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SIMULATING INTERACTION BEHAVIORS IN BI-DIRECTIONAL SHARED CORRIDOR WITH REAL CASE STUDY

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ABSTRACT

Microscopic traffic simulation tools are able to evaluate possible impacts induced by automated shuttles under various conditions. However, automated shuttles operate more and more often in shared space areas and few microscopic traffic simulation tools are able to handle networks with shared space infrastructure. Interaction behaviors between road users and automated shuttles are addressed only seldom as well. In this paper, we propose the concept of bi-directional edges in the open source microscopic traffic simulation suite SUMO to simulate road users' interactions in a bi-directional shared-space corridor. A case study, where automated shuttles and cyclists share the bike path, and the related data collection were conducted to examine the performance of the proposed concept and understand the usage of the shared corridor. The simulation results are promising. Further refinement of the proposed concept is planned for properly reflecting complex interaction behaviors among diverse road users, and their surrounding environment.

1 INTRODUCTION

Innovative technology development has facilitated the realization of various customized mobility solutions, which benefits not only the overall transport system performance but also improves the accessibility to suburban areas and travelers' travel experiences. At the same time, it is becoming more and more common to consider automated shuttles (AS) as part of mobility solutions to help to extend and enhance current public transport service and quality by providing flexible and/or last-mile transport service. The applied fields mainly include hospital areas, campuses, shopping districts and suburban/remote residential areas, and AS share road space with other road users in some of these areas. Many related national and international demonstration projects are carried out or on-going worldwide. The European projects (FABULOS 2021; AVENUE 2022; Ride2Autonomy 2022; SHOW 2023) as well as the project SPACE (UITP 2021) have devoted to investigate and demonstrate benefits brought by the introduction of automated shuttles with different use cases. In the project SHOW, large-scale demonstration, related to demand-responsive transport (DRT), Mobility as a Service (MaaS) and Logistics as a Service (LaaS), has been undertaken at the test sites within 20 cities located in 13 countries across Europe.

Currently, most automated shuttles are legally allowed to run at a speed less than 20 km/h with a safety driver on board, and their respective performance is therefore limited. A review about current AS operation situations can be found in (Iclodean et al. 2020). Moreover, AS routes need to be prepared, tested and approved by authorities to allow trials, and personnel staffs need to be trained. Accordingly, it takes much time and effort before automated shuttles can operate in practice. Traffic simulation provides an alternative to explore possible impacts induced by automated shuttles under variable conditions, and has also already been applied broadly.

In addition, more and more road space is designed with shared-space philosophy, such as living streets and free-crossing areas, in urban areas. Some AS operate in such areas at several test sites within the project SHOW. However, AS and their interactions with other road users, especially when they share space, are addressed in simulations to a limited extent only. Regarding microscopic shared space simulation several models are proposed and mainly based on the social force model, such as (Anvari 2015; Pascucci 2015). They are not applicable for the general public yet. Schmid (2018) established a built-in function and use conditional probabilities to model the interaction behaviors between pedestrians and vehicles in a free crossing area. Another approach is the one in (Olstam 2020), which further developed the approach in (Gibb 2015), and models shared space by using consecutive virtual pedestrian crossings every 0.5 meters and double representing vehicles using large dummy pedestrians. General commercial or open-source microscopic traffic simulation tools cannot fully consider shared-space situations yet, where involved users can interact with each other and their surrounding environment in all directions. This is mainly due to the limitation that each edge (road) in a simulation is designated for one direction and involved users consider other road users' movements only on the same edge before approaching an intersection.

In this paper, a concept to simulate road users' bi-directional interaction behaviors in a shared corridor with the open-source traffic simulation suite SUMO is proposed. Furthermore, the proposed concept is applied to the selected case study located in the city of Linköping, Sweden. Real data was collected and analyzed for better understanding the interaction behaviors of the involved users and for properly setting parameters in the simulation. The performance of the proposed concept is then examined. In the end, the conclusion and the perspectives are given.

2 EXISTING SHARED-SPACE ORIENTED SIMULATION IN SUMO

The open-source traffic simulation suite SUMO, standing for Simulation of Urban Mobility, has been developed since 2001, and aims to simulate traffic in large areas in real-time (Alvarez Lopez 2018). Different road users can be considered and even customized with given sizes and characteristics in SUMO. Interactions between road users and between road users and road infrastructure can be simulated microscopically. The amount of produced emissions and energy consumption (fuel, battery) can be derived as well. For different research and application purposes, SUMO can not only be used to simulate traffic and to provide background traffic for driving simulators, but also to optimize traffic. The latter one mainly focuses on traffic assignment and signal control strategies. Some tools for flow calibration exist as well for adjusting traffic demand/flows with use of sensor data. To facilitate simulation for different circumstances and research questions, different models to handle with car-following, lane-changing, pedestrian movements and interactions at intersections are available to choose from. In addition, SUMO can also handle shared-space oriented simulation to a certain degree. It can be generally divided into two cases and is further explained below.

2.1 Within an Intersection

When an intersection is identified as a "walkingarea" in SUMO, where pedestrians are allowed to move freely, all road users within the intersection will consider the other road users' movements and avoid collisions before making any movement. Pedestrians can move freely, while other users (vehicles, bicycles) follow the pre-defined, allowed internal links, as indicated in Figure 1, across the given intersection. An illustration is shown in Figure 2.

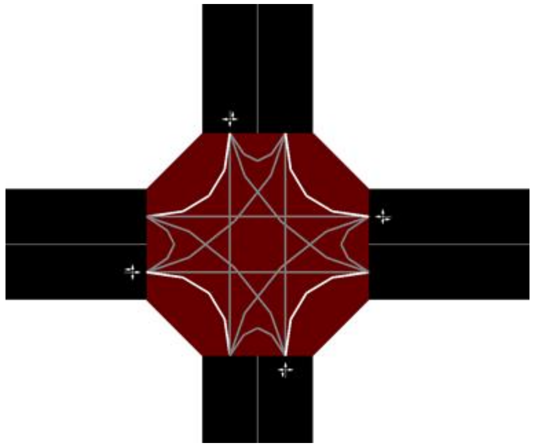

Figure 1: Exemplary layout of internal links at an intersection in SUMO.

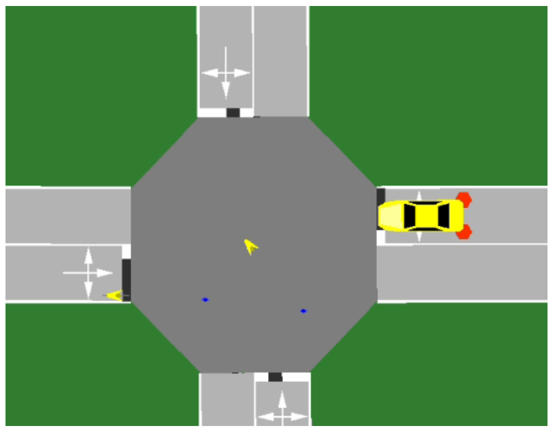

Figure 2: Illustration of shared area within an intersection in SUMO, where blue ovals represent pedestrians.

2.2 On a Road Section

The second case is to simulate road users' interactions on a road section. Such interactions exist only between road users running in the same direction, as shown in Figure 3, where users can change their lateral positions for further proceeding in their journeys without possible conflicts. However, road users do not consider other road users in the opposite direction for movement decision.

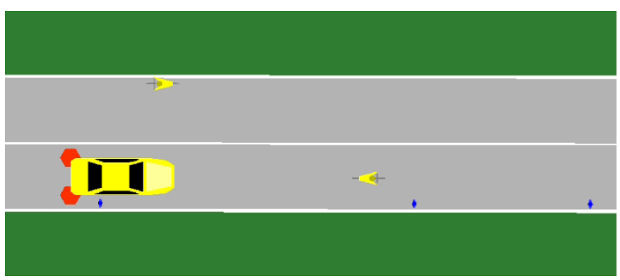

Figure 3: Illustration of shared area on a road section in SUMO, where blue ovals represent pedestrians.

3 PROPOSED CONCEPT OF BI-DIRECTIONAL EDGES

To close the gap that road users do not consider other road users' movements in opposite direction, e.g. on a two-way path/corridor, the concept "bidi-edge" (bi-directional edge), is proposed and implemented under the sublane model for road user simulation in SUMO version 1.15.0. Under the sublane model (Semrau, and Erdmann 2016), a lane can be further equally divided into several "sublanes" according to the user-defined resolution value. For example, a 3.6 m-wide lane will have 3 sublanes when the lateral resolution is given as 1.2 m. Each vehicle may occupy multiple sublanes but at most one vehicle may occupy each sublane at the same longitudinal position. When the sublane model is active, vehicles can move continuously between the sublanes, which facilitates to simulate a mixed traffic situation, e.g. vehicles, mopeds and motorcycles, closer to the reality. In prior versions, bidi-edges were used in a limited capacity for railway simulation. In the railway domain, the same track must often be used in both directions. But no interactivity between trains is needed since there is no lateral movement, and using tracks in two directions simultaneously is generally prohibited. In contrast, shared space simulation should consider roads, where the whole space can be used in both directions at the same time with a higher degree of lateral freedom, especially for bicycles and pedestrians.

Based on the prior existence of railway's bidi-edge concept, no changes to SUMO's network model were necessary. When a network contains a pair of directed edges E and -E, where E originates in Junction A and ends in Junction B and its reverse edge -E originates in B and ends in A, and if the geometry of E is equal to the reversed geometry of -E, then these two edges can be declared as "bidi-edges" by users (either manually or in an automated fashion). In addition, edges must have the attribute spreadType=center to be eligible for bidi-status. This ensures that their lane geometries fully overlap with each other. An example of such a geometry is shown in Figure 4.

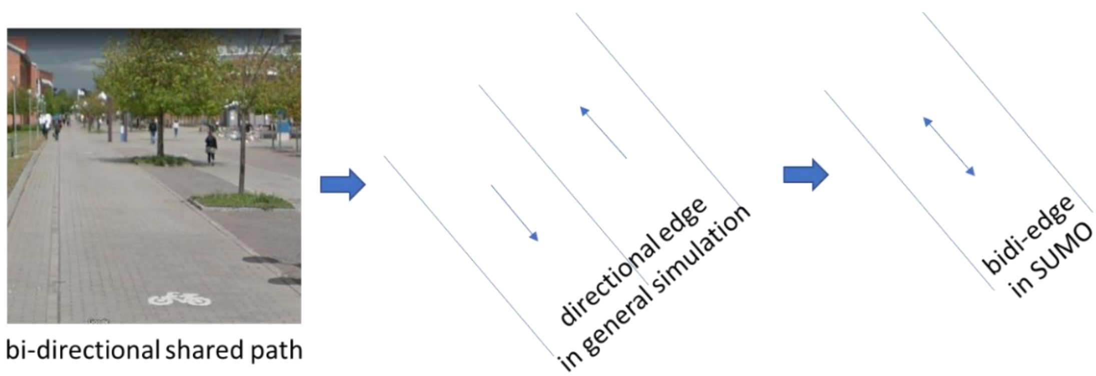

Figure 4: Sketch of the bidi-edge concept implemented in SUMO.

Furthermore, road users' trajectories are defined in reference to directed edges, i.e. E and -E, regardless of the respective bidi status. If road users encounter each other on such a pair of bidi-edges, they will "sense" each other and, if necessary, perform evasive maneuvers. Evasive maneuvers are evaluated under the sublane model. When two or more road users are approaching each other on the same sublane, their time headway (time to collision) is evaluated. If that headway is below a configurable threshold, the sublane is deemed unsafe and will be abandoned if possible. This re-uses the model for tactical lane changes which finds a set of sublanes for faster travel (with the unsafe sublane being classified as achieving speed 0). While running on a bidi-edge, preference is given for evasion to the right but evasion may also happen towards the left. If evasion is not possible, the opponents will brake to avoid collision. Such perception from road users in the opposite direction extends up to at least a comfortable braking distance in downstream direction and may encompass multiple sequential edges and intersections along the route of the respective road user. If necessary, road users will prefer to overtake the other ones from the right side on bidi-edges. Additionally, it is possible to have multiple lanes on a bidi-edge and the allowed road users on each lane can be further specified, e.g. bicycles and/or vehicles share a two-way path and pedestrians walk on both sides next to the two-way path.

Generally, road users in simulation follow the given rules/algorithms to 100% and cannot be so flexible like those in reality. Therefore, sometimes dead-locks occur in the simulation. To resolve a dead-lock on bidi-edges a distinct time threshold for "teleporting" blocked road users on bidi-edges can be set by users. With the "teleporting" feature, dead-locked road users will be moved to the next edges on their journeys when they are waiting longer than the pre-defined time threshold. The corresponding edge travel times will be calculated and considered in the total travel time according to their current speeds and positions.

4 CASE STUDY

To examine the proposed bidi-edge concept, a case study of the SHOW test site in Linköping, Sweden is carried out.

4.1 Overview of the Test Site Linköping

The test site in Linköping, part of the Swedish Mega Sites in the European project SHOW, is located in the Linköping university campus and the neighboring residential area. Three AS provide a regular transport service at the pre-defined bus stops with the objectives to improve road users' travelling experiences and quality. The AS traverse not only on normal roads and bus lanes, but also in a bi-directional shared corridor, where cyclists and the AS share the two-way bike path in the middle, while pedestrians walk on both sides and can freely cross the bike path. The test site overview is illustrated in Figure 5.

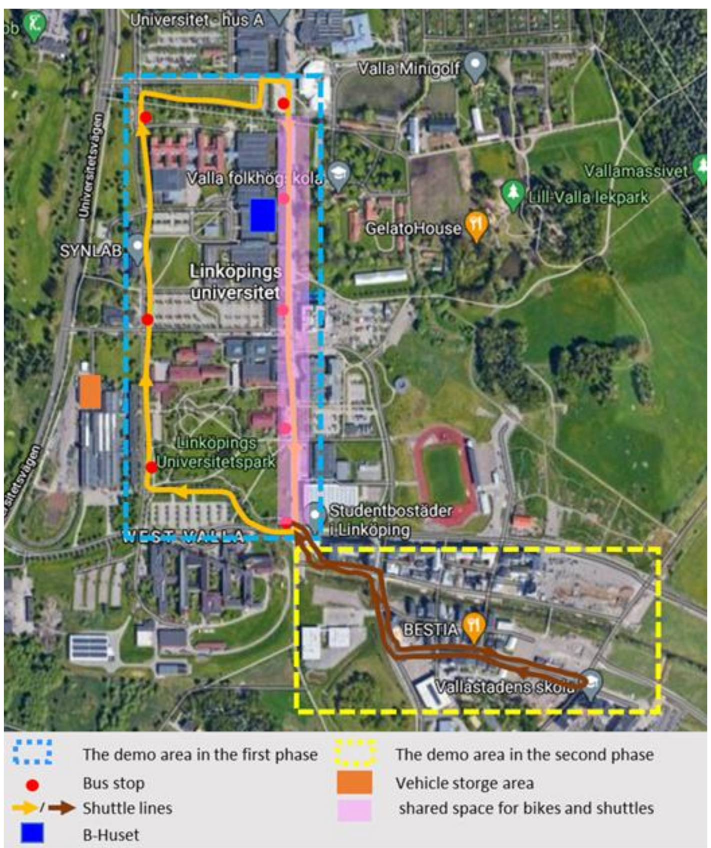

Figure 5: Overview of the test site Linköping.

4.2 Data Collection and Analysis

To understand the interactions between road users in the shared corridor, video data was collected with use of the Viscando OTUS3D system for five days in September 2021. The measurement location, the respective bird's-eye view and the layout of the shared corridor are shown in Figure 6 (a), (b) and (c) respectively. After data cleaning, the utilization of the shared corridor and the speeds and accelerations of the existing road users as well as their interactions were analyzed for better understanding the interaction between AS, cyclists and pedestrians and for setting up a simulation environment. More detailed analysis and the influence of the AS introduction on the shared corridor can be found in (Flötteröd et al. 2021; Pereria and Olstam 2022; Flötteröd et.al. 2022).

(a) (b) (c)

Figure 6: Location of the installed Viscando video system and the layout of the shared corridor.

4.2.1 Space Usage

The distribution of the extracted trajectories with the AS presence in Figure 7 shows clearly that shuttles and cyclists mainly used the bike path, as planned, and pedestrians walked on the sidewalks most of the time. The analysis further indicates that around 50% and 70% of the cyclists used the bike path with and without AS appearance respectively. Thus, cyclists were directly affected by the AS introduction, since they drove on the sidewalks more commonly when AS passed the location. Pedestrians were also affected due to that cyclists used the sidewalks sometimes under the AS presence. No respective conflicts were observed.

4.2.2 Speed and Acceleration

Table 1 and Figure 8 show the speed averages and the standard deviations of the AS, cyclists and pedestrians for each direction and the respective distributions, when AS appeared. Although AS's maximal speed was 3.63 m/s, their mean speed was around 2 m/s in the shared corridor and the corresponding speed standard deviation was around 0.5 m/s. AS's acceleration was around 0 m/s^2 with a standard deviation of 0.6, which corresponds to the comfort riding criteria for non-belted passengers ($-1 < \text{acceleration} < 1$). Bikes had the highest mean speed and the highest speed standard deviation, around 3.5 m/s and 1.3 m/s respectively.

When comparing AS to pedestrians, it shows that AS might run at the speed the pedestrians moved at in some circumstances. In general, there is no significant speed difference between these two directions.

Table 1: Speeds and accelerations of road users in the shared corridor.

Direction		**Southbound**			**Northbound**	
Road user type		**Pedestrians**	**Bikes**	**AS**	**Pedestrians**	**Bikes**
Speed (m/s)	Mean	1.42	3.44	2.08	1.32	3.56
	Standard deviation	0.35	1.31	0.49	0.51	1.19
Acceleration (m/s^2)	Mean	0.00	0.01	-0.02	0.014	0.06
	Standard deviation	0.39	0.90	0.63	0.45	0.87

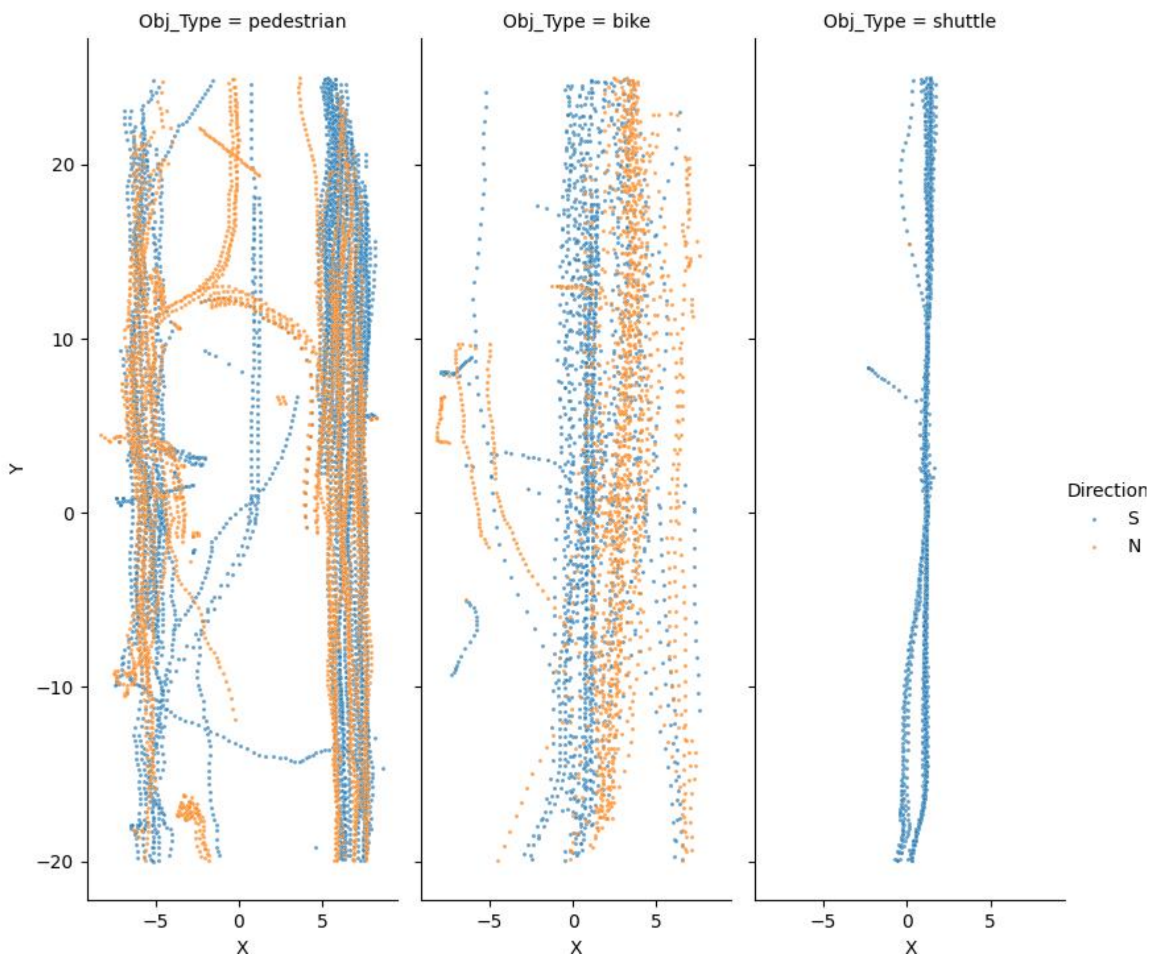

Figure 7: Overview of road usage situation in the shared corridor.

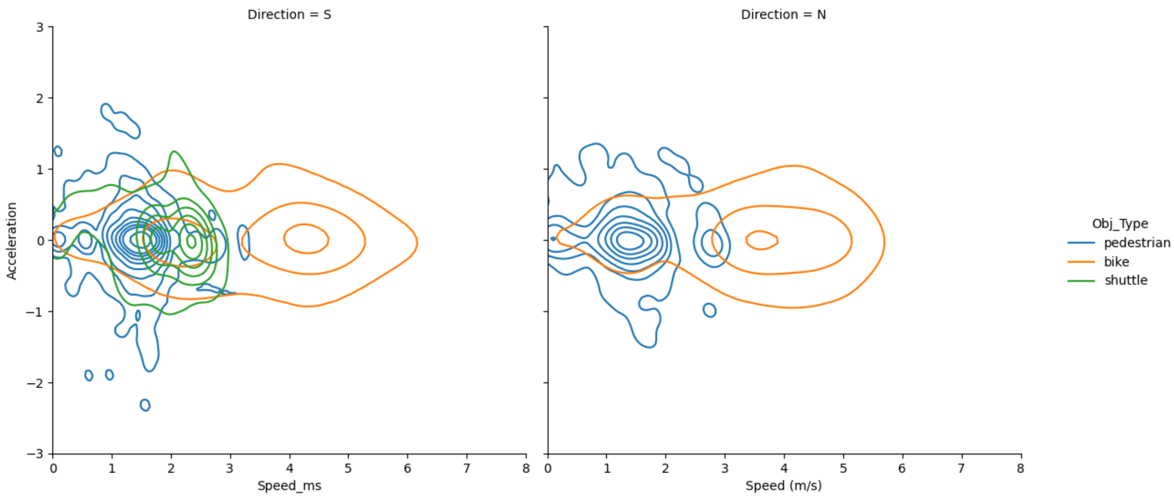

Figure 8: Distribution of road users' speeds and accelerations in the shared corridor.

4.3 Simulation Set-up

The simulation network is based on OpenStreetMap (OSM). In the OSM-based bi-directional shared corridor, pedestrian paths are fully separated from the bike path. Accordingly, there will be no interaction between pedestrians, bikes and AS in the simulated shared corridor. According to the data analysis, the interactions between pedestrians and AS and between pedestrians and cyclists are quite limited. Therefore, the focus is put on the interactions between cyclists and AS, and no further network structure adjustment was made in the simulated shared corridor.

Furthermore, all edges in the corridor are set to bidi-edges for enabling the bi-directional interactions between AS and cyclists. In addition, the respective parking facilities, local bus lines and bus stops are considered in the simulation. The built simulation environment for the whole test site and the simulated shared corridor are illustrated in Figure 9 (a) and (b) respectively. In addition, the main analysis period is set to the late afternoon, when students finish their last lectures and employees leave from the university parking lots for home.

(a) overview of the simulation scope

(b) the shared corridor with bidi edges

Figure 9: Simulation environment built with SUMO.

4.4 Model and Parameter Settings in the Simulation

According to the aforementioned data analysis results, the parameters related to the behaviors of bicycles and pedestrians were adjusted with focus on speed-related parameters. In SUMO, bicycles can be modelled either as pedestrians with fast walking speed or as vehicles. The latter one is chosen here with the consideration that cyclists and drivers have more similar behaviors regarding car-following and lane-changing concerns. Although overtaking and conflict-avoiding situations were not significantly observed in the collected data, such maneuvers could still happen, especially since the simulation considers a much longer distance than the measurements. Thus, SUMO's sublane model, that divides a lane into several sub-lanes with the given sub-lane width, is adopted so that overtaking or yielding behavior could happen when one or several of the speed difference related thresholds are reached, which are described in detail in the SUMO user documentation (SUMO 2023). Due to the observed low appearance of overtaking maneuvers the parameters related to overtaking speed factor and speed gain are set to lower than the default values in SUMO.

The parameters related to AS are set mainly according to the calibration and validation work result described in (Gugsa Gebrehiwot 2021). The original IDM-model is chosen as the car-following model for AS. The acceleration exponent is set to 4, the internal step length for computing follow speed is set to 0.25 s and the minimal gap is set to 2 m. The ac- and decelerations are set to 0.45 m/s^2 and 0.48 m/s^2 correspondingly in addition to the adjustment of the shuttle physical size. Furthermore, AS are not allowed to make lane-changes since they follow a pre-defined virtual rail track.

4.5 Travel Speed Calibration

Mean travel speed and its standard deviation are chosen as indicators to examine to what extent the respective measurements in the shared corridor can be reflected in the simulation after calibration. According to the aforementioned analysis period only the data collected in the afternoons (after 14 o'clock) is used as reference. With the consideration of the speed distribution, both speed factor and speed deviation in SUMO are considered as the main parameters for calibration. The result in Table 2 shows that the southbound bikes' mean speed difference between the real and the simulated data is around 4%, and the other mean speed differences are less than 1% when applying the following parameter values: speed deviation = 0.08 m/s and speed factor = 1.05 for AS, and speed deviation = 0.4 m/s and speed factor = 1.45 for bikes. The standard deviations of the simulated speeds are generally slightly higher than the real ones for both AS and bikes, especially the latter one. An introduction of more cyclist types to represent cyclists' heterogeneity may help to better reflect the measured standard deviation. However, more parameters for added cyclist types need to be calibrated as well.

Table 2: Comparison between the real and simulated speeds and accelerations in the shared corridor.

Direction		**Southbound**				**Northbound**	
User type		**Bikes**		**AS**		**Bikes**	
Data type		**Real data**	**Simulated**	**Real data**	**Simulated**	**Real data**	**Simulated**
Speed (m/s)	**Mean**	3.98	4.14	2.06	2.08	3.90	3.95
	Standard deviation	0.88	0.98	0.55	0.68	0.78	1.09

5 CONCLUSION AND PERSPECTIVES

AS have been recognized as a part of the mobility solutions nowadays and in the future, especially for improving the chain of public transport service city- and/or region-wide. Shared space philosophy is getting a lot of attention in urban and space planning. Therefore, more and more AS are also applied in shared-space oriented areas to improve travelling experience and quality. In this paper, the concept "bidi-edge" is proposed for enhancing the possibility to simulate users' interaction behaviors in a bi-directional shared space, and this concept is implemented in the open-source tool SUMO for the general public. The simulation shows promising results. The development of the bidi-edge concept for road traffic is in the experimental phase and is still on-going. More data is needed for testing and validation, which will be carried out later. Currently, no special conflict resolution behavior is implemented in the lane-changing model for high-demand encounters yet. This may lead to a situation where e.g. two opposing groups of cyclists, riding shoulder to shoulder, fail to provide clearance for passing/relieving a bottleneck and thus create a dead-lock situation. Apart from handling the aforementioned limitation of the bidi-edge application the respective modelling work will be continually refined together with the pedestrian and bicycle modelling in SUMO. If overtaking-related data becomes available, simulated cyclists' overtaking maneuvers can be quantitatively evaluated as well. In addition, the consideration of the interaction behaviors between road users and their surrounding environment, e.g. street furniture, trees, static obstacles can facilitate a shared-space simulation closer to reality.

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