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Traffic flow at signalized intersections with large volumes of bicycle traffic

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Abstract

The popularity of utilitarian bicycling is increasing in many urban areas. As a result, growing volumes of bicycle traffic on road networks have significant impacts on traffic flow and the capacity of vehicular traffic, particularly at intersections. The goal of this paper is to quantify the impact of large volumes of bicycle traffic on the capacity of signalized intersections concerning vehicular streams crossing the intersection, turning right, and turning left. Empirical studies are conducted to gain insight into the speed, acceleration, queue density, queue discharge, and conflict zone occupancy time of bicycle traffic. Data were collected at sites with varying infrastructure designs and bicycle traffic volumes. The results of the empirical studies are used to assess the effects of bicycle infrastructure on traffic efficiency and build, calibrate, and validate microscopic traffic simulation models. The bicycle traffic volume is incrementally increased in the simulation models to supplement the data from the empirical studies. Based on the empirical findings and simulation results, the average queue discharge time per bicyclist based on the facility width is derived and two factors for the reduction in the capacity of vehicular traffic turning left and turning right based on the actual green time ratio and the volume of crossing bicycle traffic are proposed. If a bike box is present on an intersection approach, findings show that crossing bicycle traffic has a negligible effect on the capacity of crossing vehicular traffic, which bicyclists turning left impede vehicular traffic.

Keywords: Bicycle traffic, Intersection efficiency, vehicular capacity, Highway Capacity Manual

1. Introduction

The bicycle as a mode of transport offers numerous personal and societal advantages including low environmental impacts, negligible noise emissions, a reduction in traffic congestion, minor parking requirements, affordability, and positive health effects. As the potential of bicycling in urban areas is realized, the number of people bicycling and consequently the modal split of the bicycle and the volume of bicycle traffic are increasing. In Germany, the modal split of bicycling increased from 9 % in 2002 to 15 % in 2017 (Nobis and Kuhnimhof, 2019). As expected, the bicycle volume in urban areas has increased accordingly. For example, a continuous counting station installed in Munich, Germany detected just over 1 million bicyclists in 2012. Five years later in 2017, more than 1.3 million bicyclists were detected, an annualized increase of approximately 5.4 % per year (Landeshauptstadt München, 2019). Growth of this magnitude has significant consequences on the traffic flow of urban road networks with particularly prominent effects at intersections.

As a result of the bicycle traffic growth, new types of bicycle infrastructure are introduced to accommodate the increasing share of bicycle traffic in urban areas. These may include bike boxes

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(also called advanced stop lines), bicycle lanes or bicycle paths, or bicycle lanes with advanced stop lines and a stop area for bicyclists downstream of an intersection approach for facilitating an indirect left turn also referred to as a two-stage turn (National Association of City Transportation Officials (NACTO), 2014). Dedicated traffic signal control measures, such as bicycle traffic signal coordination and bicycle traffic prioritization are also introduced in order to improve bicycle traffic efficiency, safety, and the attractiveness of cycling (Baumann, 2016; Grigoropoulos et al., 2019, 2018; Hoegh, 2007; Karl and Felix, 2013; Kaths et al., 2019; Peter Koonce, 2015; Preethi et al., 2016). However existing tools and methods, such as the ones included in the German Highway Capacity Manual (HBS) (Forschungsgesellschaft für Straßen- und Verkehrswesen (FGSV), 2015) or the American Highway Capacity Manual (HCM) (National Research Council, 2016) that are extensively used by experts to assess the traffic quality and quantify the effects of different design scenarios, are limited in considering the effects of increasing bicycle volumes and new types of bicycle infrastructure on traffic quality.

In this paper, the methods for including bicycle traffic in the computation of vehicular capacity at intersections in the HBS are extended to accurately reflect situations with large volumes of bicycle traffic. Thanks to parallels between the methods used in the HBS and other guidelines such as the HCM, these extensions can be useful to practitioners and researchers in many countries. Research was carried out within a German research project and some of the results are presented in German in the final project report (Busch et al., 2019). This paper summarizes and expands this unpublished research, results, and conclusions sections by reviewing additional literature, analyzing the present HCM methodologies for assessing the effects of bicycle volumes on traffic efficiency and capacity, as well as in integrating the proposed adjustments and extensions to the HCM. All references to road user movements in this paper refer to right-hand-traffic (RHT).

2. Related research

The literature review is presented in two parts: First, the behavior of bicyclists is investigated to link this with the effects on traffic capacity. Second, findings of research investigating the effects of bicycle traffic flow on intersection efficiency and capacity are highlighted.

2.1. Behavior of bicyclists at intersections

The tactical behavior includes short term maneuvers chosen consciously by a bicyclist to address specific traffic situations, such as the pathway used when crossing an intersection as well as positioning at a stop (Michon, 1985). According to previous studies, bicyclists exhibit different behaviors based on their maneuver and the traffic state at the intersection approaches (Angenendt et al., 2005; COWI, 2013; Twaddle and Busch, 2019). Bicyclists are found to use the roadway instead

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of an available cycling facility if the cycling facility is blocked by an obstacle, the bicyclist is preparing for an anticipated left or right turn maneuver, the bicyclist is not satisfied with the bicycle infrastructure quality or for overtaking (Falkenberg et al., 2003; Kuller et al., 1986). Narrow bicycle lanes (<1m wide) and on-road bicycle lanes are found to have a lower rate of acceptance than other types of bicycle infrastructure (Alrutz et al., 2009).

The majority of crossing bicyclists at an intersection use the intended bicycle infrastructure while bicyclists carrying out a turn maneuver are more likely to use the sidewalk (Angenendt et al., 2005; COWI, 2013).Angenendt et al., (2005) investigated the behavior of bicyclists at different types of infrastructure. According to the definition provided by NACTO (National Association of City Transportation Officials (NACTO), 2014), bike boxes (also called advanced stop lines (Allen et al., 2005)) are designated areas at the head of a traffic lane at a signalized intersection that provide bicyclists with a safe and visible way to get ahead of queuing traffic during the red signal phase. If a bike box is available, bicyclists riding straight mainly position themselves less than 2 m from the right side of the bike box (85.3 %) (Angenendt et al., 2005). Another study also found that 78% of bicyclists riding straight use the bike box position themselves in front of motor vehicle traffic in comparison to 54% of bicyclists at approaches without a bike box (Allen et al., 2005). For bicyclists turning left at an intersection, findings indicate that a direct left-turning maneuver is more likely if bicycle infrastructure supporting this type of maneuver is available, such as a bike box or an intermediate bicycle lane for left-turning bicyclists (Angenendt et al., 2005). Thus, left-turning bicycle traffic over a bike box can potentially affect the capacity of motor vehicles as bicyclists position themselves in front of the motor vehicle traffic.

Operational behavior, on the other hand, encompasses subconscious actions to control the bicycle within the environment, including speed control, acceleration, deceleration, gap acceptance, and spacing (Michon, 1985). Several studies focus on the relationship between the bicyclist desired speed and the type of cycling facility (Alrutz et al., 2009; Opiela et al., 1980; Schleinitz et al., 2016). The results of these studies are included in the meta-analysis presented by Twaddle (Twaddle, 2017), in which a comparison of observed bicyclist speeds as a function of the bicycle infrastructure is presented. The results of the meta-analysis suggest that bicyclist travel at a higher speed on on-road bicycling facilities. Bicycle speeds on separated bicycling facilities and mixed lanes are similar (~5 m/s), with the lowest speeds observed on sidewalks.

Bicyclists crossing a prioritized vehicular traffic stream are found to accept time gaps of 3 – 4 seconds on average (Kwigizile et al., 2017; Opiela et al., 1980). Motor vehicle drivers crossing a prioritized bicycle traffic stream are found to accept average time gaps of 6 – 7s between crossing bicyclists (Petzoldt et al., 2017).

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2.2. Bicycle traffic efficiency and capacity effects

Several methodologies have been developed to assess the efficiency of bicycle traffic and to consider the effects of bicycle traffic on vehicular traffic at signalized intersections. These methodologies are developed for guidelines assessing traffic flow at signalized intersections, as a part of models to calculate the capacity effects of bicycle traffic on vehicular traffic flow and to calculate the effect of cross-section width on bicycle traffic flow.

The HCM evaluates traffic performance at signalized intersections with independent methodologies for motorized and non-motorized modes. The effect of bicycle traffic flow on vehicular traffic flow is considered using adjustment factors. These factors account for the effect of both pedestrian and bicycle traffic flow on the saturation flow of right and left turning vehicular traffic streams and are a function of the expected duration of the occupancy of the conflict zone. The expected duration of the occupancy of the conflict zone is a function of the actual green time ratio and bicycle traffic volume. Chen et al. (2014) developed a platoon width model and a polynomial regression model, which are used to generate an adjustment factor for the saturation flow calculation in the HCM for left-turning motor vehicles.

A Level of Service score is described in the HCM for non-motorized traffic based on multiple parameters describing the traffic performance and intersection characteristics. This method for non-motorized modes is limited to intersection approaches with less than a 2 % gradient. Additionally, bicycle traffic delay is calculated and assessed independently of the Level of Service score. For this calculation, bicycles are considered to ride on the road on a dedicated facility (e.g. bicycle lane). Bicycles that travel on the road in mixed traffic are assumed to experience the same delay as vehicular traffic. The bicycle traffic capacity is a function of the effective green time share and the bicycle saturation flow (2000 bicycles/h). It is assumed that bicyclists do not experience any incremental delay or initial queue delay, bicyclists are intolerant to delays over 30 s/bicycle and comply with the traffic signal indication if their expected delay is less than 10 s/bicycle.

Bicycle traffic is considered in the HBS as a source of impendence for the movements of partially conflicting streams of motor vehicles, for example by assessing the occupancy of the bicycle-vehicle-conflict zone for vehicles turning right. In this case, the capacity is reduced based on the number of bicyclists and pedestrians occupying the conflict area in each cycle. At the same time, bicyclists are considered part of the opposing traffic flow (PCU = 1) for permitted left-turn movements. The Level of Service for non-motorized traffic is based on the maximum waiting time for the complete crossing of an intersection approach.

In both the HCM and the HBS, the capacity is a critical parameter for the calculation of the Level of Service or other traffic quality parameters. When it comes to the capacity of bicycle traffic

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infrastructure, capacity values found in the literature range significantly (Botma and Papendrecht, 1991; Greibe and Buch, 2016; Hein et al., 2013; Jin et al., 2017; Li et al., 2015; Pu et al., 2017) and depend primarily on available width, number of lanes, bicycle type and bicycle desired speed. Bicycle traffic capacity is found to be linearly dependent on the bicycle infrastructure width. The capacity increases by 1.11 bicycles/s for every additional meter path width in the range of 0.50– 1.50 m width (Wierbos et al., 2019). In the case of the HCM, the bicycle infrastructure width is considered in the calculation of the bicycle delay and not in the calculation of the bicycle traffic capacity. In the HBS, no special methodology for estimating the capacity of bicycle traffic at a signalized intersection approach is presented. The number of lanes, bicycle type, and bicycle desired speed is not considered. Finally, no special considerations are made concerning special types of bicycle infrastructure such as bike boxes or approaches with stop areas for indirect left turning.

Several researchers have suggested methods for analysing the capacity of signalized intersections with bicycle traffic and modelling bicycle traffic performance. Chen et al. (2009) present a methodology for calculating capacity considering the influence of bicycle blockage, waiting bicyclists in partially conflicting streams, traversing bicyclists and bicyclists waiting inside the intersection. A similar approach in which models are developed to quantify the effects of bicycle traffic on the saturation flow of the turning vehicles by defining different stages of bicycle movements is proposed by Guo et al. (2012). Allen et al. (1998) proposed, calibrated, and validated a model for estimating the share of the green phase in which the conflict area is occupied using bicycle traffic volume as an input. Another study assesses the Level of Service based on traffic volume, the total width of the outside through lane, and the intersection crossing distance for through movements (Landis et al., 2003). Finally, researchers in the Netherlands studied the bicyclist queue discharge process at a signalized intersection approach. The bicyclist jam density is found to positively influence the queue discharge rate and a regression model was fitted to the empirical data. The results were validated through an experimental study with test subjects. A bicycle discharge rate of 1.2 to 1.4 bicycle/s was measured in the experiment (cross-section width = 3m) while a rate of 1.5 bicycle/s was measured at the intersection approach (width = 3m two-way bicycle path) (Wierbos et al., 2020). In general, most models developed to account for the influence of bicycle traffic at signalized intersections focus on mixed traffic conditions and do not account for the influence of bicycle infrastructure. Models that estimate the capacity effects of bicycle traffic on vehicular traffic typically utilize the occupancy duration of the conflict area between motor vehicles as the critical traffic parameter. Such models are mostly not easily integrated into the existing methods in the HCM and HBS due to their inherent complexity. Thus, our research aims to propose methods that can be easily integrated into existing methods for assessing the effect of different bicycle traffic streams and bicycle infrastructure on the intersection capacity.

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3. Method

The aim of this research is to analyse the traffic flow at signalised intersections with a high bicycle traffic volume and, develop new methods that can integrate into existing methods for assessing the effect of different bicycle traffic streams and bicycle infrastructure on the intersection capacity. Results from past research contribute the development of the methodology followed to develop new methods for assessing the effect of bicycle traffic and bicycle infrastructure on intersection capacity.

Empirical studies at signalized intersections are necessary to gain insights on bicyclist behaviour using different types of bicycle infrastructure and their interaction with motor vehicle traffic. The estimation of the effect of large volumes of bicycle traffic on the flow of vehicular traffic at signalized intersections is based on the combination of results coming from empirical studies and simulation studies. In a first step, study intersections with different types of bicycle infrastructure are selected. Empirical studies are carried out to measure the acceleration, speed, queue density, and discharge time as well as the occupancy duration of conflict zones between bicycle and vehicular traffic. These parameters provide the basis for subsequent simulation studies. Simulation studies are required as a complete, representative empirical survey of all relevant cases and variations of bicycle infrastructure and signalization (traffic infrastructure parameters) combined with different traffic compositions are not feasible only through empirical observations. Simulation studies also allow the analysis of scenarios or intersection characteristics that are not included in the study intersections as well as the measurement of parameters that are difficult to estimate empirically. Therefore, data collected in the empirical studies are used to calibrate and validate microscopic traffic simulation models. The volume of bicycle traffic is increased incrementally in the simulation to derive the effect of large volumes of bicycle traffic on vehicular traffic flow. The empirical data and the output of the simulation studies are used to propose adjustments to the calculation methods in the HBS. Finally, general recommendations for other capacity manuals are derived.

3.1. Empirical studies

A survey of possible study sites was conducted across German cities to identify possible study intersections. Intersection approaches with high gradients or other types of environmental factors that could potentially influence the bicyclist driving behavior were not considered. After the initial search, a total of 32 intersections were considered for the video data collection across six different German cities. Eventually, to analyse motor vehicle and bicycle traffic flow at signalized intersections with varying types of cycling infrastructure, data were collected at eight intersections in Germany (two intersections in Berlin, two intersections in Freiburg, and four intersections in Munich). The study intersections are presented in Table 1.

1. B3: Intersection Berlin, Karl-Liebknecht-Strasse / Spandauer Strasse
2. B4: Intersection Berlin, Oranienburger Strasse / Friedrichstrasse
3. FR3: Intersection Freiburg, Lehner Strasse / Eschholzstrasse
4. FR6: Intersection Freiburg, Eschholzstrasse / Basler Strasse / Lörracher Strasse
5. M1: Intersection Munich, Marsstrasse / Seidlstrasse
6. M2: Intersection Munich, Arnulfstrasse / Seidlstrasse
7. M3: Intersection Munich, Kapuzinerplatz
8. M4: Intersection Munich, Schellingstrasse / Luisenstrasse

The study intersections were selected based on three criteria:

1. Best possible coverage of infrastructure design options according to the Guidelines for Urban Road Design (German: Richtlinien für die Anlage von Stadtstraßen, RASt) (Forschungsgesellschaft für Straßen und Verkehrswesen (FGSV), 2006) and the Recommendations for Cycling Facilities (German: Empfehlungen für Radverkehrsanlagen, ERA) (Forschungsgesellschaft für Straßen und Verkehrswesen (FGSV), 2010).
2. High volumes of bicycle traffic.
3. Practical possibilities for collecting video data, including a high building in near proximity of the intersection or space to park the Urban Traffic Research Car (UTRaCar) (Deutsches Zentrum für Luft and Raumfahrt, 2020).

For a detailed analysis of the operational behavior of bicyclists, trajectories are automatically extracted from the video data and are further processed to extract parameters such as the acceleration and average speed. The video cameras were installed as high as possible and with the best possible viewing angle of the intersection approaches. Two different systems were used for data collection: a mobile system consisting of two cameras mounted on a 12 m high mast on the UTRaCar test vehicle. The system was used for data collection in the Berlin study intersections. The second system consists of a camera installed on a mast or on/in a high building and was used to collect video data in Munich and Freiburg. Figure 1 shows the camera view from the rooftop of the building at the Marsstrasse / Seidlstrasse intersection in Munich. Video data were collected during one day at each intersection. Periods of 1h to 2h duration for each intersection with high traffic volumes were selected for further analysis. The vehicle trajectories were extracted using automated image processing methods and are classified according to the vehicle type, such that trajectories of bicyclists motor vehicles, and pedestrians are available (in orange, blue and yellow in Figure 1). Trajectory data were manually verified to ensure the accuracy of the automated tracking and classifying procedures. As no significant interactions were observed among bicyclists and pedestrians, the pedestrian trajectories were excluded from further analysis.

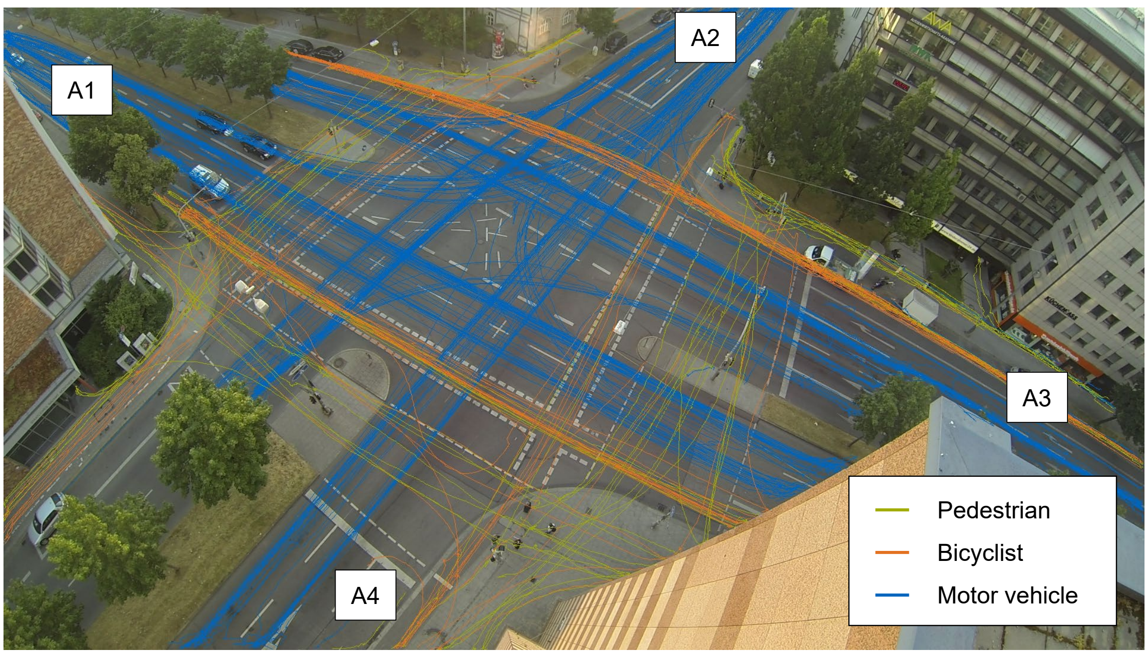
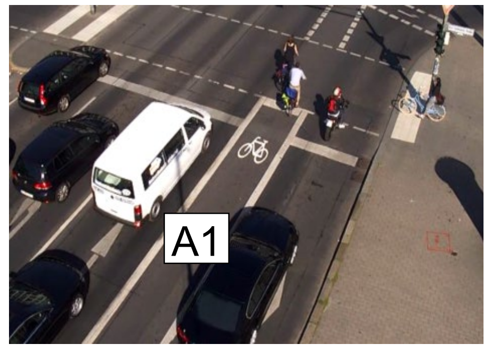
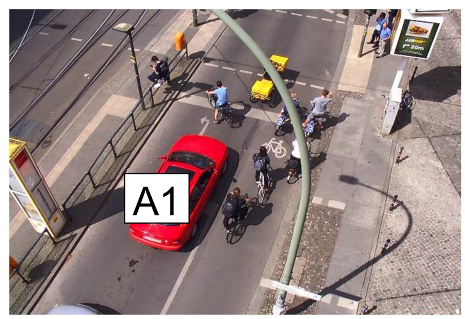
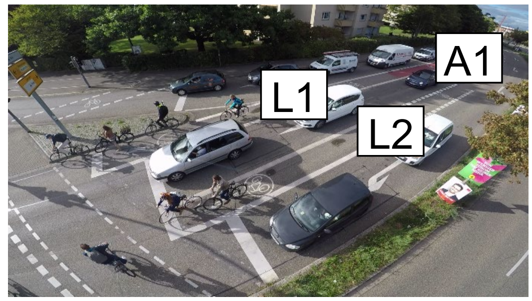
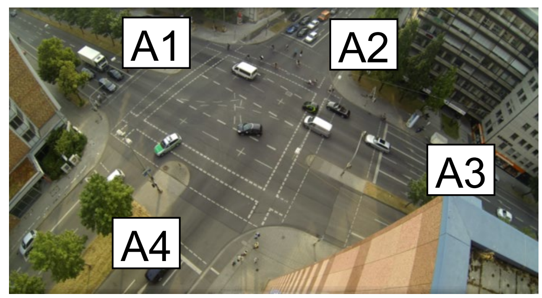
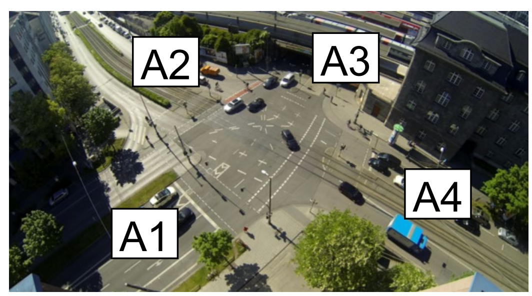
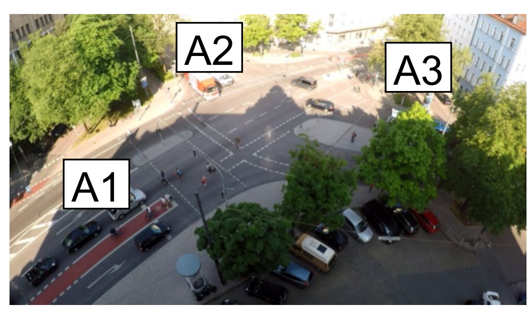


Figure 1 Camera view at the intersection Marsstrasse / Seidlstrasse in Munich with extracted trajectory data.

Table 1 Study intersections.

ID	Approach	Bicycle infrastructure type	Bicycle infrastructure width [m]	Bike box size [m²]	Camera View
B3	A1	Bicycle lane	1.8	-	
B4	A1	Bike box	4.75	23.8	
FR3	A1	Bike box	7	35	
	A2	Bike box	6.5	39	
FR6	A1 (L1)	Bicycle lane	1.5	-	

ID	Approach	Bicycle infrastructure type	Bicycle infrastructure width [m]	Bike box size [m^2]	Camera View
	A1 (L2)		1.8	-	
M1	A1	Bicycle lane	2.0	-	
	A2	Bicycle path	1.8	-	
	A3	Bicycle lane	2.0	-	
	A4	Bicycle path	1.5	-	
M2	A1	Bicycle lane	2.0	-	
	A2	Special form	-	-	
	A3	Bicycle path	1.6	-	
	A4	Bicycle path	2.2	-	
M3	A1	Bicycle lane	2.5	-	
	A2	Bicycle path	1.5	-	
	A3	Bicycle lane	2.5	-	

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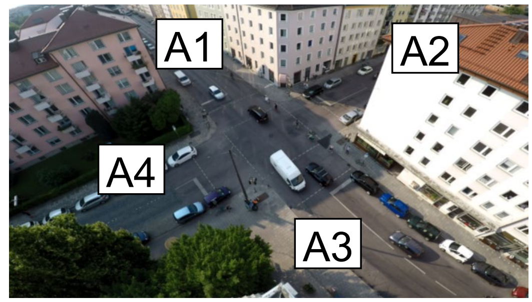
ID	Approach	Bicycle infrastructure type	Bicycle infrastructure width [m]	Bike box size [m^2]	Camera View
M4	A1	Mixed traffic	-	-	
	A2	Mixed traffic	-	-	
	A3	Mixed traffic	-	-	
	A4	Mixed traffic	-	-	

3.2. Simulation studies

Simulation is used to extrapolate empirical findings to other traffic scenarios and bicycle infrastructure, and to derive data that is typically not observable (capacities). The results from the empirical studies and the literature findings serve as the basis for the creation of simulation models. The results of Angenendt et al.(2005) on the lateral positioning of bicyclists with respect to different available types of bicycle infrastructure (bike boxes, bicycle lanes and bicycle paths) and the results on the respective bicyclist desired speeds are used for the design of the simulation models in combination with the results from the empirical studies. The literature results on the bicyclist speed distribution, the desired speed and the acceleration behavior confirm the findings from the empirical studies and are used to model the bicyclist operational behavior (Figliozzi et al., 2013; Parkin and Rotheram, 2010; Taylor, 1993; Twaddle and Grigoropoulos, 2016). Finally, the cumulative speed distribution function of bicyclists generated using the trajectory dataset from the empirical studies Figure 7 (right) confirms findings from past research (Falkenberg et al., 2003).

PTV Vissim was used to carry out the simulation studies. PTV Vissim is a software for multi modal microscopic traffic flow simulation. It includes dedicated behavior models for bicyclists and their interaction with motorized vehicles. Particularly important features are the realistic lateral movement and positioning of the bicyclists according to the observations in the video recordings. Figure 2 shows impressions from a simulation model with a bike box. As observed in the empirical studies, simulated bicyclists riding straight across the intersection remain within the width of the bicycle lane and do not make use of the entire bike box (Figure 2a). These bicyclists mainly hinder the movement of motor vehicles turning right (Figure 2b). Motor vehicles crossing the intersection are delayed if

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several bicyclists wait or ride two or more abreast. Bicyclists turning left using a direct maneuver (Figure 1) usually move into the left lane upstream of the intersection, pass waiting motor vehicles, and queue in front of the vehicles in the bike box (Figure 2c). At the start of the green phase, these bicyclists ride as a group in front of vehicles (Figure 2d) and turn into the bicycle lane or pathway on the right side of the road, if available (Figure 2e).

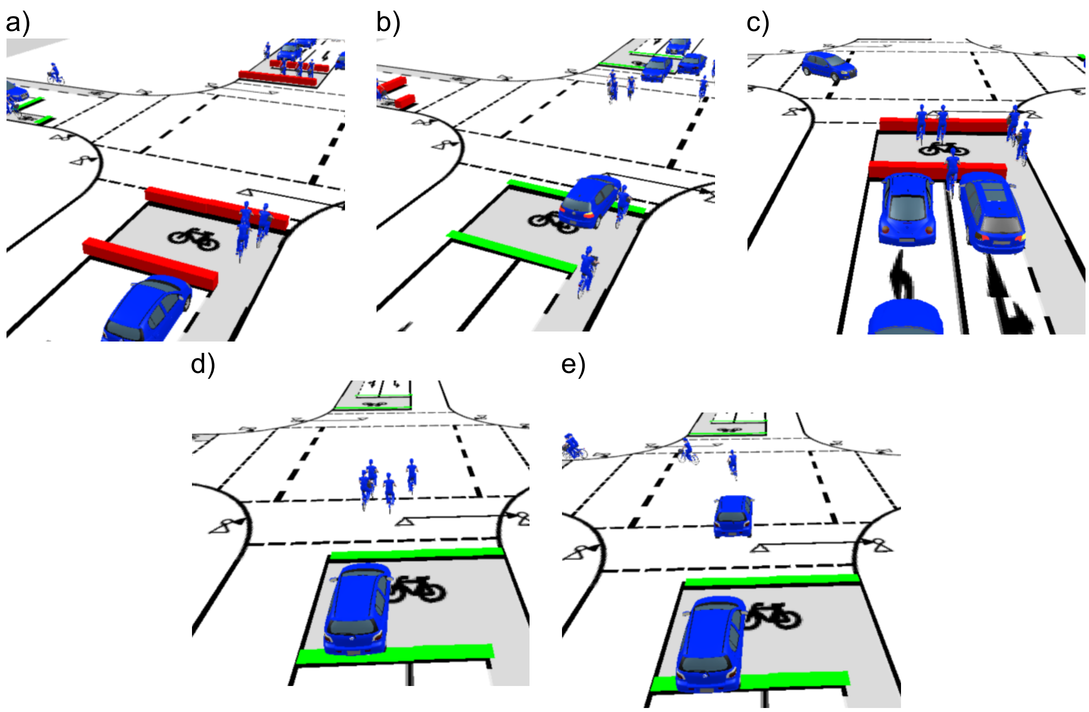

Figure 2 Impressions of road user behavior on the simulated bike box (PTV VISSIM).

The simulation models are based on example study intersections with typical infrastructure design and dimensions are created according to the design guidelines in the German Guidelines for Urban Road Design (German: RASt - Richtlinie für die Anlage von Stadtstraßen) (Forschungsgesellschaft für Straßen und Verkehrswesen (FGSV), 2006) and Recommendations for Cycling Facilities (German: ERA - Empfehlungen für Radverkehrsanlagen) (Forschungsgesellschaft für Straßen und Verkehrswesen (FGSV), 2010) (see Figure 11).

4. Results

4.1. Empirical studies

Video data were collected at each of the intersections on a weekday during the summer months when the volume of bicycle traffic is particularly high. Depending on the conditions at the intersection, the UTRaCar, an adjacent building, or a mast are used to mount the video camera(s).

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In the first step of the analysis, the segments of the video data are viewed manually to gain insights into the queuing behavior of bicyclists on separated bicycle paths, on-road bicycle lanes, and bike boxes as well as the behavior of bicyclists turning left. It is possible that bicyclists are adapting their behavior according to the respective infrastructure, the traffic situation, or the traffic signal state. Also, it had to be ensured that in the recorded data no irregular or recurring obstruction of bicycle traffic flow was taking place by other road users.

Table 2 presents the total number of road users detected in each intersection for each analysis period. Figure 3 shows a schematic of the routes used by bicyclists turning left on one approach using as an example the Lehener Strasse / Eschholzstrasse intersection in Freiburg. The percentage of bicyclists observed carrying out each type of left turn is shown in Figure 4.

It is found that bicyclists approaching the intersection on the road and using the bike box proceed to carry out a direct left turn. About a fifth of the bicyclists arriving during the red phase uses the pedestrian crosswalk to cross the street (about 26% of those approaching on the road and about 4% of those approaching on the bicycle lane) in an effort to avoid a stop and reduce their delay at the intersection approach. Eventually at this intersection, due to the bike boxes, only a very small proportion of bicyclists turn left indirectly, as the respective indirect left turn shares significantly increase in the other examined intersection where no such infrastructure is provided (see Figure 5 and Figure 6). These findings highlight the importance of bike boxes in enabling the direct left turn maneuver for bicycle traffic.

Table 2 Total number of detected road users per intersection for the analysis period.

ID	Analysis period (hr)	Total bicycles	Total motor vehicles
B3	3	795	945
B4	2	926	369
FR3	2	1964	4342
FR6	2	361	1462
M1	2	1412	7256
M2	2	1440	4768
M3	2	2458	4210
M4	1	579	852

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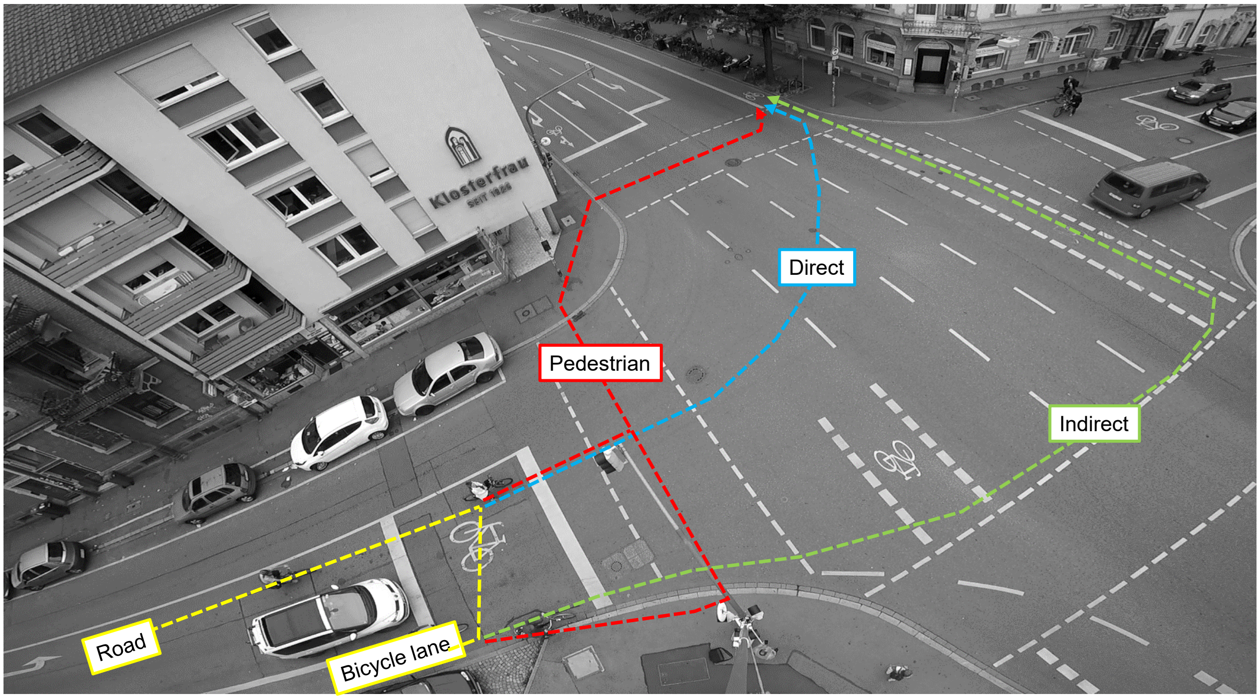

Figure 3 Types of observed left turn pathways

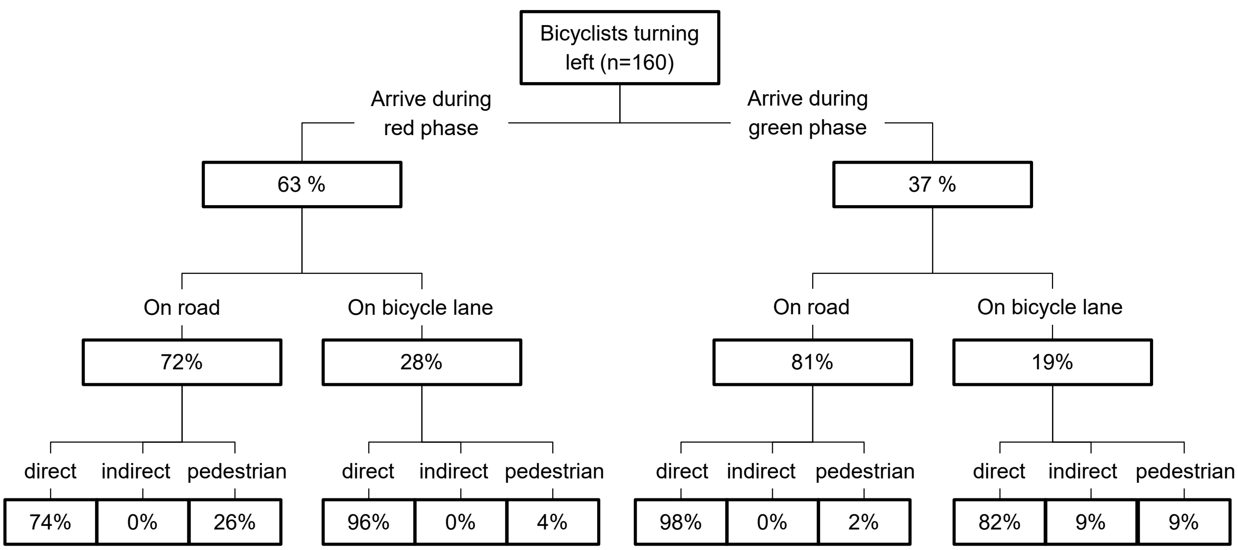

Figure 4 Proportion of bicyclists observed using each type of left turn at the Lehener Strasse /Eschholzstrasse intersection in Freiburg.

At intersection Kapuzinerplatz (M3) (Table 1) the left-turning bicyclists use the bicycle lane and the road in roughly equal parts. At this intersection, bicyclist lanes are provided only for bicycle traffic riding straight at the intersection. A downstream bicyclist stop area is provided for left turning bicyclists. Most bicyclists riding on the road and arriving at the intersection approach during the green phase performed a direct left turn (97%), while most bicyclists riding on the bicycle lane and arriving

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at the intersection approach during the green phase performed an indirect left turn (86%). At the same time, bicyclists riding on the road and arriving at the intersection during the red phase performed a direct left turn (62%), while 38% used the pedestrian crossing to turn left, to reduce their expected delay at the intersection. Finally,65% of bicyclists riding on the bicycle and arriving at the intersection during the red phase used the pedestrian crossing while 35% proceeded to an indirect left turn. These results signify the differences in the left turning behavior between bicyclists using the respective available infrastructure in the form of bicycle lanes, pedestrian crossings or downstream bicyclist stop areas and bicyclists that are not, showing that bicyclists making use of the available bicycle infrastructure also tend to use bicycle or pedestrian infrastructure to perform their intended maneuver and do not mix with motor vehicles. Also, the same group of bicyclists made use of the available bicycle infrastructure to turn left when arriving during the green phase, while upon during the red phase, made use of the pedestrian crossing in an effort to reduce their delay. Empirical results are presented in Figure 5.

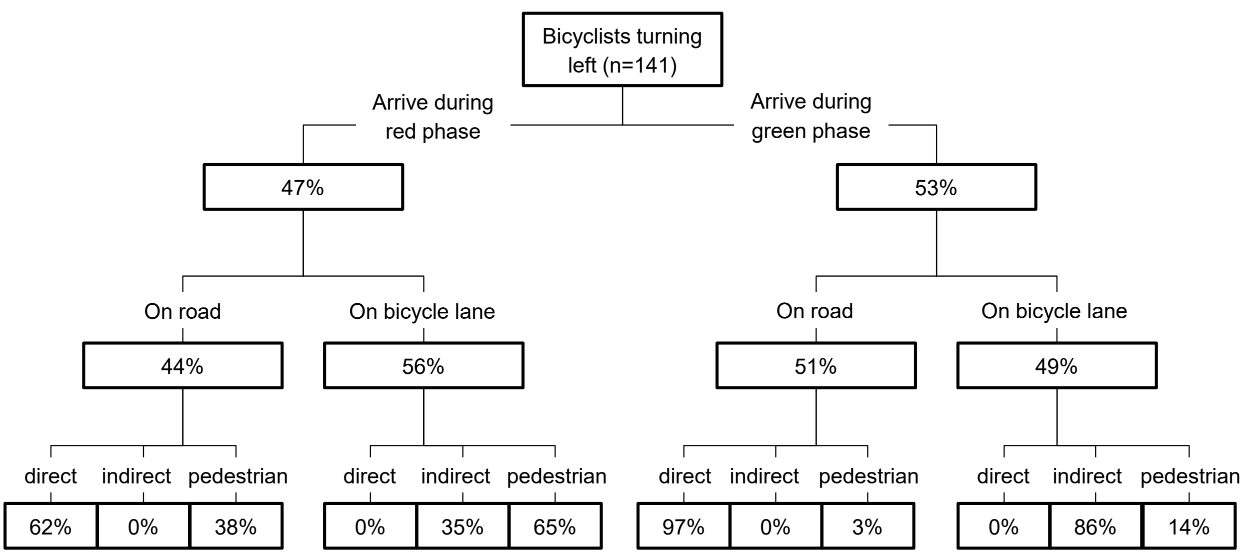

Figure 5 Proportion of bicyclists observed using each type of left turn at the Kapuzinerplatz intersection in Munich.

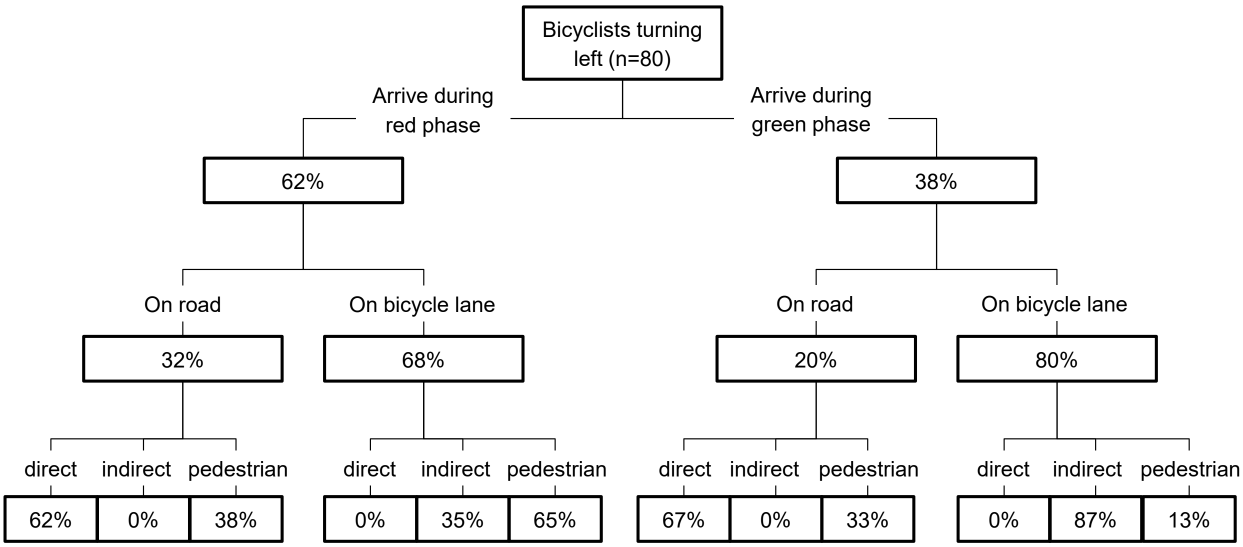

Figure 6 Proportion of bicyclists observed using each type of left turn at the Marsstraße/Seidlstraße intersection in Munich.

At the intersection M1 Marsstraße/Seidlstraße (Table 1) most bicyclists make use of the bicycle lane or bicycle path to turn left. The majority of bicyclists riding on the road will perform a direct left turn regardless of the traffic signal state (62% when arriving during red phase and 67% when arriving during green phase). However, this does not apply for bicyclists using the bicycle lane as they will turn left either using the pedestrian crossing during the red phase (65%) or use perform an indirect left turn during the green phase (87%), effectively adjusting their behavior to reduce their expected delay at the intersection. Empirical results are presented in Figure 6.

Results across the three intersections suggest that most bicyclists will make use of dedicated bicycle infrastructure if such is provided at the intersection approach and directly facilitates their intended maneuver. However, in the absence of dedicated bicyclist infrastructure, it is more probable that bicyclists will make use of motor vehicle or pedestrian infrastructure to execute their intended maneuver and adjust their behavior and infrastructure choice depending on the traffic signal state. These results are also supported by previous research (Twaddle and Busch, 2019).

In the second step of the analysis, trajectories are automatically extracted from the video data and are further processed to extract parameters such as the acceleration and average speed. The parameters determined from the bicyclist trajectories are explained below and presented with an example evaluation:

- **Acceleration from stop**: The acceleration from a complete stop at the beginning of the green phase directly affects the queue discharge time and the time in which bicyclists occupy the conflict zone with vehicles turning left and right. It is therefore an essential parameter for the parameterization of driving behavior in the simulation. Figure 7 (left) shows acceleration as a function of speed at the Marsstrasse / Seidlstrasse intersection in Munich as an example. The sample size *n* refers to the total number of bicyclist acceleration recordings in all observed bicyclist positions along their respective trajectories.

- **Desired speed distribution**: This is an important parameter to create realistic bicycle traffic in simulation models. Because the desired speed cannot be measured directly, the mean speed travelled by each observed bicyclist after completion of the acceleration process is taken as a surrogate measure. The cumulative density function of the desired speed surrogate measure from all research intersections is shown in Figure 7 (right). The sample size *n* refers to the total number of bicyclist acceleration recordings in all observed bicyclist positions along their respective trajectories.

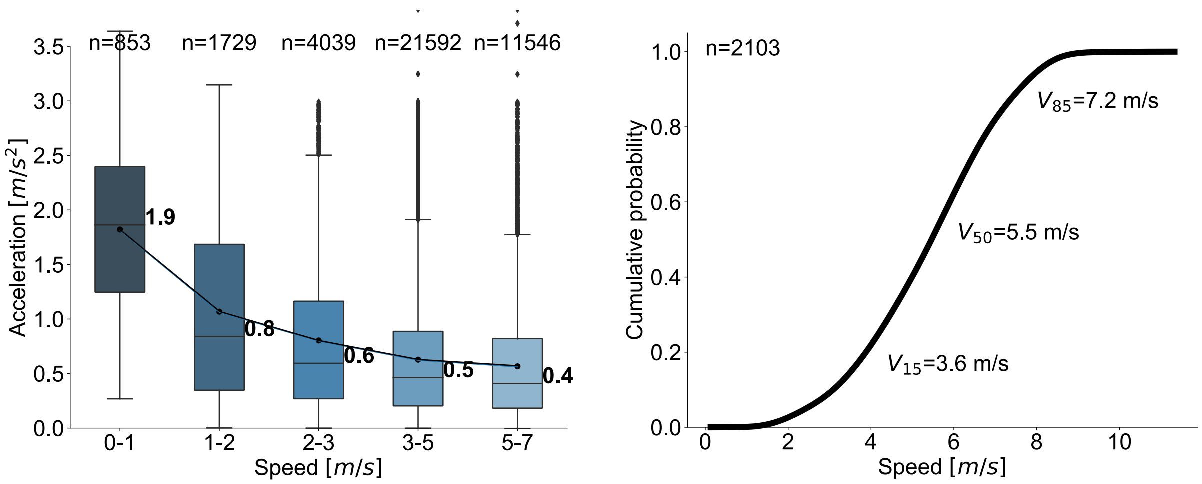

Figure 7 Observed acceleration as a function of speed (left) and cumulative density functions for the desired speed (right).

- **Queue density**: This parameter describes the number of bicyclists per square meter in a queue at a stop line on a cycling facility. It is calculated by dividing of the number queued bicyclists at the start of green time by the area formed by the respective infrastructure width and the length of the present queue (measured from the stop line). The queue density can serve both as a calibration parameter for traffic simulation and the design of road infrastructure (dimensioning of waiting areas at stop lines). The observed queue density for bicycle lanes and separated bicycle paths are shown in Figure 8 (left). The sample size *n* refers to the number of analysed queues.

- **Average discharge time**: This parameter indicates how long it takes on average for each bicyclist to exit a queue at a stop line. Depending on the width of the cycling facility, bicyclists can ride two or more abreast, which makes it necessary to use a different method for determining the duration of queue discharge than used for motor vehicle traffic. Here, the duration of time between the beginning of the green phase and the moment the last bicyclist in the queue completely crosses the stop line is taken as the queue discharge time. This duration is divided by the number of bicyclists in the queue. Figure 8 (right) shows the average queue discharge values for different widths of the cycling facility. There is a slight upward trend in the average queue discharge time at a width of 2.5 m (in comparison to 2.0 m). This likely stems from variation in the bicyclist behavior at the two approaches at the study intersection Kapuzinerplatz in Munich, or possibly indicate that bicycle lanes wider than 2m may lead to bicyclists forming queue formations that do not discharge efficiently. In any case the data were collected at a single intersection with two approaches with that width size and therefore further research is required. The general trend, however, is that the average discharge time per bicyclist decreases as the width of the cycling facility increases. The sample size *n* refers to the number of analysed discharge processes.

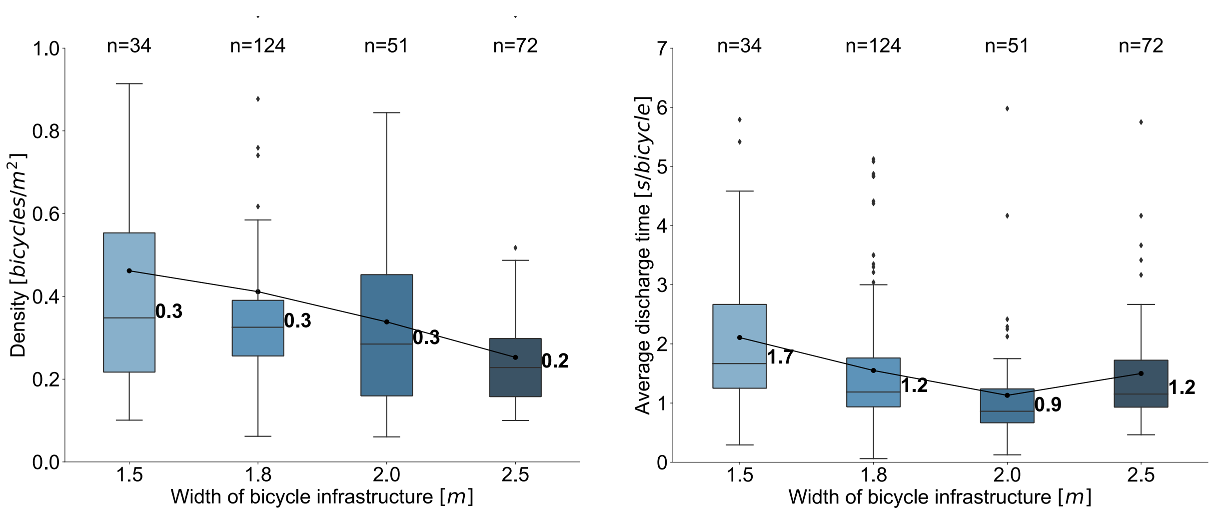

Figure 8 Observed queue density (left) and average discharge time (right) by infrastructure width.

- **Occupancy time**: This parameter is defined as the duration in seconds that the conflict area between right-turning motor vehicles and bicyclists riding straight across the intersection in the same direction is occupied by bicyclists. Only the group of bicyclists queued before the signal turned green is considered in the evaluation. The occupancy time is the duration that the conflict area is continuously occupied by at least one bicyclist. Bicyclists arriving during the green phase are not considered in the calculation of this parameter. Figure 9 (left) shows the occupancy times for bicyclist queues of different sizes on on-road and separated cycling facilities. The occupancy time on a bike box at the intersection Oranienburger Strasse /

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Friedrichstrasse by the number of bicyclists in the queue size is shown in Figure 9 (right). The sample size *n* refers to the number of analysed bicyclist groups (group sizes *s = 1* (individual bicyclist) to *s = 9*) occupying the conflict area at all relevant intersection approaches with a bicycle lane, a bicycle path or a bike box. The occupancy time is increasing stepwise together with the increase in the number of bicyclists, which might be explained by the fact that bicyclists can ride side by side across the conflict area. In the case of the bicycle box the occupancy time increases slightly with the increase in the number of bicyclists. This is attributed to the fact that the bike box has a sufficiently wide area that allows several bicyclists standing side by side to ride through the intersection approach at the start of green time.

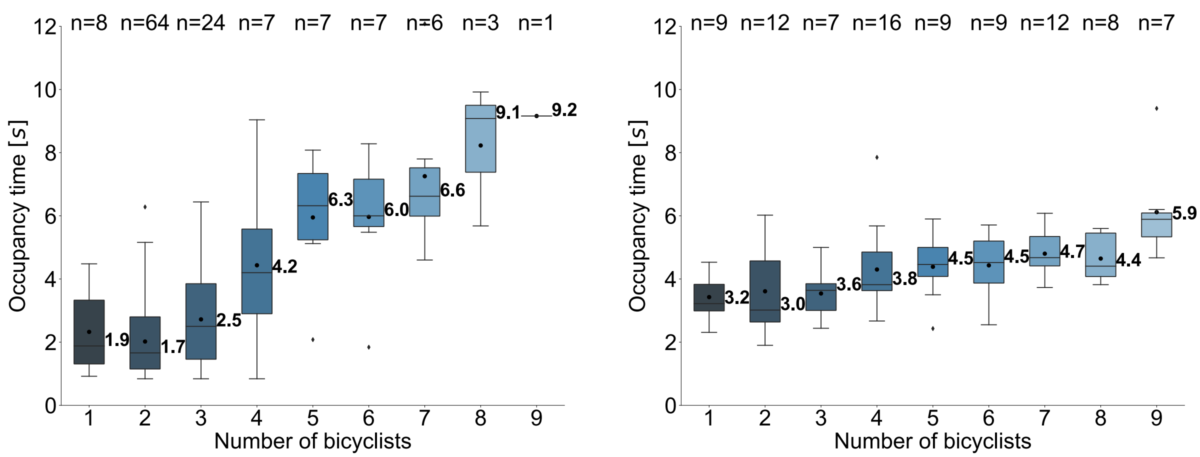

Figure 9 Observed occupancy times for on-road and separated cycling facilities (left) and bike boxes (right)

4.2. Simulation Studies

The developed simulation models are used to study the traffic performance parameters at typical intersection approaches with different types of bicycle infrastructure. Additionally, in the simulation studies increasing bicycle traffic volumes can be simulated that could not be observed in the empirical studies.

Therefore, it is important for the simulation models that the aggregation of the individual bicyclist dynamic and operational behaviour characteristics results in the accurate estimation of bicycle traffic flow performance indicators even for traffic flow compositions that either have not been or cannot be observed in the empirical studies. The empirical studies focused on the derivation of distributions of fundamental traffic parameters for individual bicyclists (speed, acceleration) and bicycle traffic flow (queue density, average discharge time) for different settings (e.g. lane width) rather than the analysis of situations (e.g. days). This setting allows for model calibration but not for validation by out of sample testing, since all usable observations make up the traffic parameter distributions and random sampling from a distribution should lead to a similar distribution. Thus, in our research, we distinguish between calibration (or adjustment) of input parameters and calibration based on simulation output.

On the input side, acceleration functions and the desired speed distributions in PTV Vissim are set according to the results of the empirical studies (Figure 7). Acceleration is crucial for the queue discharge process with bicyclists starting from a complete stop to cross the stop line and eventually clear the intersection. Desired speed might be a relevant factor for queue discharging and intersection clearance as well (if the distance from the starting position to the stop line is long enough to reach the desired speed).

On the output side, the empirically determined queue density, the average discharge time, and the occupancy time are used to calibrate the parameters of the longitudinal and lateral behavior models. Vehicular traffic is calibrated so that the discharge times and capacities for a given signal plan are reproduced in accordance with HBS. Finally, the empirically observed effect of bicycle traffic on the average discharge time of the first vehicle turning right is used to validate the simulation models.

Figure 10 shows comparisons of empirical data and simulation output for two traffic parameters. Figure 10 (left) shows the queue density on bicycle lanes in front of a stop line in the simulation and from the empirical studies. The simulated bicyclists form slightly denser queues than the observed bicyclists, but the relative error of the means is small (percent error = 1.5 %). The median values, rounded to one decimal place, are equal (0.3 bicycles/m^2). The mean waiting times of motor vehicles turning right per bicyclist crossing the intersection from the same approach is shown in Figure 10 (right). The relative error of the means is larger than for the density (percent error = 11 %), The median values, rounded to one decimal place, are equal (2 s/bicycles).

Additionally, we further assess the simulation results through statistical testing. We use the Levene test to evaluate the equality of variance between the two populations, as it is more robust in comparison to the F-test which assumes distribution normality. The p-value is 0.28 (density) and 0.92 (waiting time), respectively, such that the null hypothesis of equal variances for both cases is rejected. Therefore, the Welch-test is applied to determine if the hypothesis of equal means must be rejected, as it performs better with unequal population sizes and variances. The null hypothesis of equal means in both populations is rejected if the p-value is smaller than 0.05. The p-value is 0.86 (density) and 0.22 (waiting time), respectively, such that the null hypothesis of equal means for both cases cannot be rejected, also indicating that simulation results are in accordance with the empirical observations.

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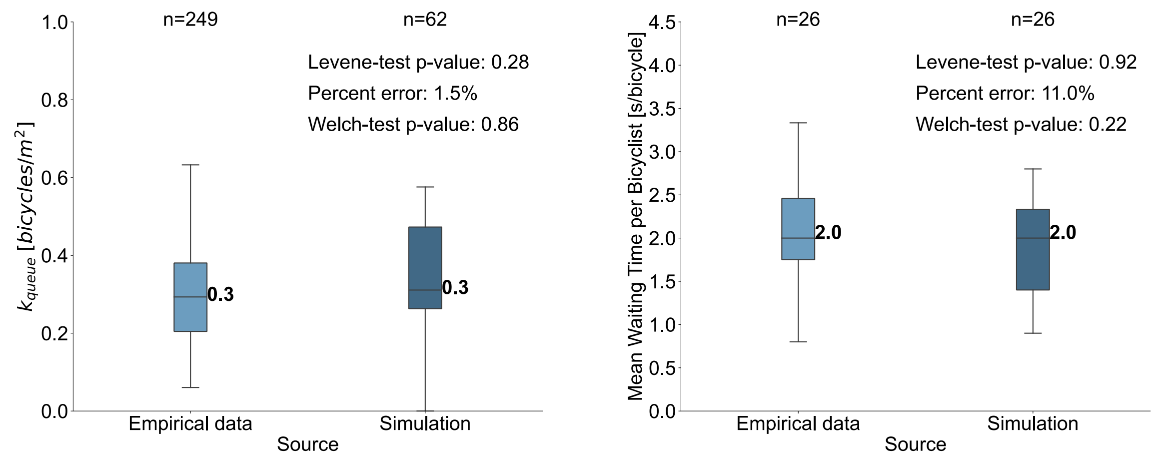

Figure 10 Comparison of the simulation results and the empirical findings: bicycle queue density at the stop line (left) and mean waiting time for right-turning vehicles per bicyclist crossing the intersection (right)

Only comparable cases from the empirical studies were used for the calibration of the simulation model. Therefore, all the simulation results depend on the relationships identified in the observed data and continue to apply beyond the range of observations. Respectively the direct applicability of results from such studies on real world applications may proceed with some caution, however the use of simulation tools is deemed as a necessary step towards the development of further methodologies when empirical data is insufficient, or their collection is not feasible.

A total of four simulation scenarios with typical infrastructure design and dimensions are examined. In the simulation scenarios, the bicycle volume $v_{bicycle}$, the vehicular volume v_{veh}, the signal cycle length C and the actual green time ratio (G/C) are systematically altered. Figure 11 presents the four scenarios and the parameter sets used. The capacity is analysed in all scenarios as this parameter is also used to determine the degree of capacity utilization, waiting time, congestion length, and Level of Service according to the HBS. The simulation results show the relationship between the bicycle volumes and capacities of the affected vehicular streams in each scenario.

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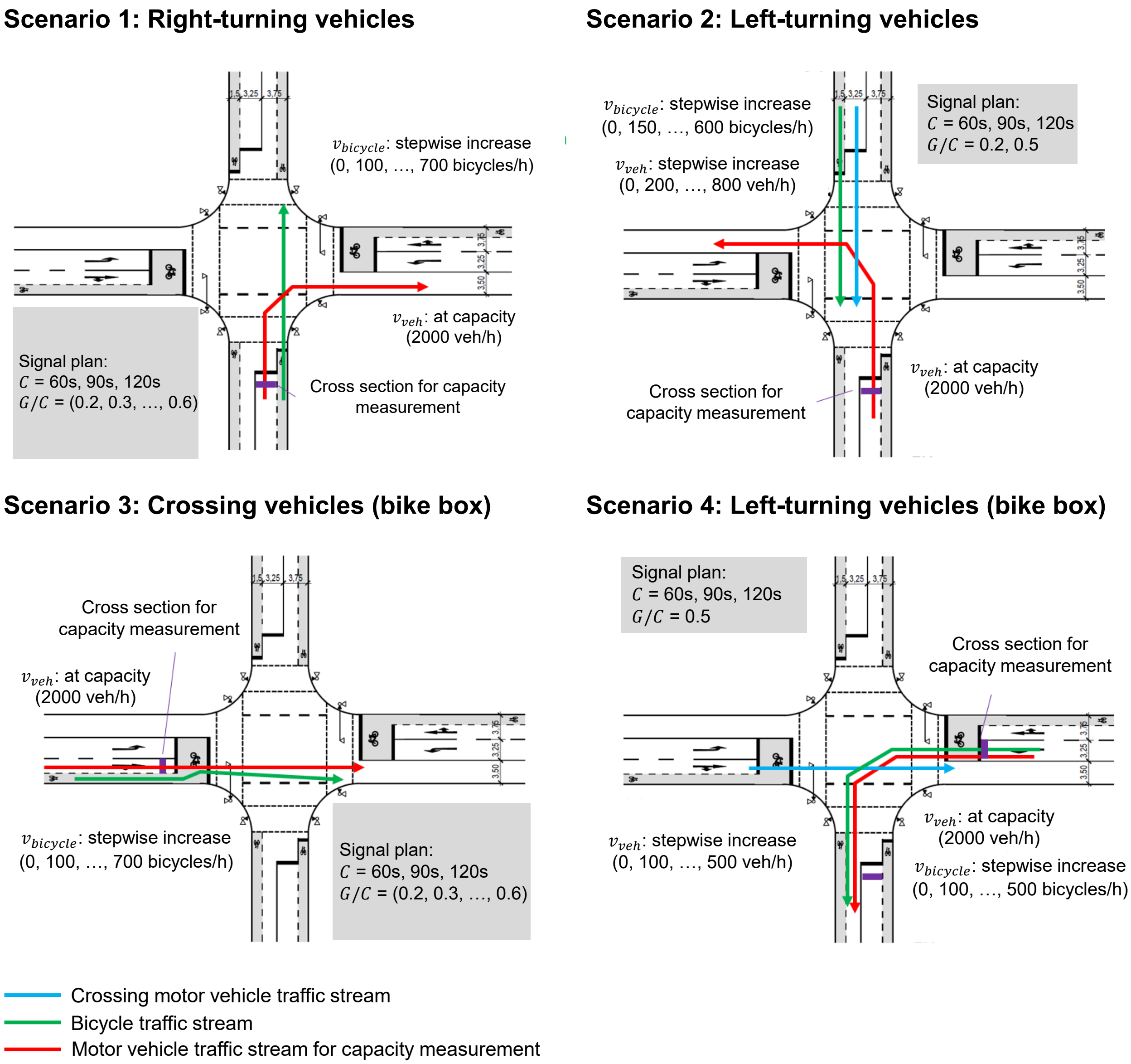

Figure 11 Overview of the simulation scenarios

Scenario 1: Capacity of right-turning vehicular traffic with parallel bicycle traffic crossing the intersection.

The capacity of the right-turning vehicular traffic decreases with the volume of bicycle traffic, as expected, but to a lesser extent at very high bicycle traffic volumes (see

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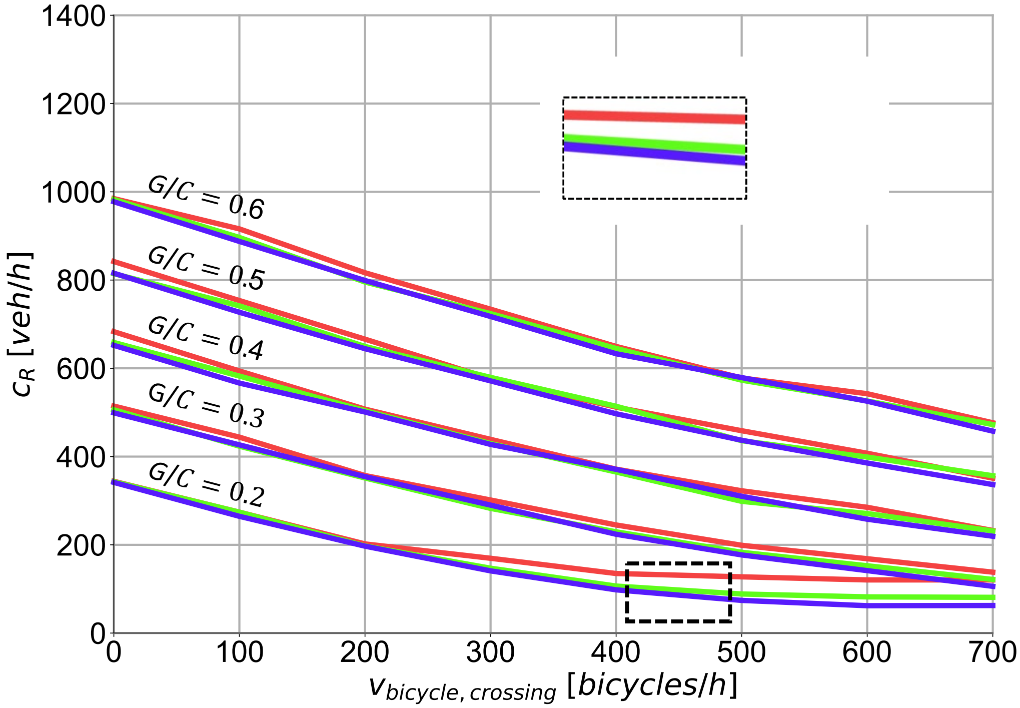

Figure 12). Concerning signal control, the capacity is mainly influenced by the actual green time ratio (G/C). However, it can also be observed that the cycle length C has an influence on the capacity at very high bicycle traffic volumes and low actual green time ratios (G/C). The influence of the cycle time depends on the distance between the stop line and the point of conflict between the right-turning vehicles and the parallel crossing bicyclists, as vehicles waiting here can cross during the signal phase change. The capacity of right-turning vehicles is dependent on the type of approach, as shown in Figure 13. The average capacity of right-turning vehicles is slightly reduced in the case of a bike box when compared to an intersection approach with a bike lane. Results also suggest that the allocation of a bike path at the intersection approach improves the capacity of right turning vehicles in comparison to the other examined approach infrastructure. Therefore, in combination with the results of the empirical analysis (see Figure 4) bike boxes are beneficial for facilitating direct left turns at the intersection approach for bicycle traffic, however in the absence of significant shares of left turning bicycle traffic as defined by the goals and policy of the respective transport authorities, the allocation of a bicycle lane or a bicycle path offer improved capacity conditions for motor vehicle traffic.

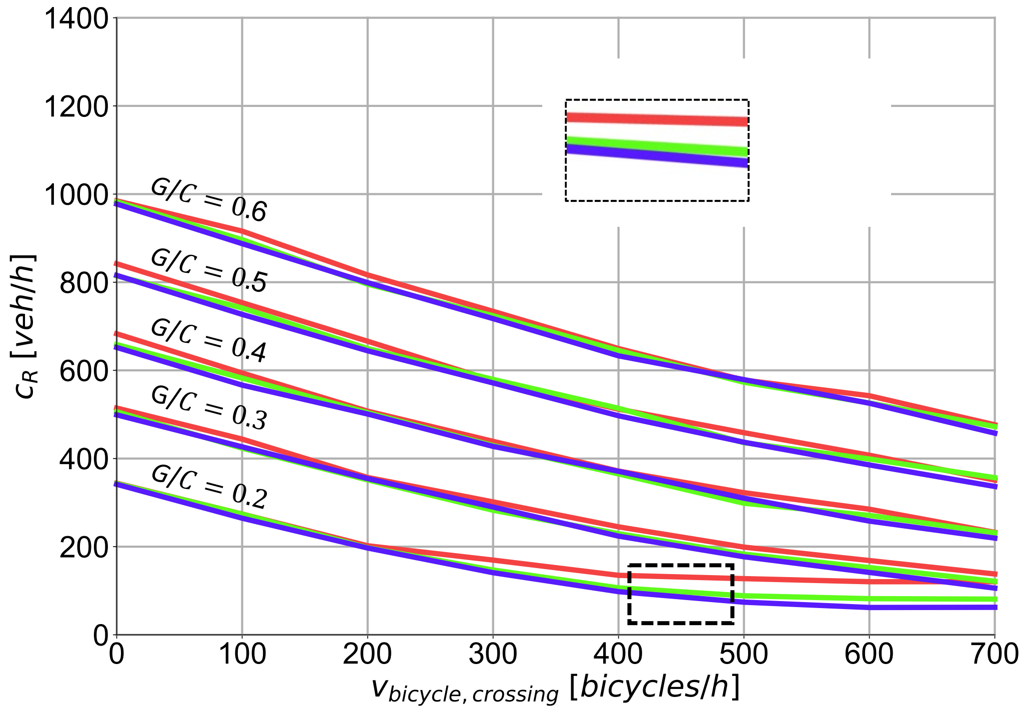

Figure 12 Capacity of right-turning motor vehicles with parallel bicycle traffic riding straight at the intersection approach.

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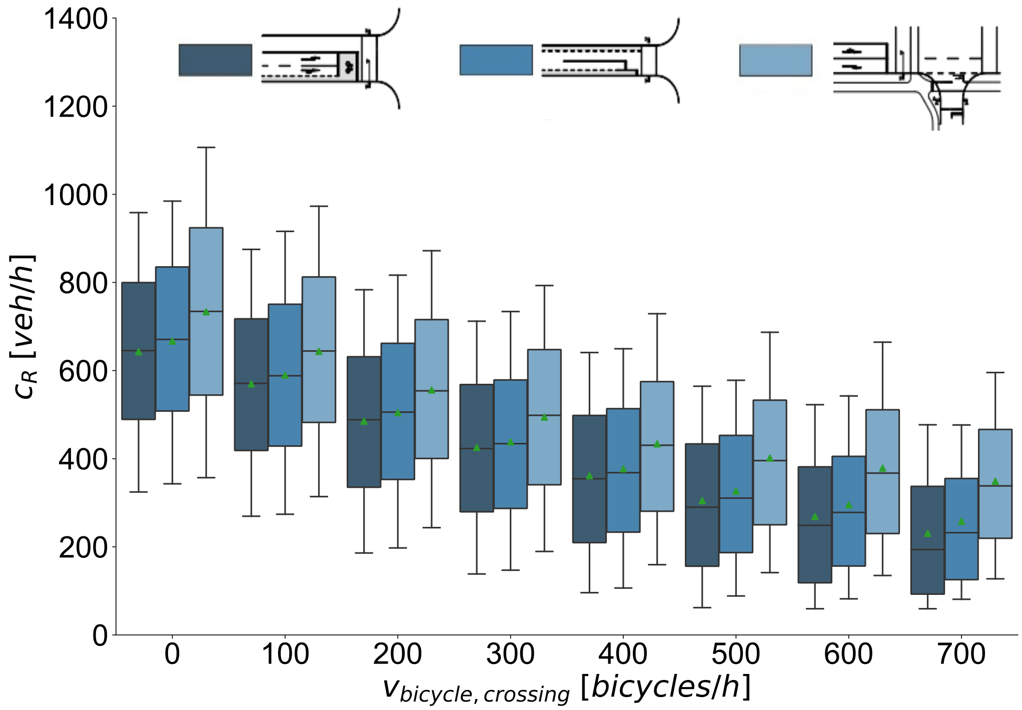

Figure 13 Capacity of right-turning vehicles by type of approach infrastructure ($C = 90\ s$).

Scenario 2: Capacity of left-turning vehicular traffic with opposing bicycle and vehicular traffic crossing the intersection.

The capacity of left-turning vehicular traffic streams is strongly influenced by oncoming bicyclists and motor vehicles crossing the intersection. A comparison of the simulation studies (Figure 14) shows that the actual green time ratio (G/C) has a significant influence on the capacity of this vehicle stream. The effect of the cycle length C increases with the volume of oncoming motor vehicle and bicycle traffic. The higher the volume of oncoming motor traffic and the higher the volume of oncoming bicycle traffic, the more the capacity of the turing motor vehicle traffic stream is reduced, while a capacity threshold is reached at $c_L \approx\ 200veh/h\ (C = 60s)$ and $c_L \approx\ 100veh/h\ (C = 120s)$, where turning motor vehicles primarily turn off at the intersection during the integreen time. The longer the cycle length, the smaller the capacity becomes with the same actual green time ratio (G/C), which demonstrates the large influence of the capacity during phase changes.

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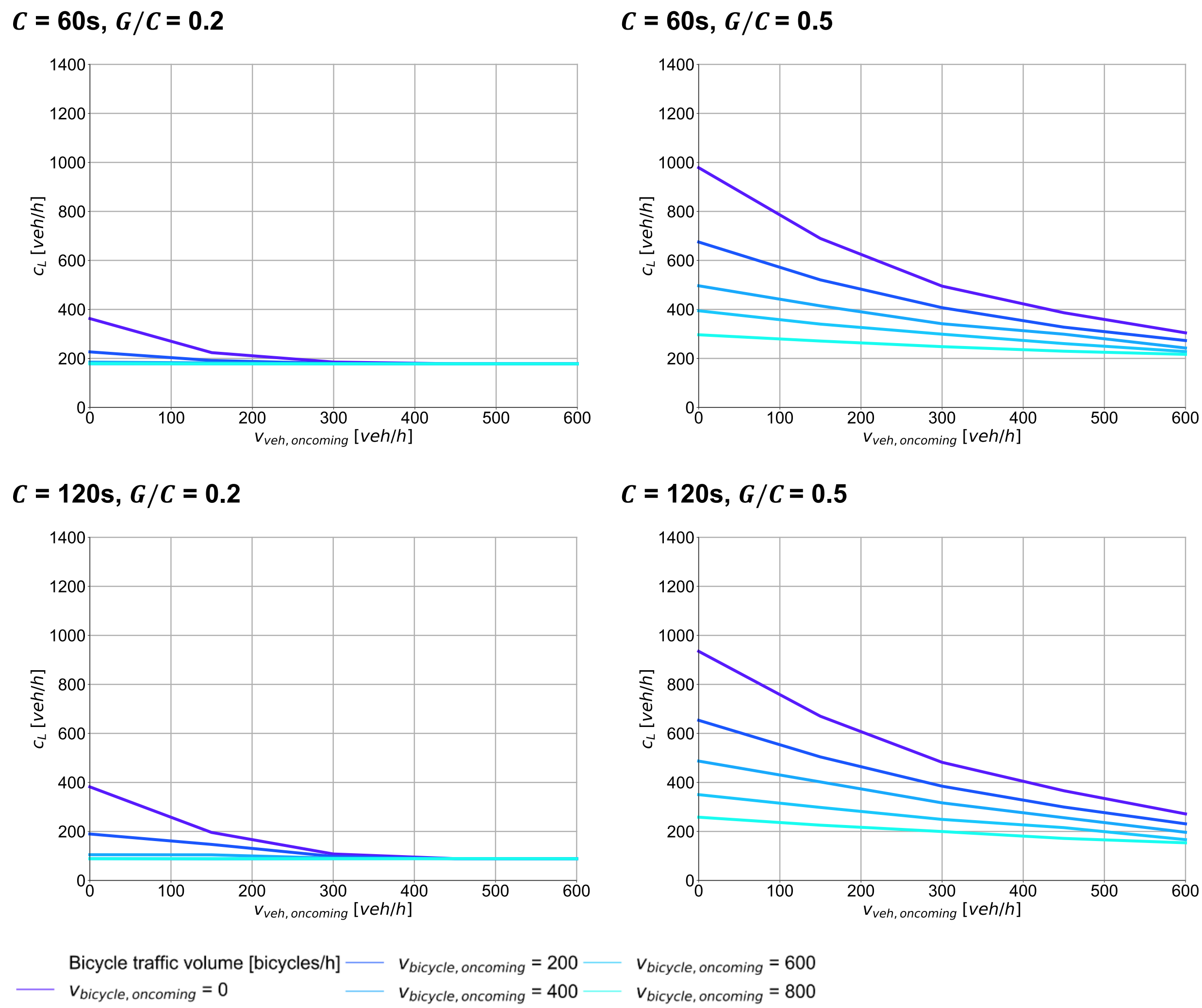

Figure 14 Capacity of left-turning motor vehicle streams with opposing bicycle and motor vehicle traffic.

Scenario 3: Capacity of crossing vehicular traffic with parallel bicycle traffic crossing the intersection using a bike box.

Results (Figure 15) show that the vehicular capacity crossing the intersection is relatively independent of the volume of bicycle traffic crossing the intersection. Bicyclists crossing the intersection are observed to queue on the right side of the bike box and did not significantly affect the movement of motor vehicles crossing the intersection at the start of the green phase. This queuing behavior is carefully recreated in the simulations. With very large bicycle traffic volumes, the queue of bicyclists waiting on the right side of the bike box spills back into the bicycle lane such that bicyclists reaching the intersection cannot enter the bike box and do not influence the capacity of motor vehicle traffic.

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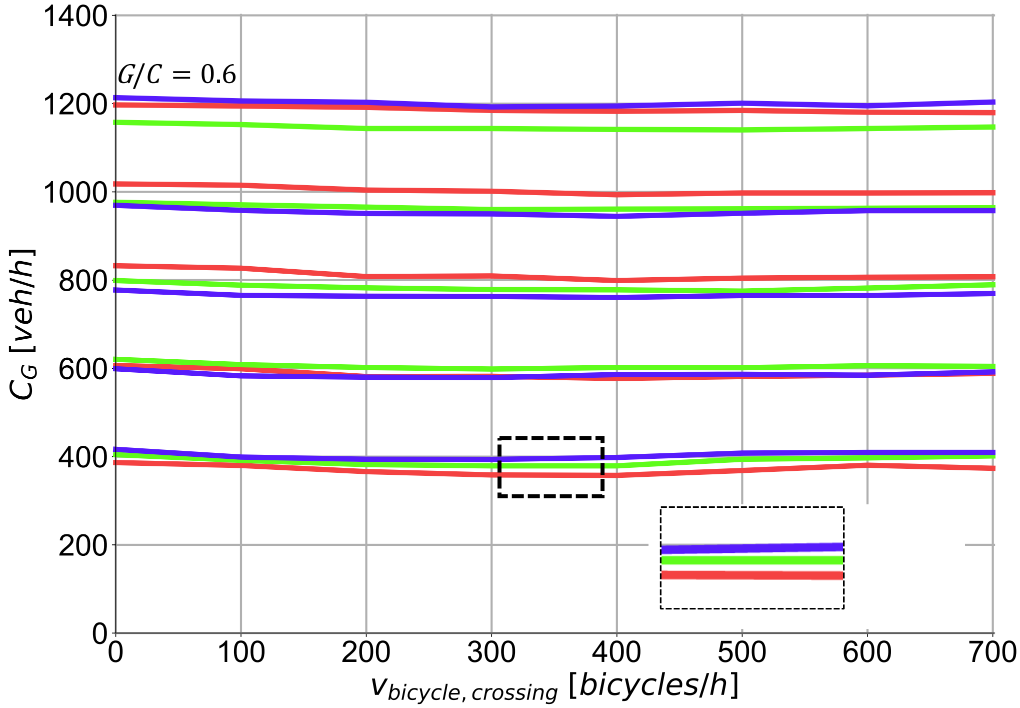

Figure 15 Capacity of crossing vehicular traffic with parallel bicycle traffic crossing the intersection using a bike box.

Scenario 4: Capacity of left-turning vehicular traffic with opposing bicycle traffic crossing the intersection with a bike box**.**

The vehicular capacity decreases as the number of cyclists turning left increases. When using a bike box, left-turning bicyclists queue in front of motor vehicles, and therefore the capacity of left-turning vehicle streams depends on the time gap acceptance of bicyclists turning left. With increasing volumes of oncoming bicyclists crossing the intersection, smaller time gaps can be expected, leading to a further reduction in capacity. Results are presented in Figure 16.

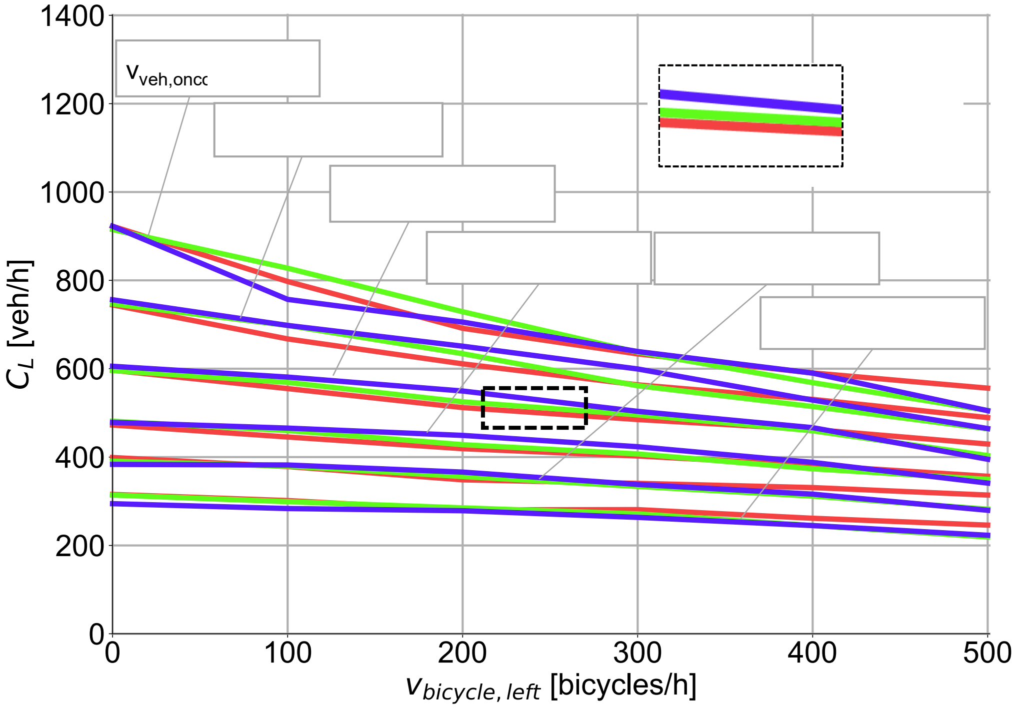

Figure 16 Capacity of left-turning vehicular traffic with opposing bicycle traffic crossing the intersection with a bike box.

5. Implications for Practice

Several adjustments and extension to the design and evaluation approaches defined in the HBS are proposed.

1. Discharge time for bicycle traffic on a separated cycling facility

The capacity of a cycling facility can be determined analogously to the capacity of vehicular traffic with unobstructed flow using the discharge time per vehicle and the actual green time ratio (G/C). This is of particular interest with large volumes of bicycle traffic because a queue can remain at the end of a green phase. Based on the empirical data (see Figure 8), the observed bicycle density as a function of the infrastructure width is only slightly decreasing, while the median bicycle queue density is almost constant with increasing infrastructure width. Therefore, average queue discharge time $t_{W_{bl}}$ is defined as a function of the width of the cycling facility W_{bl} and is presented in Table 3. Figure 17 Queue discharge time for bicyclist groups by facility width.presents the expected queue discharge times by facility width for bicyclist group sizes 1 to 15 using Table 3.

Table 3 Average discharge times for bicycle traffic by facility width.

W_{bl} [m]	$t_{W_{bl}}$ [s/bicycle]
≥ 2.00	1.0
1.80 ≤ W_{bl} < 2.00	1.4
1.60 ≤ W_{bl} < 1.80	2.0
< 1.60	2.2

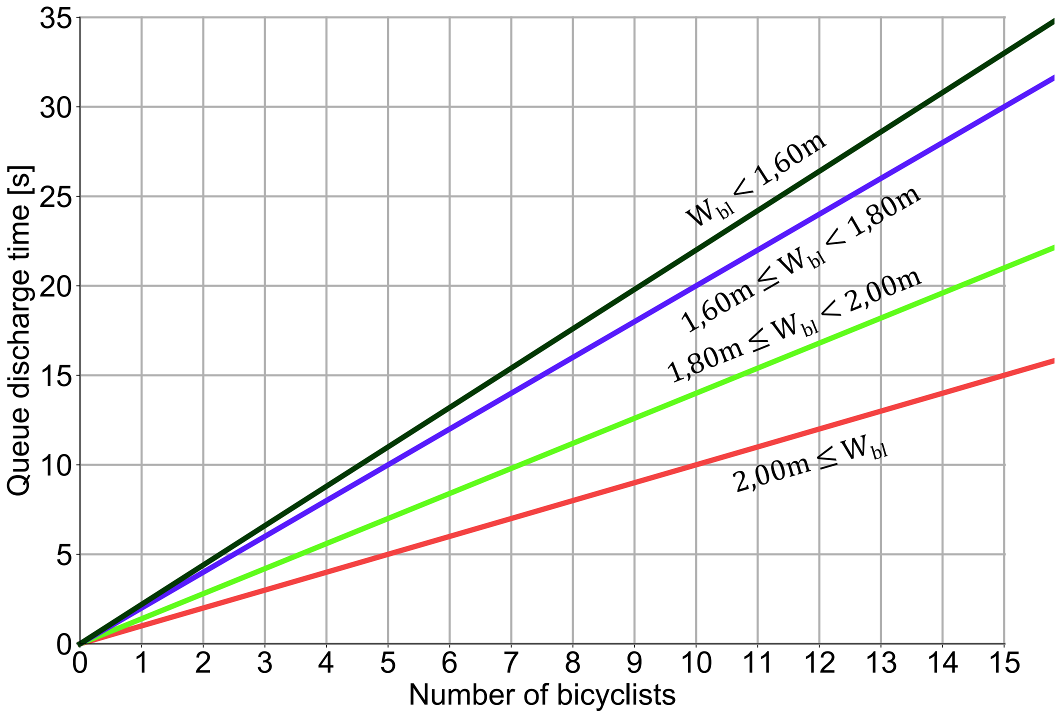

Figure 17 Queue discharge time for bicyclist groups by facility width.

2. Influence of bicyclists in a bike box on crossing motor vehicle traffic

If a bike box is present, an effect on the capacity of vehicular traffic can only be detected if the volume of bicycle traffic is greater than approximately 100 bicycles/h (leading to more than one bicyclist arriving at red in the majority of the cases). Based on this finding, it is proposed to apply no time deduction for bicycle traffic volumes less than 100 bicycles/h and a time deduction of 1 s for bicycle traffic volumes greater than 100 bicycles/h.

3. Occupancy time of the conflict area between right-turning motor vehicles and parallel bicyclists crossing the intersection.

The empirical and simulation results show that the capacity of vehicular traffic depends on the volume of parallel bicycle traffic and the actual green time ratio (G/C) for motor vehicle traffic.

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Adjustment factors are typically used in both the HBS and HCM to account for the effect of different factors on unobstructed traffic flow at the respective traffic facility. Based on these findings, a factor for the reduction of the capacity of vehicular traffic with unobstructed outflow is derived:

$$c_{R,i} = c_{0,R,i} \cdot f_{cR,veh} \tag{1}$$

Where $c_{R,i}$ is the capacity of the right-turning motor vehicle stream i [veh/h], $c_{0,R,i}$ is the capacity of the right-turning motor vehicle stream i with unobstructed outflow using Equation S4-8 of the German HBS [veh/h] and $f_{cR,veh}$ is a factor to reduce the capacity of the right-turning traffic depending on the volume of parallel bicycle traffic and the actual green time ratio (G/C) for the motor vehicle traffic. The reduction factor is estimated from the results of the capacity of right-turning motor vehicle streams with parallel bicycle traffic (

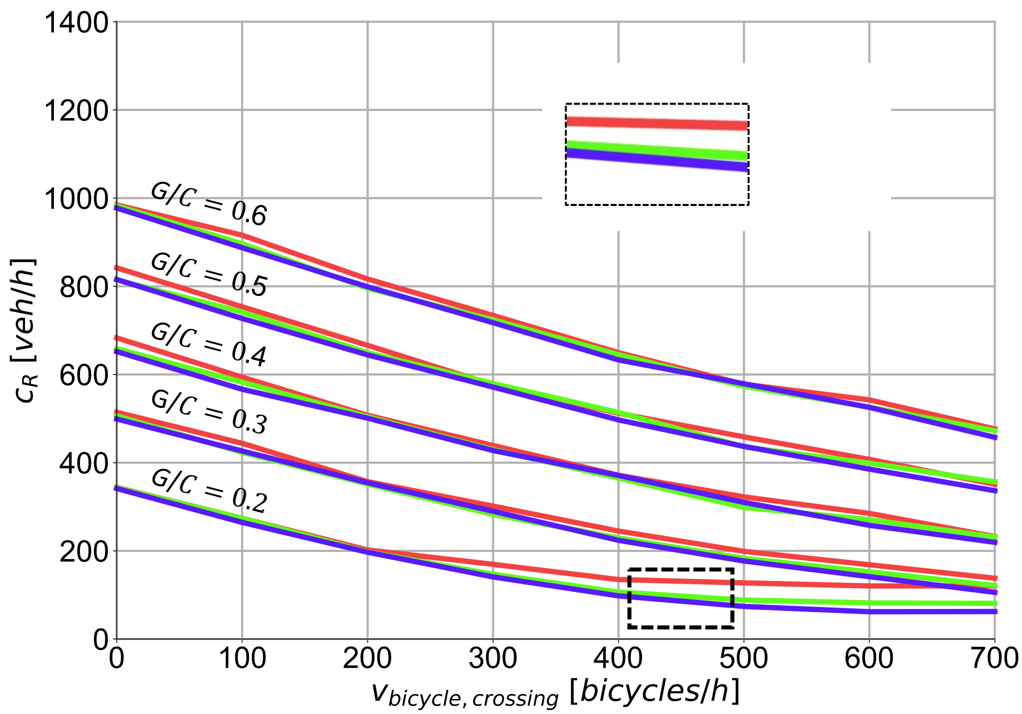

Figure 12). Subsequently the capacity reduction share is estimated as a function of the capacity reduction divided by the free flow capacity ($v_{bicycle} = 0$). The reduction factor is formulated as a single function with decreasing G/C and increasing bicycle volumes $v_{bicycle}$ leading to stronger reduction of the capacity. The basic shape and the constants in the formula, as shown in Equation 2 and Figure 18, are found by regression.

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$$f_{cR,veh} = e^{-\left(\frac{1}{\sqrt{G/C}\cdot 1000}-\frac{(G/C)^2}{s_R\cdot 0{,}85}\right)\cdot v_{bicycle}} \quad (2)$$

Where C is the cycle length, (G/C) is the actual green time ratio for the right-turning vehicular traffic, s_{veh} is the saturation flow of right-turning vehicular traffic [veh/h] and v_{bicycle} is the flow of parallel bicycle traffic [bicycles/h].

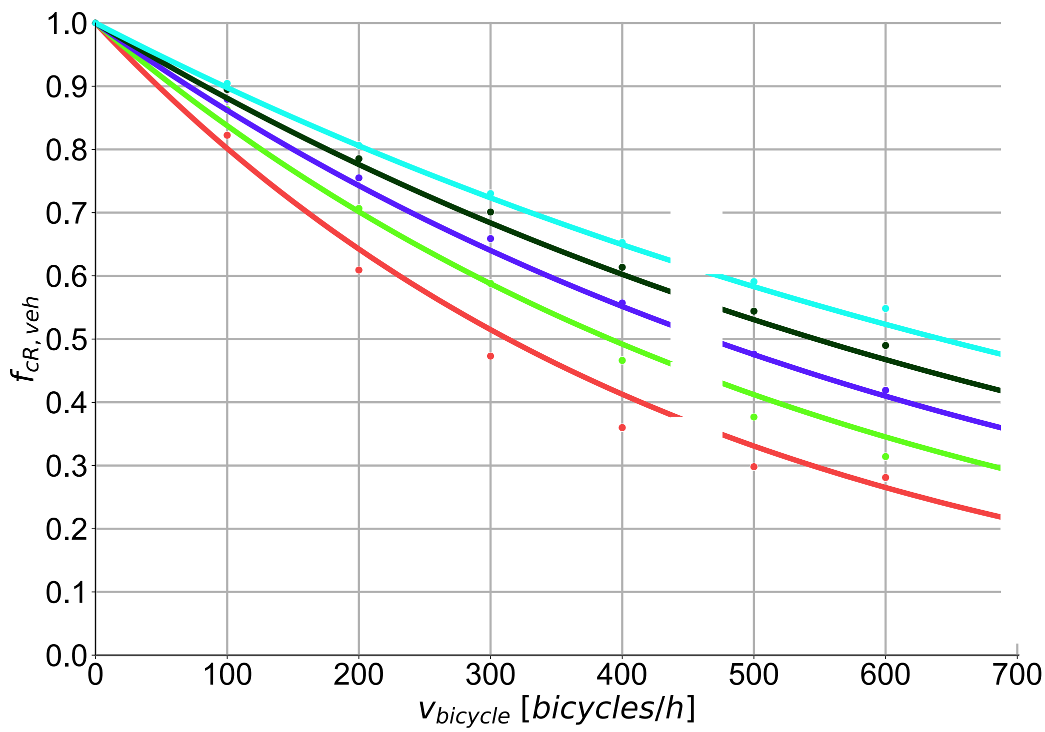

Figure 18 Factor for reducing the capacity of right-turning vehicular traffic based on bicycle traffic flow and actual green time ratio (G/C).

4. Influence of oncoming bicycle traffic on left-turning motor vehicle traffic

As expected, and as the simulation results show, oncoming motor vehicle and bicycle traffic have a considerable influence on the capacity of the left-turning vehicular traffic flows. Indeed, the capacity reduction for left-turning vehicle traffic due to oncoming motor vehicles and bicyclists is directly dependent on these two volumes. For this purpose, a conversion to vehicle units with 0.75 cyclists = 1 vehicle unit is suggested. $c_{L,i}$ is the capacity of the left-turning motor vehicle stream i and is derived using Equation 3.

$$c_{Lc,i} = c_{0,L,i} \cdot f_{cL,veh} \quad (3)$$

Where $c_{0,L,i}$ is the capacity of the left-turning motor vehicle stream i with unobstructed outflow using Equation S4-8 of the HBS. $f_{cL,veh}$ is the reduction factor for the capacity for left-turning vehicular traffic depending on the green time (G/C) ratio for the left-turning motor vehicle traffic, as shown in Figure 19. The reduction factor is estimated from the results of the capacity of left-turning motor vehicle streams with opposing bicycle and motor vehicle traffic (Figure 14), where the bicycle and motor vehicle traffic volumes are aggregated into vehicle units. Subsequently the capacity reduction share is estimated as a function of the capacity reduction divided by the free flow capacity $(v_{oncoming} = 0)$. A regression function is then used to model the capacity reduction and derive the reduction factor for the respective green time (G/C) ratios.

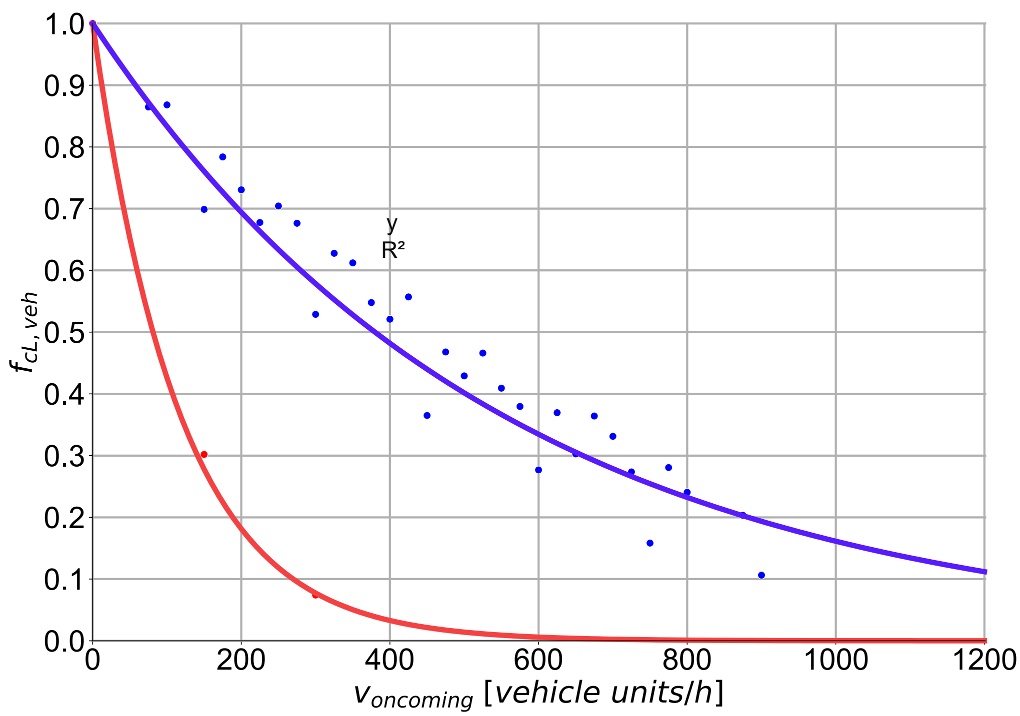

Figure 19 Factor for reducing the capacity of left-turning traffic based on the combined bicycle and vehicular traffic flow and actual green time ratio.

6. Conclusion

The aim of this research is to investigate traffic flow at signalized intersections with large volumes of bicycle traffic and based on this, to review the existing calculation method in the HBS as well as other official design manuals, such as the HCM, for determining traffic quality and, if necessary, adapt or extend the present methods. Empirical data were collected and used to build, calibrate, and validate microscopic traffic simulation models. Data are generated with the resulting simulation models for situations with large bicycle traffic volumes as the empirical investigations could not cover all situations and the entire spectrum of relevant vehicle and bicycle traffic volumes.

Microscopic traffic simulation proved to be a suitable instrument for generating data for the verification and further development of the calculation methods. The behavior of cyclists and motor vehicles in traffic are parametrized to create realistic bicycle and vehicular traffic flows. Additionally, the data required for the development of calculation methods can be generated and output relatively directly using microscopic traffic simulation tools. While extensive findings are now available on the speeds, accelerations, and queuing and queue dispersion behavior of cyclists, detailed information concerning the acceptance of time gaps for the parameterization of the models is still lacking. While the results from the model extrapolate the results of the empirical studies, still results for higher or saturated traffic flows have not been verified with empirical data. Finally, our developed methods are based on empirical data collected only at intersections in Germany with specific types of bicycle infrastructure and traffic conditions. The behavior of bicyclists across all study intersections did not seem to variate significantly however it is expected that the driving behavior of bicyclists in other countries or in different traffic situations might deviate from our observations.

Based on the empirical and simulation results, additions and/or adaptations to the calculation method in HBS are suggested for the following aspects:

- Management of bicycle traffic on a dedicated cycling facility (bicycle path or bicycle lane),
- Consideration of the influence of bicyclist queue formation and discharge with a bike box,
- Consideration of the influence of parallel crossing bicycle traffic on the capacity of right-turning motor vehicle traffic,
- Consideration of the influence of bicyclists in oncoming traffic on the capacity of the left-turning motor vehicle traffic.

The proposed adjustments and extensions to the design and evaluation approaches for the German HBS can be integrated or used together with the HCM in the process of calculating the adjustment factor values for vehicular capacity. The findings for the bike boxes and the proposed time deduction can be integrated into the HCM in cases, where such bicycle infrastructure is provided. Also, the proposed adjustment factors $f_{cR,veh}$ and $f_{cL,veh}$ for the capacity of right and left turning vehicular traffic can be used to account for the influence of the bicycle flow independently of that of the pedestrian flow or for cases with minimal to no pedestrian interference.

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Future research to extend the results presented in this paper could focus on the collection and analysis of empirical data during events of bicyclist congestion, the extension of the calculation methods for bicyclists in mixed traffic (with and without protective strips) and the resulting passing on the right of a queue of motor vehicles, the effect of pedestrians on bicyclists turning right and left at an intersection and the consideration of indirect left-turning bicyclists.

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8. References

Allen, D., Bygrave, S., Harper, H., 2005. Behaviour at cycle advanced stop lines. Transport for London (TRL).

Allen, D., Hummer, J., Rouphail, N., Milazzo, J., 1998. Effect of bicycles on capacity of signalized intersections. Transp. Res. Rec. J. Transp. Res. Board 1646 , 87–95.

Alrutz, D., Bohle, W., Müller, H., Prahlow, H., Hacke, U., Lohmann, G., 2009. Unfallrisiko und Regelakzeptanz von Fahrradfahrern. Berichte der Bundesanstalt für Straßenwesen, Unterr. Verkehrstechnik 184, 1–127.

Angenendt, W., Blase, A., Klöckner, D., 2005. Verbesserung der Radverkehrsführung an Knoten.

Baumann, F., 2016. Berner Ampeln stehen auf grün [WWW Document]. Velojournal. URL http://www.velojournal.ch/vj-online/nachrichten/2016/berner-ampeln-stehen-auf-grün.html (accessed 4.4.17).

Botma, H., Papendrecht, H., 1991. Traffic Operation Of Bicycle Traffic. Transp. Res. 1320 , 65–72.

Busch, F., Grigoropoulos, G., Kaths, H., Baier, M., Reinartz, A., Schuckließ, L., Junghans, M., Lücken, L., Leonhardt, A., 2019. Verkehrsablauf an signalisierten Knotenpunkten mit hohem Radverkehrsaufkommen – Schlussbericht FE 70.0925/2015.

Chen, J., Wang, W., Li, Z., Jiang, H., Chen, X., Zhu, S., 2014. Dispersion Effect in Left-turn Mixed Bicycle Traffic and Its Influence on Capacity of Left-turn Vehicles at Signalized Intersections, in: Transportation Research Board, 93rd Annual Meeting. doi:10.3141/2468-05

Chen, X., Shao, C., Li, D., Dong, C., 2009. Capacity reliability of signalized intersections with mixed traffic conditions. Tsinghua Sci. Technol. 14 3 , 333–340.

COWI, 2013. Micro Simulation of Cyclists in Peak Hour Traffic.

Deutsches Zentrum für Luft and Raumfahrt, 2020. UTRaCar and MoMoCar [WWW Document]. URL https://www.dlr.de/ts/desktopdefault.aspx/tabid-1237/5441_read-12153%0A (accessed 9.17.20).

Falkenberg, G., Blase, A., Bonfranchi, T., Cosse, L., Draeger, W., Vortisch, P., Kautzsch, L., Stapf, H., Zimmermann, A., 2003. Bemessung von Radverkehrsanlagen unter verkehrstechnischen Gesichtspunkten. Berichte Der Bundesanstalt Fuer Strassenwesen. Unterr. Verkehrstechnik 103 .

Figliozzi, M., Wheeler, N., Monsere, C., 2013. A Methodology to Estimate Bicyclists' Acceleration and Speed Distributions at Signalized Intersections. Transp. Res. Rec. J. Transp. Res. Board 2387, 66–75.

Forschungsgesellschaft für Straßen- und Verkehrswesen (FGSV), 2015. Handbuch für die Bemessung von Straßenverkehrsanlagen (HBS).

PREPRINT
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Forschungsgesellschaft für Straßen und Verkehrswesen (FGSV), 2010. Empfehlungen für Radverkehrsanlagen (ERA), 2010th ed. Forschungsgesellschaft für Straßen- und Verkehrswesen (Hrsg.), Köln.

Forschungsgesellschaft für Straßen und Verkehrswesen (FGSV), 2006. Richtlinien für die Anlage von Stadtstraßen (RASt). Köln.

Greibe, P., Buch, T.S., 2016. Capacity and Behaviour on One-way Cycle Tracks of Different Widths. Transp. Res. Procedia 15, 122–136. doi:10.1016/j.trpro.2016.06.011

Grigoropoulos, G., Kazakovtsev, S.M.M., Kaths, H., Krämer, K., 2019. Evaluation of a Traffic Signal Coordination for Bicycles in a Mixed Motor Vehicle and Public Transport Urban Network. Cycl. Res. Board 2019.

Grigoropoulos, G., Twaddle, H., Spangler, M., Hagenbring, M., Düsterwald, M., 2018. Evaluierung der dynamischen Grünen Welle für Radfahrer-Sitraffic SiBike-in Marburg. Straßenverkehrstechnik 268–274.

Guo, Y., Yu, Q., Zhang, Y., Rong, J., 2012. Effect of Bicycles on the Saturation Flow Rate of Turning Vehicles at Signalized Intersections. J. Transp. Eng. 138 1 , 21–30. doi:10.1061/(ASCE)TE.1943-5436.0000317

Hein, M., Conference, G., Hutchison, D., 2013. LNCS 8142 - Pattern Recognition.

Hoegh, N., 2007. Green waves for cyclists in Copenhagen Denmark - Copenhagen. Work. Velo-city “From Vis. to reality.”

Jin, S., Shen, L., Liu, M., Ma, D., 2017. Modelling speed–flow relationships for bicycle traffic flow. Proc. Inst. Civ. Eng. Transp. 170 4 , 194–204. doi:10.1680/jtran.15.00115

Karl, M., Felix, B., 2013. Koordinierung von Lichtsignalanlagen fuer den Radverkehr. Straßenverkehrstechnik.

Kaths, H., Grigoropoulos, G., Krämer, K., 2019. Green signal countdown timers for bicycle traffic–Results from a field study. Cycl. Res. Board 2019.

Kuller, E.C., Gersemann, D., Ruwenstroth, G., 1986. Regelabweichendes Verhalten von Fahrradfahrern. Forschungsberichte Der Bundesanstalt Für Straßenwesen, Bereich Unfallforsch. 142 .

Kwigizile, V., Oh, J., Ikonomov, P., Hasan, R., Villalobos, C.G., Kurdi, A.H., Shaw, A., 2017. Real Time Bicycle Simulation Study of Bicyclists ’ Behaviors and their Implication on Safety FINAL REPORT.

Landeshauptstadt München, 2019. Daten zum Radverkehr [WWW Document].

Landis, B.W., Vattikuti, V.R., Ottenberg, R.M., Petritsch, T.A., Guttenplan, M., Crider, L.B., 2003. Intersection level of service for the bicycle through movement. Pedestrians Bicycl. 2003 Saf. Hum.

Perform. 1828 1828 , 101–106. doi:10.3141/1828-12

Li, Zhibin, Li, Zheng, Huang, R., Yang, Z., Zhou, W., Ye, M., 2015. Operational Features in Bicycle Traffic Flow : An Observational Study 328.

Michon, J.A., 1985. A critical view of driver behavior models: what do we know, what should we do? Hum. Behav. traffic Saf. 485–520. doi:10.1007/978-1-4613-2173-6

National Association of City Transportation Officials (NACTO), 2014. Urban Bikeway Design Guide. Island Press.

National Research Council, 2016. Highway Capacity Manual, Transportation Research Board. Transportation Research Board, Washington DC.

Nobis, C., Kuhnimhof, T., 2019. Mobilität in Deutschland – MiD Analysen zum Radverkehr und Fußverkehr.

Opiela, K.S., Khasnabis, S., Datta, T.K., 1980. Determination of the characteristics of bicycle traffic at urban intersections. Transp. Res. Rec. 743, 30–38.

Parkin, J., Rotheram, J., 2010. Design speeds and acceleration characteristics of bicycle traffic for use in planning, design and appraisal. Transp. Policy 17 5 , 335–341. doi:10.1016/j.tranpol.2010.03.001

Peter Koonce, 2015. Bicycle Countdown Signal - Time to Green [WWW Document]. URL http://koonceportland.blogspot.de/2011/07/bicycle-countdown-signal-time-to-green.html (accessed 11.27.15).

Petzoldt, T., Schleinitz, K., Krems, J.F., Gehlert, T., 2017. Drivers' gap acceptance in front of approaching bicycles–Effects of bicycle speed and bicycle type. Saf. Sci. 92, 283–289.

Preethi, P., Varghese, A., Ashalatha, R., 2016. Modelling Delay at Signalized Intersections under Heterogeneous Traffic Conditions. Transp. Res. Procedia 17 December 2014 , 529–538. doi:10.1016/j.trpro.2016.11.107

Pu, Z., Li, Z., Wang, Y., Ye, M., Fan, W., 2017. Evaluating the Interference of Bicycle Traffic on Vehicle Operation on Urban Streets with Bike Lanes. J. Adv. Transp. 2017. doi:10.1155/2017/6973089

Schleinitz, K., Petzoldt, T., Franke-Bartholdt, L., Krems, J., Gehlert, T., 2016. The German Naturalistic Cycling Study – Comparing cycling speed of riders of different e-bikes and conventional bicycles. Saf. Sci. doi:http://dx.doi.org/10.1016/j.ssci.2015.07.027

Taylor, D.B., 1993. Analysis of Traffic Signal Clearance Interal Requirements for Bicycle-Automobile Mixed Traffic. Transp. Res. Rec. J. Transp. Res. Board 1405, 13–20.

Twaddle, H., 2017. Development of tactical and operational behaviour models for byclists based on automated video data analysis. Technische Universität München.

Twaddle, H., Busch, F., 2019. Binomial and multinomial regression models for predicting the tactical choices of bicyclists at signalised intersections. Transp. Res. Part F Traffic Psychol. Behav. 60, 47–57. doi:10.1016/j.trf.2018.10.002

Twaddle, H., Grigoropoulos, G., 2016. Modeling the speed, acceleration and deceleration of bicyclists for microscopic traffic simulation. Transp. Res. Rec. (TRR), J. Transp. Res. Board.

Wierbos, M.J., Knoop, V.L., Goñi-Ros, B., Hoogendoorn, S.P., 2020. The Influence of Jam Density and Merging Cyclists on the Queue Discharge Rate. J. Adv. Transp. 2020. doi:10.1155/2020/9272845

Wierbos, M.J., Knoop, V.L., Hänseler, F.S., Hoogendoorn, S.P., 2019. Capacity, Capacity Drop, and Relation of Capacity to the Path Width in Bicycle Traffic. Transp. Res. Rec. 2673 5 , 693–702. doi:10.1177/0361198119840347