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Traffic Simulation Analysis of Bicycle Highways in Urban Areas

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Abstract: The ongoing increase of bicycle traffic in urban areas forces transport authorities to reconsider the space allocation for different transport modes. Transport policies favor the introduction of high-quality bicycle infrastructure along urban corridors to improve the traffic quality and safety for bicyclists but more importantly to increase the attractiveness of bicycling and over vehicular modes. Especially in urban areas with an already established high and steadily increasing share of bicyclists, the introduction of bicycle highways is considered to further alleviate saturated interurban public transport and motor vehicle connections and increase the average traveled distance by non-motorized modes. Due to the expensive implementation costs and the space restrictions in already built-up urban environments, there should be an extensive planning phase for defining the expected changes in traffic efficiency and safety. However, the effects of urban bicycle highways on traffic performance metrics of bicyclists as well as other road users are not thoroughly studied. This paper aims to quantify and assess the potential effects of urban bicycle highway on road users. The study considers a possible inner-city pilot route in the city of Munich, where the present bicycle infrastructure is planned to be upgraded to a bicycle highway. A simulation model is designed using traffic data from field observations and future estimates for the traffic composition. Through microscopic traffic simulation, the potential effects of the introduced infrastructure on road users are determined for different study scenarios. Results show that traffic quality thresholds for bicycle highways, as defined in official guidelines, can only be fulfilled through the implementation of special bicycle traffic control measures such as bicycle coordination or bicycle passage time extension. Finally, unidirectional bicycle highways together with bicycle passage time extension provided the best overall traffic performance for bicycle traffic and motor vehicle traffic.

Keywords: bicycle highways; bicycle traffic; traffic control; traffic efficiency

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1. Introduction

Bicycling as a mode of transport is increasing in popularity across the world and provides a sustainable and low-cost solution to commuting and recreational travel. Mainly in urban areas, bicycles offer multiple advantages as they produce fewer environmental emissions, occupy less space, reduce traffic congestion, and have positive health effects. As authorities realize the potential of bicycling and its potential advantages in improving the quality of life and transport in urban areas, special transport policies are designed and introduced in urban areas around the world in an effort to improve the attractiveness of the bicycle as a transport mode. Such transport policies often rely in the introduction of new forms of bicycle infrastructure to improve traffic safety and traffic quality for bicyclists and allocate more space for bicycle traffic in urban road networks. These may include bicycle paths, bicycle boxes [1], and bicycle highways [2].

According to the working paper of the German Highway Research Institute "Einsatz und Gestaltung von Radschnellverbindungen" (Allocation and Design of Bicycle Highways) [3], bicycle highways, bicycle superhighways, or cycle freeways are connections of the bicycle transport network of a community or a city and its surrounding area that connects important origin and destination points over long distances and enable high speed, safe, and attractive bicycle travel. As a high-quality network and infrastructure element, it serves as the backbone of the bicycle network and makes bicycling more attractive, reduces vehicular traffic, and promotes longer bicycle trips.

Most of the scientific research examines the user experience and evaluates the effects from the introduction of bicycle highways [4–9]. These primarily include effects on bicycle share, demand induction, safety, health benefits, and user satisfaction. Based on this analysis, recommendations are provided for the planning, design, and alignment of bicycle highways. However, with the exception of [10], effects on the traffic performance metrics of bicyclists as well as other road users are not thoroughly studied.

Official guidelines for designing bicycle highways [3,11–16] offer recommendations to the planning and design elements for bicycle highways; however, they provide little to no information on the expected changes on traffic performance through the implementation of such measures. Especially, in the case of bicycle highways in urban environments where intersection points between the bicycle highways and the rest of the road network are found, the quantification of such effects is extremely important for design and planning decisions. Finally, the effect of the heterogeneous composition of bicycle traffic and the influence of the bicyclist behavior reinforced by the different bicycle types such as pedelecs, cargo bikes, and bicycles with trailers together with the influence of traffic control measures along a bicycle highway have not also properly been examined.

In this paper, urban bicycle highways are evaluated, and the influence of design elements and traffic control measures for bicyclists is investigated. The effects on traffic performance indicators from the introduction of a bicycle highway network in an urban area are quantified, and valuable insights from the implementation of urban bicycle highway infrastructure are gained. For this purpose, a simulation network of the investigation area in the city center of Munich, Germany is modeled, and different study scenarios with varying cross-section design, bicycle traffic composition, and traffic signal control operation are investigated. First, a review of published literature is provided (Section 2) followed by the definition of the methodological approach (Section 2) and the simulation study results (Section 3). Finally, the most important scientific findings are summarized and discussed in Section 4.

2. Literature Review

2.1. Bicycle Highways

A bicycle highway is an infrastructural element that provides high-quality connections in the cycle network of a municipality or region that connects important origin and destination points over greater distances [3]. Bicycle highways have been introduced in Tilburg and The Hague in the Netherlands as early as 1980s to relieve congested road networks from vehicular traffic. The Netherlands were the first to develop a bicycle highway concept that should enable commuters within up to 15 km to get to their destination quickly and safely by bicycle. Under the title "Less traffic jams by bicycle", the development of bicycle highways was promoted on a national level. By 2015, there were 27 high-speed bicycle routes in various stages of implementation and planning (a total of 400 km). Complete results on the effect of bicycle highways in the Netherlands on daily mobility are not available. First results for the Leiden–The Hague connection show an increase in bicycle use of 25% (on several urban sub-connections even by 30%) [17].

In Germany, there are several bicycle highway projects in different stages of development. These include but are not limited to the Bicycle Highways Ruhr (RS1) [18], Euregio [19], the bicycle highway Ostwestfalen-Lippe (OWL) [20], the bicycle highway connecting Köln and Frechen [21], and the bicycle highway network of Munich [8].

In contrast to most of the existing bicycle highways, which mostly serve suburban or interurban connections, the London Cycle Superhighway Network [10,22] rebranded by the Transport of London as "Cycleways" [16] serves as an example of a bicycle highway network in a dense urban metropolitan area. The London Cycleway Network consists of 1.5 m wide barrier-free bicycle paths for each direction of travel with blue surfacing that connect the outskirts of London to the London city center [10].

Most of the present scientific research on bicycle highways focuses on the quantification of the expected changes in the mobility behavior and the modal split as a result of the introduction of the bicycle highways and the assessment of the bicycle highways after their construction with respect to modal split and end user perception and acceptance. The introduction of bicycle highway infrastructure may lead to a 0.7% decrease in trips by car and 1.3% increase in bicycle trips according to [23].

Results from a study for bicycle highways in the western suburbs of Copenhagen, Denmark showcase the significant increase in bicycle volumes along the respective routes, which is attributed mostly to bicyclists switching from alternative routes. Trips made by bicycle along the routes that were previously made by another transport mode account for only 4–5%. However, this small increase is attributed to the fact that the bicycle share is already high [9]. Finally, another study quantifies the impacts on mode share for bicycle highways using a discrete choice model for the planned bicycle highway network of the Munich Metropolitan Region. The study predicts only a modest shift in trips to bicycle after the implementation of the bicycle highway, indicating that the introduction of a bicycle highway network alone cannot lead to a major shift in bicycle use [8].

Some scientific studies focus on the case of the London Cycleway Network and assess the effects on modal split, traffic demand, bicycle traffic performance indicators, safety, and user acceptance after the introduction of the bicycle highway network. The evaluation report for the London Cycleway Network routes 3 and 7 indicates that the bicycle count share has increased (83% increase of bicyclist counts along route 3 and 46% increase along route 7) with a 20% increase along route 3 and 32% increase along route 7 being attributed to new bicyclists. An average of 5-min decrease of travel times for bicyclists has been observed for both routes. Additionally, bicyclists perceived the travel times as more reliable. Split Cycle Offset Optimization Technique (SCOOT) has proven important for mitigating the impact of the bicycle highway on general traffic [24]. In [22], the effects of the London Cycleways on the London Cycle Hire Service are studied. The travel speed increased by 13.3%, and travel times were reduced by 11% for bicycle hires.

Another study assesses the causal relationship between the traffic volume increase and collision rates across the London Cycleway Network. Despite the significant increase of bicycle traffic by 19.6% and an increase in absolute numbers of bicyclist collisions, there is no significant difference in bicyclist collision rates between the London Cycleway Network and the studied control segments [6].

Finally, a statistical framework is proposed in [10] for quantifying the expected effects from the introduction of cycle superhighways on traffic volumes and speeds. The results indicate that bicycle highways have the potential to improve traffic flow; however, only marginal improvements in speed are found.

2.2. Design Guidelines for Bicycle Highways

Multiple guidelines and directives published by official authorities across several countries provide an official framework for supporting planning and design decisions for bicycle highways, as well as defining requirements for their implementation [3,11–15]. Recommended design speeds for bicycle highways are set to 30 km/h and 40 km/h outside built-up areas. The average speed limit that considers deceleration, acceleration processes, and waiting times at intersections is set to 20 km/h. The maximum stop frequency is set to 0.4–0.5 stops/km in general or 1 stop/km in urban areas [14] or is substituted with the average travel speed limit of 20 km/h. Maximum waiting times vary among all design standards. CROW suggests a maximum average waiting time of 15 s [14]. The German guidelines define 30 s per kilometer as a maximum waiting time for urban areas [3]. For signalized intersections, the German guidelines suggest less than 25 s of average waiting time with a minimum of 35 s average waiting time. Finally, most of the guidelines define 4.0 m as the minimum recommended width for a bidirectional bicycle path and 2.5–3.0 m for unidirectional bicycle paths. Except for waiting time, the minimum or recommended values proposed by multiple guidelines lie in close value ranges between each other. However, the examined guidelines do not include recommendations for the service of different bicycle types such as cargo bikes or e-bikes. Specific requirements as a result from the higher space demands from the former or higher speeds for the latter are not considered in present guidelines. No recommendations are also made for the advantages and disadvantages of unidirectional and bidirectional cycle paths. Finally, the effects of the introduction of bicycle highways are considered only for deciding the degree of separation from motor vehicles across the bicycle highway segments, which is a function of the speed limit and expected daily vehicular traffic volume. Nevertheless, no assessment is made for the effect of bicycle highways on vehicular traffic quality as the case is at intersections with bicycle lanes or bicycle paths [25,26].

2.3. Bicycle Traffic Control

Alongside infrastructure measures, special traffic control measures, such as bicycle traffic signal coordination and bicycle traffic prioritization, are often proposed and introduced in conjunction with other measures in order to improve bicycle traffic efficiency, safety, and the overall attractiveness of cycling [27–34]. Such traffic control measures for bicycle traffic have the potential to improve the bicycle traffic flow quality at bicycle highways. A detailed description and evaluation of traffic-related measures for bicycle traffic is given in [35]. The specific requirements of bicycle traffic are considered for the design of traffic signal plans in the guidelines for the design of traffic facilities [1,36–38]. These includes traffic measures such as the offset of the green time, the reduction of the cycle time to a maximum value of 90 s, and the design of signal coordination for bicycles.

Various traffic control measures, which consider the requirements of bicycle traffic, have also been deployed in European cities. These measures aim at accelerating bicycle traffic along signalized corridors through the implementation of bicycle-friendly signal coordination measures and the prioritization of bicyclists at intersection approaches. Examples include European cities with high traffic volumes, such as Copenhagen [28], Amsterdam [39], Rotterdam [40], Vienna [29], Bern [27], and Munich [34].

Newly developed innovative traffic control applications either assist the bicyclists along the coordinated route or consider the bicycle traffic state. Such a technique is used in Rotterdam in the Netherlands to support the coordination of bicycles through structural measures. The system named Evergreen consists of light-emitting diode (LED) lights, starting a few hundred meters in front of the considered traffic signal system. The LEDs show green blocks and thus signal cyclists the correct progression speed to allow a stop-free passage [40]. Sitraffic SiBike [41] is a mobile application developed by Siemens that prioritizes bicyclists at signalized intersection while considering the traffic controller state. Results from an evaluation study showed that travel times significantly improved for bicycle traffic, while the change of travel time for motor vehicle traffic was not statistically significant [30].

2.4. Review Summary

The results of the literature review show that most of the present scientific research focuses on the quantification of the expected changes in the mobility behavior and the modal split as a result of the introduction of the bicycle highways. Another share of the present scientific research focuses on the assessment of the bicycle highways after implementation with respect to modal split and end user perception and acceptance, which is usually based on a specific study case of a recently implemented bicycle network. In most cases, results are not easily transferable or generalized for future bicycle highway implementations.

Moreover, there is no significant research on the effects of bicycle highways on relevant traffic performance indicators for bicycle traffic and no evaluation for the special characteristics of bicycle highway infrastructure. Design standards provide threshold values for which the effects on traffic performance indicators of influenced road users is not fully researched. In addition, no suggestions are made on the advantages and disadvantages of different types and bicycle highway infrastructure layouts and dimensions. Finally, despite the abundance of possible traffic signal control strategies proposed for bicycle highways, little research has been performed on the quantification of their effects on bicycle traffic performance, and the traffic efficiency of other road users such as motor vehicles and pedestrians and is lacking. Most scientific research based on case studies of bicycle highways suggests that along the route of the bicycle highway, a significant increase in bicycle traffic volumes is to be expected. A decrease for bicycle travel times is also expected. In the urban context, road users constantly compete for more road space. Practitioners planning, designing, and dimensioning bicycle highways need to be provided with appropriate tools for assessing different design alternatives and perform informed decision making using quantifiable traffic performance indicators, which will ultimately lead to more efficient design balancing the requirements of all road users.

3. Methodology

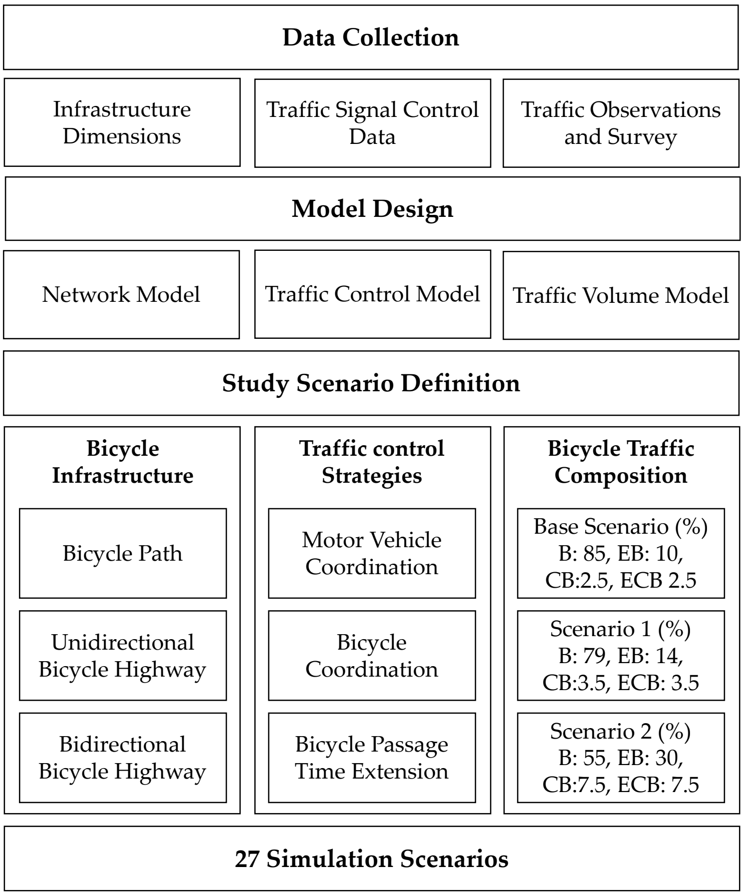
Microscopic traffic modeling is used for the study and quantification of the effects of bicycle highways on traffic performance. Microscopic traffic modeling offers researchers the possibility to model complex dynamic traffic systems, reproduce road user behavior accurately, and simulate realistic traffic conditions. In this context, microscopic modeling is the most suitable tool to assess the effects of bicycle highway infrastructure on traffic performance in different study scenarios with varying transport infrastructure properties, traffic composition, and traffic signal control strategies. In a first step, the study area of the bicycle highway is defined. The study area definition is based on the case study of a planned section of the bicycle highway network in the city of Munich, Germany. Then, empirical studies are carried out in the study area to gather traffic data for the calibration and validation of traffic simulation models. Through the definition of the research gaps in the literature review section, specific study scenarios are defined. The assessment of the traffic performance effects is based on the quantification and evaluation of relevant traffic performance parameters. General recommendations for the design of bicycle highway infrastructure in urban areas are derived. Figure 1 presents an overview of the defined methodology. Details on the individual steps in the methodological approach are provided in the subsequent sections.

3.1. Study Area

The bicycle highway study area is aligned across an important corridor of the Munich city center: starting from the Munich city center, the Ludwigstraße that after the Siegestor monument and to the north becomes Leopoldstraße. These streets connect the city center of Munich to the northern suburbs. This corridor is part of the urban section of the planned bicycle highway that will connect Munich with Garching and Unterschleißheim, two towns north of the City of Munich [42]. Figure 2 presents the study area and Figure 3 presents the typical cross-section of the existing road infrastructure. Each direction of travel typically is served with three traffic lanes per direction of travel with some sections reduced locally to two lanes per direction of travel with or without dedicated turning lanes. A unidirectional bicycle path serves the bicycle traffic in the respective travel directions. The dimensions of the road infrastructure elements vary locally across the entire network. The length of the entire study network is 2.2 km and includes 8 signalized intersections (≈3.64 traffic signals/km).

3.2. Data Collection

Traffic data are collected at several locations across the network in order to design an accurate microscopic traffic model. The aim of the study is to assess the effects of bicycle highways on the traffic performance, provide insights for designing and dimensioning bicycle highways in urban areas, and define the limitations between different alternative solutions. As the design and dimensioning of transport infrastructure and traffic signal control takes place for the prevailing traffic conditions and the highest traffic demand, it is important to collect traffic data during the peak traffic periods [26,43]. Germany has the highest average bicycle traffic volumes between May and September when the weather conditions are considered adequate and attractive for bicyclists [44]. Therefore, the traffic volume for the investigation area is collected in July in order to consider the highest possible bicycle demand. Traffic data are collected by installing cameras at key intersections. Video cameras are mounted on top of buildings with clear and unobstructed view to the respective intersection approaches. The turning ratios and traffic flow are extracted from video data, and the origin–destination matrices are created for different road users as a model for route selection at the intersection level. Video data were collected for the time period 8:00 a.m. to 7:00 p.m. at all intersections.



Conventional Bicycle (B), Electric Bicycle (EB), Cargo Bicycle (CB), Electric-Cargo Bicycle (ECB)

Figure 1. Methodology overview.

After initial video data observations, the video recordings covering the peak traffic hours in the evening (5:00 to 6:00 p.m.) are selected for further analysis as they demonstrate the highest bicycle traffic volumes. The number of bicycles, cars, and trucks are also derived through manual observation of the video data by three human observers. Videos were reproduced at normal speed, and traffic at each intersection approach was counted independently to avoid errors. Since cargo bicycles can also be identified in the video data, the number of cargo bicycles was separated from other bicycles. However, the number of other types of bicycles such as electric bicycles was determined from other sources because of the difficulties in recognizing the electric bicycles and their differentiation from other types.

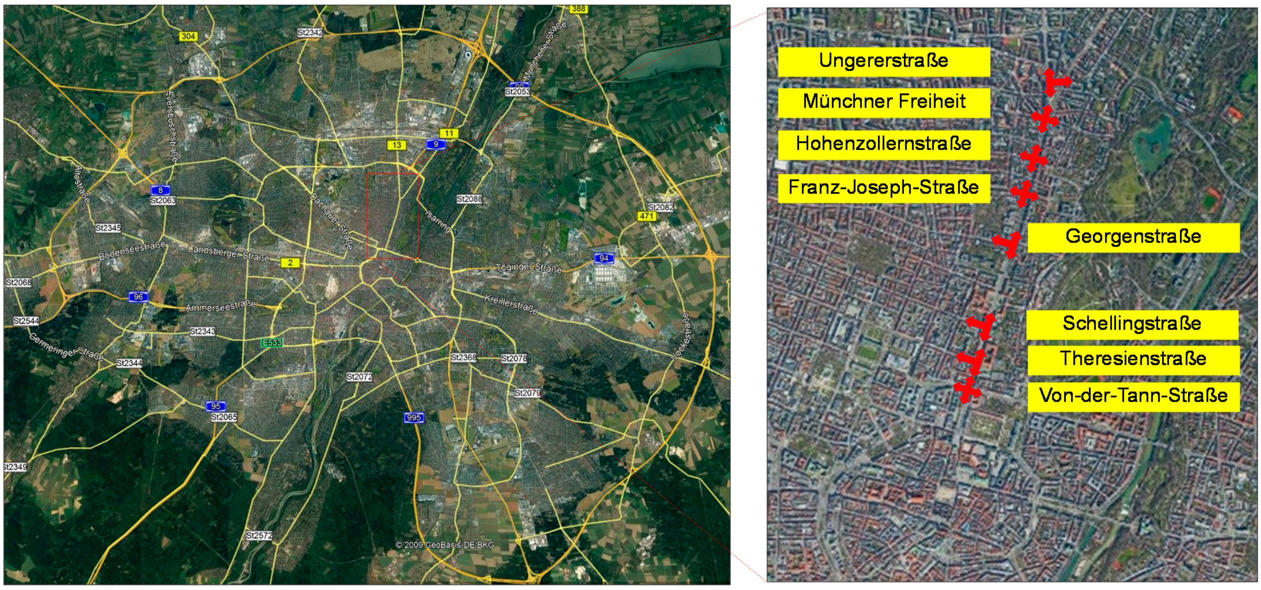


Figure 2. Map of the study area.

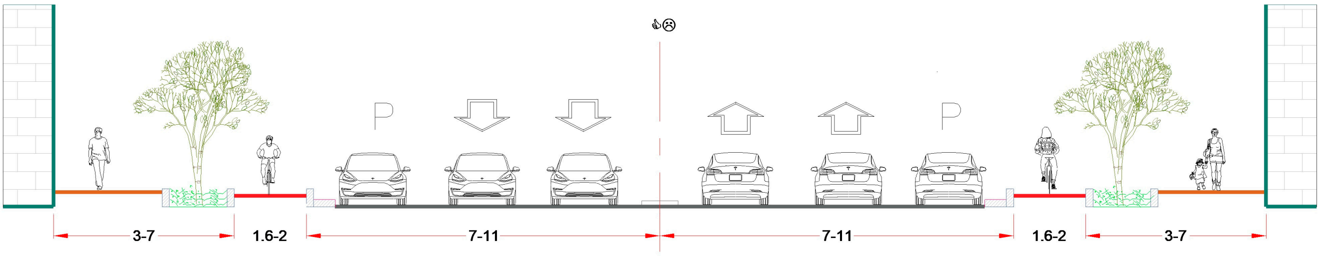


Figure 3. Typical cross-section dimensions (m) of the investigation area.

The traffic signal control plans are also provided by the City of Munich together with the signal controller data for all intersections for the days where the video data collection took place. The traffic signal control is actuated, and public transport is prioritized across the network.

3.3. Scenario Definition

The scenario definition is built on the results from the literature review. Official guidelines for the design of bicycle highways already provide information for the dimensioning of the bicycle infrastructure and define minimum or recommended values for respective traffic performance parameters. Therefore, the study scenario definition will focus on providing pairwise comparisons of relevant design elements of bicycle highways and their corresponding effect on traffic performance indicators that are used by the guidelines for ensuring the infrastructure design quality. The present state of the bicycle network in the study area will serve the base scenario for the respective comparisons. These include the comparison between unidirectional and bidirectional bicycle highway networks and the dimensions of the bicycle infrastructure.

Furthermore, the influence of the heterogeneous composition of bicycle traffic flow along the bicycle highway is evaluated. Compared to motorized private transport, there is a much wider diversification regarding the driving behavior of different user groups, which is reinforced by the different bicycle types such as pedelecs, cargo bikes, and bicycles with trailers. Especially, the bicycle traffic composition is of key importance for the effect of bicycle highway on traffic performance. Reasons for this are the different dimensions of bicycle length and width, which fundamentally influences the traffic flow, overtaking maneuvers, estimated speeds, or acceleration and deceleration profiles. Cargo bikes generally occupy a larger area of space, which strongly influences the interaction with other cyclists. At the same time, in the case of a bicycle with a trailer for child transport, due to the increased responsibility for safety, lower speeds are also expected.

Finally, traffic signal control measures can have a significant influence on traffic performance indicators for various road user groups. Although official guidelines recommend specific minimum values such as average number of stops per km or average waiting times, it is not specified which traffic control measures are appropriate and what the expected effect will be for the traffic performance of the vehicular flow.

In total, 27 different scenarios are defined in this study, which differ in traffic control strategies, infrastructures, and time horizon. In addition to the current state, the network is modeled with two traffic control strategies for bicyclists, namely coordination and prioritization, and in two bicycle traffic infrastructures, namely one-way and two-way bicycle tracks. The infrastructures and traffic control strategies are described below in detail.

3.4. Model Design

3.4.1. Simulation Model

The open source microscopic traffic simulation software SUMO (Simulation of Urban MObility) [45] is used in this study to create a microscopic simulation model. Since 2001, the software has been gradually updated, and various application programming interfaces (APIs) have been added to make it easier to define and implement simulation scenarios. In the simulation model, the individual characteristics of the road users, interaction between them, as well as predefined behavior models such as the car following model, lane change model, and route selection model should be defined.

The network is extracted from OpenstreetMap [46] and imported into SUMO using the NETCONVERT module. The imported version suffers from several conversion issues and inaccuracies. These include errors in network alignment, number and type of lanes, wrong infrastructure dimensions, missing traffic signal control, missing or inaccurate connections inside junctions, and increasing junction complexity, where a single junction reality is modeled with multiple smaller junction elements through the conversion process. Therefore, extensive corrections and checks are made using data provided by the City of Munich as well as data collected on site. Finally, the traffic signal data provided by the city Munich is used to model the traffic signal control across the network.

3.4.2. Traffic Composition

Four different types of bicycles are defined in the study: normal bicycle, electric bicycle, cargo bicycle, and electric cargo bicycle. Then, the share of bicycles and their future prediction is defined by combining results from the empirical data collection and the existing literature. In 2008, the share of electric bicycles corresponded to 8% of the total bicycles sold in Germany [47]. In a study on electric bicycles, a share of 10% is assumed for Germany in 2015 [48]. A study showed that by 2015, the share of electric bicycles of in the total number of bicycles sold in Germany was 11% [49]. Another forecast estimates a long-term growth of up to 40% for the share of electric bicycles in Germany [50]. Considering the growth rate of sales of electric bicycles in Germany between 2013 and 2018, it is estimated that the share of electric bicycles for the years in 2025 can be increased to around 18%.

Concerning the share of cargo bicycles, the ownership of cargo bicycles in Germany was estimated at 8% [51]. However, by observing the recorded videos in the study area, the share of cargo bicycles (including electric cargo bicycles and non-electric cargo bicycles) was determined to be 5%. No data were found on the growth of cargo bicycles in Germany.

Therefore, the same growth rate is assumed for cargo bicycles as for electric bicycles. Respectively, no data were found for the share of cargo bikes that are equipped with electric motors. Thus, we assume that 50% of the cargo bicycles are equipped with electric motors. Table 1 shows the share of each type of bicycle by time horizon.

Table 1. Introduction of various types of bicycle and their proportions in time horizon from the base scenario to 2030.

Type of Bicycle	**Year**		
	Base Scenario	**2025**	**2030**
Conventional Bicycle (B)	85	79	55
Electric Bicycle (EB)	10 [1]	14 [2]	30 [3]
Cargo Bicycle (CB)	2.5	3.5	7.5
Electric Cargo Bicycle (ECB)	2.5	3.5	7.5

[1] [49], [2] [48,50,52], [3] [50].

The speed distribution for the different bicycle types are taken from different sources. The maximum acceleration and deceleration of bicycles result from a study in Germany with two types of cargo bike as well as the project. The physical and dynamic properties of various bicycles are shown in Table 2.

Table 2. Physical and dynamic specifications of bicycles as SUMO simulation input with information [1] [45], [2] [49], [3,4] [53–55].

Specifications	**Conventional Bicycle**	**Electric Bicycle**	**Cargo Bicycle**	**Electric Cargo Bicycle**
Length (m)	1.6	1.9	2.4	2.4
Width (m)	0.7	0.7	0.85	0.85
Average speed (km/h) [1]	15.3	17.4	13.6	18.97
Max speed (km/h) [1]	22	31	20.7	25.7
Min speed (km/h) [1]	10.1	12.2	10.7	11
Standard deviation [1]	2.3	4.4	2.2	3.1
Max acceleration (m/s^2) [2]	1.8	1.8	1.8	1.94
Max deceleration (m/s^2) [2]	4.0	4.0	4.0	4.25
Lateral alignment [3]	Compact	Compact	Compact	Compact
Minimum gap [m] [4]	0.5	0.5	0.5	0.5
Minimum lateral gap [m] [3]	0.5	0.5	0.5	0.5

3.5. Traffic Control Strategies

3.5.1. Bicycle Traffic Signal Coordination

The coordination of neighboring intersections ensures smooth traffic movement. Due to large differences in bicyclists speed (between 10 and 25 km/h), it is not possible that all bicyclists benefit from a common coordination. In fact, bicycle coordination is most effective if the distance between the intersections is less than 200 m. In this situation, a common coordination for bicyclists and motor vehicles is possible if the green time is long enough for both groups. By increasing the distance between the intersections to 400–750 m, the group of bicyclists will be more dispersed. In this case, great efforts should be made to match the travel speed and offset time. However, if the intersections are not oversaturated by motor vehicles, an independent green wave for bicyclists is feasible. As presented in Figure 4 the distance between intersections is 170–380 m, which offers suitable application for bicycle traffic coordination.

The analysis of the collected video data suggests that the main direction of the bicycle traffic flow in the peak hour is the north–south direction. Since the distances between the intersections are different, and therefore, a coordination can only be generated effectively in one direction, the coordination is implemented for this direction of travel. However, since the green phase of the bicyclists starts together in both directions, the bicyclists in the opposing direction also benefit.

First, the average speed of bicyclists between the intersections is calculated (queue zones are excluded) based on infrastructural type and time horizon. Then, the offsets of traffic signal controllers are calculated and assigned to the network. The cycle time, signal groups, and signal program of the controllers are kept same to the current situation to ensure a comparable state. For implementation of coordination, the green time of the intersections starts 5 s sooner to ensure that the possible queue of bicyclists from the previous cycle time has already dissolved. This strategy is implemented across all simulation scenarios.

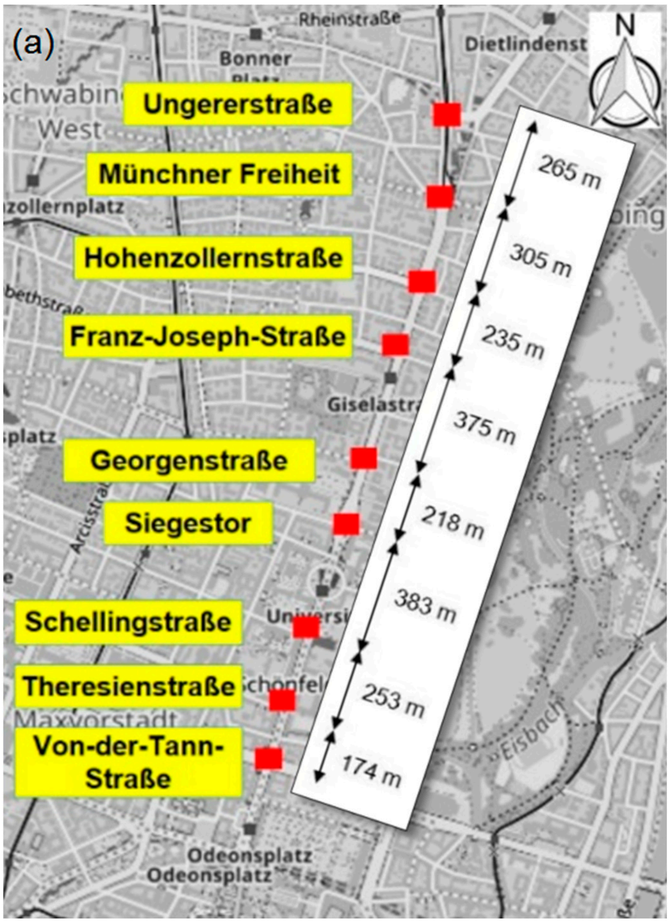


Figure 4. The study area in Munich, Germany, with distances between intersections.

3.5.2. Bicycle Prioritization through Passage Time Extension

In traffic signal prioritization, traffic controllers may assign additional green time to bicyclists, which may result in fewer stops, less delay, and lower travel time of bicyclists. The prioritization direction is optimized for the north–south travel direction. Here, the prioritization strategy is based on the extension of the green time for bicyclists by applying the concept of passage time extension. In this strategy, although some features of controllers such as signal groups and signal programs are kept similar to the current state, the cycle time may change based on the present bicycle traffic demand.

In order to extend the green time efficiently and prevent bicyclists from stopping and considering the average observed bicycle travel speeds, the position of the detectors is set to 20 m from the stop line. Since the average speed of bicyclists is around 15 km/h, the riding time from the detection line to the stop line is calculated to be around 5 s. Moreover, to avoid extreme cycle times, the maximum green time extension is set to 20 s (a maximum cycle time of 110 s). If a bicycle is recognized at any point between the detection line and the stop line and at the same time, the remained green time is not enough to allow the bicycle to pass the stop line, then the current green phase will be extended by 5 s so that the bicyclist can still cross the junction. As mentioned before, this process can be repeated to a maximum of four times per cycle.

It is important to mention that in the current state, the green time of the bicyclists ends at the same time as the green time of the motor vehicles (north–south direction). Therefore, the motor vehicles benefit from the extended green times. However, due to different phases at the Von-der-Tann-Straße intersection, bicycle green extension cannot affect the green time of motor vehicles. Since this intersection has separated phases for bicyclists and motor vehicles (the first phase for motor vehicles and the second one for bicyclists) and the prioritization takes place only in the last phase, the delay of motor vehicles could be increased due to more cycle times. Therefore, this intersection is excluded from the results of prioritization implementation.

3.5.3. Bicycle Highway Design

In addition to the bicycle infrastructure in the current state, two further variants are defined, namely two-sided one-way bicycle path (variant A) and one-sided two-way bicycle path (variant B). These variants are chosen as they are the two most common variants found in the official guidelines for bicycle highway infrastructure. However, no information is provided for the potential advantages and disadvantages of both variants [3,11–15]. As it is shown in Figures 5 and 6, the width of the bicycle path in both variations is increased by 3.0 m, which is the minimum width for a bicycle path that is part of a bicycle highway infrastructure according to [3] compared to the current state, which is between 1.6 and 2.0 m. The bidirectional bicycle highway is designed by shifting the two bicycle paths to the north–south travel direction. As the west side of the study area has two more intersections than the east side and the bicycles volume in the west side outweighs the east side, it was decided to design the bidirectional bicycle highway at the east side of Leopoldstraße and Ludwigstraße.

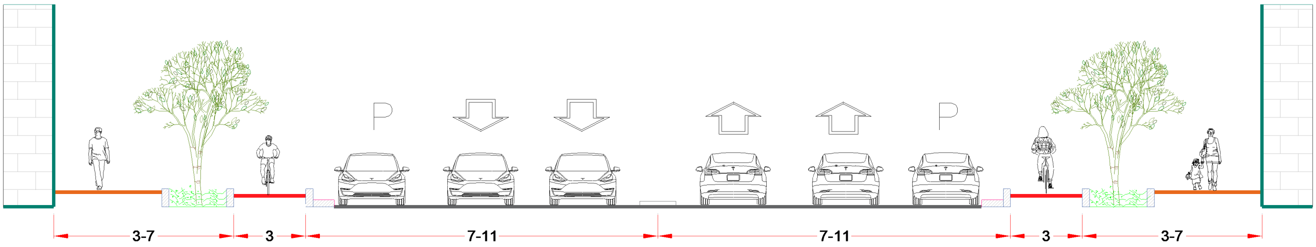


Figure 5. Typical cross-section and dimensioning (m) of one-way bike path (variant A) in the study area.

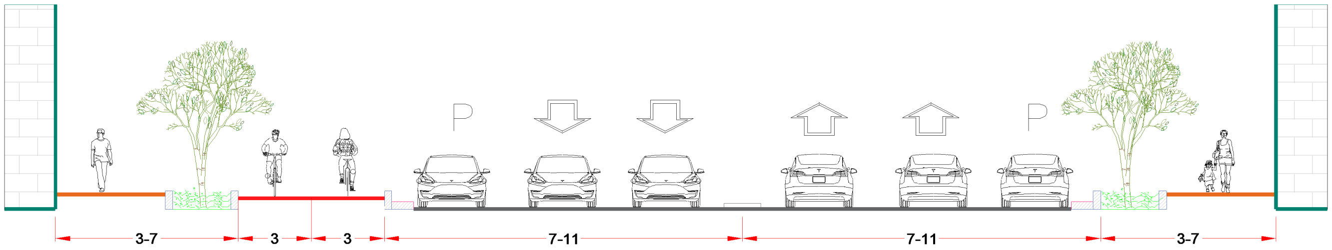


Figure 6. Typical cross-section and dimensioning (m) of two-way bike path (variant B) in the study area.

Regarding the quality requirements for the forms of bicycle highway infrastructure, the width of the bicycle lanes for unidirectional and bidirectional bicycle highways should be at least 3 m, respectively, plus the safety dividing strips next to the on-street parking.

3.5.4. Calibration and Validation

The settings for the simulation scenarios are summarized in Table 3. Regarding the Student's t distribution with a 95% confidence interval and 90% as the desired confidence interval (maximum deviation from averages from real data is 10%), 15 simulation runs are the required number of simulation runs.

Traffic volume and travel time for bicyclists and motor vehicles are defined as parameters for calibration and validation. The traffic volume is determined from the video data collected at the intersections. The travel time is derived from a field study with a conventional bicycle and a passenger car. The calibration is carried out during an evening off-peak hour (between 3:00 and 4:00 p.m.), and the parameters are calibrated in the simulation model. The simulation results for the selected parameters were evaluated with the root mean square error (RMSE). A good calibration provides a set of parameters that minimizes the root mean square deviation (RMSE). Then, the validation of the network is assessed with a different dataset for the evening peak hours (between 5:00 and 6:00 p.m.). It is crucial that the parameter settings of the simulation model are not changed during validation. The simulation results showed that there are less than 10% deviations between reality and model (RMSE < 10%), which is within the limits proposed in the German guidelines [56].

Table 3. Evaluation settings and simulation horizon.

Parameters	Values
Simulation period	90 min
Simulation resolution	0.5 s
Warm-up time	30 min
Evaluation horizon	60 min

4. Results

When designing a bicycle highway, it is important to determine the quality requirements beforehand. According to German guidelines, the most important factor for assessing the design quality of bicycle highway infrastructure is the bicyclist delay per kilometer. The average delay per kilometer is defined in as a quantity that should not exceed 30 s/km in urban areas [3].

In addition, other measures of traffic efficiency are also considered, which are important for the evaluation and design as well as to compare current state with new scenarios. Travel time is a general parameter for evaluating the bicycle highway in which an increase in attractiveness of bicycle highway can be demonstrated here by a reduction of at least 10% in travel time. The average number of stops, waiting time, and average travel speed are also introduced for the evaluation and for comparing the study scenarios.

This section presents the analysis of the traffic flow simulation studies. Results are presented for both the bicycle and vehicular traffic. The confidence intervals for the average values of the different indicators define the size of the standard deviation for the respective set of values. Based on the analysis of the simulation results, insights for the implementation and design of bicycle highways are derived.

4.1. Bicycle Traffic Performance

4.1.1. Bicycle Traffic Flow

Figure 7 presents the average bicycle traffic density as a function of the average bicycle travel speed across the network, the traffic signal control measures, and the bicycle infrastructure for each of the bicycle compositions in the future time horizons. The average travel speed is calculated across the entire travel time duration and thus accounts also for delays across the entire network ($\approx$3.64 traffic signals/km). Results showcase that the average travel speed for bicyclists is linearly decreasing with increasing bicycle traffic density. Three clusters are identified as a function of the combined implementation of bicycle traffic signal control measures and the introduction of bicycle highway infrastructure. Overall, in the base scenario, the average bicycle travel speed ranges between 10 and 11 km/h. Thus, the increased width of the bicycle path from 1.6–2.0 to 3 m increases the capacity for the bicycle traffic, as there is more space available for lane changing and overtaking. In the case of the implementation of bicycle highway infrastructure, the average travel speed ranges between 11 and 12 km/h. The combined implementation of bicycle highway infrastructure with bicycle traffic control measures further increases the average travel speed range to 12–13.8 km/h.

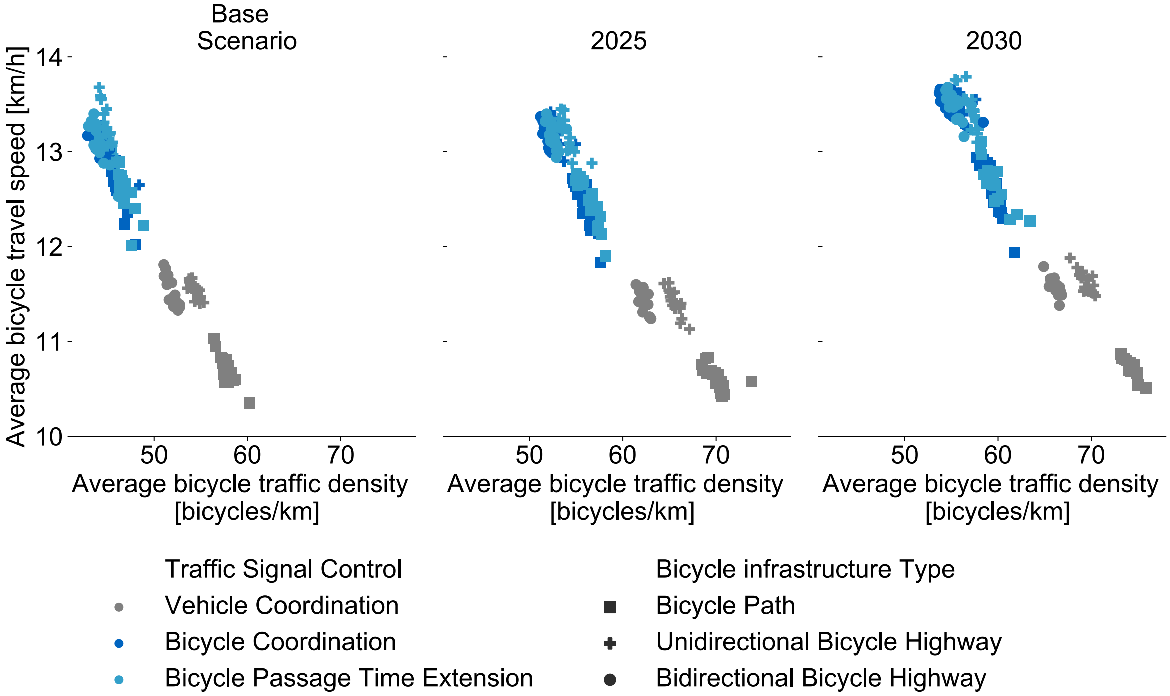


Figure 7. Average bicycle traffic density as a function of the average bicycle travel speed across the network, the traffic signal control measures, and the bicycle infrastructure for each of the bicycle compositions in the future time horizons.

Figure 8 presents the average bicycle traffic volume as a function of the average bicycle travel speed across the network, the traffic signal control measures, and the bicycle infrastructure for each of the bicycle compositions in the future time horizons. Results suggest that despite the increase in bicycle traffic volume, the average travel speed for bicyclists is not significantly affected for future time horizons. This is partially explained from the increasing share of electric bicycles in the future bicycle traffic composition. In addition, results indicate that the bicycle traffic flow operates in free flow conditions in all future time horizons and that the capacity of the infrastructure is not reached. Therefore, the signal traffic control at the intersection approaches remains the bottleneck for the bicycle traffic efficiency.

4.1.2. Delay

A change from the current bicycle infrastructure to the unidirectional bicycle highway or the bidirectional bicycle highway has a significant impact on bicycle traffic performance. The reason is the increased width of the bicycle path cross-section from 1.6–2.0 to 3 m, which increases the capacity for the bicycle traffic. At the same time, there is more space for lane changing and overtaking. As shown in Figure 9, the average delay for both variants of bicycle highway infrastructure, compared to the current state, has decreased the average delay for bicycles by almost 7% (T-value = 9.29; *p*-value = 0). Both variants, the unidirectional and bidirectional bicycle highway alignments, exhibit almost the same average delay.

The effects of the introduction of new infrastructure variants and of the new traffic control strategies on the average delay are also presented in Figure 9. Results suggest that the change of the traffic signal control strategy from the vehicle coordination to the bicycle coordination has the greatest effect on the reduction of the delay experienced by bicyclists. The coordination and the bicycle passage time extension strategies have reduced the average delay by almost 54% (T-value = 70; *p*-value = 0). In addition, the bicycle coordination slightly outperforms the bicycle passage time extension strategy in most cases.

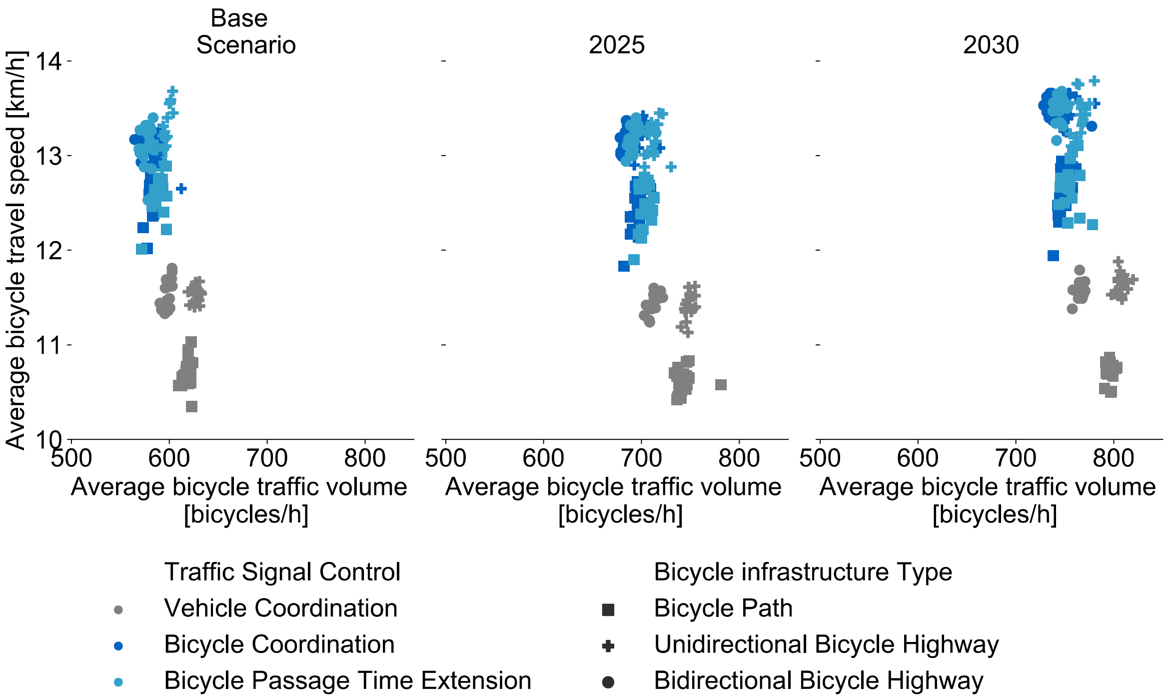


Figure 8. Average bicycle traffic volume as a function of the average bicycle travel speed across the network, the traffic signal control measures, and the bicycle infrastructure for each of the bicycle compositions in the future time horizons.

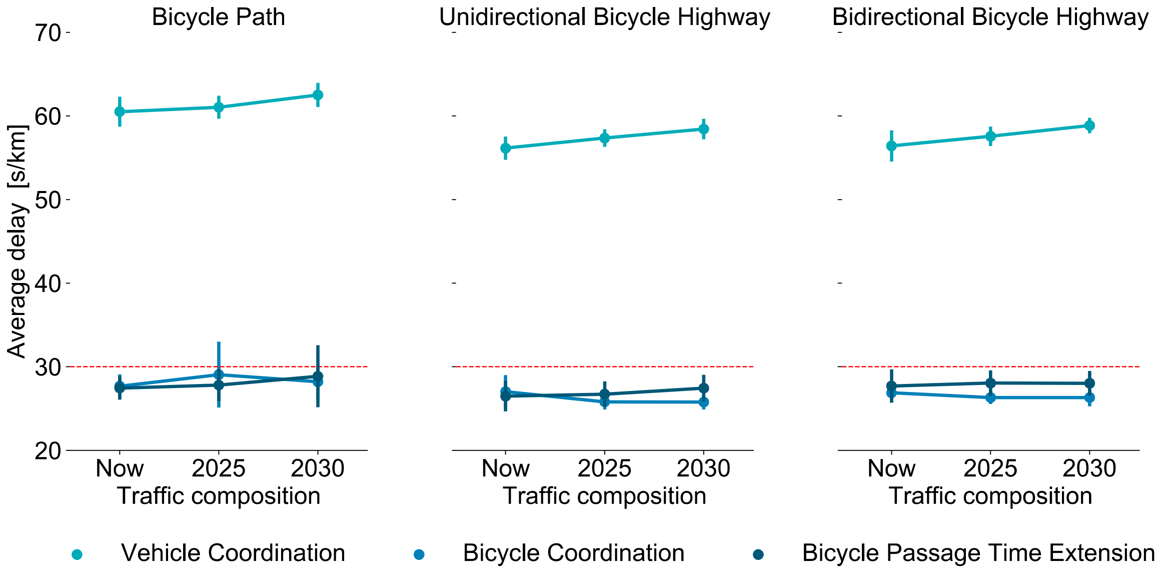


Figure 9. Average delay for bicyclists as a function of bicycle infrastructure type, traffic signal control strategy, and bicycle traffic composition. The error bars define the standard deviation.

According to the German guidelines for the design of bicycle highways [3], a threshold value of 30 s/km is defined as the maximum average delay for bicycle highway in the inner city, which is shown in Figure 9 by a dashed red line for comparison. Thus, the quality of service criterion for the delay threshold is only fulfilled through the introduction of special traffic signal control measures for bicycle traffic. Therefore, the upgrade of the existing bicycle infrastructure to a bicycle highway should be accompanied with special signal control measures for bicycle traffic. Finally, it is also important to mention that through the introduction of bicycle infrastructure, the standard deviation of the bicyclist delay is also reduced when compared to the present infrastructure. As a result, bicyclists experience more reliable travel times, as expected delays will not vary greatly among bicyclist trips. These results are consistent with the evaluation results for the bicycle superhighways in London [24].

4.1.3. Waiting Time

Waiting time is defined as the time in which the bicyclists have a speed of less than 0.2 m/s. The results of the mean waiting time per intersection are shown in Figure 10. All scenarios meet the Level of Service B (waiting time $\leq$ 25 s); however, only scenarios equipped with the coordination or passage time extension can meet the Level of Service A (waiting time $\leq$ 15 s) as defined in the German Highway Capacity Manual (HBS) [26]. For signalized intersections, the German guidelines for bicycle highways suggest less than 25 s of average waiting time with a minimum of 35 s average waiting time in urban areas [3]. Thus, for the German guidelines, this threshold can be serviced in all scenarios without the requirement of special traffic signal control measures for bicyclists. However, this is not the case for the Dutch guidelines, which require an average waiting time of 15 s for urban areas. In that case, special traffic signal control measures are required for all scenarios examined.

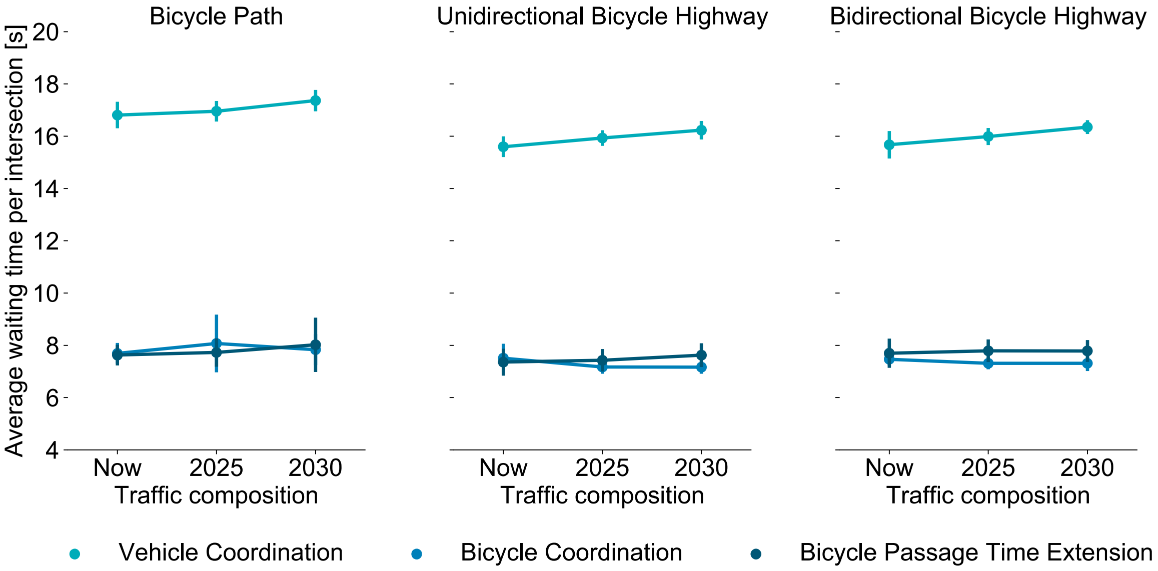


Figure 10. Average waiting time for bicyclists as a function of bicycle infrastructure type, traffic signal control strategy, and bicycle traffic composition. The error bars define the standard deviation.

4.1.4. Number of Stops

The influence of infrastructural types on the average number of stops per hour is shown in Figure 11. For the base scenario, the average number of stops for the current infrastructure is 2.33 stops/km, which is slightly reduced to 2.2 stops/km (−5%) and 2.1 stops/km (−11%) for the unidirectional and bidirectional bicycle highway, respectively (t-Value = 10 and 11; p-value = 0). However, the bicycle coordination and prioritization strategies drastically reduce the average number of stops further by almost 53% and 52% (T-value = 69 and 29; p-value = 0), respectively. Similar trends could also be seen for years 2025 and 2030. Overall, without the introduction of special bicycle traffic control measures, the average number of stops increases slightly for the different bicycle traffic composition scenarios. Coordination and passage time extension reduce the number of stops at the intersections by coordinating the bicyclists into groups and extending the green time. Since the distances between the intersections are short enough to prevent the group of bicyclists from breaking up, the more bicyclists that pass the intersections in a group formation, the lower the average number of stops that could be achieved. Bicycle coordination slightly outperforms the passage time extension strategy by the year 2030. The Dutch guidelines for bicycle highways suggest an average of 1 stop/km for urban areas [14]. This threshold is only reached in the case of a unidirectional bicycle highway with bicycle signal coordination and for the bicycle traffic composition in 2030, where a great share of e-bikes is expected. It is important to note here that all other scenarios with special traffic signal control measures are slightly over this threshold. Thus, in order to reach the traffic quality threshold for the average number of stops per kilometer, further allocation of green time for bicycle traffic is required. Despite the fact that the percentage reduction in the average number of stops through the introduction of special traffic signal control measures is equivalent to the percentage reduction of the waiting time and average delay, where the respective guideline thresholds were met with ease, this does not appear to be the case for this traffic quality measure for bicycle highway design.

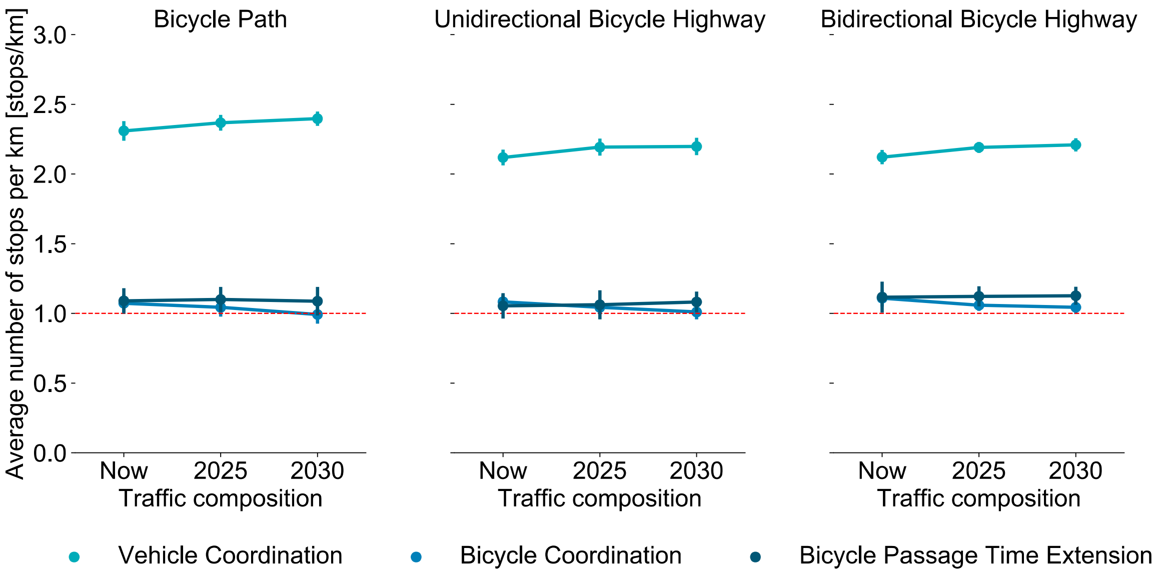


Figure 11. Average number of stops for bicyclists as a function of bicycle infrastructure type, traffic signal control strategy, and bicycle traffic composition. The error bars define the standard deviation.

4.1.5. Travel Time

Regarding the results for the base scenario, by implementing the coordination for bicyclists (Figure 12), the travel time is reduced by an average of 13%, 16.9%, and 17.4% (T-value = 29, 48, and 50; *p*-value = 0) for the current infrastructure, the unidirectional bicycle highway, and the bidirectional bicycle highway, respectively. Similarly, the passage time extension strategy improves the average travel time by 13%, 17.3%, and 16.9% (T-value = 30, 39, and 41; *p*-value = 0) for the current infrastructure, the unidirectional bicycle highway, and the bidirectional bicycle highway respectively. However, the further reduction of the average travel time is not only attributed to the introduction of better bicycle infrastructure or only to the special traffic signal control strategies but also to expected increase of the share of e-bikes in the future bicycle traffic composition scenarios for the years 2025 and 2030.

Figure 13 demonstrates that the average travel time per kilometer is a linearly increasing function of the average bicycle traffic density per kilometer experienced. Additionally, different clusters are formed in relation to specific types of bicycle infrastructure and traffic signal control measures. We observe that the combination of bicycle highway infrastructure and traffic signal control greatly reduce the travel time. With increased bicycle traffic in the studied future time horizons, the average traffic density increases; however, no increase is observed for the average travel time in all scenarios with bicycle highway infrastructure and special bicycle traffic control measures.

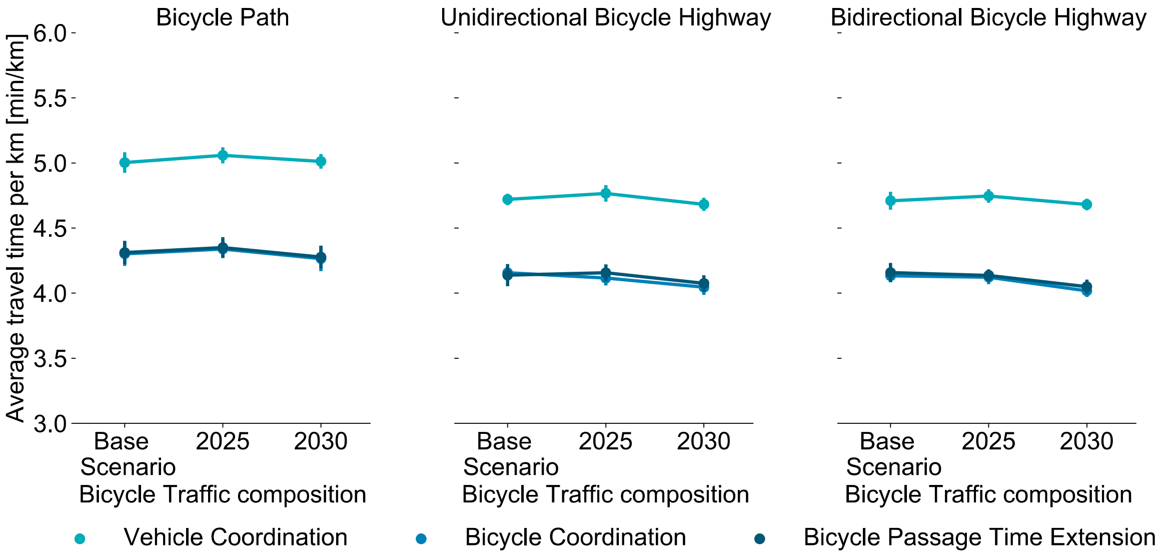


Figure 12. Average travel time for bicyclists as a function of bicycle infrastructure type, traffic signal control strategy, and bicycle traffic composition. The error bars define the standard deviation of the observation sample.

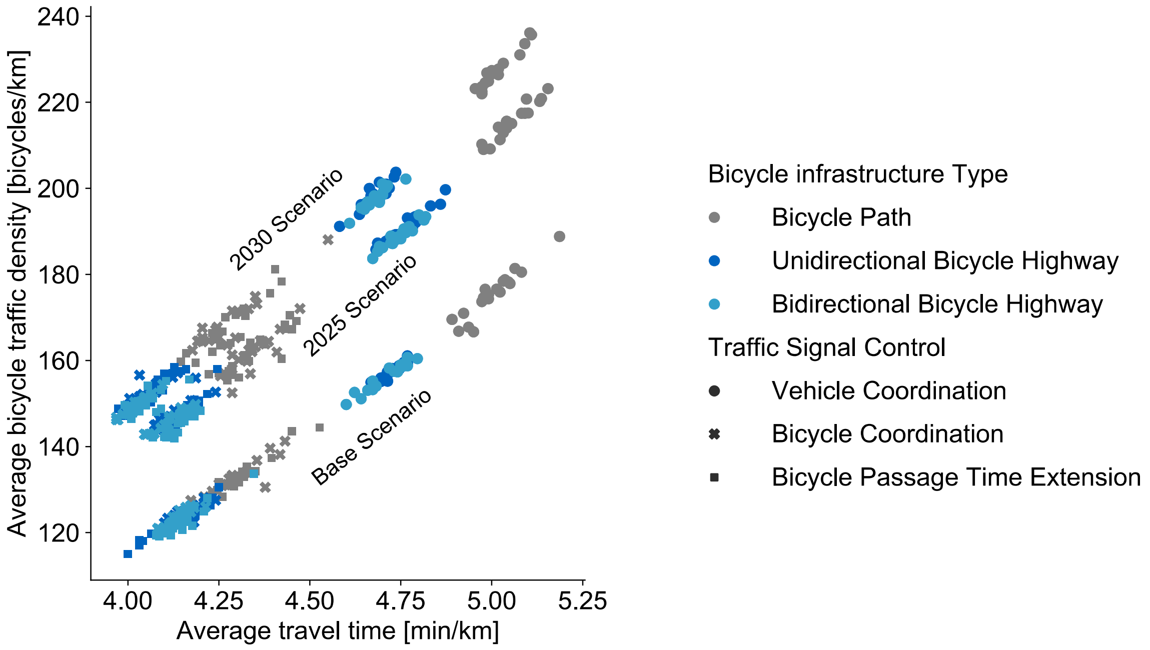


Figure 13. Average travel time for bicyclists as a function of the average bicycle traffic density, bicycle infrastructure type, traffic signal control strategy, and bicycle traffic composition.

4.2. Motor Vehicles Traffic Performance

So far, the results for different combinations of various types of bicycle highway infrastructure, traffic signal control measures, and bicycle traffic compositions for future time horizons have been presented. As motor vehicles are a crucial road user category in urban areas and have been also included in the simulation model, it is also important to consider them in the analysis and quantify and assess the effects from the introduction of the bicycle highway in the urban setting.

Figures 14 and 15 present the effect on travel time of motor vehicles in both travel directions as a function of the bicycle infrastructure, the traffic signal control strategy, and the bicycle traffic composition in future time horizons. The results are aggregated in minutes of travel time per kilometer. Figures 16 and 17 show the changes on the average number of stops of motor vehicles per kilometer in the directions from north to south and south to north, respectively, when the new infrastructures and control strategies are implemented for bicycle traffic.

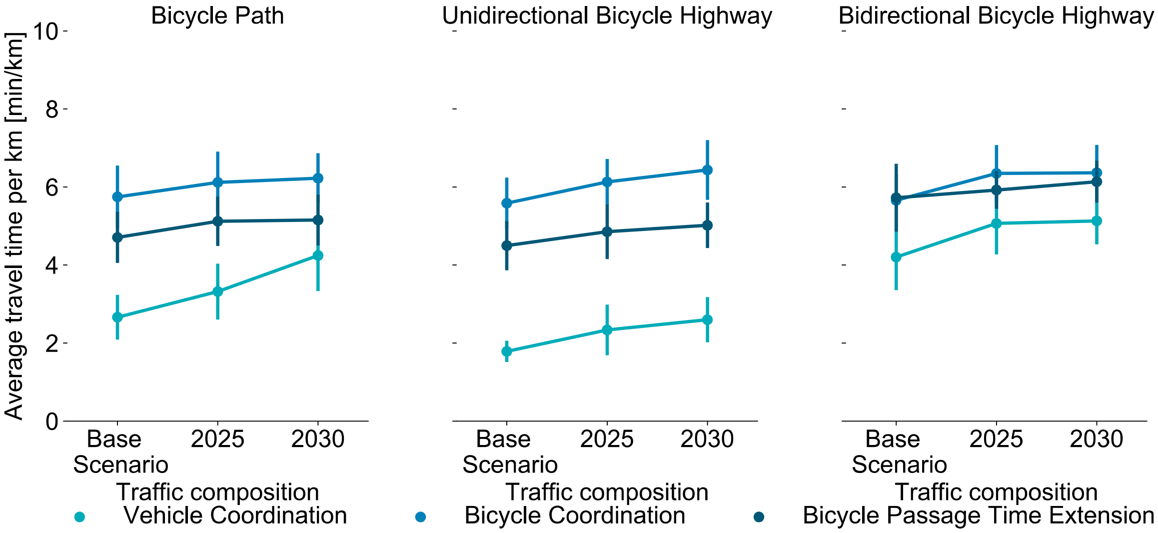


Figure 14. Average travel time of motor vehicles in the north–south direction as a function of bicycle infrastructure type, traffic signal control strategy, and bicycle traffic composition in future time horizons. The error bars define the standard deviation of the observation sample.

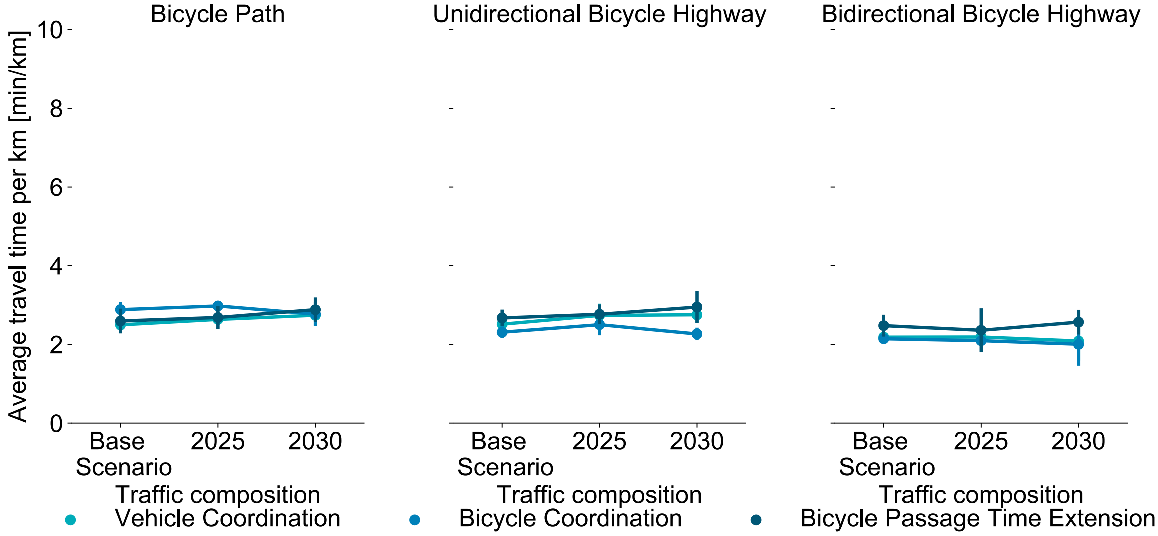


Figure 15. Average travel time of motor vehicles in the south–north direction as a function of bicycle infrastructure type, traffic signal control strategy, and bicycle traffic composition in future time horizons. The error bars define the standard deviation of the observation sample.

The lowest travel time for motor vehicles in the north–south travel direction (Figure 14) is achieved for the vehicle traffic signal coordination and the unidirectional bicycle highway for each respective future time horizon. The travel time is reduced by 21% (T-value = 7; *p*-value = 0). The reason would be the widened cross-section from 1.6–2 m in the base scenario to 3 m, which leads to an increased capacity of bicycle traffic. This is also supported from the results of the average number of stops per kilometer for motor vehicle traffic in Figure 16. The results for the average number of stops per kilometer for motor vehicle traffic appear to follow a similar pattern to the travel time of motorized vehicles. Therefore, at the start of the green time, the bicycle queue dissipation time is reduced as a result of the wider bicycle lane, which in turn enables the right-turning vehicles to turn off at the intersection with reduced delay. It is also important to mention that in almost all cross-sections in the north–south direction, there is no dedicated right-turn lane for motor vehicles. Therefore, the crossing vehicles are also affected by the right-turning vehicles waiting for crossing bicyclists, which results in the increase of the average travel time. This fact also explains the worse results for the average vehicular travel times in the bidirectional bicycle highway. As in this case both bicycle travel directions are positioned at the right side of the north–south travel direction, this increases the waiting time for right turning motor vehicles, as they must provide priority for bicyclists crossing both travel directions instead of only one travel direction (north–south), as it is the case for the unidirectional bicycle highway.

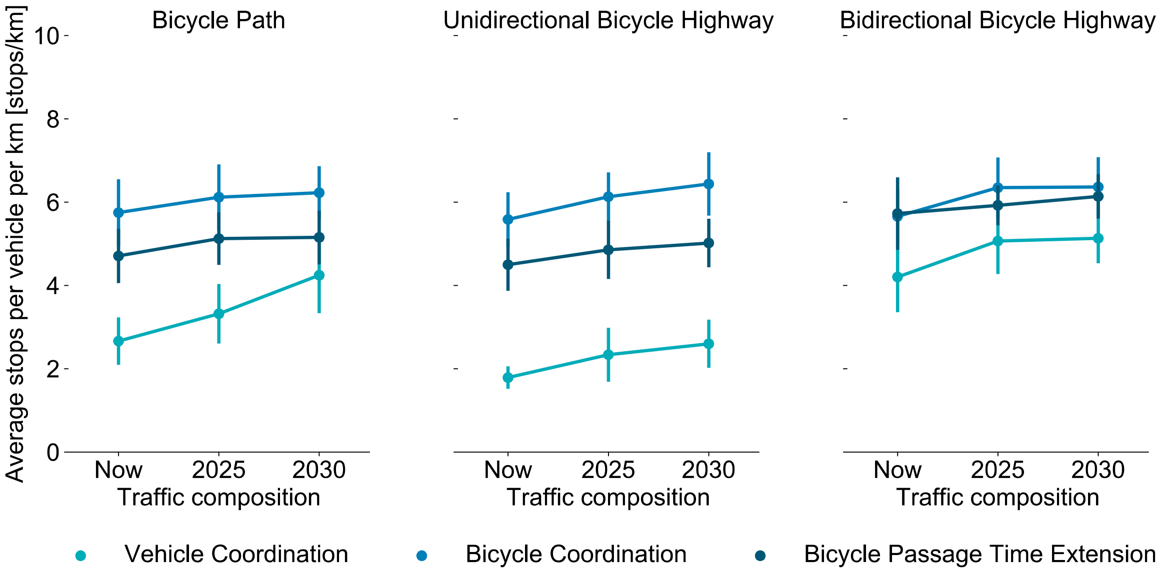


Figure 16. Average number of stops of motor vehicles in the north–south direction as a function of bicycle infrastructure type, traffic signal control strategy, and bicycle traffic composition in future time horizons. The error bars define the standard deviation of the observation sample.

On the other hand, compared to the base scenario, the bicycle coordination and the passage time extension strategies worsened the travel time of motor vehicles in the north–south travel direction. Since the traffic signal control in the current state is designed for motor vehicles, any kind of changes in the offset between controllers for favoring bicycle traffic will deteriorate the pre-designed offsets for vehicular traffic. However, still, motor vehicles get benefits from the extension of green time for bicyclists as they are in the same phase. That is why the travel time of motor vehicles in the prioritization strategy is lower than that in the coordination strategy.

Finally, results for the expected bicycle traffic composition in the respective investigated future horizons showcase that the upgrade of the existing bicycle infrastructure to a unidirectional bicycle highway will have positive effects on the average vehicular travel time and help mitigate the effects of the increased bicycle traffic flow on motor vehicle traffic.

On the other hand, as shown in Figure 15, the travel time patterns for motor vehicles differs from when the south–north is compared to the north–south direction. There are several reasons for that:

- Three intersections in study area (Theresienstraße, Schellingstraße, and Georgenstraße) are T-junctions in which motor vehicles from south to north cannot turn right. Therefore, motor vehicles do not need to stop for crossing bicyclists. This factor explains the slightly improved vehicular travel times with the bidirectional bicycle highway over the unidirectional bicycle highway.
- There are dedicated right turn traffic lanes in two intersections in the south–north travel directions (Von-der-Tann-Straße and Ungererstraße). Therefore, crossing motor vehicles are less affected by the right-turn motor vehicles.
- The traffic volume of motor vehicles from north to south is almost twice that from south to north. Since the infrastructure for both directions is similar, the traffic situation is less critical for south–north than in the north–south direction. Therefore, changing the bicycle infrastructure or their signal control strategies does not affect significantly the travel time of motor vehicles in the south–north travel direction.

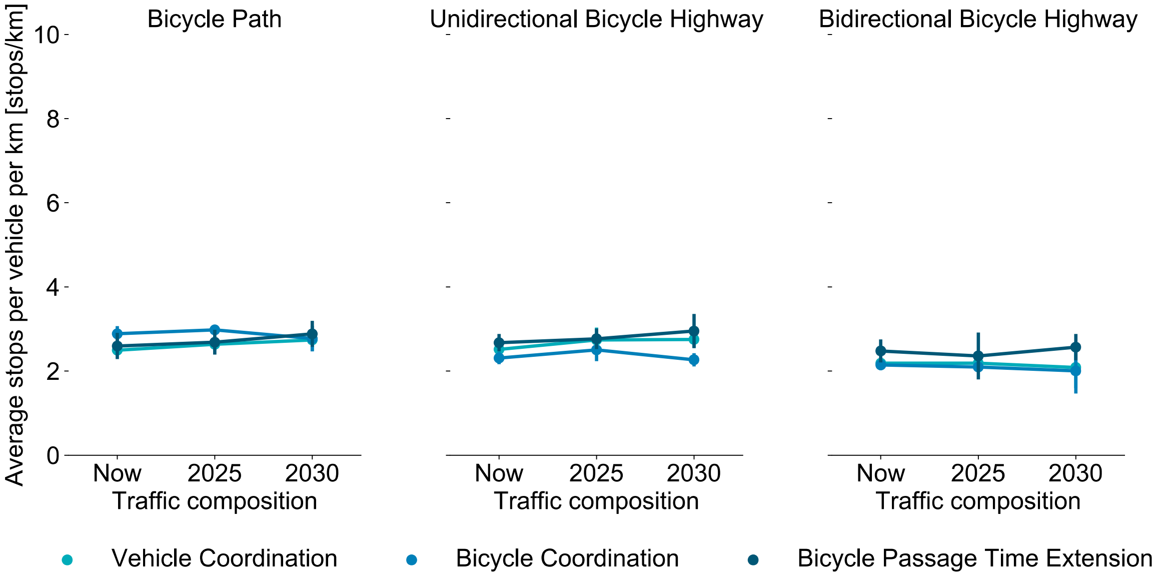


Figure 17. Average number of stops of motor vehicles in the south–north direction as a function of bicycle infrastructure type, traffic signal control strategy, and bicycle traffic composition in future time horizons. The error bars define the standard deviation of the observation sample.

Results for both directions of travel showcase the importance of remodeling the existing motor vehicle infrastructure alongside the construction of bicycle highway infrastructure in order to account for the expected negative effects on vehicular traffic flow as a result of the expected increase in bicycle traffic flow. Results demonstrate the importance of introducing dedicated right-turn lanes for motor vehicle traffic in order to reduce the effect from waiting vehicles on the crossing vehicular flow as a result of the increased bicycle traffic flow on the bicycle highway. Simultaneously, results showcase that there are negative effects of a bidirectional bicycle highway alignment over a unidirectional bicycle highway alignment in cases with high intersection density along the network where right turning off maneuvers are permitted. As this is typical for an urban setting, identifying positions and segments across the network where due to the size and form of the residential blocks or other factors, a bicycle highway network with the minimum number of intersections with the existing motor vehicle network can be built and positions and network segments where the expected volume of right turning motor vehicle traffic is low can result in a bicycle highway alignment design with reduced effects on vehicular traffic flow.

Finally, and in contrast to the results from the bicycle traffic efficiency analysis, where the bicycle coordination slightly outperformed in most cases the bicycle passage time extension strategy, in the case of the vehicular traffic efficiency analysis, the bicycle passage time extension strategy significantly outperformed the bicycle coordination strategy. As the former is an actuated traffic signal control strategy and adaptive to the traffic demand, it managed to achieve better results. Despite the fact that they are both significantly outperformed by the vehicular coordination, the results from the bicycle traffic efficiency analysis already suggest that bicycle highway infrastructure should always be designed together with special traffic signal control measures for bicycle traffic, as only through such measures can the bicycle level of service thresholds defined by official guidelines [3,14] can be achieved. Thus, and under consideration of the bicycle traffic efficiency analysis results, the bicycle passage time extension strategy proves to be the optimal strategy for both bicycle and vehicular traffic.

5. Discussion

Results demonstrate that bicycle traffic performance generally improves with the introduction of bicycle highway infrastructure. Bicycle travel times have reduced across the examined network. In addition, bicycle travel time reliability improved with the introduction of bicycle highway infrastructure, as the standard deviation of average travel times is slightly reduced in comparison to the base scenario. This statement is also reinforced by the fact that the standard deviation for the average delay and waiting time experienced by bicyclists is greatly reduced in all study scenarios with bicycle highway infrastructure. These results are consistent with findings in previous scientific research [22,24]. Despite the improved values for bicycle traffic performance indicators, quality thresholds provided by official standards can only be achieved through the introduction of special traffic signal control measures for bicycle traffic. Even with the highest examined bicycle traffic volumes, bicycle traffic operated under free flow conditions indicating that the signalized intersection approaches remain the bottleneck for the examined traffic performance indicators. Therefore, during the planning process, practitioners should always try to identify possible alignment routes with the minimum number of intersections and crossings in an effort to provide a more efficient solution and a higher quality of service for end users, which is a difficult task for an urban context.

Results for motor vehicle traffic performance showcase the benefits from the increased width of bicycle infrastructure as queue dissipation times at intersection approaches improve. The unidirectional bicycle highway is the optimal layout for mitigating negative effects on motor vehicle traffic performance. The introduction of special bicycle traffic control measures significantly affects the average travel times for motor traffic, whereas the results were slightly better with the bicycle passage time extension strategy. These results can be partially attributed to the lack of dedicated turning lanes for right turning motor vehicle traffic. It is expected that through the remodeling of motor vehicle infrastructure and the addition of dedicated right turning lanes, motor vehicle performance can be further improved. Thus, practitioners should always consider the effects on motor vehicle traffic and consider the remodeling of the existing road infrastructure alongside the introduction of bicycle highway infrastructure. In addition, especially in routes with high vehicle traffic volumes, practitioners should consider applying actuated traffic control strategies for both motor vehicle and bicycle traffic to further mitigate adverse effects on motor vehicle traffic performance after the introduction of bicycle highway infrastructure.

6. Conclusions

This paper presents the traffic efficiency analysis from the introduction of bicycle highway in an urban scenario. Microscopic traffic modeling is used for the study and quantification of the effects of bicycle highways on traffic performance parameters. In a first step, the study area for the bicycle highway is defined. Then, empirical studies are carried out to gather traffic data for the calibration and validation of traffic simulation models. Through the identification of the research gaps in the literature review section, specific study scenarios are defined. The assessment of the traffic performance effects is based on the quantification and evaluation of relevant traffic performance parameters. General recommendations for the design of bicycle highway infrastructure in urban areas are derived.

According to the results, the introduction of bicycle highway infrastructure leads to an improvement of bicycle traffic efficiency; however, the traffic quality thresholds that are defined in official guidelines can be fulfilled only through the implementation of special traffic control measures (bicycle coordination and bicycle passage time extension) for bicycle traffic. For bicycle traffic, bicycle coordination and bicycle passage time extension provided comparable results with bicycle coordination only slightly outperforming the bicycle passage time extension strategy. In addition, the introduction of these traffic signal control strategies decreases the variance of the average bicyclist delay, which in turn results in more reliable travel times as expected delays do not vary greatly among individual bicyclist trips. Finally, there was no significant difference among the examined bicycle traffic performance indicators with respect to the two examined types of bicycle highways.

With respect to the traffic efficiency results for motor vehicle traffic, results showed that motor vehicles would benefit from the introduction of a unidirectional bicycle highway when motor vehicle traffic signal coordination is preserved. The introduction of the bidirectional bicycle highway has a further negative effect on the vehicular traffic performance as it increases the obstructions from crossing bicyclists for right-turning motor vehicle traffic. Therefore, the introduction of dedicated turning lanes at intersections with bicycle highways can help to mitigate the effects from the introduction of bicycle highway infrastructure on motor vehicle traffic performance. The bicycle passage time extension provided better travel times for motor vehicles in comparison to the bicycle coordination. The bicycle passage time extension compared to the bicycle coordination strategy decreased the travel time of motor vehicles in the base scenario and for the unidirectional bicycle highway by almost 20% and 23% (T-value = 6 and 8, p-value = 0) respectively, whereas no significant influences were found between unidirectional bicycle highway and bidirectional bicycle highway (difference = 3%, T-value = 0.9, p-value = 0.4).

Overall, the implementation of a unidirectional bicycle highway together with passage time extension or any other type of actuated bicycle prioritization strategy has the potential to improve the traffic quality of bicycle traffic and meet the requirements bicycle highway infrastructure while at the same time minimizing the effects on motor vehicle traffic performance.

This paper primarily focuses on the effect of the introduction of a bicycle highway on bicycle and vehicular traffic flow performance. In this context, we do not examine the effect of the bicycle highway infrastructure on other road users. Future research may focus on further examining the effect of bicycle highway infrastructure on pedestrian traffic. Especially in densely populated urban areas, the introduction of bicycle highway may lead to unforeseen interactions among bicyclists and pedestrian flows, especially at intersection areas. Therefore, the analysis of such interactions with respect to traffic safety and traffic performance indicators is crucial for the high-quality design of new bicycle highway infrastructure. Also, the present research only assesses bicycle highway infrastructure through traffic performance indicators. However, the acceptance of the investigated measures by the end users and its relationship with traffic performance is also an important aspect for future work.

Additionally, official bicycle highway design guidelines [3,14] often include solutions for bicycle highway cross-sections that resolve interactions with other road users or are defined for shared use with other road users. For example, these include the alignment of the bicycle highway along access roads, the mixed use of bicycle highway lanes with public transport, roundabouts, and unsignalized intersections. Such solutions have not been thoroughly evaluated until now in terms of the expected effects on traffic safety and traffic efficiency, especially in cases with high bicycle flow or with increasing shares of e-bikes or cargo bikes. The present study could only provide some insights on the traffic performance effects with interacting right turning motor vehicles and bicyclists at intersection approaches with bicycle highway infrastructure. It established the importance of remodeling the existing motor vehicle infrastructure alongside the construction of bicycle highway infrastructure in order to account for possible negative effects on vehicular traffic flow. Given the fact that the effects on traffic performance and traffic safety have not been quantified for such special cross-sections, the expected future bicycle traffic composition along with the expected increase in e-bikes and cargo bikes will result in new challenges for traffic efficiency and traffic safety. As road users constantly compete for space in urban areas, the quantification of such effects is highly important for the planning, design, and dimensioning of urban highway infrastructure.

Finally, as our research has shown that the introduction of bicycle highway infrastructure in an urban area has to be accompanied with the implementation of special traffic control measures (bicycle coordination or bicycle passage time extension) for bicycle traffic in order to fulfill the traffic quality thresholds that are defined in the bicycle highway design guidelines, future research may focus on combining such measures with other traffic signal control strategies such as adaptive signal control with motor vehicle traffic or in cases with public transport prioritization, as this is a common case for network traffic control along important urban corridors.

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References

1. National Association of City Transportation Officials. *Urban Bikeway Design Guide*; Island Press: Washington, DC, USA, 2014; ISBN 1610915658.
2. Agarwal, A.; Ziemke, D.; Nagel, K. Bicycle superhighway: An environmentally sustainable policy for urban transport. *Transp. Res. Part A Policy Pract.* **2020**, *137*, 519–540. [CrossRef]
3. Forschungsgesellschaft für Straßen-und Verkehrswesen (FGSV). *Arbeitspapier: Einsatz und Gestaltung von Radschnellverbindungen*; FGSV Verlag: Köln, Germay, 2014.
4. Liu, G.; Te Brömmelstroet, M.; Krishnamurthy, S.; van Wesemael, P. Practitioners' perspective on user experience and design of cycle highways. *Transp. Res. Interdiscip. Perspect.* **2019**, *1*. [CrossRef]
5. Van Lierop, D.; Soemers, J.; Hoeke, L.; Liu, G.; Chen, Z.; Ettema, D.; Kruijf, J. Wayfinding for cycle highways: Assessing e-bike users' experiences with wayfinding along a cycle highway in the Netherlands. *J. Transp. Geogr.* **2020**, *88*. [CrossRef]
6. Li, H.; Graham, D.J.; Liu, P. Safety effects of the London cycle superhighways on cycle collisions. *Accid. Anal. Prev.* **2017**, *99*, 90–101. [CrossRef] [PubMed]
7. Atkins. Advanced Stop Line Variations Research Study: Research Findings. 2005. Available online: http://content.tfl.gov.uk/ASL-Findings-Report-October-011106.pdf (accessed on 15 January 2021).
8. Rayaprolu, H.S.; Llorca, C.; Moeckel, R. Impact of bicycle highways on commuter mode choice: A scenario analysis. *Environ. Plan. B Urban Anal. City Sci.* **2018**, *47*, 662–677. [CrossRef]
9. Hans, S.; Jette, J.; Suzanne, V.; Alexander, T.; Nielsen, S.; Simon, R. Effects of upgrading to cycle highways—An analysis of demand induction, use patterns and satisfaction before and after. *J. Transp. Geogr.* **2017**, *64*, 203–210. [CrossRef]
10. Bhuyan, P.; McCoy, E.J.; Li, H.; Graham, D.J. Analysing the causal effect of London cycle superhighways on traffic congestion. *arXiv* **2020**, arXiv:2003.08993.
11. Transport for London. London Cycling Design Standards. 2014. Available online: https://tfl.gov.uk/corporate/publications-and-reports/streets-toolkit (accessed on 15 January 2021).

12. Dufour, D. PRESTO Cycling Policy Guide—Cycling Infrastructure. 2010, p. 45. Available online: https://ec.europa.eu/energy/intelligent/projects/sites/iee-projects/files/projects/documents/presto_policy_guide_cycling_infrastructure_en.pdf (accessed on 15 January 2021).
13. COWI. Koncept 2.0 Planlægning, Udformning Og Drift. 2018. Available online: www.supercykelstier.dk (accessed on 15 January 2021).
14. CROW. *Design Manual for Bicycle Traffic*; CROW: Ede, The Netherlands, 2016.
15. Brenner BERNARD Ingenieure GmbH Planersocietät and EG Planungsbüro VIA. Qualitätsstandards für Radschnellverbindungen in Baden-Württemberg. 2018. Available online: https://www.fahrradland-bw.de/fileadmin/user_upload_fahrradlandbw/1_Radverkehr_in_BW/i_Radschnellverbindungen/Qualitaetsstandards_RSV_BW.pdf (accessed on 15 January 2021).
16. Transport of London. Cycleways. 2020. Available online: https://tfl.gov.uk/modes/cycling/routes-and-maps/cycleways (accessed on 15 October 2020).
17. Spape, I.; Fuchs, C.; Jürgen, G. Status quo und Erfahrungen mit der Planung und dem Betrieb von Radschnellwegen in den Niederlanden, Daenemark, Grossbritannien und Deutschland. *Straßenverkehrstechnik* **2015**, *59*, 639–652.
18. Regionalverband Ruhr. Über den Radschnellweg Ruhr RS1. 2020. Available online: http://www.rs1.ruhr/radschnellweg/planung.html (accessed on 23 January 2017).
19. Ingenieurbüro, H. Berg & Partner GmbH. Radschnellweg Euregio. 2016. Available online: https://bueroberg.eu/wp-content/uploads/2019/08/Ref_IB-Berg_Stra%C3%9Fe_B%C3%BCrgerbeteiligung_opt.pdf (accessed on 15 January 2021).
20. PGV-Alrutz GbR; PGV Dargel-Hildebrandt GbR. Radschnellweg OWL: Überprüfung der Machbarkeit für den Radschnellweg Ostwestfalen-Lippe. Hannover, Germany. 2016. Available online: https://opus.ostfalia.de/frontdoor/deliver/index/docId/642/file/Groeger_2016_Knotenpunkttypologien_Radschnellverbindungen.pdf (accessed on 14 January 2021).
21. AFGS Radschnellwege in NRW. 2017. Available online: https://www.radschnellwege.nrw/fileadmin/user_upload/downloads/RSW_Planungshilfe_RZ_web.pdf. (accessed on 15 January 2021).
22. Li, H.; Ding, H.; Ren, G.; Xu, C. Effects of the London Cycle Superhighways on the usage of the London Cycle Hire. *Transp. Res. Part A Policy Pract.* **2018**, *111*, 304–315. [CrossRef]
23. Van Goeverden, K.; Godefrooij, T. *The Dutch Reference Study: Cases of Interventions in Bicycle Infrastructure Reviewed in the Framework of Bikeability*; Delft University of Technology: Delft, The Netherlands, 2011; ISBN 9789078271079.
24. Transport for London Barclays Cycle Superhighways Evaluation of Pilot Routes 3 and 7. 2011, pp. 1–61. Available online: https://www.whatdotheyknow.com/request/162841/response/402026/attach/3/BCSpilotevaluationreport.pdf (accessed on 15 January 2021).
25. National Research Council. *Highway Capacity Manual*; Transportation Research Board: Washington, DC, USA, 2016.
26. Forschungsgesellschaft für Straßen-und Verkehrswesen (FGSV). *Handbuch für die Bemessung von Straßenverkehrsanlagen (HBS)*; Forschungsgesellschaft für Straßen-und Verkehrswesen e. V., FGSV Verlag: Köln, Germany, 2015.
27. Baumann, F. Berner Ampeln Stehen auf Grün. Velojournal. 2016. Available online: http://www.velojournal.ch/vj-online/nachrichten/2016/berner-ampeln-stehen-auf-grün.html (accessed on 4 April 2017).
28. Hoegh, N. Green waves for cyclists in Copenhagen Denmark—Copenhagen. In *Workshop at Velo-City "From Vision to Reality"*; European Cyclists' Federation: Munich, Germany, 2007.
29. Mensik, K.; Beyer, F. Koordinierung von Lichtsignalanlagen fuer den Radverkehr/Coordinating of traffic lights for bicycle traffic. *Straßenverkehrstechnik* **2013**, *57*, 621–627.
30. Grigoropoulos, G.; Twaddle, H.; Spangler, M.; Hagenbring, M.; Düsterwald, M. *Evaluierung der dynamischen Grünen Welle für Radfahrer-Sitraffic SiBike-in Marburg*; Kirschbaum Verlag GmbH: Bonn, Germany, 2018; pp. 268–274.
31. Koonce, P. Bicycle Countdown Signal—Time to Green. Available online: http://kooncеportland.blogspot.de/2011/07/bicycle-countdown-signal-time-to-green.html (accessed on 27 November 2015).
32. Kaths, H.; Grigoropoulos, G.; Krämer, K. Green signal countdown timers for bicycle traffic—Results from a field study. In *Cycling Research Board 2019*; Delft University of Technology: Delft, The Netherlands, 2019.
33. Preethi, P.; Varghese, A.; Ashalatha, R. Modelling Delay at Signalized Intersections under Heterogeneous Traffic Conditions. *Transp. Res. Procedia* **2016**, *17*, 529–538. [CrossRef]
34. Grigoropoulos, G.; Kazakovtsev, S.M.M.; Kaths, H.; Krämer, K. Evaluation of a Traffic Signal Coordination for Bicycles in a Mixed Motor Vehicle and Public Transport Urban Network. In *Cycling Research Board 2019*; Delft University of Technology: Delft, The Netherlands, 2019.
35. Knight, P.; Bedingfeld, J.; Gould, E. *Traffic Management Techniques for Cyclists: Final Report*; Transport Research Laboratory (TRL): Wokingham, UK, 2011.
36. Federal Highway Administration. Manual on Uniform Traffic Control. Devices for Streets and Highways. 2009. Available online: https://mutcd.fhwa.dot.gov/pdfs/2009/mutcd2009edition.pdf (accessed on 15 January 2021).
37. Forschungsgesellschaft für Straßen-und Verkehrswesen (FGSV). *Hinweise Zur Signalisierung Des Radverkehrs*; Forschungsgesellschaft für Straßen-und Verkehrswesen e.V., FGSV Verlag: Köln, Germany, 2005.
38. Richardson, D.; McLaughlin, D.; Kowpak, D.; Mang, J.; Parker, M.; Hardenbrook, D.; Vanderputten, R.; Noxon, G. Traffic Signal Guidelines for Bicycles. 2014. Available online: https://trid.trb.org/view/1343377 (accessed on 14 January 2021).

39. Deutsches Institut für Urbanistik gGmbH. Amsterdam führt Grüne Welle für den Radverkehr ein. 2007. Available online: https://nationaler-radverkehrsplan.de/de/aktuell/nachrichten/amsterdam-fuehrt-gruene-welle-fuer-den-radverkehr (accessed on 4 April 2017).
40. CROW Fietsberaad. Rotterdam First with Green LED Wave for Cyclists. 2010. Available online: http://www.fietsberaad.nl/index.cfm?section=repository&repository=Rotterdam+first+with+green+LED+wave+for+cyclists (accessed on 4 April 2017).
41. Siemens, A.G. Weltpremiere in Marburg—Präsentation der Grüne-Welle-App für Radfahrer. 2017. Available online: www.siemens.com/presse/sibike (accessed on 4 May 2017).
42. Deutsches Institut für Urbanistik (Difu) GmbH. Radschnellweg Zwischen München Und Garching Bzw. Unterschleißheim Kommt Weiter Voran. 2020. Available online: https://nationaler-radverkehrsplan.de/de/aktuell/nachrichten/radschnellweg-zwischen-muenchen-und-garching-bzw (accessed on 12 January 2021).
43. Forschungsgesellschaft für Straßen-und Verkehrswesen (FGSV). Empfehlungen für Verkehrserhebungen (EVE). 2012. Available online: https://scholar.google.co.jp/scholar?hl=en&as_sdt=0%2C5&q=Empfehlungen+f%C3%BCr+Verkehrserhebungen+%28EVE%29.+2012&btnG= (accessed on 14 January 2021).
44. Nobis, C.; Kuhnimhof, T. *Mobilität in Deutschland—MiD Analysen zum Radverkehr und Fußverkehr*; Infas Institut für angewandte Sozialwissenschaft GmbH: Berlin, Germany, 2019.
45. Lopez, P.A.; Behrisch, M.; Bieker-walz, L.; Erdmann, J.; Fl, Y.; Hilbrich, R.; Leonhard, L.; Rummel, J.; Wagner, P.; Wießner, E. Microscopic Traffic Simulation Using SUMO. In Proceedings of the 21st International Conference on Intelligent Transportation Systems (ITSC), Maui, HI, USA, 4–7 November 2018; pp. 2575–2582.
46. Haklay, M.; Weber, P. Openstreetmap: User-generated street maps. *IEEE Pervasive Comput.* **2008**, *7*, 12–18. [CrossRef]
47. Gehlert, T.; Schleinitz, M.K.K.; Petzoldt, T.; Schwanitz, S.; Gerike, R. The German Pedelec Naturalistic Cycling Study—Study Design and First Experiences. *Proc. Int. Cycl. Saf. Conf.* **2012**, *2012*, 15.
48. Astegiano, P.; Tampère, C.M.J.; Beckx, C. A preliminary analysis over the factors related with the possession of an electric bike. *Transp. Res. Procedia* **2015**, *10*, 393–402. [CrossRef]
49. Schleinitz, K.; Petzoldt, T.; Franke-Bartholdt, L.; Krems, J.; Gehlert, T. The German Naturalistic Cycling Study—Comparing cycling speed of riders of different e-bikes and conventional bicycles. *Saf. Sci.* **2016**, *92*, 290–297. [CrossRef]
50. Zweirad-Industrie-Verband. Zahlen—Daten—Fakten zum Deutschen Fahrrad-und E-Bike Markt 2019 Dynamischer Wachstumskurs der Fahrradindustrie Setzt Sich Ungebremst Fort. 2019. Available online: https://www.ziv-zweirad.de/fileadmin/redakteure/Downloads/PDFs/PM_2020_11.03._Fahrrad-_und_E-Bike_Markt_2019.pdf (accessed on 15 January 2021).
51. Gruber, J.; Kihm, A. Reject or embrace? Messengers and electric cargo bikes. *Transp. Res. Procedia* **2016**, *12*, 900–910. [CrossRef]
52. Fishman, E.; Cherry, C. E-bikes in the Mainstream: Reviewing a Decade of Research. *Transp. Rev.* **2016**, *36*, 72–91. [CrossRef]
53. Assmann, T.; Müller, F.; Bobeth, S.; Baum, L. Planung von Lastenradumschlagsknoten. Ein Leitfaden für Kommunen und Wirtschaft zur Planung von Umschlagspunkten für Neue, Urbane Logistikkonzepte. 2019. Available online: https://repository.difu.de/jspui/handle/difu/576712 (accessed on 15 January 2021).
54. Nürnberg, M. Analysis of using cargo bikes in urban logistics on the example of Analysis of using cargo bikes in urban logistics on the example of Stargard Green Cities 2018. *Transp. Res. Procedia* **2019**, *39*, 360–369. [CrossRef]
55. COWI. *Micro Simulation of Cyclists in Peak Hour Traffic*; City of Copenhagen: Copenhagen, Denmark, 2012.
56. Forschungsgesellschaft für Straßen-und Verkehrswesen (FGSV). *Hinweise zur Mikroskopischen Verkehrsflusssimulation-Grundlagen und Anwendung*; Forschungsgesellschaft für Straßen-und Verkehrswesen (Hrsg.): Köln, Germany, 2006; ISBN 3939715115.