic graphs, simulation environments, and geographic elements within MongoDB. In parallel, data scrapers are configured to collect dynamic information for the area, and static contextual layers are populated from public repositories or APIs. This ensures that static and dynamic layers are consistently stored, easily queried, and interoperable with the dashboard and analytical modules.
- 2) *Generating the Simulation Environment.* Once the dynamic and static data layers have been prepared, the simulation environment is configured. Although UM-DS supports integration with traffic simulators like SUMO, the system remains agnostic to the simulation backend thanks to its modular structure. Simulations can be run independently or connected to the UM-DS dashboard through data interfaces, supporting both offline scenario evaluation and real-time prediction workflows.
- 3) *Deploying the Dashboard and (Optional) AI Modules.* Once data ingestion and simulation infrastructure are in place, the UM-DS dashboard can be deployed. The platform also supports the integration of AI modules for users seeking deeper insights or predictive capabilities. Traffic and environmental data collected by the system can be used to train machine or deep-learning models, to support tasks such as traffic forecasting, anomaly detection, and optimization of simulation scenarios.

From UM-DS to MUM-DS: Instantiating the framework in Malaga

Instantiating UM-DS to a new city mainly consists of configuring the following deployment steps: (i) defining the area of interest and its spatial boundaries; (ii) downloading the OSM road network for the selected area and generating the corresponding GraphML representation; (iii) selecting data providers for dynamic layers (e.g., traffic and incidents) and configuring the corresponding scrapers, including API endpoints and credentials, update periodicity, and the mapping strategy to align provider outputs with street segments; and (iv) selecting static contextual data sources and ingesting them into MongoDB, either through bulk loading of exported datasets or via dedicated ingestion APIs.

To demonstrate the city-agnostic design of UM-DS in practice, we instantiated the framework in Malaga, yielding MUM-DS, a concrete deployment that we use as a running case study. The generic deployment steps are based on the following choices:

- Two districts, i.e., Teatinos and Soho, were selected as areas of interest.
- Traffic level rates and estimated speeds are ingested at a 5-minute cadence; traffic incidents are also updated every 5 minutes; weather is refreshed hourly.
- SUMO was adopted as the traffic simulator. The dashboard connects to dynamic and static contextual layers, merges dynamic and static layers with the Road Network Layer, and supports both real-time exploration and historical playback.

MUM-DS: Logical View

MUM-DS provides the following set of key functionalities that enable users to analyze, monitor, and simulate urban mobility for two districts of the city, Teatinos, and Soho:

- **Interactive area selection:** Users can select custom urban zones for analysis and simulation.
- **Real-time and static custom layers:** The level and the incidents of traffic are updated every 5 minutes, while other data layers such as transport networks, establishments, defibrillators, and weather conditions are static or updated less frequently.
- **Historical traffic data exploration:** This functionality supports both: manual exploration, where users can inspect any past moment in detail, and automatic mode, which reproduces

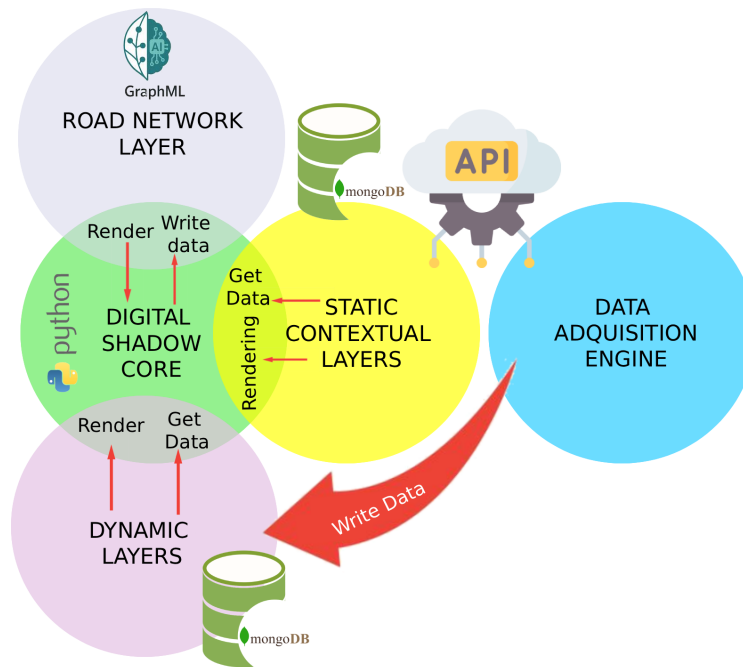


FIGURE 1. UM-DS framework architecture, including the five layers.

the evolution of traffic over time like a temporal simulation. This enables the analysis of recurring patterns and validation of predictive models or traffic strategies based on real historical data.

- **Traffic simulation launch:** Users can initiate SUMO-based simulations directly from the dashboard using road constraints. The simulation includes various mobility agents moving through the network while respecting traffic rules such as speed limits, directions, and traffic lights.

MUM-DS: Technological View

Figure 2 shows the core of the general customizable architecture of UM-DS instance for MUM-DS, where the following components could be identified:

- **DS Core:** Interface that allows users to select the area and static layers of interest, and to launch traffic simulations based on the city's traffic rules and the street-level graph. The dashboard, implemented in Python using Dash and Mapbox GL³, renders the road network and map markers, displaying information such as street name, speed limits, highway type and traffic direction.

Traffic simulation scenarios are generated using the SUMO Scenario Wizard, which automatically builds the simulation environment for the selected area from OpenStreetMap data. MUM-DS integrates the SUMO engine through the TraCI [7] API, enabling real-time interaction from the DS backend and retrieval of vehicle positions, speeds, and types for visualization on the dashboard. Simulations respect street directions, speed limits, and traffic lights to ensure rule-consistent behavior.

In the current implementation, SUMO simulations in MUM-DS do not aim to reproduce the real traffic state observed in the DS. Traffic flows are generated as exploratory simulations that respect road topology and regulations, but are not calibrated against empirical, time-dependent demand profiles.

- **Road Network Layer:** To draw the graph on the map and provide detailed information for the nodes and edges corresponding to each street edge, the dashboard merges real-time data, such as traffic intensity and estimated maximum speed per street-edge, with static street meta-data extracted from a pre-generated GraphML file of the selected area.
- **Data Acquisition Engine:** Public APIs and

³<https://docs.mapbox.com/mapbox-gl-js/>

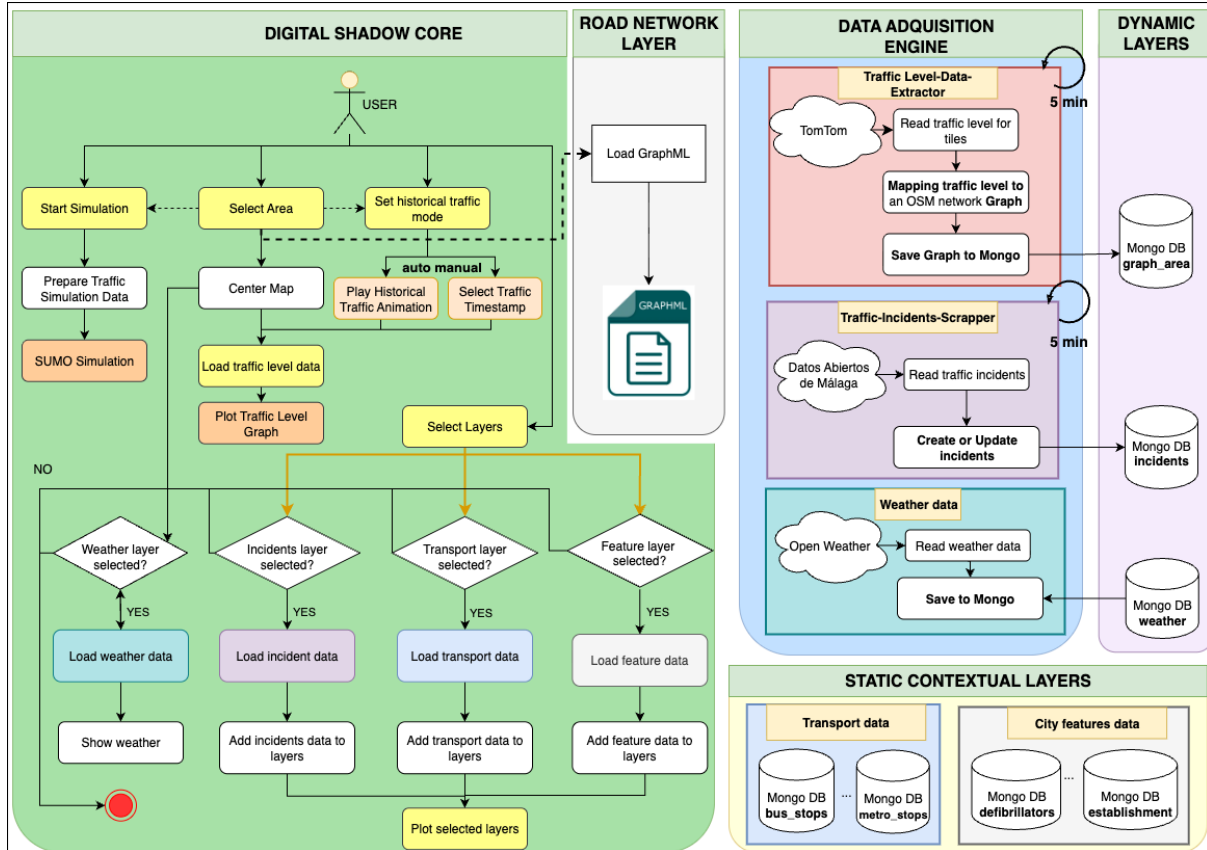


FIGURE 2. MUM-DS framework architecture, including the data acquisition engine, dynamic and static layers, and the DS Core components.

scraping techniques are used to collect dynamic data layers:

- **Traffic-Level-Data-Extractor:** updates traffic intensity and estimated average speed for each street edge every 5 minutes using the TomTom API, mapping provider data to the OSM-based road graph stored in MongoDB.
- **Traffic-Incidents-Scraper:** retrieves traffic incidents from Malaga City Council's Open Data Portal⁴ every 5 minutes, recording location, type, affected streets, and timestamps.
- **Weather data:** an hourly scraper collects meteorological information from Visual Crossing Weather⁵, including temperature, humidity, wind, and precipitation, to

contextualize traffic patterns.

- **Dynamic Layers:** These layers integrate multiple sources: traffic data managed by the *Traffic-Level-Data-Extractor*, traffic incidents collected by the *Traffic-Incidents-Scraper*, and meteorological information gathered by the *Weather Data* extractor. By organizing these heterogeneous inputs in MongoDB, the dynamic layers provide a structured and unified foundation for further analysis, visualization, and decision making.
- **Static Contextual Layers:** These layers provide essential context for environmental simulations and mobility analyses. Additionally, they serve as reference points for generating vehicles or creating meaningful routes in SUMO-based simulations. The data of these layers, when necessary, must be refreshed on demand by retrieving updated information from the corresponding sources and replacing the existing datasets.

⁴<https://datosabiertos.malaga.eu>

⁵<https://www.visualcrossing.com>

- **Transport data:** It provides comprehensive information on public transportation infrastructure across the city. The layer includes bus stops, metro stations, and taxi stands and is essential for multimodal mobility analysis and developing realistic traffic simulation scenarios. These data have been collected from three primary sources: i) EMT (*Empresa Malagueña de Transportes*)⁶, which manages the bus network; ii) City Council's Open Data, taxi stand information; and iii) MetroMalaga⁷, the company responsible for operating the metro system.
- **City features data:** MUM-DS integrates multiple static contextual layers that enrich the urban mobility analysis. These include the establishments (e.g., shops, clinics, restaurants), defibrillators, electric vehicle charging stations and bicycle parking facilities. These elements provide essential context for interpreting traffic patterns, designing realistic simulations, and supporting emergency mobility planning. Establishment data has been extracted from Google Maps⁸.

Finally, note that in MUM-DS, the Road Network Layer comprises 4,096 street segments in Teatinos and 131 in Soho. Dynamic layers are updated every 15 minutes (traffic and incidents) and hourly (weather), resulting in approximately 92 traffic observations per area and day. UM-DS and MUM-DS are scalable in terms of network size, data volume, and historical depth.

A Use Case of MUM-DS

Figure 3 illustrates a use case in the Soho district of Malaga. The user selects the area of interest, chooses a map style, and activates relevant layers such as public transport stops, defibrillators, bicycle parking, electric vehicle charging points, establishments, and traffic incidents. The traffic graph, representing intensity along each street segment, is always displayed for the selected area.

Users can then launch a traffic simulation by clicking the *Start Simulation* button, which visualizes different mobility agents moving along the network while

respecting local traffic rules. The historical traffic visualizer enables temporal navigation and analysis of traffic conditions across user-defined time frames.

Discussion

Table 1 compares UM-DS against representative digital twin and simulation-oriented platforms across key functional dimensions. The column *Traffic Simulation* indicates whether the system incorporates or interfaces with a mobility simulation engine. *Scraping Engine* captures the ability to extract and standardize heterogeneous data streams from external providers through configurable ingestion pipelines. *Real-time Data* reflects support for continuously updated information, such as traffic speeds, incidents, or environmental conditions. *Historical Playback* denotes whether the platform enables retrospective exploration of past states beyond real-time dashboards. *City-agnostic* assesses the portability of the system to different urban areas without substantial re-engineering. Finally, the *Characteristics* column summarizes the unique scope, strengths, and intended application context of each platform.

Large-scale urban observatories such as the London ViLO model provide valuable city-wide insights by integrating extensive sensing infrastructures, high-level analytics, and policy-oriented visualizations. These platforms excel at macroscopic monitoring and long-term strategic planning. In contrast, UM-DS targets a complementary research gap by focusing on lightweight deployment, street-level data fusion, and tight integration with traffic simulation and AI pipelines. Rather than relying on bespoke sensor installations, UM-DS leverages existing urban data ecosystems and emphasizes historical playback, exploratory simulation, and city-agnostic configurability. This positioning allows UM-DS to bridge the gap between large-scale observatories and simulation-centric tools, enabling rapid experimentation, data-driven modeling, and decision support at fine spatial and temporal granularity, which existing urban observatories do not explicitly target.

Beyond data collection and visualization, the proposed UM-DS framework enables several promising research directions. In particular, future work will focus on the development of multi-agent and *what-if* simulation scenarios to evaluate traffic management and control strategies under different conditions. The framework also provides a suitable basis for short-term prediction of traffic variables, such as speed and flow, at street level, leveraging the historical data continuously collected by UM-DS. In addition, spatio-temporal analyses can be conducted to identify recur-

⁶<https://www.emtmalaga.es>

⁷<https://www.metromalaga.es>

⁸<http://www.google.com/maps>

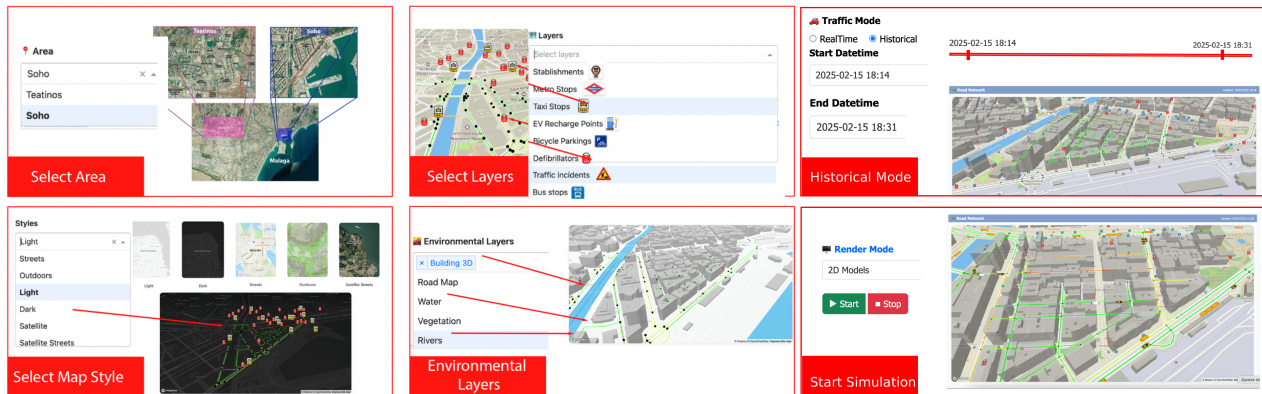


FIGURE 3. Screenshot of the main steps for MUM-DS

rent congestion patterns, critical areas, and peak periods, supporting evidence-based traffic planning and policy making. Altogether, these extensions position UM-DS as a flexible foundation for advanced traffic analysis and decision-support systems, going beyond descriptive urban mobility monitoring.

From a broader DT ecosystem perspective, UM-DS is intentionally positioned as a DS rather than as a full DT implementation. Its role is to manage operational mobility data, enabling real-time and historical monitoring, data fusion, and simulation-based exploration at street level. In this context, the Digital Master (DM) is assumed to operate as a complementary layer responsible for governance, documentation, metadata, configuration management, and the definition of conceptual or analytical models. UM-DS consumes configuration parameters and model definitions provided by the DM to execute simulations and analyses, while producing operational outputs such as traffic states, simulation traces, and historical records that can be used by the DM for validation, comparison, and knowledge management. This loose coupling between DM and DS aligns with the DS paradigm adopted in this work, where feedback from the digital representation to the physical system is not enforced in real time but supports iterative refinement and decision making.

Limitations and Future Works

One of the main limitations of the framework is its reliance on the availability and quality of external open data sources. Specifically, UM-DS depends on detailed OSM graphs being available for the target city, as well as on access to reliable traffic data providers such as TomTom to capture traffic intensity.

Furthermore, the fidelity of the traffic simulations

heavily depends on how accurately the simulation engine, such as SUMO, can replicate real-world conditions. This includes the calibration of traffic light timings, road rules, and vehicle behavior models, which can vary significantly between cities and are not always available or accurate. Improving simulation fidelity and calibration is therefore considered out of scope for the present work and are left for future research.

In the current implementation, SUMO is used to generate exploratory traffic flows that respect the road network topology and traffic regulations of the selected area. However, traffic demand is not yet driven by empirical, time-dependent profiles derived from real measurements. As future work, we plan to integrate realistic traffic demand into SUMO through the TraCI interface, using the historical traffic data collected by MUM-DS. This will enable the automatic generation of time-varying traffic demand profiles (e.g., hourly or peak-period flows) grounded in observed conditions, closing the loop between the DS and traffic simulation.

These dependencies highlight the need for adaptable integration pipelines and careful validation of local data sources when implementing and deploying the UM-DS framework in different urban contexts.

An interesting avenue for future research lies in the integration of urban DSs as a comprehensive source of heterogeneous data streams. In particular, MUM-DS is currently being exploited to extract diverse information sources considered relevant by domain experts (e.g., meteorological conditions, incidents, public transport activity, and socio-infrastructure features). Leveraging such a unified digital representation enables the development of deep-learning models for short-term traffic forecasting at the granularity of individual street segments and areas of interest, which are already being applied in Malaga within our ongoing national

project aimed at improving urban mobility, access to services, and sustainability under the *15-minute city* paradigm [15].

Beyond predictive modeling, the same digital representation will be used as the basis for multi-agent and *what-if* simulation studies, enabling the evaluation of alternative mobility strategies, demand scenarios, and policy interventions before real-world deployment. This evolution positions UM-DS as a shared experimentation layer that bridges data-driven prediction and simulation-based decision support for improving urban mobility, while the historical and real-time traffic data collected by UM-DS will be used to reproduce and calibrate realistic city-wide traffic conditions in SUMO, enabling the simulation of real traffic dynamics rather than exploratory baseline flows.

Conclusions

UM-DS is a modular framework that facilitates the development of DSs for urban mobility modeling. It enables city stakeholders to explore, monitor, and simulate traffic conditions by integrating real-time data acquisition, traffic simulation, and multi-layered visualization into a single extensible dashboard.

The platform has been successfully tested in the city of Malaga as a proof of concept, demonstrating its ability to integrate dynamic and static data sources, including traffic intensity, public transport networks, incidents, and urban infrastructure, with periodic updates via dedicated scrapers. Its SUMO-based simulation engine, enhanced through TraCI, enables users to trial realistic mobility strategies prior to real world implementation.

In addition to real-time monitoring, the ability of UM-DS to access and visualize historical traffic data is one of its key differentiators. Users can explore traffic evolution across specific time ranges, either manually or through automatic playback, enabling retrospective congestion analysis, preparation and validation of AI models, and contextual interpretation of anomalies and incident impact over time.

By supporting both real-time and historical perspectives, UM-DS enables users to react to current conditions and learn from the past states, allowing them to anticipate future scenarios with greater accuracy.

In summary, UM-DS bridges the gap between raw mobility data and intelligent decision making, providing a replicable and extensible basis for developing next-generation urban mobility systems.

This paper also provides an online demo ⁹ and a video tutorial ¹⁰ to illustrate how the system supports urban mobility analysis and AI-ready simulation pipelines.

ACKNOWLEDGMENTS

This research is supported by the Spanish Ministry of Science, Innovation and Universities through the research projects PID2021-122381OB-I00 and PID2024-1620110B-100.

List of Acronyms

- **ABMS**: Agent-Based Modeling and Simulation
- **AI**: Artificial Intelligence
- **API**: Application Programming Interface
- **DS**: Digital Shadow
- **DT**: Digital Twin
- **EMT**: Empresa Malagueña de Transportes
- **GPS**: Global Positioning System
- **GraphML**: Graph Markup Language
- **MongoDB**: Mongo Database
- **MUM-DS**: Malaga Urban Mobility Digital Shadow
- **OSM**: OpenStreetMap
- **SUMO**: Simulation of Urban MObility
- **TraCI**: Traffic Control Interface
- **UM-DS**: Urban Mobility Digital Shadow

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⁹<http://mumds.uma.es>

¹⁰<https://www.youtube.com/watch?v=Xqzp9vj2rhw>

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Juan Palma-Borda received the B.S. Degree in Software Engineering in 2019 and the Master's Degree in Science and Data Engineering in 2021, both from the UMA, where he is currently pursuing a Ph.D. Degree in Computer Science. His research interests include modeling and optimization of complex urban environments through data science and AI, with particular interest in applications related to criminology, urban planning, and multi-agent systems. He is currently a member of the (IA)² research group, which develops interdisciplinary solutions to real-world problems using AI. He has participated in several conferences related to criminology, public safety, and emergency response, and has over six years of experience in software development.

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currently an Associate Professor at the Department of Languages and Computer Science, UMA. In the area of predictive policing, from 2018, and as a result of the collaboration with the National Police of Malaga, she has obtained public funding through competitive projects applying ABMS and data science in this area. In addition, in the field of urban mobility, she is currently leading a contract with the company Vodafone. She has co-authored more than 80 international scientific publications. Her research activity focuses on the use of ABMS, data science, and machine learning in different application areas.

TABLE 1. Comparison of UM-DS with Related Systems

Platform	Traffic Sim.	Scraping Engine	Real-time Data	Historical Playback	City-agnostic	Characteristics
BlueCity [8]	Yes	–	Yes	No	Yes	Real-time mobility analysis at intersections using AI and camera-based sensing. Limited to specific nodes of the road network, without a broader integration of mobility layers or predictive capabilities.
CityEngine [9]	Yes	No	No	No	Yes	Procedural urban modeling and 3D visualization tool focused on urban design. Its primary focus remains on 3D visualization and urban form modeling, rather than on the integration of dynamic mobility data for analysis or forecasting.
DTUMOS [10]	Yes	No	No	No	Yes	Open-source DT framework for scalable urban mobility systems, featuring AI-based ETA (Estimated Time of Arrival) modeling and high-performance simulation validated across large cities such as Seoul, New York, and Chicago.
DUET [11]	Yes	–	Yes	No	Yes	DT platform for smart cities with sensor integration and policy-oriented analysis. Tailored to a few pilot cities and lacks general-purpose extensibility or open access for broader research applications.
SMDT [12]	Yes	No	Yes	No	No	DT integrating connected autonomous vehicles and roadside units for real-time traffic coordination in controlled environments. Tailored to specific test environments and relies on high-density sensor infrastructure, which may limit scalability and adaptability to diverse urban contexts.
Urban-ITE [13]	Yes	Yes	No	No	Yes	Platform for urban decision-making support with a DT focus for public administrations. Limited flexibility for custom deployments.
Unity-based Urban Traffic DT System [14]	Yes	Yes	Yes	No	Partial	Multi-layer DT system built in Unity, integrating multi-source APIs (traffic and weather), GIS data, and 3D building modeling for real-time traffic simulation, high-fidelity visualization, and decision support.
UM-DS	Yes	Yes	Yes	Yes	Yes	Modular DS framework supporting historical playback of traffic evolution at street level, configurable scrapers, real-time and static data integration, and compatibility with external simulators such as SUMO, offering a distinctive blend of lightweight modular design, traffic-oriented scraping, traffic simulation integration, and scalability across cities.