10 Integration of an External Bicycle Model in SUMO

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Abstract

Bicyclists are amongst the most flexible road users and can tactically choose their pathway across an intersection using available bicycle lanes, roadways and sidewalks, riding either with or against the direction of travel. This flexibility makes it difficult to accurately include the pathfinding behaviour of bicyclists in microscopic traffic simulation tools due to the limitations imposed by the internal design structure of the network elements. In this paper, a method for simulating the pathfinding behaviour of bicyclists crossing an intersection based on observed trajectory data is integrated with SUMO. This is done using a SUMO extension that enables exact road user placement in the simulation. The position coordinates [x,y] of externally simulated bicycles are translated within SUMO and the bicyclist is inserted at the given location on a lane of one of the edges or junctions in each simulation step. This approach for model integration in SUMO is evaluated and recommendations for future research are given.

10.1 Motivation

In urban areas with high volumes of bicycle traffic, the overall traffic efficiency and the capacity of the road network is greatly affected by the actions of bicyclists. This is particularly true at intersections, where streams of traffic held separate on road segments must interact with each other to carry out their desired manoeuvres. Partially compatible and incompatible traffic streams are controlled using either a traffic signal or right of way regulations to optimize intersection efficiency while ensuring road user safety. Unfortunately, bicyclists are disproportionally affected by persisting issues with traffic safety. In 2010, 17.5% of all injured and killed road users in Germany were bicyclists (11) despite an average modal share of bicycling of 10% in urban and rural areas (8). This disproportion is even more pronounced at urban intersections, where according to Gerstenberger (5), 39.1% of all collisions involve a bicyclist. Clearly, overall traffic efficiency and bicycle safety, particularly at urban intersections are important aspects to consider in the assessment of infrastructure planning and traffic management strategies.
Microscopic simulation tools are frequently used to predict the effects of infrastructure design, traffic control and driver assistance systems on traffic safety and efficiency. Considering the growing significance of bicycle traffic, it is essential to include realistic models of bicyclist behaviour in these microscopic simulation tools. Currently, the majority of available simulation tools do not feature a calibrated and validated model for bicycle traffic (7). According to the SUMO wiki web page (1), there is presently no specific model available in SUMO for simulating bicycle traffic and either a modified pedestrian or car model must be used. Additional issues arise in simulating bicycle traffic

realistically in SUMO, including difficulty simulating indirect left turns, simulating bidirectional bicycle lanes and shared space areas. Many of these issues are due to the construction of the network as a collection of one directional links. The network, route and flow computations in SUMO were extended for bicycle and pedestrian flow within the project COLOMBO (3). However, a method for modelling the pathfinding behaviour of bicyclists was not developed within the project as the car pathfinding method was deemed sufficient. In this paper a method for simulating the pathfinding behaviour of bicyclists as they cross an intersection is presented. Issues with indirect left turns, bidirectional bicycle lanes and shared space are addressed.

A secondary motivation of this paper is to investigate the potential of integrating and testing externally developed models in SUMO. Microscopic traffic simulation is improved through the development of new models for simulating and predicting road user behaviour as well as the adaptation and extension of existing models. Model developers generally focus their efforts on one very specific component of traffic simulation. However, it is necessary to embed the developed model within a simulated road environment, including the road network, signal control and simulated behaviour of other road users, in order to develop, verify and validate the new model. There are typically three options available for model development (13); create an independent simulation environment, modify the source code of an open simulation software, or use a commercially or publically available simulation software with a provided API. The first option offers utmost flexibility to the developer in terms of the structural framework within which the model operates. Disadvantages of this approach include considerable development time and lack of comparability or capability with other simulation software. The second option restrains the flexibility of the developer to the framework of the open source simulation but reduces the required development time. The third option requires the smallest investment in terms of development time. Consequently, the developer is at the mercy of the capabilities of the selected software and the documentation of the provided API. In this paper the potential of integrating an independently developed behaviour model operating within a unique framework (option 1) with the open source simulation software SUMO (option 2) will be investigated. A SUMO extension that enables that precise positioning of road users and the interface TraCI (Traffic Control Interface) are used to implement and test a method for simulating the flexible behaviour of bicycles at signalized intersections.

The approach presented in the following section, *Methodology*, offers a means for integrating observed road user trajectories within the traffic simulation software SUMO. In the first sub-section, *Data Analysis*, the methods used for collecting and analysing trajectory data at the study intersection are described and the analysis results are presented. The simulation approach for including bicycle behaviour based on these observed trajectories is presented in the second sub-section, *Simulation Approach*. The integration of the external method within SUMO is explained in the following section, *Integration with SUMO through TraCI*. The results are summarized in the subsequent section followed by a conclusion.

10.2 Methodology

10.2.1 Data Analysis

Video data was collected for four days at a signalized intersection in Munich, Germany with a relatively high volume of bicycle traffic of approximately 800 bicycles/hour. A two hour segment of video data was processed using the open source software *Traffic Intelligence* (10) to extract the trajectories of all observed road users. The resulting trajectory data is stored in an SQLite database, which contains the position and velocity for each tracked road user in each video frame. An automated method for classifying the road users as cars, pedestrians or bicycles based on their positions and dynamic attributes was developed (6) and used. The database was nevertheless manually controlled to remove erroneous or superfluous trajectories, correct falsely classified road users and reconnect disjointed trajectories. The quality of each of the trajectories was qualitatively assessed to ensure that trajectories with jumps or discontinuities were not included in the analysis. Qualitative variables describing the situation and the actions of the bicyclists that were difficult or impossible to collect using automated processes were manually appended to the trajectory database. The timing of the signal phase changes for the observation days were provided by the City of Munich. An example of the trajectory data overlaid over the raw video is shown in Figure 10.1.

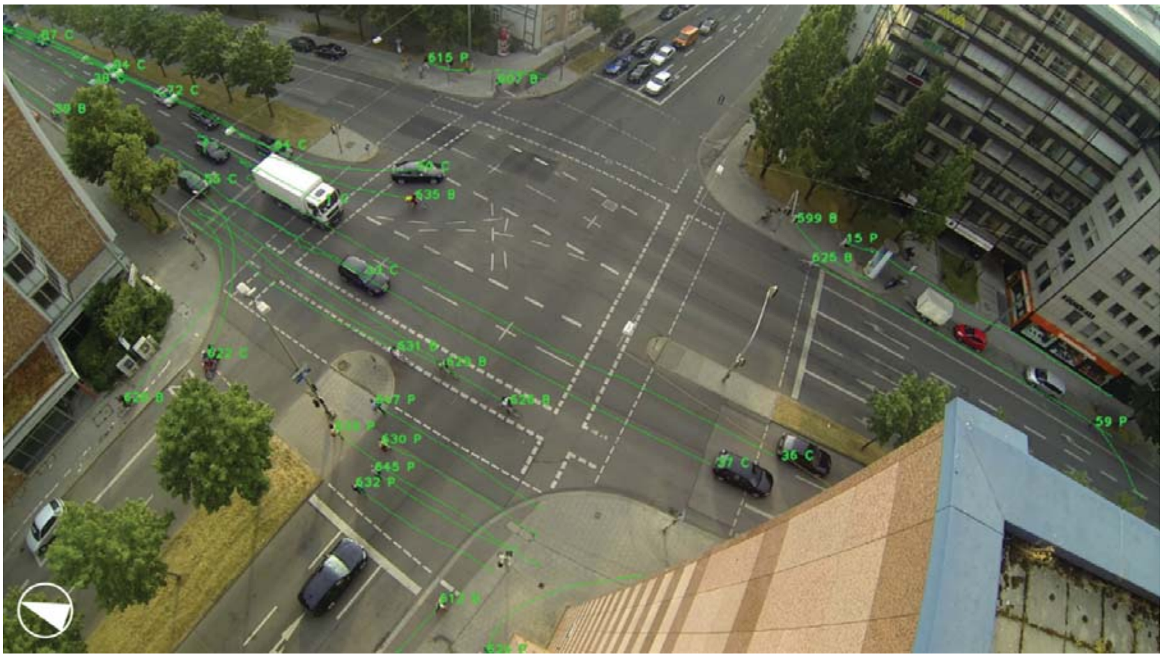

Figure 10.1: Trajectory data extracted using *Traffic Intelligence* (10)

The trajectories were analysed to gain a better understanding of the operational characteristics of bicyclists, which are defined by Michon (9) as subconscious behaviours that take place on a timescale of milliseconds, such acceleration and deceleration (12) as well as maintaining a safe distance to other road users and obstacles. In addition, the tactical decisions of the bicyclists, which are conscious decisions made on a time scale of seconds to minutes to allow road users to cope with the current traffic situation (9), were investigated.
Unlike motorized road users, bicyclists have a number of permissible and prohibited options regarding how, when and where to cross an intersection. The bicyclist can choose between riding on the roadway, the sidewalk or a bicycle lane, if available, either with or against the expected direction of travel. The observed trajectories were classified into 15 groups according to the type of manoeuvre implemented and the infrastructure used upon approaching the intersection. The type of manoeuvres available depended on the desired route across the intersection (left turn, right turn or straight). In this classification structure, right turning bicyclists and bicyclists riding straight across the intersection only had one available manoeuvre, as shown in Figure 10.2. Bicyclists turning left have three available manoeuvres. They can ride with the motorized traffic and complete the turn in one signal phase (direct left turn, manoeuvre 2 in Figure 10.2). Alternatively, they can ride with the pedestrian traffic and can complete their turn in two signal phases (indirect left turn, manoeuvre 3 in Figure 10.2). A third option is a pedestrian style turn but against the allowed direction of travel for bicyclists (indirect wrong way left turn, manoeuvre 4 in Figure 10.2).

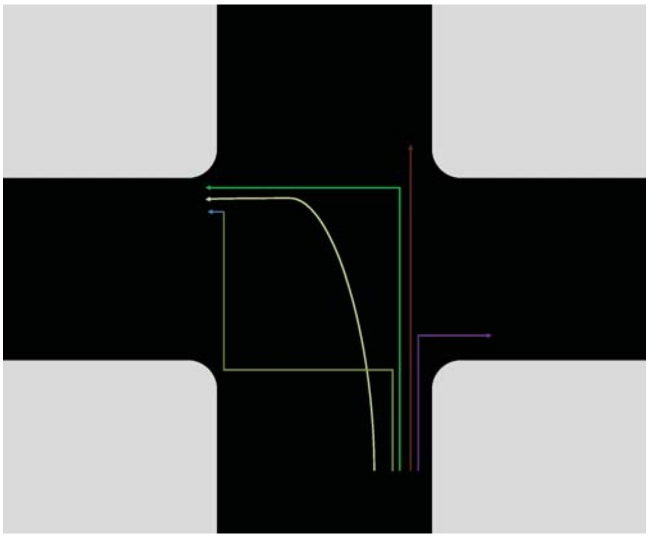

Figure 10.2: Classification of bicyclist manoeuvres

For each of the manoeuvres, the bicyclist can either arrive on a bicycle lane, sidewalk or on the roadway. This classification structure is a very simplified way of grouping the observed trajectories. More complex structures with additional options to include the possibility of bicyclists riding again the direction of travel could also be included in future work. The distribution of the observed bicyclists in the 15 groups is shown in Table 10.1.

Table 10.1: Distribution of observed bicycle manoeuvres

Route	Manoeuvre	Infrastructure	Approach				Total
			East	North	South	West	
Straight	-	Bicycle Lane	126 (97.7%)	499 (99.0%)	519 (92.2%)	121 (90.3%)	**1265**
		Sidewalk	3 (2.3%)	3 (0.6%)	3 (0.6%)	10 (7.5%)	**19**
		Roadway	0 (0.0%)	2 (0.4%)	1 (0.2%)	3 (2.2%)	**6**
	Total		**129**	**504**	**523**	**134**	**1290**
Right turn	-	Bicycle Lane	14 (87.5%)	51 (91.1%)	35 (85.4%)	2 (28.6%)	**102**
		Sidewalk	2 (12.5%)	5 (8.9%)	6 (14.6%)	4 (57.1%)	**17**
		Roadway	0 (0.0%)	0 (0.0%)	0 (0.0%)	1 (14.3%)	**1**
	Total		**16**	**56**	**41**	**7**	**120**
Left turn	Direct	Bicycle Lane	0 (0.0%)	1 (1.3%)	0 (0.0%)	1 (5.6%)	**2**
		Sidewalk	0 (0.0%)	0 (0.0%)	1 (3.3%)	0 (0.0%)	**1**
		Roadway	0 (0.0%)	3 (4.0%)	2 (6.7%)	0 (0.0%)	**5**
	Indirect	Bicycle Lane	16 (40.0%)	29 (38.7%)	14 (46.7%)	4 (22.2%)	**63**
		Sidewalk	1 (2.5%)	1 (1.3%)	0 (0.0%)	0 (0.0%)	**2**
		Roadway	0 (0.0%	0 (0.0%	0 (0.0%	0 (0.0%	**0**
	Indirect wrong way	Bicycle Lane	22 (55.0%)	35 (46.7%)	11 (36.7%)	11 (61.1%)	**79**
		Sidewalk	1 (2.5%)	0 (0.0%)	1 (3.3%)	2 (11.1%)	**4**
		Roadway	0 (0.0%)	6 (8.0%)	1 (3.3%)	0 (0.0%)	**7**
	Total		**40**	**75**	**30**	**18**	**163**
Total			**185**	**635**	**594**	**159**	**1573**

The trajectories from two observed bicyclists were selected from each of the 15 groups. Bicyclists were selected which were tracked for a large portion of their crossing manoeuvre (long trajectory) and carried out an average manoeuvre in relation to other bicyclists in the same group. This was determined by plotting all the observed trajectories in each group and qualitatively selecting the most representative trajectory. Two observed bicyclists were selected, one that stopped at the traffic signal and another that did not. For groups with very few observations, the available trajectory in the group was used and an addition trajectory was created for the missing case. Examples of two trajectories from bicyclists travelling straight on the south approach on the bicycle lane are shown in Figure 10.3. The trajectory on the right is from a bicyclist who stopped at the signal and the trajectory on the left is without a stopping manoeuvre.

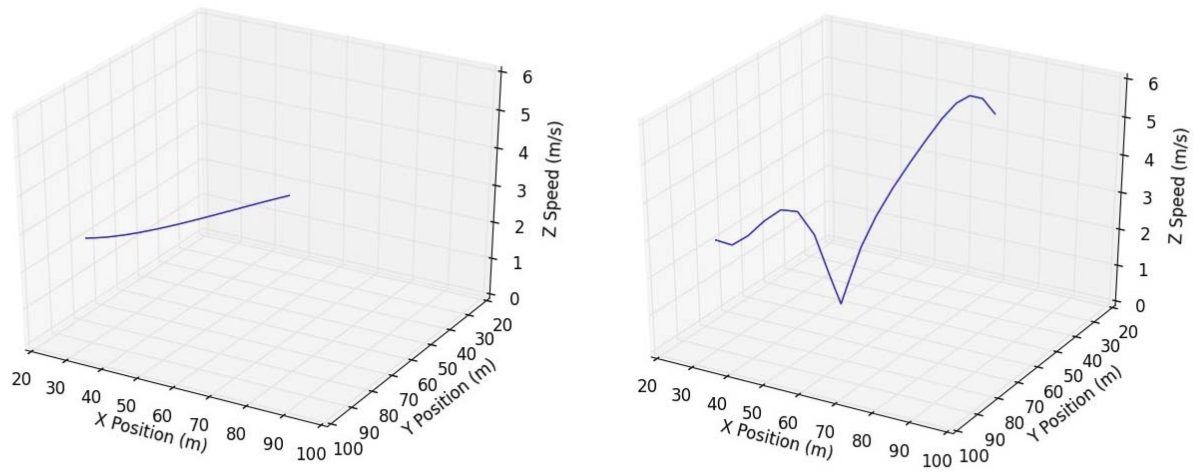

Figure 10.3: Examples of selected trajectories from bicyclists travelling straight on the south approach without stopping (left) and with a stop at a red signal (right)

10.2.2 Simulation Approach

The concept behind the simulation approach is to directly integrate the observed behaviour of bicyclists at an intersection with microscopic traffic situation SUMO. The representative trajectories selected for the 15 groups of tactical manoeuvres are used as 3D guidelines for the simulated bicyclists. In each time step, an action is selected for the simulated bicyclist that will result in the lowest cost, as defined in Equation 10.1. This approach is quite similar to the discrete choice model of pedestrian behaviour proposed by Antonini, Bierlaire and Weber (4).

$$Cost_\alpha = \beta_{dist} dist_\alpha + \beta_{\Delta v} \Delta v_\alpha + \beta_{iSG} iSG_\alpha \qquad (10.1)$$

Where:

$Cost_\alpha$ = cost of carrying out a given action α
$dist_\alpha$ = distance between the position after action α and the guideline (m)
v_{obs} = velocity at a given point on the guideline (m/s)
v_α = velocity after carrying out a given action α (m/s)
$\Delta v_\alpha = \mid v_{obs} - v_\alpha \mid$
iSG_α = inverse space gap (m^{-1}) ($iSG_\alpha = 0$ if $SG \geq 5m$, $iSG_\alpha = \infty$ if $SG \leq 0m$)
$\beta_{dist}, \beta_{\Delta v}, \beta_{iTTC}$ = weighting parameters (m^{-1}, s/m, m, respectively)

The cost of an action is a unitless measure that combines weighted terms to account for the physical distance from the 3D guideline in the x,y plane, the difference between the current speed and the

speed defined by the guideline (z plane) and the inverse distance (space gap) to other road users or objects. Each of these three terms is weighted using a β parameter that carries the inverse unit of the term, as done in discrete choice modelling approaches. For example, the unit of β_{dist} is m^{-1}. The values of the β parameters can be varied throughout a population of bicyclists to account for differences in personality and riding preferences. The distance from the 3D line is broken into two terms, physical distance and speed difference, in order to enable the application of different weighting values (β parameters.) In this trail implementation, β_{dist}, $\beta_{\Delta v}$ and β_{iTTC} were set as 0.3 m^{-1}, 1 s/m and 5 m, respectively. To reflect real behaviours, these values must be calibrated. An approach similar to that carried out by Antonini, Bierlaire and Weber (4) could be used to calibrate the model based on observed data. A value of zero is assigned to the inverse space gap if the distance is greater than 5 m based on the judgement of the authors. This limitation is not essential, however, as the influence of the term decays exponentially.
An action is defined here as the acceleration or deceleration in combination with the change in steering angle and is expressed using an [acceleration, angle change] pair. The range of acceleration and deceleration values is defined and divided into a set of discrete values. For example, an acceleration range of -1.0 m/s^2 to 1.0 m/s^2 can be defined and divided into the following set of five discrete values {-1.0, -0.5, 0.0, 0.5, 1.0 m/s^2}. The same approach is taken to discretize a given range of direction changes. In this example a minimum and maximum direction change of $\pm\pi/6$ is divided into set of five values $\{-\pi/6,\ -\pi/12,\ 0,\ \pi/6,\ \pi/12\}$. The values in both sets are combined to form a complete choice set of action pairs with 25 options in total. The cost of each action is calculated using Equation 10.1 and the action with the lowest cost is selected and executed. If more than one action is found to have the minimum cost, the action with the acceleration or deceleration closest to zero and smallest change in steering angle is selected. Two controls are applied in the creation of the choice sets to prevent unrealistic behaviour from occurring in the simulation. Firstly, no deceleration can be carried out that will result in a speed less than zero. Secondly, if a simulated bicycle has a speed of zero, a restraint is enacted to prevent a change in angle, which may result in the bicyclist spinning on the spot.

10.2.3 Integration with SUMO through TraCI

The study intersection was simulated in SUMO to test the developed method. The simulated traffic volumes for pedestrians, cars, trucks and bicycles and turning rates of all modes were based on traffic counts from the video data. The intersection is controlled using a fixed cycle control and was created in SUMO based on observed signal changes in the video. All road users are simulated using default models for the given vehicle types in SUMO. A plan of the study intersection provided by the City of Munich (left) and a picture of the intersection simulated in SUMO (right) are shown in Figure 10.4.
TraCI was developed to offer a generic interface for connecting a road traffic simulator with a network simulator (2). Using this interface in conjunction with SUMO, it is possible to extract and manipulate many attributes of the simulated road users and environment. Here, TraCI is used to extract the position of the other road users and the phase of the traffic signal and to manipulate the position and speed of the externally controlled bicyclists. The externally controlled bicyclists are steered using the default SUMO model until they reach the intersection. The bicyclist is detected upon approaching the intersection and is lead across the intersection using the proposed simulation approach. Once the manoeuvre is complete, the bicyclist is returned to SUMO control. In order to realize this, pick-up lines are defined approximately 10 m back from the stop lines of the intersections. Upon crossing the pick-up line, the bicyclist is assigned a manoeuvre (column 2 of Table 10.1) based on the route assigned by SUMO (column 1 of Table 10.1) and the probability of the observed manoeuvres in the video data, as given in Table 10.1. If the light is green, the guideline without a stop is assigned (left in Figure 10.3.) If the light is red upon crossing the pick-line, the bicyclist is

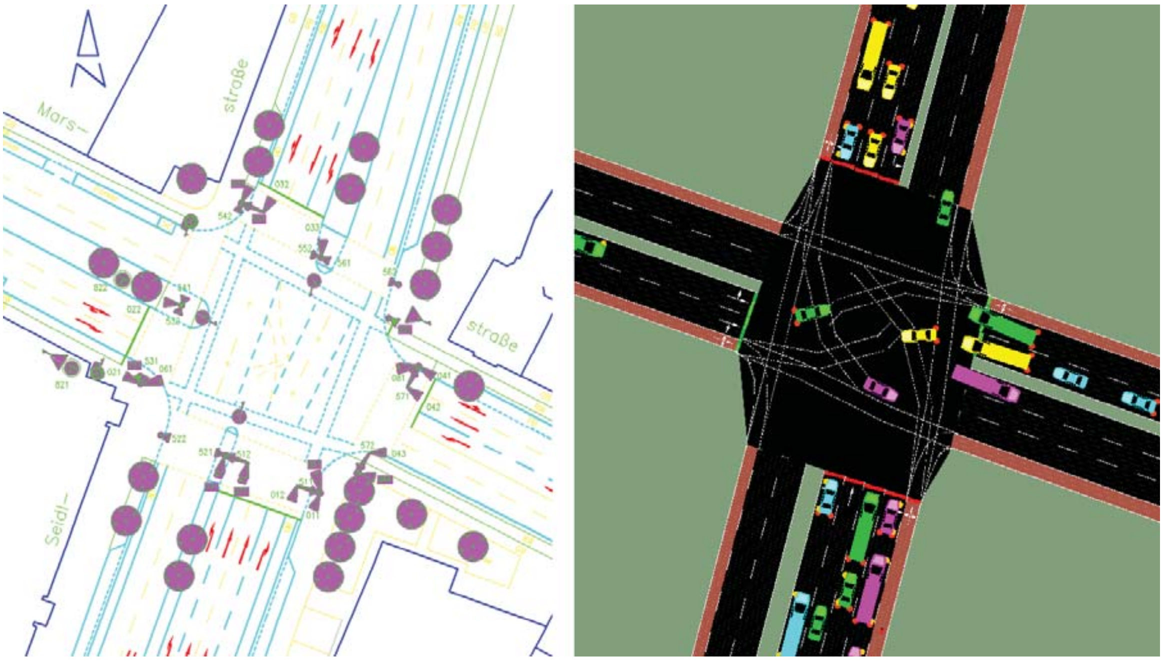

Figure 10.4: Study intersection Marsstraße/Seidlstraße plan (left) and SUMO simulation (right)

assigned the guideline with a stop (right in Figure 10.3.) If the light changes while the bicycle is between the pick-up line and the stop line, the guideline is switched to the respective phase. The selected guideline is extended to the point at which the bicyclist crosses the pick-up line. From this point on, the position and speed of the bicyclist are controlled through the *moveToVTD* and *setSpeed* SUMO functions in accordance to the external simulation approach. The bicyclists are steered using the external model until they reach the predefined drop-off line of their desired route. The bicyclists are introduced to the network using the standard SUMO approaches for creating bicycle traffic flows on the edges and assigning routes.

One issue in integrating an external model with a simulation tool is the alignment of the coordinate systems of the two environments. The best option is to develop both environments using the same coordinate system. However, in some cases, the externally developed model operates on a uniquely defined coordinate system and adjusting this system to fit the coordinate system of the simulation environment is difficult. In this case, the 3D trajectories extracted from the video data are given in a local coordinate system in which the point [0 px, 0 px] is at the top left corner of the video frame. The movement of the road users, which is originally measured in pixels per frame, is translated to a local coordinate system in meters using a perspective transformation of the coordinates and a measured meter per pixel value. The resulting position and speed data is based on a coordinate system defined by this initial perspective transformation. Unfortunately, it is relatively difficult to construct a road network in SUMO based on this coordinate system.

To address this issue, the same perspective transformation approach that was implemented to translate the video frame to the local coordinate system was used. Using the function *findHomography* of the open source library *OpenCV* (http://opencv.org), a perspective transformation matrix H is found between two plans defined by a number of corresponding points. The coordinates of points that can be identified in both the model (original plane) and simulation (target plane) environments, such as start and end points of stop lines at intersections, are input into the function. The resulting perspective transformation matrix H is then used to translate the coordinates of the guidelines to those of the simulation environment.

10.3 Results

The initial implementation of the external method for simulating bicycle traffic based on observed trajectory data in the simulation tool SUMO delivered promising results. The placement accuracy of the externally controlled bicyclists in SUMO was found to be highly dependent on the location of the bicyclist. Small placement errors ranging between 0.1 cm and 0.3 cm were found on road edges, regardless of the lateral resolution. Within the junction, error values were found to be similarly small. However, much larger placement errors were observed when an externally controlled bicyclist crossed from a road edge into a junction. During these transition phases, much larger placement errors of up to 6.7 m were observed. This can be seen in the jumps in the trajectories in Figure 10.5 (right.) Without the extension for exact vehicle placement, the average distance between the desired position of the externally controlled bicyclist and the position realized in SUMO was found to be 3.70 m. The extension was found to reduce this error to 0.40 m, a reduction of 89.2% of the placement error. In the figure below, the resulting modelled trajectories using the cost function in Eq.10.1 (left) and the resulting trajectories in SUMO (right) are shown. A qualitative assessment of the proposed simulation approach was carried out and the method was deemed to produce realistic trajectories with variation due to the position and actions of other road users. The trajectories realized in the simulation SUMO reflect the difficulties expressed above; the positioning of externally controlled road users near the edges of the junctions tends to be problematic. The placement error was not found to be correlated with the type of manoeuvre.

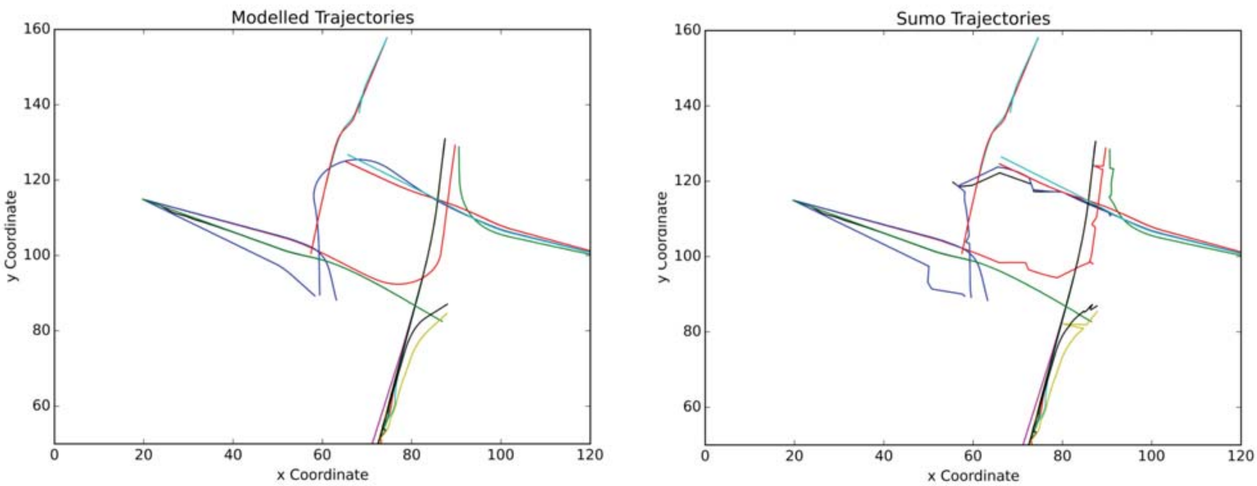

Figure 10.5: Modelled trajectories (left) and the realized SUMO trajectories (right) of the externally controlled bicyclists

The simulated road users in SUMO were found to be able to detect and react to the externally controlled bicyclists in the same way that they react to other SUMO controlled road users. Even in cases where the externally controlled bicyclists moved against or perpendicular to the direction of travel on a given edge, the SUMO road users stopped and waited for the road user to pass. The reaction of the externally controlled bicyclists to the SUMO simulated road users was found to be satisfactory. The current approach uses the position of the simulated road user as provided by TraCI, which is the front middle point of the vehicle. The shape of the simulated road user is not taken into account. As a result, the externally controlled bicyclists react very well to short and narrow road users (other bicyclists), but not as well to larger and wider vehicles (trucks.)

10.4 Conclusion

The paper describes an approach used for integrating a simulation method based on observed trajectory data with the microscopic simulation tool SUMO. The approach enables the simulation of realistic trajectories of bicyclists crossing signalized intersections, both with regard to the speed and the position. Although the bicyclists are not assigned explicitly to edges in the SUMO simulation, the TraCI function *moveToVTD* automatically translates the x,y coordinates of the externally controlled bicycle to the nearest point along an existing lane and edge. The other road users in the simulation can therefore react to the presence of the externally controlled bicyclists, even if they are moving in the wrong direction across or along a given edge.
The implementation of the model within the SUMO simulation environment was deemed to be successful enough to use for further development and validation of the external approach for simulating bicycle traffic. The simulation approach itself has not yet been validated or compared to other simulation models for bicycle traffic. Although this approach offers a good starting point for integrating observed trajectory data into a microscopic traffic simulation, a number of potential improvements have been identified for future work. Currently, the choice between manoeuvres given a route across the intersection is random according to the observed probabilities of that manoeuvre being chosen. It is hypothesized, however, that the choice between manoeuvres is dependent on both the personal characteristics of the bicyclist and the current traffic situation in which the bicyclist finds himself or herself. The realism of the simulation could be improved by introducing more advanced choice models that take into account the geometric attributes of the intersection, the presence and actions of other road users and the state of the traffic signal. The signal timing and the time of arrival are likely highly correlated with the type of manoeuvre carried out, particularly for left turning bicyclists. The approach could be further improved by introducing an unsupervised learning approach for clustering manoeuvres based solely on the observed trajectory data and not on a predefined classification structure. In this paper, a representative trajectory was selected for each manoeuvre. The generality of the approach would be greatly improved if a method for combining the observed trajectory data into an average 3D trajectory was developed.

10.5 References

[1] *SUMO Wiki Webpage - Information for Simulation/Bicycles*.

[2] A. Wegener, M. Piorkowski, R. Maxim H. Hellbrück S. Fischer and J. P. Hubaux: *TraCI: An Interface for Coupling Road Traffic and Network Simulators*. In *Proceedings of the 11th Communications and Networking Simulation Symposium*, pages 155 – 163, 2008.

[3] D. Krajzewicz, J. Erdmann, J. Hï¿½rri and T. Spyropoulos: *Including Pedestrian and Bicycle Traffic in the Traffic Simulation SUMO*. In *10th ITS European Congress*, page 10, 2013.

[4] G. Antonini, M. Bierlaire and M. Weber: *Discrete choice models of pedestrian walking behavior*. Transportation Research Part B: Methodological, pages 667 – 687, 2006.

[5] Gerstenberger, M.: *Accidents at Intersections: Basic Analysis of Causation and Approaches for Improvements*. Elektronik, 2015.

[6] H. Twaddle, T. Schendzielorz, O. Fakler S. Amini T. U. München H. Boesefeldt and T. Gmbh: *Use of automated video analysis for the evaluation of bicycle movement and interaction*. In *Proc. SPIE 9026, Video Surveill. Transp. Imaging Appl. 2014*, 2014.

[7] H. Twaddle, T. Schendzielorz and O. Fakler: *Bicycles in Urban Areas: Review of Existing Methods for Modeling Behavior*. Transp. Res. Rec. J. Transp. Res. Board, pages 140 – 146, 2014.

[8] infas Institute für angewandte Sozialwissenschaft and DLR: *Mobilität in Deutschland 2008*, 2010.

[9] Michon, J. A.: *Critical view of driver behavior models: what do we know, what should we do?* In *Human behaviour and traffic safety*, pages 485 – 520, 2014.

[10] S. Jackson, L. Miranda-Moreno, P. St-Aubin and N. Saunier: *A Flexible, Mobile Video Camera System and Open Source Video Analysis Software for Road Safety and Behavioural Analysis*. Transp. Res. Rec., pages 90 – 98, Vol. 2365,no. January 2013.

[11] Statistisches Bundesamt: *Unfallentwicklung auf Deutschen Straßen*, 2011. Beuth Verlag GmbH, Berlin.

[12] Twaddle, H. and G. Grigoropoulos: *Modeling the speed, acceleration and deceleration of bicyclists for microscopic traffic simulation*. In *To be published in Transportation Research Record (TRR), Journal of the Transportation Research Board*, 2016.

[13] W. Schakel, B. Van Arem, H. Van Lint and G. Tamminga: *A Modular Approach for Exchangeable Driving Task Models in a Microscopic Simulation Framework*. In *Intelligent Transportation Systems-(ITSC) 16th International IEEE Conference*, 2013.