Bikeability in Basel

Working Paper

Author(s):
Grigore, Elena; Garrick, Norman; Fuhrer, Raphaël; Axhausen, Kay W.

Publication date:
2018

Permanent link:
https://doi.org/10.3929/ethz-b-000283763

Originally published in:
Arbeitsberichte Verkehrs- und Raumplanung 1372

BIKEABILITY IN BASEL

Elena Grigore
IVT ETH Zurich
Stefano-Franscini-Platz 5, 8093 Zurich, Switzerland
Tel: +41 767 27 8162; Email: grigorelena@gmail.com

Norman Garrick. PhD, Professor
University of Connecticut
Storrs, CT 06269, USA
Tel: 860-486-2990; Email: norman.garrick@gmail.com

Raphael Fuhrer, PhD Candidate
IVT ETH Zurich
Stefano-Franscini-Platz 5
8093 Zurich, Switzerland
Tel: +41 44 633 67 37; Email: raphael.fuhrer@ivt.baug.ethz.ch

Dr.-Ing. Kay W. Axhausen, Professor
IVT ETH Zurich
Stefano-Franscini-Platz 5
8093 Zurich, Switzerland
Tel: +41 44 633 31 05; Email: axhausen@ivt.baug.ethz.ch

Word count: 6,905 words text + 2 tables x 250 words (each) = 7,405 words

Submission Date: 01.08.2018

ABSTRACT

"Bikeability" is becoming increasingly relevant in the fields or transport- and urban planning. However, it is not always clear how bikeability is defined, let alone how it can be modeled. The goal of this project is to develop a quantitative method to model bikeability. A case study area in the city of Basel, Switzerland has been selected for assessing the model. Here "bikeability" is understood as the ability and convenience to reach important destinations by bike, based on perceived safety, comfort and attractiveness of the streets and intersections along the routes, as well as the travel distances. The underlying assumption is that cyclists try to minimize the distance traveled and maximize the perceived safety, comfort and attractiveness of their route of choice. Unlike previous bikeability assessements that we have reviewed, our method uses existing route choice studies to quantify the cycling quality, which presumably results in a model, which more accurately reflect real life behavior. Many relevant attributes are included in this work that have not been captured by previous models, such as the gradient, tram tracks and the turn direction at intersections. The method is suitable for a multitude of applications in urban planning, such as the identification of locations that need improvement and the comparison of various planning measures. The current analysis is designed to model conventional bikes being used by commuting cyclists. However, the method can be used for E-bikes and non-commuting cyclists, by applying the appropriate input values.

Keywords: Bikeability, Perceived distance, Route choice, cycling quality, Sustainable transport, Basel

INTRODUCTION

Cycling has become increasingly relevant in transport- and spatial planning because it has the potential to replace motorized transportation for shorter trips. Many cities aim to increase the local modal share of cycling by improving the attractiveness of their cycling network. However, it is not always clear how to quantify the influence of various cycling measures, nor how to prioritize the locations in the network that need improving.

The goal of this work is to develop a method to model bikeability within the Swiss context. It is important to note that there is no consensus in literature about the definition of the term bikeability. In the work of Krenn et al. (*1*) bikeability is used to assess the perceived comfort and –safety of streets. Lowry et al. (*2*) define bikeability as the the ability and convenience to reach important destinations by bike. Thus, bikeability depends on the distance to destinations and on the cyclists' perceived comfort and safety of routes. Their approach in both these studies enables the comparison of various planning measures, by assessing their effect on bikeability. The current work adopts a similar approach. We improve upon the previous state of the art by quantifying the perceived comfort and -safety based on route choice studies found in the literature. Our method includes many relevant attributes of streets and intersections that have not been included in previous assessments of bikeability. The values chosen in this paper are suitable for conventional bikes and commuter cyclists, but the method can be adopted for non-commuters and for E-Bikes.

The approach to assessment in this paper consists of three main steps: first, the perceived comfort, -safety and attractiveness for cycling is evaluated for streets and intersections according to a number of attributes. This will be described by the term "cycling quality". As a second step, a measure of perceived distance for cycling routes is defined according to the cycling quality and the along the actual distance a route. Finally, the perceived distance to the destinations of interest is used to compute bikeability for each cell in the case study area. We define the following terms:

- Cycling quality: a measure of perceived safety, -comfort, and -attractiveness for cycling on each individual street and intersection.
- Perceived distance: a measure of perceived safety, comfort, and attractiveness for cycling for each route in the cycling network, based on the cycling quality of each street and intersection along this route, as well as the actual travel distance.
- Bikeability: a measure of ability and convenience to reach important destinations in the cycling network, based on perceived distances. The underlying assumption is that for each destination, cyclists will choose the route with the shortest perceived distance, which will be refered to as "shortest path".

This work has been carried out in collaboration with the Office of Mobility of Canton Basel-Stadt and for this reason Basel is used as the case study in developing the model. The City of Basel has the highest modal share of cycling of any city in Switzerland (17% in 2015) and is continuously developing its cycling infrastructure published in the document comparing mobility in Swiss cities of Planungsbüro Jud (*3*). The goal is that this bikeability framework will provide agencies such as the Basel Office of Mobility with a suitable tool to identify which parts of the cycling network need improvement, and to asseess which measures are needed to more effectively improve the attractiveness of their cycling network.

LITERATURE REVIEW

Evaluating the cycling quality

For most existing methods to evaluate cycling quality, various attributes of the street are assessed and each attribute is assigned a number of points, which are combined into a total score. Examples of models using this approach are the Bicycle Compatibility Index (BCI) of Harkey et al. (*4*), and the bicycle level of service (BLOS), described in the Highway Capacity Manual (HCM) (*5*). However, these methods do not include many attributes that are found to be relevant in the route choice of cyclists, such as the gradient, cycle tracks and specific intersection treatments (e.g. bike lanes or bike boxes). Moreover, they have been developed for the US, and their application into the European context must be done with care.

Furthermore, the scores of BCI and BLOS are assigned according to an arbitrary scale, and are not developed based on route choice studies, as can be observed in the Implementation Manual of the BCI of FHWA (*6*) and in HCM (*5*). A more suitable method to identify and quantify the attributes important for cyclists is to conduct a route choice study, by comparing GPS traces of the cyclists' actual routes with the shortest possible routes, as has been done by Krenn et al. (*1*), Winters et al. (*7*) and Broach et al. (*8*).

Because such an analysis goes beyond the scope of this work, the choice and quantification of attributes will be largely based on the findings of Broach et al. (*8*). This is the most extensive study found in literature regarding the route choice of cyclists.

Of course, adopting attribute values identified in a different city must be done with care. The analysis of Broach et al. (*8*) was conducted in Portland, Oregon while the current analysis is for Basel. One could argue that cyclists' expectations in Portland are different than in Basel, since fewer people cycle in Portland. According to Pucher & Buehler (*9*) the modal share of cycling in Portland amounts to 6%, which is about 3 times lower than in Basel, according Planungsbüro Jud (*3*). It is expected that cyclists' safety is higher in Basel, and cyclists in Portland are part of a social group who is more likely to take risks.

Cycling quality attributes of streets

This section presents the attributes selected to assess perceived safety, -comfort and attractiveness of streets for cycling. The selection is based on how influential the attributes are for cyclists, according to existing literature and to existing policy guidelines in Switzerland and other high biking places including the Netherlands and Denmark. Finally, a number of attributes that have not been included in the analysis will be mentioned.

The first attribute selected for inclusion in this model is the street gradient. Cycling uphill requires more physical effort than riding on a flat surface, while cycling downhill can be dangerous due to increased cycling speeds, as found by Pestalozzi und Stäheli (*10*). Krenn et al. (*1*), Winters et al. (*7*) and Broach et al. (*8*) identify the gradient as one of the most influential attributes in the route choice of cyclists.

The next attributes selected are the type of cycling infrastructure along with the speed limits and the level of motorized traffic volumes According to the Swiss, Danish and Dutch cycling guidelines, different types of cycling infrastructure are recommended at different speed limits and different levels of motorized traffic volumes, measured as annual average daily traffic (AADT) in vehicles/day (veh./day) (*11*,*12*,*13*). Different widths are recommended for different types of cycling infrastructures, according to Basel's guideline for cycling (*14*).

The third class of attributes considered are a variety of hazardous conditions. The Swiss Federal Roads Office (ASTRA) (*11*) specifies that certain street elements and layouts pose danger to cyclists. Examples are the presence of car parking and tram tracks in combination with insufficient space or steep gradients. If the AADT is too high for the given street width, dangerous overtaking situations might take place. Streets with a percentage of heavy traffic higher than 8% should not be included in the cycling network (*12*). These additional risks will be refered to as "hazards" in the current work.

Finally, the forth attribute class considered is the attractiveness of the riding environment which from the literature is known to play a role in the route choice of cyclists. Krenn et al. (*1*) find that cyclists prefer to ride along routes with green and water. Green and water improve the cycling experience due to better aesthetics, but also due to cooling in the summer.

Other attributes of streets that are positively perceived by cyclists are smooth surfaces, the presence of lighting, and lack of interruptions, according to ASTRA (*11*). These appear less frequently in the revealed- and stated preferences studies reviewed. Therefore, they are assumed to be less influential on the cyclists' route choice than the attributes mentioned above, and they will not be included in the analysis.

Cycling quality attributes of intersections

This section presents the attributes selected to assess perceived safety, -comfort and attractiveness of intersections for cycling. The selection is based on existing literature and policy guidelines. Attributes that have not been included are mentioned at the end of this section.

The first attribute selected is the intersection AADT. Broach et al (*8*) find that the AADT plays a role in cyclists' route choice for unsignalized intersections (without traffic light), and that its influence depends on the turn's direction, with left turns being more problematic than right turns.

The second and the third attributes selected are the presence of traffic lights and stop signs. Broach et al. (*8*) find that cyclists in Portland try to avoid traffic lights and stop signs. Carter et al. (*15*) find that the number of car lanes reduces perceived safety, while Buch and Jensen *(16)* state that the presence of a car lane turning right can be a source of conflict for cyclists going straight. The number of car lanes and the presence of a car lane turning right will be included in the analysis.

Proper intersection treatments can offset the negative effects of these factors. Carter et al. (*15*) find that bike lanes improve cyclists' comfort, while Dill et al. (*17*) find that bike boxes increase the cyclists' perceived safety and comfort. The use of bike lanes and bike boxes is prescribed by the Swiss norm regarding intersection design (*18*) and if there is no space for them, protected spaces for indirect left turns must be provided instead. The presence of bike lanes, bike boxes and spaces for indirect left turns have been selected for the analysis.

Other important intersection attributes are the crossing distance (included in BLOS in HCM) (*5*) and the speed limits, according to Carter et al. (*15*). Both attributes are expected to be relevant especially for unsignalized intersections with high traffic volumes. The presence of bicycle specific traffic lights is expected to improve perceived comfort, according to Basel's guideline for cycling (*14*). Nevertheless, there is no quantification found in literature about these three attributes, and bicycle specific traffic lights are found at very few intersections in Basel. In order to keep the analysis simple, they will not be included in this work.

Bikeability

Few attempts to compute bikeability incorporate distance to destinations into the calculation. An example is the method of McNeil (*19*), who calculates accessibility for cyclists by assigning points to various types of destinations within a 20 minutes bicycle ride, based on distance. His method is similar to the Walk Score (*20*) and does not incorporate the cycling quality. Klobucar and Fricker (*21*) assume that cyclists make decisions such as to minimize the distance and to maximize the cycling quality. They weigh the length of each link in the network by the Bicycle Compatibility Index (BCI). Lowry et al. (*2*) take this idea further, by calculating the accessibility to destinations, using the link length times the cycling quality as travel cost. Instead of using BCI, they used BLOS to calculate the cycling quality.

The current work builds on the examples of Klobucar and Fricker (*21*) and Lowry et al. (*2*), by assuming that cyclists choose their route such as to minimize the distance and to maximize the cycling quality. We improve upon the existing state of art by identifying and quantifying the cycling quality attributes based on existing route choice studies, which more accurately reflect real life behavior. The goal is to find a suitable manner of scaling the actual distance to obtain the perceived distance, based on cyclists' actual route choice. Because the BCI and BLOS scores use an arbitrary scale, they are not very suitable to be multiplied with the distance. For example, a BLOS of 2 for a street segment does not indicate that a cyclist prefers that segment two times more than a segment with a score of 4.

METHOD

Overview

The underlying assumption is that cyclists chose their route as to minimize the actual distance and to maximize the quality of streets and intersections along the way. In reality, other factors play a role in cyclists' route choice. Götchi et al. (*22)* point out the importance of the so called "unreasoned behavior", driven by habits and impulsiveness. However, a quantification of these two factors has not been found in existing literature on route choice, and goes beyond the scope of the current work. Therefore, they will not be included in our method.

It is assumed that, if the route with the shortest actual distance does not provide the desired quality, cyclists are willing to detour from it and travel along a longer route of better quality, as found by Krenn et al., Winters et al., and Broach et al. (*1*,*7*,*8*). The lower the quality of a street or intersection, the longer cyclists are willing to detour from it. Therefore, the quantification of this detour for each street- and intersection attribute will be used to define a cost for each attribute. The separate attribute costs are combined into a total cost for each street and for each intersection. The perceived distance for each route is calculated by scaling the actual distance by the cycling quality costs of the streets and intersections along the way. At the end, bikeability is computed for each cell in the case study area, using the shortest perceived distance to each destination of interest as travel cost.

The case study area is located in the City of Basel (Figure 1). It consists of the part of the city center south of the Rhine River along with the adjacent neighborhood of St. Johann that lies to the northeast of the center. Basel is densely built and there is little space available for new cycling infrastructure. Typical challenges for cyclists in Basel are posed by the presence of tram tracks, high curbs, car parking, as well as hilly topography in the center.

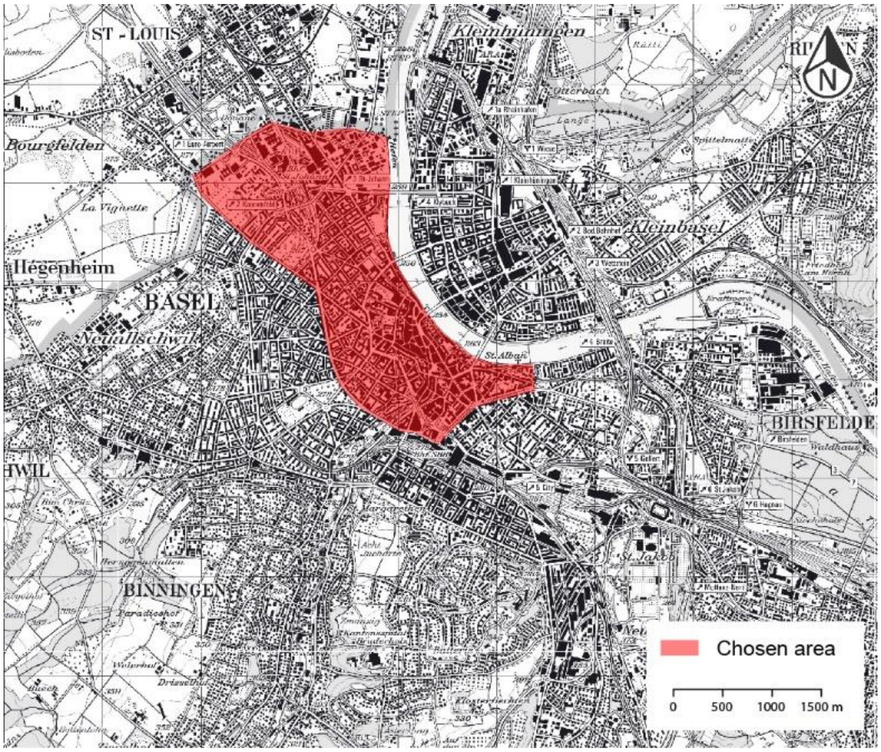

FIGURE 1: Selected case-study area within the City of Basel

Assessing the cycling quality of street segments

The cycling quality of streets will be assessed for each street segment in the case-study area. A segment is defined as having a continuous type of cycling infrastructure, such as a bike lane or a cycle track. If the type of infrastructure changes, a new segment is defined. Moreover, when at least two streets come together (at intersections) new segments are defined.

The cycling quality of each segment will be measured by the “perceived length” of the segment. In other words, a segment of good quality is assumed to be perceived as shorter than its actual length, while a segment of lower quality is perceived as longer. To obtain the perceived length, the actual length is multiplied by a scaling factor, called a “cost multiplier”. Cost multipliers greater than 1 indicate that the quality is lower than expected by cyclists and therefore the perceived length will be longer than the actual length. Values lower than 1 indicate good quality (better than expected) and cost multipliers equal to 1 indicate neutral or as expected quality.

In order to assess the cycling quality of segments, the following attributes have been selected for inclusion in the assessment based on our survey of the literature and the various design standards: the gradient, the type and dimensions of the cycling infrastructure (relative to speed limits and AADT), the presence of hazards, and the esthetic and comfort of the riding environment. For each of these four attributes, a cost is defined guided by our interpretation of the existing literature. The cost multiplier of segments is calculated by adding up the separate costs of each attribute, following the examples of Krenn et al. (*1*) and Winters et al. (*7*). The riding environment will be assessed as a benefit instead of a cost, and it will therefore be subtracted from the total. The formula to compute the cost multiplier of segments is given by:

$$CM_s = C_{Gr} + C_{Inf} + C_{Hz} - B_{Env} \tag{1}$$

Where CM_s is the cost multiplier of street segments, C_{Gr} is the cost due to gradient, C_{Inf} is the cost due to the type and dimensions of cycling infrastructure, C_{Hz} is the cost of additional hazards, and B_{Env} is the benefit of the riding environment.

In order for the costs to add up to 1 for the neutral situation, one attribute (cycling infrastructure) will be assigned a cost of 1 for the neutral condition, while all the others attributes will be assigned a cost of 0 for their corresponding neutral condition. For example, a cost of 1.3 for cycling infrastructure represents a cost increase of 30% in comparison to the neutral situation, while for any other attributes, a 30% increase in cost is given as a score of 0.3.

Quantifying the cycling quality attributes of streets

The first attribute selected for the analysis is the gradient. The gradient cost for uphill slopes is quantified based on a graph that shows how the cycling speed varies with gradient. This graph is found in the Swiss norm regarding bicycle traffic (*23*). From the speed reduction for each positive gradient, one can deduce by how much the distance covered by the cyclist is lowered, assuming the same physical effort for cycling compared to a level road. Steep negative gradients increase collision risks for cyclists due to higher cycling speeds, but unlike positive gradients, they have not been identified by route choice studies and they are assumed to have a lower cost. Small downhill slopes are expected to have a benefit, due to decreased effort without affecting the safety. Based on these considerations, a gradient cost function is defined (Figure 2).

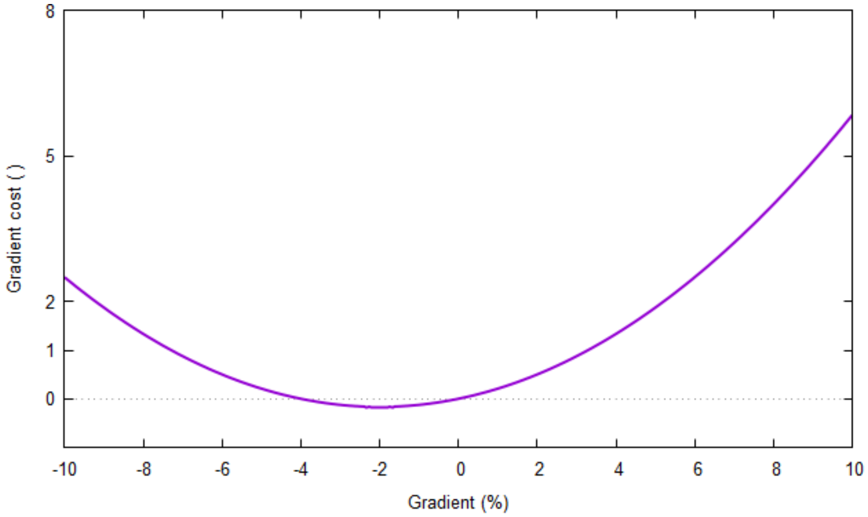

FIGURE 2: Gradient cost function

The second attribute included is the cycling infrastructure. This accounts for the type of cycling infrastructure chosen, based on the speed limit and AADT, as well as for the widths of bike lanes and cycle tracks. The types of cycling infrastructure identified in Basel's guideline for cycling *(14)* are listed below:

- Bikes + pedestrians
- Bikes + motorized + pedestrians
- Bikes + motorized
- Bike lane
- Bus lane with bikes allowed
- Cycle track
- Bike boulevard

Different types of cycling infrastructure are recommended for different AADT and speed limits, according to the Swiss, Danish and Dutch guidelines (*11*,*12*,*13*). Cost functions are defined for the cycling infrastructure types "Bike + motorized" and for bike lanes, for the speed limits of 30- and 50 Km/h, according to AADT. Bus lanes are considered to be the same as bike lanes.

The first function to be defined is that of "Bikes + motorized" at 30 Km/h. In this case, the neutral condition is assumed to be an AADT of less than 3,000 veh./day, because this traffic volume is found to be acceptable for bikes riding together with cars at 30 Km/h, according to the national Swiss guideline in ASTRA (*11*). As discussed earlier, this neutral condition is given a score of 1 for cycling infrastructure. The growth rate of the function "Bikes + motorized" at 30 Km/h is defined based on the findings of Broach et al. (*8*). Segments with higher speeds or with bike lanes are penalized according to the schedule shown in Figure 3. It is assumed that an increase in speed or the addition of a bike lane leads to a change in cost of about 20-30%. This estimation is based on the fact that improvements in cycling infrastructure (such as the addition of a cycle track or a bike boulevard) in the work Broach et al. (*8*) lead to cost reductions of about 10-20%. Only bike lanes of widths between 1.5 m and 1.8 m are included in this graph.

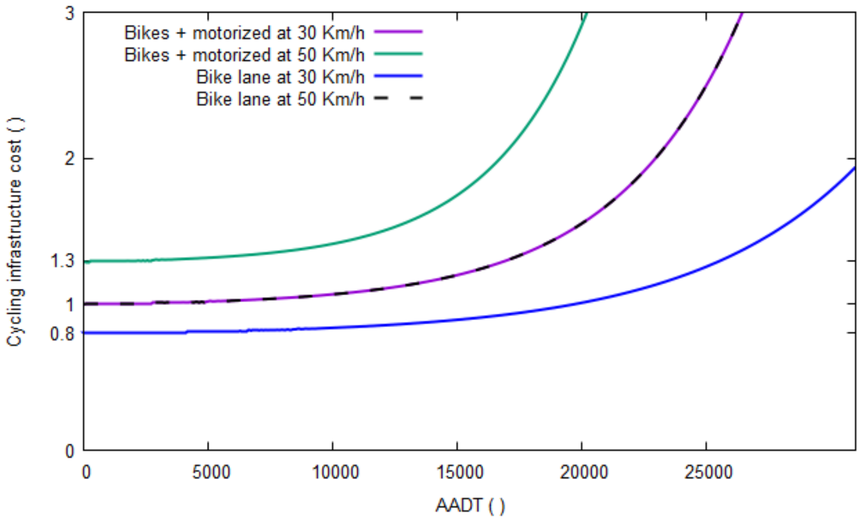

FIGURE 3: Cycling infrastructure cost functions for the ca "Bikes + motorized" and bike lanes at speeds 30 and 50 Km/h

For the other types of cycling infrastructure, constant costs are assumed. Bike boulevards are assigned a cost of 0.9 based on the findings of Broach et al. (*8*), while for the cases when bikes ride together with pedestrians, a higher cost of 1 is assumed, due to collision risk with pedestrians. For cycle tracks and bike lanes, the cost depends on the widths: cycle tracks of optimal widths are assigned a cost of 0.8, which has been found by Broach et al. (*8*) to be the cost of cycle tracks. For narrower widths, higher costs of 0.9 and 1 are assumed. Bike lanes within the recommended widths of 1.5 m -1.8 m are penalized according to the functions shown in Figure 3. Bike lanes narrower than the minimum width of 1.2 m are not included at all, while for widths of 1.2 m -1.5 m, a weighted average is taken between the function of bike lane, and the one of "Bike + motorized" shown in Figure 3. The recommended widths are identified based on Basel's guideline for cycling (*14*), Dutch guideline CROW (*13*) a Swiss norm on cyling (*24*). A summary of all cycling infrastructure costs is shown in Table 1.

TABLE 1 Cycling infrastructure costs

Type of cycling infrastructure	Cycling infrastructure costs
Bike + motorized at 30 Km/h	Figure 3
Bike + motorized at 50 Km/h	
Bike lane (1.5 -1.8 m) / bus lane at 30 Km/h	
Bike lane (1.5 -1.8 m) / bus lane at 50 Km/h	
Bike lane (< 1.2 m)	The same as "Bike + motorized"
Bike lanes (1.2 -1.5 m)	Weighted average between "Bike + motorized"- and bike lane functions at each speed limit
Bike + pedestrians	1
Bike + motorized + pedestrians	1
Bike boulevard	0.9
Cycle track of 3.0 m (one direction) or 3.4 m (bidirectional)	0.8
Cycle track 2.6 – 2.9 m (one direction) Or 2.8 – 3.3 m (bidirectional)	0.9
Cycle track < 2.6 m (one direction) Or < 2.8 m (bidirectional)	1
Bike lanes > 1.8 m	1

The third attribute included are the hazards discussed earlier. The list of hazards and their costs is shown in Table 2. These are identified based on the recommandations of ASTRA (*11*) and Pestalozzi and Stäheli (*10*). Tram tracks and high curbs are found at many places in Basel and are typical of European cities. Because they increase the collision risk for cyclists and are negatively perceived, their planning requires special attention.

A previous quantification of the hazards listed below has not been found in existing literature on cyclists' route choice. A maximum penalty of 50% has been chosen. It is not expected that cyclists detour longer than 50% from the shortest route, because according to Broach et al. (*8*) the average detour of commuter cyclists amounts to 11%. If there are more hazards along a segment, the maximum cost value of any of the given hazard will be used as the hazard cost for that segement.

TABLE 2 Chosen hazards and their costs

Hazard	**Hazard cost ( )**
Longitudinal parking + Bike lane closer than 50 cm	0.2
Longitudinal parking + Bike lane closer than 50 cm + Gradient < -4% or Gradient > 4%	0.5
Longitudinal parking + tram tracks closer than 2.65 m	0.3
Longitudinal parking + tram tracks closer than 2.65 m + Gradient < -4% or Gradient > 4%	0.5
Longitudinal parking + „Bike + motorized“ + Gradient < -4% or Gradient > 4%	0.3
Angular or perpendicular parking	0.2
High curbs along tram stops without bike specific measures	0.2
Percentage of heavy traffic > 8% of AADT (traffic oriented streets)	0.2
AADT too high for the given street width	0.2

The fourth and final attribute used to assess the cycling quality of segments in this paper is the riding environment. Erath et al. (*25*) find that the presence of greenery leads to a reduction of 20% in the perceived travel time for pedestrians, in comparison to the actual travel time. Because directness is more important for commuting cyclists than for pedestrians, a maximum decrease in cost of 10% is assumed. The benefit function is based on the coverage of green and water within a buffer of 20 m around the center of the roadway. The benefit function is given in Figure 4.

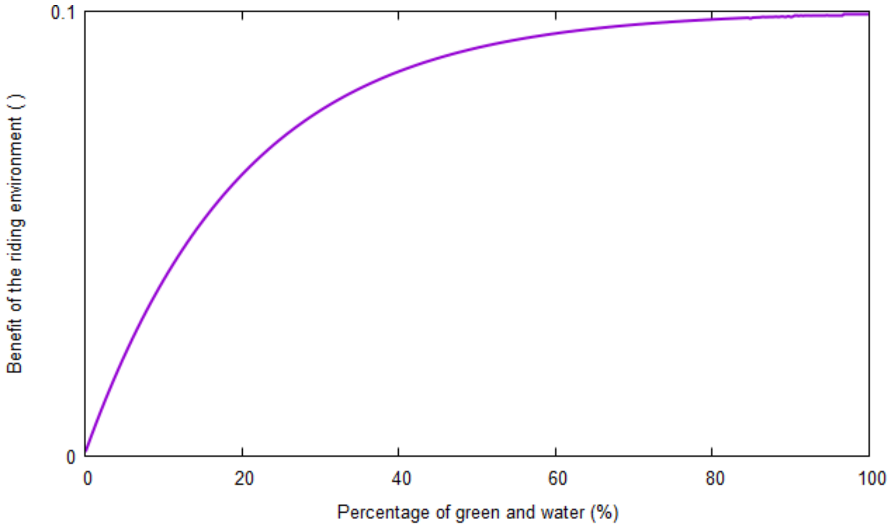

FIGURE 4: Benefit of the riding environment

Assessing the cycling quality for intersections

In order to assess the cycling quality of intersections, turn costs are defined, corresponding to the distance cyclists are willing to detour from the shortest route, in order to avoid taking that turn. The following attributes are identified and quantified as turn cost components based on the findings of Broach et al. (*8*): basic turn, traffic light, AADT and stop signs. The basic turn cost accounts for the fact that cyclists always try to avoid turns. If the intersection is signalized, a traffic light cost (except for right turns) is added to the basic turn cost. If it is unsignalized, an AADT cost is added instead, depending on the AADT of the intersection and the turn direction. A stop sign cost is added, if necessary.

The next step is to account for intersection treatments and layout characteristics, using the following attributes: bike lanes, bike boxes, spaces for indirect left turns, number of car lanes (for direct left turns), and the presence of a car lane turning right at unsignalized intersections (for bicycle traffic going straight). Because there is no quantification of these attributes found in cycling route choice studies, these attributes will be quantified in comparison to each other, based on existing literature. For example, indirect left turns are generally avoided by cyclists, as mentioned in the Swiss norm regarding intersection design (*18*), therefore their benefit is assumed to be lower than that of bike lanes or bike boxes. A so called “layout multiplier” has been defined, to quantify the influence of these factors.

The procedure to compute the turn cost is shown in Figure 5. First, the basic turn is added to the traffic light cost (for signalized intersections), or to the AADT cost (unsignalized intersections). A stop sign cost is added if necessary. Afterwards, the result is multiplied with the layout multipliers corresponding to the intersection characteristics shown in Figure 5.

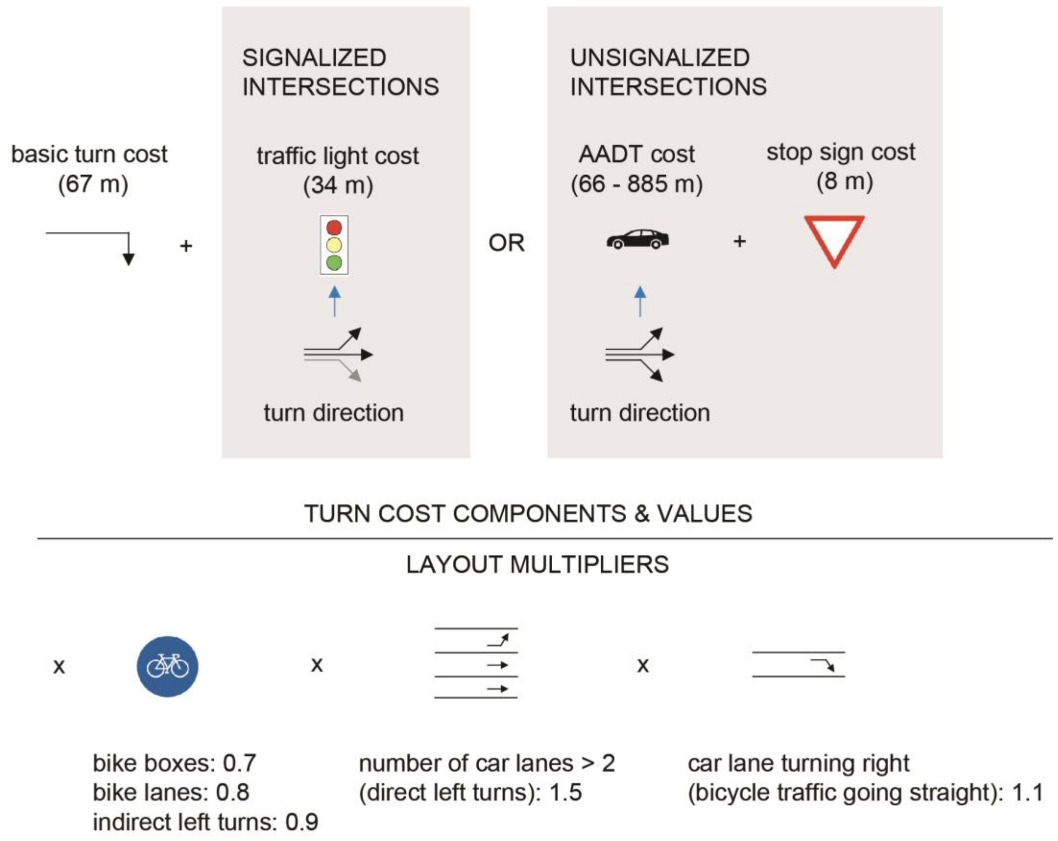

FIGURE 5: Procedure to compute the turn cost

Perceived distance

The perceived distance along a route is defined by the sum of the all perceived lengths of the segments (m) and the all turn costs (m) along the route. This can be written formally as:

$$P_{ij} = \sum_{s \in R_{ij}} (M_s L_s) + \sum_{t \in I_{ij}} C_t \qquad (2)$$

where P_{ij} is the perceived distance along the route from i to j, s is a segment along the route, R_{ij} is the subset of segments along the route, M_s is the cost multiplier of each segment, L_s is the actual length of each segment, t represents each turn along the route, I_{ij} is the subset of intersections along the route, and C_t is the turn cost.

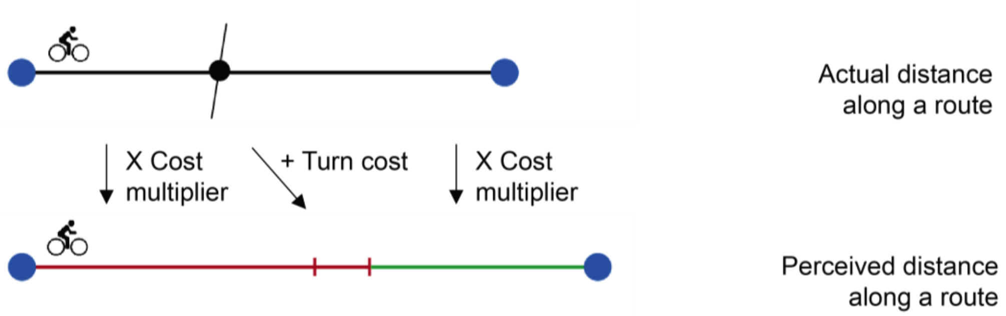

FIGURE 6: Actual distance vs. perceived distance along a route

Mapping bikeability

Once the cycling quality has been calculated and important destinations have been identified, bikeability can be computed for each 100 m x 100 m cell in the case-study area. This section explains the rationale behind the calculation and the equation.

For this analysis, workplaces have been chosen as destinations, because the case study is done for commuter cyclists. Nevertheless, any type of destinations could be used to assess bikeability.

As explained earlier, it is assumed that cyclists choose the route with the shortest perceived distance, which is refered to as "shortest path". Bikeability is computed as the average of the perceived distances along the shortest paths to all destinations of interest, weighted by the intensity of activities at destinations (number of workplaces). Normalizing by the number of workplaces is necessary, so that bikeability depends only on perceived distances, and not on the absolute number of workplaces. This rationale can be written formally as:

$$b_i = \frac{\sum_{j \in D} (w_j \times p_{ij})}{\sum_{j \in D} w_j} \qquad (3)$$

where b_i is the bikeability of source i, j represents each destination hectare center in the subset D, w_j is the intensity of activity (number of workplaces) at the destination j, and p_{ij} is the perceived shortest path (measured in m) from source i to each destination j.

Although the cycling quality of segments and intersections is assessed only for the case study area, all the workplaces in the canton of Basel-Stadt will be included in the computation. This includes the City of Basel and two nearby villages, Riehen and Bettingen. Outside the case study area, the average cost multiplier of segments and the average turn cost found within the case study area will be used for calculations.

RESULTS

Overview

This section presents first the results for the cycling quality of streets and intersections as maps. Afterwards, the bikeability map will be presented.

Cycling quality of streets

The cycling quality of streets for the case study area can be seen in Figure 7 for both directions of travel. The coloured segments represent the streets included the case study area, while the black ones are located outside of this area, but within the canton Basel-Stadt. The light grey area is located in Switzerland, while darker surface is in France. Green segments indicate high cycling quality (lower cost multipliers), while the red ones represent lower quality (high cost multipliers).

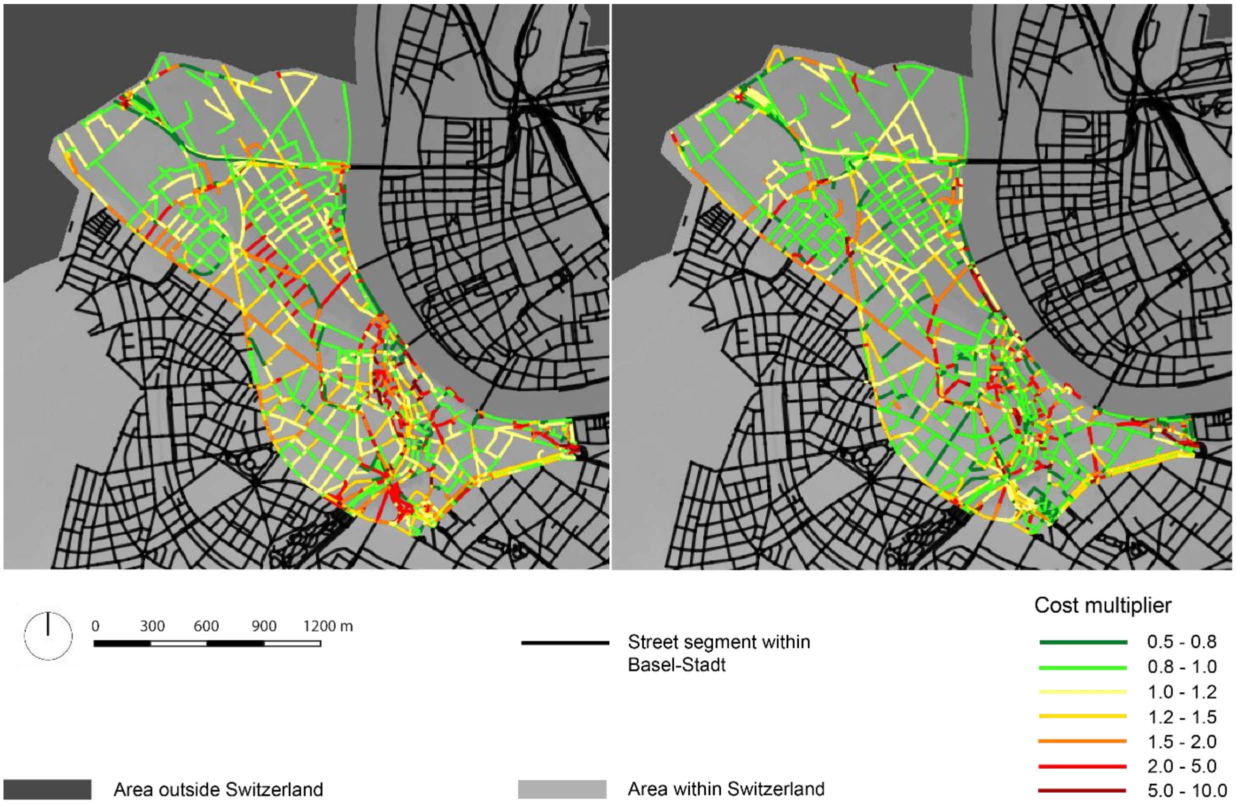

FIGURE 7 Cycling quality for segments in the case study area for both directions of travel

Residential streets generally have higher quality than traffic oriented ones, except when they are located along steep slopes. Cost multipliers higher than 2 are due either to high gradients, or to high AADT and speed limits for the case when bikes ride together with cars.

Cycling quality of intersections

Because each intersection consists of more than one turn, it is not possible to visualize all turn costs in one map. However, it is possible to visualize any separate attribute, by depicting the number of turns having that attribute for each intersection. In this case, a visualization based on the number of left turns without cycling infrastructure (bike lane or –box) for traffic streets, as well as the intersection AADT is made. This helps us visualize problematic turns, since left turns are more negatively perceived at high AADT than going straight or turning right, as found by Broach et al. (*8*), and their cost reaches a value of 885 m by an AADT > 20,000 veh./day for unsignalized intersections.

The vizualisation is shown in Figure 8. The color represents the number of traffic streets without bike lanes or bike boxes for left turns at the intersection, while the bullet size shows the AADT of the intersection.

FIGURE 8 Number of traffic streets without cycling infrastructure for direct left turns, for each intersection in the case study area

A number of intersections can be observed, for which there is no cycling infrastructure for left turns along traffic streets available. These are not comfortable for cyclists, especially by high AADT. Moreover, one can observe many large yellow dots along the middle axes. These are problematic for cyclists turning left towards the residential streets.

Bikeability

Bikeability is calculated with the method described earlier and is mapped in Figure 9 for the case study area. Green represents higher bikeability, corresponding to a shorter average perceived distance to workplaces, while orange indicates lower bikeability due to longer perceived distances.

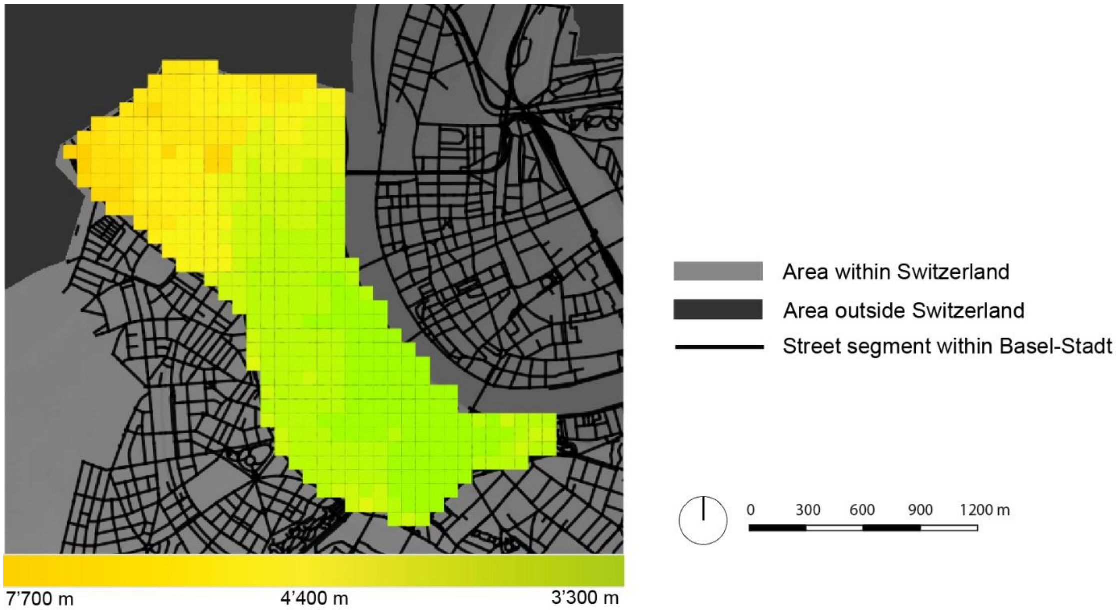

FIGURE 9 Bikeability for the case study area

As expected, better values are found in the city center, because the distances to all workplaces in the canton are shorter. Because this measure is strongly dependent on the actual distance, a new measure is needed that removes this dependency, and enables the identification of places where improvements in the bicycling network are necessary.

ANALYSIS

Identifying locations that need improvement

This section presents a procedure to identify locations that need improvement. First, this procedure will be explained in detail. Afterwards, a map depicting the locations to be improved will be shown.

The procedure can be summarized as follows: first, bikeability is computed for each cell. Afterwards, the average distance to all destinations along the shortest possible routes is calculated. As a next step, the average distance is scaled and then it is subtracted from bikeability for each cell in the case study area.

The rationale behind this can be explained by looking at the growth rate of the (scaled) actual distance and the perceived distance during a cycling trip shown in Figure 10. The actual distance increases linearly during the trip, while the perceived distance increases according to the cycling quality of each segment. Along segments of lower quality than average, it increases at higher rate, and along segments of higher quality it increases at lower rate than the actual distance. When the cyclist rides from a lower quality to a higher quality segment, the perceived distance becomes higher than the actual distance, as seen in Figure 10. The same is true at network level: if, for a particular cell in the area, bikeability is higher than the scaled average distance to destinations (along the shortest possible route), it means that the outgoing segments from that cell are of lower quality than the average. These poorly connected spots are shown in orange in Figure 10. Similarly, green spots are well connected and their outgoing segments are of high quality.

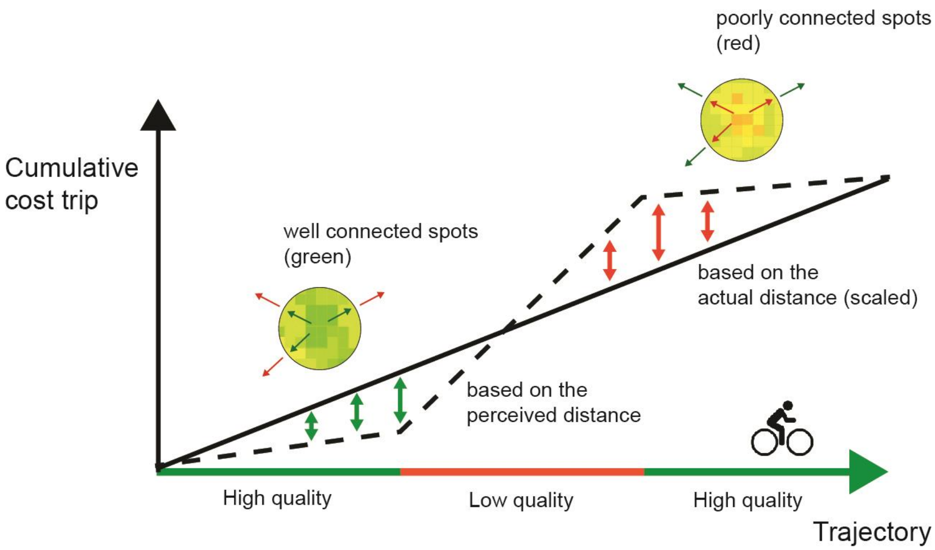

FIGURE 10: Comparison between the cumulative cost of a cycling trip based on the (scaled) actual distance and cumulative cost of a cycling trip based on perceived distance

Therefore, the average (scaled) distance to destinations is subtracted from bikeability. The result is mapped in Figure 11 and is expressed in meters. Orange cells represent the larger values greater than 0 (around 1,000 m), and are the less well-connected to the surrounding cells than the rest. Green shows values lower than 0, corresponding to the cells that are better connected than the others. Yellow represents values greater than 0 that are not very large (around 0 - 500 m). These cells are not very well connected, but they are not the most problematic in the area.

FIGURE 11 Subtraction of scaled average distance to workplaces from bikeability to workplaces

Identifying locations that need improvement is relevant in the planning process. The cycling quality maps of segments and intersections show locations of poor quality, but they do not tell us where improvements are relevant. For example, if a cyclists can choose between two parallel routes that are significantly different in quality but comparable in distance, improving the route with lower quality might not bring any appreciable advantage for most cyclists.

Sensitivity analysis

A sensitivity analysis has been carried out for the case study area, whereby improvements in cycling infrastructure has been proposed at the locations identified in Figure 11 (e.g. adding cycle tracks). It has been found that improvements in cycling infrastructure have limited impact on the average bikeability score of the area. Possible explanations for this are that the score is more influenced by the actual distance and by the gradient than by the cycling infrastructure. Nevertheless, cells located in the vicinity of the proposed measures show high reductions in perceived distances to workplaces. An analysis of all perceived distances to workplaces from one cell shows a maximum reduction of 881 m in perceived distance compared to the base scenario. A more detailed explanation of the sensitivity will not be presented, because it goes beyond the scope of this paper.

Applications in urban planning

The current method is suitable for a multitude of applications in urban planning, such as:

- Visualize the quality of both streets and intersections
- Identify locations where improvements in the cycling quality are necessary
- Compare different planning measures by assessing their impact on bikeability
- Provide insight into which streets are suitable to be included in the cycling network of a city
- Assess and compare different neighborhoods according to their bikeability level

Strengths and comparison to other methods

The framework developed has several advanges compared to the previous state of the art. First, the cycling quality is quantified according to route choice studies, while the methods of Lowry et al. (*2*) and Klobucar and Fricker (*22*) use the arbitrary scales of BLOS and BCI, which are less suitable for routing calculations. Second, the method includes relevant attributes that are not included in BLOS and BCI, such as the gradient, the hazards, the presence of tram tracks for segments, as well as bike lanes, bike boxes and indirect left turns for intersections. Furthermore, the method presented here takes into account separate turn directions at intersections in the routing calculation, while previous analyses assess intersections as a whole. Finally, the method enables the identification of locations for which improvements are necessary, and is suitable for other applications in planning named above.

CONCLUSION

The bikeability framework proposed provides planners with a powerful tool in assessing the impact of different planning measures on cycling, as well as identifying relevant locations for improvement. It relies on a holistic approach, because it considers relevant attributes for both streets and intersections. Although the analysis has been conducted only for commuter cyclists and conventional bikes, the method can be applied for non-commuters and E-bikes, by using different values for the cycling quality attributes. Furthermore, the assessment can be carried out for different areas and different types of destinations.

Further refinement of this approach should focus on conducting stated- or revealed preferences surveys, in order to help refine the identification and quantification of the cycling quality attributes, for the location to be analyzed. This can be done by comparing GPS traces of the actual routes chosen by cyclists with the shortest possible routes, following the examples of Krenn et al. (*1*), Winters et al. (*7*) and Broach et al. (*8*). More sensitivity analyses are necessary to investigate the influence of each quality attribute on the final score. Finally, one could investigate the relationship between bikeability and the modal share of cycling.

AKNOWLEDGEMENTS

This project has been carried out in collaboration with the Office of Mobility of Canton Basel-Stadt. GIS data regarding the cycling network and a number of attribute values have been provided.

AUTHOR CONTRIBUTION STATEMENT

The authors confirm contribution to the paper as follows: study conception and design: Elena Grigore, Norman Garrick, Raphael Fuhrer; data collection: Elena Grigore; analysis and interpretation of results: Elena Grigore, Norman Garrick, Raphael Fuhrer, Kay W. Axhausen; draft manuscript preparation: Elena Grigore, Norman Garrick. All authors reviewed the results and approved the final version of the manuscript.

REFERENCES

1. Krenn, P. J., P. Oja, and S. Titze. Development of a Bikeability Index to Assess the Bicycle-Friendliness of Urban Environments. *Open Journal of Civil Engineering*, 2015. 05: 451–459.
2. Lowry, M.B. , D. Callister, M. Gresham and B. Moore. Using Bicycle Level of Service to Assess Community-wide Bikeability. *Transportation Research Record: Journal of the Transportation Research Board*, 2012. 2314**:** 41-48.
3. Planungsbüro Jud: *Städtevergleich Mobilität. Vergleichende Betrachtung der Städte Basel, Bern, Luzern, St.Gallen, Winterthur und Zürich im Jahr 2015*. ActivPrint AG, Zürich, 2017.
4. Harkey D., D.W. Reinfurt and M. Knuiman. Development of the Bicycle Compatibility Index. *Transportation Research Record: Journal of the Transportation Research Board,* 1998. 1636: 13-20.
5. *2010 Highway Capacity Manual*. Transportation Research Board, 2011.
6. FHWA. The Bicycle Compatibility Index. A Level of Service Concept, Implementation Manual, 1998.
7. Winters, M., E.M. Setton, K. Teschke and M. Brauer. Mapping bikeability: a spatial tool to support sustainable travel*, Environment and Planning B: Planning and Design,* 2013. 40: 865 – 883.
8. Broach, J., J. P Gliebe, and J. Dill. Bicycle Route Choice Model Developed from RevealedPreference GPS Data. Paper presented at the 90th Annual Meeting of the Transportation Research Board, Washington D.C., 2011.
9. Pucher J. and R. Buehler. *City Cycling*. MIT Press, Cambridge, 2012.
10. Pestalozzi & Stäheli *Technischer Bericht zum Teilrichtplan Basel-Stadt.* Department of Construction and Civil Engineering Basel-Stadt (BVD), Basel, 2012.
11. Swiss Federal Roads Office (ASTRA), SchweizMobil, Road Safety Fund. *Planung von Velorouten*. *Handbuch*. ASTRA, Bern, 2008.
12. Celis Consult. *Håndbog i cykeltrafik en samling af de danske vejregler på cykelområdet*. Celis Consult, Egå, 2014.
13. CROW. *Design Manual for Bicycle Traffic*. CROW, Ede, 2007.
14. Baker, J., and M. Schmidt. *Planungshilfe für die Gestaltung von Anlagen des Fuss- und Veloverkehrs. Grundsätze und Projektierung*. Department of Construction and Civil Engineering Basel-Stadt (BVD), Basel, 2017.
15. Carter, D.L., W.W. Hunter, C.V. Zegeer and J.R. Stewart. *Pedestrian and Bicyclist Intersection Safety Indices*. Turner-Fairbank Highway Research Center. *Federal Highway Administration, FHWA-HRT-06-130*, 2007.
16. Buch, T. S., and Jensen, S. U. *Sikkerhedseffekter af tilbagetrukne stopstreger - før-efter uheldsevaluering af 123 signalregulerede kryds*. Trafitec, Copenhagen, 2012.
17. Dill, J., C.M. Monsere and N. McNeil. *Evaluation of Bike Boxes at Signalized Intersections*. Transportation Research and Education Center (TREC), University of Portland, Portland, 2011.
18. Swiss Association of Road and Traffic Professionals (VSS) *SN 640 252: Knoten Führung des Veloverkehrs*, Zurich, 2017.
19. McNeil, N. Bikeability and the Twenty-Minute Neighborhood: How Infrastructure and Destinations Influence Bicycle Accessibility. Paper presented at the 90th Annual Meeting of the Transportation Research Board, Washington D, 2011.

20. Walk Score. Walk Score Methodology, https://www.walkscore.com/methodology.shtml, 2018, accessed on 25.06.2018.
21. Klobucar, M., and J. Fricker. Network Evaluation Tool to Improve Real and Perceived Bicycle Safety. *Transportation Research Record: Journal of the Transportation Research Board*, 2007. 2031: 25-33.
22. Götschi, T., de Nazelle, A., Brand, C., Gerike, R., & PASTA Consortium. Towards a comprehensive conceptual framework of active travel behavior: A review and synthesis of published frameworks. *Current environmental health reports*, 2017. *4*: 286-295.
23. Swiss Association of Road and Traffic Professionals (VSS). *SN 640 060* Leichter Zweiradverkehr Grundlagen. Zürich, 1994.
24. Swiss Association of Road and Traffic Professionals (VSS). *SN 640 262: Knoten, Knoten in einer Ebene (ohne Kreisverkehr)*. Zürich, 1999.
25. Erath, A., M.A.B. van Eggermond, S.S. Ordonez and K.W. Axhausen. *Introducing the Pedestrian Accessibility Tool (PAT): open source GIS- based walkability analysis*. ETH Zurich, Zurich, 2016.

26.