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Building a Motorway Digital Twin in SUMO: Real-Time Simulation of Continuous Data Stream from Traffic Counters

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***Abstract*—In contrast to prevailing studies, in this paper, we focus on the application of microscopic simulation during system run-time by using fine-grained actual traffic data streams from motorway traffic counters as input to on-the-fly synchronized Digital Twin of the Geneva motorway (DT-GM). Particularly, motivated by the lack of detailed steps on how to systematically use third-party controllers to dynamically generate and calibrate traffic flow in running simulation scenarios in the microscopic traffic simulator SUMO, we present technical details of methodological approaches used to build DT-GM in SUMO. In this context, we highlight the dynamic flow calibration (DFC) mechanism based on the calibrator objects embedded in SUMO, as well as the dynamic rerouting. Both of which can be controlled (adjusted) during the simulation run-time by interacting with a third-party controller through the SUMO TraCI interface. These are essential building blocks of DT-GM, which are used to dynamically generate the desired traffic volumes and continuously calibrate the simulated traffic scenario as the corresponding physical traffic dynamics change. Thus, the actual speeds and number of vehicles with the vehicle class recorded by the traffic counters in minute resolution are directly fed into the running DT-GM. Accordingly, DT-GM continuously adjusts to its physical correspondence in real-time, ensuring calibration on-the-fly as opposite to traditional offline calibration.**

***Keywords*—Digital Twin; SUMO; Calibration; Microscopic Traffic Simulation; Real-Time Data; Smart Motorway.**

I. INTRODUCTION

Today's availability of Big Data generated by transportation systems (e.g., from road sensors or the vehicles themselves) enables the real-time digitization of the transportation system. The digitization of services and real-time monitoring combined with advanced traffic control approaches are making motorways smart. This offers many benefits for travelers and traffic management (TM) in general. With this information, operators can deploy intelligent transportation systems and take measures to optimize the performance of motorway systems, make the best use of existing motorway infrastructure, etc. [1], [2]. Meanwhile, the enormous potential of information technologies in road transport enables real-time fusion of the physical road system and the digital world (simulations) in traffic modeling and analysis [3–5]. In general, such integration is known as the Digital Twin (DT), which envisions a merging of the virtual and physical worlds [6].

However, the strategic advantage of this integration is still in its infancy and is not yet fully exploited in the motorway sector. Motivated by the predominance of traditional (offline) simulation approaches, in our article [7] the possibilities of modeling the digital twin in the microscopic traffic simulation software Simulator of Urban Mobility (SUMO) [8] were presented. Thus, we proposed the DT of Geneva Motorway (DT-GM) driven by newly available real-time motorway traffic data from traffic counters accessible via the Open Data Platform Mobility Switzerland (ODPMS)[1], the customer information platform for public transport and individual mobility in Switzerland, provided by Swiss Federal Roads Office (FEDRO). This allows us to pay attention to the simulation application during the run-time of the motorway system. To encourage other research and further development and application of digital twining in transportation, we decided to provide detailed technical steps for creating a motorway DT in SUMO. Therefore, this paper serves as a technical complement to DT-GM, which we proposed in [7], by providing systematic steps for creating it. In addition, we make our DT-GM model with source code publicly available[2] to serve as a basis for further investigation by the community. To take full advantage of our run-time DT-GM model, one must register with ODPMS to access the actual traffic counter data.

II. USE CASE AND APPLIED METHODOLOGY

The aim of this paper is to provide a detailed technical description of the structure of the DT-GM in SUMO, thus, we strongly recommend visiting the provided links in section I.

A. Physical twin - Geneva motorway

The section of $A1$ motorway in the Geneva region is used as the basis for DT-GM microscopic traffic modeling (Figure 1b). The motorway network consists of a large grade-separated interchange with interchanges to Geneva (east), border with France (south), and (north) toward Geneva Airport. The main sections of the motorway consists mainly of two or three lanes. In addition, the motorway contains entry ramps x_{11}, x_{12}, x_{15}, x_{16}, and exit ramps x_9, x_{13} (Figure 1a), where x_i represents the corresponding traffic flow $[veh/h]$. It is worth mentioning that the model has slight simplifications. For example, some minor entrances and exits to the main sections, for which

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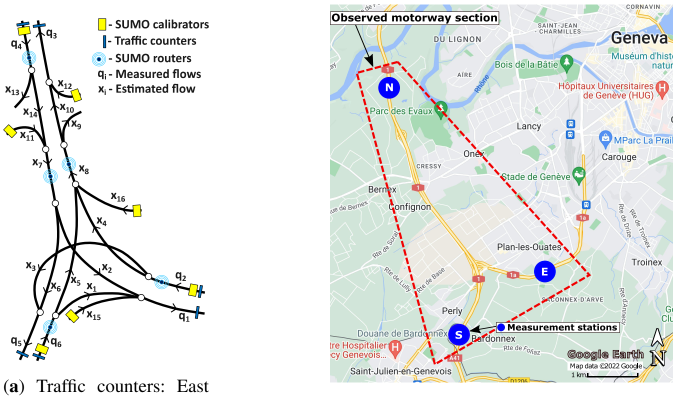
[1] https://opentransportdata.swiss/en/rt-road-traffic-counters/

[2] https://github.com/SiLab-group/DigitalTwin_GenevaMotorway



(**a**) Traffic counters: East (E), North (N), South (S)

(**b**) Physical motorway with traffic counters

Figure 1. Physical motorway and abstract correspondent model [7]

ODPMS does not provide data, were not included in the model to reduce the unknowns in the traffic flow model (2).

B. 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. Instead, if one sets up traffic counters that capture most of the incoming and outgoing motorway traffic ($q_i[veh/h]$), one can estimate the traffic in between. Thus, from partial data, one can set up a system of linear equations (1) using the law of conservation of traffic flow and calculate (or estimate) the unknown traffic flows on the road network.

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

$$\vec{X} = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \\ x_6 \\ x_7 \\ x_8 \\ x_9 \\ x_{10} \\ x_{11} \\ x_{12} \\ x_{13} \\ x_{14} \\ x_{15} \\ x_{16} \end{bmatrix} = \begin{bmatrix} q_1 \\ 0 \\ q_5 \\ q_2 - q_5 \\ q_6 - q_1 \\ 0 \\ 0 \\ q_2 - q_1 - q_5 + q_6 \\ q_2 - q_1 - q_3 - q_5 + q_6 \\ q_3 \\ 0 \\ 0 \\ q_4 \\ 0 \\ 0 \\ 0 \end{bmatrix} + \begin{pmatrix} 1 & -1 & 0 & -1 & -1 & 0 \\ -1 & 1 & 0 & 1 & 0 & 0 \\ -1 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 \\ -1 & 1 & 0 & 1 & 1 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 1 & 0 & 0 \\ 0 & 1 & 0 & 1 & 1 & 1 \\ 0 & 1 & 1 & 1 & 1 & 1 \\ 0 & 0 & -1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} \times \begin{bmatrix} x_6 \\ x_{11} \\ x_{12} \\ x_{14} \\ x_{15} \\ x_{16} \end{bmatrix} \tag{2}$$

In the context of a motorway, we assume that the roads are *one-way* streets and that a vehicle entering the observed network leaves the network (no terminal states in between). Thus, 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 (Figure 1a). The solution (2) of the linear system of equations (1) represents the general solution of the flow balance in the flow model. From a practical point of view, all flows must be non-negative, so we add the constraints (3) on (2).

$$\vec{X} \geq 0 \tag{3}$$

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 (3) 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 $\vec{X}_{free} = [x_6, x_{11}, x_{12}, x_{14}, x_{15}, x_{16}]^T$ 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 10 intensity levels. Once the feasible ranges are known, we further restrict the solution space by defining the desired intensity vector of the free variables $\vec{X}_{free-des}$. 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 of $\vec{X}_{free}$ is determined by calculating the minimum relative error using formula $\frac{\|\vec{X}_{feasible} - \vec{X}_{free-des}\|}{\|\vec{X}_{free-des}\|}$ between the vector of desired intensity and the given set of feasible solution vectors. 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 $\vec{X}$.

C. SUMO's Calibrators Objects

In SUMO, calibrators (*trigger-type objects*) enable the modeling of location-dependent changes in the dynamics of traffic flow 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.

1) Calibrator Definition: Each calibrator is uniquely associated with a particular edge (a street in the simulation model) or even to a particular lane at the edge where it is placed. 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 length of the interval defines the aggregation period for comparison of observed and desired flows. The goal of the calibration is to ensure that the correct number of vehicles are deployed at the end of the 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 [8]. 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 $[veh/h]$, as well as vehicles can be assigned with the desired speed

$[m/s]$. Each calibrator with its attributes must be defined in the so-called additional file *cali.add.xml* and loaded together with other files during the simulation start up. This means that the calibrator in its basic configuration works like a static object and modifies the traffic flow according to the predefined attributes stated above, so that different flows and speeds can be used for different simulation time intervals.

2) Run-time calibrator modification via TraCI: Moreover, SUMO provides the ability to access the calibrator via TraCI while the simulation is running. TraCI is the abbreviation for "Traffic Control Interface." It provides access to a running road traffic simulation and allows for retrieving values from simulated objects and manipulate their behavior during the run-time of the simulation [9]. This allows one to call a specific calibrator and change the flow rate, speed, and even vehicle type in the current time interval. In our experiment, we defined intervals so small (one minute long) so that they correspond to the frequency of receiving actual traffic data from motorway sensors. Since automated counting stations (see Figure 1b) imply traffic counters installed per lane, in our microscopic simulation model we placed the calibrators at the corresponding positions of the real counters located on the motorway sections in the Geneva region. These calibrators are, thus, used to continuously adjust the flows to match the current simulation traffic demand with changes of actual traffic in the real motorway with one minute resolution. Also, during the calibration process, it is possible to apply a so-called *filter*, which specifies a particular type of vehicle to be changed by the calibrators in the traffic flow. In this way, two calibrators can be used on the same edge (or lane), one for the calibration of cars and the other for the calibration of heavy vehicles, without interfering with each other.

D. Dynamical Rerouting of Vehicles

The realism of traffic flow behind or between calibrators depends on the correspondence between random routes and real routes. The importance of this correspondence increases with the size and complexity of the network between calibrated edges. In conjunction with calibrators, rerouting allows the desired traffic flow to match other edges (routes). Thus, once the desired traffic flow is inserted by the calibrator, it can be distributed across the network by assigning routes to individual vehicles. Note that routes can also be distributed with certain probabilities that determine how likely it is that the route will be assigned to a vehicle. It is worth noting that the calibration object can work with so-called route probe detectors. If the *routeProbe* attribute is specified in the calibration definition, a route is selected from the distribution of sampled routes by probe detector. This method is better suited for large city networks with a large number of possible routes. However, for 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 basis for introducing the DFC mechanism to reroute the traffic flows computed by (2) across the observed motorway (Figure 1a).

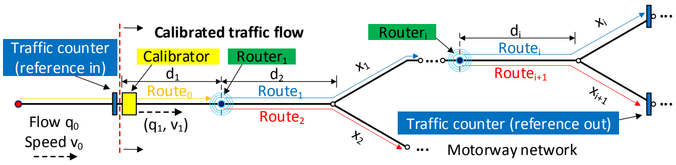


Figure 2. Dynamic Flow Calibration principle in SUMO [7]

E. Principle of Dynamic Flow Calibrator Mechanism

Given the locations of the physical traffic counters (Figure 1b), 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 Dynamic Flow Calibrator (DFC) mechanism to match the traffic flow on other observed motorway segments (Figure 1a). DFC uses information about all possible routes from a given point (manually defined in the file *route.xml*). Next, the information about traffic flow on the edges (calculated by (2)) is used to compute the probability distribution of the traffic flow among all possible routes. 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 Figure 2. Given the initial traffic flow q_0 with speed v_0 arriving at the starting point of the model, 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 (calculated by (2)). For example, the probability P_{x_1} that a vehicle is assigned to traffic flow x_1 (on $Route_1$) is calculated as follows $P_{x_1} = 1 - P_{x_2} = 1 - x_2/q_1$, where P_{x_1} and P_{x_2} are calculated every minute and transmitted via TraCI to a particular edge on which routing is performed. Since the sum of probabilities is always equal to one, the probabilities of assigning a vehicle to a particular route among two possible routes are defined as an ordered pair and can take the following discrete values $\{(P_{x_1}, P_{x_2}) : (1,0), (0.9, 0.1), \ldots, (0.1, 0.9), (0,1)\}$. Thus, the process of rerouting assumes that the desired probability distributions have been upfront in the file *routesDistributions.rou.xml* and loaded along with other configuration files during the initialization of the simulation. This rerouting handling follows the same principle for the entire motorway model in areas with multiple possible directions of travel.

To avoid assigning new calculated routes to the vehicles already inserted in the simulation, and thus to prevent incorrect rerouting of vehicles arriving late in the router area (due to delays caused by possible congestion), an additional *marker* is added to each vehicle when it is inserted in the simulation. It contains the information about the routes calculated by DFC for a certain time window when the vehicle was inserted into the simulation. Thus, once a vehicle reaches the router area, it is re-routed based on encoded routes in *marker*. In addition, sufficient distance d_i between the router and the next junction should be ensured to have enough space for smooth lane-change maneuvers in order to follow the desired travel route.

The summary of the execution of the DT-GM microscopic simulation model is represented by an algorithm 1. After all variables are initialized, the algorithm loads the initial simulation scenario $\vec{S}$ with all necessary SUMO files. The simulation is started and controlled by TraCI. At each simulation step, SUMO calibrates and updates the simulated traffic scenario. For every multiple of 60th second of real-time, a new request for actual traffic data is sent to the FEDRO server via ODPMS. The data (traffic flows $\vec{q}$, speeds $\vec{v}$, and vehicle type $\vec{v}_{type}$) are received and forwarded to the DFC mechanism. In this way, the calibrators $\vec{C}$ are entrusted with the task of generating the desired traffic flow (considering the received speeds and vehicle types), which is detected by the traffic counters. Moreover, DFC computes all traffic flows $\vec{X}$ in the network and, accordingly, the route distribution probabilities $\vec{P}$ to distribute the traffic flows generated by the calibrators through the network such that $\vec{X}$ is satisfied for a current time window of one minute. The process is repeated until the specified end, saving the state of DT-GM. In addition, the process can be reloaded by loading the saved simulation state and executing from that point.

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 $\vec{X}$ (see (3))
      Update $\vec{C}$ and $\vec{P}$ using $\vec{X}$
    end if
    Calibrate and update simulation scenario
  end for
  Save DT-GM simulation state and close simulation
```

III. EXPERIMENTAL SET-UP

The framework of DT-GM used in our experiments consists of the microscopic simulator SUMO, the Python programming environment, and the ODPMS web service (see [7]).

A. Simulation model and initial traffic demand

To create a simulation model with a realistic representation of the geometry of a real road network, geometric elements with appropriate attributes must be converted into the simulation network model. For this purpose, the Netedit module from SUMO is used to create a digital motorway network from open source geographic data. Since the OpenStreetMap (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:

(i) A large file *.osm.pbf* containing all OSM objects in the area of Switzerland is downloaded from the website[3]; (ii) From this file, filtering using a specific polygon determined by longitude and latitude coordinates was performed to extract a specific region of interest (region of Geneva in our case). Filtering was performed using the software *osmconvert*. The result is the file *.osm.pbf* containing a specific region; (iii) To convert it to *.osm* file, *osmconvert* was applied again; (iv) In addition, *osmosis* software can be used to extract the motorway network from the generated *.osm* file; and (v) From this, the SUMO tool *osmNetconvert* is used to convert OSM data into a *.net.xml* file suitable for loading into the SUMO engine. Also, we found it worthwhile to make some changes to the network manually in SUMO's NETEDIT to get more details about the motorway topology, so we skipped step (iv).

Once the motorway network is defined, the traffic flow can be generated in the form (from-to), where (from) is associated with the starting edge and (to) is associated with the ending edge. The sequence of edges between the starting edge and the ending edge forms a route. The initial traffic flow is defined to be coupled with the oscillating traffic demand because the calibrator works by waiting a while to see if any traffic passes over it, and if not, it starts generating traffic to achieve the desired traffic volume for a given calibration period. Since we use very short time intervals for calibration, the traffic generated (during peak hours) may appear too high at the end of the calibration period, forming an additional platoon of vehicles. To avoid this calibrator's manna (this seems to be changed in the future by SUMO), the initial traffic flow is generated so that there is a uniform traffic flow. Thus, if no vehicles are detected by the traffic counters, the calibrators simply delete the incoming vehicles. If the traffic volume measured by the traffic counters is higher than the current generated traffic volume at a particular edge, the calibrator adds additional vehicles to meet the required demand. Finally, the routes and the associated initial traffic flows q_{init}, defined by the certain probability of inserting vehicles per second veh/s, can be found in the source code in the files *routes-Distributions.rou.xml* and *flows.flows.xml*.

B. 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 with the basic simulation configuration (default parameters) resembles actual traffic by using the underlying motorway system information through the fine-grained real-time traffic data and run-time calibration of traffic flow with DFC (Figure 2). Therefore, the observation between actual (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.

1) SUMO simulation parameters: Traffic flow data consists of cars and trucks, as these classes were distinguished by traffic counters. At the moment, we used the latest SUMO version (1.13.0). The longitudinal (speed choice) vehicle behaviour uses the Enhanced Intelligent Driver Model (EIDM) car-following model [10], while lateral (lane changing, overtaking, merging) behaviour uses the lane change model LC2013 [11].

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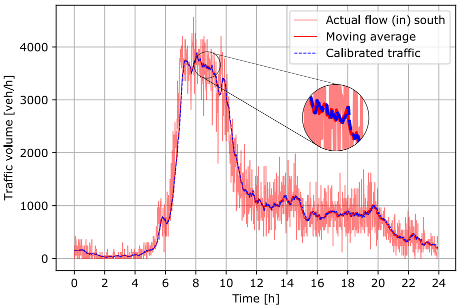
[3] http://download.geofabrik.de/

Additionally, several parameters within mentioned models were modified. The parameters tau (time headway) defining the time interval between successive vehicles in the traffic flow, measured in seconds was defined by a lognormal distribution generated using a Python *numpy.random.lognormal* module with the shape parameter $\sigma = 0.05$ and the location parameter $\mu = 0$ [12]. Thus, 300 different vehicle types for both, cars and trucks were defined within *vtype* file in SUMO. Cars were assigned the entire range of headway values, while trucks were assigned the headway greater than $1\ s$. Considering [13], [14], the next parameters are customized as follows. The lane change parameter $lcstrategic$ for vehicles is defined using the normal distribution with the values mean 0.8 and standard deviation 0.05 for cars. The value of 1 is used for trucks. The minimum gap parameter $minGap$ is defined using the normal distribution with a mean value of 1.5 and a standard deviation of 0.02 for cars. We use a ballistic update with the simulation step set to a quarter of a second, which means that four simulation steps result in one simulated second. Also, we have assumed nominal maximum allowable speed limits values on Swiss motorways [120 km/h] for main sections. Finally, actual traffic on Thursday, March 24, 2022, and the results of corespondent run-time simulated traffic replica by DT-GM were summarized in the next section.

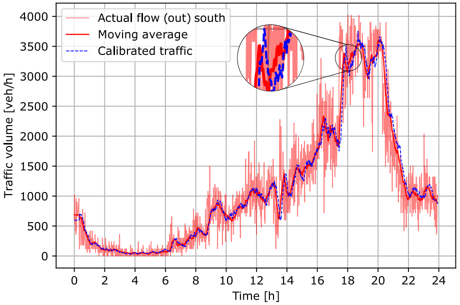
2) Flow model parameters: The free variables in the traffic flow model, x_6, x_{11}, x_{12}, x_{14}, x_{15} and x_{16} are defined by choosing the desired intensity levels defined by the vector $\vec{X}_{free-des}$ rather than absolute values. Thus, the defined intensity level for these variables is approximated by observing the GPS traces on the OSM and Google Map traffic website as a function of time of day and experimenting with run-time test simulations. Thus, 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 approximation intensities of the actual traffic, they are accurate enough to be used by DFC, which generates a final feasible solution that clearly satisfies 3. Thus, eight different intervals with respect to the time of day and corresponding desired intensity vectors $\vec{X}_{free-des}$ are defined for free variables. Also, when solving the inequality to find a feasible solution for (3), the Simplex algorithm (*scipy.optimize.linprog*) is performed in two steps (see [7]).

IV. RESULT ANALYSIS AND DISCUSSION

As part of our main work in [7], in-depth analysis of simulated workday traffic flow at run-time by DT-GM and comparison with actual traffic is presented. Therefore, we largely refrain from describing the overall performance of the model in this section. Instead, we focus our analysis and discussion on specific traffic counters and the accuracy of associated traffic flow generated by calibrators at the main section of the motorway at southbound. The smoothed curves in Figure 3a are generated by the moving average of 20 samples of one-minute traffic volumes and show the evolution of traffic flows for a selected workday from the French border to Switzerland, while Figure 3b shows the traffic flow from Switzerland toward the border. Similarly, for traffic flow indicators, we show GEH statistics as a measure of calibration of simulated traffic by run-time DT-GM.



(**a**) Flow (in) south



(**b**) Flow (out) south

Figure 3. Corresponding simulated flow by DT-GM and actual traffic

The total traffic demand in the observed area of the motorway for the analyzed workday has a symmetrical characteristic. Traffic generated by commuters from France contributes significantly to the creation of the morning peak hour (from 7 to 10 a.m.) on the observed section, and conversely, travelers returning to Geneva in the afternoon provide for the afternoon peak hour (from 6 to 8 p.m.). The detailed analysis of traffic flow behaviour is provided in our article [7].

A. *Comparison between DT-GM and actual (real) traffic*

As it can be observed from the results, there is no significant difference between the traffic generated by the run-time DT-GM (blue curves in Figure 3) and the actual motorway traffic (red curves in Figure 3). Both the morning and evening peak hour traffic and the stationary traffic between peak hours match well with actual traffic at the one-minute traffic granularity.

B. *Quantitative workday simulation analysis*

The observation from Figure 3 proves that the calibrator generated (calibrated) traffic flows (in) almost exactly match the traffic flows measured by the traffic counters. Therefore, due to space limitations, we only present the GEH statistics for the southbound traffic flow (out), which is affected by all calibrators generating the eastbound traffic flow (in), the northbound traffic flow (in), and the associated flows from ramps (see Figure 1a), as well as by the DFC mechanism itself. Therefore, the correspondence with actual traffic at some time over the day is slightly delayed (shifted to the right) due to the spatial displacement of the mentioned traffic generators (calibrators) with respect to the observed measurement point, mainly during the high traffic. Nevertheless, the accuracy of traffic flow (out) is still high compared to actual (real) traffic

TABLE I. GEH STATISTIC FOR FLOW (OUT) SOUTH

Morning time $[h]$	0	1	2	3	4	5	6	7	8	9	10	11
GEH $\sqrt{veh/h}$	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 $\sqrt{veh/h}$	0.7	1.0	1.5	0.2	0.1	2.2	0.2	0.4	3.5	3.8	1.4	0.1

measurements, as confirmed by GEH statistics in Table I, where GEH values are in the accepted range from 0 to 5. The highest values are observed during peak hours, when congestion events delay traffic in the intermediate parts of the motorway network by increasing the travel time of vehicles. Despite te fact that 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 let the running simulation scenario evolve as the conditions on the real motorway in areas of traffic counters.

C. Discussion

In general, the results indicate that the run-time DT-GM model accurately represents the actual traffic volume in the area of the (southern) traffic counters on the analyzed section of the Geneva motorway, which supports the methodological approach used to build DT-GM. Moreover, this confirms that SUMO, which was mainly used for offline motorway simulations, is also suitable for run-time simulations. Thus, DT-GM itself (and the underlying technologies) can be used to map actual traffic during the run-time of a motorway system to a virtual run-time microscopic simulation based DT model. Further directions for DT-GM enhancement, are detailed in [7].

V. CONCLUSION AND FUTURE WORK

This paper presents a technical description for building a motorway DT. The study led to several important findings. First, it fills a gap in the field by presenting DT-GM: a novel microscopic simulation based DT of the Geneva motorway implemented in SUMO. Second, the process described for creating DT-GM leverages SUMO's calibrators objects, which were used to calibrate (generate) the desired traffic volume at run-time via the TraCI interface. In this way, DT-GM itself continuously adjusts the traffic volume in the simulated scenario at run-time by interacting with the DFC mechanism and the ODPMS as the actual traffic on the real motorway changes. Although this work provides a rather innovative approach to motorway simulation, it is heavily dependent on access to real-time traffic data. Therefore, this paper highlights the importance of the ODPMS platform and real-time traffic data by presenting the application of newly available fine-grained actual traffic data with minute resolution from traffic counters on the Swiss motorway. This enables the creation of a real-time microscopic simulation of traffic during the lifetime of a motorway system, an essential requirement for the creation of DT in general. Nonetheless, the DT-GM design guide presented provides the basis for further research to utilize and extend the existing model and explore opportunities for microscopic simulation in real-time motorway traffic analysis that were not previously possible. In addition, this paper serves as a technical supplement to our main article, in which we presented the detailed methodology and conceptual foundation of DT-GM in real-time TM applications on motorways.

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