A Multicriteria Methodology for Maintenance Planning of Cycling Infrastructure

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Abstract

The importance of cycling as a sustainable mode has been widely recognized and, recently, its effectiveness in mitigating the spread of infectious diseases has also been under the spotlight. Fostering its use requires developing and deploying decision tools to help authorities assess the performance of their cycle infrastructure for maintenance and improvements. This article presents a multicriteria methodology based on engineering best practices and uses the ELECTRE TRI method to assign segments of the cycling network to predefined performance classes, with an aim at maintenance planning. The approach is demonstrated with a case study, which also proves scalability of the method's data collection procedure. Case study results show that lack of safety and inadequate intersections are the main problems. These stem mostly from non-existent segregation between motorized traffic and cyclists, both along the segments and at intersections. This is typical of cities which, over the years, have prioritized motorized transportation.

Keywords: Decision-Making, Maintenance & Inspection, Performance Measurement, Town and City Planning

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1. Introduction

Sustainability worries, congestion, energy efficiency, and health concerns have been the chief reasons prompting municipal decision-makers to look at the bicycle as a desirable transport mode (de Nazelle et al., 2011; Doorley et al., 2019; EC, 2020; Kang and Fricker, 2018; Kenworthy, 2018; OECD, 2013; Tight, 2016). Being an active, non-polluting, and low congestion mode (Wang et al., 2008), the bicycle combines flexibility and readiness of use with competitive circulation speeds. These speeds can go as high as 20 km/h in the urban environment (Parkin and Rotheram, 2010), which is four to five times that of walking and often higher than the average automobile speed during the rush hour in a congested city center (Roth, 1963; Yong-chuan et al., 2011) (average car speeds at avenues can go higher; Wang et al., 2016). Recently, its role in mitigating the spread of infectious diseases has also been recognized (Awad-Núñez et al., 2021; Barbarossa, 2020; Büchel et al., 2022; Kraus and Koch, 2021). These characteristics make cycling a promising alternative transport mode, and indeed an increasing number of initiatives to foster this mode have been undertaken all around the world (Caulfield, 2014; Deegan and Parkin, 2011; Forsyth and Krizek, 2010; Handy et al., 2014; Mairie de Paris, 2015; van Goeverden et al., 2015; Yang et al., 2010). Such initiatives do increase cycling levels, as shown by Buehler and Dill (2016), Deegan (2016), Frank et al. (2021), Harms et al. (2000), and Pucher et al. (2010). A recent review by Volker and Handy (2021) also found that investments in pedestrian and cycling infrastructure have positive or non-significant economic effects on local businesses, proving such investments constitute a win-win situation. One final advantage of the bicycle, brought to the spotlight by the COVID-19 pandemic, is its potential to mitigate the spread of infectious diseases. Moving in an open-air environment and providing social distancing during transport, the bicycle limits the chance for contagion both *per se* (De Vos, 2020) and because it contributes to reduce crowdedness in public transportation (Anke et al., 2021; Scorrano and Danielis, 2021; Shibayama et al. 2021; van der Drift et al., 2021). Indeed, after controlling for home office work and unemployment, bicycle use has increased in many locations during the pandemic (Buehler and Pucher, 2021; Doubleday et al., 2021; Shibayama et al. 2021), creating an unprecedented opportunity to provide for this active mode (Barbarossa, 2020; Brooks et al., 2021; Combs and Prado, 2021; Kraus and Koch, 2021; Nikitas et al., 2021).

Despite all its advantages, conditions are necessary for cycling to become a viable transport mode in the urban environment. As shown Heinen et al. (2010) and Reid (2017), social and environmental factors play a role in the choice for this mode. However, the later authors also recognized the high importance of infrastructural condition in this choice, in line with similar findings by Rowangould and Tayarani (2016) and Song et al. (2017). Thus, existence of an adequate, well-maintained infrastructure is necessary for fostering the cycling mode and indeed practice has shown that cities which invest in their cycling infrastructure are the ones that ultimately have higher modal shares for this transport mode (Caulfield et al., 2012; Hull and O'Holleran, 2014; Krizek et al. 2009; Pucher and Buehler, 2010; Schoner and Levinson, 2014). Investment however comes at a cost and municipalities may not be able undertake the large-scale projects that would be necessary to provide for state-of-the-art cycling infrastructure everywhere. As such, careful planning is required concerning infrastructure maintenance and regeneration, which in turn requires decision support tools to prioritize those actions (see e.g., Chen and Bai [2019] for a review and Zuo and Wei [2019] for an example). This article proposes one such tool, a multicriteria methodology to assess the performance of segments of the cycling infrastructure, whose output provides a natural intervention priority indicator. Performance assessment of individual segments is an indispensable first step towards understanding how well the existing infrastructure responds to the transport needs of citizens willing to use the cycling mode. Indeed, many accessibility and mobility assessment methods build upon ratings of individual components of the transport network to derive global indicator values for the former (Lowry et al. [2012]; Sousa et al. [2018]).

The proposed assessment methodology is inspired in previous work done for the walk mode (Sousa et al., 2017a) and aims to provide a practical, robust maintenance planning instrument to decision-makers. It is guided by three main ideas: a vision of the infrastructure systems (i.e., segments; see below) as entities whose multiple elements all play essential roles in providing a service to its users, scalability of the data-collection procedure, and practicality of the output for subsequent decision-making. To translate these ideas, the methodology uses the non-compensatory multicriteria method ELECTRE TRI to classify segments (ELimination and Choice Translating Reality; see Figueira et al. [2005]; Mousseau et al. [2000], [2001]); feeds on data whose collection is expedite; and focuses on infrastructural elements which can be subsequently intervened by municipal authorities, assessing their individual performance according to engineering principles and codes of practice. The objective of the methodology is thus the assessment of the cycling infrastructure condition for maintenance planning. Because of this objective, and because it is done on a per-segment basis, global aspects of the cycling network such as e.g., route directness or attractiveness (TfL, 2016) are not scrutinized by it. Those aspects are to be considered in network design methodologies, whereas this research has a different objective.

1.1 Literature review

The use of multicriteria methods in infrastructure management is well established in the literature. See Kabir et al. (2014) for a review and Song et al. (2021) and Vuillet et al. (2016) for recent examples. In what concerns cycling infrastructure assessment, most research focuses either on specific tools for the cycling mode (usually aiming at improvements), which is the direction this article follows, or on instruments that are part of more wide-ranging bikeability indicators. The later approach bears resemblance to some literature on pedestrian infrastructure assessment, in that instruments looking at the condition of the pedestrian infrastructure are often part of walkability indicators. Walkability/bikeability are concepts that evaluate the degree to which a neighborhood is walk- or bike-friendly and encompass various measures such as accessibility, pleasantness of environment, land-use, along with aspects of infrastructure condition. Since bikeability indicators usually do not look at technical aspects of the cycling infrastructure, often concentrating on pavement suitability issues, they may disregard other infrastructural elements which are also important for a correct assessment of the cycling network performance. The reviews of Kellstedt et al. (2020) and Vale et al. (2016) list recent work on walkability/bikeability indicators, some of which indeed incorporate infrastructure condition measures. One example is described by Emery and Crump (2003), which developed the WABSA walkability and bikeability index, following up on a correlational study which determined the relevant variables (Emery et al., 2003). WABSA was used by Sisson et al. (2006) to assess adequacy of bicycling commuting to elementary schools in a case study. An example connected to health issues is Hoedl et al (2010), whose BiWET audit tool contained measures such as speed limits, lane number and existence of cycle lanes. Weighted-sum methods were used by Horacek et al. (2012) to obtain walkability and bikeability assessments of campus environments, and by Lowry et al. (2012) to define a bicycle level-of-service for road segments and subsequently cycling accessibility maps. Winters et al. (2013) developed a GIS-based bikeability mapping tool containing bicycle-road separation as a layer. This tool evolved into the BikeScore® and was used by Winters et al. (2016) to study the association between bikeability and cycling behavior.

In what concerns specific cycling infrastructure assessment tools, these were found by Turner et al. (1997) to fit into one three categories: stress-level based, condition/suitability index based, and capacity based, a division which still appears on recent studies and codes of practice. Examples are Nuñez et al. (2018) (stress-based), Majumdar and Mitra (2018) (condition-based), and HCM (2010) (capacity-based). Because this article proposes a condition/suitability index assessment, it makes sense to delve deeper into the literature for this tool. The research of Landis et al. (1997) is one of the first examples of a condition index. It operates on a per-road segment basis and applied multiple linear regression to field and survey data to derive a bicycle level-of-service. A similar approach was followed by Harkey et al. (1998) and Jensen (2007), the later using a logit regression model. Recently, Majumdar and Mitra (2018) proposed an ordered-probit regression model, whose output can be used to prioritize interventions in the cycling infrastructure. Their case study showed an unexpected positive coefficient for traffic speed, hinting that higher traffic speed is associated with higher cycling level-of-service. However, this was shown by authors to be a regional effect due to poor road pavements, which demonstrates one of the downsides of regression-based methods: model calibration requires on-site surveys, which depend on regional and cultural issues, and may not extrapolate to other situations, limiting its usefulness. Another difficulty with these models is that some of the data, e.g., average motor vehicle speeds, are hard to collect at a city scale. A practical approach was proposed by Geller et al. (2008) for Portland, USA, which relied on a weighted-sum multicriteria method run over a dataset of technical and non-technical aspects of the cycling infrastructure, to obtain a bikeway quality index (BQI). This index was used by McNeil (2011) to evaluate the bikeability of Portland and propose new bikeways. Comparative studies include Parks et al. (2013), who assessed three cycling infrastructure quality-of-service metrics by comparing their output with actual user preferences, having found shortcomings with the HCM approach, and LaMondia and Moore (2015), who evaluated four bicycle level-of-service measures in Auburn, Alabama, and found discrepancies between measured values and route suitability as perceived by cyclists. Clark et al. (2019) took on the topic of finding actual cyclist preferences for infrastructural design. Their survey revealed that separation and comfort are important factors.

Practical application of current methods in the literature to large, city scale is hampered by two issues. One is resource-consuming data collection procedures; the other is that current methods are compensatory in nature, meaning bad scores in a particular criterion can be offset by good scores in other criteria, potentially hiding infrastructural weaknesses (Banihabib et al., 2017) and leading to average scores for an infrastructure which may be underperforming. This may result in an overall picture that is more favorable than what is perceived by cyclists. In non-compensatory methods poor performances in some criteria cannot be compensated by high performances in other criteria, and the aggregated performance reflects this. Therefore, these techniques offer insights to decision-makers not provided by compensatory techniques. Cycling infrastructure assessment methods based on non-compensatory methods are, to best of our knowledge, absent from the literature, a research gap this article proposes to fill. Note that the methodology deals with assessing the cycling infrastructure condition from an engineering viewpoint, whose requirements are well-established (Parkin, 2018). It is not intended to be a bikeability indicator, although its output can form a basis for methodologies to evaluate bikeability. See Sousa et al. (2019a) for an example of how a similar performance indicator for the pedestrian infrastructure can be integrated into a walkability indicator and McNeil (2011) for another example of the link between performance indicators and bikeability.

2. Methodology

The cycling network of a city is an infrastructure composed of multiple systems. These systems are in turn composed of multiple elements, all working together to provide the intended service to users. Since each element has a specific function, all elements need to perform adequately: if engineering requirements fail on one of them, overall system performance may be compromised. In this article, the *infrastructure systems* of the cycling network are road segments, i.e., the individual arcs that form that network, and *elements* are the constituents of the arcs that support the cycling mode (pavement, intersection facilities, lightning, separation buffers, etc.). Some of these elements ultimately become evaluation criteria, other contribute towards the later. Note that 'cycling network' refers to all arcs of the road network which allow cycling, regardless of other transport modes they may simultaneously allow. It does not refer only to dedicated cycle tracks, as that would be too restrictive. Combining the effectiveness of all elements into a single performance indicator for a segment requires using a multicriteria method which, as argued, should not allow good scores in one element to compensate bad scores in another, e.g., a nicely paved cycleway will be unfit if it is not wide enough. ELECTRE TRI was selected as the multicriteria method, a non-compensatory method which can evaluate real infrastructure conditions against what they should be according to engineering codes of practice and assign each system a (previously defined) performance class representing its overall performance. The outcome of this classification process can be represented in a geographic information system (GIS) for spatial visualization, giving municipal authorities a graphical overview of the city's cycling network suitability.

It is important that data collection is expedite and that it focuses on infrastructural elements that can be intervened by municipal authorities. This puts aside some hard characteristics, such as slope or land-use, which play a role in the propensity to cycle (see e.g., Tralhao et al., 2015), but cannot be easily altered by those authorities. For each system, elements can be evaluated by visual inspection, which ensures quick data collection.

2.1 Criteria set

Criteria express the various, often conflicting dimensions of reality which need to be considered simultaneously in multicriteria decision-making. The proposed criteria set includes infrastructural elements, as well as other aspects deemed essential for a correct assessment of the cycling network performance (Beura et al., 2017; Callister and Lowry, 2013; Emery et al., 2003; Turner et al., 1997). This set includes criteria made from physical characteristics, such as e.g., pavement type, lane width, or intersection facilities, and space-sharing issues, such as the intensity of use by other transport modes.

Comfort and safety, being too abstract to assess directly, were broken down to more tangible subcriteria, a procedure recommended by Wang (2011) which is common in the context of hierarchical approaches to decision-making (see e.g., Torres-Machi et al. [2019] for a recent application in engineering). Criteria made from subcriteria are called constructed criteria (Keeney, 2009). Width refers to the lateral space designated for cycle traffic, whose optimal values depend on the type of infrastructure supporting the cycling mode in the segment. Table 1 displays the proposed criteria set and the scoring proposed for each criteria/subcriteria.

Except for width, all criteria values are collected on the field through visual inspection, based on surveyor judgement. Visual inspection is common in engineering when measurement based on rigorous definitions is difficult, time-consuming, or outright impossible (Qian et al., 2020; see e.g., Dirksen et al. [2013] or Quirk et al. [2018] for recent examples) and is likely to continue to have a vital role (See et al., 2017). Because surveyor judgement may vary from person to person, it is recommended that common standards are previously agreed upon (e.g., by a guidebook) and that each segment is evaluated by two surveyors (Emery and Crump, 2003; TRL, 2003), averaging in case of divergent scores or reaching a consensus value by surveyor meeting. Judgements are coded in 3, 4 or 5-point Likert scales, depending on the characteristics of the item being evaluated. A low number of scale points was for chosen for simplicity and quickness of survey, given that Likert scales with 7+ points do not provide a significant increase in reliability (Lissitz and Green, 1975). In criteria or subcriteria that are subject to judgement (i.e., do not have strict scales, such as width) surveyors are not obliged to select a particular value of a Likert scale: the methodology does not require integer criteria values, so surveyors are free to select half-integer values whenever they feel that is a better fit to the criterion score.

Segments are surveyed in both directions unless traffic signs forbid cycle traffic in one of them. Usually, survey scores are the same for both directions, but may differ on occasion. For segments that are highly heterogeneous a division into homogeneous segments is recommended, rather than just taking average values.

Table 1 – Criteria/subcriteria and evaluation values.

Criteria	Description/Type/Values	Subcriteria	Description	Value
Comfort	Cycling rolling comfort Benefit 0-4	Type of pavement (benefit)	Inappropriate (e.g., cobbled roads)	0
			Poor (e.g., dirt floor)	1
			Moderate (e.g., rough sidewalk)	2
			Good (e.g., ceramic or cement slabs)	3
			Very good (e.g., bituminous roadways or cycle tracks)	4
		Conservation defects (cost)	No pathologies	0
			Few or specific pathologies, interventions not required	1
			Some pathologies requiring simple interventions	2
			Various pathologies, timely intervention required	3
			High number of serious pathologies, compromised use	4
Safety	Safety from motorized traffic Benefit 0-4	Motorized traffic volume (cost)	Restricted road/very low traffic volume and speed	0
			Low traffic volume and speed	1
			Low traffic volume and moderate speed, or considerable traffic volume and low speed	2
			Considerable traffic volume and moderate speed	3
			High traffic volume or high speed	4
		Heavy vehicle traffic volume (cost)	Non-existent flow of heavy vehicles	0
			Low flow of heavy vehicles	0.5
			High flow of heavy vehicles	1
		Separation (benefit)	No segregation from motorized traffic	0
			Cycle lane without physical separation buffer or an easily transposed one, *or* physical separation but poor road markings	1
			Cycle lane with physical separation and good road markings	2
			Cycle track without rigid elements in separation (sidewalk, grass)	3
			Cycle track with rigid elements in separation (trees, parking)	4
Conflicts	Frequency and extension of roadside conflicts Cost 0-3	N/A	No conflicts	0
			Low chance of conflicts	1
			Moderate chance of conflicts	2
			High chance of conflicts	3
Width	Cycling space width Benefit 0-4 (One of:)	Shared space (Speed limit 50 km/h)	3.10 m < width ≤ 4.30 m	0
			width ≤ 3.10 m	1
			width > 4.30 m	3
		Shared space (Speed limit 30 km/h)	3.10 m < width ≤ 3.80 m	0
			width ≤ 3.10 m	1
			width > 3.80 m	3
		Cycle lane/track (one-way)	width ≤ 1.25 m	1
			1.25 m < width ≤ 1.75 m	3
			1.75 m < width ≤ 2.65 m	4
		Cycle lane/track (two-way)	width ≤ 2.00 m	1
			2.00 m < width ≤ 2.75 m	3
			2.75 m < width ≤ 3.90 m	4
Intersections	Existence of adequate intersection facilities Benefit 0-3	N/A	No dedicated cycling facilities and high (3-4) motorized traffic volume	0
			No dedicated cycling facilities and moderate (2) motorized traffic volume	1
			No dedicated cycling facilities and low motorized traffic volume (0-1), *or* facilities exist but are incorrectly sized; ≤ 1.25 m (one-way); ≤ 2.00 m (two-way); no bike-box if signal-controlled	2
			Correctly sized cycling facilities; > 1.25m (one-way); > 2.00 m (two-way); and bike-box if signal-controlled	3
Lighting	Cycle space lighting Benefit 0-3	N/A	No lighting	0
			Alternating bright and dark zones	1
			Continuous lighting, but of low luminosity or not dedicated to the cyclists	2
			Continuous lighting, abundant luminosity	3

Comments:

Comfort

Comfort is a constructed criterion, consisting of pavement type and conservation defects. Pavement type is evaluated from inappropriate to very good and transformed onto a numerical value on a 0-4 Likert scale. Conservation defects are also evaluated on a 0-4 scale and reflect the actual pavement status, based on typical pathologies, e.g., uneven ground, floor holes, cracks, existence of rain collectors, root bumps, or ease of debris accumulation. The two subcriteria intend to show that different types of pavement with different conservational defects can change cyclists' perceived comfort. Values for comfort are obtained from:

$$\text{Comfort} = \max\{\text{type of pavement} - \text{conservation defects}; 0\}$$

There are no strict guidelines when evaluating how appropriate/smooth a pavement is or how compromised its use is. The surveyor exercises judgement upon visual inspection at the site, taking Table 1 descriptions into account. Comfort scores may alternatively be derived using automated methods, such as the one proposed by Qian et al. (2020), which combines both pavement roughness and existence of defects. However, such methods require surveyors to cycle through, which may be slower than visual inspection and requires specialized equipment and data curation.

Safety

Safety is a constructed criterion, determined by motorized traffic volume, heavy traffic volume, and separation between the cyclist and motorized vehicle traffic. Survey data concerning traffic volume should be carried out during peak hours, so surveyors should be familiar with traffic volumes throughout the day and have knowledge road network hierarchy. A restricted road may score 0, a quiet local access road 0 or 1, and a busy street would score 3 or 4.

Heavy vehicle motorized traffic volume (public transport and freighters) further penalizes safety due to the increased lateral space they occupy, and the air draft caused by their passage. Roads with little to no heavy traffic at peak hour score 0, whereas roads with high flow of public transport or trucks score 1.

Separation between the cyclist and the motorized vehicle traffic is determined considering which of Table 1 applies to the segment. Cycle lanes with separation but poorly marked may be scored 1 if their visibility is bad.

Values for the safety criterion are obtained from:

$$\text{Safety} = \begin{cases} 0 & \text{if } \; 4 - (TV + HT - SP) < 0 \\ 4 - (TV + HT - SP) & \text{if } \; 0 \leq 4 - (TV + HT - SP) \leq 4 \\ 4 & \text{if } \; 4 - (TV + HT - SP) > 4 \end{cases}$$

Where:

TV: motorized traffic volume (0-4)
HT: heavy traffic volume (0, ½, 1)
SP: separation between cyclists and motorized traffic (0-4)

Conflicts (roadside)

This criterion highlights potential roadside conflicts between cyclists and motor vehicles, which may occur in two manners: the first is if entryways of buildings or public places lead through cycling spaces, in which case lack of visibility may cause a car's front to prop out and collide with a passing cyclist or cause him to go off course. The second is parking lots alongside the cycling space, which can endanger cyclists due to invasion of their space when a car backs off (perpendicular parking) or a door opens (parallel parking).

Both aspects are evaluated considering frequency and extension throughout each segment. A segment without parking or entryways would score 0 (no risks, very good), whereas a segment with several busy entryways and/or dense parking would score 3 (considerable risk, poor).

Width

Width is the length of the cross-section of each segment, scored according to the segment's cycling infrastructure. Width measurements are obtained on the field with a laser meter, drone survey or any other adequate measurement tool. Width measurements are subsequently transformed into criteria values on a discrete scale depending on the underlying cycling infrastructure type and according to the engineering guidelines of Parkin (2018), based on the distinction between 30 km/h and 50 km/h speed limits for shared space (respectively 20/30 mph). Cycling infrastructure may consist of shared space with motor vehicles, one-way cycle lane/track, or two-way cycle lane/track. Shared space refers to segments where cyclists share the road with motorized traffic, without dedicated lanes. Cycle lane or cycle track (one-way) refers to segments with dedicated cycling infrastructure, with physical separation between each direction (one lane/track each side of the road). Cycle lane or cycle track (two-way) refers to segments where dedicated infrastructure exists, without physical separation between directions (a split lane/track serves both directions). Larger width requirements can be chosen if the cycling infrastructure was planned for higher adaptability (TfL, 2016) or if local legislation so imposes. The values suggested in Table 1 are adequate to the case study.

Shared space width is transformed into discrete values according to Table 2, following the guidelines of Parkin (2018) and motivated is as follows. For shared space, 0 corresponds to a critical width interval in which motorized vehicles try to overtake without leaving their lane, risking a sideways collision with the cyclist (Parkin, 2018). Smaller widths, of less than 3.1 m, are safer for the cyclist (thus score 1) because vehicles, having no space for overtaking without occupying the opposing lane, tend to stay behind him and wait for an opportunity to overtake safely. Widths larger than 3.80 m score 3 because in this case there is enough lateral space for a safe overtaking inside the lane, provided the cyclist assumes the secondary riding position (cycling close to the kerb). Note that cycle lanes that are too wide tend to be invaded by motor vehicles, hence the limitation on maximum width, which only applies to cycle lanes.

Intersections
Intersections refers to existence of adequate facilities for cyclists in road crossings and mergers. It is important to consider intersections as a separate criterion, as recent work showed that lack of these facilities greatly increases cyclist stress (Nuñez et al., 2018). Facility adequacy depends on traffic volume so this criterion, which is evaluated at the endpoint of segments, follows the scale of Table 2. Evaluating what high/moderate/low traffic volume is at the intersection depends on surveyor judgement. Usually, the traffic volume value evaluated for the safety criterion is considered, but this may be higher if the intersection is busy at rush hour. For signal-controlled intersections, an advanced stop line (e.g., bike-box) should be present for maximum score.

Lighting
This criterion describes the lighting shining on cyclists on each segment. This only applies at night, but it is an important criterion because cycling speeds are high enough to cause serious injury in case of a crash caused by poor visibility. Surveying of lighting must be carried out at night, following Table 2.

Some of the discrete values proposed deliberately jump one point to facilitate and systematize parameter calibration. The scoring scale on Table 1 is the authors' proposal. Other scales and values can be used. Note also that different typologies of the cycling infrastructure have different requirements. Criteria which require surveyor judgement are to be evaluated considering those requirements. For example, pavement defects of a cycle track are different than those of a cycle lane.

2.2 Assessment methodology

Assigning alternatives (i.e., segments) to the most appropriate class according to their overall performance is a multicriteria problem of the "sort problematic" kind (Figueira et al., 2005). ELECTRE TRI is one of the most used non-compensatory methods for this purpose (Govindan and Jepsen, 2016), because it does the assignment in a way which mimics human judgement. Each class is delimited by upper and lower profiles, or 'reference alternatives', for each criterion, whose values may be defined by codes of practice or decision-maker choice.

The method compares criteria values of the alternatives against values of the reference alternatives, utilizing an outranking procedure to ultimately assign a class to the alternatives. It considers indifference, preference, and veto thresholds to accommodate in a natural way the imprecision inherent to human decision processes. The veto threshold is especially important, since it prevents an alternative from progressing into the best classes if it has inacceptable scores in any particular criteria. Applying ELECTRE TRI requires defining the aforementioned thresholds, criteria weights, and a cut-off parameter, λ, and a class assignment rule (pessimistic or optimistic).

3. Case-study

The methodology was applied to the city of Coimbra, Portugal (circa 100,000 inhabitants), with 1704 segments covering the central area selected for survey and analysis. Heterogeneous segments divided into homogeneous ones, as recommended. Two surveyors collected the data on the field in four months, proving the methodology is scalable and easily applicable, as required by design.

Table 2 below shows how the collected data was organized. Values for compound criteria were calculated from a spreadsheet and the columns in bold form the multicriteria decision matrix, i.e., the list of alternatives (segments) and respective criteria values, and an ID label for geographic referencing.

Table 2 - Collected data and values for each criterion

ID	Street name	Pavement	Defects	**Comfort**	TV	HT	SP	**Safety**	**Confl.**	Speed limit	**Width**	**Intersect.**	**Light.**
N17001	N17	4	0	**4**	1	0,5	0	**2,5**	**1**	50	**1**	**2**	**2**
N17002	N17	4	0	**4**	1	0	0	**3**	**1**	50	**1**	**2**	**2**
…													
SCLARA006	JdR Ave.	4	1	**3**	4	1	0	**0**	**0**	50	**0**	**0**	**3**
SCLARA007	AAG St.	4	2	**2**	2	0	0	**2**	**2**	30	**0**	**1**	**1**
…													

3.1 ELECTRE TRI parameterization

Reference classes

For the case study, four performance classes were defined, corresponding to qualitative judgements of 'bad', 'mediocre', 'satisfactory' and 'good'. This requires defining three class boundaries, i.e., the reference alternatives. Their criterion values were made to coincide with Likert scale values, an option also followed in Sousa et al. (2017a) for sidewalk evaluation, thus allowing for a more direct cycle/walk infrastructural condition comparison. They are as follows: (order of Figure 1)

A1 = (1, 1, 2, 1, 0.5, 0.5)   A2 = (2, 2, 1, 2, 1, 1)   A3 = (3, 3, 0.5, 3, 2, 2)

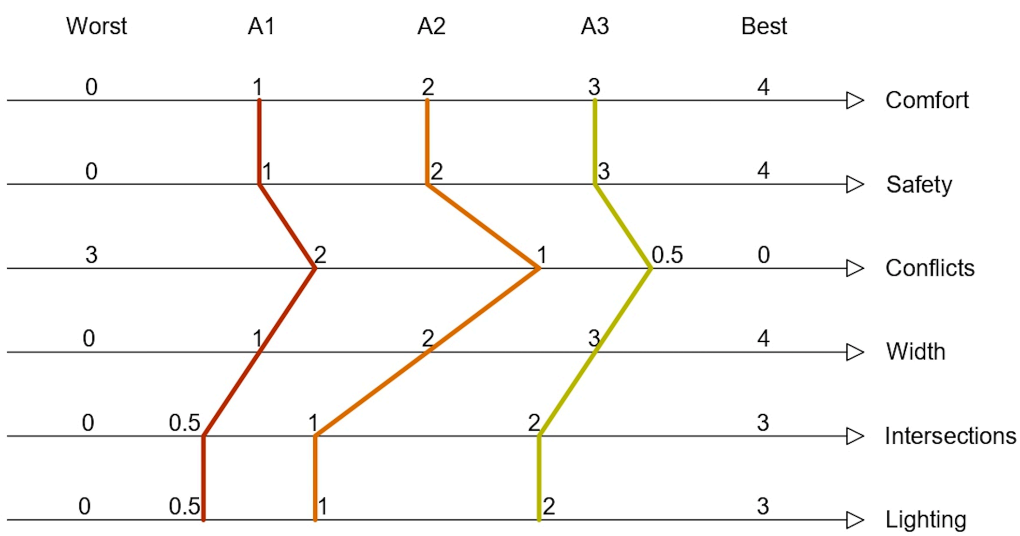

Figure 1. Reference alternatives, A1, A2, A3.

Weights

Following Clark et al. (2019), who mentioned safety and comfort as important criteria in cyclist perception, two sets of criteria weights were adopted. Set W1 focuses on safety perceived by cyclists and set W2 on segment comfort. Weights values were obtained by expert consensus and are:

W1 = (2, 9, 4, 3, 2, 2)   [focus on safety]   W2 = (9, 2, 4, 2, 2, 3)   [focus on comfort]

Thresholds

Indifference, preference, and veto thresholds were chosen to be consistent with each criterion scale. These are

Indifference = (0.1, 0.1, 0.1, 0.1, 0.1, 0.1)
Preference = (0.4, 0.4, 0.4, 0.9, 0.4, 0.4)
Veto = (1.1, 1.1, 1.6, 2.1, 1.6, 1.6)

A stricter veto threshold was put on safety and comfort because these are the most critical performance attributes.

Cut-off and assignment rule
The cut-off level was set to $\lambda = 0.50$ and the pessimistic assignment rule was chosen, as this rule typically leads to poorer scores, highlighting the need to undertake improvement measures.

In appendix A photographs of typical examples of roads with classification 1-4 are given, for both weight sets. Surveyors validated this parameterization and its results by looking at the ELECTRE TRI scores for randomly selected segments and comparing them with their intuitive notion of that segment's assessment score, having found a good agreement.

3.2 Results and discussion

Results were derived from software developed by the author's research centre, but any other ELECTRE TRI software package could be used. In Figures 2 and 3 spatial visualizations of the results for both weight sets are presented, with road segments colored according to its assigned class, from 1 (worst) to 4 (best). Table 3 below provides summarizing statistics for number of segments and length spanned.

Table 3 - ELECTRE TRI results statistics

Weight set	Safety based (W1)	Length spanned (W1)	Comfort based (W2)	Length spanned (W2)
Class 1	368 (22%)	72,0 km (29%)	268 (16%)	47,4 km (19%)
Class 2	795 (47%)	108,8 km (44%)	860 (50%)	126,0 km (51%)
Class 3	511 (30%)	62,6 km (25%)	549 (32%)	70,7 km (28%)
Class 4	30 (2%)	5,9 km (2%)	27 (2%)	5,2 km (2%)

Regardless of weight set, the study area cannot be classified as bike friendly. Concentrating on Figure 2 (safety), a geographical analysis shows reveals that most segments assigned to class 1 (23%) are main distributor roads with high motorized traffic volume. Segments assigned to class 2 correspond mostly to local distributor roads, and segments assigned to the top classes 3 and 4 (31%) correspond to local access roads with low or no motorized traffic and to a small subset of roads with well-dimensioned cycle lanes/paths alongside. When the focus is on safety and few dedicated cycling facilities exists, this close relationship between road hierarchy and cycling infrastructure assessment is not at all surprising, as safety concerns are one of the chief deterrents of cycling (Winters et al., 2011; Majumdar et al., 2020).

Moving on to Figure 3 (comfort), it is seen that some of the main distributor roads improve performance, mostly due to good comfort scores of these segments. Still, with 67% of the segments assigned to bad/mediocre classes, the situation is only marginally better than the W1 weights set (69% in bad/mediocre classes).

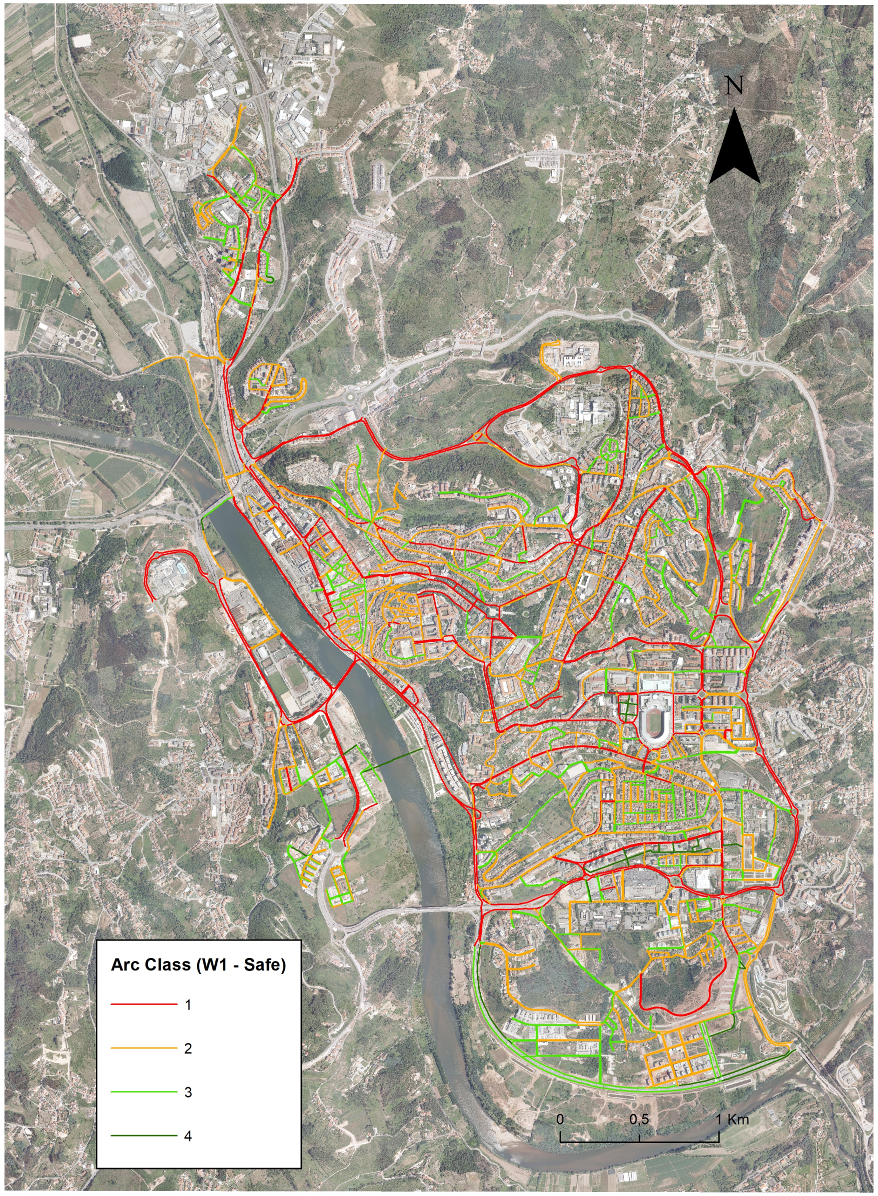

Figure 2 – Arcs' classification (set of criterion weights W1) – focus on safety

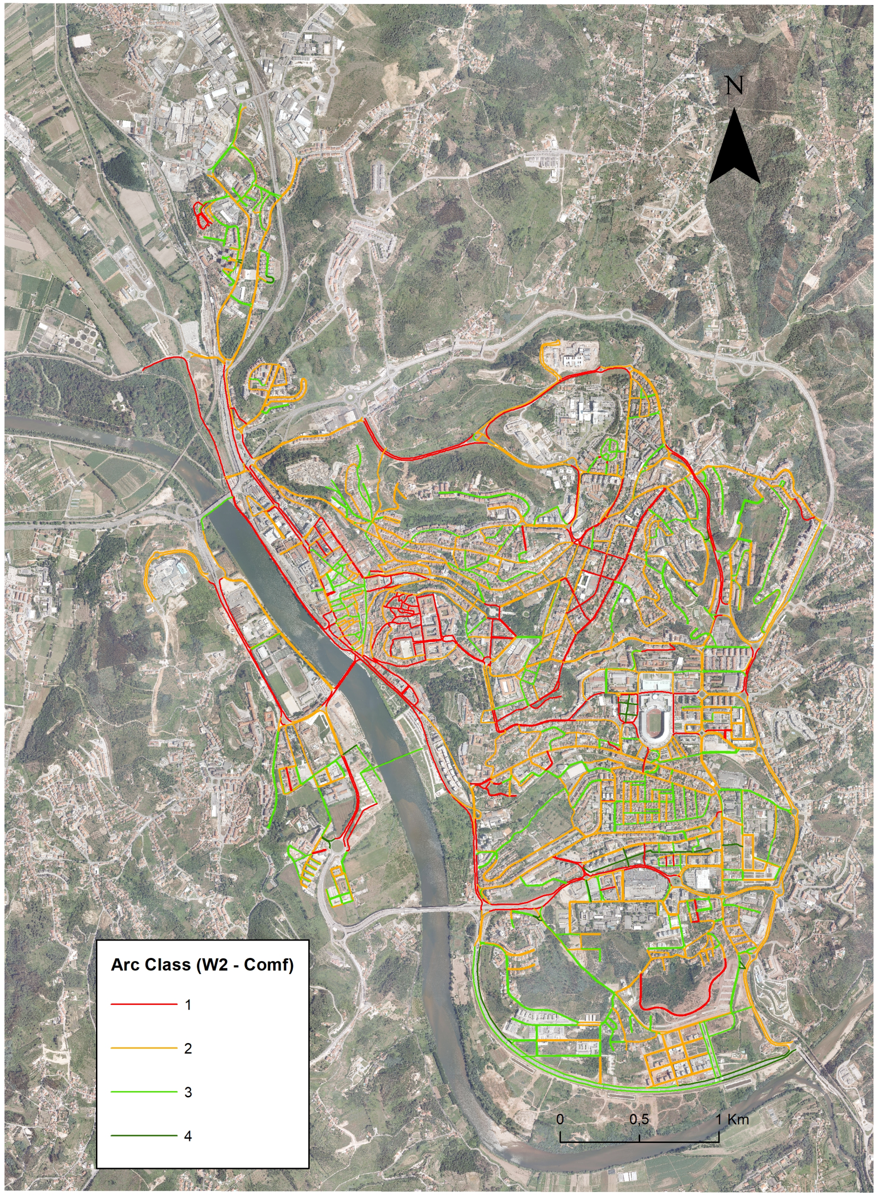

Figure 3 – Arcs' classification (set of criterion weights W2) – focus on comfort

1

To better understand of how final classifications are formed from individual criteria, Table 4 provides non-parametric Spearman correlations between individual criteria scores and segment final classifications. A complete explanation for each segment classification could, in principle, be found from analyzing ELECTRE TRI intermediate calculations. But the number of segments is too large for such a detailed analysis, hence a statistical approach is necessary.

Table 4 - Spearman Correlations between individual criteria values and final classification

Criteria	Type	Class Safety (W1)	Class Comfort (W2)
Comfort	Benefit	0.166*	0.397*
Safety	Benefit	0.661*	0.411*
Conflicts (roadside)	Cost	-0.050*	-0.096*
Width	Benefit	0.297*	0.233*
Intersections	Benefit	0.618*	0.381*
Lighting	Benefit	-0.476*	-0.307*

(*) Statistically significant at 5%. Critical value for significance: $|r| > 0.0475$.

As expected, safety and comfort show high correlations with the final classifications for weight sets W1 (safety) and W2 (comfort), respectively. For the latter case, safety remains an important predictor of final classification due to the vetoes this criterium imposes. Intersections also turn out to be relevant, due to a circumstantial factor: a high correlation between safety and intersections values (>95%, not shown in table). This correlation appears in part due to similar values for traffic volume in the safety and intersection criteria, but also because segments with poor provisions for cyclists also tend to have inadequate intersections, increasing the chance of an overall poor classification. Lighting shows unexpected negative correlations to final classifications, suggesting that good street segments are poorly lit. Given that local access roads have good final scores, this anti-correlation should alert decision-makers to check out on lighting conditions of these neighborhoods.

The case study results show that Coimbra's cycling network infrastructure has considerable shortcomings. Its overall poor performance, with many main distributor roads classified as 1 or 2, happens mostly due to inadequate safety provisions for cyclists, as these would need to share space with motorized vehicles in dense traffic conditions and potentially conflict at intersections. The situation for local distributor roads and local access roads surveyed is slightly better, but this is mostly due to lower traffic volumes. Results are evidence that the city has been planned almost exclusively with motorized modes in mind and action is necessary if cycling is to be fostered.

Hostile conditions for cycling play a large role in explaining low shares for this mode (Hong et al. 2020; Heinen et al. 2010; Winters et al., 2011), which for the case of Coimbra can go as low as 1%. Note that while class 1 represents an outright unsuitable, sometimes dangerous, cycling environment, class 2 still signals inadequate infrastructure which many cyclists are likely to eschew. Thus, the differences between W1 and W2 results are, for practical purposes, less significant than what map colors might suggest.

Use of results for decision-making

The data collected covers the most important streets in the central area of Coimbra, which will inevitably be traversed in cycling trips beyond neighborhood distance, making Figures 2 and 3 a useful overview of the city's cycling network performance. The fact that output is readily interpreted is useful for municipal authorities, as this information can be used in multiple ways, from its overall impact on cyclability to maintenance planning. Decision-makers familiar with the city and its generator and attractor points may quickly detect, from map inspection, the quality of cycling from one to the other. Precise measurements of this quality, e.g., average segment class from origin to destination, are possible using GIS (Sousa et al., 2019a). Such an analysis may precede intervention on the infrastructure: rather than applying simple rules such as e.g., intervening on class 1 or 2 segments, decision-makers may wish to prioritize segments serving locations where more cycling trips are likely to be generated. Other approaches can also be envisioned, e.g., use of segment classification values as input for cost-benefit optimization models.

4. Conclusions and future work

This article presented a multicriteria methodology to assess the performance of a city's cycling network infrastructure. Based on engineering requirements, the methodology looks at the infrastructure systems that constitute the network as whole entities, whose performance depends on each element carrying out its function as intended and, as such, uses a non-compensatory method, ELECTRE TRI, to assign the systems to pre-ordered performance classes. Focusing on criteria that can intervened by municipal authorities and whose surveying is expedite, the methodology offers a valuable decision-aid tool for prioritizing maintenance and upgrade works.

The methodology was applied to a case study of considerable dimension, in which a large fraction of the road network of a mid-sized city (Coimbra, Portugal) was surveyed, proving both its effectiveness and scalability. Results showed that the chief problems lay in main distributor roads, whose lack of safety features and adequate intersection facilities for cyclists compromises overall network performance. Considering literature views on the importance of safety for cycling, is reasonable to assume these shortcomings play a role in explaining the low modal share for the bicycle in Coimbra, suggesting that action is very much needed if authorities wish to foster the use of this sustainable and low-congestion transport mode.

Future work may involve studying how cycling network performance impacts the quality of cycling on accessibility-related trips, i.e., integrate performance into a bikeability indicator. Eventually a combination of bikeability and walkability indicators may be constructed, to give municipal authorities a global look on how friendly the city is with respect to active transport modes. Another possibility is to design a multi-objective model for planning maintenance and repair actions, using ELECTRE TRI output as an objective of benefit type, and e.g., investment spending as another, cost-type objective. Such planning could follow a modelling approach similar to that of Sousa et al. (2017b), eventually considering investment leveling for large-scale actions (Sousa et al., 2019b). ELECTRE TRI output may also be used as assessment indicator in routing models for cycling (e.g., Kang and Fricker, 2018). We hope to address some of these issues soon.

Data Availability Statement

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

Acknowledgements

This work was partially supported by the Portuguese Foundation for Science and Technology under project grant UIDB/00308/2020.

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Appendix A

Examples of typical segments with final classification 1-4 and score formation.

Figure A1s – Class 1 segment W1 (focus on safety)

Figure A1c – Class 1 segment W2 (focus on comfort)

Criterion and scale (worst-to-best)	Subcriteria	Subcriterion Score	Criterion score	ELECTRE class W1
Comfort (0-4)	Pavement type (0-4)	4	4	**1**
	Conserv. Defects (4-0)	0		
Safety (0-4)	Motor traffic vol. (4-0)	3	0.5	
	Heavy traffic vol. (1-0)	0.5		
	Separation (0-4)	0		
Conflicts (3-0)			0	
Width (0-4)	Shared space (50 km/h)		0	
Intersections (0-3)			0	
Lighting (0-3)			3	

Criterion and scale (worst-to-best)	Subcriteria	Subcriterion Score	Criterion score	ELECTRE class W2
Comfort (0-4)	Pavement type (0-4)	0	0	**1**
	Conserv. Defects (4-0)	2		
Safety (0-4)	Motor traffic vol. (4-0)	1	3	
	Heavy traffic vol. (1-0)	0		
	Separation (0-4)	0		
Conflicts (3-0)			2	
Width (0-4)	Shared space (50 km/h)		3	
Intersections (0-3)			2	
Lighting (0-3)			2	

Figure A2s – Class 2 segment W1 (focus on safety)

Figure A2c – Class 2 segment W2 (focus on comfort)

Criterion and scale (worst-to-best)	Subcriteria	Subcriterion Score	Criterion score	ELECTRE class W1
Comfort (0-4)	Pavement type (0-4)	4	2	**2**
	Conserv. Defects (4-0)	2		
Safety (0-4)	Motor traffic vol. (4-0)	3	1	
	Heavy traffic vol. (1-0)	0		
	Separation (0-4)	0		
Conflicts (3-0)			1	
Width (0-4)	Shared space (50 km/h)		3	
Intersections (0-3)			0	
Lighting (0-3)			3	

Criterion and scale (worst-to-best)	Subcriteria	Subcriterion Score	Criterion score	ELECTRE class W2
Comfort (0-4)	Pavement type (0-4)	4	1	**2**
	Conserv. Defects (4-0)	3		
Safety (0-4)	Motor traffic vol. (4-0)	1	3	
	Heavy traffic vol. (1-0)	0		
	Separation (0-4)	0		
Conflicts (3-0)			1	
Width (0-4)	Shared space (50 km/h)		3	
Intersections (0-3)			2	
Lighting (0-3)			2	

Figure A3s – Class 3 segment W1 (focus on safety)

Figure A3c – Class 3 segment W2 (focus on comfort)

Criterion and scale (worst-to-best)	Subcriteria	Subcriterion Score	Criterion score	ELECTRE class W1
Comfort (0-4)	Pavement type (0-4)	4	3	**3**
	Conserv. Defects (4-0)	1		
Safety (0-4)	Motor traffic vol. (4-0)	1	2.5	
	Heavy traffic vol. (1-0)	0.5		
	Separation (0-4)	0		
Conflicts (3-0)			1	
Width (0-4)	Shared space (50 km/h)		0	
Intersections (0-3)			2	
Lighting (0-3)			1	

Criterion and scale (worst-to-best)	Subcriteria	Subcriterion Score	Criterion score	ELECTRE class W2
Comfort (0-4)	Pavement type (0-4)	4	2	**3**
	Conserv. Defects (4-0)	2		
Safety (0-4)	Motor traffic vol. (4-0)	1	3	
	Heavy traffic vol. (1-0)	0		
	Separation (0-4)	0		
Conflicts (3-0)			0	
Width (0-4)	Shared space (50 km/h)		3	
Intersections (0-3)			2	
Lighting (0-3)			2	

Figure A4s – Class 4 segment W1 (focus on safety)

Figure A4c – Class 4 segment W2 (focus on comfort)

Criterion and scale (worst-to-best)	Subcriteria	Subcriterion Score	Criterion score	ELECTRE class W1
Comfort (0-4)	Pavement type (0-4)	4	2	**4**
	Conserv. Defects (4-0)	2		
Safety (0-4)	Motor traffic vol. (4-0)	3	4	
	Heavy traffic vol. (1-0)	0		
	Separation (0-4)	3		
Conflicts (3-0)			0	
Width (0-4)	Cycle track (two-way)		3	
Intersections (0-3)			3	
Lighting (0-3)			2	

Criterion and scale (worst-to-best)	Subcriteria	Subcriterion Score	Criterion score	ELECTRE class W2
Comfort (0-4)	Pavement type (0-4)	4	3	**4**
	Conserv. Defects (4-0)	1		
Safety (0-4)	Motor traffic vol. (4-0)	2	2	
	Heavy traffic vol. (1-0)	0		
	Separation (0-4)	0		
Conflicts (3-0)			0	
Width (0-4)	Shared space (50 km/h)		3	
Intersections (0-3)			1	
Lighting (0-3)			3	

Figure A5 – Class 4 segment W1 and W2

Criterion and scale (worst-to-best)	Subcriteria	Subcriterion Score	Criterion score	ELEC. class W1/W2
Comfort (0-4)	Pavement type (0-4)	4	4	**4**
	Conserv. Defects (4-0)	0		
Safety (0-4)	Motor traffic vol. (4-0)	2	4	
	Heavy traffic vol. (1-0)	0		
	Separation (0-4)	4		
Conflicts (3-0)			0	
Width (0-4)	Cycle track (one-way)		1	
Intersections (0-3)			3	
Lighting (0-3)			2	