Are we connected? Assessing bicycle network performance through directness and connectivity measures, a Montreal, Canada case study

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ABSTRACT

Over the last two decades, cycling has seen a rise in popularity in North American cities, which are continuously expanding their bicycle networks. While studies highlight that a good network should provide direct bicycle routes for cyclists to reach their desired destination, most network assessments measure the length of bicycle facilities or street connectivity. Building on a set of complementary indicators to account for directness of bicycle facilities, this study assesses the performance of the bicycle network in Montreal, Canada. The study uses data from two large-scale online surveys (2,917 and 2,644 respondents) conducted Summer 2009 and 2013. Actual home to work/school routes are generated using bicycle facilities and the street network based on three different cycling route preferences. Diversion and proportion of route on bicycle facilities are calculated to assess directness of bicycle routes. Based on these two indicators, connectivity is measured. The Montreal network did show a low level of connectivity of less than 51% on every level of preference. Areas with low levels of connectivities were then highlighted spatially. Finally, using circuitry measures, results showed that the extent to which existing transportation network favors driving with a circuity of 1.22 for home to work trips compared to 1.33 for trips made by bicycle. Using a simple set of performance measures, this study highlights the need to incorporate bicycle network connectivity objectives into transportation plans to improve the efficiency of the network and hence promote bicycle use. Cities wishing to promote bicycle use can use these measures to better evaluate their bicycle network connectivity through a metrics of network efficacy reflecting cyclists’ trade-off when prioritizing the construction of bicycle routes.

Keywords: Bicycle network efficiency, Connectivity, Directness, Cycling routes, Mode share
INTRODUCTION

Over the last two decades, cycling has seen a rise in popularity in North American cities in terms of use, funding, and policies (1). Research shows that the supply of bicycle facilities generally provides a positive experience for cyclists and is related to higher cycling levels and mode shares (2-5). Accordingly, cities in North America are focused on expanding and improving their bicycle networks (1) to offer an alternative to motorized commuting modes. While the length or density of bicycle facilities is used in most studies and planning documents to assess a city’s network (6-8), these metrics indicate little about the efficiency of the network for commuting. An efficient bicycle network should allow cyclists to reach their desired destinations using bicycle-friendly routes without undue detours (4; 9; 10). A lengthy network around a lake or a river can be of great value for recreational purposes but be impractical for commuting. Inversely, a straight route along busy boulevards can provide fast and direct connections, but raise concerns regarding safety and comfort. As there is a trade-off between route directness and quality of route, multiple indicators have to be addressed to assess the general bicycle network performance. However, very few quantitative indicators addressing the general network performance, other than length, have been adopted (6; 9).

The current study proposes a set of complementary indicators to assess the general performance of bicycle networks. Three indicators were selected, accounting for route directness and presence of bicycle facilities. The first one measures bicycle route diversion compared to the shortest street network distance including short cuts. The second indicator takes into account the presence of bicycle routes, measuring the proportion of the trip along bicycle facilities. While the third indicator depends on the directness using circuity, the ratio between network and airline distances (11) to compare the directness across modes (car vs bicycle networks). Building on these three complimentary indicators and on previous work (10), network connectivity is assessed. These three indicators were selected as they reflect cyclists’ route choice preferences and are easy to communicate and interpret.

Using these indicators, this paper assesses the performance of the bicycle network on the Island of Montreal, Canada. The study uses data from two large-scale online cycling behavior surveys conducted during the Summers of 2009 (12) and 2013 (4). The 2009 survey provides detailed information on actual bicycle trips including detailed route information, while the 2013 survey provides actual home and work/school locations of cyclists in 2013 in addition to a series of detailed questions about home location choices and travel preference. Although the area of study is the Island of Montreal, this research provides methodological insight on how to assess the general performance of cycling networks in addition to their size, using available data and resources. This methodology can benefit transport engineers and planners around the world as they try to promote bicycle adoption for commuting through the increase in new bicycle facilities.

LITERATURE REVIEW

What Makes a Good Bicycle Route?

Bicycle commuting is positively related to the provision of off-street paths and on-street lanes, as they provide more positive travelling experiences for cyclists (3; 13). Cyclists are sensitive to the characteristics of the path they use. Altogether, studies report that the presence of bicycle lanes, the low volume of motorized traffic and the suitability and safety of bicycle routes are major attributes of an attractive bicycle network (4; 5; 14; 15). Furthermore, cyclists value route directness, high travel speed (4; 14), low travel time (5; 15; 16) and continuous bicycle infrastructure (5).

Since cyclists value direct connections and suitable routes, numerous studies have looked into how cyclists balance these two criteria when choosing a route. Hunt & Abraham's (16) analyzed stated preference regarding bicycle routes and found that time spent in mixed traffic is 2.7 or 4.1 more costly to cyclists than time spent on bicycle paths or bicycle lanes, respectively. Accordingly, cyclists are willing to make detours to use bicycle facilities. In a study in Montreal, Larsen & El-Geneidy (12) found that respondents who used bicycle facilities added an average of 2.2 km to their trips in terms of detours compared to non-path users. Similarly, Tilahun et al. (17) reported that cyclists add up to 20 minutes to their trips to use an off-road bicycle trail instead of using an on-road lane with side parking, this study depended on a stated preference survey. Nevertheless, not all cyclists consider such detours, as segmented
analyses reveal that route choices and stated preferences differ based on types of cyclists. For example, Hunt & Abraham (16) report that cyclists with higher level of comfort and experience in mixed traffic give lower cost value to time spent in mixed traffic. Broach et al. (15) found that commuting cyclists value trip directness more than the presence of infrastructures, while recreational cyclists are more likely to use bicycle infrastructures (12). A large amount of literature also explores the influence of different types of bicycle paths on cyclists (10; 12; 15). However, this is not the focus of the present study.

Network Performance Assessment

Although a lot of research has been conducted on bicycle route choice and cyclists preferences, few measures have been developed to assess the general performance of cycling networks (9). Based on preferences of cyclists, a good network should provide direct connections requiring minimal detours (9). While most research on network efficiency has focused on transit and street networks (11; 18; 19), some recent studies have developed efficiency measures for bicycle networks. In this regard, Schoner & Levinson (9) measure directness and connectivity of bicycle networks of 74 American cities and find a positive relation between directness of route and bicycle commuting. Connectivity is assessed through various indices of ratios between the numbers of edges and vertices of bicycle facilities. In another vein, Mekuria et al. (10) measure low-stress connectivity of bicycle networks in San José, California. The authors defined low-stress connectivity as the ‘percent of trips connected’ using bicycle-friendly routes and without excessive detours as an indicator of connectivity.

Regarding transit and street network, Levinson & El-Geneidy (11) measured car network circuity, defined as the ratio of the shortest network distance divided by Euclidian distance, in 20 cities in the United States. Their findings support that residents select their home location based on direct commuting routes. Building on circuity measures, Lee & Choi (18) proposes another measure of directness for transit networks, comparing the actual transit route to the shortest street network distance. Lee & Choi (19) compare transit circuity and street network circuity in five Korean cities and find that transit ridership is strongly related to the directness of the transit network. Circuity in general is a good measure to assess the differences between networks and their directness.

Given the mounting interest in improving cycling networks in North American cities, developing accessible quantitative assessment methods is essential to provide planners and engineers with the necessary tools to design and improve their network. The review of literature reveals that while multiple criteria need to be accounted for when assessing bicycle network performance, very few general performance indicators accounting for multiple factors. This study builds on network performance measures and bicycle route choice literature to offer easy to communicate indicators that are adapted to bicycle networks. The indicators are sensitive to cyclists’ preferences, as they incorporate the proportion of the route on bicycle facilities as well as the route directness. They are also sensitive to local context as the connectivity thresholds are obtained from actual cyclists route choices in Montreal.

STUDY CONTEXT

The area of study is the Island of Montreal, in Quebec, Canada, with a population of 1,988,243 residents (20) and an area of 499.1 km$^2$ (21). The agglomeration, an administrative entity encompassing the territory of the Island of Montreal (Figure 1), includes the City of Montreal divided in 19 boroughs, and 13 independent municipalities. It is governed by the City of Montreal, with the participation of the independent municipalities.

Montreal is generally presented as one of the best cycling cities in the world, and the best cycling city in North America (22-24). In the last ten years, the Island of Montreal has experienced a rise in bicycle popularity, namely with the introduction of the bicycle sharing system, BIXI, in 2009. The total length of bicycle paths has increased continuously, from 400 km in 2009 to 602 in 2013 and 680 km in 2015 (7; 8). Figure 1 illustrates the bicycle network on the Island of Montreal, with the majority of the infrastructure in central Montreal, and one major bicycle facility around the island. In 2010, the bicycle share of workers was 2.4% (1).
DATA AND METHODOLOGY

Route choice of cyclists in Montreal

Data collected in a previous survey in 2009 with 2,917 cyclists in Montreal provides information of actual trips made by bicycle, both for cyclists using bicycle paths and for cyclists not using bicycle paths (12). The survey was an online survey that was heavily advertised through social media, in the local newspapers, and at major cycling events through distributing flyers about the survey to different cyclists. The origin, the destination, as well as the locations where the cyclist got on and off the bicycle facility, if they used any, were collected as part of the survey. The sample included 1,382 (70%) cyclists who used bicycle facilities and 591 (30%) cyclists who did not use bicycle facilities in their daily commute to work or school. This dataset allows calculating the distance each cyclist added to his or her trip in order to use a bicycle facility and the proportion of the trip travelled along bicycle facilities. It thus provides average diversion, together with proportion of trip on facilities, for cyclists who used bicycle paths. Obtaining these measures allows benchmarking the connectivity measures, as will be discussed later. In order to provide performance assessment based on cyclists’ actual behavior, the benchmarks should reflect an average cyclist’s behavior regarding route choice.

Home and work/school locations

In order to assess the extent the bicycle network allows individuals to reach their desired destinations, actual origin and destination locations must be used (10; 11). Accordingly, this study uses two sets of data providing actual home-work/school locations. The first one is a survey conducted by the TRAM research group with 2,644 cyclists in Montreal (4). This survey was conducted online in 2013 using similar advertising technique as the 2009 survey. Each respondent reported his home, work/school, and shopping locations where they commute to by bicycle. Since the bicycle network evolves rapidly in Montreal, data from 2013 are used as they correspond to the bicycle network that is assessed (2013 map).

The second set of data comes from the 2008 Origin-Destination Survey conducted by the Agence métropolitaine de transport de Montréal (AMT). The dataset contains detailed information on respondents’ trips including trip origin, trip destination, main transportation mode and purpose of the trips. The home location of the respondent is also provided. From this database, trips made by bicycle and/or car, originating at home and ending at work or school are selected. This dataset allows exploring route efficiency across
transportation modes.

Bicycle Facility-Prioritized Network
A first network is generated using a map of the bicycle facilities in Montreal from Summer 2013, obtained through the open data website of the City of Montreal (25). Since most of the cyclists using bicycle facilities do a part of their trip on the street network, it is necessary to generate a network that allows portions of routes to be on streets that are available to cyclists (excluding highways) and other portions to be along the existing facilities.

Accordingly, a second network is created, combining bicycle facilities (25) and streets that are available to cyclists (26). Using ArcGIS network analyst, a level of preference can be assigned for bicycle facilities, which sets a lower cost coefficient for bicycle facilities (compared to streets) when calculating the shortest route. In order to account for various cyclists’ preferences for cycling facilities (10; 12), three different levels of preference are assigned (low, medium, high) using the following coefficients: 0.2, 0.5 and 0.8. A coefficient of 0.5 means that streets are two-times more costly than bicycle facilities in terms of length. In other word, a bicycle facility of 1 km counts as 0.5 km.

Performance assessment
Using each level of preference, routes are generated for each pair of home-work/school locations from the 2013 cycling survey. Using the generated routes, two performance indicators (diversion and percentage of route along a path) are calculated for each level of preference. Diversion, commonly used in the literature (10; 19), is calculated by dividing the detour travelled (shortest route subtracted from actual route) by the shortest route. The proportion of the route along bicycle facilities is calculated through GIS network software, intersecting the actual route with the bicycle network. Once these two indicators are obtained for each route, a normalized value is calculated for each, in order to allow comparative measures.

Since there is a tradeoff between proportion of route on bicycle facilities and diversion, it is necessary to assess these two indicators simultaneously. A measure of connectivity is generated, as it allows incorporating multiple criteria and is easy to interpret. Based on previous work (10), connectivity is defined as the number of routes that are connected (as a percentage of the total number of routes) respecting specific criteria. In our case, connectivity is based on route diversion and proportion of route on bicycle facilities. Put simply, routes that travel a minimal proportion along facilities without exceeding a maximal detour are considered connected. The maximal threshold for diversion and the minimal threshold for proportion of route along facilities are set based on Montreal cyclists’ average preferences, obtained through the 2009 survey data. Accordingly, connectivity allows measuring the proportion of people that have direct bicycle facilities to reach work or school, taking into account local preferences. Nevertheless, depending on the planning or research objectives, different thresholds can be specified.

Finally, spatial analysis is conducted to assess performance disparities across the boroughs on the Island of Montreal. Routes are assigned to the boroughs, based on home locations. Hence, a route departing in borough 1 and ending in borough 2 will be assigned to borough 1. Out of 34 boroughs/municipalities, 24 are included in the analysis, as ten were excluded because they had fewer than two routes beginning in them. For simplicity reasons, we present the results for only one preference level. For each borough, the average dispersion and proportion on bicycle facilities is calculated. Additionally, the connectivity is calculated for each borough using the same thresholds as above.

Network performance and mode
Lately, using the 2008 Origin-Destination survey, circuity measures are provided as they allow efficiency comparisons of different networks, in our case, the street network (for trips and made by car) and the bicycle and street network with preference (for trips made by bicycle). Such comparisons is important as it shows to what extent cycling network is underserving cyclists and imposing more travel on them compared to car drivers.

Limitations
Given the data available, some limitations must be considered. First, driving directions of the streets and
bicycle facilities are not included in the network, as they were not provided in the original files. As a result, network distances might be underestimated, allowing routes to use all segments in both directions. Since both bicycle facilities and streets are considered two-way, diversion measures should not be significantly affected. However, the circuitry is probably underestimated, since using both directions provides shorter network distances. Additionally, for the spatial analysis, measures are based on the routes originating in the borough. It therefore does not account for the destination. However, since an average is provided for all routes, it gives a good indication of borough interconnectivity.

RESULTS

Route Characteristics of Cyclists in Montreal

First, data from the 2009 cycling survey are used to assess cyclists’ route choices in Montreal using the 2009 street and bicycle network. For each cyclist surveyed, his/her actual route is generated, based on his/her origin and destination, and based on where he/she got on and off the bicycle facility, if he/she used any. If a cyclist used more than one facility in his/her trip, he/she was asked to report the details of the facility they used the most in their trip in terms of distance. As an example, Figure 2 illustrates the actual route of one respondent, together with the shortest route and the Euclidian distance. Based on these lengths, the detour, the circuitry and the portion of the trip on bicycle facilities are calculated (Figure 2). The portion of the trip on bicycle facilities is based on the distance traveled on the main facility, and does not take into account facilities that might have been used to access the main facility from the origin and to access the destination from the facility.

![Figure 2: Shortest Route, Actual Route and Euclidian Distance (Example from the 2009 Survey)](image)

<table>
<thead>
<tr>
<th>Trip Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Euclidian distance (m)</td>
<td>3046</td>
</tr>
<tr>
<td>Length – Shortest Route (m)</td>
<td>3207</td>
</tr>
<tr>
<td>Length – Actual Route (m)</td>
<td>4788</td>
</tr>
<tr>
<td>Circuity</td>
<td>1.57</td>
</tr>
<tr>
<td>Detour (m)</td>
<td>1580</td>
</tr>
<tr>
<td>Detour (%)</td>
<td>49</td>
</tr>
<tr>
<td>Portion of Trip on Facilities (%)</td>
<td>63</td>
</tr>
</tbody>
</table>

The average route characteristics of the cyclists who used a bicycle facility (path-users) and those who did not (non path-users) are presented in Table 1. Results show that for commuting to school or work, path-using cyclists divert from the shortest path with an average detour of 12% (695 m) and have a circuitry of 1.33, compared to 1.22 for the non path-using cyclists.
TABLE 1 Average Route Characteristics for Path-Users and Non Path-Users

<table>
<thead>
<tr>
<th>Route Characteristic</th>
<th>Path-Users</th>
<th>Non Path-Users</th>
</tr>
</thead>
<tbody>
<tr>
<td>Euclidian distance (km)</td>
<td>4.91</td>
<td>4.23</td>
</tr>
<tr>
<td>Length – Shortest Route (km)</td>
<td>6.46</td>
<td>5.02</td>
</tr>
<tr>
<td>Length – Actual Route (km)</td>
<td>5.76</td>
<td>5.02</td>
</tr>
<tr>
<td>Circuity</td>
<td>1.33</td>
<td>1.20</td>
</tr>
<tr>
<td>Detour (m)</td>
<td>695</td>
<td>0</td>
</tr>
<tr>
<td>Detour (%)</td>
<td>12</td>
<td>0</td>
</tr>
<tr>
<td>Portion of Trip on Facilities (%)</td>
<td>50</td>
<td>0</td>
</tr>
<tr>
<td>Connectivity</td>
<td>29</td>
<td>6.0</td>
</tr>
</tbody>
</table>

*Note that values between path-users and non path-users are significantly different from one another, with p-values lower than 0.05.

Performance of the Bicycle Network

Three levels of preference are assessed to account for different types of cyclists, which may have varying preferences in terms of diversion and proportion along facilities. Table 2 presents performance indicators and the average length for every level of preference, using the 2013 home-work/school locations of cyclists. Connectivity is measured based on the 2009 path-user averages, using 12% maximal diversion and 50% minimal proportion of the routes. In other words, only routes with a detour lower than 12% and with a proportion of route along facilities higher than 50% are considered as connected.

As expected, higher levels of preference for using bicycle facilities yield on average greater diversion and proportion of route on facilities. Generally speaking, the network provides low connectivity (all below 51%). Using only bicycle facilities, the connectivity drops to 5%. For comparison purpose, the 2009 path-users average trip characteristics are included in Table 2. The medium preference aligns best with 2009 path-user preferences with an average diversion of 12%. Regarding the portion of the route on bicycle facilities, it is much higher for the medium preference than for the 2009 path-users. This can be explained by the fact that the 2009 portion of the trip on bicycle facilities only includes the main facility used, as explained above. Moreover, 202 km of facilities were added since 2009, possibly explaining this discrepancy.

TABLE 2 Average Route Characteristics for Every Level of Preference

<table>
<thead>
<tr>
<th>Route Characteristic</th>
<th>No</th>
<th>Low</th>
<th>Medium</th>
<th>High</th>
<th>Bicycle facilities only</th>
<th>Path-Users</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bicycle facilities cost coefficient</td>
<td>0</td>
<td>0.8</td>
<td>0.5</td>
<td>0.2</td>
<td>Infinite</td>
<td>Unknown</td>
</tr>
<tr>
<td>Route Length (km)</td>
<td>5.8</td>
<td>6.1</td>
<td>6.5</td>
<td>7.1</td>
<td>5.6</td>
<td>5.8</td>
</tr>
<tr>
<td>Diversion</td>
<td>0</td>
<td>4.3</td>
<td>12</td>
<td>24</td>
<td>20</td>
<td>12</td>
</tr>
<tr>
<td>Proportion of Route on Facilities (%)</td>
<td>19</td>
<td>32</td>
<td>82</td>
<td>89</td>
<td>100</td>
<td>50</td>
</tr>
<tr>
<td>Connectivity (%)</td>
<td>20</td>
<td>36</td>
<td>51</td>
<td>51</td>
<td>5</td>
<td>29</td>
</tr>
</tbody>
</table>

For simplicity reasons, only results for the medium level preference are presented in the rest of the paper. This level of preferences was chosen as it provides high connectivity and average diversion similar to the preferences of cyclists of 2009.

Home location choice and directness

In the 2013 survey, several home location questions were included to assess the impacts of bicycle facilities on home location choices. This was done by asking a series of questions about how important was the following criteria when selecting your current home. These criteria included the presence of bicycle paths and others like the size of the home or being near public transport. Surprisingly, the average diversion and
proportion along bicycle facilities of people who selected their homes based on the presence of bicycling facility (30% of the sample) was similar to those who did not consider these facilities (no statistical significance difference was present). In other words, although cycling facilities can be used as a motivation for choosing a specific neighborhood to live in, yet the current structure of the network does not lead to a more direct route for those who selected to live in a neighborhood due to the presence of cycling facilities.

Spatial Analysis

This section assesses the relative bicycle network performance across boroughs/municipalities on the Island of Montreal using the previously discussed measures. Figure 3 shows the relative indicators for proportion of route along facilities (Fig. 3A) and diversion (Fig. 3B). Generally speaking, boroughs scoring high for the proportion along facilities are located on the periphery of the Island. However, apart from two boroughs located in the southwest (Dorval and Lachine), peripheral boroughs also have higher levels of detours. This is due to the presence of a major recreational cycling facility around the Island. Although this facility is long and provides low divergence, few direct routes are available to access this peripheral path. This finding confirms the need to include multiple indicators when assessing network performance. For example, the borough at the extreme northeast of the Island (Pointe-aux-Trembles-Rivières-des-Prairies) and the two boroughs in the southwest of the Island (Dorval and Lachine) are characterized by a relatively high proportion along facilities. However, when looking at the diversion indicator, Pointe-aux-Trembles-Rivières-des-Prairies experiences the highest level of diversion while Dorval and Lachine experience the lowest level. Inversely, the Ville Mont-Royal borough, located in the centre of the Island, is characterized by a relatively low diversion score. However, it also shows a very low proportion on bicycle facilities. This suggests that direct routes are used, travelling mainly on streets. This is likely due to the quasi-absence of bicycle facilities in this borough.
In order to account for proportion of route on facilities and diversion simultaneously, the connectivity measure based on these two indicators is presented in Figure 4. Results show that apart from the Dorval and Lachine boroughs, central boroughs north of downtown experience the highest connectivity. This is due to the presence of bicycle facilities on both north-south and east-west axes, connecting each borough to the boroughs around it. Inversely, the southern tip of the Island, while encompassing many bicycle facilities, has a major east-west connection, but no north-south facilities connecting to other boroughs, which may explain its low connectivity. Unexpectedly, Dorval and Lachine experience the highest levels of connectivity. A brief assessment of the cyclists’ home location in these boroughs reveals that they mainly reside near the peripheral bicycle facility, which provides a direct link to downtown (compared to the street network). This may account for the high proportion of route on facilities with low
diversion.

FIGURE 4 Connectivity Indicators at the Borough Level

Transport Mode and Network Efficiency

Finally, since previous work found a positive association between route directness, provision of bicycle facilities and mode share, network efficiency across modes is explored, using the 2008 AMT Origin-Destination survey (11; 19). Circuity measures are calculated for all origin-destination pairs of cyclists and drivers for trips for work and school purposes. The calculations for cyclists were done using the medium level of preference for the bicycle network, which includes bicycle facilities and street network, excluding highways. For driver, the network was constructed using the street network only and including highways. These two networks reflect the routes that are available to cyclists and car users respectively. Results suggest that the overall transportation network allows more direct routes for drivers than for cyclists, as they have statistically significant lower circuity (1.35 for cyclists vs 1.22 for car users). Note that the car value is in line with previous work (11). One plausible explanation is that expressways provide direct, unhindered routes through the city. As a corollary, the results suggest that the bicycle network does not provide significant shortcuts compared to the street-only network. A brief comparison of circuity between the bicycle facility and street network, and the street only-network suggests that shortcuts provided by bicycle facilities are negligible, with an average lower distance of only 11 m (0.5%). This is likely to due to the fact that bicycle networks are built as add-ons to the street network. Also it suggests that bicycles facilities were not designed as a network in Montreal, but rather small projects responding to certain needs or addressing an engineering problem that exists in the city.

Furthermore, using bicycle network (bicycle facilities and street network, excluding highways), average circuity was also calculated for origin-destination pairs of drivers. Data show that bicycle origin-destination pairs have significantly lower circuity (1.35) compared to car origin-destination pairs (1.40), using the bicycle and street network with a medium level of preference. Results indicate that higher bicycle mode share could be associated with lower bicycle and street network circuity. Also having a circuity of 1.40 for car users when they use the bicycle network shows that with the current infrastructure it will be difficult for a car user to switch to using a bicycle. This highlights a major challenge in attracting car users to use bicycle in the future.

Generally speaking, the results provide insight on the usefulness of circuity to compare the
efficiency of different transportation networks, in this case bicycle network vs street network. Furthermore, it supports the importance of directness indicators for assessing bicycle network performance and increasing bicycle use.

**DISCUSSION AND CONCLUSION**

This paper assesses Montreal’s bicycle network performance, building on a set of complementary indicators. Two indicators reflecting a major attribute of good bicycle routes according to cyclist criteria are generated: route diversion and proportion of route along bicycle facilities. These two indicators are then assessed simultaneously, with the connectivity measures. Using these indicators, the performance of Montreal network is assessed for three levels of preference regarding bicycle facilities, accounting for different types of cyclists. Generally speaking, all levels show low connectivity (all lower than 51%). In other words, using criteria that reflect cyclists’ preferences, the network provides good connectivity to less than 51% of the population. Furthermore, results show a clear trade-off between route directness and proportion of route along bicycle facilities. The spatial analysis illustrates the need to include both indicators to evaluate the performance of the bicycle network. Finally, using circuity measures, results found that the Montreal transportation network generally favors trips made by car, with a circuity of 1.22 compared to 1.33 for trips made by bicycle.

From a transportation planning standpoint, the study provides an applicable method for assessing bicycle network performance. First it provides a simple method to generate a bicycle network that reflects various cyclists’ behavior, allowing cyclists to travel on streets while assigning a preference for bicycle facilities. The level of preference for bicycle facilities can be specified to a desired level that can be adjusted depending on planning objectives. Furthermore, connectivity criteria can be set to reflect actual preferences in the real world. A good connected cycling network should be the one where 100% of the cyclists can reach their desired destinations with minimum diversion to use a bicycle facility (less than 12%), travel is along cycling facilities most of the time (more than 50%), and the circuitry between the home and destination is the same as other modes (1.2 or less).

Second, this research suggests indicators that are easy to generate, interpret and communicate, and they are indicators that have shown to impact bicycle use and cyclists’ experience (1; 3; 5). While this study focused on diversion and proportion of route along bicycle facilities, other indicators can be developed to account for more factors influencing route choices. Such factors include travel speed, esthetic of the route and presence of crossing intersections. Performance indicators developed in this study can be generated by planners and researchers to assess different improvement scenarios, as done by Mekuria et al. (10), or to conduct a comparative study across cities as done by Schoner & Levinson (9). Also, as shown in this study, performance indicators can be used to implement spatial analysis and identify the areas that are in need of improvement the most.

This study also provides insight on bicycle network performance indicators, which go beyond the simple length of bicycle facilities in a city. While the length of the network provides a good indication of bicycle facilities supply, it does not account for desired trips and for efficient resource allocation. While most planning documents provide quantitative objectives in terms of length, connectivity is increasingly seen as a concern, as it is the case in Montreal (7; 8). Accordingly, the development of quantitative connectivity measures becomes increasingly relevant for practitioners and should be included in transport plans as key performance measures. Moreover, assessing the performance of bicycle network connectivity offers insight into the spatial scale of planning bicycle infrastructures for a city. In Montreal, while the vision for transportation networks is determined at the agglomeration level, boroughs and independent municipalities are responsible for implementing bicycle lanes, perhaps leading to the poor connectivity revealed in this study.

Finally, exploring the relation between transportation mode and circuity suggests that the directness of the route could influence mode choice, and more research is needed in this area to confirm our finding. Additionally, the comparative circuity analysis shows that drivers are favoured by the overall transportation network compared to cyclists. Hence, in order to promote bicycle use, cities have to address the directness of their bicycle routes that are provided by the overall network.
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