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A digital twin in transportation: Real-time synergy of traffic data streams and simulation for virtualizing motorway dynamics

Krešimir Kušić [a,b,*], René Schumann [a], Edouard Ivanjko [b]

[a] Smart Infrastructure Laboratory, University of Applied Sciences and Arts Western Switzerland Valais/Wallis (HES-SO), Techno-Pôle 3, Sierre 3960, Switzerland
[b] Faculty of Transport and Traffic Sciences, University of Zagreb, Vukelićeva Street 4, Zagreb 10000, Croatia

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ABSTRACT

The introduction of digital twins is expected to fundamentally change the technology in transportation systems, as they appear to be a compelling concept for monitoring the entire life cycle of the transport system. The advent of widespread information technology, particularly the availability of real-time traffic data, provides the foundation for supplementing predominated (offline) microscopic simulation approaches with actual data to create a detailed real-time digital representation of the physical traffic. However, the use of actual traffic data in real-time motorway analysis has not yet been explored. The reason is that there are no supporting models and the applicability of real-time data in the context of microscopic simulations has yet to be recognized. Thus, this article focuses on microscopic motorway simulation with real-time data integration during system run-time. As a result, we propose a novel paradigm in motorway traffic modeling and demonstrate it using the continuously synchronized digital twin model of the Geneva motorway (DT-GM). We analyze the application of the microscopic simulator SUMO in modeling and simulating on-the-fly synchronized digital replicas of real traffic by leveraging fine-grained actual traffic data streams from motorway traffic counters as input to DT-GM. Thus, the detailed methodological process of developing DT-GM is presented, highlighting the calibration features of SUMO that enable (dynamic) continuous calibration of running simulation scenarios. By doing so, the actual traffic data are directly fused into the running DT-GM every minute so that DT-GM is continuously calibrated as the physical equivalent changes. Accordingly, DT-GM raises a technology dimension in motorway traffic simulation to the next level by enabling simulation-based control optimization during system run-time that was previously unattainable. It, thus, forms the foundation for further evolution of real-time predictive analytics as support for safety–critical decisions in traffic management. Simulation results provide a solid basis for the future real-time analysis of an extended Swiss motorway network.

1. Introduction

Motorway systems, have become increasingly smart in recent decades, mainly based on the foundation of data collected by roadside sensors and the vehicles themselves, and the application of advanced traffic control approaches. These data enable services like real-time monitoring of the transportation system, and in general, the digitization of the transportation system, providing many benefits to travelers and operations centers [10]. With this information, operators (or autonomous road transportation support [36] can deploy Intelligent Transportation Systems (ITS) services and apply Traffic Management (TM) approaches (control strategies) to improve traffic flows [27]. However, the impact of the control strategies on the motorway system is not apparent until they are deployed in real world motorway applications. Due to the high speeds on motorways, inappropriate TM strategies placed wrongly in space and time can pose a serious threat to motorway safety and operations [46].

Nevertheless, control strategies and their impact on traffic can be analyzed in various traffic simulators with the numerous models at the microscopic and macroscopic levels [29]. Despite their widespread use, up to today's traffic simulations have mainly been used for (offline) verification, validation, and optimization of proposed traffic solutions and a system design in the early planning phase. Such an approach enables safety analyzes and control strategies design in their early

* Corresponding author at: Smart Infrastructure Laboratory, University of Applied Sciences and Arts Western Switzerland Valais/Wallis (HES-SO), Techno-Pôle 3, Sierre 3960, Switzerland

E-mail addresses: kresimir.kusic@fpz.unizg.hr (K. Kušić), rene.schumann@hes-so.ch (R. Schumann), edouard.ivanjko@fpz.unizg.hr (E. Ivanjko).

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planning phase. However, it is necessary to gain confidence in the control system's performance also in unforeseen (unexpected) traffic situations. Having a control strategy that performs well in all relevant traffic states (generalization) is often more important than superior performance in some states, but in general, this is hard to achieve in a stochastic dynamic system (like a motorway with its corresponding complex, non-linear traffic dynamics) in which the state changes with time randomly. Traffic control systems must, therefore, adapt to traffic demand that varies significantly in time and space. The real-time tuning of such systems becomes infeasible to a human operator and the prevailing offline simulation approaches unsuitable, making tool support essential.

Meanwhile, the enormous potential of information technologies in road transportation enables real-time fusion of physical road system and the digital world (simulations) in traffic modeling and analysis [22], [9], [1]. In general, such integration is referred to as the Digital Twin (DT) concept, which considers a fusion of the virtual (digital) and the physical world systems or processes [45]. As such, the applications of DT offer a promising way to address the growing complexity of transportation systems through the concept of monitoring their entire life cycle. *Continuously synchronized* DT model with its physical counterpart enables real-time bidirectional interaction between the physical system and corresponding digital replica in the early stages of design, construction, reconstruction, traffic planning or control, and various other analysis purposes. The DT has shown considerable potential in several areas and is attracting considerable interest from industry and academia [24].

However, the strategic advantage of this integration has yet to be exploited in the motorway domain. Motivated by the aforementioned predominance of traditional (offline) simulation approaches, we decided to explore the possibilities of integrating the Simulator of Urban Mobility (SUMO) [25] and newly available real-time motorway traffic data from the Open Data Platform Mobility Switzerland (ODPMS) [30], which allows us to pay attention to the simulation application during motorway system run-time.

Thus, in this paper, we propose a run-time synchronized DT of the Geneva motorway (DT-GM). Compared to the existing literature on DT in road traffic applications in general, the novelty of our approach is the use of fine-grained traffic data streams coming directly (in real-time) from motorway traffic counters. The traffic data are recorded by the traffic counters on the motorways and sent to the Swiss Federal Roads Office (FEDRO) servers in real-time. These actual traffic data (in minute resolution) are now available in real-time via ODPMS, the customer information platform for public transport and individual mobility in Switzerland. Thus, the number of passing vehicles, their speeds and vehicle category are continuously fed into the running simulation through the SUMO's Traffic Control Interface (TraCI). TraCI provides access to a running road traffic simulation and allows for retrieving values from simulated objects and manipulating their behavior during simulation run-time [44]. To the best of our knowledge, there is no research on simulating dynamic motorway flows in SUMO, so we consider our research as a novelty in this field. In particular, we leverage the capabilities of SUMO *calibrators* objects to make the traffic demand within the running simulation scenario adjustable (controllable) via TraCI and highlight the importance of these objects in creating our synchronized DT-GM. In addition, based on calibrators, we propose the Dynamic Flow Calibrator (DFC) mechanism that continuously calibrates traffic flows and re-routes vehicles in the running simulation so that our *continuously synchronized* microscopic simulation-based motorway DT is updated (in a spatio-temporal manner) as the physical motorway traffic change in the areas of installed traffic counters. This brings DT-GM closer to the actual dynamics of the Geneva motorway, as it continuously adapts itself in real-time to changes in the physical motorway dynamics. Moreover, the behavior of a random system is governed by one or more random variables. Knowledge of the distributions of these random variables is required to simulate the behavior of the system properly [12]. Fortunately, access to fine-grained real-time traffic data allows DT-GM to extract three types of random variables that govern traffic flow directly from the real motorway system (traffic volumes, speeds, and vehicle classes) by using the near-instantaneous probability distribution (the *natural distribution*, so to speak) instead of an estimated distribution. Ideally, we would use the traffic counter information about the presence of vehicles (event-based data) for each simulation step, but with the minute resolution we get very close to the real distribution of traffic flow. By doing so, DT-GM creates the calibrated simulation frames (nearly exact replicas of real traffic) along the *live* simulation path.

Since DT-GM is based on microscopic simulation, it allows the simulation of the entire motorway system (traffic dynamics and traffic control strategies). Moreover, since it takes into account actual real-time traffic data, DT-GM can be integrated into the decision-making process in TM on motorways. Thus, DT-GM can serve as additional real-time feedback to TM, providing not only actual traffic, but, also traffic conditions predicted by simulations in a safety–critical decision-making process. Consequently, a better understanding of traffic behavior and the impact of different control strategies on the spatio-temporal evolution of traffic can be predicted clearly enough in advance through the detailed microscopic run-time simulation analysis before the control strategies are deployed in the real system.

In this way, DT-GM provides a foundation for strategic TM [21], an approach to ensure overall system performance by confidently selecting the overall good strategy among several competing strategies. This implies assessing of control strategies in an online yet safely manner by using parallel Digital Twin Instances (DTI) initialized from running DT-GM. Such a concept (DTI-GM) may encourage the integration of advanced (*adaptive*) control technologies like complex machine-learning models [36],37,41] in real-time TM, thus, pushing the new (*black box* machine learning) algorithms closer to the real application on motorways.

This fundamentally changes the paradigm of traffic simulations in general, hence, it makes preparation for the development of the *continuously synchronized* simulations providing a run-time framework for real-time safety analysis, rather than the so far applied offline approach in predominated traditional simulation approaches. In the scope of this, we presented a conceptual application of DT-GM in real-time TM on motorways regarding the variable speed limit deployment.

To sum up, this article provides detailed methodological steps for the integration of different technologies in developing of DT-GM, particularly the open data platform ODPMS and simulator SUMO and presents the possible conceptual applications of DT-GM in motorway traffic control. Additionally, our DT-GM model differs from other introduced DT traffic models in the sense, that it is a run-time calibrated digital microscopic simulation model continuously updated with actual high-resolution traffic data collected directly from motorway traffic counters every minute. This makes it possible not only to visualize actual traffic in real-time, but also to simulate traffic during run-time and use simulation models for detailed traffic forecasts and early detection of traffic anomalies. In addition, simulation enables the testing of control strategies (e.g., variable speed limits on motorways). Thus, DT enables the run-time safe testing of control strategies considering the current traffic situation in the most cost-effective way.

This allows for using traffic simulations for dynamic control optimization and instantaneous traffic analytics during system run-time, thus, providing a framework for an early warning detection on a system (or process) failure. This was not feasible in the past, when simulations were generally considered synonymous with offline validation and optimization using historical or artificial data. As such, DT-GM raises the current simulations' capability to the next level and lays the foundation for further research on DT in the transport domain, developing a simulation technology on motorways that can be fused together with real-time measurements from motorways' sensors or with the Internet of Things (IoT) in general. As well, to encourage the further provision of the use of traffic simulator SUMO for modeling run-time traffic systems in general, we make our DT-GM model with source code publicly available[1] to serve as a basis for further investigation by the community.

Therefore, the contribution of our study includes:

- Novel paradigm in microscopic simulation traffic modeling, a virtual microscopic simulation-based DT instance of the physical Geneva motorway continuously calibrated as real traffic changes over time.
- Reveals the importance of open, real-time mobility data in advancing and promoting DT in transportation, emphasizing fine-grained actual traffic data streams from traffic counters provided by ODPMS.
- The detailed methodological process of the development of DT-GM emphasizing the calibration features of SUMO, which allow (dynamic) continuous calibration of the running simulation scenario via DFC.
- Real-time simulation-based support in safety–critical decision-making in transportation systems based on predictive analytics through the concept of parallel DT instances.

The structure of this article is organized as follows: Section II discusses related work in the area of DT application in transportation systems. Section III introduces the methodology and microscopic simulation-based DT design for motorways. Section IV provides insight into the modeling of DT using actual traffic data streams generated by traffic counters from the Geneva motorway, hence, describes the simulation setup, and Section VI delivers the results and analysis of our experiments. The discussion can be found in Section VII. Section VIII summarizes our results with conclusions.

2. Related work

It has been demonstrated that microscopic simulation models provide a high level of detail in terms of interactions between vehicles and network modeling (which makes them more computationally intensive) [6]. Nevertheless, as such, they can be used for in-depth analysis of smaller traffic networks or isolated sub-networks such as motorways [13], to analyze advanced traffic control approaches [5,19,46], or to analyze, for example, the energy consumption of electric vehicles [17]. Also, simulators can be used as a basis for testing new traffic simulation models, e.g., a lane-free traffic model targeting Connected Automated Vehicles (CAV) built on the existing SUMO simulation infrastructure [39]. Or for a more general simulation analysis of different CAV penetration levels and their impact on the traffic system [13]. Moreover, calibrated microscopic simulation allows for very realistic traffic simulations that closely resemble reality. This makes such models attractive, because given current traffic conditions and appropriate simulation parameters, they can be used for traffic forecasting. In a microscopic simulation model, actual vehicle and traffic dynamics can be simulated and visualized in real-time. This feature makes it possible to introduce the concept of DT into traffic modeling. As mentioned in Section 1, DT represents a virtual instance of a physical system that is continuously updated with performance, maintenance, and health status data throughout the lifecycle of the physical system [26], [24]. In essence, Big Data, the floating car data, wireless sensor networks, GPS tracking, traffic counters, etc., are rapidly evolving and offer great potential for the development of DT in the transportation sector [38]. However, the time component of the data plays an important role in the creation of run-time DT, i.e., data need to be available in *near real-time* to be integrated in a timely fashion into the simulation model. Thus, it is important to ensure real-time data transmission for run-time synchronization of DT with real traffic.

Since real-time transmission of high resolution traffic data is still in its infancy, it is the bottleneck in the development of *continuously synchronized* DTs and their use in traffic analysis. However, several research studies have used microscopic traffic simulations to model the accurate digital replicas of physical traffic systems with some delay (remarkable latency) and low resolution of the traffic data used. Consequently, several articles [32], [1], [9] have used DT terminology in the context of traffic simulation modeling using a more (*traditional*) offline simulation approach. They emphasized the use of real, yet historical, traffic data regarding the notable latency in modeling realistic traffic models. In this context, the aggregated historical traffic data were down-scaled to finer data resolution (depending on the purpose of the analysis) by using an estimated probability distribution of random traffic variables like flows, trips, vehicle arrivals, speeds, etc.

Although the prevailing microscopic simulation models appear to be a potent tool that can be used at any stage of transportation system design, planning, or testing of control solutions [7], [28], they lack the ability to be used in the real-time safety–critical decision making process in TM because they are calibrated offline and do not account for actual traffic. As a result, offline simulation approaches (based on historical or artificial data) are useful in transportation planning if analytical changes in traffic flow patterns are related to long-term changes in infrastructure, traffic demand, mode choice distribution, etc. In contrast, unexpected events that are likely to occur in reality may not be captured by simulated artificial results due to their inherent characteristics. Thus, using actual run-time traffic data in simulations allows for capturing and predicting such events. In addition, real-time data combined with simulations enable powerful mathematical simulation models to visualize, analyze, interpret, predict, and optimize traffic. Such real-time predictive analytics is essential for real-time TM and proactive decision-making. Therefore, it may be useful to continuously use fine-grained real-time traffic data (if available) as input to the simulation so that the simulation model can evolve (calibrate itself online) as motorway traffic evolves. In this way, the physical transport system with its corresponding traffic sensors can be used in combination with the run-time simulation model to provide a more accurate digital replica of real traffic and to see if it is possible to predict traffic failures clearly enough in advance so that preventive measures can be taken. This gives the DT simulations a foundation as they can be used as additional support in real-time TM while raising questions about whether such data could improve the simulations themselves, what benefits such live simulation models might have, and to what extent compared to traditional offline simulations.

Inherently, the integration of DT technologies and the real world motorway system offer the ability to augment the existing motorway performance monitoring systems with the digital virtual instance so that the created DT simulation can be updated in near real-time as the physical motorway equivalents change. As such, DT could play an important role in TM by allowing the virtual model to interact bidirectionally with the physical entity in real-time [24]. This is conceptualized in Section 3 using the example of DT application for monitoring and controlling motorway speed limits.

From the perspective of a microscopic simulation-based DT traffic model (running in real-time and corresponding to real traffic), the evolution of spatial and temporal traffic characteristics can be predicted from a respective moment forward, taking into account the current state of traffic. Initializing from that particular state, several parallel simulations from the running DT simulation can provide a basis for traffic forecasts. Thus, each of these simulations can serve as a test environment to evaluate different strategies and finally identify potential traffic problems before they occur. In this way, failures can be avoided, and future actions can be planned while reducing uncertainties about the system's response [45]. However, neither the development of the DT for motorway traffic nor the strategic advantage of the conceptual application of DT with TM on motorways has yet been fully realized. In continuation, we summarize the findings of other researchers related to microscopic simulation modeling and concepts that point to the definition of DT in transportation in general.

[1] https://sumo.dlr.de/docs/Data/Scenarios.html.

In [32], an application of SUMO microscopic simulation was presented in the application of ITS Austria West. Aggregated vehicle loop sensors and floating car data were used together with an origin–destination (OD) matrix based on historical traffic data from the road network of Upper Austria to generate routes that were used in a microscopic simulation to generate traffic demand. The simulation model was used for five-minute traffic simulations (short-term forecasts) to calculate the new traffic state from a given current state. The traffic condition at the end of each period is integrated with the newly obtained traffic data. These integrated data were used to create snapshots of the calculated Level-of-Service (LoS) information used by the services from ITS. Finally, the simulation scenario is adjusted using the aggregated real-time network sensor data along with the route distribution based on the estimated OD. The updated scenario is then used as the basis for the next short-term estimate of traffic conditions.

In view of the next generation of ITS, a concept for a virtual vehicle model was presented in [18]. The goal of this concept is to use vehicle and traffic information via edge clouds and specific analytics (deep machine learning algorithms) to predict driver intention. Information about the driver is taken into accounts, such as preferences, which lane the driver or automated vehicle is likely to choose, and route plans. The intent is then used by the Virtual Vehicle (VV) to compute interactions with other vehicles within the DT model, with the goal of finding the best routing through the network to reduce congestion. Yet, this is a more conceptual approach at the moment and will be more favorable in the vehicle-to-everything communication environment in the future [3].

The article [9] presents a proof-of-concept application of DT for Adaptive Traffic Signal Control (ATSC). The control algorithm aims to distribute the waiting time over a network of signalized intersections instead of loading a single intersection. Although the use of real-time data was emphasized, the data itself were generated by the simulation process and used as input to the ATSC. Thus, the simulation scenario itself does not use external inputs from the physical roadway network to calculate the optimal traffic signals, and the initial traffic demand was used during the simulation process (no online change in traffic load). Online changes were only applied to the traffic signals during the simulation within the scenario via the TraCI interface with respect to the ATCS algorithm.

In [23], the simulation process is extended by connecting the traffic simulator SUMO with the game engine Unity, which provides virtual insights into the simulated scenario through 3D virtualization. The synchronized platform enables SUMO to control legacy vehicles, while Unity controls CAV with the proposed algorithm to achieve optimal coordination of CAV in mixed traffic. As the trends in the automotive industry are focused on autonomous driving, a DT for security and safety validation of autonomous driving was presented in [40]. A method is proposed to address a selection of exposed vulnerabilities using virtualization through DT of complex systems. In [43], the integrated conceptual framework of the Unity game engine and SUMO is presented for the virtualization of CAV, and in [42], it is used to demonstrate the mobility-DT framework for personalized adaptive cruise control (P-ACC) in Connected Vehicles (CV) environment. Combined with Artificial Intelligence (AI) based data-driven cloud-edge computing in Amazon Web Services (AWS) IoT Core, the conceptual framework consists of three building blocks in the physical world: human, vehicle, and traffic, and the associated digital spaces human DT with user management and driver type classification, vehicle DT with cloud-based driver assistance systems, and traffic DT with traffic monitoring and variable speed limit advisors. Finally, a case study is presented with the application of Mobility-DT to P-ACC for vehicles. However, the approaches are quite conceptual, at least in part, because they all do not cover the integration of real world (run-time) data and are therefore only partially a DT. In [22], the first field test of DT for cooperative ramp metering is presented. Three vehicles were equipped with on-board devices that send data to the cloud server where the DT of vehicle locations is created. Based on this, a cloud server calculated the target speed for the vehicles in real-time to perform the cooperative merging from the entry ramp to the motorway.

The authors of the article [45], present a DT-Smart City for citizen feedback and urban planning. The structure of the DT model is based on different layers (including mobility) aiming to provide an online urban planning view of skylines and green spaces in Dublin so that users can interact through the 3D virtual model and provide feedback on planned changes. In [1], a new large-scale traffic microscopic simulation model for the Barcelona urban area was presented. The 24-hour simulation scenario is based on fine-grained empirical Big Data that includes mobility data from cell phone records with traditional annual mobility surveys. The objective of this research was to develop an operational and effective approach to create a large-scale digital (microscopic simulation) replica of Barcelona traffic based on empirical mobility data in SUMO. Finally, hourly trips were generated using OD matrices and used to calibrate the simulation model.

In reviewing related work (see summary in Table1), we found that the results presented in existing studies can be distinguished depending on the extent of virtualization, the temporal resolution of DT, and the data source (real or artificial). Depending on the data resolution, the quality of the collected data used as input to the simulation model may be overestimated, and these errors are reflected in the aggregate results, leaving the degree of confidence in the results and conclusions incompletely known [4]. The lack of reliable real-time high resolution traffic data during the DT life cycle seems to be the most limiting factor so far, which ultimately dictates the update frequency of the simulated DT model, and, thus, system error. None of the above approaches were actually able to present a functioning integration of actual run-time traffic data into a running microscopic simulation, and, thus, the potential of implementing a DT for TM was a kind of *open promise*.

Moreover, there is virtually no research on the methodological development (and application) of microscopic simulation-based DT of the motorway system. Therefore, the work presented in our article extends the body of knowledge by proposing a run-time synchronized DT of the Geneva motorway, along with a method for developing such DTs. Since we have access to real-time sensor data streams (minute accuracy) from traffic counters on the Geneva motorway (via ODPMS), we can propose for the first time the methodological steps needed to build a motorway DT to, thus, virtualize the motorway's traffic dynamics in real-time. Unlike existing DT models in transportation in general, we consider our DT model as a virtual, microscopic simulation-based instance of the physical motorway system that is continuously updated as real traffic changes over time. Such a run-time synchronized DT-GM model provides the foundation for a wealth of new ideas and concepts in TM and in general mobility research that were previously unfeasible. Therefore, we also discuss some of them in the context of safety–critical decision processes on motorways.

3. The digital twin motorway concept

While simulations help to understand what can happen when changes are introduced to a motorway system, a DT helps to understand what is happening now (during run-time) and what can happen when particular changes (e.g., control strategies) would be implemented in the current traffic situation. The continuous transfer from the physical environment (motorway) to the digital simulation enables real-time simulation during the traffic run-time. If later on decisions can be made, a DT based on simulations can close the information loop with the physical motorway system. Therefore, in this section, we introduce the DT-GM concept and its physical twin, the segment of the Geneva motorway.

3.1. Physical twin - Geneva motorway

The section of the $A1$-motorway located in the Geneva region is used as a base for DT-GM microscopic simulation modeling. The approximate

Table 1
DT in the transport systems and urban mobility.

Ref./Year		Physical model/Data source	Virtual model/Calibration	Contribution
[32]	2013	Traffic counters, floating car data, historical OD matrix	Scenario generator module - periodic calibration every 5 [min] (SUMO)	Visualization of the traffic situation
[8]	2016	Offline simulation of CV and Big Data	OMNET++,SUMO,Veins coupled with Cassandra based Big Data cluster, not calibrated	Identifying congestion and rerouting vehicles accordingly
[18]	2018	TAPAS (computed mobility plans for an area population)	Offline (SUMO)	Concept of coordination of learning VVs in virtual transport network
[9]	2021	Synthetic network and data	Interaction with traffic signals in SUMO via TraCI, not calibrated	DT concept to allocate signal phase and timing of ATSC
[43]	2021	DT simulation of CAV in integrated Unity-SUMO	Conceptual framework, not calibrated	A case study of P-ACC
[22]	2021	Vehicle to Cloud communication (V2C)	On-board devices send data to the cloud (synchronized in real time)	DT advises CV for cooperative RM (real experiment with three vehicles)
[23]	2021	Unity-SUMO Co-Simulation	Synchronized SUMO-Unity platform	Merging coordination of CAV in mixed traffic
[45]	2021	Dublinked (Opendata store)	3D DT smart city with mobility layer of pedestrian simulation (Unity)	Virtual feedback of citizens on urban planning and policy decision
[16]	2022	Real data (coarse granularity) from IoT and static geo-data for building OD matrices	An hourly OD flow estimation of each mode of transportation	Simplified field test for a modal split estimate within an interval of two hours in a small district
[42]	2022	Adopted AWS IoT Core to design AI based data driven cloud-edge-device framework for CV	Mobility-DT framework with human DT, vehicle DT, and traffic DT	P-ACC
[1]	2022	Hourly scaled OD flows of cell phone data based on yearly mobility surveys	Large-scale 24-hour simulation in SUMO for the Barcelona urban area	Effective approach to creating a large-scale digital replica of traffic
Our research	2022	Real-time data streams (minute accuracy) from sensors on the Geneva motorway (via ODPMS)	Continuously calibrated simulation with actual run-time traffic (synchronized SUMO-ODMPS)	DT of physical Geneva motorway and concept of DT-GM application in real-time TM

observed motorway length in both directions is about 13,200 m. As shown in Fig. 8a, the network topology consists of a major grade-separated interchange with junctions to the east (center of Geneva), south (border with France), and north (toward Geneva airport). The main sections of the motorway consist mainly of two or three lanes. Furthermore, the motorway contains four entry ramps and two exit ramps (see Fig. 1b). It is worth noting that the model contains slight simplifications. For example, some minor entrances and exits, for which ODPMS does not provide data, were not included in the modeling in order to reduce the unknowns in the traffic flow model (1). As a result, they are ignored in our model due to the small amount of traffic they generate.

Although our experiment does not aim to solve existing problems on an observed motorway section, the most striking feature is the occurrence of congestion once in the morning (and in the evening) in the southern region between Switzerland and the French border due to daily commuter traffic over the motorway network. This is the reason for choosing this particular location. As such, it can later serve as a benchmark for future research on traffic optimization using DT-GM technology. In particular, in the context of safe traffic control proposed in this article through DT-GM application in real-time safety–critical decision-making processes in TM.

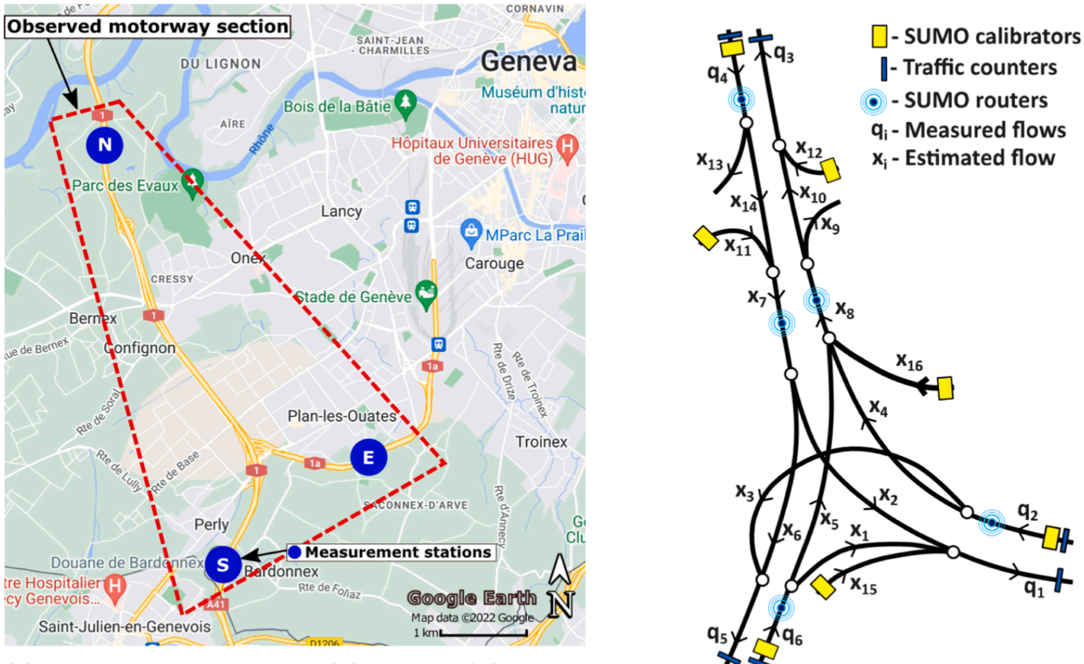
3.2. Digital twin of Geneva motorway

In Fig. 2, the concept of run-time synchronized microscopic simulation-based DT motorway framework is presented. It consists of the physical world, in our case the part of the Geneva motorway (Fig. 1a), the information technology that ensures the communication between the local computer and the ODPMS platform in a continuous process of sending requests and receiving the new traffic data collected by the traffic counters on the motorway. On the local computer, the running microscopic simulation is continuously calibrated as the dynamics of traffic flows on the physical motorway change in real-time. As an example of the foundation of DT-GM, we have included TM in the proposed scheme, which can use the DT model for the safety–critical decision-making process. The proposed scheme provides a conceptual foundation for the bidirectional interaction of the virtual model with the physical motorway in real-time.

3.3. Concept of parallel DTI-GM in TM

In any control optimization problem, the goal is to move the system along a desired path, that is, to move it along a desired trajectory of states. In most states, one must choose among several actions. The actions in each state essentially define the trajectory of states the system is likely to follow [12]. By analogy, the optimization of variable speed limits on motorways involves choosing the right actions (the desired speed limits) for states characterized by congestion [15]. Thus, the objective is to slow down and harmonize the incoming traffic in the congestion zone in order to relieve the congested sections of the motorway and restore the traffic flow to a steady state if possible.

Thus, DT-GM generally provides a basis for TM as additional support (real-time feedback) for observing and predicting the system response in the safety–critical decision-making process through the bidirectional interaction (action/reaction) between DT-GM and real motorway traffic. In this way, DT-GM and DTI-GM (parallel instances of DT-GM) provide a basis for investigating a motorway's system performance issues during its run-time and developing potential improvements, with the goal of generating valuable insights that can then be applied to the real motorway in real-time. This process is depicted in Figs. 2 and 3, where each DTI-GM (running faster than real-time) enters the running scenario with a different action a_n that is deployed from the current time t. By doing so, we can extend the boundaries (time horizon $t + T$) and explore what will happen (i.e., the evaluation of each action can be measured by its impact on the predicted traffic dynamics) without risking negative



(a) Traffic counters: East (E), North (N), South (S) Google Earth (2022)

(b) Directed weighted network model

Fig. 1. Physical motorway (left) and abstract correspondent model (right).

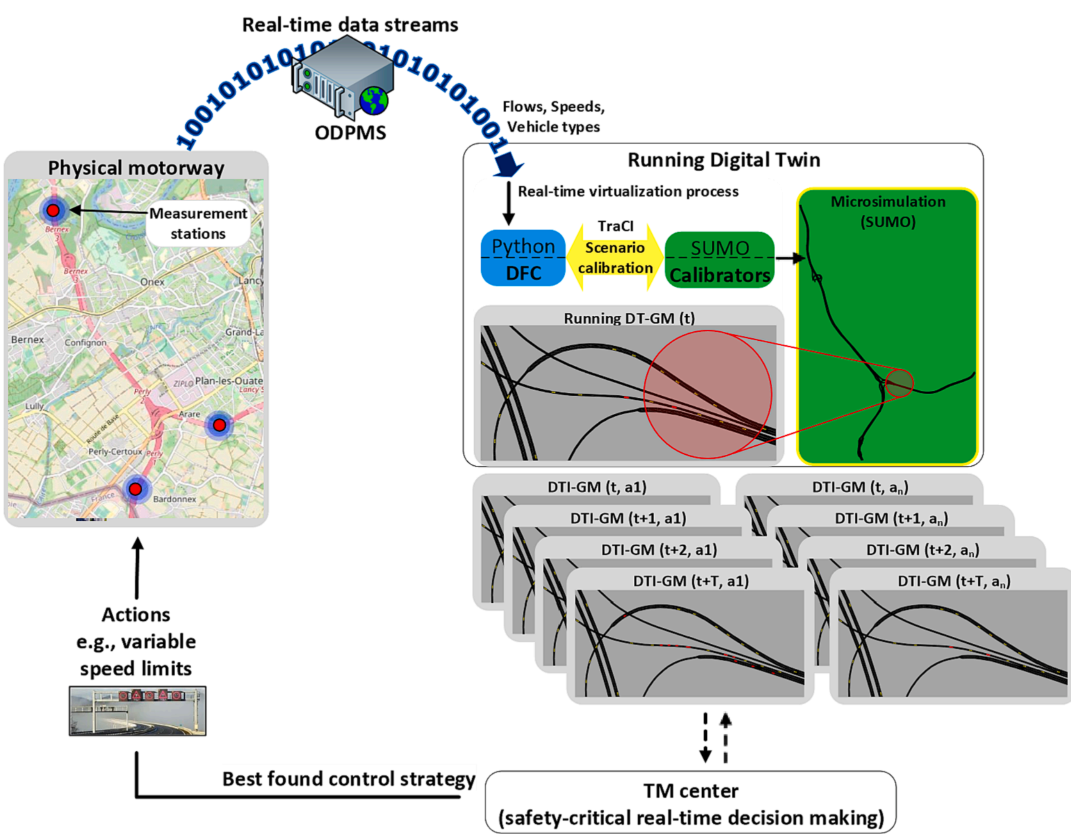


Fig. 2. Scheme of run-time synchronized DT-GM and concept of bidirectional interaction between virtual and physical motorway using DTI-GM in real-time TM.

impacts on physical motorways.

In this way, the best action among many can be selected based on certain objective criteria (e.g., what speed limits are appropriate for the next few minutes on the main sections of the motorway to increase throughput) and safely deployed in the real motorway environment. In general, using DT-GM and parallel DTI-GM, we can anticipate problems. If we identify problems early enough, we have enough options (control strategies) to mitigate them and, thus, optimize the motorway

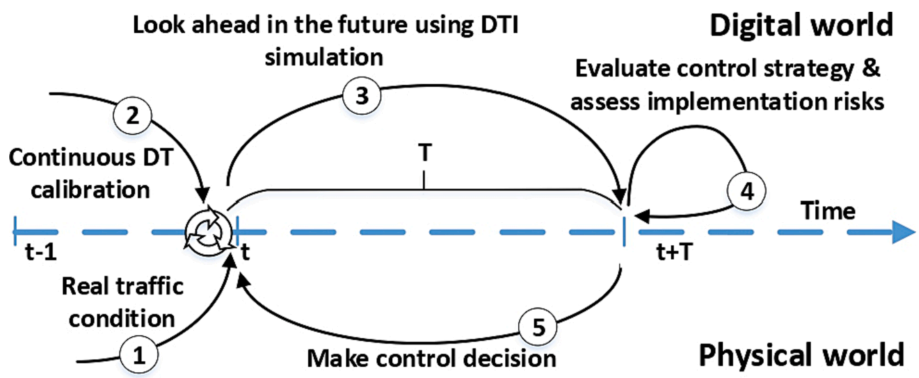


Fig. 3. Predictive analytics with DTI.

performance. This has not been feasible before and is not discussed in this way in the existing literature. Thus, the proposed concept fundamentally changes the application of microscopic simulation tools in traffic analysis by enabling simulation-based control optimization of traffic in real-time during the motorway run-time.

4. Methodology of synchronizing DT-GM with Run-time motorway traffic

In this section, we focus on the capabilities of SUMO for dynamic online calibration of traffic flow via TraCI. Therefore, in this section, we describe the methodological steps on how SUMO's calibrators are set up and can be used to dynamically generate the desired traffic volume and continuously calibrate the simulated traffic scenario as corresponding physical traffic changes in real-time at specific locations and thus become essential building blocks for the DT-GM. Calibrator's locations in the simulation model represent sources that emit the desired number of vehicles on the main section of a motorway and at entry ramps. Thus, they enable the straightforward use of SUMO to create a microscopic DT of motorway systems in real-time.

Therefore, in the following, we introduce the properties of SUMO objects *calibrators* and highlight their use in conjunction with dynamic routing via TraCI by proposing the DFC mechanism. Since, DFC is used to calibrate the run-time DT-GM model in order to approximate the real motorway dynamics at the locations of available measurements and over the other observed motorway parts. It is also important to note that it is not the scope of this article to go into the technical details of the DT framework implementation. Therefore, we refer readers interested in more technical details to our paper [20], in which we provide detailed technical descriptions and steps on how to build a DT of motorway traffic.

4.1. Integrating real-time traffic data

What distinguishes our analysis from the existing literature is the use of available real-time data streams obtained directly from the traffic counters implemented on the motorways. For motorways and national networks, traffic demand is measured in Switzerland by the Swiss Federal Roads Office (FEDRO).[2] Traffic counters are set up along major road sections to measure all traffic movements by direction and time. They can count vehicles (per lane), classify vehicles, and determine the speed of vehicles passing a particular location. The actual traffic data are updated every minute and refer to the traffic movements of the last full minute. The data are, thus, aggregated and recorded every minute on FEDRO's server and can be accessed in real-time through the ODPMS platform exclusively via an available API.[3] Essentially, the number of vehicles and average speed are reported in two categories: (i) light vehicles such as cars, motorcycles, buses, and small delivery trucks, and (ii) heavy goods vehicles such as trucks and trucks with trailers. We leverage these capabilities by obtaining real-time traffic data from traffic counters on the motorway in the Geneva region to build the DT-GM. Circles in the region of interest (see Fig. 1a) represent the locations of installed traffic counters. A single (blue) dot represents multiple sensors (sensors per direction and lane). Therefore, we can create a bounded linear model (1) for both directions of travel that can estimate unknown traffic flow at the edges between the boundaries of E, N, and S.

This allows us to feed our DT-GM model with raw traffic data in real-time taken from the physical system. Moreover, with this fine granularity of data, the original traffic pattern (distribution of traffic flows) is preserved, since the distribution of the real system in spatio-temporal terms is directly contained in the fine-grained traffic data. In contrast to the current state-of-the-art, where a longer aggregation period is used, and, thus, the simulation approach requires an estimation of the distributions of the governing variables in order to simulate and analyze the system at a finer scale. Namely, suppose the aggregation period is one hour, and traffic is generated based on the estimated distribution. In that case, some intervening events (in a finer time resolution) may not be adequately captured by the model, thus, increasing the error in the simulation.

Moreover, in traditional simulation modeling, the internal calibrated features become dominant for a particular scenario defined in the simulation. For example, the calibrated scenario of a particular weekday may not simulate traffic accurately on other days of the week, non-workdays or holidays, and vice versa. Thus, conventional simulation models need to account for the different traffic demands for the weekday and holiday scenarios separately to overcome the above problem. It is also true that if the model is calibrated based on aggregated weekly traffic data, the accuracy of the simulation of traffic events at daily resolution (even worse at hourly or minute resolution) may contain significant errors.

As DT-GM is based on continuous, instantaneous sampling and calibration, we reduce the sources of error in our model (the finer the granularity, the smaller the error). Therefore, our DT-GM model can adapt online in the spatio-temporal domain and closely resemble the underlying structures in the evolution of real traffic for each minute (regardless of the day of the week) with high accuracy.

4.2. Run-time flow estimation

In practice, it would be very costly to survey all roads, as a large number of traffic counters would have to be installed and maintained.

[2] https://www.astra.admin.ch/astra/en/home.html.

[3] https://opentransportdata.swiss/en/rt-road-traffic-counters/.

Instead, if the traffic counters are placed in a way that they capture most of the incoming and outgoing traffic, it is possible to reconstruct the traffic in between. Thus, from partial data, one can define a system of linear equations using the conservation law of traffic flow and calculate the unknown traffic flows in a road network. In the context of a motorway, the situation can be simplified, as it is safe to assume that the roads are *one-way* and that a vehicle entering the observed network also leaves the network (no terminal states within the motorway network). In reality, however, a vehicle may linger for a while at a gas station or a public facility such as a rest area, but this can be neglected in the context of our DT-GM modeling. The flow in the network is balanced, i.e., the total flow into the network is equal to the total flow leaving the network. This is true for all branches in the observed network (Fig. 1).

$$\overrightarrow{X}=\overrightarrow{X}_p+\overrightarrow{X}_n=\begin{bmatrix}x_1\\x_2\\x_3\\x_4\\x_5\\x_6\\x_7\\x_8\\x_9\\x_{10}\\x_{11}\\x_{12}\\x_{13}\\x_{14}\\x_{15}\\x_{16}\end{bmatrix}
=\begin{bmatrix}q_1\\0\\q_5\\q_2-q_5\\q_6-q_1\\0\\0\\q_2-q_1-q_5+q_6\\q_2-q_1-q_3-q_5+q_6\\q_3\\0\\0\\q_4\\0\\0\\0\end{bmatrix}+\begin{pmatrix}1&-1&0&-1&-1&0\\-1&1&0&1&0&0\\-1&0&0&0&0&0\\1&0&0&0&0&0\\-1&1&0&1&1&0\\1&0&0&0&0&0\\0&1&0&1&0&0\\0&1&0&1&1&1\\0&1&1&1&1&1\\0&0&-1&0&0&0\\0&1&0&0&0&0\\0&0&1&0&0&0\\0&0&0&-1&0&0\\0&0&0&1&0&0\\0&0&0&0&1&0\\0&0&0&0&0&1\end{pmatrix}\times\begin{bmatrix}x_6\\x_{11}\\x_{12}\\x_{14}\\x_{15}\\x_{16}\end{bmatrix} \tag{1}$$

The complete solution (1) of the flow balance in the flow model contains the particular solution $\overrightarrow{X}_p$ (where $q_1,\ldots,q_6$ are measured flows by traffic counters and the special solution $\overrightarrow{X}_n$. For the special solution, the free variables $\overrightarrow{X}_{free}=[x_6,x_{11},x_{12},x_{14},x_{15},x_{16}]^T$ can be chosen arbitrarily. However, from a practical point of view, all flows must be non-negative. This implies adding constraints (2) on the complete solution, thus, limiting $\overrightarrow{X}_{free}$.

$$X\geq 0 \tag{2}$$

Since we have six free variables and need to estimate them in such a way that we obtain positive solutions, we formulate a linear program that allows us to search for feasible solutions using the Simplex algorithm. Thus, in order to find the solution to the given problem, we performed two steps of the Simplex algorithm. In the first step, the inequalities from (2) were used as constraints, while randomized cost coefficients of the objective function were used in each Simplex run. In this way, the extreme points of the feasible region for free variables $\overrightarrow{X}_{free}$ can be defined. Based on the calculated bounds for each free variable, the positive interval is defined starting with the minimum positive value and ending with the maximum value. Also, the interval is divided into 10 parts so that each free variable is defined with ten intensity levels. Once the feasible ranges are known, we further restrict the solution space by defining the desired intensity vector of the free variables $\overrightarrow{X}_{free-des}$. By doing so, the range of each free variable is further restricted with respect to the desired intensity level. Such a newly constrained problem is again solved by several Simplex runs. The best found solution for the free variables $\overrightarrow{X}_{free}$ is determined by calculating the minimum relative error using the formula (3) between the vector of the desired intensity and the given set of feasible solution vectors.

$$\frac{\left\|\overrightarrow{X}_{feasible}-\overrightarrow{X}_{free-des}\right\|}{\left\|\overrightarrow{X}_{free-des}\right\|} \tag{3}$$

After all flow variables were computed, DFC calculates the routes' distribution, which is used to distribute the vehicles (flows) generated by calibrators throughout the network in order to satisfy (2).

4.3. SUMO's calibrators objects

In SUMO, calibrators (*trigger-type objects*) enable the modeling of location dependent changes in traffic flow dynamics and driving behavior. Once defined in the initial simulation scenario, they allow for dynamic adjustment of traffic flows and speeds along with changes in vehicle parameters by assigning different predefined vehicle types.

4.3.1. Calibrator definition

Each calibrator is uniquely associated with a particular edge or even by a particular lane on the edge on which it is placed in the simulation model. In order to use the calibrator, it is necessary to define the interval (start, end), which specifies the time during which the calibration takes place. Thus, the interval length defines the aggregation period for comparison of the observed and desired flows. The calibration goal is to ensure that the correct number of vehicles is deployed at the end of the respective time interval, and also in that particular place. At the same time, the space–time structure of the existing traffic should be preserved as much as possible [25]. Thus, a calibrator removes vehicles that exceed the specified traffic volume and inserts new vehicles (of the specified type) when the normal traffic demand in a simulation does not reach the specified number of vehicles (*veh/h*), also vehicles can be assigned with the desired speed if adjustments are required. This means that the calibrator in its basic configuration works like a static object and modifies the traffic flow according to the predefined attributes mentioned above: traffic flow (*veh/h*), speed (*m/s*) and vehicle types within certain time intervals. Thus, different flows and speeds can be used for different time intervals during the simulation.

4.3.2. Run-time calibration of simulation via TraCI

Moreover, SUMO provides the ability to access the calibrator via TraCI while the simulation is running. This allows for calling a specific calibrator and changing the flow rate, speed, and even vehicle type in the current time interval during the execution of an actual simulation. In our experiment, we set intervals for calibrator adjustments to match the frequency at which actual traffic data is received from the motorway sensors (one minute).

We placed the calibrators in our microscopic model in the positions where their corresponding traffic counters are implemented in the real motorway (see Fig. 1). These calibrators are, thus, used to continuously adjust the flows to match the current traffic demand as it changes in the real motorway with a minute resolution. For more technical details on the setup and technical implementation of the calibrator in DT-GM, we refer to the paper [20] as mentioned above.

4.4. Dynamical rerouting of vehicles

In this section, we explain the routing mechanism in SUMO in a rather abstract way, and in the next section, we elaborate on our implementation. The realism of traffic flow behind or between calibrators depends on the correspondence between simulated and real routes. This correspondence importance increases with the network's size and complexity between calibrated edges [25]. Rerouting with calibrators allows the desired traffic flow to match other edges (routes). Thus, once the calibrator inserts the desired traffic flow, it can be distributed across the network by assigning routes to individual vehicles. Routes are assigned to a vehicle by the *routing device*, which is an abstraction of the location (a particular edge in the simulated motorway network) monitored by DFC during simulation run-time. Accordingly, DFC assigns the desired route to the vehicle based on the calculated route distribution when the vehicle drives onto that edge.

4.5. Principle of dynamic flow calibrator mechanism for DT-GM

Given the locations of the physical traffic counters (Fig. 1a), we design the simulation model to use the available measurements as much as possible. Therefore, the boundary points of DT-GM are defined by the locations of the traffic counters. At these locations, the model is equipped with calibrators from which the desired traffic flow (measured by traffic counters) is distributed using DFC to match the traffic flow on other observed motorway segments (Fig. 1b). Thus, DFC uses information about all possible routes from a given point. Following, the information about the traffic flow on the edges (calculated by (1)) is used to compute the probability distribution of the traffic flow among all possible routes. In our experiment, we have predefined routes and route distributions that are dynamically assigned to vehicles using TraCI in conjunction with the calibrators. This forms the base for introducing the DFC mechanism to reroute the traffic flows over the observed motorway segment (Fig. 1b). Accordingly, the number of vehicles that need to continue their direction of travel or switch to other routes is calculated. This process is illustrated in Fig. 4. Given the initial traffic flow q_0 with speed v_0 arriving at the model's starting point, the calibrator adjusts the traffic flow and speed according to the real-time measurements provided by the traffic counters on the real motorway. The modified traffic flow (q_1, v_1) continues the trip according to the predefined initial route $Route_0$. When the vehicles reach the point where the routing device $Router_1$ is installed, they are assigned (according to the calculated probability) the new route corresponding to the desired traffic flows on the next parts of the network (computed by (1)). For example, the probability P_{x1} that a vehicle is assigned to traffic flow x_1 (on $Route_1$) is calculated as follows:

$$P_{x1} = 1 - P_{x2} = 1 - x_2/q_1, \tag{4}$$

where P_{x1} and P_{x2} are calculated every minute and transmitted via TraCI to a particular edge on which the routing is performed. The probabilities of assigning a vehicle to a particular route among two possible routes are defined as an ordered pair (P_{x1}, P_{x2}) and, thus, can take discrete values whose sum equals one (see [20]). Thus, the process of rerouting assumes that the desired probability distributions have been predetermined. This rerouting solution follows the same principle for the entire motorway model in areas with multiple possible directions of travel.

An additional *marker* is added to each vehicle when it is inserted into the simulation. This contains the information about the routes assigned to it according to the calculation performed by DFC for that time window. This prevents vehicles that have already been inserted from being assigned the newly calculated routes. Specifically, the vehicles that arrive late in the router area (which may be the case in traffic jams when the vehicles are stuck for a certain period of time) are not assigned with the currently calculated route distribution, but they follow the original route plan (encoded in *marker*) that was set when they were inserted in the simulation. In this way, the traffic flow maintains a balance between the flow (in) and (out) in the DT-GM model, otherwise a mishmash could occur and the flow model (1) could not be fulfilled.

The summary of the execution of the DT-GM microscopic simulation model is represented by the Algorithm 1. After all variables are initialized, the algorithm loads the simulation scenario with all necessary SUMO files. The simulation is started and controlled by TraCI. At each simulation step, SUMO calibrates and updates the simulation scenario. For every multiple of 60th seconds of real-time, a new request for actual traffic data is sent to the FEDRO server via ODPMS. The data are received and forwarded to the DFC mechanism, which calculates all flows in the network and, accordingly, the route distribution to satisfy the desired flows in the network for a given time window of one minute. The process is repeated until the specified end, saving the status of DT-GM. Also, the process can be reloaded by loading the saved simulation state and running it from that point. When the real-time TM concept is enabled, new parallel simulation instances are initialized and started by loading the states of the running DT-GM. Such parallel DTI-GM simulations (running faster than real-time) are associated with different control strategies to test each one and predict their impact on motorway traffic during system run-time. The description of all variables is available in our previously mentioned paper [20].

Algorithm 1. DT-GM at each simulation step
// Set parameters and load sim. model.
Init $\vec{S}, \vec{T}, \vec{C}, \vec{P}, \vec{q}, \vec{v}, \vec{v}_{type}, \vec{X}, \vec{X}_{free}, \vec{X}_{free-des}$
for each simulation step
  if simulation time % 60 [s] == 0 **then**
    Get new actual traffic data via ODPMS: $\vec{q}, \vec{v}, \vec{v}_{type}$
    // DFC computations
    For given $\vec{X}_{free-des}$ and $\vec{q}$ calculate $\vec{X}_{free}$ and $\vec{X}$ (see (2))
    Update calibrators $\vec{C}$ and routes distributions $\vec{P}$ using $\vec{X}$
    // Conceptual run-time analysis in real-time TM
    if TM_{active} == True **then**
    Save current DT-GM simulation state
    Initialize new sim. using the current state of running DT-GM
    Run DTI-GM
    Test different control strategies
    Return best strategy

(*continued on next page*)

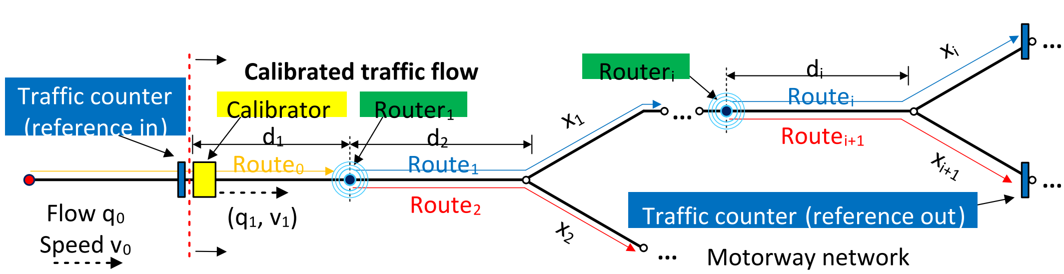


Fig. 4. Dynamic Flow Calibration principle in SUMO.

(*continued*)

Deploy the best found strategy on the physical motorway
end if
end if
Calibrate and update simulation scenario
end for
Save DT-GM simulation state and close simulation

5. Experimental setup

To validate the proposed DT approach, the created DT-GM is compared with a baseline, in our case, actual run-time traffic measured by installed traffic counters on the motorway in the Geneva region. The simulation framework used in our experiments to build and run DT-GM consists of the microscopic simulator SUMO, the Python programming environment, and the ODPMS server accessed remotely every minute (Fig. 2).

5.1. Simulation model

To create a simulation model with the exact replica of the geometry of a real road network, geometric elements with appropriate attributes of geographic data from the free geographic database of the world OpenStreetMap (OSM) [31] must be converted into the simulation network model.

For this purpose, the NETEDIT module from SUMO is used to create a digital motorway network. The network model consists of interconnected edges representing roads. Within an edge, a lane is specified according to the real motorway topology. Connecting the edges by nodes forms a complete SUMO motorway network. Since the OSM website limits the size of the region to be extracted, additional steps were taken to obtain the final OSM file from which the SUMO motorway network is generated. More technical details on extracting the network from OSM can be found in [20].

Once the motorway network is defined, the traffic flow can be defined, e.g., as repeated emissions of vehicles (flows) or by calibrator objects as generators of traffic demand during simulation run-time. Since we use calibrator functions as essential building blocks in the creation of DT-GM, this is a main component of the research and is therefore explained in detail in the following. The additional definition of flows and their purpose in our DT-GM is again explained in [20].

5.2. DT-GM parameters

It is important to note that the purpose of this study is not to calibrate the simulation parameters, but to investigate the extent to which our DT-GM with the basic simulation configuration (mainly counting for default parameters) resembles real traffic by using the underlying motorway system information through fine-grained real-time traffic data and run-time calibration of the traffic flow with DFC (Figs. 2 and 4). Therefore, the observation between real and simulated traffic should be considered mainly as a comparative measure of how closely the model resembles reality, rather than an absolute measure of performance.

5.2.1. SUMO simulation parameters

Traffic flow data consists of cars and trucks, as these classes were distinguished by traffic counters. At the moment, we use the latest SUMO version (1.13.0). The longitudinal (speed choice) vehicle behavior uses the Enhanced Intelligent Driver Model (EIDM) car-following model [35], while lateral (lane changing, overtaking, merging) behavior uses the lane change model LC2013 [11]. Additionally, several parameters within the mentioned models were modified. The parameter *tau* defines the time interval between successive vehicles in the traffic flow, measured in seconds (time headway) was defined by lognormal distribution (with the shape parameter $\sigma = 0.05$ and the location parameter $\mu = 0$) [14], [34]. The headway distribution model is shown in Fig. 5. In this way, stochastic effects are introduced into the car-following model to better suit the behavior of real drivers. Similarly, adjustments have been made for the lane change parameters (see [20]. The simulation step used in our analysis is set to a quarter of a second, which means that four simulation steps lead to one simulated second. Also, we have assumed nominal maximum allowable speed limit values on Swiss motorways (120 km/h) for main sections, as access to speed limit information via ODPMS is under development. Finally, actual traffic on Thursday, March 24, 2022, and the results of the correspondent simulated traffic replica by run-time DT-GM are summarized in the next section.

5.2.2. Flow model parameters

As explained in Section 4.2, the free variables in the flow model, x_6, x_{11}, x_{12}, x_{14}, x_{15} and x_{16} are defined by intensity levels rather than absolute values. Therefore, the defined intensity level for these variables is approximated by observing the GPS traces on the OSM and Google Maps traffic website as a function of time of day and experimenting with run-time test simulations. Therefore, they should not be considered as an exact representation of the actual traffic volume on the corresponding motorway sections (edges), but only as an approximation. Although they are an approximation of the actual traffic volume, mathematically they represent a stable, feasible solution that clearly satisfies the system (2). Therefore, eight different intervals with respect to the time of day and corresponding desired intensity vectors $\overrightarrow{X}_{free-des}$ for free variables x_i, $i = 6,11,12,14,15,16$ are defined as follows:

- From 6 to 8 am with values 10,1,2,7,3,1, respectively;
- From 8 to 10 am with values 10,1,2,4,3,1, respectively;
- From 10 to 12 am with values 10,2,2,5,2,1, respectively;
- From 12 to 4 pm with values 6,1,1,10,1,1, respectively;
- From 4 to 6 pm with values 6,1,3,8,1,3, respectively;
- From 6 to 8 pm with values 7,2,2,8,1,2, respectively;
- From 8 to 10 pm with values 7,2,2,7,1,2, respectively;
- For the rest of the day with values 7,1,1,7,1,2, respectively.

Also, the Simplex algorithm is performed in two steps, as discussed before, when solving the inequality to find a feasible solution for the system (2). Both times, it is run 300 times with random initialization of objective function coefficients to find the feasible bounds for x_{free} (see Section 4.2).

6. Results and analysis

In this section, we present the overall joint analysis of results related to the methodology used in the development of the DT-GM by testing the accuracy and timeliness of workday traffic simulated at run-time via DT-

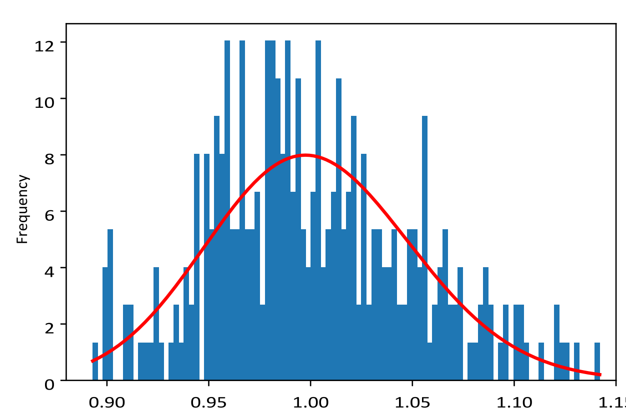


Fig. 5. Lognormal headway distribution model.

GM. Flow analysis is used to analyze the spatio-temporal behavior of DT-GM adaptation with respect to measured real eastbound, northbound and southbound traffic (flows-in and flows-out). Thus, curves in Fig. 6 show the evolution of the flows for the selected workday. Similarly, for traffic flow indicators, we show *GEH* statistics. The *GEH* statistic is a formula used in traffic engineering, traffic forecasting, and traffic modeling to compare measured (real) traffic volumes with model-generated traffic (simulation). In addition, Fig. 8 shows the spatio-temporal snapshot of the evolution of traffic flow speeds of the actual run-time traffic on the physical motorway and the flow speed in the run-time simulation performed by DT-GM. Thus, we focus mainly on the impact on spatial and temporal correspondence between the DT-GM model and real traffic.

6.1. Traffic flow analysis

The overall traffic demand in the observed motorway area for the analyzed workday has a symmetric characteristic. Traffic generated by commuters from France has a major contribution to the morning peak hours eastbound to Geneva (Fig. 6d). Additionally, the eastbound is partially loaded by commuters from the north, which use the motorway as a bypass to avoid driving through the city center in order to reach the southern part of Geneva.

Similarly, for traffic on northbound (Fig. 6e), traffic generated by

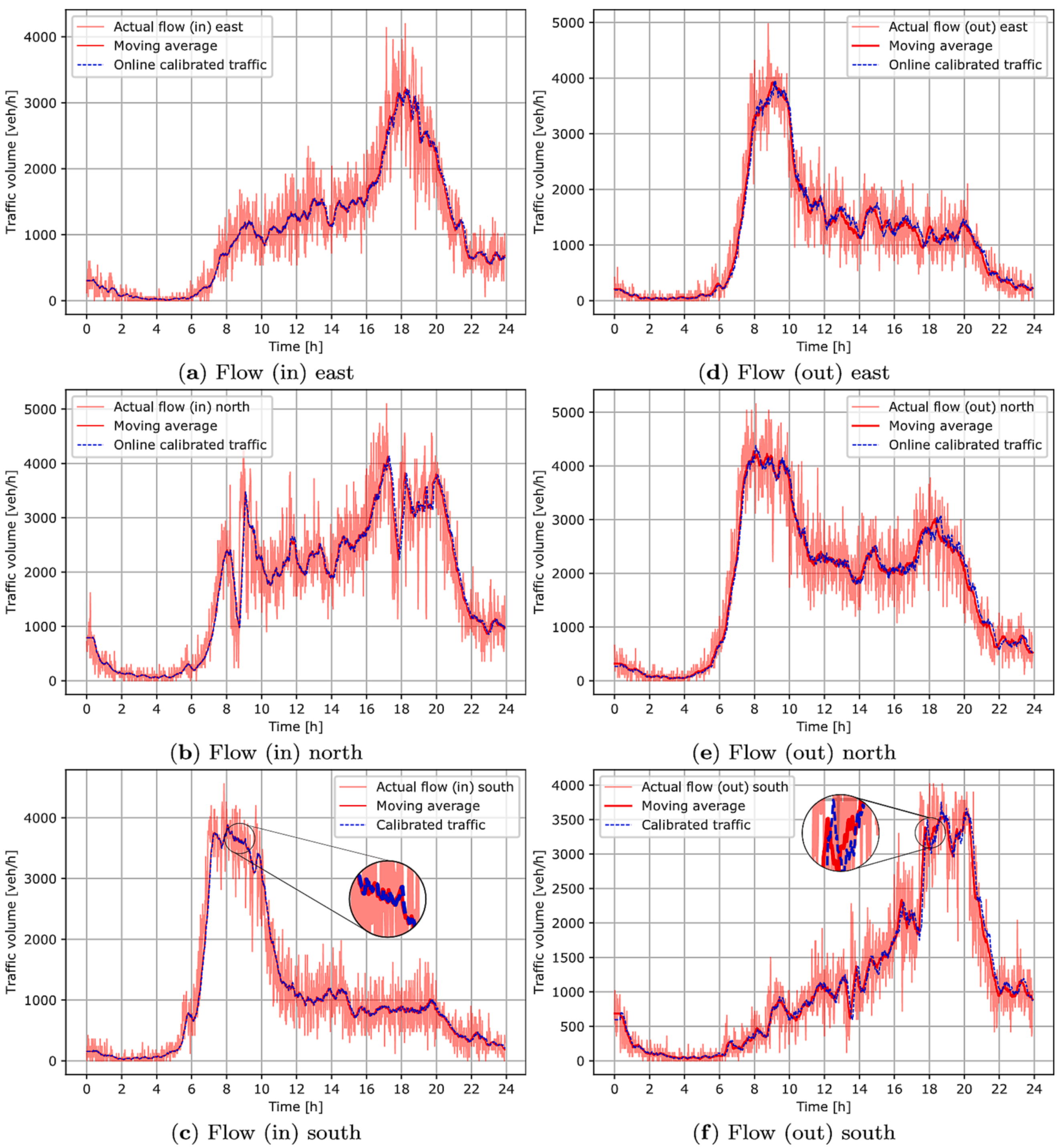


Fig. 6. Comparison of actual and simulated daily flow with minute resolution.

commuters partially from southbound (flow-in) from France (Fig. 6c), and eastbound (flow-in) from Geneva (Fig. 6a) have a major contribution to morning peak hours northbound across the main sections. However, traffic entering the motorway on entry x_{12} contributes, too.

The peak hours in the afternoon have an opposite character, i.e., the commuters return, and the peak hours are symmetrically reversed. The high traffic flow is mainly present in the southbound motorway sections towards the Swiss-French border (Fig. 6f), partly caused by commuters from eastbound of Geneva and the main motorway traffic from the north.

6.1.1. Comparison between DT-GM and real traffic

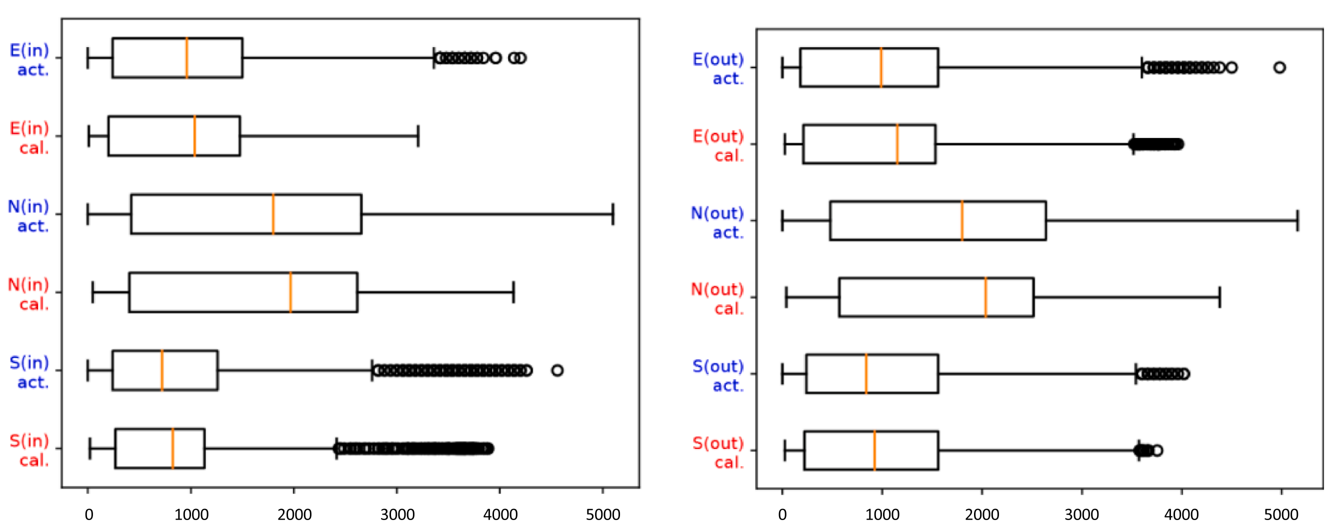
As it can be observed from the results (the graphs are created using the moving average over 20 measurements), there is no significant difference between the traffic generated by the run-time DT-GM and the actual motorway traffic. In the one-day-long simulation on March 24, 2022, both the morning and evening peak traffic and the stationary traffic between the peak hours simulated by run-time DT-GM match well with the actual traffic conditions at the granularity of one minute.

The small temporal shifts between measured and simulated flows (out) are collectively attributed to the fact of the simplification in the model, where we omitted some local motorway entry ramps for which ODPMS does not yet provide traffic data. Therefore, additional traffic is generated on the included entry ramps (x_{11}, x_{12}, x_{15} and x_{16}) to achieve the required overall traffic flow balance on the observed motorway segment. In addition, the spatial displacement of the calibrators (*traffic emitters*) on main sections in the east, north, and south compared to the symmetric measurement points of flow-out may result in a small delay in the response time of the flow model (1). Consequently, the time to reach the desired flow on the exit sides of the motorway section may be slightly shifted to the right (Fig. 6d, e, f), because vehicles have to travel a longer distance to reach the desired points. Nevertheless, while there might be shifting to the right expected, we talk here only on a very small scale time resolution as the run-time adjustment of DT-GM is minute-based, so even though we are timely slightly shifted, that is still pretty accurate.

Therefore, the time at which the output values first reach the steady-state of desired traffic volumes for a given simulation time window may be slightly delayed, especially during peak hours. Therefore, additional delayed traffic in the network may show up as a slow increase (or decrease) between the simulated traffic and the reference traffic measured by the traffic counters (Fig. 6). However, the cumulative error is negligible since we are still at a fine-grained temporal resolution.

However, outliers can cause a significant bias in commonly used numerical measures such as the average. Therefore, the Box-Whistler diagram (Fig. 7) is presented for actual run-time traffic and on-the-fly calibrated traffic. It gives a rough summary of the data distribution using five numbers: the smallest traffic volume, the lower quartile $Q1$, the median, the upper quartile $Q3$, and the largest traffic volume. Even though there are no recorded errors in received actual run-time data, a data set contains measurements that differ markedly from the others in the set, both east and south (in/out) actual traffic flow (upper fence for outliers: $Q3 + 1.5(IQR)$, where $IQR = Q3 - Q1$). Without going into the nature of the outliers (observational errors or the fact that outliers themselves may contain important information about the traffic dynamics), those similarities mostly reflect on-the-fly calibrated traffic flow. The most striking outliers are found in the eastern and southern regions. The main reason could be unexpected traffic patterns due to traffic lights in Geneva (east) urban areas and uncertain traffic dynamics in the south at the border crossing, accompanied by high commuting between these regions. It is also noticeable that in the east, for flow (in) (Fig. 7a), the calibrators were not able to reproduce outliers at all. The reason could be that the calibrators cannot completely generate higher sudden traffic volume in a short interval due to the specific waiting properties explained in the discussion. Thus, this additional traffic is generated in subsequent intervals to compensate for the loss previously incurred. In this way, all traffic is maintained, but with some delay. The calibrators can also insert only some vehicles if the traffic in their lane is congested (no space to insert a vehicle safely). This ensures that invalid congestion is not passed through a calibrator. Such behavior can be controlled in SUMO and should be further investigated, as such congestion can occur on motorways and thus poses an issue for the current calibration design and implementation.

However, the calibrators reflect the maximum traffic flow values (in) and (out) in the east and south. In contrast, significant differences in maximum values are observed for traffic in the north, explainable by the same arguments mentioned above. Since the medians are to the right of the center of the box in all cases, the distributions are skewed to the left, i.e.; there are some small measurements of traffic volume caused by low traffic at night. Even so, there are high traffic volumes due to peak hours, particularly in the northern region. Thus, all flows are characterized by high variability. Nonetheless, these phenomena are generally quite well



(a) Flow (in) (b) Flow (out)

Fig. 7. Box-Whistler diagram for actual and calibrated traffic at minute resolution.

reproduced by DT-GM at the granularity of one minute.

Finally, a numerical evaluation of the deviation between the curves of actual run-time traffic and traffic simulated on-the-fly by DT-GM is presented in the next section.

6.1.2. Quantitative workday simulation analysis

The traffic flows generated at the calibrator locations (flow in) match almost exactly the actual traffic (see Fig. 6d, e, and f). Therefore, the *GEH* statistics (Tables 2, 3, and 4) are presented only for the case of outflows to show the accuracy of the model with respect to the proposed DFC mechanism for distributing the traffic generated by the calibrators over the simulated motorway network.

$$GEH = \sqrt{\frac{2(m-c)^2}{m+c}} \tag{5}$$

Thus, a comparison is made between the measured traffic flow leaving the network (flow out) and the measurements recorded by the traffic counters. It can be seen that the *GEH* values are within the accepted range of 0 to 5 (a *GEH* of less than 5.0 is considered a good match between simulated on-the-fly m and observed actual run-time traffic volumes c). The highest values are observed during peak hours when congestion events delay traffic in the middle parts of the motorway network by increasing the travel time of vehicles. Even though the running simulation is continuously fed (every minute) with new traffic data from the traffic counters, the traffic simulation is well run-time calibrated. Thus, DT-GM allows the scenario of running simulation to evolve as the conditions on the physical motorway in the areas of the traffic counters.

6.2. Space-time analysis

In Fig. 8, a space–time diagram of vehicle speeds in the motorway network is shown. Speeds are color delineated, ranging from low speed (dark-red) to free flow speed (green). The spatio-temporal color map is obtained from Google Maps[4] (Live traffic) on Wednesday, March 30, 2022, at 5:15 pm, while the colors in our model are defined as follows: dark-red for slow traffic (speeds less than 50 % of free flow speed), red for 75 % of free flow speed, orange for 90 % of free flow speed and green for free flow speed regarding the nominal speed limit of the edges. Despite the similarity, the comparison with the baseline (speed presented by Google Maps (real traffic)) should be considered primarily as a playground for comparison between the physical traffic dynamics and simulated traffic by DT-GM rather than an absolute measure of performance since we do not have exact values for matching the colors with speeds. Particularly, we do not know the aggregation period and the length of segment on which vehicle speeds are aggregated in Google Maps, and we assume nominal speed limits on the main section. Such visualization reveals DT-GM potential for estimating traffic dynamics on motorway segments for which direct measurements are not available. For example, DT-GM can be used to identify and position traffic sensors to observe traffic flow fully or to account for sensor failures. In addition, it can estimate time-varying origin–destination matrices by observing the fraction of traffic flow on the path with dynamic flow screening of flows. Such visualization can, thus, serve as a mechanism to alert authorities to revise critical sensor locations in the network. It can also serve as a benchmark for validating other approaches for estimating real-time traffic flow, e.g., estimation methods based on cellular network data. In addition to traffic flow under normal conditions, DT-GM may also reflect anomalies, such as the effects of accidents on traffic flow. When such an anomaly occurs near the traffic counter, the travel speed of vehicles is drastically slowed, which is reflected in the running simulation by a color change from green to red. The reflection time depends on the distance between the location of the event and the traffic counter. However, this requires additional systematic research and is beyond the scope of this article.

Nevertheless, we observe a high variability of speeds in the motorway network near the main sections, where two or more sections merge into one and vice versa, and in the areas of the entry ramps and some exit ramps, as well as in the areas of the Swiss-French border, caused by a lower capacity of the border crossing infrastructure. These are accompanied by strong vehicle interactions when traffic volumes are high (Fig. 8). Such phenomena trigger congestion activation. Once the congestion is triggered and the traffic volume is high, it usually spreads upstream to the main sections. On the main sections, it has also been observed that delayed lane changes disrupt traffic flow as vehicles urgently slow down and sometimes even stop and wait for a gap in the right lane to perform a safety maneuver to change lanes (areas of merge sections or exit ramps) and continue on the desired route.

7. Discussion

With a foundation of actual traffic data provided by ODPMS, we were able to present and test for the first time a *live* motorway DT replica in the microscopic simulator SUMO. Moreover, based on preliminary results, we have shown that the proposed DT-GM itself is able to accurately reflect real traffic dynamics with a very fine temporal resolution during system run-time.

Therefore, in this section, based on the overall joint analysis and the obtained results, we highlight the possible further directions for enhancing the proposed DT-GM model. It is also worth noting that the comparison with the baseline (real traffic on the studied motorway section) should be considered primarily as a benchmark for comparison between real traffic and the newly proposed DT-GM, allowing for critical review in terms of uncovering gaps and room for possible improvements in terms of design and development, rather than as an absolute measure of performance.

In general, the results allow us to conclude that the run-time DT-GM model almost exactly replicates the actual traffic in areas of traffic counters on the analyzed section of Geneva motorway, which supports the methodological approach used to create DT-GM. Furthermore, this confirms that SUMO, which was mainly used for offline motorway simulations, is also suitable for run-time (online real-time) simulations. Thus, DT-GM itself (and its underlying technologies) can be used to map real traffic to a virtual microscopic simulation-based DT model during the run-time of a motorway system.

Furthermore, results indicate further directions for DT-GM enhancement. Information about vehicles' instantaneous location and dynamics is imminent in the context of pervading CV and CAV technology. The further granularity of traffic data (ideally, the event-based data) that ODPMS could provide in the foreseeable future would form the basis for generating instantaneous traffic demand inputs in the running simulation. This would allow for the original distribution of traffic flow on the motorway to be maintained during run-time, allowing DT-GM to evolve as an exact replica of the physical correspondence. In addition, this information will enable an online calculation of parameters, e.g., the distribution of the headway parameter, which is a fundamental microscopic traffic parameter within the car-following model that reflects driver behavior and traffic flow characteristics. Ultimately, headway is a dynamic parameter, i.e., depending on the traffic flow state and roadway characteristics [33]. Thus, further analysis is required to define adaptive headway over time and space rather than a single constant value [34]. Additionally, the lane change model parameters that define lane change, merging, and overtaking need to be further analyzed (e.g., the look-ahead parameter that allows modeling the delay in driver reaction time [29], which is still experimental to some extent in SUMO), as the current simulation setup mainly uses default parameters of the LC2013 lane change model [11]. An in-depth analysis of the parameters

[4] https://www.google.com/maps/@46.1680111,6.1025731,6847m/data=!3m1!1e3!5m1!1e1.

Table 2
GEH statistic for flow (out) east.

Morning time (h)	0	1	2	3	4	5	6	7	8	9	10	11
GEH $\sqrt{\frac{veh}{h}}$	0.0	0.0	0.5	0.8	0.6	1.6	2.8	3.0	0.0	1.3	1.5	0.7
Afternoon time (h)	12	13	14	15	16	17	18	19	20	21	22	23
GEH $\sqrt{\frac{veh}{h}}$	0.9	3.5	0.4	0.7	1.1	0.9	0.9	0.2	2.3	2.1	1.8	0.7

Table 3
GEH statistic for flow (out) north.

Morning time (h)	0	1	2	3	4	5	6	7	8	9	10	11
GEH $\sqrt{\frac{veh}{h}}$	1.3	0.1	0.6	0.0	1.8	1.6	2.4	1.9	0.4	0.8	0.6	0.2
Afternoon time (h)	12	13	14	15	16	17	18	19	20	21	22	23
GEH $\sqrt{\frac{veh}{h}}$	0.3	0.2	0.1	0.1	0.0	1.3	0.2	3.3	4.1	1.5	1.6	1.5

Table 4
GEH statistic for flow (out) south.

Morning time (h)	0	1	2	3	4	5	6	7	8	9	10	11
GEH $\sqrt{\frac{veh}{h}}$	0.0	0.2	0.6	0.3	0.9	1.7	0.0	0.9	0.0	0.7	2.4	0.3
Afternoon time (h)	12	13	14	15	16	17	18	19	20	21	22	23
GEH $\sqrt{\frac{veh}{h}}$	0.7	1.0	1.5	0.2	0.1	2.2	0.2	0.4	3.5	3.8	1.4	0.1

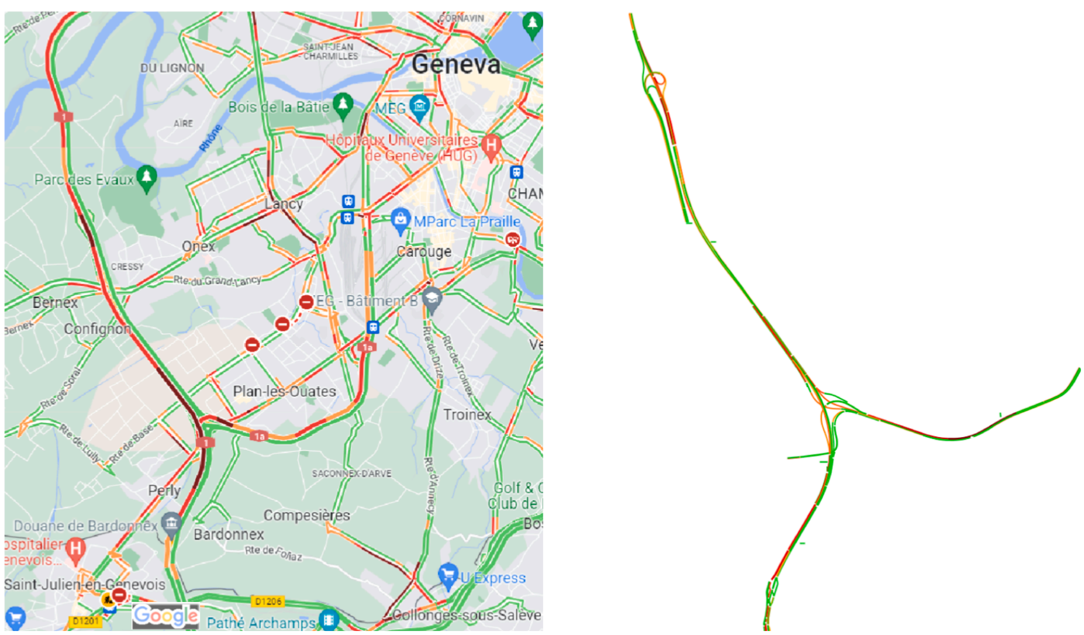


Fig. 8. Comparison of spatio-temporal speed distribution between actual real traffic and run-time DT-GM.

of the EIDM car-following model [35] is recommended for future work, too.

In addition, speed limits need to be taken into account because they strongly influence vehicle dynamics and, thus, traffic flow parameters (throughput, density, etc.) on a given motorway section. Therefore, speed limits are of great importance when modeling traffic flow dynamics on motorways. In the current model, the motorway's real speed limit system was unavailable to us and, therefore, could not be utilized. Instead, the predefined (static) speed limits for Swiss motorways were used for the modeling. The lack of speed limit information across the network could affect the traffic dynamics and, thus, can represent a cause for potential errors in the DT-GM if the speed limit changes significantly over time while nominal speed limits are considered. This will be further investigated and also included in the model once ODPMS provides speed limit data.

Moreover, conditions such as weather can affect traffic behavior on motorways. Thus, DT-GM can take into account not only information from sensors about traffic flow on the motorway (traffic counters), but also sensors from the environment, i.e., sensors that describe the condition under which traffic flow operates. All of these changes can, therefore, be captured by a run-time DT in order for a model to accurately reflect traffic changes and provide better insight into the monitored motorway system. Thus, an interesting future work direction would be to investigate the possible integration of hidden, latent variables of environmental sensors, such as weather conditions or daytime and nighttime visibility conditions on the motorway [2]. In addition, the road maintenance component with information about lane closures or road surface conditions should also be integrated into the microscopic DT model.

So far, it has often happened that *calibrators* wait until the end of the interval and then generate a higher number of vehicles to meet the desired traffic volume on edge, which might form the vehicle platoon. This can be observed with short intervals (one minute long calibration period) when the traffic volume that needs to be calibrated by the calibrator varies a lot. Thus, it would be a good way to enable the calibrator to scan the few edges upstream to get an approximate insight of the amount of traffic that will pass in the current calibration interval so that it can uniformly (or using other distributions) generate the desired amount of vehicles during the calibration interval. In our case, when the calibration interval is one minute, the dominance of platoons in moderate traffic is not apparent. However, if the calibrators are demanded to generate a higher traffic volume, they may create a platoon that affects the ongoing traffic in an unrealistic way. Nevertheless, this seems to be changed in the future by SUMO.

Even traffic counters on motorways provide accurate information about the traffic flow for a given micro location, the current limitation is the sparse coverage of the motorway with traffic counters, where there are a larger number of entry and exit ramps that are not equipped with traffic counters. A satisfactory DT model is subject to two conflicting requirements. It must be sufficiently detailed to represent actual traffic with relative accuracy, and simultaneously, it must be simple enough to make real-time simulation analysis practical. In this manner, the traffic flow models (1) and (2) for estimating traffic volumes on unknown routes can be further simplified by integrating new traffic counters on the aforementioned ramps, which might form the basis for a more stable solution (fewer unknowns) of the traffic flow model and, thus, might increase the accuracy of DT-GM even further. This is critical to accurately reflect changes in traffic dynamics across the motorway while reducing computations when the DT-GM model is extended to a larger motorway network.

So far, the final solution of (1) is affected by the manually defined desired level of intensities ($\overrightarrow{X}_{free-des}$) for free variables in the model (see Section 5.2.2). Since different distributions of flows can be observed over the weekdays, further development of defining the adaptive mechanism for $\overrightarrow{X}_{free-des}$ is needed to match traffic intensity on intermediated network elements. In particular, the bottleneck in DFC is the search of the space for feasible bounds on $\overrightarrow{X}_{free}$, which is performed by the Simplex algorithm and relative error formula. So far, we have minimized the simplifications of the model to preserve most of the traffic dynamics (further simplifications reduce the number of unknowns in the model, but at the expense of the accuracy of DT-GM). Thus, we found that the limiting number of free variables in DT-GM is 6, for which DFC can still find the system's feasible solution (2) in a reasonable time.

In addition, indications from the design phase and modeling of DT-GM imply that it would be possible to make this mechanism dynamic, i.e., to adjust (reduce or increase) the number of Simplex runs depending on the measured error between $\overrightarrow{X}_{free}$ and $\overrightarrow{X}_{free-des}$ and defined error threshold. So far, we have found that it is better to use the formula for the relative error (see Section 4.2) between a vector of the desired intensity and the vectors from the given set of feasible solutions to search for the best $\overrightarrow{X}_{free}$, (comparing the mentioned vectors using the cosine distance gives worse results during peak periods). The above shortcomings may pose a challenge for large-scale DT simulation of a more complex road network. One possibility to improve the scalability of DT-GM is to use the *divide-and-conquer* approach. It can parallelize the simulation processes of each motorway region and use the (in/out) flow of a particular region as the (out/in) flows for the simulation process of the neighboring regions and vice versa. Finally, a possible extension of the used mathematical tool (Simplex algorithm) with, e.g., Genetic Algorithms or advanced machine learning algorithms together with the fusion of traffic flow data with other available data sources, such as mobility behavior through smartphone positioning data [4] could be an interesting future work direction to improve robustness of DFC and thus DT-GM itself. IoT [16] and Big Data [8] in urban mobility raise the question of a synergy of DT microscopic simulation and AI technology in the future.

8. Conclusion and future work

This article presents a comprehensive methodological process for developing a motorway DT. Comparison of our study with existing research on recent advances in the development of DT in transportation leads to several important findings. First, it fills a gap in the literature by presenting DT-GM: a novel microscopic simulation-based digital twin of the Geneva motorway implemented in the microscopic simulator SUMO. Second, the results show that the proposed DFC mechanism exploits the full potential of SUMO to dynamically adapt the running scenario by leveraging the SUMO's calibrators objects used to calibrate the traffic flow at run-time via the TraCI interface. Thus, DT-GM itself continuously adjusts the run-time traffic scenario as the spatio-temporal traffic changes on the real motorway. Finally, our DT-GM model uses the newly available fine-grained real-time traffic data received every minute from the traffic counters on the Geneva motorway via ODPMS. This allows for comparing the performance of DT with the actual motorway traffic at run-time. Experimental results confirm the reliability of DT-GM, as it reflects the actual traffic with high accuracy. This means that DT-GM responds to the physical motorway with relatively low latency, which is made possible by the current development of ODPMS.

Although this article is a fairly comprehensive study, the work is based on some assumptions that might affect the run-time microscopic simulation results. One important factor is the limited number of traffic counters on the observed motorway section. We partially overcome the lack of measurements with the traffic flow conservation model (used with DFC), which replaces the missing traffic data for particular locations in the DT-GM model. However, further development and implementation of traffic counters are expected, which will allow for better capturing of the overall traffic dynamics. Another important factor appears to be the evolving traffic on the motorway network, which is likely to be affected by the introduction of variable speed limits. This is especially true for motorway dynamics, where we have assumed nominal (maximum allowable) speed limits on Swiss motorways for the main sections, as access to speed limit information via ODPMS is currently in development.

Nevertheless, DT-GM provides the basis for a wealth of new concepts in TM that were not possible before. DTI-GM parallelization provides a foundation for assessing the implementation risk of control strategies during system run-time, i.e., before the control scheme is applied to the actual physical system. Future work will therefore explore the applications of DT in the optimization of variable speed limits in a safety–critical decision context using advanced self-regulating adaptive controllers. That will provide further details on the design of the proposed bidirectional interaction between DT-GM and the physical motorway, i.e., closing the information loop between DT and the physical world and realizing digital-physical convergence. Finally, the presented results and discussions can signal to authorities the future inclusion of other real-time information in ODPMS, which could stimulate and initiate further research on applying DT technology in mobility in general.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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