A Modelling Methodology Towards Automated Generation of Road Network Digital Twins

Author
Paulo Ribeiro

Supervisor
Prof. Rosaldo Rossetti

Receiving Enterprise
ARMIS

Company's Supervisor
Eng. José Macedo

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Master in Informatics and Computing Engineering

U.PORTO
FEUP FACULDADE DE ENGENHARIA
UNIVERSIDADE DO PORTO

Agenda

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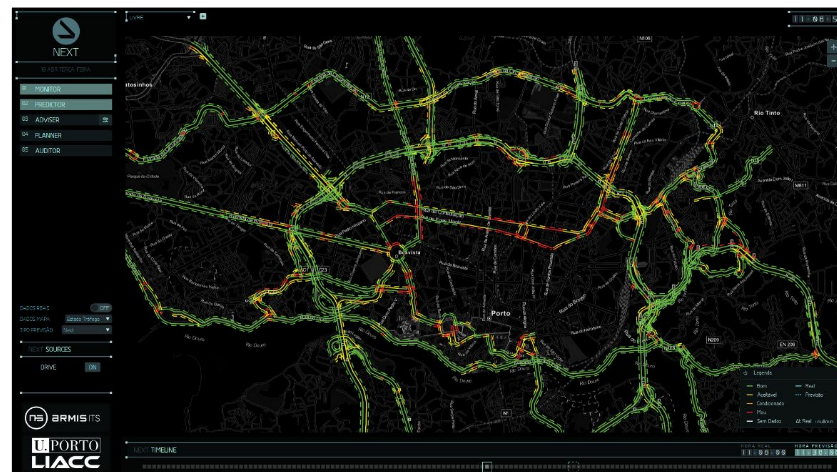
2. Related Work
3. Baseline Methodology
4. Proposed Framework
5. Results and Analysis
6. Conclusions & Future Work

Context

Urban mobility has been facing increasing challenges, such as traffic congestion and accidents.

All these problems stem from the inefficient management of transport flows, which led to the emergence of Intelligent Transport Systems (ITS).

A new concept emerges to ensure the effectiveness of the ITS: the Digital Twin.



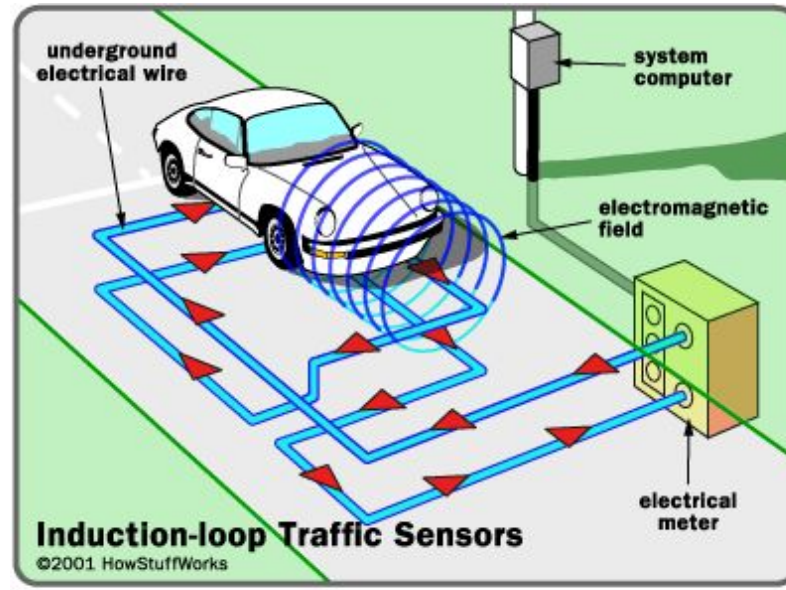
Problem

Building a Digital Twin for Road Networks is an extremely challenging task.

Stationary detectors like Inductive Loop Detectors have limited network coverage.

Furthermore, building a realistic traffic simulation scenario is a time-consuming task.

Each instance of building a Digital Twin for a new road network requires following this exhaustive process.



Motivation

In addition to promoting the proliferation of this new technology in the literature, the proposed framework will significantly accelerate the creation of Digital Twins for road networks.

The spared time by the automatic preparation of a base simulation can be leveraged to develop additional functionalities to augment its capabilities.

Goals

To develop a framework for building Digital Twins, applicable to all road networks.

Specifically, the framework should automatically generate a Digital Twin that reliably simulates the actual traffic behaviour given a representation of the roads and data of the Inductive Loop Detectors present in that network.

In order to achieve this goal, the following specific objectives need to be fulfilled:

- Scrutiny and processing of data from sensors;
- Development of the framework using the microscopic traffic simulator SUMO;
- Model validation through comparison with sensor data.

Related Work

Several implementation scenarios for these tools were analysed in order to identify common steps or problems in their development:

- ➢ Acquiring and preparing a digital network representation is a typical initial stage.
- ➢ Inductive Loop Detectors continue to serve as the predominant data source.
- ➢ SUMO has emerged as one of the most widely employed simulators.

All these works were all developed with an intense focus on the road network under study.

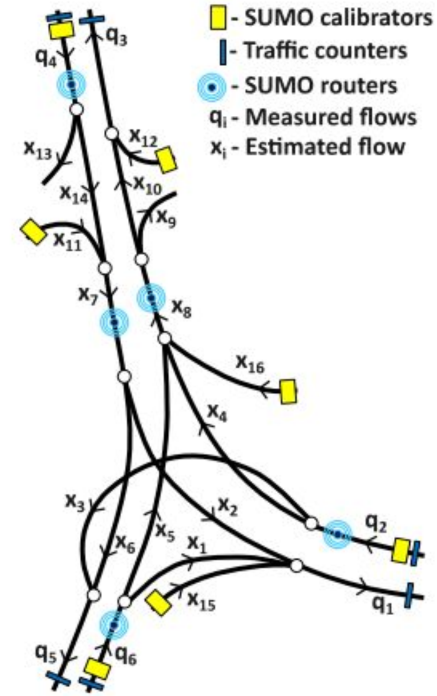
Consequently, their methodologies are intricately tailored to the peculiarities of the respective scenarios, hindering the potential for the methodology’s reuse in different contexts.

Baseline Methodology

The framework's baseline methodology is based on the works in [1] and [2], which present a methodological approach for building a Digital Twin for the Geneva Motorway (DT-GM), in Switzerland, in SUMO.

The authors initially sketched a schematic diagram to represent the network structure, denoting each road segment with a variable representing the traffic flow in *veh/h*.

Then, they extracted the region of interest from OpenStreetMaps, converting it to SUMO format, and used SUMO's NETEDIT module to perform manual adjustments to the network.



[1] Krešimir Kušic, Rene Schumann, and Edouard Ivanjko. «Building a Motorway Digital Twin in SUMO: Real-Time Simulation of Continuous Data Stream from Traffic Counters». In 2022 International Symposium ELMAR, 2022
[2] Krešimir Kušic, René Schumann, and Edouard Ivanjko. «A digital twin in transportation: Real-time synergy of traffic data streams and simulation for virtualizing motorway dynamics», 2023.

Baseline Methodology

The proposed methodology employs a workaround to the limitation of sensor coverage by estimating the traffic flow between network segments.

For this, the authors begin by establishing a system of linear equations based on the principle of conservation of traffic flow.

$$x_1 + x_2 + x_{15} = q_1$$

$$x_3 + x_4 = q_2$$

$$x_4 + x_5 + x_{16} - x_8 = 0$$

$$x_1 + x_5 = q_6$$

$$x_2 + x_6 - x_7 = 0$$

$$x_3 + x_6 = q_5$$

$$x_8 - x_9 - x_{10} = 0$$

$$x_{10} + x_{12} = q_3$$

$$x_{13} + x_{14} = q_4$$

$$-x_7 + x_{11} + x_{14} = 0$$

Baseline Methodology

Subsequently, the authors proceed to derive the solution of the linear system of equations, which represents the flow balance's general solution in the flow model.

In practice, all flows must be non-negative.

Therefore, restriction $\vec{X} \geq 0$ is added.

This solution resulted in six free variables.

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

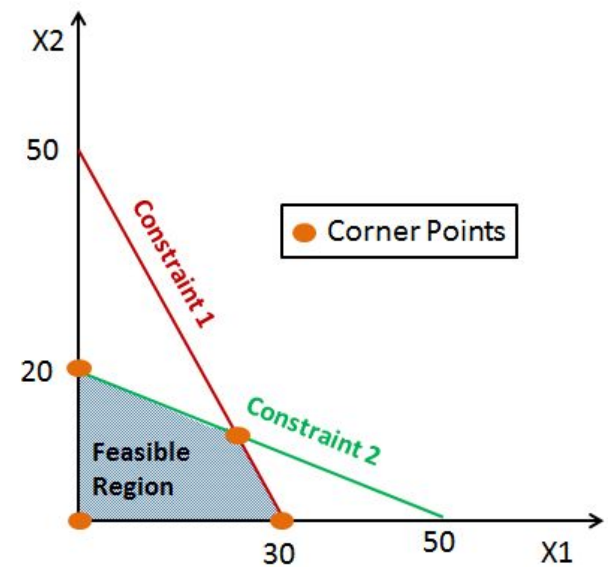
Baseline Methodology

To estimate the values of the six free variables, the authors employ a linear programming approach, which enables searching for feasible solutions using the Simplex algorithm.

More specifically, this methodology defines two steps of the Simplex algorithm.

In the first stage, the restriction $\vec{X} \geq 0$ is applied, resulting in the definition of the extreme points of the feasible region for the free variables.

The second stage imposes additional restrictions on the range of each free variable based on the intensity level for the corresponding road at each time of the day.

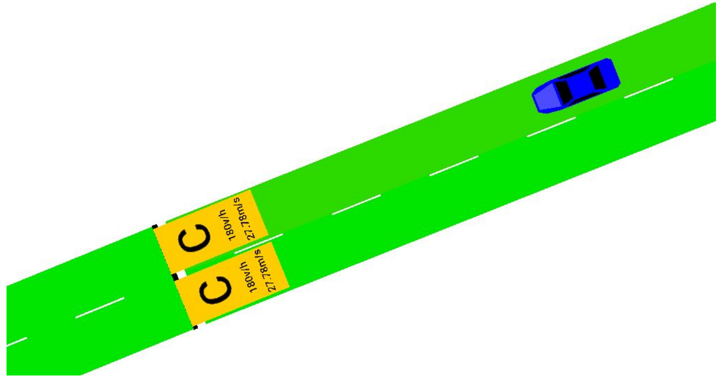


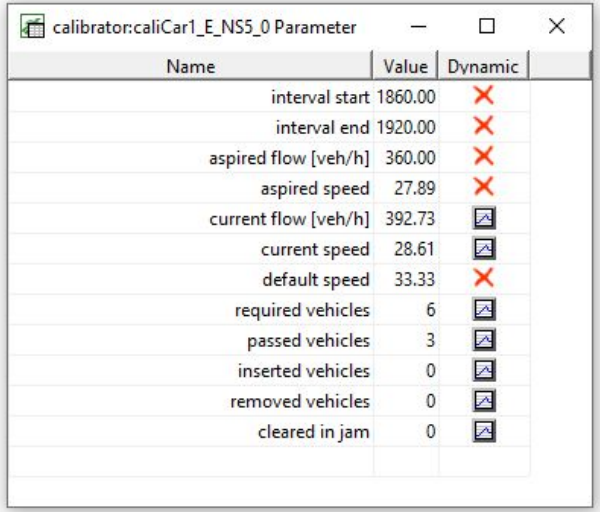
Baseline Methodology

The calculated flows must then be used for the calibration of the model, which is performed using SUMO's calibrator objects.

The authors started by defining some initial uniform vehicle entry flows, which enable the activation of these objects.

The network *calibrators* are dynamically accessed every minute via TraCI, a SUMO interface that provides access to the simulation at runtime.





calibrator:caliCar1_E_NS5_0 Parameter

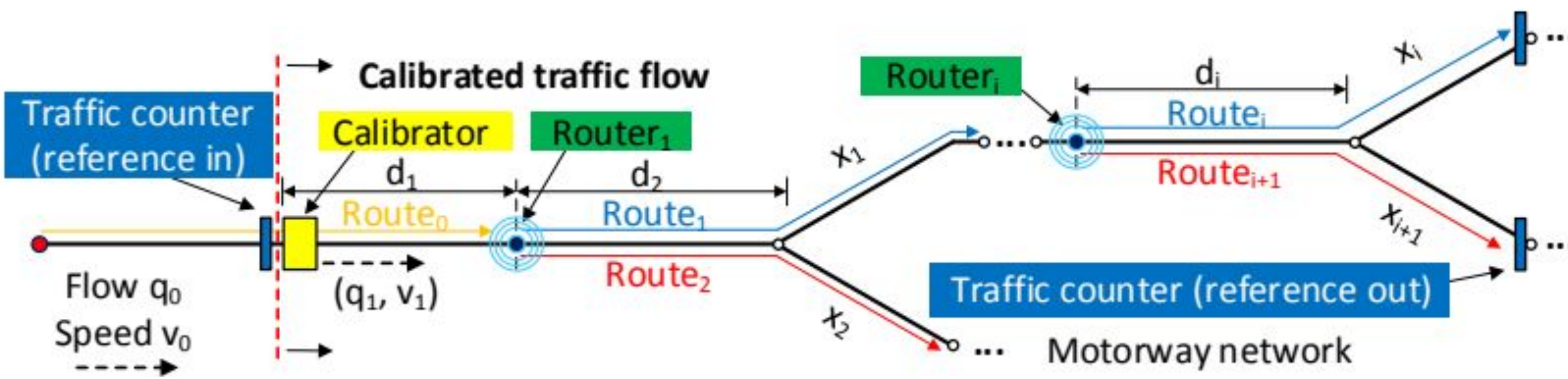
Name	Value	Dynamic
interval start	1860.00	✗
interval end	1920.00	✗
aspired flow [veh/h]	360.00	✗
aspired speed	27.89	✗
current flow [veh/h]	392.73	
current speed	28.61	
default speed	33.33	✗
required vehicles	6	
passed vehicles	3	
inserted vehicles	0	
removed vehicles	0	
cleared in jam	0	

Baseline Methodology

After the calibrator has inserted the appropriate traffic flow, it is necessary to disseminate it across the network, by allocating routes to vehicles.

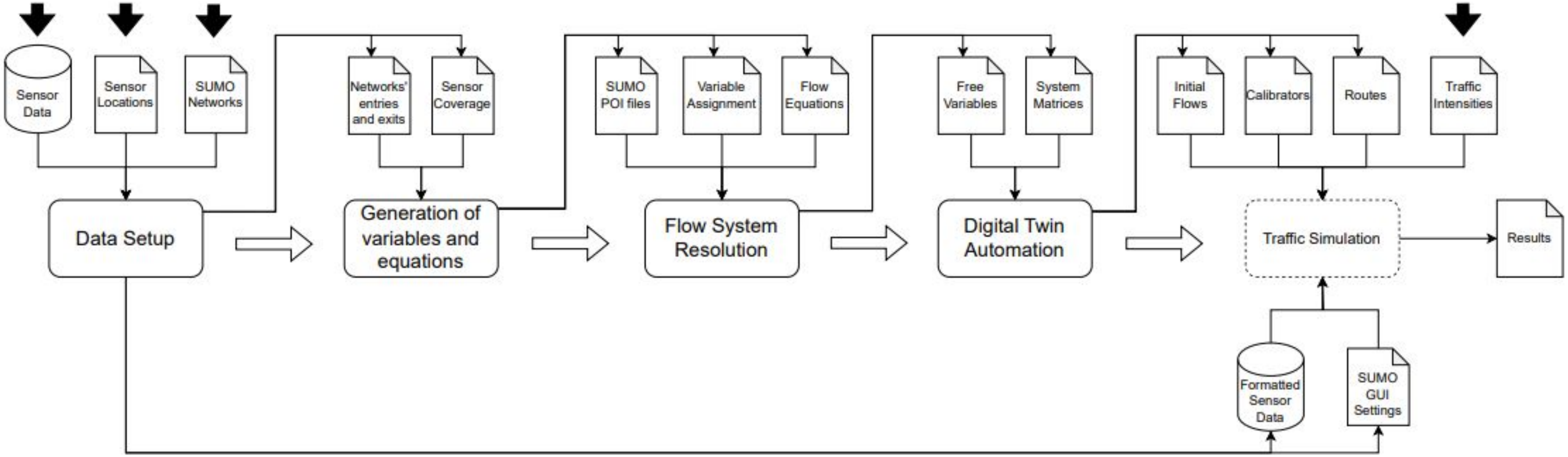
The distribution of routes is determined probabilistically, reflecting the probability of a vehicle following a given route.

The rerouting mechanism, designated Dynamic Flow Calibrator (DFC), calculates probability distributions based on the flow values calculated in the previous stage, and assigns routes to vehicles that cross a given router according to these probabilities.



Proposed Framework

The developed framework can be divided into four primary phases:



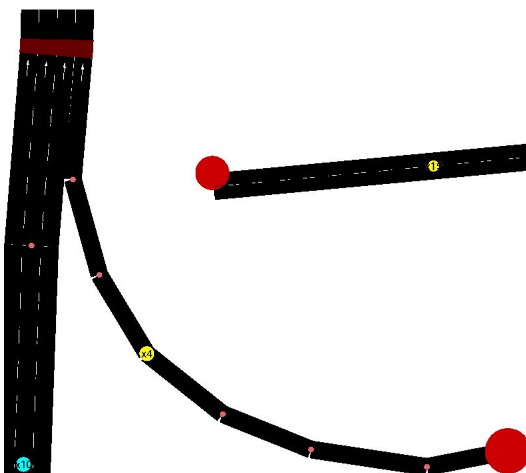
Proposed Framework

Data Setup

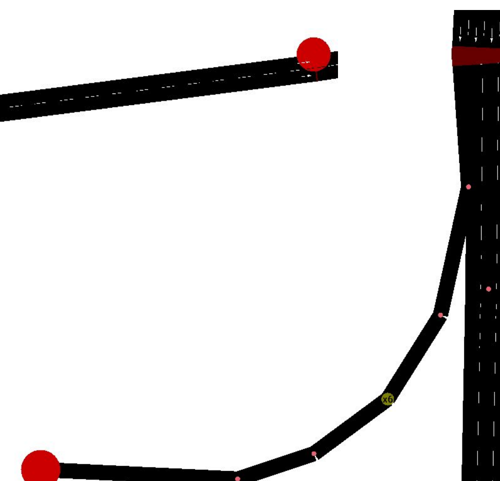
In addition to preparing sensor data by grouping vehicle counts into one-minute blocks, the first phase also deals with finding out the coverage of each sensor.
This first phase also deals with detecting the network's entries and exits:

- If the node has no incoming edges, it is an entry node.
- If the node has no outgoing edges, it is an exit node.

Example of a continuation edge



Example of an entry node



Example of an exit node

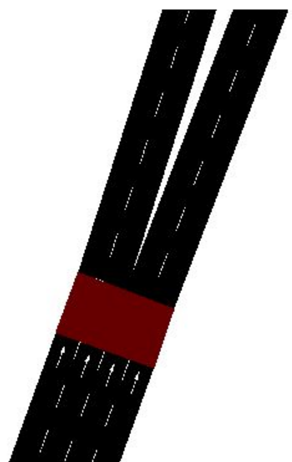
Proposed Framework

Generation of variables and equations

To assign variables to the edges of the network in the second phase, the program begins by generating new variables for the network's entries and exits. Then, a search begins by traversing the network from the entries, finding four possible scenarios:

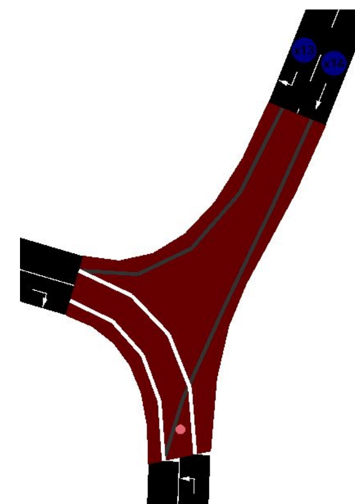
- ➢ **continuation edge**
- ➢ **split**
- ➢ **merge**
- ➢ **complex nodes**

During this stage, the program also places a router before every split.



Example of a split

Example of a merge



Example of a complex node

Proposed Framework

Flow System Resolution

In the third phase, the program generates the augmented matrix of the system of equations, and then converts it to the reduced row-echelon form, through Gaussian elimination operations.

This phase determines the free variables of the system, in addition to the matrices related to the system solution, used to calculate the remaining variables during the simulation.

Proposed Framework

Digital Twin Automation

The fourth phase begins by generating the calibrators, the initial flows and the vehicle routes.

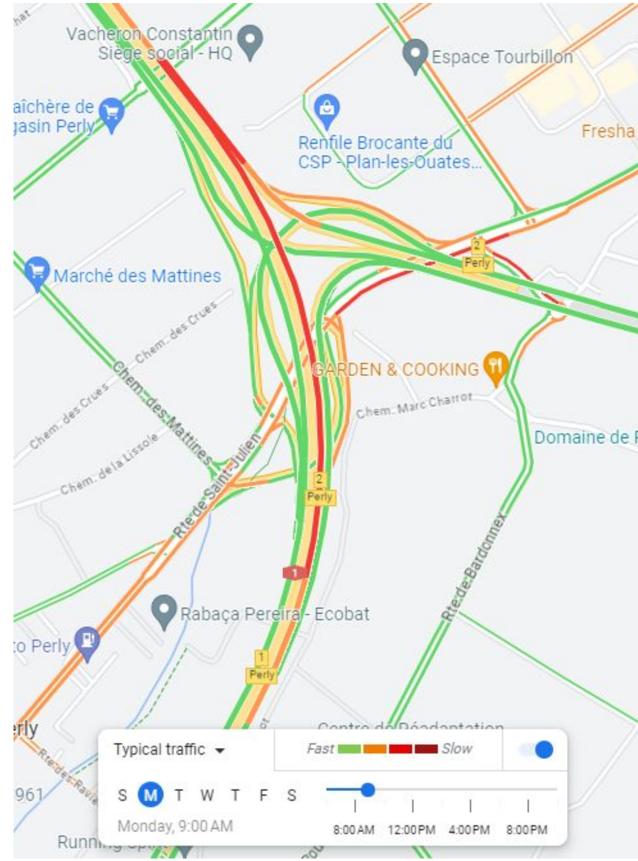
The routes of the calibrators, initial flows and vehicles are generated through a depth-first search (DFS).

For the calibrators, this search starts at each calibrator edge, for the initial flows it starts at the edge of the network entry, and for the vehicles it starts at each router edge.

For the three cases, the search ends in two possible scenarios:

- ➢ It reached a router edge;
- ➢ It reached a network exit edge.

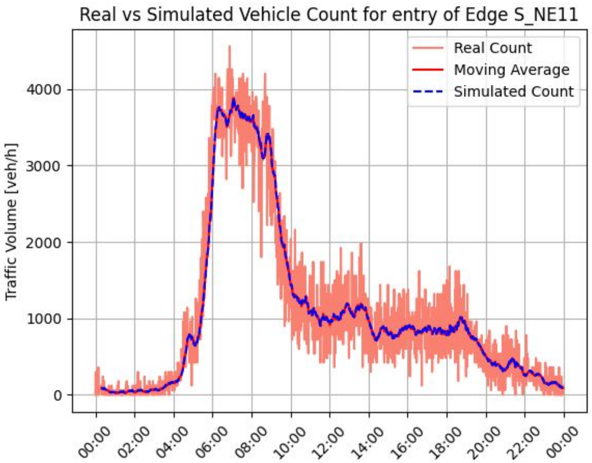
Finally, the framework executes the Digital Twin, which constantly updates the simulation flows, recording their values every minute.



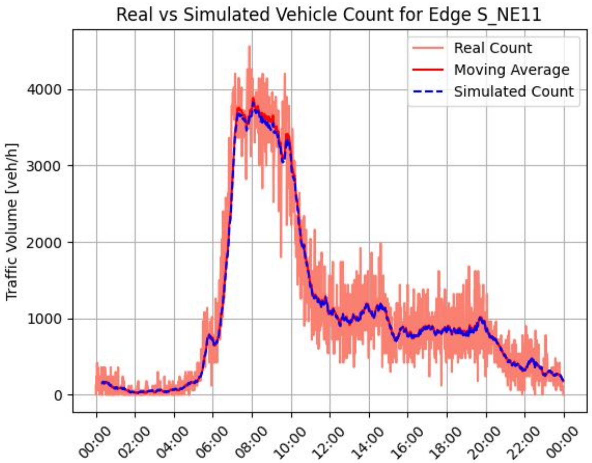
Results and Analysis

Geneva Motorway

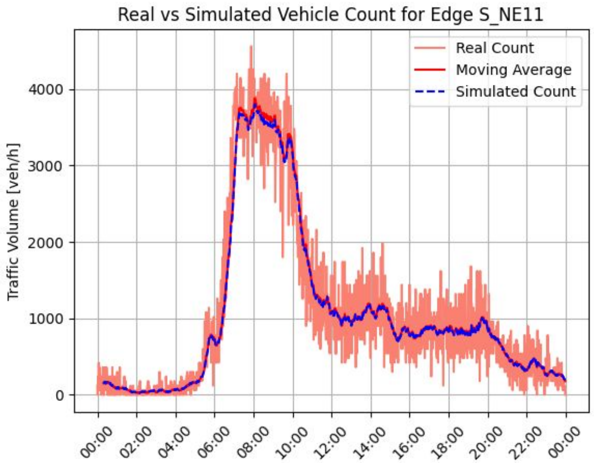
Inflow from the southern part of the network (q_6)



(a) DT-GM Methodology



(b) Framework w/ Google Maps intensities

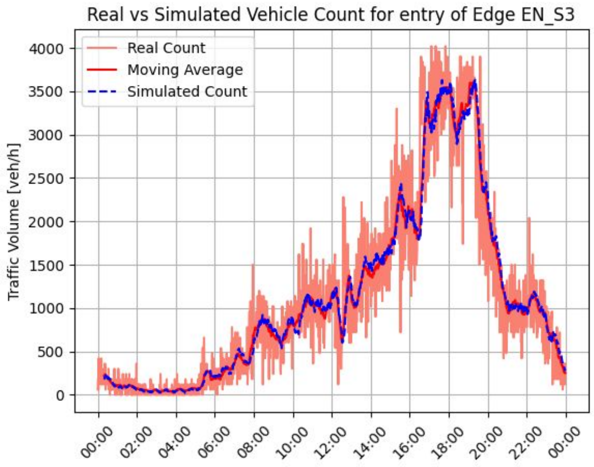


(c) Framework w/ DT-GM intensities

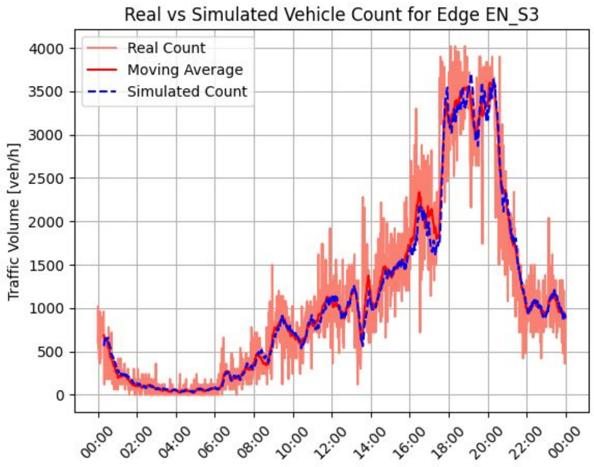
Results and Analysis

Geneva Motorway

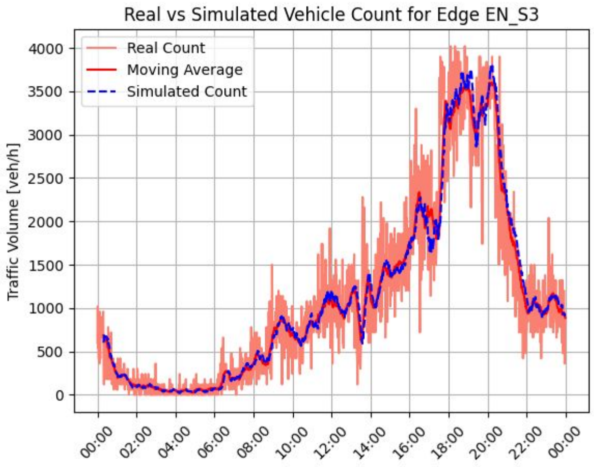
Outflow from the southern part of the network (q_5)



(a) DT-GM Methodology



(b) Framework w/ Google Maps intensities

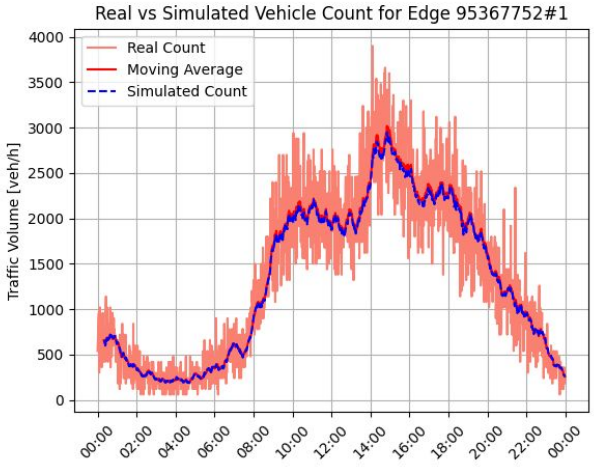


(c) Framework w/ DT-GM intensities

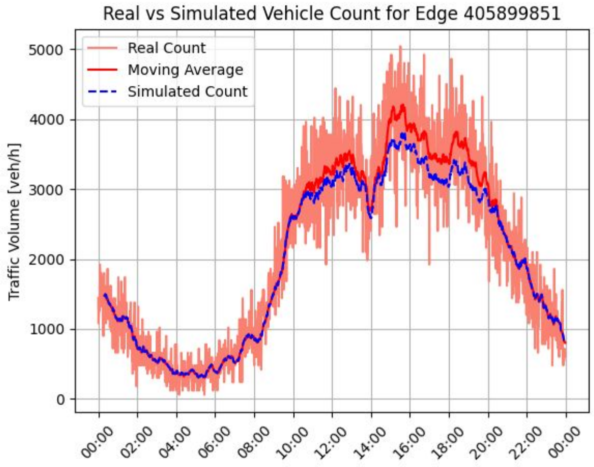
Results and Analysis

VCI’s Nó de Coimbrões

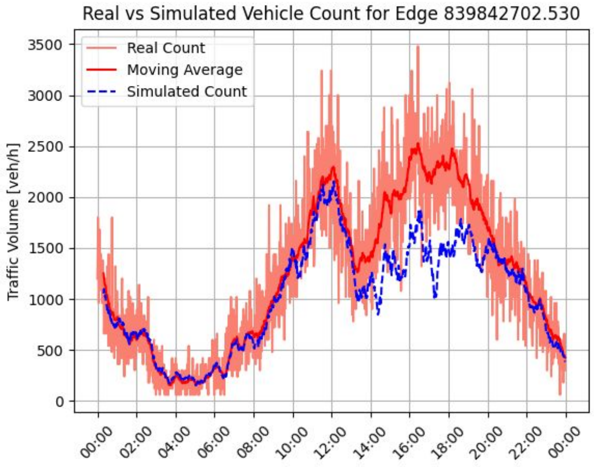
Flows on some entries and exits of the Nó de Coimbrões’ network



(a) Inflow from the eastern part of the network



(b) Inflow from the western part of the network



(c) Outflow from the eastern part of the network

Conclusions & Future Work

The results of the framework demonstrated the viability of this approach, allowing reliable traffic replication to be achieved, as long as the initial network adjustment process is adequate.

Regarding future work, it would be interesting to derive multiple instances of a base simulation to explore what-if scenarios, or include traffic prediction.

Furthermore, the framework could be adapted to work with real-time data, as the base methodology has already proven itself capable of doing so.

Finally, it is always relevant to apply the framework to new use cases, to validate its applicability.