SUMO User Conference 2024
Conference paper
TIB-OP will set DOI with \TIBdoi
© Authors. This work is licensed under a Creative Commons Attribution 4.0 International License
Submitted: 2024-04-15

Simulating Traffic Networks:
Driving SUMO towards digital twins

Axel Schaffland[1]*, Jonas Nelson[1], and Julius Schöning[1]

[1]Osnabrück University of Applied Science
*Correspondence: Axel Schaffland, a.schaffland@hs-osnabrueck.de

Abstract: For driving the roads of cities into enjoyable and relaxing places with parks, trees, and seating, a paradigm change in everyone's commuter behavior is needed. Still, individual transport via cars increases, and thus, the space required for parking and driving these cars shapes our cities — not the people. Next to the space needed, vehicles pollute the environment with CO_2, diesel particulate, and even electric cars with tire abrasion. Alternative modes of locomotion, like public transportation and shared mobility, are still not attractive to many people. Intelligent intermodal mobility networks can help address these challenges, allowing for efficient use between various transportation modalities. These mobility networks require good databases and simulation combined into digital twins. This paper presents how such a digital twin can be created in the Simulation of Urban Mobility (SUMO) software using data from available and future city sensors. The digital twin aims to simulate, analyze, and evaluate the different behaviors and interactions between traffic participants when changing commuting incentives. Using the city of Osnabrück and its different available sensor types, the data availability is compared with other towns to discuss how the data density can be improved. Creating a static network from open street data and intersection side maps provided by the city of Osnabrück shows how these data can be integrated into SUMO for generating traffic flows and routes in SUMO based on a database of historical and live data. Within the conclusion, the paper discusses how developing a digital twin in SUMO from static and dynamic data can be improved in the future and what common misconceptions need to be overcome.

Keywords: Digital Twin, SUMO (Simulation of Urban Mobility), Intermodal Mobility Networks, Sustainable Urban Planning, Traffic Simulation

1 Introduction

The need for a paradigm shift in commuter behavior towards embracing public transportation and shared mobility systems is underscored by the inefficiency rooted in the current model of private car ownership. In Germany alone, the private-passenger car fleet approximates 50 million vehicles, theoretically offering around 250 million seats—a surplus to accommodate the country's population over three times. However, the reality starkly contrasts the potential, with private vehicles sitting idle approximately 95% of the time [1] and when in use, often ferrying merely 1.2 to 1.9 individuals in urban settings [2]. This underutilization highlights a mere 2% average seat capacity usage, spotlighting an unsustainable pattern of mobility that squanders resources and exacerbates congestion and pollution in urban landscapes. Transitioning towards shared and public modes of transportation can ameliorate these challenges, driving us towards a future where mobility is both environmentally sustainable and efficiently attuned to the collective needs of urban populations.

Concurrently, transformative urban initiatives such as Barcelona's "Supermanzana" and similar concepts in Vitoria-Gasteiz demonstrate the profound impact of reorienting cityscapes away from car dominance towards pedestrian-centered environments [3]. These projects have metamorphosed streets once choked with traffic noise and emissions into vibrant community hubs, where the air is filled with the sounds of human interaction and nature rather than the drone of car traffic. This reclamation of public space not only augments the quality of urban life by fostering social cohesion and promoting healthier lifestyles but also serves as a beacon, illuminating the feasibility and benefits of reduced car reliance. These examples underscore the necessity of adopting integrated, intelligent mobility networks that prioritize public and shared transportation modes. Envisioning and executing such a shift requires not only infrastructural adaptations but also a cultural recalibration, where the value is placed on communal well-being and environmental stewardship over individual convenience. In doing so, mobility networks require good databases, simulations, and digital twins of intelligent intermodal mobility networks that will guide cities and people in optimizing the interplay between mobility, flexibility, and self-determination to shape urban commuter futures.

The mobility network simulations are done in different granularity depending on the intended use. Macroscopic simulations have a variety of use cases. These include modeling traffic volumes in cities, traffic on roads, evaluating the efficiency of public transport routes, and planning public transport timetables [4]. These macroscopic simulations use, e.g., forecasting deep Artificial Neural Networks (ANNs) [5]–[7] and customized Graph Neural Networks (GNNs) [8]–[10]. On the other hand, microscopic simulations are used for traffic flow optimization [11], for the simulation of shared autonomous vehicle fleets [12], and to simulate private and public transport [13] simultaneously. These microscopic simulations are done using various traffic simulation software [14], [15] like Simulation of Urban Mobility (SUMO) [16]. By combining the microscopic simulation with live sensor data [17], digital twins or Urban Data Plattforms (UDPs) [18] are created.

Providing valuable insights for creating a digital twin of intelligent intermodal mobility networks, a workflow, visualized in Figure 1 has been developed to trigger the discussion on the best practices in the process. A traffic network must be generated as the starting point for any simulation and digital twin. Therefore, static data like site maps, satellites, aerials, and 360° video data can be used. Based upon this, dynamic travel routes and demand are created in a second step by integrating real dynamic data. This data can stem from macroscopic sensors like passive infrared sensors (PIR Sensors) or smart cameras from which microscopic route data can be computed. Additionally, accurate microscopic route data can be used from Floating Car Data (FCD) based on data donations via apps or by Automatic number-plate recognition (ANPR)-cameras. After these two steps are completed, a simulation is available, which can be evaluated and used in applications. To take the final step from a simulation towards a digital twin, real-time (RT)-sensors generating RT data transmitted via a RT network are required, resulting in a digital twin that can be used in various applications.

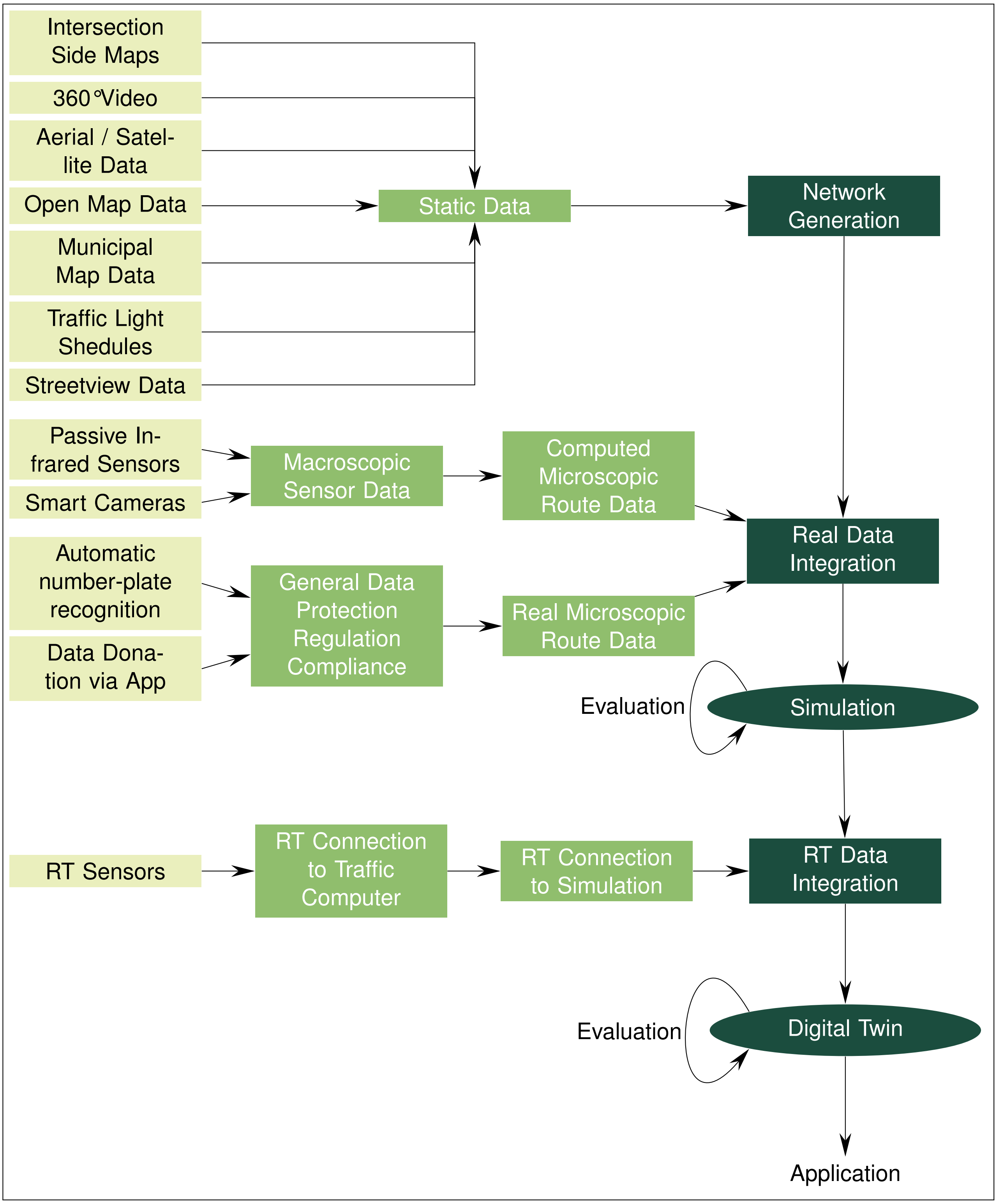

Figure 1. *Required steps to drive SUMO towards a digital twin. In the first step, network generation, static data is used to generate a SUMO network. Next, real macroscopic and microscopic data is utilized to generate routes in SUMO, allowing the simulation to be evaluated and applied. Finally, the digital twin is reached with the integration of RT data from RT sensors, modeling the research area in RT.*

After introducing the workflow on how to drive SUMO towards a digital twin in this section, Section 2 presents the ongoing realization in the city of Osnabrück by describing the existing and planned sensors and data of other sources. How this data is used to generate traffic networks and routes in SUMO is described in Section 3, followed by a discussion in Section 4 whereupon Section 5 provides an outline of future research. Finally, Section 6 states a conclusion.

2 Sensors and Data

The availability of static and dynamic data and sensors highly depends on the research location and the georeferenced freely available data. The following presents the currently available and future data for our research location in the city Osnabrück—located in Lower Saxony within Germany—and gives a brief overview of sensor and data availability in other cities.

2.1 City of Osnabrück — Research Location

The main traffic network in Osnabrück consists of an inner ring connected to an outer incomplete motorway ring with several radial routes. Both the inner ring and the outer motorway ring and these radial routes are subject to congestion and cause local NO_X and fine particulate air pollution. In 2015 main road traffic was responsible for 68% of overall NO_X-emissions in Osnabrück [19]. Moreover, both the inner ring and the radial roads can be used as alternative routes in the event of traffic jams on the motorways and motorway intersections surrounding Osnabrück. Some trucks also use these alternative routes to save on truck motorway tolls. Further, the radial roads are part of the official motorway diversions [20]. Examining the influence of this overflow traffic on the traffic and air quality in Osnabrück was also considered when selecting the routes of particular interests (RPIs).

2.1.1 Routes of Particular Interest

As shown in Figure 2, the research area is divided into RPIs. RPI A) is one of the essential radial highways into the town, connecting the city to the motorway, and is one of the hotspots regarding NO_X and fine particle air pollution [21]. RPI B) consists of two other radial highways and parts of the central city ring. This RPI is interesting because it connects the motorway in the north of the town as a through route to the motorway in the south, resulting in transit traffic through the town when parts of the motorways interchange in the west are jammed. This RPI suffers from low air quality as well [21]. RPI C) is another radial highway connecting various campuses and research institutes with downtown Osnabrück.

2.1.2 Traffic Participants

With the available sensors and data, cars and trucks can be captured. Other traffic participants like bicycles, buses, and shared mobility are not yet in the current scope. Nonetheless, additional data sources and sensors are required to capture those participants accurately. Route and delay data and bus stop information would be needed to track buses. For bicycles, existing and future sensors can be adapted. The GPS positions of the vehicles and lending stations can be captured for shared mobility. The focus of this first implementation is now on cars and trucks, which can be captured with existing and planned sensor hardware.

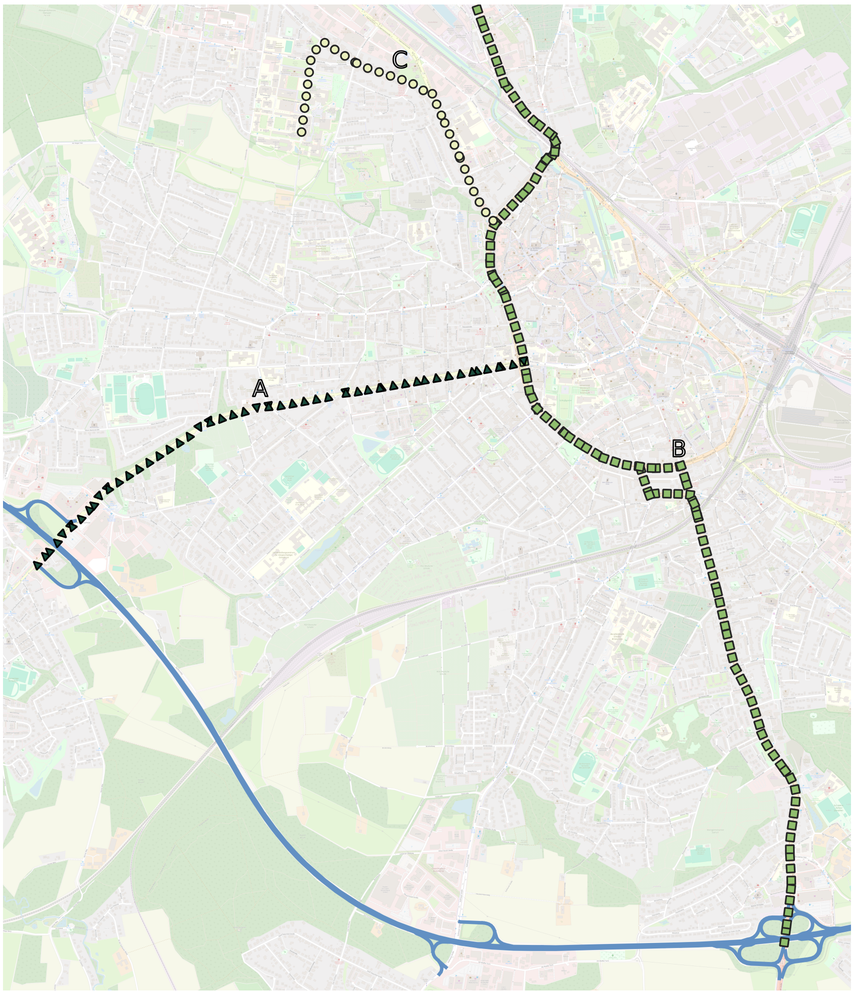

Figure 2. Overview of the research location with the three RPIs: A) in dark green triangles, B) in green rectangles, C) in light green circles, and the surrounding motorways in blue. B) connects to the motorway in the north, while Section C) connects the town center of Osnabrück to various research campuses. Map data from OpenStreetMap

2.1.3 Available Sensors and Data

A diverse set of static and dynamic data can be used. Static data is used to generate the SUMO network with the intersections and lanes, while dynamic data is used to create routes and traffic for the simulation. The following static data sources were available or generated for the research area in Osnabrück:

360° Video Data Video data is recorded for the three RPIs to have up-to-date information on the real-world situation, allowing to verify the position and type of traffic signs, construction areas, bus stops, etc. This data is georeferenced to retrieve a specific point's video data easily.

Open Map Data Data from OpenStreetMap was used and updated. New observations gained via the video recordings, official maps, and online street view data were integrated into OpenStreetMap to have an up-to-date database for SUMO integration. See Section 3.1.1.

Official Aerial Imagery of high resolution was used to gain additional information on intersections, lanes, and stop lines.

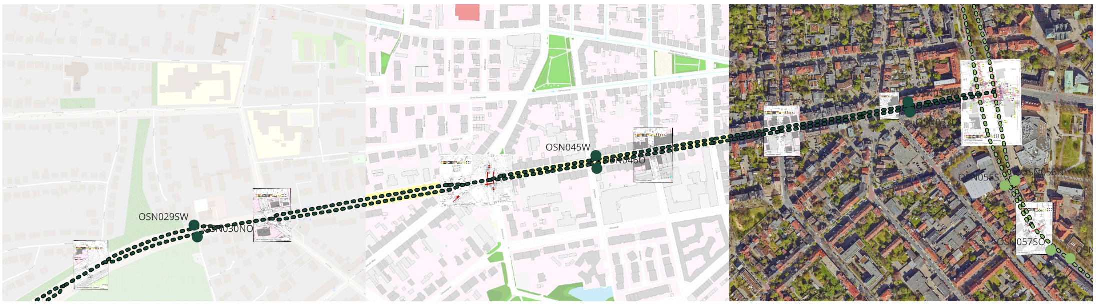

Figure 3. *Detail of Section A) with the already installed PIR Sensors measuring traffic flow and intersection side maps. Three exemplary basemaps, from left to right, OpenStreetMap data, the municipal map, and municipal aerial imagery are shown.*

Official City Map The official city map was used as an additional data source and a base map to which other data sources like intersection site maps and sensor positions were georeferenced.

Online Street View Data Google street view data was used at positions where no own 360° video data was available to allow for ground view inspection of the research area. These ground-level views were convenient for placing new sensors and cameras, which required proper mounting positions at light or traffic light posts.

Intersection Side Maps Highly detailed intersection site maps were used to link traffic light groups from traffic light schedules to the corresponding traffic light indices in SUMO. They were available as images that had to be georeferenced and integrated into our project.

Traffic Light Schedules Traffic light schedules were available in human and machine-readable formats. Various programs with defined schedules, which can be selected in the simulation, were available for each intersection.

Except for the traffic light schedules, all data was georeferenced and integrated into a Geographic Information System (GIS)-project, using QGIS [22] as open software, to profit from a fused georeferenced database. An example map extract with OpenStreetMap as a base map, intersection side maps, and sensor positions is shown in Figure 3. Next to the static data sources, passive infrared sensors (PIR Sensors) are used as dynamic data sources. PIR Sensors are stand-alone overhead detectors using passive infrared to detect and count traffic entities and measure their velocity. Following the definitions of the Forschungsgesellschaft für Straßen- und Verkehrswesen (FGSV) [23], they use the vehicle length to discriminate between the following traffic entities: cars, trucks, trucks with trailers, and undefined. For the sections of our research area, overall, 12 sensor sites are available. Two sensors are installed at each site to measure traffic in both directions. 3 sites were available for RPI A), 8 sites for RPI B), and 1 site for RPI C). The relevant PIR Sensors of RPI A) are highlighted in Figure 3 as well. Data availability of these sensors can be limited. Weather and environmental conditions can lead to short downtimes ranging from a few measurements to hours, while software or hardware errors can lead to downtimes of several months.

2.1.4 Future Sensors and Data

One of the main challenges in generating a digital twin respectively traffic simulation is to generate microscopic route data from macroscopic sensor data. While induction loops and PIR Sensors generate accurate counting data, they do not give information on the behavior of the vehicles at intersections. However, turning behavior at intersections is essential in generating realistic routes in a traffic simulation. To address this problem, other sensors specifically geared to measure the turning behavior at intersections are required. For this, smart cameras can measure how many road users turn in each direction at an intersection. In our example, cameras will be used that can detect different user types and count the number of users that turn left, right, or straight ahead. Two cameras positioned at opposite corners are required to measure all directions of an intersection completely, each looking diagonally across the intersection and measuring two of the four directions. A larger number of cameras is required for intersections with more than four possible directions. The availability of installation points, power, data connectivity, etc., also constrains camera positions. Along RPI A), two cameras are planned to be installed at each of the intersections. Next to smart cameras and PIR Sensors from which microscopic route data can be computed, real microscopic route data can also be retrieved by ANPR-cameras or by data donation via apps while taking General Data Protection Regulation (GDPR)-compliance into account.

2.2 Other Cities

The amount of available traffic sensors differs vastly between cities worldwide. While some cities have a dense sensor network measuring many traffic parameters and are well underway in creating a digital twin of their traffic network, other cities are still in the process of building up such a sensor network and starting the process of a digital twin. To name two examples from opposite ends of the scale: in Munich, a small test area with eight signaled intersections, only a few induction loop sensors were available, and from these sensors, only little data is created – to be specific, two induction sensors with data from all inflows as well as two induction loop sensors with data from some inflows [17]. On the other side of the scale, in Kyoto, the number and the data quality of the sensors were much higher, with 1100 sensors measuring in 5 minute intervals overall, resulting in 451 sensors along the research area available for route generation of private transport vehicles [13].

The same holds for the available traffic data and data sets. Live data is, in most cases, not freely available. Data sets may be relatively small, ranging only a limited timeframe, and the temporal and spatial resolution may also be limited. Ideally, both live data and large data sets ranging several years into the past measuring historical data are available. Moreover, data quality should be high, meaning temporal-spatial resolution, while errors like defect sensors, etc., should be low.

3 SUMO Integration

Driving SUMO toward digital twins, both static and dynamic data is needed.

3.1 Static Data

Static data, which does not change rapidly and does not depend on a single commuter, are maps, videos, images, traffic signs, special lanes, traffic light schedules, and road tolls. Since there are no road tolls and special lanes on the RPI, only maps, videos, images, and traffic light schedules are considered here.

3.1.1 Site Maps and Open Street Map Data

Various sensors and data sources are fused to generate an accurate and up-to-date network in SUMO. To begin, 360° video recordings, municipal maps, municipal aerial imagery, satellite imagery, and street view imagery are used to validate the map data of OpenStreetMap (OSM). Next, errors and inaccuracies in OSM are fixed directly in OSM with Java OpenStreetMap Editor (JOSM), taking road types, lanes, turning options, speed limits, right-of-way systems and precise placing of traffic lights into account. Fixing and updating OSM directly allows the reuse of the corrected data for other projects and users. The updated map data is then exported and converted via *netconvert* to a SUMO network. In the second iteration, map errors, now visible in SUMO, are again fixed in OSM. Again, the network is downloaded, and the last corrections and validations are carried out with *netedit*, whereby it should be noted that *netconvert* occasionally makes its assumptions about lanes, turning options, and right-of-way systems, which need to be corrected afterwards. More precisely, if there is an odd number of tracks for a connection, netconvert does not use the specified number for the respective direction and ignores it.

3.1.2 Traffic Light Schedules

While *netconvert* automatically calculates programs for the traffic lights, they do not model real traffic light programs and the switches between different programs. To address this, for each intersection, the actual traffic light programs available in Open Communication Interfaces for Road Traffic Control Systems (OCIT)-format are combined with the intersection maps to assign lanes to the corresponding traffic lights. This updated OCIT file can then be used in *Ocit2Sumo* to generate an Extensible Markup Language (XML)-file for SUMO simulation. *Ocit2Sumo* then generates four different traffic light schedules for most intersections of the research area, whereas the automatic program change included in the OCIT is ignored. The corresponding XML-file is then included in the simulation. The programs can be later selected depending on the simulated situation or in case of the real-time digital twin mirror the current actual program.

3.2 Dynamic Data

Dynamic data results from the interplay of commuters, traffic, and means of transport in the intermodal transportation network. Thus, it must be captured or generated by sensors, donated data, simulations, and forecasts.

3.2.1 Data Flow

In Osnabrück sensor data is transmitted via a closed network to the traffic control computer. From there, it is transferred into a spatiotemporal database. Currently, the data in the spatiotemporal database encompasses around 65 sensors spanning over 20 months with a temporal resolution of 5 minutes. It is planned to update the database regularly, possibly in real-time. The data from this database can then be used for SUMO route generation and other applications. Since the database also contains the traffic light program for each measuring interval, it can be combined with the traffic light schedules to simulate the traffic lights in SUMO correctly.

3.2.2 Route Generation

In the first implementation, only counting data from PIR Sensors is used to generate routes in SUMO. This data for a specific simulated situation is obtained from the previously mentioned spatiotemporal database. In a first step the data is preprocessed.

Outliers are detected and it is checked whether data is available from all selected sensors for the selected situation and timeframe. If only few data points are missing, they can be interpolated if sensors are completely or partially defect they have to be either excluded or if to many sensors are without data only other timeframes or situations can be simulated. After scaling the data to the correct unit, the sensors positions have to be assigned to the correct lanes in the SUMO traffic network, taking into account that sensors measure not single lanes but directions. The data, including speed and number of vehicles for both cars and trucks in 5 minute intervals for each sensor position is then saved in a format from which SUMO scripts can compute traffic demands.

In the future turning behavior measured by smart cameras positioned at intersections can also be used, supplementing the traffic count and speed measured by PIR Sensors by turning behavior of various road user types. Thus, two approaches to route generation in SUMO can be implemented, combined, and compared.

3.2.3 Evaluation of demand modeling and route generation

To preliminary gauge the accuracy of the demand modeling and route generation in SUMO, the Level of Service (LOS)-data computed from the simulation can be compared with the real-world LOS-data measured in the same time interval as the sensor data used to model the demand in the simulation. LOS uses an ordinal scale ranging from A to F to assess the traffic flow quality, with A corresponding to free flow and F corresponding to breakdown flow with higher demand than capacity [24]. For Germany, the six distinct levels of LOS, named Qualitätsstufen des Verkehrsablaufs (QSV), are defined by the FGSV ranging from A, the individual movement of traffic participants is not compromised / free traffic flow to F, the individual movement of traffic participants is always compromised / the functionality is no longer given [23].

4 Discussion

One of the main challenges in creating digital twins is data availability and accessibility. This challenge of data availability and accessibility is also the case here: Availability of static data is good in most cases. Aerial, satellite, and map data is freely available to the public. Municipal maps and intersection site maps are available from the city. However, they are not always geo-referenced, digitalized, and unavailable to the general public. 360° video recordings and street view data are either available or can be recorded relatively cheaply by the authorities. Traffic light programs, however, are problematic to obtain. They are neither available to the general public nor in a format automatically transferable into SUMO; usually, they are available in a proprietary format and are withheld from the public as important infrastructure information. While the automatically generated traffic lights programs by SUMO can be used, higher simulation accuracy is achieved with the real traffic light programs, especially if they are combined with the real-time information on which program is currently active.

On the other hand, dynamic data is challenging to obtain. Either the number of available sensors is limited, or the data quality of the sensors is low or unsuitable for this use case. Further, connectivity between the sensors and the SUMO simulation is required for the digital twin real-time connectivity. While additional sensors can be installed in the research area, this is cost-intensive and involves a large number of participants like authorities, researchers, city officials, hardware and software providers, etc. Almost all available and installed sensors record macroscopic data like average speeds or traffic counts from which microscopic demand models have to be computed. An alternative are ANPR-cameras measuring and tracking individual vehicles through the research area. However, a large number of these cameras are required to track individuals accurately. Moreover, only traffic participants with number plates can be tracked, excluding bicycles and pedestrians. An alternative to these ANPR-cameras are data donations from traffic and navigation app users. To generate a significant amount of data, however, these apps have to be used by a larger group of people for a more extended amount of time, requiring that the apps offer a suitable added value for the user to encourage them to keep these apps running and provide the data. Additionally, both ANPR-cameras and data donations must comply with general data protection regulations, requiring anonymization in one form or another.

Insufficient data availability can be caused not only by missing or inaccurate sensor data but also by missing geoinformation and digitization. While much data can be available in an analog non-geo-referenced form to use this data for a digital twin, much manual work is required for digitization and georeferencing. While multimodal image registration techniques similar to the ones used in rephotography [25] can be applied to align the various data sources, manual interaction is still required for georeferencing. Missing metadata, especially for proprietary hardware and software, can also be an issue. This issue is especially true if sensor data is used outside a proprietary municipal traffic computer with open-source tools like SUMO. While integrating sensor data into the traffic computer is good, incorporating the raw sensor data into external research databases can be challenging, requiring reverse engineering of naming schemes, data formats, unit types, etc.

Nonetheless, data fusion has not only a positive impact on the creation of a digital twin but also directly and indirectly via digital twins on other applications like traffic planning. These impacts are valid for both static and dynamic data. Combining static data from the town, the municipal works, and the private sector with own research data and open map data allows, e.g., for the update of open maps or the better planning of future sensor locations. Combining dynamic data like traffic information from the town, local public transport information from the municipal works, and shared mobility information from the private sector allows for intermodal route planning and demand analysis. Thus, while data availability is a challenge, addressing this challenge is highly rewarding.

5 Future Research

The first aspect of future research will be the deployment and integration of the smart cameras into the simulation. This next step encompasses finding suitable sensor locations, installing the sensors, and integrating the sensors into the existing network of both the town and our research network, as well as implementing demand modeling methods, taking this turning behavior information into account. Next, a comparison can be carried out, examining the influence of the additional turning behavior information provided by smart cameras with respect to the simulation accuracy.

One of the main aspects of future research will be integrating simulation results into the real traffic network. Simulation and prediction results will be provided to the public as part of the research project. Allowing, e.g., commuters to plan and adapt their route according to the simulated traffic situation. An intermodal traffic recommendation system is also possible, depending on the number of simulated traffic entities.

These intermodal traffic recommendations can be used to incentivize data donations to get additional data sources for direct microscopic data in return. Simulation results can also be used to choose the most suitable traffic light program. Allowing to act with foresight and not to react to the measured traffic at a particular intersection, the estimated traffic at a prior intersection adapts the traffic light program to the expected traffic proactively.

6 Conclusion

This research demonstrates the intricate process of developing a digital twin via SUMO, using the city of Osnabrück as a case study. The journey from conception to execution involves gathering and synthesizing both static and dynamic data to recreate both an accurate traffic network and demand models. Static data sources include diverse inputs like intersection layouts, 360° video recordings, aerial and satellite imagery, and municipal as well as open mapping data, all contributing to the foundational traffic network model. Transitioning from static to dynamic sources, this study proposes to use real-time data from PIR Sensors, smart cameras, ANPR-cameras, and voluntary data contributions through mobile apps to model traffic demand and routing behaviors. This incorporation of real-time data, in compliance with privacy laws such as the GDPR, is crucial for simulating realistic traffic flows and interactions.

The motivation of creating a digital twin, shown in Figure 1, lies in its ability to simulate and predict the interplay between various urban mobility participants under changing commuter incentives. The simulation must integrate RT data for meaningful applications, facilitating dynamic adjustments within the digital twin to reflect current urban conditions. This real-time integration bridges the gap between static planning and dynamic urban mobility management, enabling applications ranging from intermodal transit recommendations to adaptive traffic control measures.

Conclusively, constructing an operational digital twin demands comprehensive efforts in data collection, data fusion and processing, sensor deployment, system integration, and the processing of data from macroscopic observations to microscopic traffic modeling. Future advancements should focus on enhancing sensor and data availability as well as real-time capabilities, ensuring digital twins can more effectively inform urban mobility strategies. These endeavors pave the way for innovative applications, including intermodal traffic recommendations and adaptive traffic regulations, and are a basis for transforming urban spaces into more livable, sustainable, and people-focused environments.

Funding

This project has received funding from the Federal Ministry of Education and Research (BMBF) programme ”Forschungsnetzwerk Anonymisierung für eine sichere Datennutzung” under grant agreement No 16KISA120.

Acknowledgments

We would like to thank all internal and external project partners of ”Intelligenter Intermodaler Pendlerverkehr” for their tireless support and cooperation. Their expertise, insights, discussions, and commitment are invaluable.

References

[1] D. Shoup, *High cost of free parking*. Abingdon-on-Thames, UK: Routledge, 2021. DOI: 10.4324/9781351179539.

[2] eurostat, "Passenger mobility statistics," Nov. 2021, [Online; accessed 16. Feb. 2024], ISSN: 2443-8219. [Online]. Available: https://ec.europa.eu/eurostat/statistics-explained/index.php?oldid=479608.

[3] J. Scudellari, L. Staricco, and E. Vitale Brovarone, "Implementing the supermanzana approach in barcelona. critical issues at local and urban level," *Journal of Urban Design*, vol. 25, no. 6, pp. 675–696, 2020. DOI: 10.1080/13574809.2019.1625706.

[4] S. Dorokhin, A. Artemov, D. Likhachev, A. Novikov, and E. Starkov, "Traffic simulation: An analytical review," in *IOP Conference Series: Materials Science and Engineering*, IOP Publishing, vol. 918, 2020, p. 012 058. DOI: 10.1088/1757-899X/918/1/012058.

[5] X. Yin, G. Wu, J. Wei, Y. Shen, H. Qi, and B. Yin, "Deep learning on traffic prediction: Methods, analysis, and future directions," *IEEE Transactions on Intelligent Transportation Systems*, vol. 23, no. 6, pp. 4927–4943, 2022. DOI: 10.1109/TITS.2021.3054840.

[6] H. Nguyen, L.-M. Kieu, T. Wen, and C. Cai, "Deep learning methods in transportation domain: A review," *IET Intelligent Transport Systems*, vol. 12, no. 9, pp. 998–1004, 2018. DOI: 10.1049/iet-its.2018.0064.

[7] I. Laña, J. Del Ser, M. Velez, and E. I. Vlahogianni, "Road traffic forecasting: Recent advances and new challenges," *IEEE Intelligent Transportation Systems Magazine*, vol. 10, no. 4, pp. 28–41, 2018. DOI: 10.1109/MITS.2018.2806634.

[8] K.-H. N. Bui, J. Cho, and H. Yi, "Spatial-temporal graph neural network for traffic forecasting: An overview and open research issues," *Applied Intelligence*, vol. 52, pp. 2763–2774, 2021. DOI: 10.1007/s10489-021-02587-w.

[9] W. Jiang and J. Luo, "Graph neural network for traffic forecasting: A survey," *Expert Systems with Applications*, vol. 207, p. 117 921, 2022. DOI: 10.1016/j.eswa.2022.117921.

[10] M. Li and Z. Zhu, "Spatial-temporal fusion graph neural networks for traffic flow forecasting," in *Proceedings of the Thirty-Fifth AAAI Conference on Artificial Intelligence*, AAAI Press, 2021, pp. 4189–4196. DOI: 10.1609/aaai.v35i5.16542.

[11] I. Trautwein, A. Freymann, E. Reichsoellner, J. S. Kraus, and T. Schrodi, "A Technical Concept for sensor-based Traffic Flow Optimization on connected real-world intersections via a SUMO Feature Gap Analysis," *SUMO Conference Proceedings*, vol. 4, Jun. 2023, ISSN: 2750-4425. DOI: 10.52825/scp.v4i.218.

[12] E. Reichsöllner, A. Freymann, M. Sonntag, and I. Trautwein, "SUMO4AV: An Environment to Simulate Scenarios for Shared Autonomous Vehicle Fleets with SUMO Based on OpenStreetMap Data," *SUMO Conference Proceedings*, vol. 3, pp. 83–94, Sep. 2022, ISSN: 2750-4425. DOI: 10.52825/scp.v3i.113.

[13] A. Keler, W. Sun, and J.-D. Schmöcker, "Generating and Calibrating a Microscopic Traffic Flow Simulation Network of Kyoto: First Insights from Simulating Private and Public Transport," *SUMO Conference Proceedings*, vol. 4, Jun. 2023, ISSN: 2750-4425. DOI: 10.52825/scp.v4i.226.

[14] M. R. Ullah, K. S. Khattak, Z. H. Khan, M. A. Khan, N. Minallah, and A. N. Khan, "Vehicular traffic simulation software: A systematic comparative analysis," *Pakistan Journal of Engineering and Technology*, vol. 4, no. 1, pp. 66–78, 2021. DOI: 10.51846/vol4iss1pp66-78.

[15] T. Alghamdi, S. Mostafi, G. Abdelkader, and K. Elgazzar, "A Comparative Study on Traffic Modeling Techniques for Predicting and Simulating Traffic Behavior," *Future Internet*, vol. 14, no. 10, p. 294, Oct. 2022, ISSN: 1999-5903. DOI: 10.3390/fi14100294.

[16] P. Alvarez Lopez, M. Behrisch, L. Bieker-Walz, *et al.*, "Microscopic traffic simulation using sumo," in *2019 IEEE Intelligent Transportation Systems Conference (ITSC)*, IEEE, Nov. 2018, pp. 2575–2582. DOI: 10.1109/ITSC.2018.8569938.

[17] A. Keler, A. Kunz, S. Amini, and K. Bogenberger, "Calibration of a Microscopic Traffic Simulation in an Urban Scenario Using Loop Detector Data: A Case Study within the Digital Twin Munich," *SUMO Conference Proceedings*, vol. 4, Jun. 2023, ISSN: 2750-4425. DOI: 10.52825/scp.v4i.223.

[18] *DIN SPEC 91357: Referenzarchitekturmodell Offene Urbane Plattform (OUP)*, Deutsches Institut für Normung (DIN), 2017-12.

[19] LK Argus Kassel GmbH, "Luftreinhalte- und Aktionsplan Stadt Osnabrück 2008, 2. Aktualisierung 2017," Stadt Osnabrück, Fachbereich Umwelt und Klimaschutz, Tech. Rep., 2018. [Online]. Available: https://nachhaltig.osnabrueck.de/fileadmin/nachhaltig/Dokumente/LRP_Osnabrueck_Aktualisierung_2017_Bericht_Nov2018.pdf.

[20] Stadt Osnabrück, *Autobahnumleitungen (BAB-Umleitungen) in der Stadt Osnabrück*, 2014. [Online]. Available: https://geoportal.geodaten.niedersachsen.de/harvest/srv/api/records/4826693c-336c-4488-bbc7-776fa7fb01b6.

[21] Zentrale Unterstützungsstelle – Luftreinhaltung, Lärm und Gefahrstoffe, "Modellgestützte Voruntersuchungen zur Fortschreibung des Luftreinhalteplanes im Rahmen der NO2-Notifizierung," Staatliches Gewerbeaufsichtsamt Hildesheim, Tech. Rep., 2015. [Online]. Available: https://www.umwelt.niedersachsen.de/download/7280/Modellgestuetzte_Voruntersuchungen_zur_Fortschreibung_des_Luftreinhalteplanes_im_Rahmen_der_NO2-Notifizierung_Sept._2011.pdf.

[22] QGIS Development Team, *Qgis geographic information system*, Open Source Geospatial Foundation, 2009. [Online]. Available: http://qgis.org.

[23] *Begriffsbestimmungen – Teil: Verkehrsplanung, Straßenentwurf und Straßenbetrieb*, Forschungsgesellschaft für Straßen- und Verkehrswesen e. V. (FGSV), 2012.

[24] M. Treiber and A. Kesting, *Traffic Flow Dynamics*. Berlin, Germany: Springer, 2013, ISBN: 978-3-642-32460-4. DOI: 10.1007/978-3-642-32460-4.

[25] A. Schaffland and G. Heidemann, "Heritage and repeat photography: Techniques, management, applications, and publications," *Heritage*, vol. 5, no. 4, pp. 4267–4305, 2022. DOI: 10.3390/heritage5040220.