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Automatically evaluating the service quality of bicycle paths based on semantic 3D city models

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Abstract. The growing demand for sustainable mobility has led to an increased focus on the development and improvement of bicycle infrastructure, especially within cities. However, evaluating the quality of existing or planned bicycle paths is a complex task mostly done manually. This paper presents a novel approach for automatically evaluating the service quality of bicycle paths using parameters derived from semantic 3D city and streetspace models compliant with the international OGC standard CityGML version 3.0. These models contain detailed 3D information with lane-level accuracy, including precise outlines of individual surfaces. This allows for accurate and high-resolution evaluations of changing bicycle path widths and slopes, as well as information on adjacent surfaces and local disturbances such as bus stops. Additionally, estimated, measured or simulated bicycle traffic volumes are considered. Based on these parameters a method for calculating the Bicycle Levels of Service (BLOS) described in a national technical regulation is adapted and implemented for a microscopic analysis. Results of this analysis are then transferred back to the original semantic 3D city objects, allowing for the attributive description of BLOS values for bicycle paths. In addition, results are visually represented by coloring corresponding bicycle path segments according to evaluation results and integrating the colored objects within a web-based Cesium visualization of a semantic 3D city model.

Keywords: bicycle infrastructure, traffic, transportation, mobility, 3D city model, CityGML, OpenDRIVE, bicycle level of service

1 Introduction

The growing demand for sustainable and efficient transportation and mobility concepts has led to an increased focus on improving and expanding bicycle infrastructure. However, determining the quality of existing or planned bicycle paths is challenging. Kazemzadeh et al. [1] present an extensive review on methods for evaluating a Bicycle Level of Service (BLOS). While some methods for the quality assessment of bicycle infrastructure focus on specific aspects of the cycling experience such as safety, connectivity and accessibility, other methods focus on the perceived level of comfort, stress or bikeability [2]. The BLOS method is considering several aspects of the cycling experience and provides an easy to understand metric, often standardized in national technical regulations [3, 4]. There are methods for calculating levels of service for bicycle paths based on parameters such as width, slope, adjacent bus stops and bicycle traffic volumes. However, relevant input parameters for these standardized methods are so far mostly gathered manually and on a macroscopic scale. In the context of urban digital twins, several cities are in the process of gathering data for creating a detailed 3D representation of the streetspace, which contains detailed geometric and semantic information on road infrastructure including exact outlines of bicycle paths. Thus, high-resolution information with surface-based lane-level accuracy is increasingly available.

In this paper, a novel approach for automatically evaluating the quality of bicycle paths using parameters derived from semantic 3D city and streetspace models compliant to the international OGC standard CityGML version 3.0 is proposed. These models contain detailed 3D information with lane-level accuracy and thus include precise outlines of individual surfaces such as bicycle paths and its surroundings. This allows accurate and high-resolution evaluations of bicycle path widths and slopes on a microscopic level. Additionally, information on local disturbances of cyclists due to adjacent surfaces such as bus stops, driving or parking lanes can be determined. Information on bicycle traffic volumes is considered by linking estimated, measured or simulated values with corresponding semantic objects. Results of these analyses are then transferred back to original semantic 3D city objects (e.g. individual bicycle paths). In addition to the attributive description of BLOS, results are visually represented by coloring corresponding bicycle paths according to analysis results and integrating the colored objects within a web-based Cesium visualization of a semantic 3D city model.

2 Related Work

2.1 Semantic 3D representations of bicycle infrastructure

The representation of semantic 3D road and streetspace models has become increasingly relevant due to the growing demand for accurate, detailed, and up-to-date information on transportation infrastructure [5]. Additionally, increased availability of highly detailed data (e.g. from mobile mapping) allows the creation of such models. The integration of semantic information, such as classification and usage attributes, in combination with accurate geometric details and topological information ensures the usability of these models for various applications [6]. Wierbos et al. [7] show the effect of changing bicycle path widths and bottlenecks on traffic flow and capacity. Beil et al. [8] present a detailed review of different standards and data formats in the field of semantic road modelling as well as their capabilities. While standards and data formats such as OpenStreetMap (OSM), Geographic Data Files (GDF), Industry Foundation Classes (IFC) or OpenDRIVE [9] can contain information on bicycle infrastructure, representations mostly focus on linear (network-based) or parametric representations of geometries. In contrast, the newest version 3.0 of the international OGC standard

CityGML provides concepts for the integration of linear, polygonal, and volumetric (explicit) geometries within a consistent semantic 3D city model, including bicycle infrastructure [10].

2.2 Methods and concepts for determining the quality of bicycle paths

Several methods have been proposed to assess the quality of bicycle infrastructure that all differ in the type, amount and weighting of considered impact factors. In general, existing methods can be classified into seven overarching categories clustered according to their specific focus of assessment. While each of the categories and methods provides a unique perspective on the quality of bicycle infrastructure, they can all help to guide investments in bicycle infrastructure to promote a safe, convenient and comfortable cycling experience for all types of cyclists. The choice of the specific method applied may depend on the specific context and goals of the assessment, as well as the availability of data and resources. Table 1 summarizes common methods to assess the quality of bicycle infrastructure, clustered into seven overarching categories and selected exemplary methods are referenced.

Table 1. Summary of common methods to assess the quality of bicycle infrastructure.

Category	Description	Exemplary Methods
Bicycle Level of Service (BLOS)	Evaluation of the quality of cycling facilities based on quantitative factors, similar to the Level of Service (LOS) approach used for motorized traffic.	Technical regulation / Handbook for Road Infrastructure Design (HBS) [2]
		Highway Capacity Manual (HCM) [4]
Safety Analysis or Safety Audits	Evaluation of the safety of cycling infrastructure by conducting a systematic review of potential hazards and safety issues.	Bicycle Interaction Hazard Score (IHS) [11]
		Bicycle Intersection Safety Index (ISI) [12]
Connectivity Analysis	Evaluation of the extent to which cycling networks provide access to key destinations, in terms of the network connectivity.	Cyclist Routing Algorithm for Network Connectivity (CRANC) [13]
Accessibility Analysis	Evaluation of the extent to which cycling networks provide access to different user groups, such as people with disabilities or elderlies.	TUM Accessibility Atlas [14]
		Gravity-Based Accessibility Measures for Integrated Transport-Land Use Planning (GraBAM) [15]
Multi-Criteria Analysis (MCA)	Evaluation of the quality of cycling networks based on a set of pre-determined criteria related to safety, connectivity, and accessibility.	Multiple Criteria Decision Analysis (MCDA) [16]
		Explanatory Spatial Data Analysis (ESDA) [17]
Stress Level Analysis or Comfort Analysis	Evaluation of the perceived level of stress, based on quantitative factors such as traffic volume and speed or the presence of bike lanes.	Bicycle Compatibility Index (BCI) [18]
		Bicycle Stress Map (BSM) [19]

Bikeability Index	Evaluation of a range of factors that affect the quality of the bicycle experience in urban areas, taking into account both physical and social factors.	Bikeability evaluation using street view imagery and computer vision [20]
		Munich Bikeability Index [21]

In this paper, the focus is on a method for calculating the BLOS based on geometric and semantic parameters, explained in detail in section 3.1. The calculation of a BLOS is a commonly used method to assess the quality of bicycle infrastructure and is incorporated in a wide range of national standards and guidelines and thus provides a clear and standardized grading system that can be easily understood by stakeholders. It is a quantitative method that assigns a level of service of the transportation system based on the level of comfort, safety and the quality of traffic flow for cyclists. Similar to all methods presented in table 1, it is considered a macroscopic assessment method so far, since it mostly focuses on entire links or link segments of the transportation network, that stretch over a relatively long distance, or entire intersections. However, this macroscopic focus does not provide a detailed understanding of the quality of smaller elements of the transportation network or bottlenecks within longer sections, disturbing an otherwise continuously safe and comfortable cycling experience. Thus, an adapted method for analyzing the service quality of bicycle paths on a microscopic level is proposed.

3 Methodology

The general workflow of the implemented process is illustrated in figure 1 and explained in detail in the following sections.

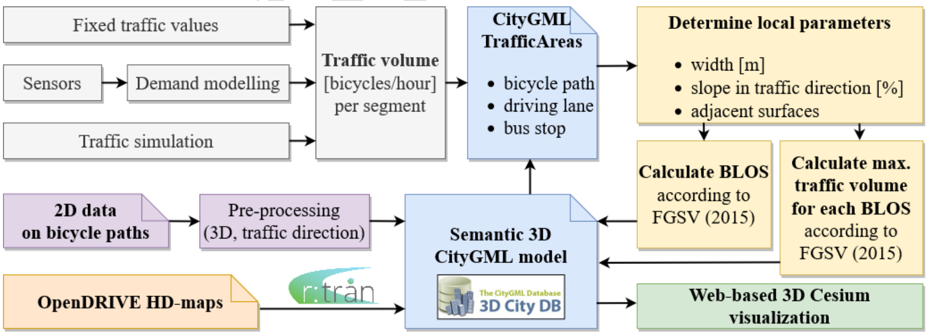

Fig. 1. General workflow for determining the Bicycle Level of Service from relevant parameters.

3.1 Implemented method for evaluating the BLOS

The method implemented to determine the service quality of bicycle paths is described in a national technical regulation called "Handbook for Road Infrastructure Design" issued by the German "Research Association for Roads and Traffic" [3]. The method is based on the calculation of a Bicycle Level of Service (BLOS) depending on a disturbance rate *DR* of cyclists. This disturbance rate is evaluated based on the local width and slope of bicycle paths, bicycle traffic volume, amount of wide bicycles and influence of adjacent disturbances such as bus stops. The method is applicable to stretches of dedicated bicycle paths with high traffic volumes. Bicycle paths need to be divided into segments as soon as one of the parameters necessary for calculating the BLOS changes significantly. The method distinguishes between one-way and two-way bicycle paths. This paper focuses on concepts for the evaluation of one-way bicycle paths, as these are generally by far the most common types of bicycle paths. This method is chosen since an increasing availability of high-resolution data allows an automated evaluation of bicycle paths based on geometric and semantic features. Limitations of this method and possibilities to extend it with additional concepts and information are discussed in section 5 of this paper. Slopes increase the width requirement of a cyclist due to lateral swaying or the need to get off the bicycle. Thus, a fictional width w_{f1} of bicycle paths due to local slope (eq. 1) results from the actual width w minus the additional width w_{A1} required due to the local slope according to table 2.

$$w_{f1} = w - w_{A1} \tag{1}$$

Table 2. Additional width required due to the local slope according to [3].

slope [%]	$\boldsymbol{w_{A1}}$ **[m]**
> 6	0.45
4 < slope ≤ 6	0.30
≤ 4	0

The fictional width w_{f2} of bicycle paths due to the amount of wide bicycles such as cargo bikes (required if more than 15 % of all bicycles are wide bicycles) results from the actual width w minus the additionally required width w_{A2} set at 0.3 meter (eq. 2).

$$w_{f2} = w - w_{A2} \tag{2}$$

The smallest fictional width w_f (due to slope or wide bicycles) is chosen (eq. 3).

$$w_f = \min\left\{\begin{array}{l} w_{f1} \\ w_{f2} \end{array}\right. \tag{3}$$

The overtake rate *OR* is evaluated with respect to traffic volume *qB*, mean speed of bicycles *V* and corresponding standard deviation σ according to equation 4. The disturbance rate for one-way bicycle paths DR_O (eq. 5) results from the overtake rate *OR*, based on number of bicycles per hour *qB* times the factor for disturbances due to overtakes f_{DO} according to table 3.

$$OR = \frac{2 \cdot qB \cdot \sigma}{V^2 \cdot \sqrt{\pi}} \tag{4}$$

$$DR_O = OR \cdot f_{DO} \tag{5}$$

Table 3. Factor for disturbances depending on local fictional width according to [3].

w_f [m]	f_{DO}	qB [bicycles/hour]
≥ 2	0 0.25 · (0.01 · qB −1) 0.5	≤ 100 100 < qB < 300 ≥ 300
1.80 ≤ w < 2.00	1.0	
1.60 ≤ w < 1.80	2.0	
< 1.60	4.0	

Punctual, local disturbances due to bus stops near bicycle paths DR_P are set at 1 for all segments within a certain proximity of bus stops. The disturbance rate DR for each segment then results from the addition of the disturbance rate of punctual disturbances DR_P (if available) plus the disturbance rate from overtakes DR_O (eq. 6).

$$DR = DR_O + DR_P \tag{6}$$

BLOS values of segments are categorized and color-coded according to table 4. The mean disturbance rate DR_m for the length L of an entire bicycle path then can be calculated as mean of the disturbance rates DR_i of all segments weighted according to respective segment lengths L_i (eq. 7). Both values (eq. 6 and eq. 7) can be translated to BLOS scores. Values of eq. 6 give BLOS scores for each (high-resolution) segment, while eq. 7 gives an aggregated (mean) value over an entire bicycle path.

$$DR_m = \frac{\sum_{i=1}^{n} L_i \cdot DR_i}{L} \tag{7}$$

Table 4. Bicycle Levels of Service (BLOS) of one-way bicycle paths depending on disturbance rates DR (for each segment) or DR_m (for an entire bicycle path) according to [3].

BLOS	Disturbance rate (DR or DR_m)
A	< 1
B	< 3
C	< 5
D	< 10
E	≥ 10

The values in table 4 correspond to the following definitions specified within the technical regulation [3]:

- A: All cyclists have unrestricted freedom of movement. Changes in the line of travel within the cross-section or changes in speed are not required.
- B: Freedom of movement is hardly restricted. Changes in the line of travel within the cross-section or changes in speed are rare.
- C: Freedom of movement is repeatedly restricted by other cyclists. Changes in the line of travel within the cross-section or changes in speed are regularly required.

- D: Freedom of movement is significantly restricted by other cyclists. Changes in the line of travel within the cross-section or changes in speed are often required.
- E: Freedom of movement is constantly restricted by other cyclists. Constant changes in the line of travel within the cross-section or changes in speed are required.

In order to calculate the maximum traffic volume (qB_{max}) of bicycle path segments acceptable to reach a certain BLOS, equations 4 and 5 are combined and rearranged to form equation 8. Where DR_{max} is the maximum disturbance rate per BLOS (cf. table 4) and f_{DO} depends on the local fictional width w_f according to table 3. For $w_f \geq 2.0$ the corresponding f_{DO} is set at 0.5. The mean speed of bicycles V and corresponding standard deviation σ are considered. Potential punctual disturbances are not considered in this evaluation. Resulting maximum traffic volume values are rounded down to give whole numbers.

$$qB_{max} = \frac{DR_{max} \cdot V^2 \cdot \sqrt{\pi}}{2 \cdot \sigma \cdot f_{DO}} \tag{8}$$

3.2 Requirements towards input data

Until now this method has mostly been used manually, which is labor and time intensive both for gathering relevant input information on bicycle paths and calculating BLOS values from this information. Thus, so far this method is mostly used for limited spatial extends of specifically relevant segments. In order to automate this process and to be able to calculate BLOS values for bicycle paths of entire cities, information provided by semantic 3D streetspace models are beneficial. Table 5 lists parameters required for this method and compares available information provided by such models. The method and implemented process require geo-referenced 3D data with lane-level accuracy. As the results of the quality assessment strongly depend on the width of individual bike lanes, surface-based representations (using explicit coordinates) used to calculate this parameter must be available with centimeter accuracy since variations in width along a bicycle path must be detected in a high resolution to be usable for the implemented method. Average widths for longer sections (as available in OSM data or procedurally generated models) are not sufficient for the presented process. Additionally, a corresponding linear representation of bicycle lanes in 3D is required in order to calculate local slopes and segment lengths. While slopes could also be derived from digital terrain models, true 3D representations are required to represent bicycle paths on bridges or through underpasses. Linear and areal representations must be consistent in order to avoid errors in the width estimation process. With respect to semantic capabilities, functions of traffic lanes (e.g. bicycle paths) as well as traffic directions must be known. For relatively flat areas (with slopes less than 4 %) information on slopes and traffic direction is not relevant. In addition to geometric information on bicycle path outlines and slopes, individual bicycle lanes should be linked with corresponding dynamic data on bicycle traffic volumes. Different methods for including this data are presented in section 3.4. Bicycle counting sensors need to have information to which lane they belong. Depending on the specific use case, up-to-date information or planned scenarios are required. OpenDRIVE data (HD-maps) are increasingly available for a number of cities and often contain the required information. However, since the standard is based on a parametric representation of geometries, this data cannot be used directly for lane width calculations. Thus, the open-source converter r:trån [5] is used to derive CityGML 3.0 streetspace models from OpenDRIVE data, which contain surface-based and corresponding linear network representations of bicycle paths with geo-referenced and explicit 3D coordinates. The original data was gathered using Mobile Mapping systems and contains the required high-resolution of geometric and semantic information.

Table 5. Parameters considered by the implemented method and availability of information in 3D CityGML streetspace models derived from OpenDRIVE data.

Parameter	**Considered by the used method** [3]	**Availability in 3D CityGML model**
width [m]	✓	is calculated
slope [%]	✓	is calculated
traffic direction	✓	✓
traffic volume [b/h]	✓	is linked
wide bicycles (> 15 %)	✓	is assumed
adjacent bus stops	✓	are derived
other adjacent surfaces	-	could be derived
shared usage	-	✓
change of direction	-	could be derived
change of slopes	-	could be derived
speed limit [km/h]	-	✓
surface material	-	✓
surface smoothness	-	-
perceived comfort	-	-

3.3 Deriving width, slope and adjacent surfaces of bicycle paths from 3D streetspace models

Key variables necessary for this method are the width and slope of bicycle paths. Since these parameters can change rapidly and potentially just over a short distance in the course of a bicycle path, it is essential to be able to calculate lane widths and slopes at short intervals. Vitalis et al. [22] use a method developed by Hoffmanns [23] for deriving road widths from polygonal representations and corresponding centerlines. A similar approach is chosen in order to calculate the width of bicycle paths at a high resolution as illustrated in figure 2. This is implemented using the software Feature Manipulation Engine (FME).

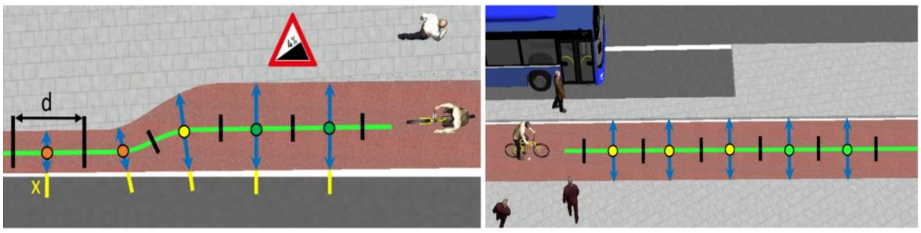

Fig. 2. Width calculation of bicycle paths at short intervals and determining adjacent surfaces.

The following processing steps are implemented in order to derive the width and slope of bicycle paths at short intervals as well as information on adjacent surfaces.

1. Filter TrafficAreas with "function = bicycle path or combined footpath / cyclepath" (CityGML codelist values = 3 or 4) or "usage = bicycle" (CityGML codelist value = 6).
2. Calculate centerline (green) of each TrafficArea and its length and assign an ID per centerline using respective FME transformers. Alternatively, directly use linear TrafficSpace representations, which correspond to lane centerlines and are available in CityGML 3.0 data derived from OpenDRIVE data using r:trån.
3. Split each centerline into segments of length *d* (indicated with black dashes) and assign IDs per segment.
4. Calculate the slope of each segment using start and end elevation and length of each segment (the length of segments at the start or end may be shorter than *d*). If the original geometry already contains 3D information (which is the case for datasets given in OpenDRIVE and converted to CityGML), the slope can be directly derived. Otherwise, information from a corresponding digital terrain model can be incorporated. Information on the traffic direction is required (and also available) to evaluate the slope in traffic direction, since the method considers additional space needed by cyclists at positive inclines greater than 4 % (cf. table 2).
5. Create the centerpoint of each segment.
6. Create orthogonal lines (blue) in each centerpoint and extend to boundary of bicycle path polygons.
7. Calculate length of each orthogonal line (equal to lane width *w* at each centerpoint)
8. Extend orthogonal lines by *x* meters and test for overlap with adjacent surfaces (yellow extensions of orthogonal lines indicate, that an adjacent driving lane is detected). This method ensures, that driving lanes are detected even if they are not directly adjacent to bicycle paths, but within a range of *x* meters. Similarly, other relevant adjacent surfaces such as pedestrian sidewalks or parking lanes can be determined.
9. Buffer bus stop polygons by *y* meters and intersect with adjacent centerpoints (yellow points in the right image of figure 2).

Each centerpoint now contains information on local width, slope in traffic direction, adjacent surfaces and nearby bus stops (if available), a segment ID and the ID of the original CityGML TrafficArea. These parameters are then used to calculate BLOS values and corresponding maximum traffic volumes for each centerpoint as well as aggregated mean BLOS values for each CityGML TrafficArea according to the method presented in section 3.1.

3.4 Including bicycle traffic volumes

Information on bicycle traffic volumes (bicycles per hour) can be included in different ways. In every case, these values are assigned to corresponding city objects in order to be used as input data for the presented method.

1. Fixed bicycle traffic volumes

In case there is no information on actual bicycle traffic volumes available, the method can be applied multiple times using various fixed values (e.g. 50, 100, 250 bicycles/h). In this context, it needs to be stated, that bicycle traffic volumes and traffic flow differ between section and intersection areas. This means results calculated using fixed traffic volumes for an entire network often do not reflect reality. However, in this way it can be determined up to which capacity the quality of individual bicycle path segments are of a certain level of service.

2. Individual bicycle traffic volumes derived from sensors

Alternatively, detailed information on actual traffic volumes can be derived from sensors such as bicycle counting stations, which are available in several cities. Usually, the location of these sensors is known, which allows a direct relation of counting results to specific bicycle lanes in the semantic 3D city model. Even if not every bicycle lane may be linked with real-world sensor information, exemplary stations can give information on the general scale and magnitude of bicycle traffic volumes in certain parts of a city, which then can be used as input for the presented bicycle path quality analysis. Typical averages or maximum capacity utilization can be derived from such analysis and linked with corresponding semantic city objects. Information derived from sensors distributed in a city can also be used as input for demand modelling techniques to estimate bicycle traffic volumes. Cities such as Hamburg provide open-access to IoT servers of bicycle counting sensors via a standardized OGC SensorThings API (https://iot.hamburg.de/).

3. Individual bicycle traffic volumes derived from simulations

Bicycle traffic volumes derived from real-world counting sensors may not be available for every bicycle path (segment). However, approximate numbers can be simulated using traffic simulation software and then linked to semantic bicycle path objects.

3.5 Evaluating the amount of wide bicycles (e.g. cargo bikes)

Detailed information on the percentage of wide bicycles may not be available. However, since there are only two options that can be taken into account (share of wide bicycles over or under 15 %), the method can be applied for both cases to compare results.

3.6 Linking results with semantic 3D city objects

CityGML provides the concept of generic attributes for storing information not considered within the definitions of the original standard. Alternatively, a built-in mechanism called Application Domain Extension (ADE) to extend the data model of the standard with application-specific concepts is available, which could be developed for the presented application. In this study, results on the quality of bicycle paths (BLOS) determined using the method described in this paper, are stored as generic CityGML attributes with corresponding CityGML TrafficAreas (bicycle lanes). Furthermore, segments are colored according to quality categories (cf. table 4) as depicted in figure 3, using the possibility of CityGML features to have appearances. This is done by transferring BLOS values of individual centerpoints to corresponding surface representations of bicycle path segments.

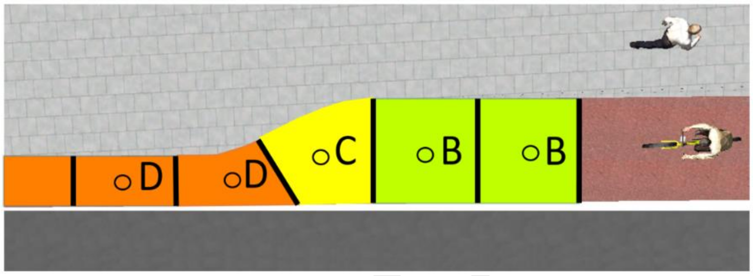

Fig. 3. Coloring bicycle path segments according to quality results of corresponding centerpoints.

3.7 Web-based visualization of results in combination with 3D city models

The 3DCityDatabase (3DCityDB) is a CityGML compliant open-source solution for importing, managing, analyzing, visualizing, and exporting virtual 3D city models [24]. The corresponding 3DCityDB Web-Map-Client is an application for web-based visualization of 3D city models using the Cesium virtual globe, which additionally offers the possibility to link city objects with semantic data for interactive exploration. Multiple layers (e.g. buildings, vegetation, road infrastructure, etc.) can be included and an incorporated tiling mechanism allows the visualization of large 3D city models. A web-based visualization is created using the 3DCityDB Importer/Exporter tool, including bicycle paths colored according to individual BLOS values (cf. table 4). Since currently, only CityGML version 2.0 data is supported by the 3DCityDB (v4.3), results are provided in CityGML versions 2.0 and 3.0. The possibility to communicate analysis results for existing or planned scenarios in an interactive and openly accessible web-based visualization has potential for improved public participation. However, resulting BLOS values need to be interpreted correctly and can be misleading. Bicycle paths, for example, are usually constructed in such a way, that at peak traffic volumes, a BLOS of category D is reached. Without this knowledge, analysis results may give a wrong impression on the actual service quality of bicycle paths to the public.

4 Results

The method and process described in section 3 is applied to data available for multiple cities including Hamburg and Munich. Since streetspace and bicycle path data according to CityGML 3.0 is available for all of these examples, the method is easily transferable.

1. Different bicycle traffic volumes for the same scenario

Figure 4 shows results of the presented method in a web-based Cesium visualization combined with a corresponding semantic 3D city model. Information on bicycle paths available in the CityGML format is used to calculate BLOS scores of the same scenario for different traffic volumes. This is done using different fixed values (e.g. 50, 100, 150, 200, 250 bicycles per hour).

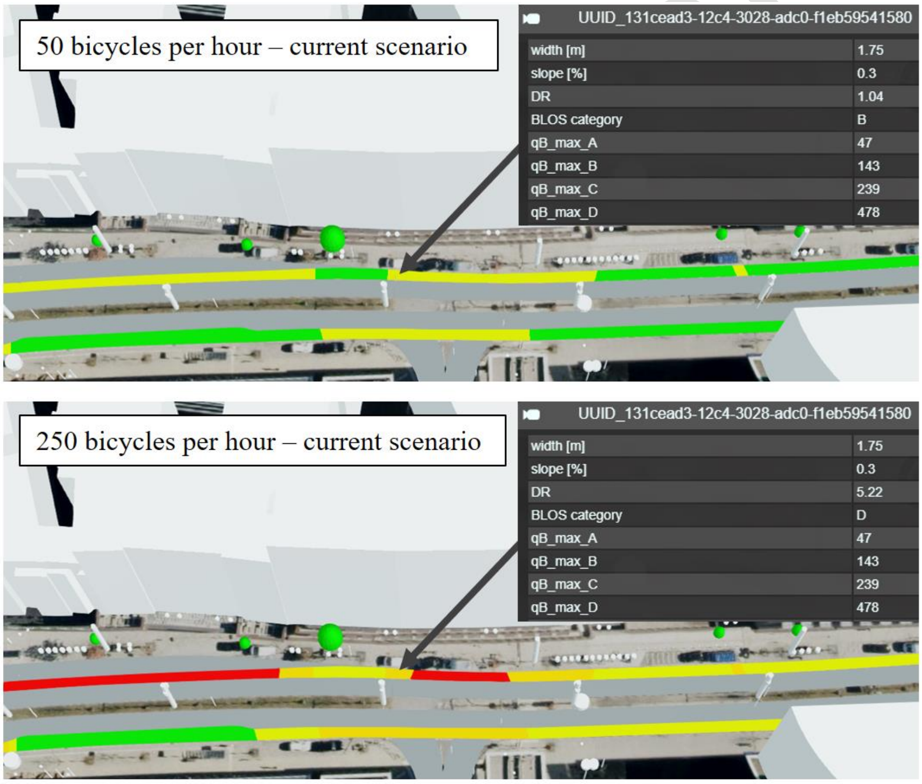

Fig. 4. Web-based Cesium visualization of BLOS results for different bicycle traffic volumes combined with a corresponding 3D city model. Green blobs represent trees.

Additionally, bicycle traffic volumes provided by bicycle counting sensors are available in the research area, providing information on typical average and peak bicycle traffic volumes. Multiple layers colored according to those results are integrated within this visualization. In this example, bicycle paths are split into 2 meter segments, resulting in a high resolution of calculated BLOS scores. The top image in figure 4 shows results for a traffic volume of 50 bicycles per hour, while the bottom image shows results of the same bicycle paths for 250 bicycles per hour.

2. Same bicycle traffic volume for current and planned scenario

Figure 5 shows a direct comparison of BLOS scores of existing bicycle paths with a planned scenario in the same area with increased bicycle path widths. Both scenarios are calculated with the same traffic volume (150 bicycles per hour in this example), showing the improved BLOS for wider bicycle paths. Visualizations of these analyses can be useful in order to present the impact of planned scenarios to the public, demonstrating improved bicycle path qualities according to the presented method.

Fig. 5. Comparison of BLOS values at 150 bicycles per hour of the current state of bicycle paths with a planned scenario.

3. Maximum traffic volume capacity for each BLOS

Using equation 8, maximum traffic volumes can be determined with which a bicycle path segment of a certain (fictional) width is still categorized within a specific BLOS category. For example: Assuming a typical mean speed of cyclists V of 18 km/h with a standard deviation σ of 3 km/h and a local (fictional) width of a segment of 1.75 meter (corresponding to a factor for disturbances due to overtakes f_{DO} of 2.0, cf. table 3), a disturbance rate *DR* of under 1 (equal to category A, cf. table 4) can be achieved for a bicycle traffic volume of up to 47 bicycles per hour. Similarly, maximum capacities for all other BLOS categories are calculated (exemplary results are visible in figure 4). These values can be calculated per bicycle path segment. Additionally, the minimum value of all segments can be determined in order to evaluate the maximum capacity of an entire bicycle path.

4. Comparison of calculated bicycle path widths with recommended minimum widths

Most countries have guidelines on the design of bicycle paths with regard to minimum widths that should be available in order to ensure usability and safety. In addition to evaluating BLOS values, calculated widths of bicycle paths can be compared with such standard widths specified within infrastructure design guidelines and regulations. This allows to determine the percentage of cycle paths (in relation to length) that adhere to these guidelines and to identify segments that do not fulfil them. Typically, bicycle path widths of at least 1.5 meters for one-way lanes are required with a recommended minimum width of 2 meters. Within the research area, over 28 km of bicycle path data is available. Widths are calculated at an interval of 0.6 meters resulting in 47,655 individual bicycle path segments. Segments are categorized by width ranges as summarized in table 6, showing that most of the evaluated bicycle paths are within the recommended ranges. Widths of under 1 meter mostly result from tapered geometries of start and end segments of bicycle paths (as visible in figure 5) and are thus filtered from this evaluation. Alternatively, start and end segments can be filtered with topological information on neighboring segments. Similar metrics can be used to compare bicycle infrastructure of different cities.

Table 6. Percentage of bicycle path widths within a certain range in a citywide research area.

Width range [m]	Nr. of segments	Length [km]	Percentage [%]
≥ 2	16,227	9,74	34.1
$1.5 \leq w < 2.0$	20,658	12,39	43.4
$1.0 \leq w < 1.5$	9,642	5,79	20.3
< 1.0	1,128	0,62	2.2

5 Discussion and Outlook

In this paper, a method for automatically evaluating the Bicycle Level of Services (BLOS) of bicycle path segments based on geometric and semantic parameters derived from semantic 3D city and streetspace models is presented. Requirements of input data and a process to calculate widths and slopes of bicycle paths in a high resolution are shown. Additionally, different ways for considering bicycle traffic volumes required for this evaluation are discussed. Results of this analysis are linked with semantic 3D city objects and visualized within an interactive and web-based Cesium visualization.

The implemented method is chosen due to the potential for automated evaluations of bicycle path qualities for large areas. Parameters relevant for other methods such as the perceived level of comfort of cyclists are not considered. Thus, this method should be combined with other approaches (such as MCA, connectivity analysis, bikeability, etc.) for evaluating the quality of bicycle paths in order to have a holistic result.

While the presented method is based on detailed studies [3], there are some limitations. BLOS is primarily focused on physical attributes of the transportation system and does not take into account social or cultural factors that may affect the perceived quality of bicycle infrastructure. It also does not consider the quality of the connections between different parts of the network or the accessibility of certain destinations that can be reached by bicycle. Results of this method highly depend on accurate calculations of bicycle path widths and slopes. Thus, in order to be able to evaluate accurate BLOS scores, the used input data must be available in great geometric detail and with explicit geometry representations. The 3D streetspace models used in this paper are derived from highly accurate OpenDRIVE data converted to explicit geometries according to CityGML 3.0 and thus provide this information with the required detail. Results of width and slope calculations additionally depend on chosen distance intervals (sampling rates) for which these evaluations are calculated. In this context, a step size of at most 2 meters is recommended. Since BLOS values are categorized based on disturbance rates calculated from bicycle path widths, a difference in width of only a few centimeters may already result in a different BLOS score. While this results in high-resolution evaluations, it can be beneficial to compare results of adjacent segments in order to identify very short segments with results differing from those of neighboring segments and considering a smoothing mechanism. In case no information on elevation or traffic directions is available, the method can still be used in relatively flat areas with slopes of less than 4 % (since this is the threshold for which slopes have an influence on the calculation of a fictional width, cf. table 2). As discussed earlier, semantic 3D streetspace models can provide additional information that could be relevant for the estimation of bicycle path qualities, which are not considered by the implemented method. This includes information on surface smoothness, change of slopes and directions, surface material or speed limits. Additionally, the method only considers bus stops as sources of local disturbances. As presented in this paper, information on adjacent surfaces can easily be determined and thus be extended to influences of adjacent pedestrian paths, driving and parking lanes or structures separating bicycle paths from other traffic members.

Information on bicycle paths and 3D city models can also be used for visibility analysis [25]. Either to determine which parts of a city are visible for cyclists (e.g. in an intersection area) or to evaluate the visibility of cyclists for other traffic members such as car drivers. This is relevant for evaluating the safety of cyclists and to identify potentially dangerous areas. Known positions of cyclists and driving lanes, in addition with information on traffic directions (and thus view direction of cyclists), can be used to calculate lines of sight, which then can be intersected with other city objects such as buildings, vegetation or parking cars. In the context of urban digital twins, an increasing availability of detailed information on the streetspace will allow these evaluations to be used for a number of cities and regions.

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