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Cycling Network Discontinuities as Indicators for Performance Evaluation: Case Study in Four Cities

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Abstract

There are several existing evaluation methods for cycling networks, each with its set of indicators, none of which provides a complete picture of the cycling network performance. For example, most studies have relied only on the coverage as an indicator for network performance, while others focused on accessibility. Reviewing existing evaluation methods, it further appears that connectivity or discontinuity indicators have not been systematically identified and are missing from many evaluation methods. Discontinuities can be either intrinsic to the cycling facilities and the cycling network, such as changes in the type of facility or end of facilities, or related to changes in the cycling network environment, in particular the usually adjacent road network and motorized traffic. This paper formalizes the concept of discontinuities in the cycling network and the various causes of discontinuities, proposes a set of indicators to measure cycling network connectivity and the methodology to calculate them, including automated methods for geospatial data with the code available under an open-source licence. The automated method is applied to the comparison of the cycling network connectivity of four North American cities: Montreal and Vancouver in Canada, Portland, and Washington D.C. in the United States.

Keywords: cycling network, performance evaluation, discontinuity, connectivity, geospatial data

1. Introduction

Transportation researchers, planners, engineers, and policy makers have proposed network performance indicators to help better plan and design cycling networks or improve existing ones. The performance of cycling networks may refer to various characteristics and therefore be evaluated through different methods and criteria. The most common measures are related to the coverage and density of the cycling network, for example in terms of the length of each type of cycling facility, and proportion of the road network with cycling facilities. However, a very long or dense cycling network may also not be well connected, for example if the cycling network is frequently interrupted or the characteristics change frequently. Few methods have evaluated how well-connected cycling networks are, and precisely characterized the various kinds of discontinuities that may affect cyclist comfort, safety and efficiency.

There are different types of discontinuities, which can be either intrinsic to the cycling facilities and the cycling network, or related to changes in the cycling network environment, in particular the usually adjacent road network and motorized traffic. The types of discontinuities, listed in Table 2, can be put in three categories related to the different causes, intrinsic, road network or other, and can be measured through different indicators.

Stated and revealed preference studies have indicated that cyclists are sensitive to the presence and types of cycling facility, traffic volume, and number of intersections (Dill & Gliebe, 2008; Gamble, Snizek, & Nielsen, 2017; Menghini, Carrasco, Schüssler, & Axhausen, 2010; Winters, Davidson, Kao, & Teschke, 2011). Since these factors are shown to influence the cycling experience, then it is expected that cyclists will be sensitive to changes in these

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factors, such as an increase in traffic volume and changes from one cycling facility type to another. Discontinuities along the road network have shown to have an effects on driver behaviour when transferring from one type of road class to another (Xie & Levinson, 2007). A small number of studies on cycling network discontinuities have demonstrated they have an effect on cyclist behaviour (Barsotti & Kilgore, 2001; Krizek & Roland, 2005; Nabavi-Niaki, Saunier, & Miranda-Moreno, 2018; Sener, Eluru, & Bhat, 2009). Discontinuity indicators are independent from usual cycling network coverage and density measures and therefore complementary to evaluate a cycling network's performance. Overlooking discontinuity indicators is likely to result in a cycling network that will have lower ridership than it could have if properly connected.

This paper formalizes the concept of discontinuities in the cycling network and the various causes of discontinuities, proposes a set of indicators to measure cycling network connectivity and the methodology to calculate them, including automated methods for geospatial data. The automated method is applied to the comparison of the cycling network connectivity of four cities. The contributions of this study include the systematic review of existing methods and indicators to characterize cycling facilities, the description and automation of the methodology to compute discontinuity indicators (making the code available under an open-source license at https://github.com/nsaunier/cycling-discontinuities), and its application to the cycling networks of four different cities across North America using in particular density maps of the discontinuity indicators. The selected cities are Montreal and Vancouver in Canada, Portland, and Washington D.C. in the United States.

The next section provides a background and methodology with a description of the case study cities. The methodology section highlights the steps to identify discontinuity measures in each city. The findings are summarized in the discussion of results section.

2. Background

The evaluation of cycling network performance has received attention in recent years, with the development of a range of performance indicators that have an effect on cyclists as found from surveys and route choice studies (for example (Harkey, 1998; Jensen, 2007; Snizek, Sick Nielsen, & Skov-Petersen, 2013)). A questionnaire-based study with 4700 respondents by Snizek identified factors that have an impact on cycling, where results showed that high traffic volume, the number of intersections along the route, and road class result in a negative cycling experience (Snizek et al., 2013). A study in Ecuador combining several datasets identified the following infrastructural attributes to increase the positive experience for cyclists: presence of cycling facility, traveling further from intersections, closer to green space, and on primary and secondary roads (Gamble et al., 2017). A Danish study of over 50000 trips identified presence of cycling facilities and lower road grade to increase the probability of cycling (Nielsen & Skov-Petersen, 2018). Data collected from over 90 American cities looking into cycling mode share indicated a higher cycling proportion for cities with longer physically separated cycling facilities (Buehler & Pucher, 2012). Milakis and Athanasopoulos proposed indicators to evaluate the performance of proposed cycling networks including road grade, intersection density, traffic volume and speed, land use and environmental indicators as well as an indicator measuring deviation from a straight line (change in direction along cyclists route) (Milakis & Athanasopoulos, 2014). Other variables commonly used for cycling network performance measures are: traffic volume, traffic speed, traffic turning volume, presence of cycling facility, cycling facility width, cycling safety, road class type, number of road lanes, presence of parking, percentage of heavy vehicles, pavement surface condition, road grade, number of intersections, average block length, directness and comfortable access to certain destinations (Barsotti & Kilgore, 2001; Boisjoly & El-geneidy, 2016; Harkey, 1998; Iseki & Tingstrom, 2014; Landis, Vattikuti, & Brannick, 1997; Lowry, Furth, & Hadden-loh, 2016; Mekuria, Furth, & Nixon, 2012; Pucher & Buehler, 2006; San Francisco Department of Public Health, 2014; Sorton & Walsh., 1994; Transportation Research Board, 2016; Winters, Teschke, Brauer, & Fuller, 2016).

Frameworks for assessing cycling network suitability have been proposed as early as 1987 and have been evolving over the years. The following frameworks do not share the same indicators and use different rankings of the indicators: the Bicycle Compatibility Index (BCI) (Harkey, 1998), Bicycle Stress Level (BSL) (Sorton & Walsh., 1994), Level of Traffic Stress (LTS) (Mekuria et al., 2012), Bicycle Level of Service (BLOS) (Transportation Research Board, 2016), Bike Score (BS) (Winters, Brauer, Setton, & Teschke, 2013), Bicycle Environmental Quality Index (BEQI) (San Francisco Department of Public Health, 2014), Metropolitan Cycling Network Planning (MCNP) (Milakis & Athanasopoulos, 2014), and Bicycle Safety Index Rating (BSIR) (Davis, 1987). Each framework uses a different combination of traffic and infrastructure attributes (roadway and network) shown in Table 1. One can see that the variables most used in the mentioned frameworks are traffic speed, number of road lanes, traffic volume, speed limit, road lane width, parking along road, pavement condition and cycling facility width.

More recently, the FHWA published the guidebook for measuring multimodal network connectivity where a number of the mentioned connectivity measures were used: proportion and length of cycling facility along roadway, proportion of road with cycling facility, proportion of roads with low level-of-stress (based on the LTS), intersection density, connected link ratio, block length, road network density, and accessibility to certain locations (measured by presence of low-stress cycling facility between origin and destination) (Dill et al., 2018). Some of the mentioned frameworks were compared and ranked based on the level of effort for obtaining and computing indicators. Their findings concluded that all of the studied frameworks have strengths and weaknesses, and in order to avoid a distorted picture, more sophisticated connectivity measures must be used, and planners must be on the lookout for emerging connectivity analysis methods and measures (Dill et al., 2018). Kang et al.'s use of the BCI (Harkey, 1998) in a statistical model to evaluate its effects on cyclist's preference revealed that a higher BCI value (better performance ranked by the BCI method), would not increase the likelihood of cycling along on-road cycling facilities (separate cycling facility or bike lane), but would increase the off-road facility use (Kang & Fricker, 2013). Parks et al. applied three performance frameworks on a before-after study of bicycle facility installations: the BEQI, the BLOS, and the Danish Road Directorate BLOS (Parks et al., 2013). They concluded that each method has shortcomings and the development of a nationally accepted bicycle evaluation tool requires more research and evaluation in order to address the different bicycle facility and cyclist characteristics (Parks et al., 2013). A similar conclusion was drawn from a study by Vale et al. where an extensive literature review on active transport accessibility methods demonstrated conceptual and computational limitations, as well as inconsistencies in accessibility, connectivity and network performance concepts and terms (Vale, Saraiva, & Pereira, 2016).

Discontinuity measures are often overlooked or measured by inappropriate "connectivity" indicators such as the length of cycling facilities, the density of cycling facilities, and the distance from shortest path (Houde, Apparicio, & Séguin, 2018). Such indicators measure coverage, density, and the directness of trips through the network, not discontinuities, since the longest or densest cycling network may have low connectivity, e.g., if there are missing links or frequent changes in the type and other characteristics of cycling facilities, while a short cycling facility of the same type in a ring will have low coverage or density, and high connectivity. For example, Boisjoly and El-Geneidy made use of cyclist route data collected from online surveys to assess the cycling network "connectivity" using three (coverage) indicators: the detour or bicycle route diversion to the shortest path (calculated as the relative difference between the travelled route length and shortest path length), the presence of a bicycle facility along observed paths, and route directness as the ratio between the network and Euclidean distances (Boisjoly & El-geneidy, 2016). A study by Semler applied the LTS method (Mekuria et al., 2012) to categorize Washington D.C.'s connectivity of cycling routes between blocks of origin-destinations (Semler et al., 2018). A recent guidebook for developing pedestrian and bicycle performance measures defines a connectivity index based on cycling network density, connected node ratio (ratio of the number of intersections to the number of intersections and dead ends), link to node ratio (ratio of number of road links to the number of intersections and dead ends), and intersection density (Semler et al., 2016). These studies demonstrate the lack of consistency in the indicators used to measure the performance of a cycling network and the need to separately measure connectivity (through discontinuity indicators) and coverage/density.

In addition to cycling network performance evaluations, discontinuity indicators can be used in route choice studies to evaluate the effects of the interruptions on the cyclists' route choice. While some measures have been considered, e.g. the end of cycling facilities to score side path suitability (Barsotti & Kilgore, 2001), this literature review shows that no framework for the characterization of a cycling network connectivity through discontinuity indicators has been proposed. Given the lack of quantitative and objective discontinuity indicators, it is reasonable that little research has directly dealt with discontinuities in the cycling network and their impact on cyclists.

Table 1 List of variables used in the main cycling network performance evaluation methods

	Variables	**BLOS**	**BSIR**	**BEQI**	**LTS**	**BCI**	**BS**	**BSL**	**MCNP**
Traffic	Traffic speed	x		x	x	x		x	x
	Turning speed				x				
	Speed limit		x	x	x				
	Traffic volume	x	x			x		x	x
	Heavy vehicle volume	x				x			
	Right-turn volume					x			
	Parking (turnover and occupancy)		x		x	x			
Road Infra.	Number of road lanes	x	x	x	x				
	Road lane width		x		x	x		x	
	Length of right turn lane				x				
	Parking along roadside	x	x	x		x			
	Parking lane width				x				
Cycling Infrastructure	Presence of cycling facility					x			
	Cycling facility type				x		x		
	Cycling facility length						x		
	Cycling facility width	x		x	x	x			
	Bicycle parking			x					
	Bike lane markings			x					
	Bike lane signs			x					
	Connectivity of bicycle lane			x					
	Dashed bike lane on intersection			x					
	Left turn bicycle lane			x					
	Marked area before bicycle traffic			x					
	Bike lane blockage				x				
General Infrastructure	Type of signalization		x						
	Right turn lane		x						
	Left turn lane		x						
	No turn on red signal		x	x					
	Presence of shoulder	x				x			
	Shoulder width		x			x			
	Paved shoulder		x						
	Pavement condition	x	x	x					
	Presence of curb	x							
	Curb radius		x		x				
	Intersection angle				x				
	Driveway		x	x					
	Restricted sight distance		x	x					
	Presence of street lighting			x					
	Traffic calming features			x					
	Raised median		x						
	Grade		x				x		x
Other	Land use		x	x		x	x		x
	Intersection density						x		x
	Trees			x					x

3. Methodology

3.1. Defining Discontinuity Indicators

Cyclists' preference for riding on a continuous path has been demonstrated in previous studies (Sener et al., 2009). The interruptions along a cyclist's route can be summarized into discontinuity measures or indicators. Examples of these discontinuities include changes in the cycling facility type and their ends, road class type, location of cycling facility on the road (e.g., the side), large changes in traffic speed and volume. Table 2 presents a comprehensive categorization of the types of discontinuities in a cycling network and examples of indicators in each category. Some normalization is necessary to compare different areas of different size or with networks of different length and type, depending on the level of the study. The indicators in Table 2 are presented before normalization and they will generally be divided by a normalization factor:

- at the level of an area (for example a city or region), the normalization factor can be the length of the cycling network in the area or the area's surface;
- at the level of a cyclist route (for example for a route choice study), the normalization factor can be the route length.

For example, these different normalizations will yield for the ends of cycling facilities the following formulations for a given area and a given cyclist route:

$$DiscEnds_{area} = \frac{number\ of\ ends\ of\ cycling\ facilities\ in\ area}{cycling\ network\ length\ in\ area} \quad (1)$$

$$DiscEnds_{route} = \frac{number\ of\ ends\ of\ cycling\ facilities\ along\ route}{route\ length} \quad (2)$$

It should be noted that the indicators have possible minimums of 0 (no discontinuity), but their maximum are not theoretically bounded, although will be in practice. Furthermore, there can be variations of the indicators in each category, depending on the way to count or weigh the changes. For example, one could choose to count differently the changes from one type of cycling facility to another, since going from a separated cycle path to a cycle lane is not the same as going to a designated roadway where cyclists have not reserved space. Many indicators related to the number of changes of continuous characteristics in the cycling facility or adjacent road traffic require a threshold as indicated in Table 2, but other formulations based on these variables are possible, such as the sum of the absolute changes. For the changes in traffic volume, an indicator could be:

$$\frac{\sum_{discontinuity\ location\ in\ area} |q_{after\ discontinuity} - q_{before\ discontinuity}|}{cycling\ network\ length\ in\ area} \quad (3)$$

where $q_{before\ discontinuity}$ and $q_{after\ discontinuity}$ are the traffic volumes before (respectively after) the discontinuity. If one wishes to compare all the discontinuities at the level of an area, the indicators could be summed, although care should be taken for the homogeneity of the result. This work will focus on the comparison of different areas such as cities. The methodology to obtain discontinuity indicators from an area's cycling network is described in the following sections.

Table 2 Types of discontinuities and examples of indicators (before normalization)

Category	Types of discontinuities	Indicators (before normalization)
Intrinsic to Cycling Network	End of cycling facility	Number of cycling facility ends
	Change in cycling facility type	Number of changes of the type of cycling facility
	Change in cycling facility width	Number of locations where cycling facility width changes*
	Change in cycling facility location on road	Number of changes of the cycling facility side on road
	Change in pavement condition	Locations where pavement conditions change from good quality to bad
	Change in road lighting	Number of locations where illuminance changes*
	Change in road grade	Number of locations where there is a change in road grade*
	Closure/rerouting of cycling facility due to construction or maintenance	Number of areas where the cycling facility is closed or rerouted
Traffic and Road Network	Change in road class	Number of locations where road class changes
	Change in number of road lanes	Number of locations where there is a change in number of road lanes*
	Change in traffic volume	Number of locations where traffic volume changes*
	Change in traffic speed	Number of locations where traffic speed changes*
	Intersections	Number of intersections along cycling facility or cyclist's path
Other	Driveways	Number of driveways along cycling facility or cyclist's route
	Bus stops	Number of bus stops along cycling facility or cyclist's path
	Parking allowed on road	Length of road where parking is allowed crossing the cycling facility

(* indicates that a threshold must be defined to characterize the considered changes)

3.2. Data Preparation

The first step in quantifying the cycling network discontinuity in an area is obtaining georeferenced road and cycling network datasets, usually available from open data repositories (for more detail on how to construct and visualize street networks see (Boeing, 2017)). If the study area's cycling network dataset includes information on the cycling facility type, then the methodology can be applied to identify the ends and changes in cycling facility type discontinuities. If other information is also available such as the side of street the cycling facility is located on and the cycling facility lane width, or the area's road network with road type and speed limit information, traffic volume and bus stop locations, other discontinuity indicators can be extracted as well.

To unify the definition of cycling facility types, four cycling facility types are proposed: physically separated bike facility (interactions with other road users can occur only at intersections and bus stops where boarding and alighting pedestrians cross the separated facility), painted bike lanes (interaction with other road users occur at intersections, when vehicles cross the facility to access driveway or parking space, and when buses cross the facility at their stops), shared road with designated marking (cyclists have no dedicated space on the road and interaction with other road users can occur everywhere), and off-road cycling facility where there is no shared space and interaction with vehicles. In this study shared roads with designated marking are not considered a cycling facility type since cyclists must share the road with other users as in any other road.

3.3. Identifying Discontinuities

Manual Method to Identify Discontinuities

After preparing the datasets, the spatial analysis steps to identify the discontinuities and compute the indicators along the cycling network using a geographic analysis tool (e.g., ArcGIS) are presented in Fig. 1. The buffer sizes used may have to be adjusted on a case-by-case basis. The first step addresses cases where the cycling facility representation is not conjoined at intersections or cycling facilities are given a different class category at intersections.

Merge facility types as one line
• Draw a 5-m buffer around each road intersection, identify intersections with two dangling cycling facility ends in a buffer, assign the intersection ID to the two ends and join ends with the same ID • Merge continuous cycling facilities into a single facility line and merge road information to the cycling facility layer using a spatial join
Change in cycling facility type
• Draw a 5-m buffer around the endpoints of the unique cycling facilities • If another facility end, or facility type is present in the 5-m buffer, this end point is considered a change in facility type
End of cycling facility
• Draw a 2-m buffer at the end of each cycling facility • If there are no other end points, or cycling facilities in the buffer, this is considered an end
Change in cycling facility location on road*
• Each end is assigned an intersection or road ID • If there is a change in location on road at an intersection or road link, it is considered a discontinuity
Change in cycling facility width*
• Each cycling facility segment is assigned an intersection or road ID • If a segment changes width on the same road or intersection, it is considered a discontinuity
Change in road class, traffic volume, and traffic speed*
• If there is a change in road class, change in traffic volume, and change in traffic speed along the cycling facility, this is considered a discontinuity
Number of intersections along cycling facility*
• Draw a 40-m buffer around the road centerline to perform a spatial join with the cycling network, so that the information of each bike facility segment merges with the road network information • Count the number of intersections that are located along a cycling facility through a spatial join between the buffer and the road intersections

Fig. 1 Discontinuity identification methodology using a geographic analysis tool (* indicates steps that can be performed only if the required information is available)

Automated Computation of Indicators

The method is automated to accelerate and simplify the computation of discontinuity indicators and made available under an open-source license to allow other researchers and users to replicate and reuse this method on other datasets (https://github.com/nsaunier/cycling-discontinuities). This automation is done through spatialite, an open source spatially enabled extension of SQLite, a relational database management system. The methodology scripts include the following treatments: 1) merging the cycling facility as one line for each facility type (separate, bike lane, and off-road), 2) dissolving the merged geometries to identify the discontinuities, 3) creating the ends of cycling facilities (points and buffers), and 4) performing a spatial intersection between the ends of cycling facilities of different types. Only the ends of cycling facilities and the changes of facility types are automated in the provided scripts and the case study presented in the next section.

First, batch scripts are made to import the shapefile data. The SQL scripts to be executed in spatialite need to be written with slight modifications for different cities based on the city's system projection value from their spatial reference system identifier (SRID), with examples provided for each city. At the end of the script, the output files are exported that include point locations of facility ends and change in facility types. To quantify the discontinuities, the number of each discontinuity type is divided by the total length of the area's cycling network to compare results between different areas.

3.4. Results Analysis and Visualization

The output of the method is the shapefile of discontinuity locations which can be plotted for visualization. The raw map of discontinuity locations on the cycling facility and road maps provides an image of target locations for improvement. For comparison purposes, a density map of the discontinuities is more suitable. In this study, a kernel density with a radius of 1500 m was applied, and a mask showing a buffer around the cycling facility is used to highlight the density only where there is a cycling facility. Fig. 4 and Fig. 5 represent the densities of discontinuities for each city.

4. Case Study in Four Areas

To evaluate discontinuity levels using our proposed methodology, cities with publicly available spatial datasets including information on bicycle infrastructure such as facility type (separate bike path, bike lanes, shared road etc.) were selected: Montreal, and Vancouver, in Canada, as well as Portland and Washington D.C. in the United States (City of Montréal, 2015; City of Portland, 2015; City of Vancouver, 2015; District of Columbia Government, 2015). In this study, since not all information was available for all city area shapefiles, only the following two discontinuities were extracted: ends of cycling facility and change of cycling facility type.

These cities were previously subject to a bikeability or cycling network performance evaluation. For example, the Copenhagenize Index (CI) evaluated cycling network performance in major worldwide cities and ranked the top 20 most bicycle friendly cities in the world based on a set of thirteen categories, ranking Montreal as the 20th most bicycle friendly city (Copenhagenize Design Co., 2015). A cycling network performance evaluation of Canada's five largest cities reported that Vancouver has the highest number of cycling trips as well as the highest cycling mode share to work (6.1 %) followed by Montreal (3.9 %) (Statistics Canada, 2016). Although no U.S. cities show up on any major rankings of the world's most cycling friendly list, Washington D.C. and Portland are ranked among the top cycling friendly cities in the U.S., where 6.5 % and 4.3 % of commuters cycle to work in Portland and Washington D.C. respectively (The League of American Bicyclists, 2015; U.S. Census Bureau, 2016). These rankings are neither comparable nor complete as they use different evaluation indicators and methods.

4.1. Dataset Standardization

The obtained datasets are prepared uniformly for comparability and consistency in data analysis. Each city has different class definitions for their road and cycling facilities. For example, Vancouver has the following cycling facility classes: separated lanes, painted lanes and shared lanes, while Portland classified their cycling facility as: bike boulevard, bike buffer, bike lane, bike shared, bike track, shoulder wide, and paths. Hence, the facility classes for the four cities are grouped into four categories using Google Street View: physically separated bike facility, painted bike lanes, shared road with designated marking for bikes, and off-road cycling facilities. For our study, shared roadways with road marking for bikes are not considered as a cycling facility type.

4.2. City Descriptions

The following sections provide a more detailed description of each city as well as their road and cycling network characteristics as summarized in Table 3. The cycling network coverage is defined as the ratio of the cycling facility length to the road length.

Table 3 Description of the road and cycling network of the selected cities

Road and Bicycle Network Characteristics						
	Measure type		*Montreal*	*Vancouver*	*Portland*	*Washington D.C.*
City Density	**Surface** *(km^2)*		432	115	376	177
City Density	**Population density in 2016** *(residents per km^2)*		3946	5491	1701	3848
City Density	**Road density** *(km per km^2)*		**13.6**	7.1	11.3	10.6
City Density	**Cycling network density** *(km per km^2)*		1.2	0.9	**1.5**	0.7
Road and Bicycle Network Summary	**Road network length** *(km)*		5861	815	4254	1875
Road and Bicycle Network Summary	**Bicycle facility network length** *(km)*		503	103	567	118
Road and Bicycle Network Summary	**Cycling network coverage**		8.5 %	12.6 %	**13.3 %**	6.3 %
Road and Bicycle Network Summary	**Proportion of each type of bike facility in the cycling network**	*Separated bike path*	**64.0 %**	54.0 %	0.7 %	8.0 %
Road and Bicycle Network Summary	**Proportion of each type of bike facility in the cycling network**	*Bike lane*	20.0 %	46.0 %	44.2 %	**92.0 %**
Road and Bicycle Network Summary	**Proportion of each type of bike facility in the cycling network**	*Off-road bike path*	16.0 %	0.0 %	**55.1 %**	0.0 %

Montreal

The island of Montreal in Quebec, Canada has a population of 1.7 million (Statistics Canada, 2016) and an area of 432 km2. It is the most populated and has the largest area compared to the other cities. Montreal also has the highest road network density as shown in Fig. 2a Montreal is considered to be one of the best cycling cities in the world (Vijayakumar & Burda, 2015). In 2014 Montreal had a total length of 503 km of cycling facility (City of Montréal, 2015), 64 % of which is separated bike paths, 20 % painted bike lanes and 16 % off-road class. Montreal has a cycling network coverage of 8.5 % over its road network length. Compared to the other three cities, Montreal has the highest share of separate cycling facility. Yet, gaps in the cycling facilities and points where cycling facility types change are observed throughout the city.

Vancouver

Vancouver, with a population of roughly 632,000 (Statistics Canada, 2016), has the highest population density among the four cities, which is related to its smallest surface of 115 km2. The city has the lowest road network density with only 7.1 km road length per square kilometer- of the city's surface (Fig. 2b). However, it has the second highest cycling network coverage among the cities of 12.6 %. Vancouver's 103 km of cycling facilities in 2015 is 54 % separated cycle tracks and 46 % painted bike lanes, and no reported off-road cycling facilities (City of Vancouver, 2015). Despite the lower population compared to Toronto and Montreal, Vancouver has the highest number of daily cycling trips, which may be associated to its high safety levels, with less than one crash involving a cyclist for every 100,000 cycling trips (Vijayakumar & Burda, 2015).

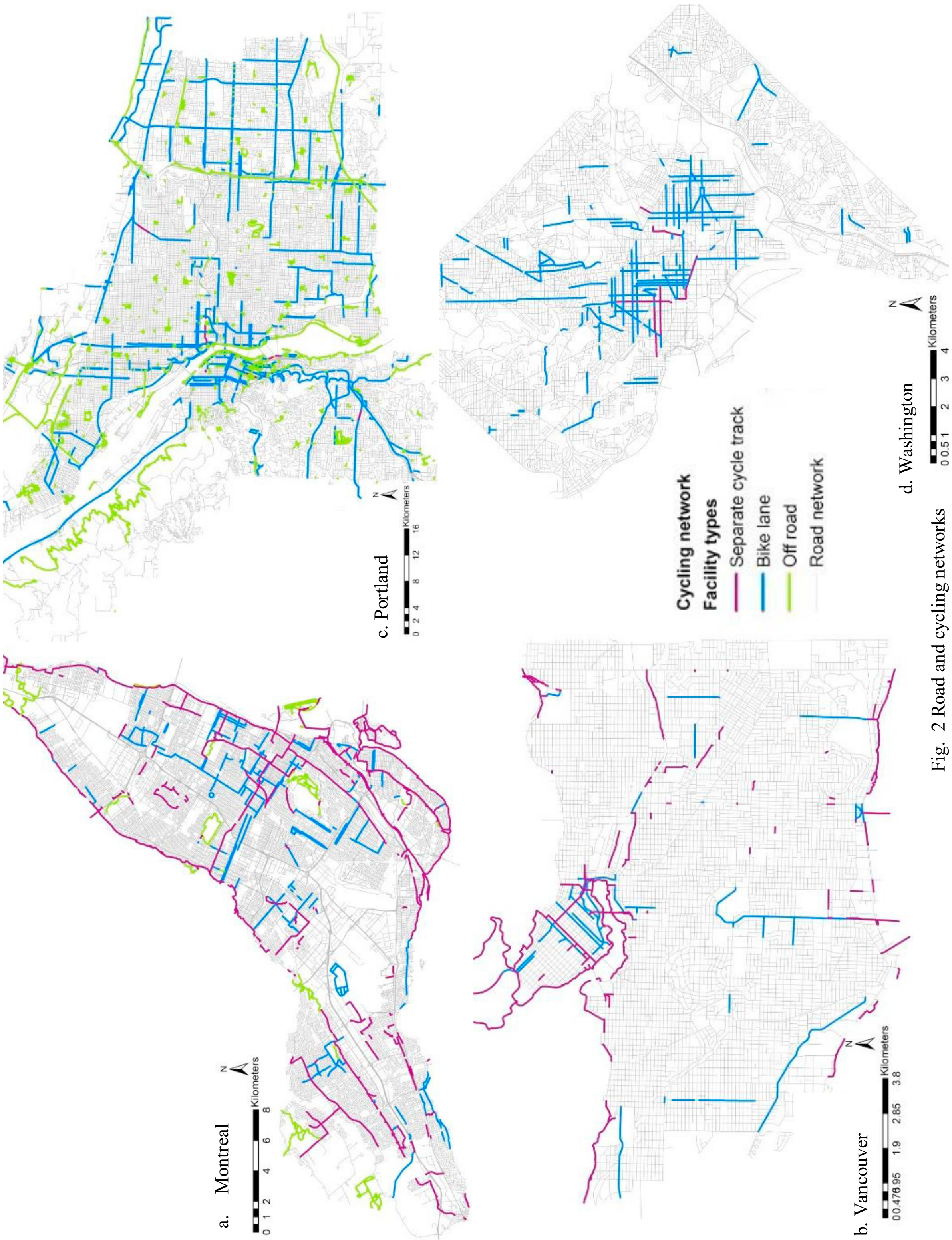


Fig. 2 Road and cycling networks

Portland

Portland has a population of about 640,000 (United States Census Bureau, 2016) and has the lowest population density among the four cities. The city has the second highest surface area of 376 km2, and second highest road density which can be observed in the compact layout of the road network in Fig. 2c. The city's cycling network coverage is the highest, being 13.3 % of its road network length in 2015 (City of Portland, 2015). Portland also has the longest cycling network of 567 km, although separated cycle tracks are only 0.7 % of the total cycling network length. This is in part compensated by the share of off-road bike paths making up 55.1 % of the cycling network, which is the highest among the four cities.

Washington D.C.

Washington's population of roughly 681,000 (United States Census Bureau, 2016) ranks in our selection as the third city for its population density, road network density, road network length and cycling network length. It has the lowest cycling network coverage. As apparent in Fig. 2d, the cycling network is composed almost exclusively of painted lanes (92 %) in 2015, with only 8 % as separate cycle tracks (District of Columbia Government, 2015).

4.3. Cycling Facility Type Distributions

Fig. 3 shows the summary of the distribution of each cycling facility type in each city. Two of the cities, Vancouver and Washington, have no available record of off-road cycling facilities. Portland has almost no separate cycling facility, only 4 km of the total 567 km of cycling network. Washington also has a low separate cycling facility class share of only 9 km out of 118 km of cycling facility, 109 km of which is dedicated to painted lanes. Montreal has a fair distribution among the different facility types.

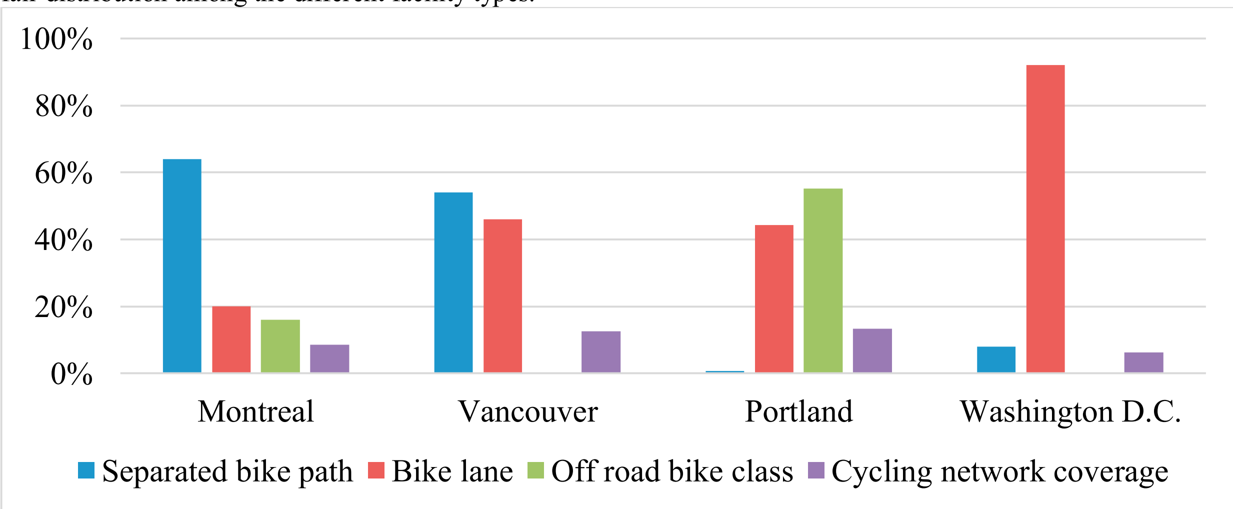


Fig. 3 Cycling facility class distribution and cycling network coverage for each city

5. Results and Discussion

Table 4 presents the normalized discontinuity measures for the cycling facility ends for each type and the change in cycling facility for each city as well as the city's total discontinuity. Fig. 4 shows the density of the cycling facility ends, and Fig. 5 shows the density of changes in cycling facility type in the four cities.

Table 4 Discontinuity indicators of the four cities

Bicycle Network Discontinuity Indicators for Four Cities						
	Measure type	**Bicycle Facility Class**	*Montreal*	*Vancouver*	*Portland*	*Washington D.C.*
Discontinuity Measures	**End of bike facility** *(per km cycle length)*	*Separated bike path*	0.48	**1.07**	0.01	0.04
		Bike lane	0.28	0.50	0.57	**1.51**
		Off-road bike class	0.09	-	**1.97**	-
		All end points	0.85	1.57	**2.55**	1.55
	Change in bike facility type *(per km cycle length)*		0.35	0.40	**0.47**	0.19
Total discontinuity			1.20	1.97	**3.02**	1.74

Based on results of the discontinuity indicators presented in Table 4, Portland ranks as the city with the most discontinuities of both types per kilometre of cycling network, which can also be observed in Fig. 4c and Fig. 5c, while Montreal has the least discontinuities. Focusing on ends of cycling facilities for each cycling facility type, Vancouver has the most separate cycling facility ends, which means there are separate cycling facilities scattered throughout the city that are not connected to each other or other facilities. Washington has the highest value for bike lane ends which is expected since almost the entire cycling network is made up of painted bike lanes (92.0 %). Among the two cities that have off-road cycling facilities, Portland has the highest off-road ends discontinuity level. In general, Montreal has the least discontinuities. The change in cycling facility type discontinuity indicators are close except for Washington which is considerably lower, again because most of its cycling network is of the same type.

Discontinuities in Montreal are distributed throughout the city as shown in Fig. 4a and Fig. 5a, while Portland's discontinuities are mostly concentrated in the downtown area (Fig. 4c and Fig. 5c). Vancouver, shown in Fig. 4b and Fig. 5b, has several hotspots for discontinuity locations throughout the city with the highest concentration in the downtown area. The distribution of discontinuities in Washington is concentrated in an area in and around its downtown covering a large portion of the city (Fig. 4d and Fig. 5d).

Summarizing the results allows ranking the four cities from the worst (most discontinuities) to the best (least discontinuities): Portland, Vancouver, Washington, and Montreal. Discontinuities appear throughout the four studied cities highlighting the importance of further evaluating the effects of these interruptions in the cycling network on cyclist behaviour and safety.

A study found that connecting the gaps in the Boston cycling network, which would result in a facility length increase by a factor of 2.5, the fraction of home-work pairs that will be connected by the network increases by a factor of 13 (Furth & Noursalehi, 2015). Fig. 4 and Fig. 5 highlight hotspot locations for improvements in the four cities. For example, the links in the darkest red in Fig. 4 highlight areas where several cycling facility ends near each other could be connected with the implementation of only a few meters of cycling facility. An example is shown in Fig. 6 where an area of Vancouver with a high concentration of cycling facility ends is chosen, and the ends are connected in ArcGIS by adding 6.5 km of cycling facilities. This improvement results in better connectivity where the discontinuity indicator for the facility ends decreased from 2.7 to 0.3.

Fig. 4 End of cycling facility density

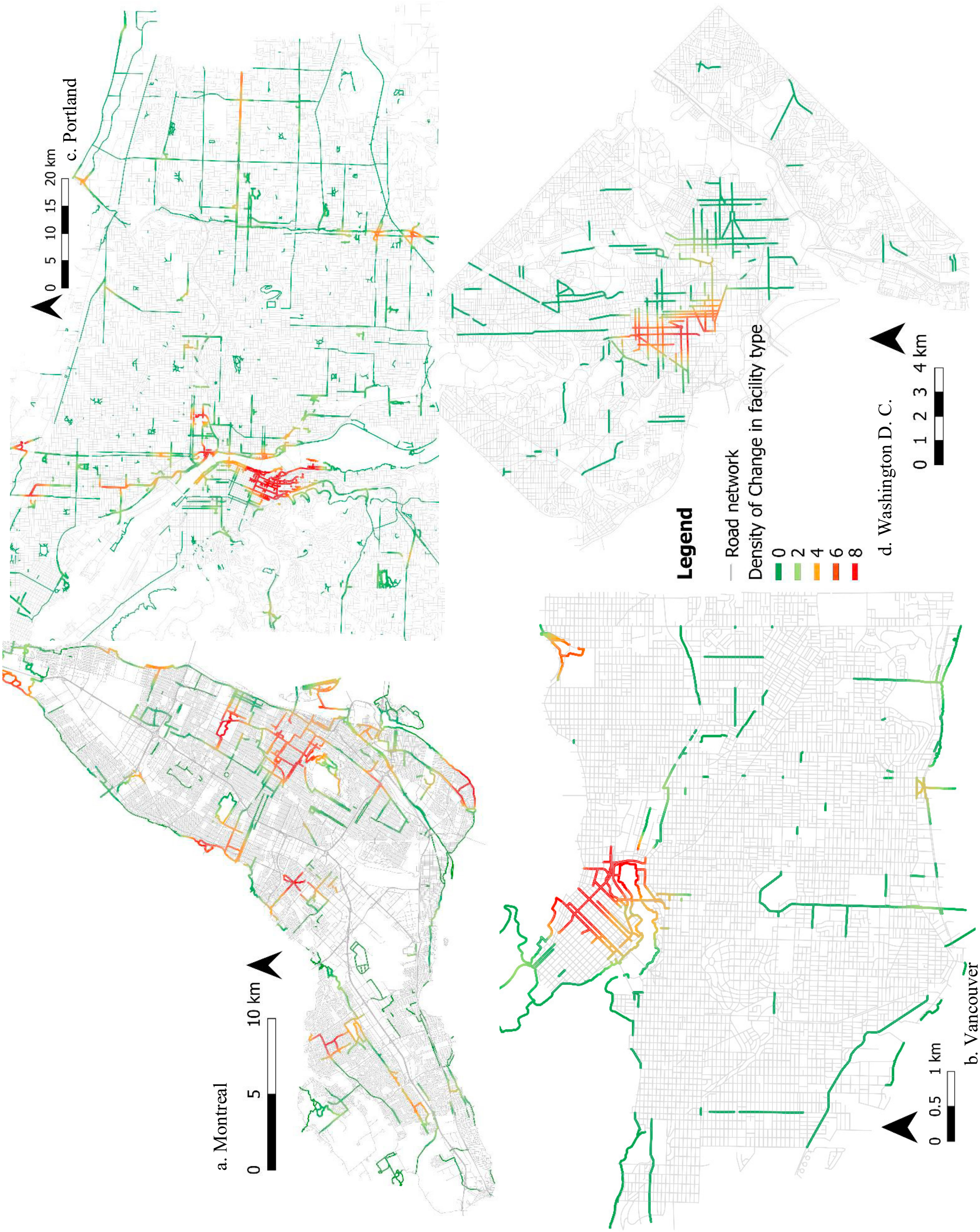
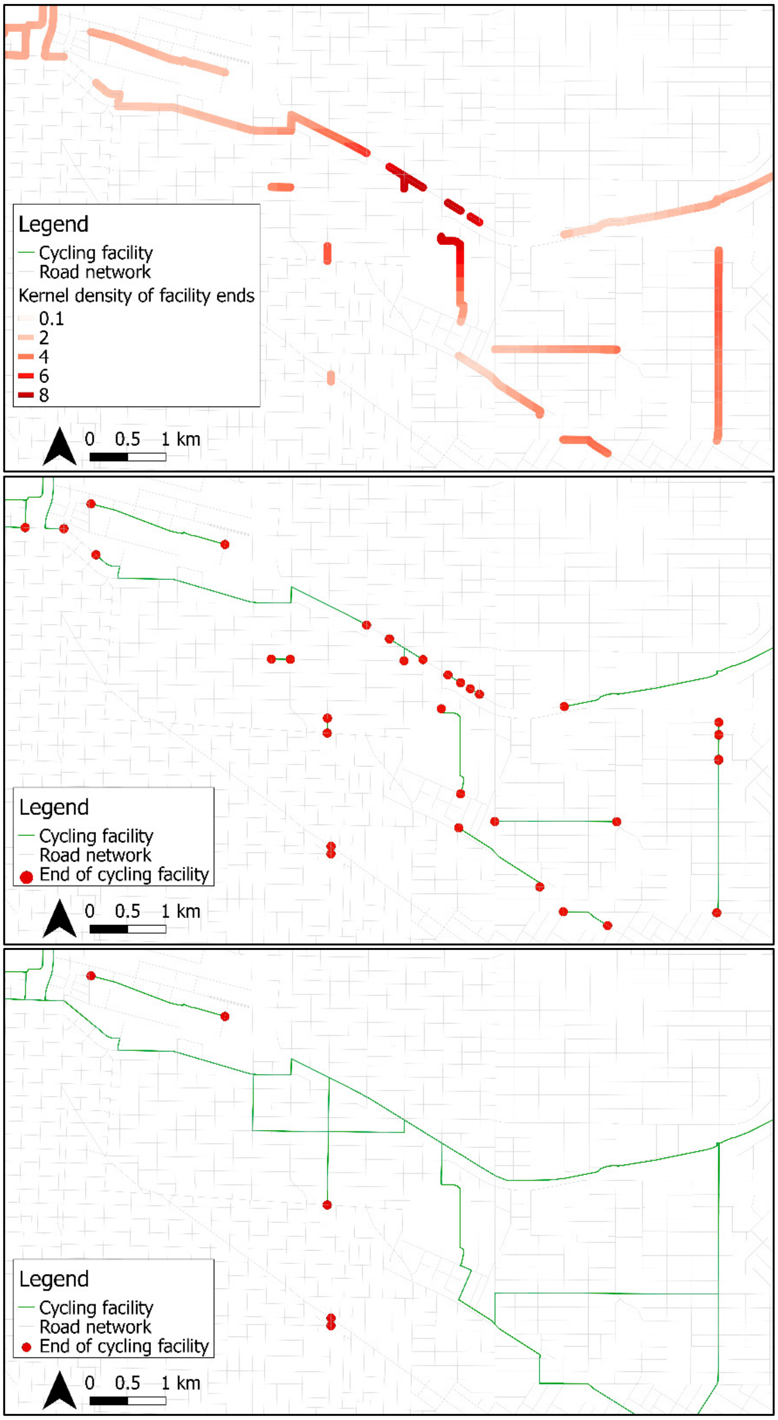


Fig. 5 Change in cycling facility type density



a. Identify locations with a high concentration of facility ends based on the kernel density

b. Identify road links for implementing connections between cycling facility ends

c. Extending the cycling facility to connect ends results in a more connected network

Fig. 6 Improving the connectivity of the cycling network by connecting the cycling facility ends

6. Conclusion

In the literature, the current methods for evaluating cycling network performance are incomplete and sometimes inconsistent. The performance of a cycling network is typically measured by its length and coverage. However, the cycling network's connectedness, or lack thereof, and its points of discontinuity are essential factors in evaluating the network's performance. Given their direct effect on cyclist behaviour, discontinuities must be identified and eliminated to improve cycling facilities and to promote cycling. As most cycling network performance studies and criteria do not include discontinuities, this work proposes a conceptual framework for discontinuities and a methodology to identify discontinuity locations and calculate discontinuity indicators. This is demonstrated in a case study on four cities and can be replicated in any city with some basic data available. For easy extraction of the discontinuity indicators, an automated methodology is made available in an open-source repository (https://github.com/nsaunier/cycling-discontinuities). The application of this methodology also helps cities identify locations that can be improved by simple connections of the cycling facility where there are several facility ends concentrated in an area.

A key strength of this method is the minimal data requirements since many areas already have the required road and cycling network geospatial data which includes: the cycling facility type, location on the road, road class, and other network geometric information (number of lanes, lane width, etc.). The results show a high density of discontinuities in the cycling networks of the four compared cities. The cycling network ranking ranks Portland as the city with the most discontinuities, following by Vancouver, Washington and finally Montreal with the least discontinuities.

Limitations of our study include the limited number of discontinuity indicators that were extracted automatically due to the limited information available from the available cycling network data. More studies are necessary to understand the range of these indicator values, and what a "good" cycling network is in terms of these indicators. Future work includes the evaluation of microscopic road user behaviour and safety at discontinuities, building upon initial work showing that cyclists behave differently at discontinuity locations compared to control sites through automated movement and speed analysis from video data (Nabavi-Niaki, Saunier, & Miranda-Moreno, 2018; Nabavi-Niaki, Saunier, & Miranda-Moreno, 2019). Cyclist GPS data can be used to study the effects of discontinuities on mode choice cyclist's observed route choice. Mode choice studies can use discontinuities as a variable that may affect an individual's choice to cycle.

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