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Is It Possible to Automatically Build a Large Scale Metropolitan Traffic Model? Evidence from a Study of Connected Transportation Applications in Montreal

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Abstract

Intelligent Transport Systems (ITS) can improve transport systems while reducing their negative impacts. The deployments of ITS applications are highly dependent on telecommunications technologies, which must be tested either in field experiments or in simulation. The traffic simulation is the least expensive and most flexible solution. Yet, models require large amounts of data and expertise to develop, and the impacts of their parameters on their outputs for ITS applications have not been much investigated. Using the Simulation of Urban Mobility (SUMO) tool as an example, this article attempts to build automatically a simple large-scale traffic model for the Island of Montreal and evaluates how this model performs. This paper considers microscopic and a mesoscopic models, along with three traffic assignment methods. The outputs are compared to travel times from global navigation satellite system (GNSS) data and from Bluetooth sensors, and a sensitivity analysis is also performed for several output indicators at different scales. The results highlight the trade-offs between more detailed and accurate microscopic models, and faster, less accurate, mesoscopic models.

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Keywords: Traffic models; Large-scale simulation; Microscopic scale; Mesoscopic scale; Intelligent transportation systems; Connected transportation applications

1. Introduction

While transportation systems are vital for societies, their negative impacts are numerous and significant, touching all the dimensions of sustainability. Transportation consumes resources for its infrastructure and vehicles, and, to move these vehicles, pollutes the environment, notably the air, and harms living beings through its pollution and road crashes. There are many ways to reduce and mitigate these impacts, including through technological innovations and Intelligent Transportation Systems (ITS). ITS depend heavily on communication technologies. New communication

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technologies enable new connected transportation (CT) applications, which, in turn, generate more traffic on the communication networks, and so on. There is therefore a need to anticipate the needs of ITS applications, current and future, with different levels of penetration in order to identify the requirements for communication networks. We use the terms ITS and CT applications interchangeably in the paper.

There are two ways to understand the impacts of CT applications on traffic in communication networks: field testing (FOT-Net, 2015) and simulation. The first solution is more realistic, but time-consuming, expensive and can be dangerous in real traffic as the fatalities and traffic injuries resulting from automated vehicle testing shows[1]. Field testing is also usually limited in scope and it is very expensive to test CT applications on the scale needed to empirically evaluate their actual impacts on communication networks.

The second solution is more economical and safer, allowing different scenarios to be replicated many times. Simulating CT applications requires simulating the traffic of users and vehicles on networks of various sizes at the right scale or level of detail with the right traffic models and parameters. Here, "right" is defined in terms of the CT applications to test and the requirements of the telecommunication simulation, while taking into account the data available to calibrate the model and the computing resources needed by the model. In some cases, a full co-simulation involving the inter-connection of the traffic and telecommunication simulations may add more requirements, in particular in terms of speed and computing resources, but will allow to better replicate how the CT applications function and their impact on transportation. The first stage of this research presented in this paper deals only with road traffic simulation, with the goal to generate realistic road user and vehicles trips (series of links) and trajectories (series of positions with the required spatial and temporal resolution) that form the basis for the simulation of their data exchanges for various CT applications. The mobility traces generated by the road traffic simulation are then used as input data for a probabilistic telecommunication network simulator (Manzanilla-Salazar et al., 2022).

The objective of this paper is to analyze the advantages and limits of building as automatically as possible a simple large-scale traffic simulation for ITS or CT applications that require road user and vehicle trajectories. Simple means using mostly open data and other public information about the road network and traffic demand, as well as an open source traffic simulation tool, in this case the Simulation of Urban MObility (SUMO) Lopez et al. (2018). Large scale means a metropolitan region, in this case the Island of Montreal. All the work is made available under an open source license for easy replication and for others to build upon, including by adapting the approach to other metropolitan regions. To the best of our knowledge, this is the first open source large-scale SUMO model for a North American city.

The paper is organized as follows: the next section is the literature review about the different approaches in traffic simulation and large-scale simulation using SUMO. The following section describes the methodology used to develop the simulation model. The fourth part is the analysis of the results compared to real traffic data from GNSS-based trip surveys and Bluetooth (BT) travel time data. The fifth and last section concludes the paper.

2. Literature Review

2.1. Traffic Model Typology

According to Hoogendoorn and Bovy (2001), traffic models can be classified based on five attributes:

- *Time scale of the independent variables*: a majority of traffic model systems are dynamic, with the variables changing values over time. Time can change either *continuously* or at *discrete* times.
- *Level of detail*: like fluid mechanics, traffic models can be described and simulated at various scales:
  - at the *microscopic* scale, vehicles and users are described individually. Such models require more resources, to describe them and the elements they interact with and to compute the evolution of the variables characterizing each individual user and vehicle. Microscopic traffic models include car-following models, lane change models and gap acceptance models for vehicles;

[1] https://www.washingtonpost.com/news/dr-gridlock/wp/2018/03/19/uber-halts-autonomous-vehicle-testing-after-a-pedestr

  - at the *macroscopic* scale, vehicles and users are not described individually, but in sets, e.g., of the vehicles present on a road segment, using the three macroscopic traffic variables flow, density and mean speed (Derbel, 2014). Such models have the advantage of lower computational requirements, which makes them suitable for large networks with a large number of vehicles and users, at the expense of the ability to model phenomena happening at the individual scale, e.g., drivers' decisions at intersections and their interactions with traffic lights;
  - the *mesoscopic* scale is an intermediary between the microscopic and the macroscopic scales (MTMDET, 2018), where traffic is described at the level of groups of users and vehicles, with models that can be closer to microscopic or macroscopic ones. For example, individual movements like lane changes are typically not represented. This scale thus requires fewer computational resources compared to microscopic models, at the expense of some individual details.
- *Representation of the processes*: the models can be either stochastic or deterministic, whether at least one variable is random, for example whether all drivers have the same perception and reaction time or if it is drawn from a probabilistic distribution.
- *Operationalisation*: some models can be solved analytically, but most models are too complex or involve the interactions of large numbers of agents and must be simulated.
- *Scale of application*: this is related to the area of application of the model, for example a road or a metropolitan area.

Models exist in the different categories and simulation software is available for the three levels of detail, both as commercial products such as VISSIM and Aimsun and research-oriented tools such as SUMO. Developed since 2000 by the Institute for Transport Systems at the German Aerospace Center (DLR) (2021a), SUMO is an open-source microscopic multimodal simulation software for modeling motorized and non-motorized trips. It is a tool of great interest for enabling reproducible models.

2.2. Main Steps to Develop a Traffic Model

Inspired by (Hollander and Liu, 2008), Gauthier et al. (2016) presented a procedure in seven steps to build and calibrate a model:

1. defining the scope of the problem;
2. determining the parameters relevant to the calibration and their feasible range;
3. determining and collecting the needed data;
4. choosing the indicators of the calibration process and the fitness function used to compare field data and simulated data;
5. determining the calibration process, including the choice of algorithm, the optimization constraints, and the evaluation budget;
6. determining the required number of replications of set of simulation parameters;
7. validating the calibrated parameters on an independent set of data.

Calibrating and validating all the microscopic models involved in a microscopic traffic simulation (car following, lane change and intersection crossing typically) requires a large amount of microscopic data that may not be available. A less demanding, but inferior, analysis consists in a sensitivity analysis and comparison to the available data.

An important aspect of most traffic models is their stochasticity and the resulting variability of their outputs. Several variables describing the user behavior and other phenomena are drawn from probability distributions to replicate their natural variation, such as the desired speed of each driver, route choices, or the initial time headway at the insertion of vehicles in the network. SUMO uses the Mersenne Twister algorithm to generate pseudo-random numbers (PRNs) for these variables that are controlled by seeds. To deal with the stochasticity of the model outputs, several replications of the model are run with different seeds to generate different PRNs.

2.3. Previous Microscopic Urban Models using SUMO

SUMO has been used in many projects, for example for multimodal simulations with the SAGA project (Codeca et al., 2020) or traffic light control (Krajzewicz et al., 2005). One can find the first large scale microscopic models built with SUMO already in 2006: in the INVENT project, Krajzewicz et al. (2006) describe a basic method of traffic management in the German cities of Cologne and Magdeburg. Behrisch et al. (2011) draw a portrait of the different tools available to build a network, describing the steps between network creation and demand generation. Since then, more complex simulation models and approaches have been developed. Codeca and Härri (2018) built a multimodal model of Monaco's transportation system (73.64 km^2 including surrounding areas) by mainly taking OSM data as input. Because of the lack of observed demand data, trips are generated by using estimates correlated to the built environment, economic activities and points of interest (POI). A group led again by Codeca built a model for the City of Luxembourg (156 km^2) (Codeca et al., 2015), using the ACTIVITYGEN (Anonymous, 2017) tool for the traffic demand. This tool generates a demand according to the road network, population data and the POIs for the area. To compare the simulation to the reality, the researchers use Typical Traffic data from Google Traffic. Interestingly, they study the impact of the routing method on the simulation output and correspondence to reality.

Another and maybe the most famous large-scale traffic model is called TAPASCologne and was developed for the City of Cologne by German Aerospace Center (DLR) (2021b) to replicate motorized traffic. The traffic demand is created using the TAPAS methodology (Travel and Activity Patterns Simulation), which is a combination of the previous methods, using population information, POIs and the residents' daily activity schedules. Thanks to a comparison to observed traffic flows, this paper also highlights potential issues caused by the choice of routing algorithms if simplistic assumptions are used. Schweizer et al. (2021) developed a multimodal model for the City of Bologna that integrates cars, public transport as well as active transportation. The model requires a large amount of data to build it: GTFS data, origin-destination (OD) matrices but also additional data from global navigation satellite system (GNSS) tracks and population activities. Several models employ this methodology and expand it to encompass a more extensive timeframe, such as the case of Turin over the course of a day (Rapelli et al., 2022). However, the validation of the model relies only on vehicle counts at road sections.

SUMO has the advantage of being interoperable with other applications at run time, in particular to model CT applications and vehicular networks (German Aerospace Center (DLR), 2021a). Intermediate software (middleware) was developed in order to couple SUMO with network simulator. The open-source framework Vehicles in Network Simulation (Veins) combines OMNeT++ and SUMO in order to study V2V communication (Sommer et al., 2011). The open-source projet iTetris combines SUMO and the ns-3 platform (analog to OMNeT++) by taking ETSI standards to model large-scale V2X communications (Rondinone et al., 2013). The Eclipse MOSAIC project [2] attempts to combine a plurality of network simulators such as OMNeT++ and ns-3, traffic simulators such as SUMO and PHABMACS for Connected and Automated Mobility and their evaluation. A recent project focuses on the city of Berlin, named BeST (Schrab et al., 2023). Finally, some researchers attempt to analyze the impact of the implementation of CAVs on safety and efficiency, for example in the Dublin city center (Guériau and Dusparic, 2020).

The construction of the model for the Island of Montreal presented in this paper follows in the steps of a small but significant number of models of urban regions using SUMO that, crucially thanks to their availability under open-source licenses, have sparked research in ITS applications: for example, TAPASCologne is cited in tens of papers, several of them re-using the model to demonstrate and test ITS applications and vehicular networks. However, as noted by Behrisch et al. (2011), much of the work using SUMO is limited to research and graduate student projects, which have not been all made available for research.

3. Methodology

SUMO is the chosen traffic simulation software for this study. The project includes several models at the microscopic and mesoscopic scale and tools to help with the creation of the transportation network by importing in particular from OpenStreetMap (OSM) (OpenStreetMap contributors, 2021). Despite the computational costs of us-

[2] https://www.eclipse.org/mosaic/

ing a microscopic traffic simulation tool, its advantages meet our stated objectives of building a simple model from open data that can be easily replicated and that produces the mobility data required by a telecommunication simulator for CT applications. The methodology, presented in Figure 1, consists in five main steps: transportation network import, travel demand creation, traffic assignment, scenario creation, validation. All the code and more information are available on a GitHub repository `https://github.com/HuguesBlache/MontrealTrafficSimulation` to help others replicate and build upon this work.

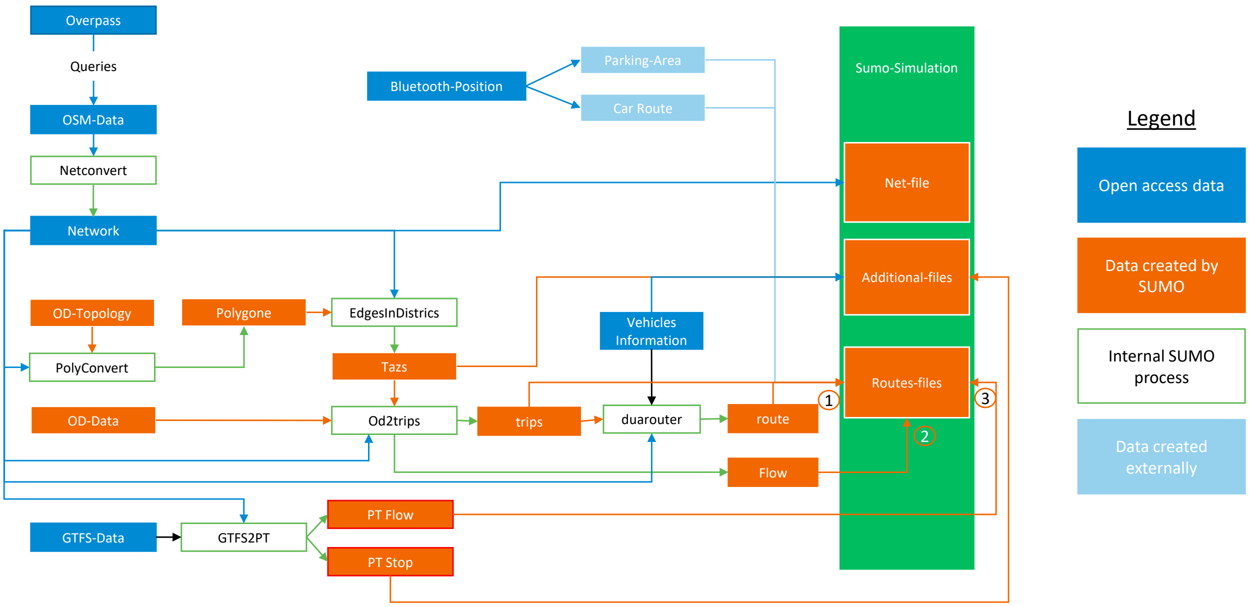

Fig. 1: Overview of the steps and data necessary to build the SUMO model.

3.1. Transportation Network and Public Transit

The transportation network is imported from OSM through the OverPass API[3]. For this iteration of the model, walking trips are not included. Roads for motorized traffic are called “highways” in OSM, within which there are several categories of roads similar to the usual road classes. Including all the roads and streets makes a large network that is more difficult to manipulate and requires more computation during the simulation. The choice was made to test two different networks, including the residential (local) and “unclassified streets” streets or not.

Furthermore, the speed parameters according to the types of road have been modified to correspond to the Montreal speed limits. In order to minimize the issues of road networks imported from OSM, the options to merge close intersections (“junction-join”), e.g., created because there is a median on an intersecting road, and to avoid U-turns at intersections (“no-turnaround”) are used. The OSM data imports lack detailed information pertaining to the cycle time of traffic lights. Nevertheless, in SUMO, the default cycle time is set to 90 seconds, representing the average cycle time observed in Montreal. [4]

The necessary information for bus service was imported from the GTFS data provided by the public transit company STM thanks to the `gtfs2pt.py` tool included with SUMO. This allows to add the bus stops and generate the bus trips.

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[3] `https://overpass-api.de/`

[4] François BOURQUE, “Feux de circulation à Québec : 33 % plus lents qu’à Montréal”, Le Soleil, 25 mars 2016, `https://www.lesoleil.com/chroniques/francois-bourque/feux-de-circulation-a-quebec-33-plus-lents-qua-montreal-a49f20954107220f9656d1c05b8314` (Consulted on May 25th, 2023)

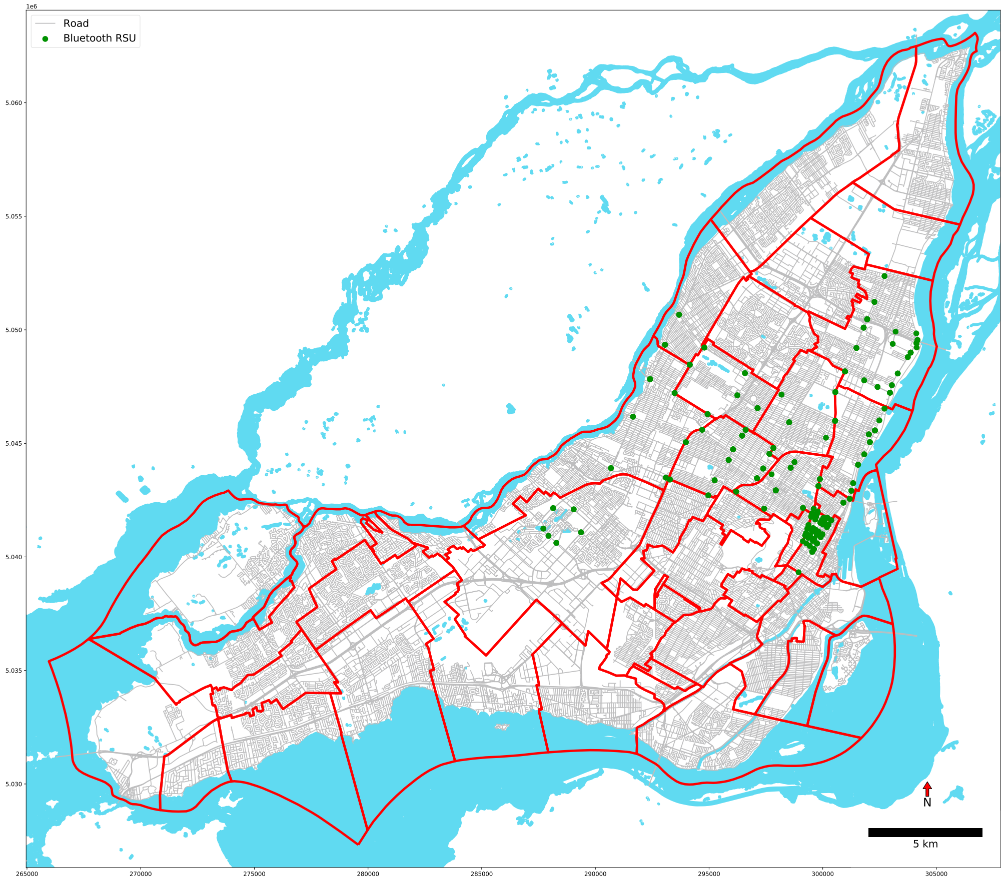


Fig. 2: Map of the road network with the SM drawn in red and installed BT road side units (RSU).

3.2. Travel Demand Creation

The travel demand comes from the OD matrix that is based on the household travel survey carried out every five years in the Greater Montreal Area (GMA) and made available by the Metropolitan Regional Transport Authority (ARTM). The most recent data from the 2018 survey was used. The spatial granularity used for the matrix is the municipal sector (SM), which corresponds to boroughs of the City of Montreal and the other independent municipalities on the Island (see Figure 2. There are 44 SMs on the Island, converted to traffic assignment zones (TAZ) using the `polyconvert` and `edgesInDistricts.py` tools, which map the road links (edges) to each TAZ/SM. The period chosen for the model is the morning peak period, from 5am to 9am.

The Island of Montreal and not the whole GMA was chosen as it is smaller and, as an island, has a natural boundary with the rest of the region, with few crossing points (bridges). Outside trips with their origin or destination outside of the Island were assigned new origins or destinations accordingly if they were expected to travel through the Island. The heuristic, illustrated on Figure 3, consists in drawing the desire line between the centroids of the origin and destination zones and, if crossing the Island, to replace the origin SM (respectively the destination SM) by the first (respectively last) SM crossed on the Island.

In order to replicate some of the diversity of the vehicles, in terms of proportion, lengths and maximum speeds, data from the provincial insurance company SAAQ about vehicle registration and from the list of the best-selling vehicles in 2018 was used. The data for the buses was also updated so that there were five categories of vehicles in the model.

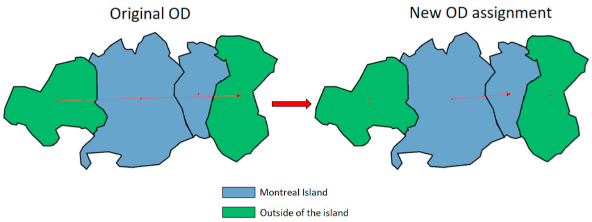


Fig. 3: Illustration of the re-allocation of ODs external to the Island of Montreal.

3.3. Traffic Assignment

There are several methods to assign the demand to the network in SUMO. Three methods, or "routers" are tested in this work and are presented briefly here. The `od2trips` tool available in SUMO imports OD matrices and splits them into single vehicle trips defined by a starting time, origin and destination link drawn randomly in their respective TAZ. Alternatively, the output can be in the form of flows, i.e., sets of vehicles, between the origin and destination TAZ over given time intervals. These two methods are tested in this work and are referred to as "od2trips" and "flow" in the rest of the paper. By default, the OD matrix would be spread uniformly over the period of interest, but it can also be scaled at given intervals based on the actual demand profile. This is done at the 15-min time interval using multimodal traffic counts at several intersections available on the Montreal open data portal[5].

The trips and flows can then be passed for simulation by SUMO or another tool called `duarouter`. Because TAZs are provided, SUMO picks the links in the origin and destination TAZ that minimize the travel time between these TAZs. While performing the traffic assignment involves finding the shortest path in terms of travel time in both case, this is done differently by both tools. SUMO simulates the traffic demand generated by `od2trips`: when a trip starts at the beginning of a flow interval, vehicles are assigned the shortest path based on current traffic conditions. On the other hand, `duarouter` computes for each trip the shortest path without any traffic. The resulting routes are then simulated by SUMO.

3.4. Scenario Creation

Several important decisions must be made for this large-scale model, whose impact on the generated trips and, in the end, the CT applications, are initially unclear. The trade-offs between a more detailed model and computation resources must also be explored. Four main parameters were chosen:

- whether the residential and unclassified streets are kept in the network;
- whether outside trips, either originating or destined outside the Island, are kept in the demand;
- whether "within" trips, where both origins and destinations are the same SM, are kept in the demand;
- the scale of the model, microscopic or mesoscopic.

SUMO is by default a microscopic model. The default car-following model by Krauss et al. (1997); Krauss (1998) and lane change model by Erdmann (2015) are used in this first model. SUMO can also run a simplified, mesoscopic, model where vehicles are placed in queues, making the model run up to 100 times faster than the microscopic models, at the expense of some types of outputs and differences in the results (Anonymous, 2021). The result is the five scenarios described in Table 1. The first two are microscopic, with the smaller road network and demand (scenario 1) or the larger network with the outside trips (scenario 2). Adding more demand from the within trips would be too time-consuming in a microscopic model. The demand with the outside trips represent 75.3 % of all trips in the peak period. Scenarios 3 to 5 rely on the mesoscopic model, with two levels of demand (all with outside trips, scenario 5

[5] https://donnees.montreal.ca/ville-de-montreal/comptage-vehicules-pietons

including also within trips) and the two sizes of network (scenario 3 without the residential/unclassified streets). In addition, the three traffic assignment methods described above are applied to each scenario.

Table 1: Summary of the scenario characteristics (the column "Trip Pct" is the proportion of the trips constituting the demand for the scenario over all trips in the OD matrix).

Scenario	Trip Pct	Residential St.	Outside Trips	Within Trips	Scale
Scenario 1	41.8 %	no	no	no	micro
Scenario 2	75.3 %	yes	yes	no	micro
Scenario 3	75.3 %	no	yes	no	meso
Scenario 4	75.3 %	yes	yes	no	meso
Scenario 5	100.0 %	yes	yes	yes	meso

3.5. Validation

A traffic model, especially a microscopic model, should generally be calibrated and validated on separate datasets (Gauthier et al., 2016). In the case of the present work, the lack of microscopic data and the large scale of the model makes it difficult to calibrate the microscopic models. The emphasis is on the parameters defining the scenarios and traffic assignment methods. It is however necessary to understand which of these scenarios and parameters better represent the real traffic. Two types of data available on the open data portal of the City of Montreal are used for the model validation:

- **MTL trajet GNSS trips**[6]: this data comes from GNSS trip data collected through the MTL Trajet mobile application each fall in Montreal. The application users validate the trips, times of travel and modes. For this study, only the car and motorcycle trips from 2017 were used. Only trips starting and ending in TAZ on the Island were kept, and trips making a detour outside of the Island were removed. Also, only the trips within the peak hours were retained, yielding a total of 3270 observations over the entire OD matrix. In all the comparisons presented in section 4.4, only the OD pairs with at least ten observations are kept.
- **BT travel times**[7]: for the purpose of tracking traffic conditions over time, the City of Montreal has installed BT sensors in some areas of the city since 2016. Their locations are shown on the map in Figure 3. The resulting travel times are provided only for pre-defined sensor pairs.

The GNSS observations are compared to the trips starting and ending in the same TAZ. For the BT data, SUMO can simulate BT onboard devices with a set detection range up to 100 m as reported in the literature. Since the TAZ are much larger, there will be a better correspondence between the simulated and observed BT travel times.

4. Experimental Results

4.1. Number of Replications

Following the methodology presented in the literature review, we must decide on the number of replications for each scenario and traffic assignment method. This work follows the method used by Gauthier et al. (2016) based on the visual analysis of the convergence of relevant output indicators. Figure 4 shows that the mean travel times for 15 randomly chosen OD pairs does not change much when the number of replications increases. The results are stable after ten replications and the final number of replications was chosen as 20 to be on the safe side and to account for differences with the other scenarios and traffic assignment methods.

[6] https://montreal.ca/en/programs/mtl-trajet-study
[7] https://donnees.montreal.ca/ville-de-montreal/temps-de-parcours-sur-des-segments-routiers-historique

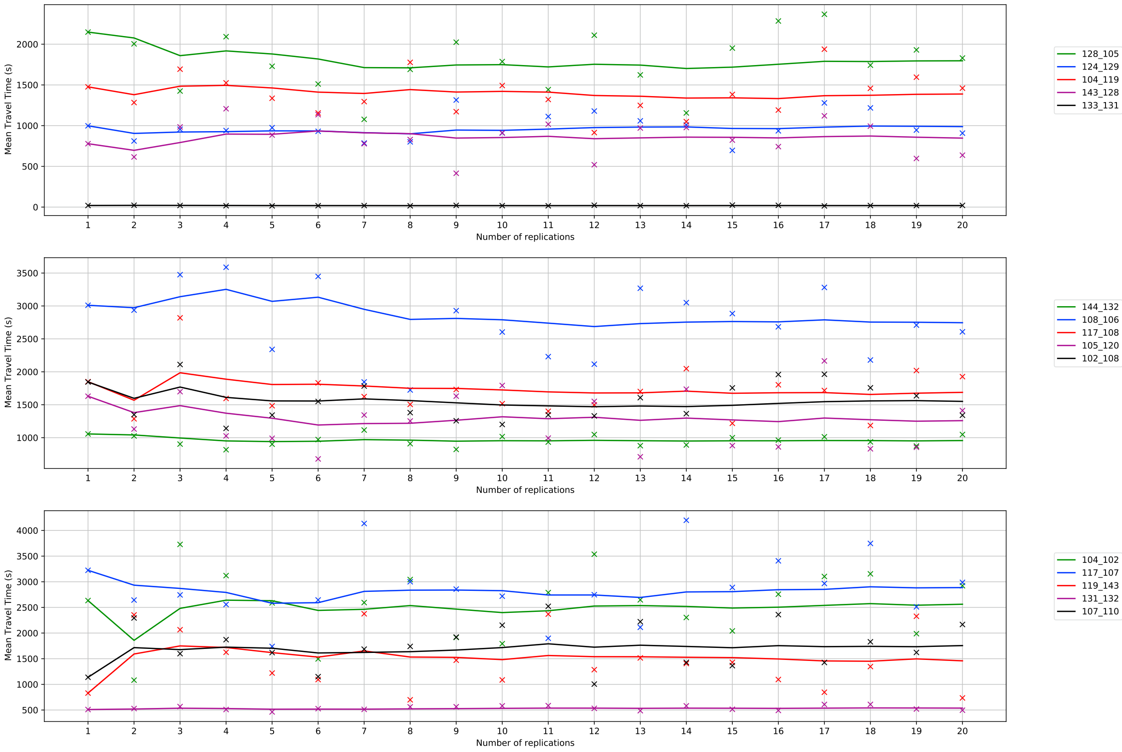


Fig. 4: Mean travel time as a function of the number of replications for 15 randomly chosen OD pairs for scenario 3 with the od2trips router.

4.2. Computation Times

The first indicator studied is the computation time for each scenario and traffic assignment method. This allows to evaluate which scenario is viable, in particular for a co-simulation, where the telecommunication simulation would require additional time. After having carried out 353 hours of simulation, i.e., 14.7 days, the computation time distributions for the 20 replications for each scenario and traffic assignment method are presented in Figure 5. For a fair comparison, the computation time for the duarouter method includes the time taken for traffic assignment.

For each scenario, the traffic assignment method with od2trips requires the most time, followed by the duarouter and flow methods. Indeed, in the od2trips method, the routes are calculated during the simulation at each vehicle insertion. Though similar, the flow method is much faster because this process is done once per 15-min time interval per OD pair. The duarouter method is a bit slower than flow, which means that assigning the trips based on the shortest path is much faster than calculating the shortest path at each insertion based on the current traffic conditions in the network, but a bit slower than doing the same thing in batches. As expected, the microscopic simulations are slower (this is very clear comparing scenarios 2 and 4). Using the simplified mesoscopic models results in simulations requiring generally less than 5000 s (except for the od2trips method). The longest median time is for scenario 2 with od2trips and takes almost 8 hours. Also as expected, the size of the road network increases the computation time (scenarios 3 vs 4). It is not as clear for the larger demand, though variability decreases (scenario 4 vs 5).

4.3. Routing and Simulation Errors

There are two main types of errors that can occur in a SUMO simulation. The first occurs during the traffic assignment step, when the traffic assignment method cannot find a path from the origin to the destination link. This happens in particular with this road network since it is automatically imported from OSM. These errors can be seen in Figure 6f. These results should be commented in light of the share of the total OD matrix that constitutes the demand

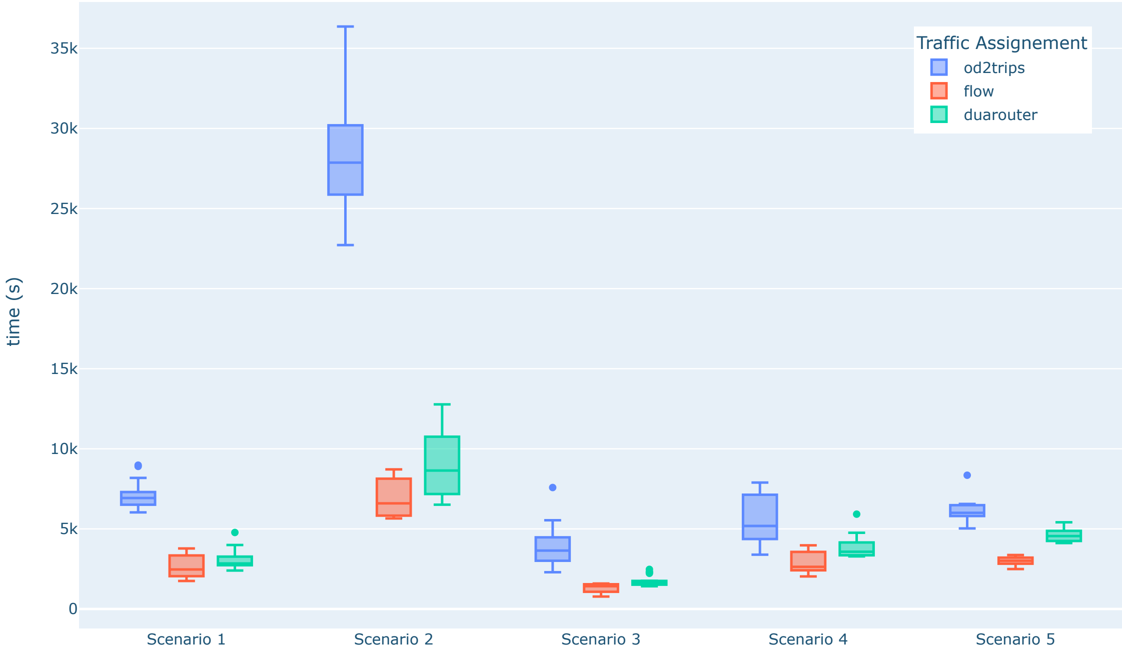


Fig. 5: Boxplot of the computation time for each scenario and traffic assignment method.

to the model: from 41.8 % for scenario 1, to 75.3 % for scenarios 2 to 4, to 100 % for scenario 5. Traffic assignment is quite easy for the lowest demand. For the intermediate demand (adding "outside" trips), not having the residential network causes the most vehicles not to find a route between origin and destination. The flow method does not seem affected by any of the scenario characteristic. The duarouter is affected only the the addition of the "outside" trips, and a bit by the lack of the residential network (scenario 3). The od2trips method shows the most variability, which is a bit surprising compared to flow. The addition of the "within" trips has proportionally little impact, which is expected since these trips are short and should be easy to route within the same TAZ.

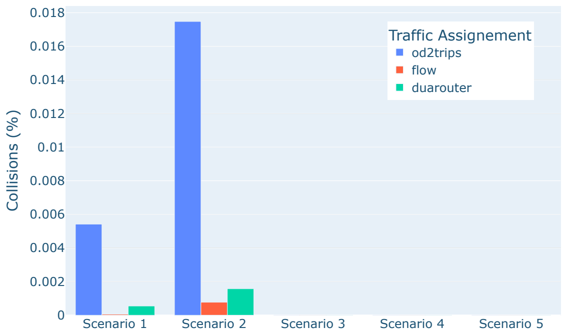
The second type of error happens during the simulation in SUMO, once the routing is done. There are two main causes for a vehicle to be "teleported", when it waited for too long at an intersection or when it has "collided" with the preceding vehicle. After a given amount of time, the teleported vehicle is moved to the next available place along its route, which may happen for three reasons:

1. "wrong lane": the vehicle is waiting on a lane which has no connection to the next link on its route;
2. "yield": the vehicle is waiting on a low-priority road and cannot find a gap in the traffic;
3. "jam": the vehicle is waiting on a priority road and there is not enough space on the next link.

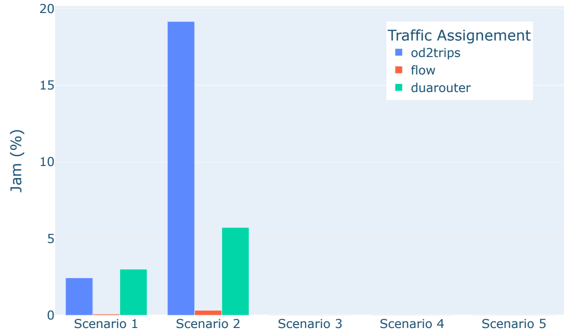
The latter occurs when the minimum gap between two vehicles is not respected, usually because of network problems and configuration. The share of the teleported vehicles for each of these reasons among all vehicles inserted in the simulation is reported in Figures 6a to 6f. It is clear that the mesoscopic model can only teleport vehicles who wait too long to find a gap at an intersection. There are very few "collisions" overall. The od2trips method is responsible for the largest share of teleported vehicles, while the flow method shows few issues.

Finally, vehicles may be removed from the simulation before reaching its destination, but the SUMO documentation does not explain the real reason. The proportions out of the number of inserted vehicles is shown in Figure 6d.

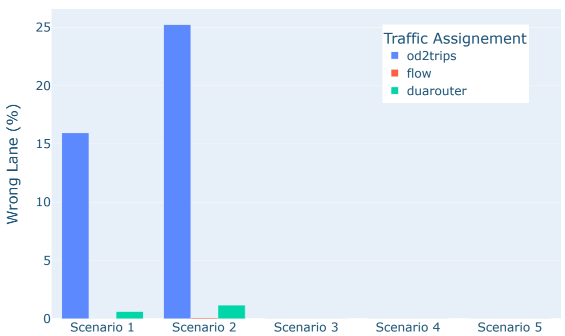
These indicators are presented to diagnose the model and understand some of its issues and their causes. The three reasons for vehicles to wait too long are occurring mostly in the microscopic model, and are most likely caused by network issues at intersections caused by the automated OSM import as discussed for other large scale models like TAPAS (German Aerospace Center (DLR), 2021b). The mesoscopic models with much fewer teleported vehicles seem



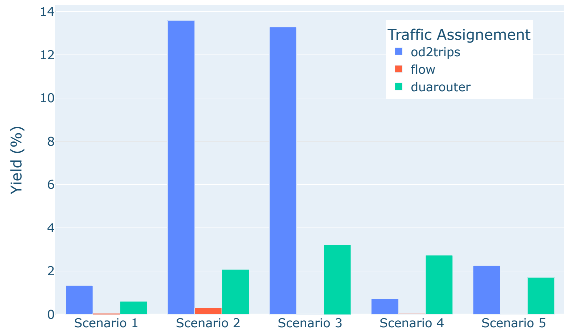
(a) Proportion of teleported with reason “collision”



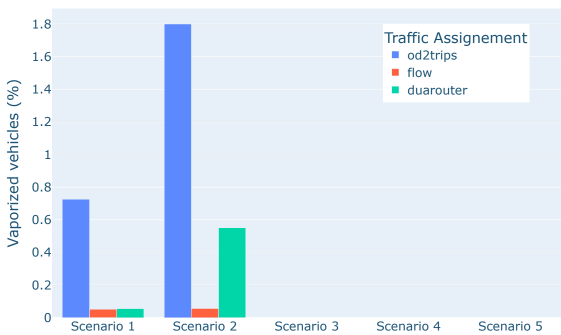
(b) Proportion of teleported with reason “jam”



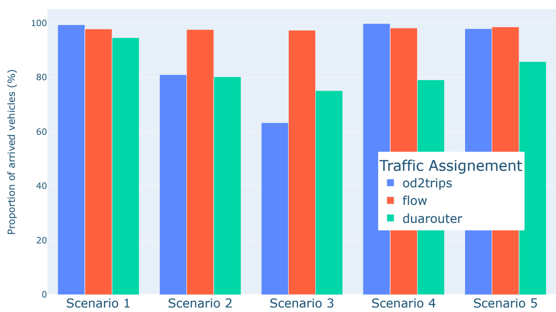
(c) Proportion of teleported with reason “wrong lane”



(d) Proportion of teleported with reason “yield”



(e) Proportion of removed vehicles



(f) Proportion of arrived vehicles

Fig. 6: Average proportions of teleported vehicles in Figures (a) to (d) and of removed vehicles in Figure (e) by scenario and traffic assignment method among vehicles inserted in the simulation; Average proportion of arrived vehicles among the total demand before routing in Figure (f).

therefore better suited to the automatically created road network. Yet, the flow method also shows few teleportations for all scenarios, whether microscopic or mesoscopic.

4.4. Validation

4.4.1. Statistical Tests

The distributions of indicators output by the simulation can be compared to the real data available for validation, i.e., the GNSS-based travel times on the Island of Montreal and the BT travel times for pre-defined pairs in the central boroughs. Two non-parametric tests are chosen to compare the simulation outputs to the real data: the Mann-Whitney *U* test (Kvam and Vidakovic, 2007)and the Kolmogorov-Smirnov (KS) test (Kim et al., 2005).

These tests are performed for each scenario and traffic assignment method. Each test is applied to the set of travel times for all replications for each OD pair with at least ten observations (for the simulated and real trips). The OD pairs where the origin and destination TAZ are identical are not considered for Scenario 5 since they are not part of the demand for the other scenarios. A 5 % type I error rate was chosen and the proportions of the OD pairs where the null hypothesis is not rejected are presented for each test in Figure 7. These proportions can be interpreted as the proportion of OD pairs where the simulation output is close enough to the observed traffic data, keeping in mind that small sample sizes are also more likely to yield a non-rejection.

One can observe that the KS test is generally more demanding than the Mann-Whitney U, i.e., it rejects the null hypothesis more often, since it tests the whole distribution. The first observation is that the comparisons are favorable to the microscopic models: the proportions of OD or BT pairs (to a lesser extent) with travel time distributions similar to the real traffic data is higher for scenarios 1 and 2. This is particularly striking for the GNSS data, where the od2trip method generates a majority of travel time distributions similar to the real data for both statistical tests, while almost none of the output distributions are similar for the mesoscopic models (except for scenario 3 with od2trips). The other clear difference for GNSS data is that only the od2trips method performs well.

For the BT data, one should note first that the proportions are much smaller than for the GNSS data. These may be related to the much larger size of these datasets compared to the GNSS data. The highest is a paltry share just above 16 % for the Mann-Whitney test and just above 8 % for the KS test. The situation is more mixed for the traffic assignment methods, where each performs the highest for different scenarios. It should be noted that the differences do not seem to be associated with differences in the total number of tests carried out, which can change if there are not enough simulated trips for a given OD or BT pair. These tests demonstrate the superior performance of the microscopic models with the od2trips routing method, then with the flow method. It seems the more detailed microscopic models have advantages as they have a higher faithfulness to real traffic. Among the mesoscopic models, scenario 3 with the smallest demand and network has the best performance.

4.4.2. Travel Time Accuracy Analysis

The second method used to compare the simulated outputs to real data consists in computing the errors between the mean travel times and displaying the corresponding scatter plots for each scenario and traffic assignment method. The following errors are computed for both sets of data: the mean absolute error (MAE) and root-mean-square error (RMSE), along with their relative version, mean absolute percent error (MAPE) and root-mean-square percent error (RMSPE).

Looking at the errors and scatter plots for the GNSS data (Figures 8 and 10) and the BT data (Figures 9 and 11), it can be seen again that relative errors are larger for the latter. Absolute errors are larger for the GNSS data because the trips between ODs are longer. But relative errors are all below 100 % for the GNSS data, except for one, while many more are above 100 % for the BT data. Overall, the relative errors are large in all cases for the BT data. The microscopic scenarios (1 and 2) have the best performance (lowest errors) for both datasets, although the flow method performs well across scenarios for the BT data. The od2trips method comes second, and even first for the mesoscopic scenarios for the GNSS data. The third, duarouter, is clearly the worst performing, although it also beats the flow method for the mesoscopic scenarios for the GNSS data as well.

The visualization of the scatter plots and regression lines confirm these remarks. The results are better for the microscopic scenarios for both datasets, with od2trips generally over-estimating the travel times for scenarios 1 to 3 on the GNSS data and flow under-estimating in most cases. One must be careful with the regression line, as it sometimes seems close to the $y = x$ line, although the errors can be large, for example for od2trips for the BT data.

A particularly striking result is the number of near-zero simulated travel times for GNSS data. This is caused by the traffic assignment with TAZ that picks the edges with the minimal travel times: for many adjacent TAZ, there will be

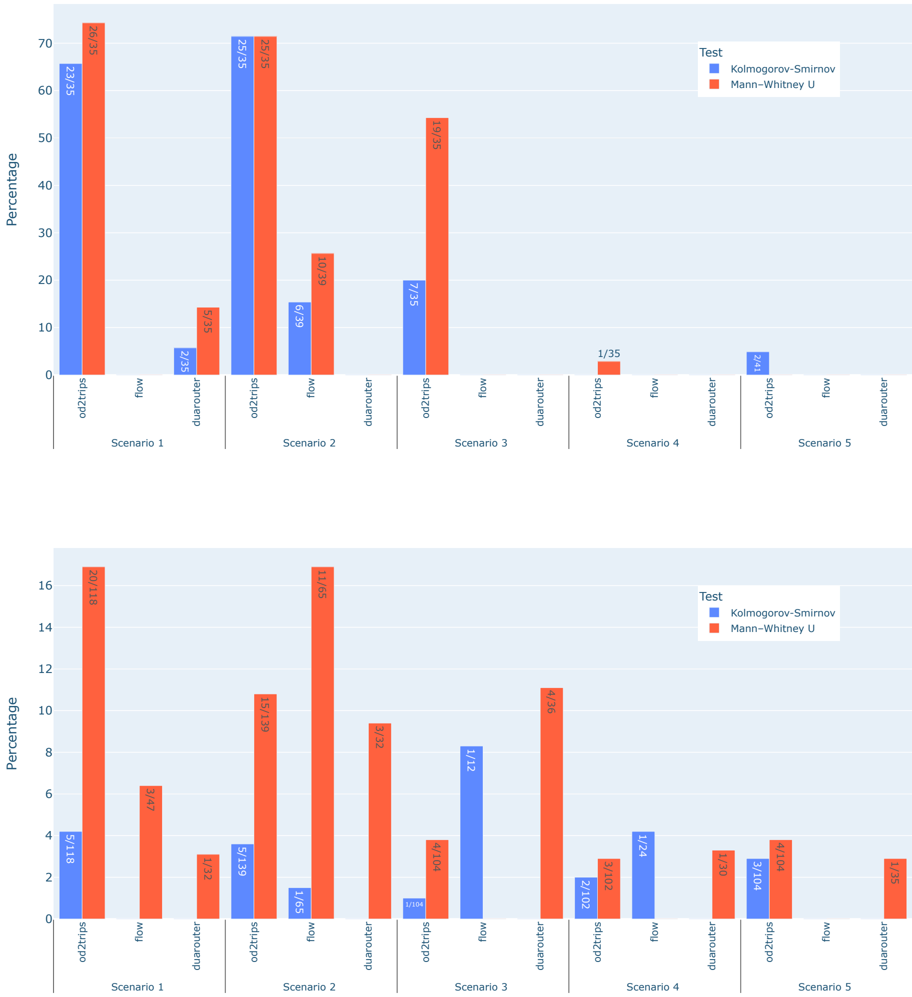


Fig. 7: Proportions of OD pairs (GNSS travel times) (top) and BT pairs (BT travel times) (bottom) for which the null hypothesis is not rejected with a 5 % type I error rate (the number of non-rejected tests over the total number of tests are shown in the bars).

two edges directly connected having the smallest travel time, which will very close to 0. This has a major impact on the performance of the flow method for the mesoscopic scenarios, and on duarouteur as well. It is surprising that the same issue does not arise with od2trips, since it assigns trips in the same way. The BT data is more interesting in that regard, as the method used in SUMO to collect these travel times is more targeted and yields more varied results that are not tied to the TAZ. This may also explain the larger errors, which reflect that travel times at a more microscopic level are not well replicated by the models.

The models do not manage to generate travel times with less than 50 % error at best (except for one), but some models, the mesoscopic, are clearly worse, systematically under-estimating the real travel times. This confirms that the traffic conditions are not as congested as they should be, as the mesoscopic models do not replicate the processes that generate the congestion.

Fig. 8: RMSE, RMSPE (top), MAE and MAPE (bottom) for the OD pairs (GNSS data) per scenario and traffic assignment method.

4.5. Sensitivity Analysis

The last analysis is a sensitivity analysis of the model. It is very relevant to the applications of the model, to know whether all scenarios and traffic assignment methods yield similar results and the extent of the variability. These are based on the coefficient of variation or relative standard deviation (RSD) and on a sensitivity index (SI) computed as the difference between the maximum and minimum values, divided by the maximum value. Both are presented in %. The RSD and SI of the mean travel times were computed for each OD pair over the 15 combinations of scenarios and traffic assignment methods (tables not shown for lack of space). The two indicators consistently reflect large variations, in particular for trips in the same TAZ. In order to analyze this phenomenon more precisely, an analysis was made with the scenarios and traffic assignment methods taken separately for a given OD pair, shown in Table 2. The variability is much higher for the microscopic models, while generally lower for the mesoscopic ones, with the exception of the od2trips router for all scenarios and duarouter for scenario 5.

A similar analysis is replicated for mean trip speeds and counts between close BT pairs to analyze changes on a sample of specific road links. Based on Table 3, there is a large variation in the vehicle speeds and counts, which indicate that vehicles may be taking different paths depending on the scenarios and traffic assignment methods. No trend is visible, except that the maximum counts and speeds are frequently returned by the od2trips method. Analyses of specific BT pairs confirm the variability of speed and counts generated by the od2trips method in all scenarios. This

Fig. 9: RMSE, RMSPE (top), MAE and MAPE (bottom) for the BT data per scenario and traffic assignment method.

sensitivity analysis shows that care should be taken for the choice of the parameters involved in the scenarios and of traffic assignment method, as their impact on output indicators can be considerable.

5. Conclusion

This paper has presented a methodology to build automatically a large-scale urban traffic model using SUMO for ITS and CT applications requiring detailed trip data for a metropolitan region. The results are mixed. There is a clear trade-off between the computational resources and the quality of the model outputs: microscopic models are computationally expensive, but are closer to the real traffic features. Yet, microscopic models also generate more routing and simulation errors as the road network currently needs manual verification and reparations. Improvements in data accuracy could be achieved by adjusting the default parameters in SUMO and the models used. One potential approach to achieving this would be to conduct sensitivity analyses by testing the models with different parameter settings. This would help to identify the parameters that have the greatest impact on the model output, allowing for more precise calibration and improved data accuracy. Future research could explore the influence of different traffic theories and models, particularly at the microscopic level, with a focus on lane changing and car following.

This paper is a first step in better understanding the consequences of these trade-offs. By making the code available to replicate this work, this method can be refined and replicated in other regions where the same data is available: good OSM data, a traffic demand (OD matrix) and some separate validation data. However, it is important to acknowledge

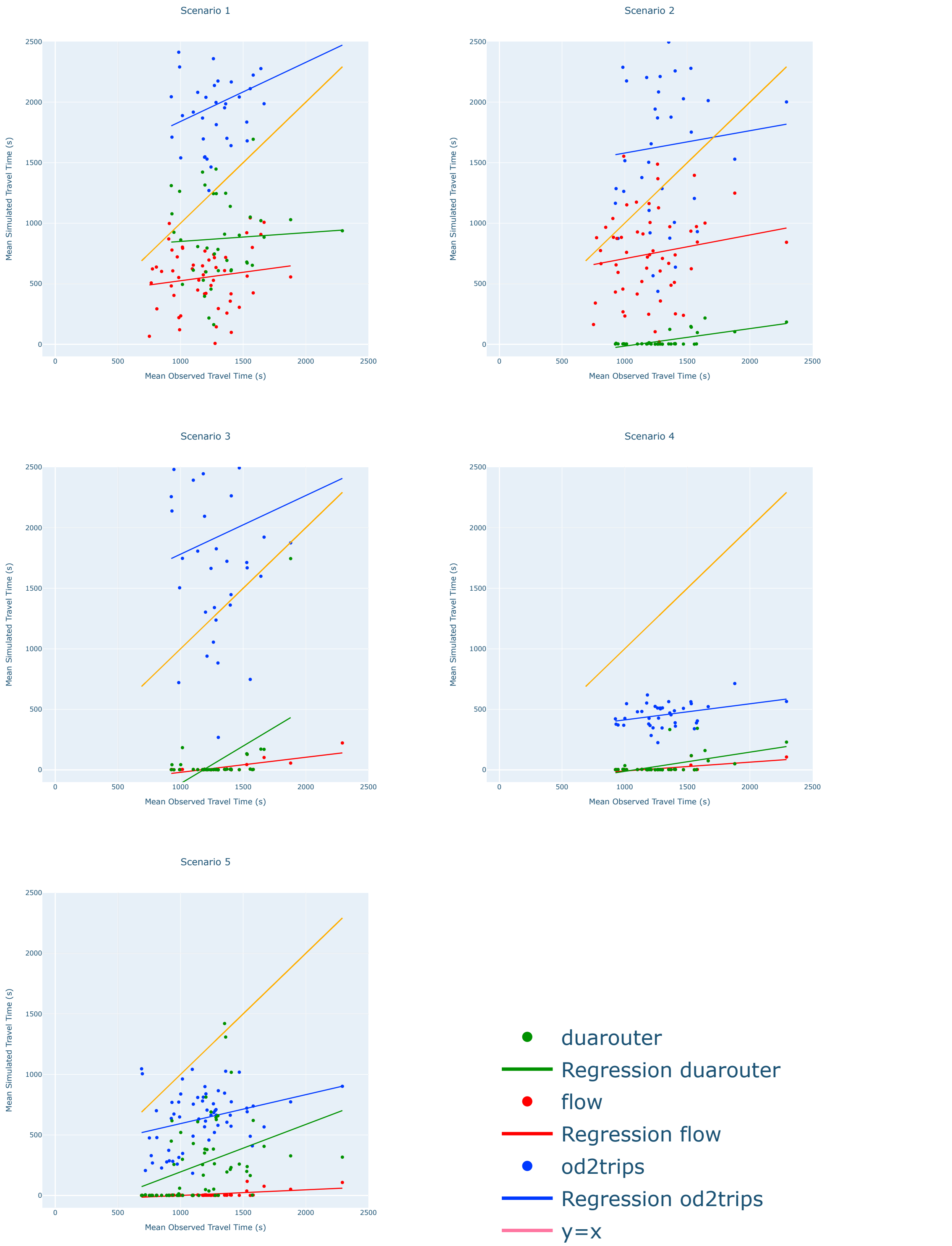


Fig. 10: Scatter plots of the mean simulated travel times as a function of the mean GNSS travel times per OD pair per scenario and traffic assignment method (note that graphs are clipped to the largest observed travel time). Regression lines are provided for each assignment method, as well as the $y = x$ line.

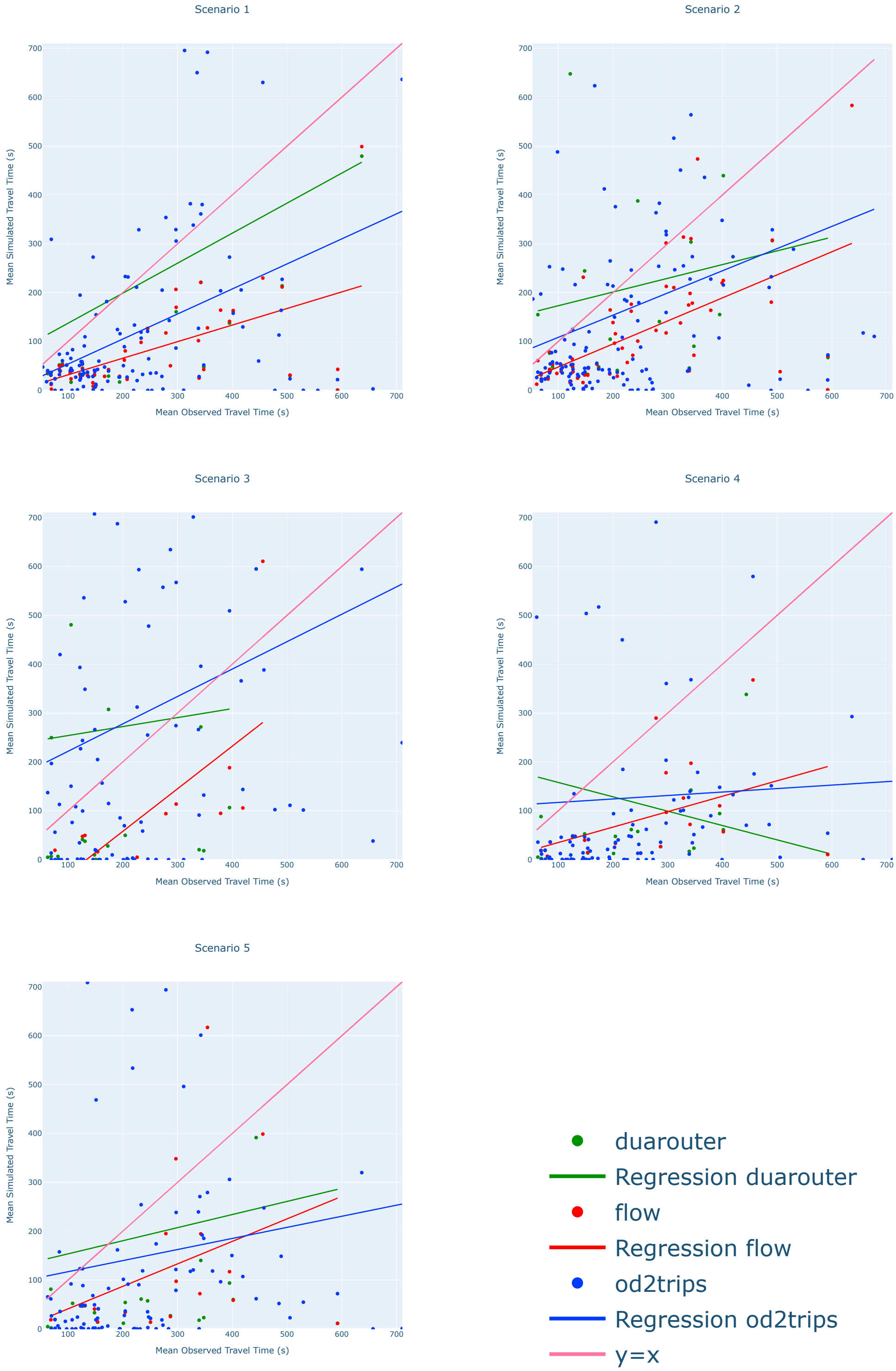


Fig. 11: Scatter plots of the mean simulated travel times as a function of the mean BT travel times per BT pair per scenario and traffic assignment method (note that graphs are clipped to the largest observed travel time).

Table 2: RSD and SI for the travel times for one OD pair (SM 101 to 102) for the different scenarios and traffic assignment methods.

Scenarios	Routing	RSD	SI
Scenario 1	**od2trips**	11,34	36,67
	flow	12,30	28,83
	duarouter	11,20	28,46
Scenario 2	**od2trips**	8,19	22,86
	flow	14,12	31,49
	duarouter	1,27	3,97
Scenario 3	**od2trips**	8,48	22,42
	flow	0,99	3,25
	duarouter	0,58	1,70
Scenario 4	**od2trips**	17,08	38,94
	flow	0,48	1,49
	duarouter	0,61	1,79
Scenario 5	**od2trips**	9,06	20,62
	flow	0,67	2,42
	duarouter	32,05	84,43

Table 3: RSD and SI for the mean trip speeds and counts per BT pairs over the scenarios and traffic assignment methods (min and max R S refer to the traffic assignment method and scenario, denoted by the initial or number, that yield the minimum or maximum value of the indicator).

BT Start	BT End	Distance (m)	Speed RSD	Speed SI	Min Speed R S	Max Speed R S	Count RSD	Count SI	Min Count R S	Max Count R S
86	90	101	278.2	100.0	D 1	O 3	89,9	96,6	O 3	O 2
24	72	114	127,5	99.8	D 3	O 4	102,3	93,6	O 5	O 1
70	68	117	76,3	98.7	D 3	F 2	97,2	97,5	F 2	O 4
87	88	127	195,7	99.5	O 2	O 4	58,6	99,7	F 1	D 5
87	92	137	213,8	99.4	O 3	O 5	149,8	95,1	O 4	O 3
80	63	145	237,9	99.8	D 2	F 3	129,5	97,9	F 1	O 2
63	80	149	161,1	97,8	O 3	D 3	107,4	97,3	D 3	O 5
24	68	170	164,2	100,0	D 3	F 1	96,8	99,6	F 4	O 4
92	93	222	167,0	99,3	O 2	O 4	133,2	98,0	F 2	O 1
68	69	239	118,2	99,9	F 4	F 2	149,5	99,8	F 4	O 1
79	74	240	72,5	96,5	D 3	D 1	138,6	99,6	D 1	O 3
74	77	247	223,0	100,0	O 2	O 5	166,3	99,4	O 5	O 1
75	78	248	94,8	99,1	O 3	O 4	120,4	98,9	O 4	O 1
26	80	280	292,4	99,7	O 3	O 5	165,6	99,6	D 4	O 2
1B	98	369	34,2	98,0	D 3	F 4	57,4	90,7	F 5	O 3
76	94	380	114,8	99,1	O 3	F 1	156,8	99,3	F 1	O 1
1E	1G	482	65,3	99,8	O 3	O 4	82,3	99,4	F 5	D 4
52	54	484	197,8	100,0	O 2	O 4	124,4	98,9	O 3	O 2
1D	1C	595	43,2	98,6	D 3	O 5	83,4	93,7	F 4	O 2
35	19	711	68,4	83,2	O 2	O 4	138,0	97,9	F 1	O 2

the limitations of GNSS and Bluetooth data. To address these limitations, one potential solution for model calibration is the integration of supplementary data, such as traffic counts.

The priorities for improvement are the road network imported from OSM and the traffic assignment methods. There are issues at intersections, in particular with the type of control and the signal timing plans. The simple traffic assignment done in this work should be improved by carrying out a proper dynamic user assignment, while finding also the right trade-off between computation needs, the quality of the outputs and the needs of the final CT applications. This article represents a foundational step towards a larger model that will enable us to integrate traffic and telecommunication simulators, extending beyond the scope of this paper. This article sets the groundwork for further research and development, which we believe will lead to more advanced and comprehensive traffic models in the future.

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