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A multicriteria methodology for maintenance planning of cycling infrastructure

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The importance of cycling as a sustainable transport mode has been widely recognised, 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 paper presents a multicriteria methodology based on engineering best practices and uses the Elimination and Choice Translating Reality (Electre) Tri method to assign segments of the cycling network to predefined performance classes, aiming at maintenance planning. The approach is demonstrated with a case study, which also proves the scalability of the data-collection procedure of the method. The case study results show that lack of safety and inadequate intersections are the main problems. These stem mostly from non-existent segregation between motorised traffic and cyclists, both along the segments and at intersections. This is typical of cities that, over the years, have prioritised motorised transportation.

Keywords: decision making/maintenance & inspection/performance measurement/town & city planning/UN SDG 3: Good health and well-being/UN SDG 9: Industry, innovation and infrastructure/UN SDG 11: Sustainable cities and communities

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; ITF, 2013; Kang and Fricker, 2018; Kenworthy, 2018; 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 centre (Roth, 1963; Zhang *et al*., 2011) (average car speeds on wider roads can go higher (Wang *et al*., 2016)). Recently, the role of cycling in mitigating the spread of infectious diseases has also been recognised (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*. (2015) 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 that such investments constitute a win–win situation. One final advantage of the bicycle, brought into 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 reducing 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 by Heinen *et al*. (2010) and Reid (2017), social and environmental factors play a role in the choice of this mode. However, the latter author also recognised 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, the existence of an adequate, well-maintained infrastructure is necessary for fostering the cycling mode, and indeed, practice has shown that cities that 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 to 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 prioritise those actions (see e.g. Chen and Bai (2019) for a review and Zuo and Wei (2019) for an example). This paper 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 on ratings of individual components of the transport network to derive global indicator values for the whole network (Lowry *et al*., 2012; Sousa *et al*., 2018).

The proposed assessment methodology is inspired by previous work done on the walking 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 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 (Electre means 'Elimination and Choice Translating Reality'; see Figueira *et al*. (2005) and Mousseau *et al*. (2000, 2001)); feeds on data whose collection is expedited; and focuses on infrastructural elements that can be subsequently addressed 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 route directness or attractiveness (TfL, 2016) are not scrutinised 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 the paper by Kabir *et al*. (2014) for a review and the papers by Song *et al*. (2021) and Vuillet *et al*. (2016) for recent examples. Regarding cycling infrastructure assessment, most research focuses either on specific tools for the cycling mode (usually aiming at improvements), which is the direction that this paper follows, or on instruments that are part of more wide-ranging bikeability indicators. The latter 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 is a concept that evaluates the degree to which a neighbourhood is walk- or bike-friendly and encompasses various measures such as accessibility, pleasantness of environment and 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 that 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), who developed the walking and bicycling suitability assessment (Wabsa) walkability and bikeability index, following up on a correlational study that 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 that by Hoedl *et al*. (2010), whose Bikeability and Walkability Evaluation Table 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 carry out 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 geographic information system (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 behaviour.

In what concerns specific cycling infrastructure assessment tools, these were found by Turner *et al*. (1997) to fit into one of three categories, stress level based, condition/suitability index based and capacity based, a division that still appears on recent studies and codes of practice. Examples are those by Nuñez *et al*. (2018) (stress based), Majumdar and Mitra (2018) (condition based) and the Transportation Research Board (TRB, 2010) (capacity based). Because this paper 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 latter using a logit regression model. Recently, Majumdar and Mitra (2018) proposed an ordered-probit regression model, whose output can be used to prioritise interventions in the cycling infrastructure. Their case study showed an unexpected positive coefficient for traffic speed, hinting that a higher traffic speed is associated with a 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 – for example, average motor vehicle speeds – are hard to collect at the 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 data set of technical and non-technical aspects of the cycling infrastructure, to obtain a bikeway quality index. This index was used by McNeil (2011) to evaluate the bikeability of Portland and propose new bikeways. Comparative studies include those by 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 TRB approach, and LaMondia and Moore (2015), who evaluated four bicycle level-of-service measures in Auburn, AL, 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 that may be underperforming. This may result in an overall picture that is more favourable than what is perceived by cyclists. In non-compensatory methods, poor performance in some criteria cannot be compensated for by high performance 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 the best of the authors' knowledge, absent from the literature, a research gap that this paper 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 the paper by Sousa *et al.* (2019a) for an example of how a similar performance indicator for pedestrian infrastructure can be integrated into a walkability indicator and the paper by 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, the overall system performance may be compromised. In this paper, the infrastructure systems of the cycling network are road segments – that is, 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; others contribute towards those criteria. Note that the 'cycling network' refers to all arcs of the road network that allow cycling, regardless of other transport modes that 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 that, as argued, should not allow good scores in one element to compensate for bad scores in another – for example, 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 that 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 GIS for spatial visualisation, giving municipal authorities a graphical overview of the city's cycling network suitability.

It is important that data collection is expedited 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. Tralhão *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 that 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 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) that 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 shows the proposed criteria set and the scoring proposed for each criterion/subcriterion.

Table 1. Criteria/subcriteria and evaluation values

Criterion	Description/ type/values	Subcriteria	Description	Value
Comfort	Cycling rolling comfort	Type of pavement (benefit)	Inappropriate (e.g. cobbled roads)	0
	Benefit		Poor (e.g. dirt floor)	1
	0–4		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 motorised traffic	Motorised traffic volume (cost)	Restricted road/very low traffic volume and speed	0
	Benefit		Low traffic volume and speed	1
	0–4		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 motorised 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	N/A	No conflicts	0
	Cost		Low chance of conflicts	1
	0–3		Moderate chance of conflicts	2
			High chance of conflicts	3
Width	Cycling space width	Shared space (speed limit 50 km/h)	3.10 m < width ≤ 4.30 m	0
	Benefit		Width ≤ 3.10 m	1
	0–4		Width > 4.30 m	3
	(One of …)	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	N/A	No dedicated cycling facilities and high (3–4) motorised traffic volume	0
	Benefit		No dedicated cycling facilities and moderate (2) motorised traffic volume	1
	0–3		No dedicated cycling facilities and low motorised 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; > 1.25 m (one-way); > 2.00 m (two-way); and bike box if signal controlled	3
Lighting	Cycle space lighting	N/A	No lighting	0
	Benefit		Alternating bright and dark zones	1
	0–3		Continuous lighting, but of low luminosity or not dedicated to the cyclists	2
			Continuous lighting, abundant luminosity	3

N/A, not applicable

Except for width, all criteria values are collected in 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 on (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 three-, four- or five-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 seven or more 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.

2.1.1 Comments

2.1.1.1 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 – for example, 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

$$\text{comfort} = \max\{\text{type of pavement} - \text{conservation defects}; 0\}$$
1.

There are no strict guidelines when evaluating how appropriate/smooth a pavement is or how compromised its use is. The surveyor exercises judgement on 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 specialised equipment and data curation.

2.1.1.2 SAFETY

Safety is a constructed criterion, determined by motorised traffic volume, heavy traffic volume and separation between the cyclist and motorised 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 of the road network hierarchy. A restricted road may score 0, a quiet local access road may score 0 or 1 and a busy street would score 3 or 4.

Heavy vehicle motorised traffic volume (public transport and freighters) further penalises safety due to the increased lateral space that 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 motorised 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

$$\text{safety} = \begin{cases} 0 & \text{if } 4 - (\text{TV} + \text{HT} - \text{SP}) < 0 \\ 4 - (\text{TV} + \text{HT} - \text{SP}) & \text{if } 0 \leq 4 - (\text{TV} + \text{HT} - \text{SP}) \leq 4 \\ 4 & \text{if } 4 - (\text{TV} + \text{HT} - \text{SP}) > 4 \end{cases}$$
2.

where TV is the motorised traffic volume (0–4), HT is the heavy traffic volume (0, 1/2, 1) and SP is the separation between cyclists and motorised traffic (0–4).

2.1.1.3 CONFLICTS (ROADSIDE)

This criterion highlights potential roadside conflicts between cyclists and motor vehicles, which may occur in two manners: the first is if the entryways of buildings or public places lead through cycling spaces, in which case lack of visibility may cause the front of a car to emerge and collide with a passing cyclist or cause them 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).

2.1.1.4 WIDTH

Width is the length of the cross-section of each segment, scored according to the cycling infrastructure of the segment. 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 and 50 km/h speed limits for shared space (20 and 30 miles/h, respectively). Cycling infrastructure may consist of shared space with motor vehicles, one-way cycle lane/tracks or two-way cycle lane/tracks. Shared space refers to segments where cyclists share the road with motorised 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 for the case study.

Shared space width is transformed into discrete values according to Table 2, following the guidelines of Parkin (2018), and is motivated as follows. For shared space, 0 corresponds to a critical width interval in which motorised 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 scoring 1) because vehicles, having no space for overtaking without occupying the opposing lane, tend to stay behind them 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 that 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 applies only to cycle lanes.

2.1.1.5 INTERSECTIONS

Intersections refer to the existence of adequate facilities for cyclists at 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 end point 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 a maximum score.

2.1.1.6 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 systematise parameter calibration. The scoring scale in 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 that require surveyor judgement are to be evaluated considering those requirements. For example, the pavement defects of a cycle track are different from 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; Natividade-Jesus *et al*., 2013), because it does the assignment in a way that 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, utilising an outranking procedure to assign ultimately 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 particularly 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 (approximately 100 000 inhabitants), with 1704 segments covering the central area selected for survey and analysis. Heterogeneous segments were divided into homogeneous ones, as

Table 2. Collected data and values for each criterion

ID	Street name	Pavement	Defects	Comfort	TV	HT	SP	Safety	Conflicts	Speed limit	Width	Intersections	Lighting
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**
…													

recommended. Two surveyors collected the data in the field in 4 months, proving that the methodology is scalable and easily applicable, as required by design.

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

3.1 Electre Tri parameterisation

3.1.1 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 – that is, the reference alternatives. Their criterion values were made to coincide with Likert scale values, an option also followed in the paper by 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):

3. $A1 = (1,\ 1,\ 2,\ 1,\ 0.5,\ 0.5)$

4. $A2 = (2,\ 2,\ 1,\ 2,\ 1,\ 1)$

5. $A3 = (3,\ 3,\ 0.5,\ 3,\ 2,\ 2)$

3.1.2 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. Weight values were obtained by expert consensus and are

6. $W1 = (2,\ 9,\ 4,\ 3,\ 2,\ 2)\quad (\text{focus on safety})$

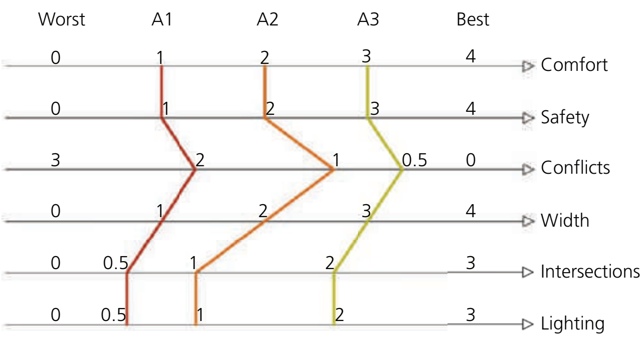

Figure 1. Reference alternatives A1, A2, and A3

7. $W2 = (9,\ 2,\ 4,\ 2,\ 2,\ 3)\quad (\text{focus on comfort})$

3.1.3 Thresholds

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

8. $\text{indifference} = (0.1,\ 0.1,\ 0.1,\ 0.1,\ 0.1,\ 0.1)$

9. $\text{preference} = (0.4,\ 0.4,\ 0.4,\ 0.9,\ 0.4,\ 0.4)$

10. $\text{veto} = (1.1,\ 1.1,\ 1.6,\ 2.1,\ 1.6,\ 1.6)$

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

3.1.4 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.

The Appendix presents, photographs of typical examples of roads with classification 1–4, for both weight sets. Surveyors validated this parameterisation and its results by looking at the Electre Tri scores for randomly selected segments and comparing them with their intuitive notion of the assessment score of that segment, having found good agreement.

3.2 Results and discussion

Results were derived from the software developed by the authors' research centre, but any other Electre Tri software package could be used. In Figures 2 and 3, spatial visualisations of the results for both weight sets are presented, with road segments marked according to their assigned class, from 1 (worst) to 4 (best). Table 3 provides summarising statistics for number of segments and length spanned.

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 (22%) are main distributor roads with a high motorised traffic volume. Segments assigned to class 2 correspond mostly to local distributor roads, and segments assigned to the top classes 3 and 4 (32%) correspond to local access roads with low or no motorised 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 exist, 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 (Majumdar *et al.*, 2020; Winters *et al.*, 2011).

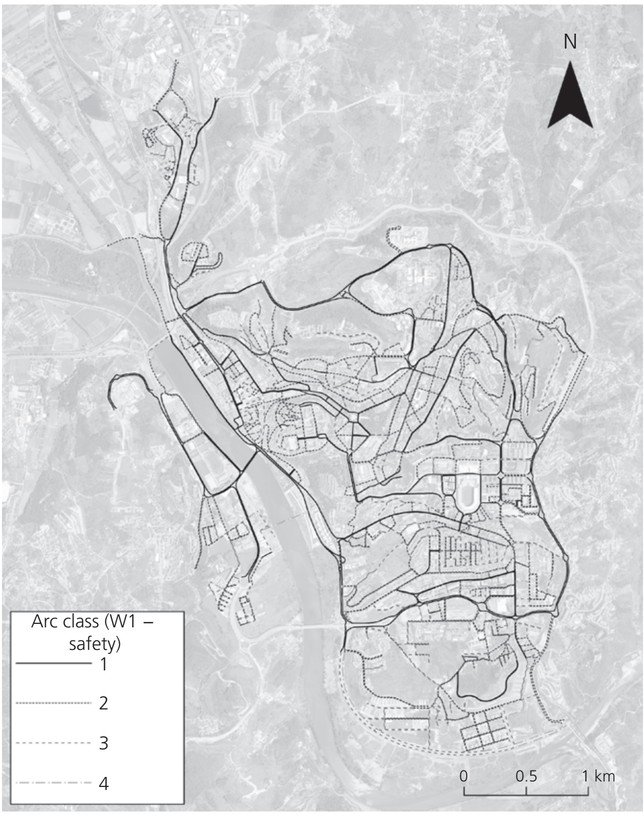

Figure 2. Classification of arcs (set of criterion weights W1) – focus on safety

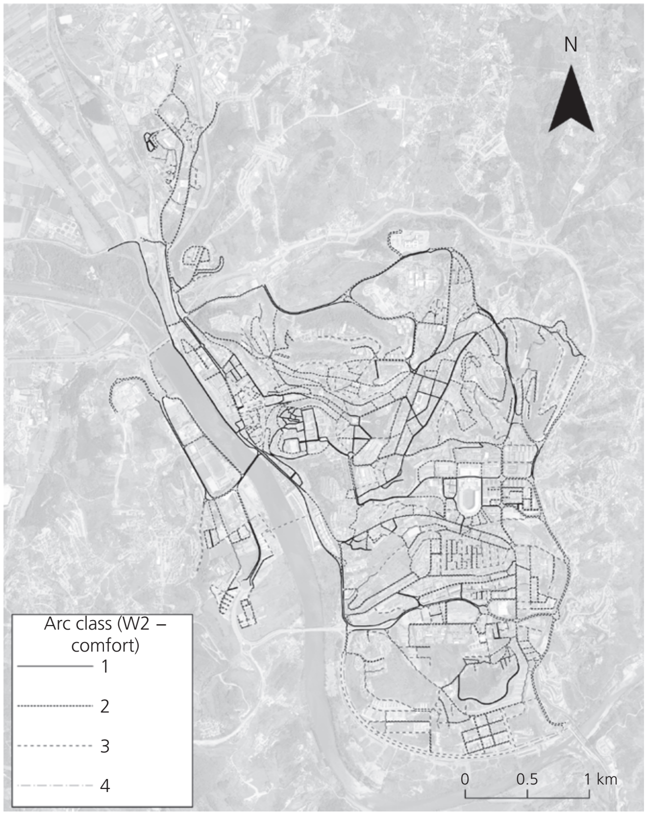

Figure 3. Classification of arcs (set of criterion weights W2) – focus on comfort

Moving on to Figure 3 (comfort), it is seen that some of the main distributor roads improve performance, mostly due to the good comfort scores of these segments. Still, with 66% of the segments assigned to bad/mediocre classes, the situation is only marginally better than the W1 weight set (69% in bad/mediocre classes).

To understand better 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 analysing Electre Tri intermediate calculations. However, the number of segments is too large for such a detailed analysis; hence, a statistical approach is necessary.

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 that this criterion 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 the table). This correlation appears in part not only due to similar values for traffic volume in the safety and intersection criteria, but also

Table 3. Electre Tri result 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%)

Table 4. Spearman correlations between individual criteria values and final classification

Criterion	Type	Class safety (W1)	Class comfort (W2)
Comfort	Benefit	0.166[a]	0.397[a]
Safety	Benefit	0.661[a]	0.411[a]
Conflicts (roadside)	Cost	–0.050[a]	–0.096[a]
Width	Benefit	0.297[a]	0.233[a]
Intersections	Benefit	0.618[a]	0.381[a]
Lighting	Benefit	–0.476[a]	–0.307[a]

[a] Statistically significant at 5%. Critical value for significance: $|r| > 0.0475$

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 on the lighting conditions of these neighbourhoods.

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, is mostly due to inadequate safety provisions for cyclists, as these would need to share space with motorised 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 motorised 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 markings might suggest.

3.2.1 Use of results for decision making

The data collected cover the most important streets in the central area of Coimbra, which will inevitably be traversed in cycling trips beyond neighbourhood 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 – for example, 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 intervening on class 1 or 2 segments, decision makers may wish to prioritise segments serving locations where more cycling trips are likely to be generated. Other approaches can also be envisioned – for example, use of segment classification values as input for cost–benefit optimisation models.

4. Conclusions and future work

This paper presents 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 prioritising 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. The results showed that the chief problems lay in main distributor roads, whose lack of safety features and adequate intersection facilities for cyclists compromises the overall network performance. Considering literature views on the importance of safety for cycling, it is reasonable to assume that these shortcomings play a role in explaining the low modal share of cycling 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 – that is, 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, for example, 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 levelling for large-scale actions (Sousa *et al*., 2019b). Electre Tri output may also be used as an assessment indicator in routing models for cycling (e.g. Kang and Fricker, 2018). The authors hope to address some of these issues soon.

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Appendix: examples of typical segments with final classification 1–4 and score formation

Figures 4–12 show photographs of typical examples of roads with classification 1–4 for both weight sets; Tables 5–13 show how their respective scores were formed.

Figure 4. Class 1 segment W1 (focus on safety)

Figure 5. Class 1 segment W2 (focus on comfort)

Figure 6. Class 2 segment W1 (focus on safety)

Figure 7. Class 2 segment W2 (focus on comfort)

Figure 8. Class 3 segment W1 (focus on safety)

Figure 10. Class 4 segment W1 (focus on safety)

Figure 11. Class 4 segment W2 (focus on comfort)

Figure 12. Class 4 segment W1 and W2

Table 5. Score formation for the segment shown in Figure 4

Criterion and scale (worst to best)	Subcriteria	Subcriterion score	Criterion score	Electre class W1
Comfort (0–4)	Pavement type (0–4)	4	4	1
	Conservation defects (4–0)	0		
Safety (0–4)	Motorised traffic volume (4–0)	3	0.5	
	Heavy traffic volume (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	

Table 6. Score formation for the segment shown in Figure 5

Criterion and scale (worst to best)	Subcriteria	Subcriterion score	Criterion score	Electre class W2
Comfort (0–4)	Pavement type (0–4)	0	0	1
	Conservation defects (4–0)	2		
Safety (0–4)	Motorised traffic volume (4–0)	1	3	
	Heavy traffic volume (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	

Table 7. Score formation for the segment shown in Figure 6

Criterion and scale (worst to best)	Subcriteria	Subcriterion score	Criterion score	Electre class W1
Comfort (0–4)	Pavement type (0–4)	4	2	2
	Conservation defects (4–0)	2		
Safety (0–4)	Motorised traffic volume (4–0)	3	1	
	Heavy traffic volume (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	

Table 8. Score formation for the segment shown in Figure 7

Criterion and scale (worst to best)	Subcriteria	Subcriterion score	Criterion score	Electre class W2
Comfort (0–4)	Pavement type (0–4)	4	1	2
	Conservation defects (4–0)	3		
Safety (0–4)	Motorised traffic volume (4–0)	1	3	
	Heavy traffic volume (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	

Table 9. Score formation for the segment shown in Figure 8

Criterion and scale (worst to best)	Subcriteria	Subcriterion score	Criterion score	Electre class W1
Comfort (0–4)	Pavement type (0–4)	4	3	3
	Conservation defects (4–0)	1		
Safety (0–4)	Motorised traffic volume (4–0)	1	2.5	
	Heavy traffic volume (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	

Table 10. Score formation for the segment shown in Figure 9

Criterion and scale (worst to best)	Subcriteria	Subcriterion score	Criterion score	Electre class W2
Comfort (0–4)	Pavement type (0–4)	4	2	3
	Conservation defects (4–0)	2		
Safety (0–4)	Motorised traffic volume (4–0)	1	3	
	Heavy traffic volume (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	

Table 11. Score formation for the segment shown in Figure 10

Criterion and scale (worst to best)	Subcriteria	Subcriterion score	Criterion score	Electre class W1
Comfort (0–4)	Pavement type (0–4)	4	2	4
	Conservation defects (4–0)	2		
Safety (0–4)	Motorised traffic volume (4–0)	3	4	
	Heavy traffic volume (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	

Table 12. Score formation for the segment shown in Figure 11

Criterion and scale (worst to best)	Subcriteria	Subcriterion score	Criterion score	Electre class W2
Comfort (0–4)	Pavement type (0–4)	4	3	4
	Conservation defects (4–0)	1		
Safety (0–4)	Motorised traffic volume (4–0)	2	2	
	Heavy traffic volume (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	

Table 13. Score formation for the segment shown in Figure 12

Criterion and scale (worst to best)	Subcriteria	Subcriterion score	Criterion score	Electre class W1/W2
Comfort (0–4)	Pavement type (0–4)	4	4	4
	Conservation defects (4–0)	0		
Safety (0–4)	Motorised traffic volume (4–0)	2	4	
	Heavy traffic volume (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	

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