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Integrating Topographical Map Information in SUMO to Simulate Realistic Micromobility Trips in Hilly and Steep Terrains

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Abstract: Nowadays, shared micromobility has become a trend in cities as an alternative to conventional automotive vehicles, especially for short-distance travel. It also plays an important role in the reduction of the number of automotive vehicles which results in a decrease of air pollution and traffic congestion. Shared micromobility is, however, influenced by the terrain characteristics. Varying elevation within a fleet operational area can cause imbalances in the use of micromobility stations if a steep terrain lies between stations. It also impacts the energy consumption of electric micromobility vehicles such as e-bicycles and e-scooters. Therefore, to simulate the state of charge (SOC) of traction batteries for micromobility close to reality, it is essential to include elevation data into the simulation model. This paper proposes a workflow for Simulation of Urban MObility (SUMO) comprising several steps with concrete implementation and validation in order to prepare and define the simulation model with micromobility stations and the integration of elevation data using a REST API. The integration of elevation and bike station data is validated with a defined vehicle type following a route in the hilly part of Stuttgart, Germany. A comparison of micromobility trips, with and without elevation data, was performed through a simulation by recording changes in energy consumption and driven altitude differences. The proposed workflow provides a basis for more complex use cases such as analysing micromobility business areas, improving vehicle distributions and developing incentive strategies for hilly and steep terrains.

Keywords: SUMO, simulation, elevation data, micromobility, shared mobility, GBFS, traction battery

1 Introduction

Two thirds of the world's population live in cities [1]. Due to the fact that the number of automotive vehicles increases more and more in urban areas, cities are faced with congestion, noise and pollution [2]. Micromobility is an auspicious approach and an alternative way of travelling that can reduce the use of private vehicles, especially for short distance journeys [3]. Additionally, micromobility has been expanded to shared micromobility systems (e.g., bike or e-bike sharing, e-scooter sharing or others) which have been introduced all around the world as an inner-city travel option [3]. Because of their low space requirements and environmentally friendly propulsion systems, micromobility vehicles offer many advantages in crowded urban areas [4].

However, using shared micromobility gets challenging if the altitude differences that have to be overcome during a trip exceed a certain amount. This causes several problems such as the imbalance problem, which in the context of station-based sharing means that some stations can get full or empty of vehicles over time. Such uneven distribution may occur when commuters want to travel to work in the morning and back in the evening (i.e., rush hour) and they are not willing to rent a bike at elevated stations if they first have to walk uphill [5]. As a consequence, this implies that users cannot freely borrow or return vehicles anymore [6]. That is, if the rebalancing problem occurs between sharing stations at different altitudes, the stations at higher altitudes are more likely to face a shortage of vehicles. Yi et al. [7] state in their work that many studies deal with the rebalancing problem and a common solution is the incentivisation of users. This means, for example, that the users receive an incentive such as a travel discount if they rent a specific vehicle or drop it at a specific station [8]. Besides rebalancing, another problem related to electric vehicles is the effect of altitude differences on the battery consumption in steep terrain. In comparison to electric cars, most of the electric-driven micromobility vehicles are not equipped with recuperation technology, which leads to faster battery drainage compared with rides in flat terrain. These challenges need to be taken into account and should be further investigated. One way of investigating micromobility is through realistic traffic simulations, which can provide useful data for analysing specific business areas.

This paper simulates micromobility for electric vehicles in combination with hilly and steep terrain. There are three important parts this work is dealing with:

- The first part of this work proposes a workflow, which describes steps to prepare and define a simulation model for the tool SUMO (Simulation of Urban MObility) [9] in the context of cities with steep terrain. The concrete workflow steps are to build the SUMO simulation model, to integrate elevation data and to integrate micromobility stations.
- The second part is the implementation of a micromobility simulation scenario using the workflow steps.
- The third part is the validation by analyzing the results of the simulation scenario addressing different *validation aspects*. These comprise the investigation of the energy consumption of electric vehicles and the driven altitude differences. In addition, the validation results can be used for future works as input data for incentivisation algorithms that try to motivate customers of micromobility services to ride a vehicle to vehicle stations that are up the hill.

Finally, this work can help to predict battery-swap intervals, to develop fleet rebalancing strategies, such as an incentive-driven customer-based approach, or to evaluate station-based charging strategies for micromobility vehicles. As scenario we choose Stuttgart, a German city which lies in a hilly landscape characterised by hills and steep streets.

The results show that the presented workflow is a well-defined process to prepare a SUMO model for micromobility in combination with elevation data. Additionally, the workflow offers a well-defined standard and possibility to process and to simulate micromobility issues in the context of steep terrains and can be used in further work and research. This helps the simulation to get closer to reality.

This work is structured as follows. Section 2 describes related work and highlights differences to this paper. In Section 3, the micromobility scenario is defined and described. In Section 4, the workflow is described that generates the SUMO Model as well as extends the model with electric micromobility vehicle and elevation data. Section 5 presents, compares and discusses results of simulation runs with and without elevation data. Finally, Section 6 summarizes this work and gives an outlook for future works.

2 Related Work

In 2018, the *Monaco SUMO Traffic* (MoST) Scenario [10] was published as the first freely-available mobility scenario for SUMO with elevation information. The scenario covers an area of approximately 70 km^2, containing Monaco and the surrounding mountain area, which makes it interesting to simulate routes with high differences in the altitude during the trip. The scenario contains predefined routes for pedestrians, for different kinds of vehicles and for the local public transport system. The topological data for the scenario comes from a specific database. These datasets are often fragmented on different servers of different countries and are not always freely available. Therefore in this work the topological data originates not from a certain database of a specific map area, but is rather accumulated by requesting the Open Topo Data REST API [11] for each node.

In 2020, the *SUMO Activity Generation* (SAGA) [12] framework was published. This framework is based on the work of the MoST scenario [10] and provides a workflow and a tool chain to create complex multi-modal activity-based simulation scenarios. Starting with an OpenStreetMap (OSM) file as input data, SAGA extracts not just the streets as functional features, but also infrastructure and environmental features (e.g., parking areas, buildings, and PoIs) and further information to utilize these features to create activity-based mobility plans for people. SAGA supports multiple travel modes (i.e., walking, cycling, public transport, on-demand mobility and user-defined vehicles) which makes it highly relevant for simulating micromobility scenarios. The SAGA framework was also applied on the MoST scenario [10] but there was no special focus on specific micromobility vehicle behaviours in the context of topological map information, which is addressed in this paper.

In 2023, the results of a workshop on bicycle modeling in SUMO were published [13]. The main results were that bicycles and other micromobility vehicle types are becoming more and more important within simulations. For this reason it is suggested to extend the SUMO environment to improve bicycle modeling and to anticipate the appearance of novel micromobility vehicles. Another important issue which is identified in the workshop was the need to include slope and elevation modeling that is addressed in this paper.

Also in 2023, a framework for simulating cyclists in SUMO was presented [14]. This framework allows a more realistic modelling of cyclists by allowing a higher degree of freedom of movement. This takes into account that cyclists are in their behaviour intermediate between motorized vehicles and pedestrians. Although the described effort brings a significant increase for a realistic modelling of cyclists, the aspect of topological map data, which is considered in this paper, was not taken into account.

3 Micromobility Scenario with Topographical Map Information

In order to analyze a micromobility scenario in Germany in combination with steep terrain requires a real-world scenario where these topographical challenges exist. Having only two points in an area, where one part is in low and the other in high altitude is not sufficient. An area is required that has different hills and valleys or rather various altitudes between stations.

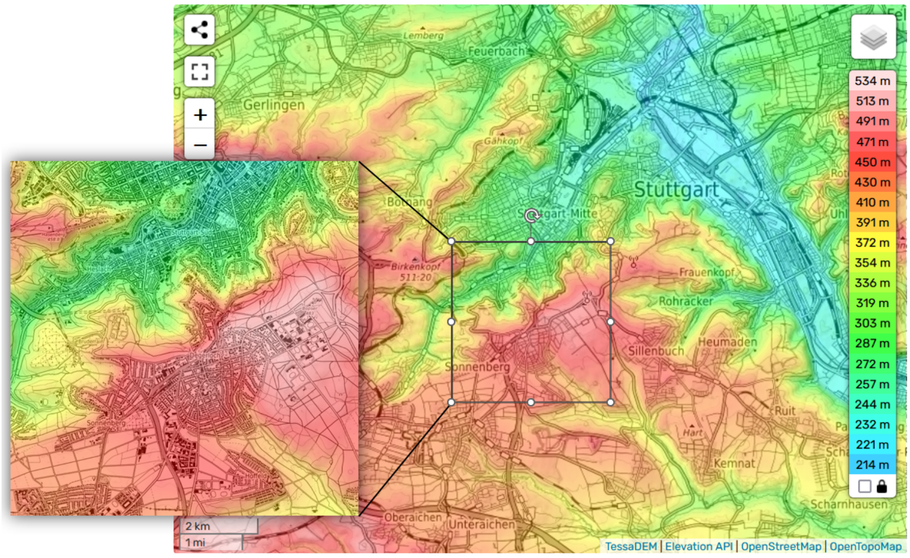


Figure 1. *Topography of Stuttgart and its different altitudes [15]*

In this work, we selected Stuttgart, a city in the southwest of Germany, due to its interesting topographic structures with altitude differences of more than 300 meters [16]. A micromobility scenario in Stuttgart is highly suitable for analyzing energy consumption of electric micromobility vehicles and height differences of the driven trips. The center of Stuttgart lies in a sink at a height of 245 meters. There are different valleys with various lengths and different elevations [16]. Figure 1 shows the different altitudes in and around Stuttgart. Especially, the southeast of Stuttgart has various and changing altitudes. The marked square represents the part of Stuttgart city that has been used for the SUMO model.

The main focus of this work is on electric micromobility vehicles (e.g., e-bikes, e-scooters and e-mopeds) for being able to investigate their energy consumption. However, the results regarding height differences in trips can be transferred to non-electric vehicles. Both, energy consumption and height differences can be used to better plan locations of micromobility stations and to define customer incentives so that the customer is continuously motivated to ride to the next vehicle station that is up the hill.

4 Preparing the SUMO Model

In this section, the workflow for preparing a SUMO simulation with topographical information is described. It consists of the following workflow steps (see Figure 2): Building the SUMO model, integration of elevation data and the integration of micromobility stations. The validation of the workflow is done by the analysis of the battery consumption and the height differences in the context of steep terrains.

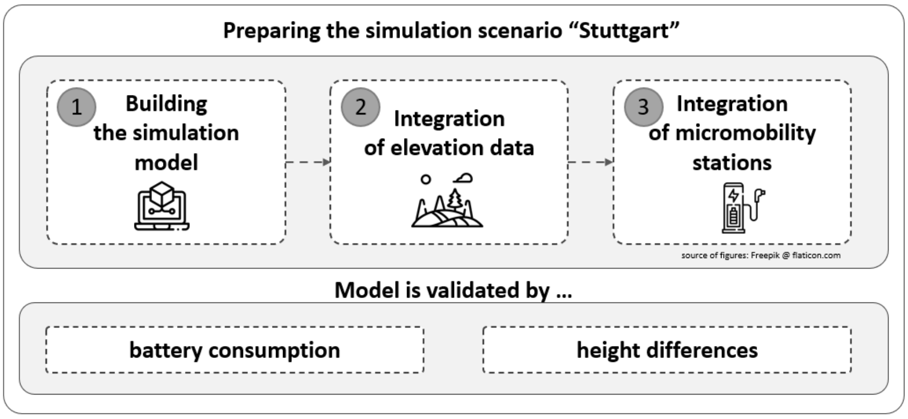


Figure 2. *Steps and validation of the workflow*

4.1 Building the SUMO Model

The SUMO environment provides a variety of tools that can be used for the creation of a specific scenario. One of these is the OSMWebWizard [17], which allows the creation of a SUMO scenario from a subset of the OSM data selected with a bounding box. In order to show the effect of elevation on the simulation data, we have chosen an urban area with significant elevation changes over the routes. Specifically, we focus on the southeast area of Stuttgart.

For a proper and realistic simulation we define a suitable agent type *e-bicycle*, which allows us to evaluate the influence of elevation on the energy consumption. The *e-bicycle* combines SUMOs *bicycle* vehicle class with the *electric vehicle* model and the *Energy/unknown* emission class. The vehicle class defines which types of roads and lanes the vehicle is allowed to travel on. In the case of *bicycle* vehicle class, the vehicle is allowed to drive on all bicycle paths (including bicycle paths in off-road terrain). Conversely, to simulate the influence of elevation on electricity consumption, we use an electric vehicle with a specific emission class. While the electric vehicle model equips the vehicle with a battery device, the emission class *Energy/unknown* allows the dynamic measurement of the consumption using TraCI, an API allowing to access a running simulation. The exact definition of the e-bicycle vehicle can be found in Figure 3. In particular, the `recuperationEfficiency` parameter of the electric vehicle model is set to 0, because most electric bicycles on the market do not support energy recuperation.

4.2 Integration of Elevation Data

A scenario generated by using the OSMWebWizard, however, does not include elevation data. Although SUMO provides a capability to incorporate the elevation data from the OSM data, the *ele* tag used for this purpose does not appear area wide in the OSM data, because it is intended to represent only the prominent topological areas and locations such as mountain ranges and peaks [18].

For a more realistic simulation model, we add the topography information to the available geographical locations within the SUMO model. There are several data source containing elevation data that can be used for integration. One possible data source are *shapefiles* from *ArcView* databases [19]. However finding such shapefiles proves itself as difficult because of missing access rights and costs. Therefore, this work fetches the elevation data from the Open Topo Data REST-service [11]. Further, a

```xml
<?xml version="1.0" encoding="UTF-8"?>

<routes xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance" xsi:
noNamespaceSchemaLocation="http://sumo.dlr.de/xsd/routes_file.xsd">

    <vType id="e_bicycle" length='1.6' width='0.65' height='1.7' minGap='0.5'
    accel='1.2' decel='3' emergencyDecel='7' maxSpeed='13.89' desiredMaxSpeed=
    '5.56' emissionClass='Energy/unknown' vClass='bicycle' speedDev='0.1'
    color="1,1,1">
        <param key="has.battery.device" value="true"/>
        <param key="device.battery.capacity" value="400"/>
        <param key="maximumPower" value="250"/>
        <param key="vehicleMass" value="100"/>
        <param key="frontSurfaceArea" value="0.5"/>
        <param key="airDragCoefficient" value="1.1"/>
        <param key="internalMomentOfInertia" value="0.01"/>
        <param key="radialDragCoefficient" value="0.1"/>
        <param key="rollDragCoefficient" value="0.01"/>
        <param key="constantPowerIntake" value="100"/>
        <param key="propulsionEfficiency" value="0.98"/>
        <param key="recuperationEfficiency" value="0"/>
        <param key="stoppingThreshold" value="0.1"/>
    </vType>

    <trip id="test_ebike" type="e_bicycle" depart="0.00" departLane="best"
    from="4821895#1" to="-96266013#0"/>

</routes>
```

Figure 3. *Vehicle and trip definition*

Python script is developed to enrich the SUMO model with elevation data for every contained geographical location. Figure 4 shows the corresponding processing steps. The script can be found on GitHub [20]. The steps comprise (1) the extraction, (2) the integration, and (3) the converting.

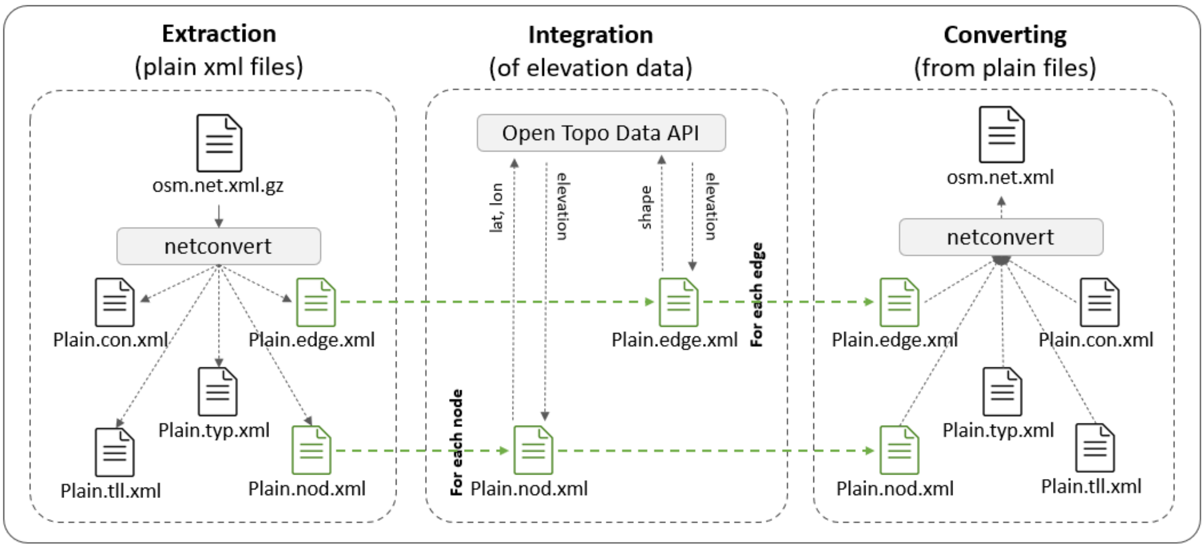


Figure 4. *Overview over the steps to integrate elevation data*

The *extraction* step (1) extracts five plain files from the *osm.net.xml.gz* file using the `netconvert -s` command with the `--plain-output-prefix` attribute. The plain files contain concrete information about the network topology and geometry [21]. For the next step, two files are relevant for the integration of the elevation data: the *egde.xml* and the *node.xml*.

The *integration* step (2) enriches these two files with the elevation data, which is fetched from the Open Topo Data API. In the *node.xml* file, the elevation data is added to the geographical points of a node (x, y attributes) as a ”z” attribute. In the *egde.xml* file, edges have a ”shape” attribute consisting of several geographical points `"x1,y1 x2,x2 x3,y3 ..."` in a string format. The elevation information is integrated into this shape attribute by adding a ”z” information to the ”x,y” pairs to a final `"x1,y1,z1 x2,y2,z2 x3,y3,z3 ..."` string. For retrieving elevation data from the Open Topo Data REST-service [11] two additional processing steps are made. The first processing step prepares the request due to some API request limitations. Daily calls are limited to 1000 where just one call can be made per 1 second. However 100 geographical points can be packed into one call. Thus, the script makes bulks for the requests containing 100 geographical points for one call. The result is then assigned back to the appropriate geographical points. The second processing step is responsible for the conversion of the virtual geographical points from the SUMO model to the original geographical points of the world map and back. The information of the conversion can be found within the *osm.net.xml* file and can be read by the `sumolib.net.readNet(...)` function. The conversion between the latitude/longitude and x/y coordinates can be realized by two functions: `convertXY2LonLat(...)` and `convertLonLat2XY(...)`. The retrieved values of the z coordinate do not have to be converted. The computation of the z value is performed by the Open Topo Data REST-service [11] using the `eudem25m` dataset with `cubic` interpolation. Other datasets and interpolation options can be used as well.

The converting step (3) uses the *netconvert* command to convert the five plain files back to the *osm.net.xml* file by using certain command attributes for the existing plain files such as `--node-files` for the node file. Finally, the *osm.net.xml* file contains all elevation data. Figure 5 shows the three dimensional SUMO model with the elevation data and proves the correctness of the presented steps.

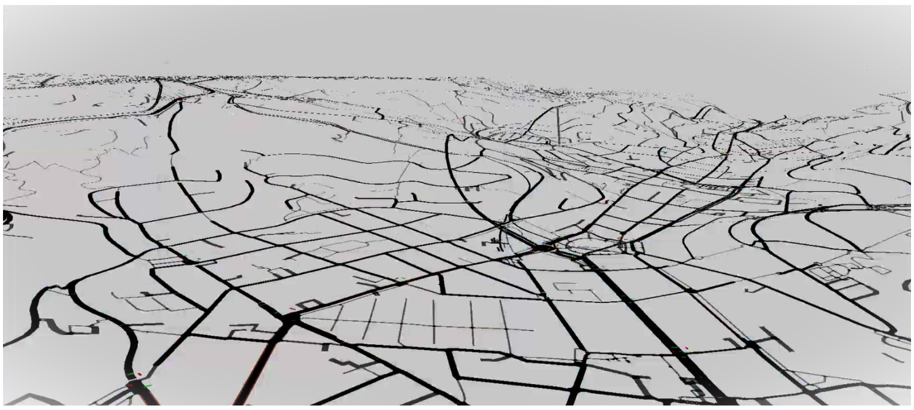


Figure 5. *SUMO model enriched with elevation data displayed in sumo-gui with 3D view*

4.3 Integration of Micromobility Stations

It is assumed that the locations of classical bike-sharing stations will be increasingly utilized for shared electric micromobility vehicles in future. For a proper simulation setup, the locations of classical bike-sharing stations need to be imported to the SUMO model, which could either be performed by extracting map data (e.g., from OSM) or by fetching General Bikeshare Feed Specification (GBFS) data from a bike-sharing service. The latter is more complex, but brings the advantage that the station data is always up-to-date and, more importantly, that it contains further information, for example, how many and which types of vehicles are available at each station. In future works this could serve as a possible source for examining micromobility trip patterns [22]. For the validation example, described in Section 5, GBFS station-data is fetched from *Regio-*

RadStuttgart [23], a regional bike-sharing operator, which is part of the *Deutsche Bahn Connect GmbH*.

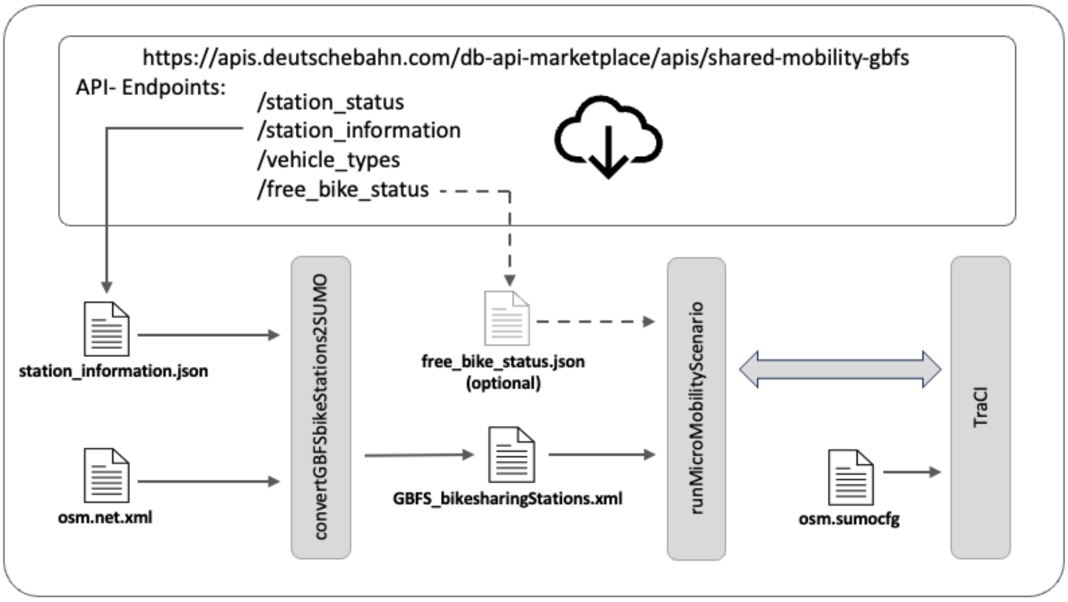


Figure 6. *Workflow to utilize GBFS data for SUMO Micromobility Simulations*

Figure 6 shows the GBFS data import for the considered scenario. The GBFS data from *RegioRadStuttgart* is fetched in JSON format from the publicly available server *apis.deutschebahn.com* [24] by using the API endpoints `station_information` and optionally `free_bike_status` with a personal API key. The personal API key is issued after a registration process at *developers.deutschebahn.com* [25]. To prepare and run a simple micromobility scenario, two Python scripts are created and published on GitHub [20]. The script `convertGBFSbikeStations2SUMO` reads the GBFS JSON file containing the station information (including the station location) and the SUMO net file. It maps the station locations to SUMO edges and outputs an XML file, which can be utilized by SUMO to display the bike-sharing stations as *points of interest*. The contained SUMO edges can be utilized by the script `runMicroMobilityScenario` to find routes for micromobility vehicles between bike-sharing stations. The XML file contains also bike-sharing station IDs from the GBFS data. In future works these IDs could be merged with the information from the GBFS `free_bike_status` endpoint to create scenarios to analyze micromobility fleets.

5 Validation

The route used to validate the implemented workflow is chosen to cover all the difficulties that arise from the inclusion of elevation in the simulation. The route connects two bike-sharing stations, as shown in Figure 7. These stations are separated by a hill and a valley, which allows us to observe the behaviour of the electric vehicles along both an upward and a downward slope. The lowest route elevation is at 276m and the point with the highest elevation is at 472m.

We have performed the simulation with and without elevation data. The influence of elevation on the simulation results can be seen in Figure 8a. On the one hand the electricity consumption of the e-bicycle in the scenario without elevation grows linearly with time, which is very unrealistic. On the other hand changes in elevation can have

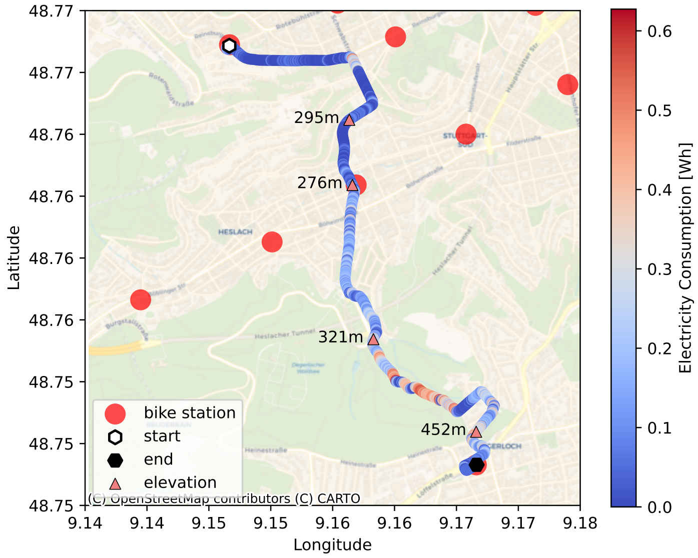
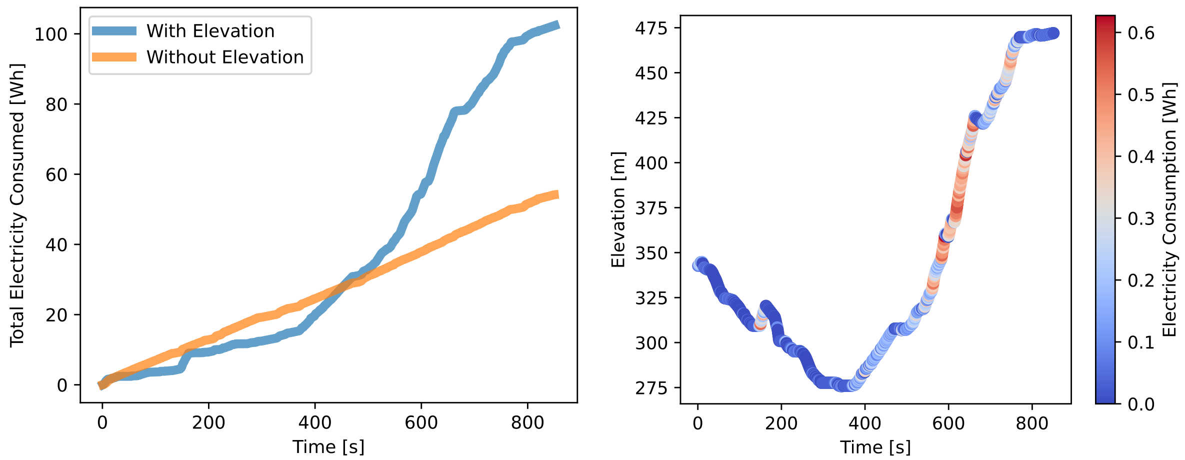


Figure 7. *Route for validation of the implemented workflow*

positive and negative effects on the energy consumption. As expected, downhill drives reduce the energy consumption, uphill drives increase it. This can be seen more clearly in Figure 8b, where increased electricity consumption can be seen in the parts of the route with increased elevation growth. This consideration provides the basis for realistic SOC simulations of traction batteries for micromobility.



(a) *Electricity consumption over time* ***(b)*** *Elevation change over time*

Figure 8. *Consumption and elevation change over time*

6 Conclusion and Future Work

In this paper, a generally applicable workflow and tool chain to include topological map information into a SUMO simulation models is presented. The advantage of the presented workflow is that through the use of REST APIs, it significantly simplifies the process and avoids the initial hurdle of finding and processing suitable topological map data for adding elevation to SUMO scenarios. Furthermore, since elevation information can in particular be important in the scope of shared micromobility, this workflow also includes the possibility of adding micromobility stations from GBFS data to the simulation configuration. The validation of the workflow was performed by defining an electric bicycle and simulating a trip in the hilly area in the southeast of Stuttgart, Germany. The validation shows significant influence of elevation on electricity consumption of the defined vehicle. The simulation model and the Python scripts, which were used for validation are publicly available on GitHub [20].

In future work, the limitations of the presented approach (e.g., topological data of bridges and tunnels are currently not considered) could be closely investigated and possible solutions could be developed. Moreover, further works can investigate the integration of the retrieval part of the elevation data into the *OSMWebWizard* if there is no limit to the requests from the Open Topo Data REST API. The current conditions of the REST API can quickly reach the maximum request amount for large map areas. This would then extend the procedure to several days which makes it currently not a suitable way to use this approach in combination with the *OSMWebWizard*. Another issue that could be considered is the driving behaviour (speed and acceleration) of micromobility vehicles which should depend on the current slope. Further work could also include the development of tools to automatically generate shared micromobility fleet scenarios from origin-destination tables representing customer interests. Finally, combining the presented approach with the *SUMO Activity Generation* (SAGA) framework and thereby considering altitude differences in decision-making models for persons (agents) could be used to develop incentive strategies. Evaluating such incentive-driven decision models could improve customer-based rebalancing and charging approaches for micromobility fleets.

Data availability statement

The data supporting the results of contribution can be accessed on GitHub [20]. Further, the topology data used to enrich the SUMO model are fetched from [11] and the GBFS data used to import bike stations are retrieved from [24]. To use this API an API key is required.

Underlying and related material

The code of the implemented method as well as the manual on its usage can be accessed on GitHub [20].

Author contributions

The authors contributed to this paper in the following ways: All authors contributed to the conceptualization and methodology. A. F. was responsible for writing the original draft of the manuscript. E. R., D. R., I.T. and M.S.contributed to reviewing and editing the manuscript.

Competing interests

The authors declare that they have no competing interests.

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