SUMO User Conference 2023

Conference paper

https://doi.org/10.52825/scp.v4i.215

The State of Bicycle Modeling in SUMO

Aboozar Roosta[1][https://orcid.org/0000-0003-1023-8189], Heather Kaths[1][https://orcid.org/0000-0003-2554-8243], Mirko Barthauer[2][https://orcid.org/0000-0003-3177-3260], Jakob Erdmann[2][https://orcid.org/0000-0002-4195-4535], Yun-Pang Flötteröd[2][https://orcid.org/0000-0003-3620-2715], and Michael Behrisch[2][https://orcid.org/0000-0002-0032-7930]

[1] University of Wuppertal, Germany

[2] German Aerospace Center (DLR), Germany

Abstract. Microscopic traffic simulation tools provide ever-increasing value in the design and implementation of motor vehicle transport systems. Research and development of automated and intelligent technologies have highlighted the usefulness of simulation tools and development efforts have accelerated in recent years. However, the majority of traffic simulation software is developed with a focus on motor vehicle traffic and has limited capabilities in the simulation of bicycles and other micro-mobility modes. Bicycles, e-bikes and cargo bikes represent a non-negligible modal share in many urban areas and their impact on the operation, efficiency and safety of traffic systems must be considered in any comprehensive study. The Differentiation between different types of micro-mobility modes, including microcars, e-kick scooters, different types of bicycles and other personal mobility devices, has not yet attracted enough attention in the development of simulation software which creates difficulties in including these modes in simulation-based studies. On November 25th, 2022, members of the SUMO team at DLR organized a workshop to assess the state of bicycle simulation in SUMO, identify shortcomings and missing capabilities and prioritize the order in which bicycle traffic related features should be modified or implemented in the future. In this paper, different aspects of simulating bicycle traffic in SUMO are examined and an overview of the results of the workshop discussions is given. Some suggestions for the future development of SUMO emerging from this workshop, are presented as a conclusion.

Keywords: Microscopic Traffic Simulation, Bicycles, SUMO

1. Introduction

Bicycle traffic is distinct from car traffic in terms of the movement and interactions of individual road users and the aggregated traffic flow, which requires special consideration in microscopic traffic simulation. As of January 2023, the official documentation of SUMO suggests two methods for simulating bicycle traffic: modeling bicycles as “slow vehicles” or as “fast pedestrians”. The former option, simulating bicycles as slow vehicles, is the method that is widely used. With some modifications to the simulation environment, the same models that describe car traffic in SUMO are calibrated to simulate bicycle traffic. A desired speed and acceleration model captures the dynamics in free flow and a car-following model is used to simulate interactions with other road users on one-dimensional lanes. Lateral movement is simulated by dividing a single driving lane into multiple narrower sub-lanes in the longitudinal direction. The width of the road user and the sub-lanes dictates the number of sub-lanes that are “blocked” by a road user. Lane selection and lane change models are employed to determine the lateral position of the road user within one driving lane, making it possible to simulate passing within this lane. The addition of sub-lanes allows for much more realism in the simulation of bicycle and mixed traffic flows.

Although sub-lanes have vastly improved the simulation of bicycle traffic, it is still difficult to completely capture the unique dynamics [1], flexible movement [2], and less rule-based interactions of cyclists [3]. At the same time, in light of its low cost, low environmental impact, minimal space requirement and negligible noise production as well as increased public health through daily movement, the bicycle is emerging as a key to the “Verkehrswende” (English: transportation revolution). The modal split in many large German cities is already reaching 20% of the total number of trips [4] and there is a national goal of doubling the number of kilometers travelled by bicycle by 2030 in comparison to 2017 [5].

Given the increased need to simulate bicycle traffic, the SUMO development team recognized the need to address these shortcomings and identify opportunities to improve the simulation of bicycle traffic. To this end, an online workshop was held on November 25th, 2022 and past and current members of the SUMO development team, researchers, and SUMO users were invited to participate. The aim of the workshop was to analyze the status of bicycle modeling and simulation in SUMO, identify aspects of bicycle behavior that require improvement, and prioritize the development of new features to improve the simulation of bicycle traffic. In this paper, we present the results of the workshop and discuss the identified areas for improvement and proposed solutions.

At the beginning of the workshop, the SUMO team made a clear distinction between “qualitative” and “quantitative” features in the context of bicycle traffic modeling. Qualitative features refer to the aspects of bicycle traffic that should be accurately reflected in SUMO's modeling approach, such as turning behavior, following behavior, lateral movements and routing. On the other hand, the term quantitative refers to numerical validation, which assesses how well simulated bicycle traffic metrics align with real-world scenarios. To date, the SUMO team has not conducted any quantitative validation of the implemented features. It is worth noting that while writing this paper, the SUMO documentation [6] was frequently utilized to obtain more data about the issues discussed in the workshop.

In this paper, the terms “bicycle” and “cyclist” are used to refer to the simulated agent, depending on whether the emphasis is on the rider or the vehicle. Moreover, the term “car” is used to describe engine-powered vehicles, including cars, trucks, and buses.

The topics covered in the workshop are divided into four sections in this paper. In Section 2, methods for routing bicycle traffic through the simulated network are discussed. Section 3 examines the modeling and simulation of the longitudinal and lateral movements and interaction of cyclists. In Section 4, the simulation of traffic at intersections is examined. Section 5 focuses on the relevant topics in network design and road grade simulation. Finally, in Section 6, we present our concluding remarks and discuss proposed ideas for future feature development of SUMO, based on the outcomes of the workshop. Nevertheless, paragraphs following other text paragraphs are indented.

2. Routing

The SUMO package consists of several individual tools, each serving a specific purpose in the simulation. Among these tools are four routing algorithms: Dijkstra, A*, ALT and CH. Each of these algorithms is well-suited for certain scenarios. Routing for all road user types can be performed by travel time, effort, distance, or edge priority, offering flexible options to simulate the various factors that impact drivers' route choices. By default, routing in SUMO is done based on travel time minimization. “Effort” is a general term that refers to providing the routing algorithm with alternative weights or in other words optimization based on the alternative costs, such as pollutants (CO, CO_2, PM_X, HC and NO_X), fuel or electricity required to travel a given route, or noise generated in the process. These weights can be either constant or time-dependent.

In SUMO, bicycle routing uses the same routing algorithms and objectives as used for vehicle routing. However, there is an additional parameter called “--device.rerouting.bike-speeds” that allows the routing module to compute separate average speeds for bicycles. This parameter is disabled by default as it adds extra computing cycles and slows down the simulation. However, enabling it for scenarios where bicycle traffic is important is recommended as it results in more accurate routing of bicycle traffic. This feature can help account for the unique speed characteristics of bicycles, such as their lower speeds.

In addition to routing preferences and behavior, modeling bicycle traffic in SUMO should also take into account the specific characteristics of bicycle movement. Cyclists should be able to exhibit a preference for using dedicated bicycle infrastructure. This preference usually stems from safety concerns or enforced traffic laws. Besides using individual weights for routing, the only other possibility to affect the routing of bicycles is specifying individual speeds for bicycle lanes. Another frequently observed behavior that should be added to SUMO is the ability for cyclists to use adjacent lanes or edges under special conditions. This makes for a more flexible and realistic cyclist behavior modeling. However, practical implementation could be difficult due to the need to identify and avoid collisions in the course of these short lane/edge changes.

Other improvements could also be made to allow for the simulation of multimodal trips and more flexible bicyclist behavior. These include allowing for bicycle use in accessing public transport, to simulate pushing the bicycle across pedestrian crossings or carrying them on infrastructure where cycling is not allowed or possible, inventing new types of settings that allow for flexible switch between cycling and walking at any time during the trip and settings that allow for leaving a bicycle in some location and returning to pick it up at a later time. It should be noted that carrying certain bicycle categories like cargo bikes and bicycles with trailers may not be feasible thus the option to switch between walking and cycling has to be more fine-grained. These simulation settings will be in more demand as usage of shared bicycles grows and implementing these features will also facilitate incorporation of other personal mobility devices in SUMO in the future.

3. Following behavior and lateral movements

As discussed in the introduction, bicycle traffic is either modeled using adapted versions of car models for lateral and longitudinal movement and interactions (slow car option) or pedestrian models (fast pedestrian option). Because the former method is more frequently used by users of SUMO, the sub-lane modeling approach for following and lateral movement were focused on in the workshop. Although bicycle traffic tends to follow lanes in the intended direction of travel, cyclists are more flexible in this domain due to their smaller size and higher maneuverability in comparison to motorists. It is acknowledged that car-following, (sub-)lane selection and (sub-)lane changing models may not be able to fully capture the complexity of bicycle traffic behavior.

3.1 Car-following models

Car-following models determine the longitudinal acceleration in each simulation step based on the location, speed and other characteristics of individual vehicles by taking into account the vehicle directly ahead in the same (sub-)lane. Numerous car-following models have been formulated in the last 50 years and many of them are included in the SUMO package. The “carFollowModel” parameter specifies which car-following model is to be used in the simulation of the vehicle.

By default, SUMO utilizes the Krauß car-following model [7], which relies on three primary variables to determine a driver's behavior: the vehicle's own speed, the speed difference with the leading vehicle, and the distance to the leading vehicle. The Krauß model is designed to maintain a safe speed that ensures a minimum distance to the leading vehicle and prevents collisions. However, according to presentations from the SUMO team, this model produces noisy speed curves. To obtain smoother position and speed curves, it is recommended to use the Intelligent Driver Model (IDM) [8] instead of the Krauß model for bicycle traffic. In contrast to the Krauß model, the Intelligent Driver Model (IDM) takes into account the time headway, leading to smoother traffic flow curves. Furthermore, the extended IDM model (eIDM) [9] combines features of both the Krauß and IDM models to offer benefits of both models. When modeling bicycle traffic and car traffic in the same lanes, it is apparent that the two modes exhibit similar patterns, except that bicycle traffic densities are significantly higher (due to a lower minimum gap of 0.5 meters). Additionally, some lane-changing activities may alter the speed patterns of bicycles.

After discussions about the behavior and properties of the Krauß and IDM models, the question was raised as to whether these models provide an accurate representation of bicycle traffic, or whether entirely new models are needed to address their inaccuracies. The consensus was that these models are sufficient for the current stage of research, but modifications are necessary to account for distinct behaviors that are present in cycling but absent in motor vehicle traffic, such as side-by-side riding, which represents leisurely bicycle activities. It was suggested that quantitative efforts should be made to calibrate the Krauß and IDM models using real-world trajectory data and/or bicycle experiments. Currently, the following parameters are recommended in the SUMO User Documentation for modeling bicycle traffic. In order to provide a comparison, Table 1 displays a selection of significant default parameters for bicycles and cars in SUMO.

Table 1. Selected bicycle parameters defined in vClass=“bicycle” and “passenger”.

Parameter	vClass=“bicycle”	vClass=“passenger”
Minimum Gap	0.5 m	2.5 m
Maximum Acceleration	1.2 m/s2	2.6 m/s2
Maximum Deceleartion	3.0 m/s2	4.5 m/s2
Emergency Deceleration	7.0 m/s2	9.0 m/s2
Length	1.6 m	5.0 m
Maximum Speed	20.0 km/h	not limited (1000 km/h)

Observational and experimental data is needed to examine the qualitative properties of various car-following models, and to calibrate and validate them. During the calibration process, special attention should be given to reproducing exact macroscopic results to ensure better validity. Calibration and validation of the car-following models for bicycle traffic would be a first step in decoupling the models of car traffic and bicycle traffic. Ultimately, these models could be used to simulate other emerging micro-mobility modes, such as e-scooters. Although simulation of these modes can also be achieved through the utilization of the “slow pedestrian” approach, further enhancements to this approach are required. In particular, the integration of proper visualization techniques, as well as the inclusion of new movement models, would be imperative to improve the accuracy and comprehensiveness of the simulation.

3.2 (Sub-)Lane changing and lateral alignment

The lateral behavior and alignment of bicycles is controlled by lane selection and lane changing, both in terms of regular driving lanes and sub-lanes. When considering the motor vehicle simulation, vehicles may need to change lanes for various reasons, such as navigation or route-following, speed gain, cooperation, and following the rules. The lane changing model in SUMO determines lane choice on multi-lane roads and speed adjustments related to lane changing [10], and now supports four motives for lane changing: strategic, cooperative, and tactical lane changes, as well as the obligation to clear the overtaking lane. Changing lanes could also be triggered remotely by the TraCI interface.

In order to simulate more flexible lateral movements and differences in lateral positioning within a lane (bicycle traffic keeping to the right), and enable passing in one traffic lane, it is possible to divide the lanes into multiple sub-lanes. The sub-lane model is used to govern movement between multiple sub-lanes. The introduction of this model has made it possible to simulate common scenarios, such as cars overtaking two-wheeled vehicles in a single lane and multiple two-wheeled vehicles driving in parallel. This is particularly useful in scenarios where a significant amount of urban traffic consists of scooters and/or bicycles. For a full list, refer to the SUMO documentation on sub-lanes [11]. To ensure accurate simulation of behavior when the sub-lane model is activated, certain parameters must be set properly. In the sub-lane model, the car-following algorithm is adjusted to consider all vehicles occupying at least one sub-lane of the lane in which the subject vehicle is located. Additionally, the lane-changing model accounts for lateral alignment and safe lateral gaps, in addition to the four motivations for lane changes mentioned previously. However, the activation of the sub-lane model can significantly increase computation costs, and is therefore disabled by default to prevent slowing down simulations in cases where high resolution of lateral movements is unnecessary. An example of a mixed traffic link simulated using the sub-lane model approach is shown in Figure 1.

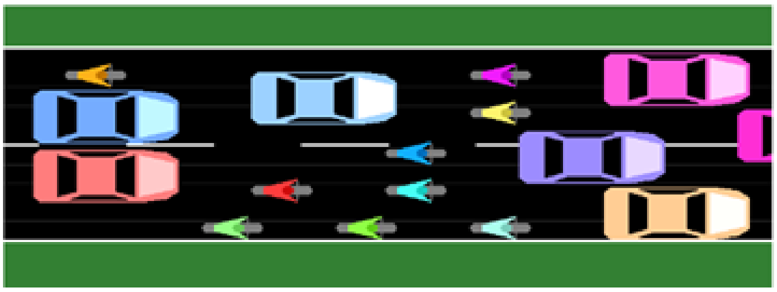

Figure 1. Application of sublane model to mixed traffic simulation [12].

In addition to the lane-change and sub-lane models, there is also a continuous lane-changing model available, which allows for more realistic lane-changing behavior by specifying the time it takes to complete a lane-change action. Compared to the sub-lane model, the continuous lane-changing model has significantly lower computation times. By default, without the sub-lane model, a single lane-change operation takes one simulation time step, which may not be entirely realistic depending on the vehicle's speed. The use of this model may be beneficial in simulating very narrow lanes where sub-lanes cannot be utilized. Incorporating a transition time during lane changes can make the maneuver more realistic.

The current implementation of the sub-lane model in SUMO has a limitation in that it cannot be enabled only for bicycle traffic while remaining disabled for car traffic. Having the sub-lane model enabled for car traffic creates more computation cost and adds little to the realistic representation of cars in the achieved flexibility of movement, except that they can move laterally to pass in the same driving lane. Nonetheless, the SUMO team has highlighted that the current implementation of the sub-lane model is beneficial for achieving smooth lane changes. Then, as for the car-following behavior, the adequacy of SUMO's lane change and sub-lane models for simulating bicycle traffic has been discussed. The consensus among the participants was that the simulated bicycle traffic in SUMO is too regular and lacks sufficient stochasticity. During the discussions, one proposal to enhance the realism of bicycle traffic simulation in SUMO was to introduce variations into the parameters that model bicycle traffic, such as incorporating a variable minimum gap for bicycles. The idea was well received by the SUMO team, who suggested that incorporating realistic variation bounds into the parameters, based on studies or publicly available data, would be preferable. It was also suggested that the regularity in the simulated traffic may be due to the vehicles, including bicycles, all being modeled with rectangular boxes instead of diamond shapes which are used in other simulation tools [12]. While the discussion favored adding variations to the parameters, the SUMO team also mentioned the possibility of adding a “diamond” shape to the bicycles’ parameters by a mathematical transformation. This transformation would be simple to implement and would not incur any additional computational costs. Diamond shape will lead to a more accurate simulation of more unconventional bicycle geometries of different types of cargo bikes and bicycles with a trailer. Another suggestion was to model the safety distance based on impatience or frustration of the cyclist which involves psychological factors and therefore requires more data.

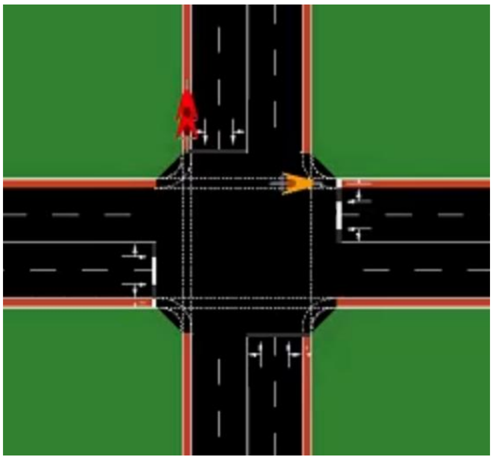

Figure 2. Demonstration of perceived conflict area by the red cyclists represented by SUMO team at the workshop.

4. Intersections

Intersections are crucial elements of the traffic network, connecting links and requiring conflicting streams of vehicles, bicycles, and pedestrians to interact. As such, simulating the behavior of road users at intersections requires special attention. Traffic signals, right-of-way rules, and the need to consider multiple types of vehicles and road users make intersections more complex than links and other segments of the road network. At intersections, the points/areas of conflict must be carefully simulated to accurately represent the behavior of all road users. This requires consideration of factors such as internal links that connect incoming and outgoing lanes, the speed at which vehicles approach and traverse the intersection, waiting times before entering and within the intersection, and outgoing flows that must be managed to avoid blocking the junction. Proper simulation of these factors can help ensure a more realistic and accurate representation of intersection behavior for all road users. Issues like direct and indirect turns for cyclists [13], adherence of cyclists to the internal links, and behavior in conflicting areas are important. For example, cyclists may be more likely to make indirect turns to navigate through crosswalks, and they may have different preferences at the intersection depending on their position relative to other road users.

The SUMO team emphasized the need for improved modeling of conflict areas, particularly in regards to bicycles. Currently, if a cyclist with right of way enters an intersection, other cyclists intending to cross the internal link must wait until the cyclist with right of way has completely left the intersection, even if there is sufficient time and space to safely cross. Figure 2 illustrates this issue, with the yellow cyclists representing the flow with right of way and red cyclists waiting due to the fact that all of the intersection is being considered a conflict area. It was suggested to alter conflict points to not be applicable to cyclists’ interactions with other cyclists, instead having cyclists slightly alter their speed and/or path to pass the conflict point without needing to wait. It was agreed that this phenomenon should be implemented as a qualitative feature. The quantitative aspect has to be further studied but there was an internal DLR study at Braunschweig which confirms that virtually no cyclist stops at a pedestrian crossing.

An additional discrepancy between actual bicycle traffic behavior at intersections and the simulation outputs produced by SUMO has been observed. While in SUMO cyclists adhere to the internal links very accurately, in reality cyclists roam more freely at intersections. One of the participants presented their work about the result of data collections at intersections in Munich and a comparison with simulated bicycle traffic in SUMO. Figure 3 compares the heatmap of speed and occupancy of bicycle traffic at one of the measured intersections.

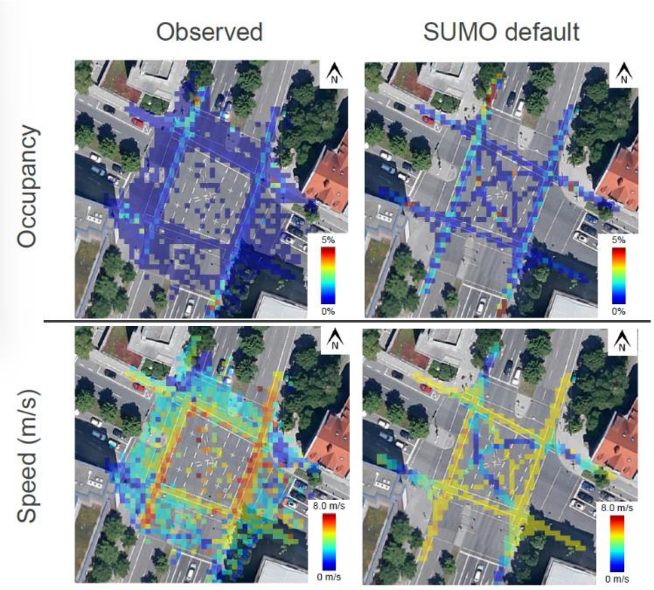

Figure 3. Comparison of real-world bicycle traffic occupancy and speeds with SUMO simulation [14].

The observed strict adherence to internal links in the simulated bicycle traffic may be partially attributed to the constant and unvarying nature of the bicycle traffic parameters, which was discussed in the previous section. Moreover, it is plausible that some cyclists may dismount from their bicycles while performing indirect left turns. Indirect left turns refer to the maneuver where cyclists continue straight at an intersection, subsequently making a 90-degree turn, before continuing in a straight direction again. Similar results have also been observed in other smaller intersections with one lane car traffic in this research. Various static and dynamic characteristics of the intersection likely influence cyclists' behavior. Traffic signals, car traffic volume and speed, physical separation between bicycle lanes and the roadway, whether islands are available at the intersection, and last but not least the geometry of the intersection are among these influencing factors.

A number of other issues were discussed briefly. Distinct signalization for bicycles and cars on the same connection should be allowed. Implementation of bicycles waiting ahead of motorized traffic could be further enhanced by making bicycles and motorcycles ignore the minimum gap of stationary cars when changing lanes. In scenarios where there are cars as well as bicycles, bicycle boxes do not work reliably. Furthermore, it is beneficial that connections with more than two internal lanes be allowed to accommodate complex junctions with multiple islands or two indirect left turns.

5. Network

Over the past two years, the SUMO team has placed emphasis on the development of network-related features, with significant advancements being made. Much of SUMO's code base had been originally developed with car-only networks in mind. As a response to this limitation, the team has been actively working on the implementation of multimodal network import capabilities, although there are challenges with regard to availability of openly available data.

The implementation of indirect left turns is now possible in SUMO. Indirect left turn is particularly favorable in larger intersections where the perceived risk associated with direct left turns for cyclists is higher. By default, direct turns are currently the default setting for bicycles. It was discussed whether indirect left turns should be the default action, and ultimately, it was decided to change the default to indirect left turns at intersections with bicycle lanes. This topic requires more observational research. A proposed idea is to enhance SUMO's network generation/import tools by advancing beyond the default option architecture and instead, making decisions based on the infrastructure's geometry and parameters. The rationale behind this suggestion is to address the limitations of open data, such as OpenStreetMap (OSM), which may contain incomplete infrastructure information. There was a discussion about the feasibility of predicting the existence of bicycle lanes based on available infrastructure data, like total road width and availability of parking lanes from OSM. However, implementing such an approach would require the development of models and studies on the correlation of different design parameters, in order to make more accurate estimations. It was decided that this feature is not a priority for development at this moment.

SUMO enables the inclusion of elevation data in the network. Currently, this information is used natively for electric vehicles, calculating emissions and in the extended Krauss car-following model. In the extended version of the Krauss car-following model, the maximum acceleration in each time step is reduced, based on the gradient of the road.

SUMO can import road network data from major data formats, some of which include elevation data. However, creating networks based on OSM is usually preferred as it offers its data under a free license. One of the downsides of using OSM is that there are not enough elevation data points in OSM to allow for reliable simulation of networks with varying road grades. Network grade and its variability has a considerable impact on mode choice and route choice, especially of active mobility road users [14].

SUMO includes a method for modeling and simulating electric powered vehicles, which includes additional variables that are not normally considered in a microscopic traffic simulation software such as the vehicle mass, the coefficient of drag, and the frontal surface area. This feature was developed in order to test different charging scenarios and technologies. As the physical relationships that describe the power required to move a bicycle are quite similar to those describing the power needed to move a car, this existing model will prove very valuable in developing an improved model for e-bikes in SUMO. The main difference lies in the combination of power supplied by the person and the electric motor. According to European law, an electric motor on a e-bikes can supply a maximum of 250W and can only provide power up to a speed to 25 km/h [15]. If a cyclist exceeds this speed or stops pedaling, the electric motor must immediately or gradually stop providing power to the bicycle.

6. Conclusions and suggestions

This workshop provided an opportunity for discussion on important aspects of bicycle traffic modeling and simulation in SUMO. During the workshop, researchers, users, and other interested parties contributed to discussions regarding the identification of critical features and priorities for future development. As a result of these discussions, certain issues were identified as requiring less effort to be implemented, indicating the possibility for their prioritization in the development process. These include the addition of diamond shapes to bicycle models in order to enhance their realism and add more variety to bicycle traffic simulations. Additionally, the possibility of assigning weights to different types of infrastructure to enable infrastructure-aware routing for bicycles was discussed. Such a system would give preference to certain infrastructure types, such as bicycle lanes, by assigning them lower weights in the routing process. Other low effort improvements include making indirect left turns the default behavior for cyclists, and enhancing bicycle boxes positioned in front of car traffic prior to intersections. In addition to the aforementioned topics, several other issues were identified as important and requiring additional attention. These include the development of concepts such as conflict areas for bicycles and pedestrians, as well as improvement of shared space simulations capabilities. There was also a recognition of the need to improve slope and elevation modeling and to enhance lateral movements in bicycle traffic simulations. Another general concern was isolating the cyclist behavior characteristics from sufficiently large empirical datasets and acquiring appropriate datasets needed for more accurate implementation of some proposed changes.

This workshop highlighted the need for models that can simulate unique bicycle traffic flow behavior. More improvements on top of the issues discussed in the workshop can be envisioned. It would be beneficial to researchers if SUMO allowed for easy implementation of force models and physics-based models. Software like NetLogo [16] provide this opportunity for simulating different models with subject agents. However, testing models in more realistic scenarios in the context of urban traffic networks is also required to accelerate research and development of these models. There is already a partnership with Jülich research center to integrate the JuPedSim pedestrian model [17] into SUMO and this suggestion could be considered during this integration. Integrating such models in SUMO could be an opportunity to create flexible frameworks that can accommodate similar models.

Much of the focus on modeling bicycle traffic has gone into the option “slow car”, meaning that modeling approaches for car traffic have been adapted, calibrated and applied to bicycle traffic. Far less attention has been placed on the option “fast pedestrian” and the use of social force like models in recreating bicycle traffic, both in this workshop and by researchers and developers. The formulation, calibration and validation of social force models for bicycle traffic could offer an important way forward in including the flexible behavior and the fluid interactions of cyclists in SUMO.

One possible enhancement would be augmenting the intended implementation of a diamond shape transformation for bicycle models with additional shapes that better reflect the wide range of cargo bicycles and bicycles with trailers that are currently available. As new types of micro-mobility vehicles continue to emerge, it is crucial to anticipate their use cases and adapt the SUMO software accordingly, in order to minimize the need for extensive reworking of the codebase in the future. Another suggestion is the implementation of shared mobility in the form of stations for shared bicycle providers and bicycle parking with high capacity to improve simulation of seamless pedestrian-bicycle trips.

Data availability statement

This paper is not based on data.

Author contributions

The authors contributed to this paper in the following ways: All authors contributed to the conceptualization and methodology. A. R. was responsible for writing the original draft of the manuscript. H. K., Y. P., M.B. and J.E. contributed to reviewing and editing the manuscript.

Competing interests

The authors declare that they have no competing interests.

Acknowledgement

The content of this paper is based on a workshop that was organized by DLR and held online on November 25th, 2022.

References

[1] A.-S. Karakaya, K. Köhler, J. Heinovski, F. Dressler and D. Bermbach, "A Realistic Cyclist Model for SUMO Based on the SimRa Dataset," in 2022 20th Mediterranean Communication and Computer Networking Conference (MedComNet), 2022.

[2] H. Twaddle, T. Schendzielorz and O. Fakler, "Bicycles in urban areas: Review of existing methods for modeling behavior," Transportation research record, vol. 2434, p. 140–146, 2014.

[3] H. Kaths, "Cyclists' interactions with other road users from a safety perspective," Cycling, p. 187, 2022.

[4] C. Nobis, "Mobilität in Deutschland- MiD: Analysen zum Radverkehr und Fußverkehr," 2019.

[5] Bundesministerium für Verkehr und digitale Infrastruktur (BMVI), Nationaler Radverkehrsplan 3.0: Fahrradland Deutschland 2030, Berlin, 2021.

[6] "SUMO User Documenation," 10th Feb. 2023. [Online]. Available: https://sumo.dlr.de/docs/index.html.

[7] S. Krauß, "Microscopic modeling of traffic flow: Investigation of collision free vehicle dynamics," 1998.

[8] A. Kesting, M. Treiber and D. Helbing, "Enhanced intelligent driver model to access the impact of driving strategies on traffic capacity," Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, vol. 368, p. 4585–4605, 2010.

[9] D. Salles, S. Kaufmann and H.-C. Reuss, "Extending the intelligent driver model in SUMO and verifying the drive off trajectories with aerial measurements," in SUMO Conference Proceedings, 2020.

[10] J. Erdmann, "SUMO's lane-changing model," in Modeling Mobility with Open Data: 2nd SUMO Conference 2014 Berlin, Germany, May 15-16, 2014, 2015.

[11] "SublaneModel," 10th Feb. 2023. [Online]. Available: https://sumo.dlr.de/docs/Simulation/SublaneModel.html.

[12] G. Falkenberg, A. Blase, T. Bonfranchi, L. Cosse, W. Draeger, P. Vortisch, L. Kautzsch, H. Stapf and A. Zimmermann, "Bemessung von Radverkehrsanlagen unter verkehrstechnischen Gesichtspunkten," Berichte Der Bundesanstalt Fuer Strassenwesen. Unterreihe Verkehrstechnik, 2003.

[13] S. Amini, H. Twaddle and A. Leonhardt, "Modelling of the tactical path selection of bicyclists at signalized intersections," in Transportation Research Board 95th Annual Meeting, 2016.

[14] A. Meister, K. W. Axhausen, M. Felder and B. Schmid, "Route choice modelling for cyclists on dense urban networks," Available at SSRN 4267767, 2022.

[15] Regulation (EU) No 168/2013, 2013.

[16] U. Wilensky, "NetLogo. http://ccl.northwestern.edu/netlogo/. Center for Connected Learning and Compter-Based Modeling, Northwestern University, Evanston, IL.," 1999.

[17] A. U. Kemloh Wagoum, M. Chraibi and G. Lämmel, "JuPedSim: an open framework for simulating and analyzing the dynamics of pedestrians," 2015.