Transit-oriented development and bikeability: Classifying public transport station areas in Montreal, Canada

Arianne Robillard[a], Geneviève Boisjoly[a]*, Dea van Lierop[b]

[a]*Polytechnique Montreal, 2500 Chemin de Polytechnique, Montreal H3T 1J4, Canada*
[b]*Utrecht University, Princetonlaan 8a, Utrecht 3584 CB, Netherlands*

Abstract

Transit-oriented development (TOD), characterized by a high and mix development around public transport stations, is gaining traction as a sustainable way to support the use of public transport for regional trips and active transport for local trips. To support integrated land use and transport planning, several TOD typologies have been developed, with a focus on land use and transport characteristics, and more recently walkability. While TOD aims to motivate the use of active modes, including cycling, assessments of bikeability have been left out of TOD typologies. To fill this gap, this study seeks to develop a bicycle-oriented TOD typology that combines indicators related to the cycling environment with traditional land use and transport indicators. Using Montreal, Canada as a case study, 14 indicators are generated to develop a TOD typology oriented on bikeability and the 114 public station areas are grouped into seven distinct clusters. The results demonstrate that the addition of bikeability criteria to the TOD typology helps discriminate the different types of stations based on their current bikeability and bikeability potential. The proposed framework enables identifying and prioritizing targeted interventions to station development. This study is of relevance to planners and researchers aiming to integrate cycling in the development of TOD.

Keywords: Bikeability, Bicycle, Transit-oriented development, TOD typology

* Corresponding author.
E-mail address: gboisjoly@polymtl.ca

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1. Introduction

In response to the challenges associated with car-dependent development, cities and regions are implementing transit-oriented development (TOD) in North America, Europe (van Lierop, Maat, & El-Geneidy, 2017), and Asia (Thomas et al., 2018), to propose urban transport policies that are more sustainable from an economic, social, and environmental point of view. TOD is a concept that originates from the United States of America, proposed by Calthorpe (1993), which can be defined by a mixed and dense urban development within walking distance of public transport (PT) facilities (e.g., 400-800m; representing 5-10-min walk). While the development is focused around PT stations, it encourages the use of PT for longer trips and promotes walking and cycling for shorter distances and access to the station. By making public and active transport more convenient and desirable, it contributes to reducing car dependency and car use (Ibraeva, de Almeida Correia, Silva, & Antunes, 2020).

TOD is an integral part of urban development plans for many cities (Thomas et al., 2018; van Lierop et al., 2017). However, its implementation remains a challenge (Curtis, Renne, & Bertolini, 2009) and varies widely depending on the context. Accordingly, the concept is difficult to transfer between regions, especially internationally. Cities need and tend to adapt the malleable definition of the TOD concept to better apply it to their political, cultural and territorial context (Cournoyer-Gendron, 2017; Thomas et al., 2018).

To better understand how the concept of TOD is implemented around the world and inside a region, the development of a TOD typology is a useful tool. By grouping PT stations with common characteristics together, based on indicators that reflect the different components of TOD, a TOD typology is useful to diagnose common issues shared by different stations and to propose development and policy recommendations to improve the implementation of the concept (Ibraeva et al., 2020). A TOD typology can also indicate which aspects of a given area more closely represent the principles of TOD, thereby identifying the strength and weaknesses of different actual and potential TOD locations. Constant efforts are made to develop typologies that better reflect the complex definition of the TOD concept, while being specific to the regions to which they are applied. Since the traditional 400-800 m TOD buffer implies a reasonable 5-10 minutes' walk to the stations, walking is typically considered as the main access mode to PT stations in TOD. Walking has therefore received a lot of attention from planners and researchers. Indeed, walkability measures are now well integrated in the classification of PT station areas and some typologies are oriented towards walkability, to better capture the quality of the walking environment (Han, Zhang, Mitani, & Li, 2021; Jeffrey, Boulangé, Giles-Corti, Washington, & Gunn, 2019; Vale, 2015). To our knowledge, it is still not the case for bikeability measures, and no typology has been proposed to classify stations based on bikeability. Cycling can play an important role in developing TOD that support sustainable mobility(Lee, Choi, & Leem, 2016). As such, cycling can contribute to increasing catchment areas of stations (Forouhar & van Lierop, 2021) which can improve accessibility to stations and support mixed-used developments. In doing so, it supports active modes such as walking and cycling, as well as public transport, while reducing car use and the amount of public space devoted to cars (Higgins & Kanaroglou, 2016; Kamruzzaman, Baker, Washington, & Turrell, 2014). In line with the TOD objectives, it stimulates social interactions and physical activity, while reducing greenhouse gas emissions, cutting noise pollution, and reducing car dependency (Niu, Hu, Shen, Huang, & Mou, 2021). Although it is important to differentiate cyclable environments from walkable environments (Muhs & Clifton, 2016), the literature tends to neglect the importance of cycling in the context of TOD. Yet, increasing bicycle mode share is on the agenda of many cities around the world, and to achieve this, the infrastructure and cycling environment must allow for safe and convenient cycling both around the stations and on a metropolitan scale.

To support integrated bicycle and transport planning, this study sets out to propose a methodology to classify PT stations by combining indicators related to the cycling environment with traditional land use and transport indicators. It is applied to Montreal Census Metropolitan Area (CMA), using a partitioning around medoids (PAM) cluster analysis. The resulting typology consists in seven clusters of PT station areas, and implications in terms of planning and policies are discussed. The inclusion of a bikeability criterion in this classification of PT stations enables the development of a typology that distinguishes stations according to their current bikeability and their bikeability potential. The proposed framework illustrates how the assessment of the bikeability potential in the context of TOD enables the prioritization of land use and transport interventions and policies in the region, depending on station type. These efforts can contribute to promote bicycle as a feeder mode to PT for the first and last miles, as well as to encourage bicycle trips around PT stations. It is as relevant for regions that have already adopted cycling as a transport mode as it is for regions where cycling is still under-used. Overall, the proposed methodology allows for more strategic, targeted, and organized planning of TOD, which focuses on bikeability.

2. Literature review

2.1. TOD typologies: Classification and Characterization of PT Station Areas

In the literature, commonly used indicators to develop TOD typologies are related to the 5D variables, which act as measures of the built environment (Ewing & Cervero, 2010). Originally, the concept started with the 3Ds (density, diversity and design), as the main features of TOD (Cervero & Kockelman, 1997). Two additional Ds were added (destination accessibility, and distance to transit) by Ewing and Cervero

(2001) to create the 5Ds, and demand management and demographic were later included in a few studies as the sixth and seventh Ds (Ewing & Cervero, 2010). While criteria to develop PT station typologies typically involve the D variables (Ibraeva et al., 2020), Liu, Singleton, and Arribas-Bel (2020) highlight that several studies include variables that extend beyond these variables. Building on a comprehensive literature review of 29 studies (2009 to 2018) on TOD typologies, the authors propose a new categorization that more closely reflects the current state of the art (Liu et al., 2020). The authors group all indicators into the following four domains: land use and built environment (e.g., population/jobs/intersection density, mixedness of land use, average block size, property values), location and accessibility (e.g., distance to station, measures of accessibility from stations, travel time/distance to work/activities/amenities, individuals' perceptions, distance to the city centre), socioeconomic and demographic characteristics (e.g., ethnicity, age, vehicle ownership, education level, household income and composition), and PT-related characteristics (e.g., frequency, directions served, ridership of the service, number of stations nearby, walkability/cyclability, parking facilities). While most TOD typologies in the literature share common variables that relate to these four domains, distinct and new variables are included depending on the study objectives, the proposed improvements of the original node-place model, the data availability and the specific context of the location of the study (Ibraeva et al., 2020; Liu et al., 2020; Lyu, Bertolini, & Pfeffer, 2016; Niu et al., 2021).

The node-place model, introduced by Bertolini (1999) as a conceptual framework to investigate the PT and land-use characteristics of PT station areas, serves as a basis for several TOD typologies. This model charts the different PT stations based on two dimensions: the accessibility of the transport node (node) and the diversity and intensities of the activities around that transport node (place). The model was applied to the Amsterdam and Utrecht agglomerations in the Netherlands (Bertolini, 1999). Four typical stations were distinguished: the stations under stress, where both the node and the place values are high; the dependant areas, where both values are low; the unsustained nodes, where the PT services are more developed than the urban activities; and the unsustained places, where there is a lack of PT service as compared to the number of activities. Recent studies have built on the node-place model to improve the classification method of PT stations areas in different contexts. For example, Monajem and Nosratian (2015) added spatial indices to the node-place model to evaluate the quality of the local street network in Teheran; Zhang, Marshall, and Manley (2019) combined it with a strategic network indicator to characterize the metro stations from a system perspective in Greater London; Dou, Wang, and Dong (2021) also added a network component to classify station areas in Shanghai; and Liao and Scheuer (2022) integrated demand characteristics to facilitate the comparison of stations in Beijing. Recently, Rabiei, Nasiri, and Eicker (2022) have proposed a three-stage TOD assessment applied to the case of the Montréal metro network. They applied a weighted node-place model to identify stations that can increase density and diversity of land use to a specific optimum that will maximize PT accessibility, while maintaining the same transportation supply.

Many studies have also attempted to add a walkability component to existing TOD typologies. For example, Vale (2015) extended the node-place model by adding a third dimension that characterizes the walking environment of PT station areas. More specifically, the author added a "pedshed ratio" as an indicator of walkability to develop a TOD typology for the Lisbon Metropolitan Area. The pedshed ratio corresponds to the ratio between the area accessible via the pedestrian network and the area of the circular buffer around the station, both based on the same distance threshold. According to Vale (2015), this indicator contribute to better describe the efficiency of the station location (within the urban fabric as opposed to adjacent to it). Similarly, Lyu et al. (2016) proposed to group TOD indicators into 'Transit'(node), 'Development'(place), and a third 'Oriented' criteria to evaluate the functional and morphological interrelations between the first two criteria. The morphological interrelations are described by the proximity and accessibility to and from the PT node, and by the walkability (Walk Score) and bicycle facilities around the stations (Lyu et al., 2016). To better account for the complexity of walkability and its role in TOD's success, Jeffrey et al. (2019) developed a train station typology using fourteen walkability indicators to classify stations and identify potential TOD in Melbourne, Australia. In a nutshell, walkability is now increasingly considered in TOD typologies in various forms, such as Walk Score (Dou et al., 2021; Lyu et al., 2016; Su, Zhang, Wang, Weng, & Kang, 2021), density/length of pedestrian network (Dou et al., 2021; Huang, Grigolon, Madureira, & Brussel, 2018; Niu et al., 2021; Singh, Lukman, Flacke, Zuidgeest, & Van Maarseveen, 2017; Yang & Song, 2021), pedshed ratio (Singh et al., 2017; Vale, 2015; Vale, Viana, & Pereira, 2018; Yang & Song, 2021), accessibility measures (Woo, 2021) , and others (Dou et al., 2021; Han et al., 2021).

In contrast, the multiple components of bikeability have been neglected in the TOD typology literature. As such, few indicators related to bikeability have been included in typologies and, to the authors knowledge, no TOD typology oriented on bikeabilty has been developed.

2.2. Bikeability and TOD

A bikeable environment can be described as an environment that is suitable and safe for cycling (Schmid-Querg, Keler, & Grigoropoulos, 2021). Bikeability, on the other side, is an assessment of an entire bikeway network and/or environment in which cycling is taking place; this implies that the quality of individual bicycle paths or lanes are considered within the full capacity of the overall network (Nielsen & Skov-

Petersen, 2018). In that sense, it is important to differentiate walkable environments that are characterized by the level of density, land use mix and connectivity, and bicycle environments that are more often characterized by the quality of the infrastructure and the completeness of the network (Muhs & Clifton, 2016).

The bikeability indices found in the literature proposed different combinations of indicators to assess the bikeability of an environment. Castañon and Ribeiro (2021) have conducted a literature review on bikeability indices that specifically assess the bikeability of an environment. Studies from 2009 to 2019 that specifically assess bikeability (i.e., not mixed with walkability), while addressing issues related to transport and the built environment were retained. The authors grouped all 138 indicators found in the 14 studies into four domains and 17 criteria: cycling infrastructure (availability, quantity, quality, typology, design, multimodal features, and bicycle sharing system), accessibility (land-use and network features), safety (traffic, segregation, conflicts, and behaviour), and surrounding environment (topography, landscape aesthetics, and pollution). The frequency of use of the criteria in all studies is presented and availability, quantity (e.g., length), and design (e.g., number/width of lanes, surface type/condition) are the most common criteria for cycling infrastructure; land use (e.g., density, mixedness of land use) for accessibility; and traffic (e.g., speed limit, traffic volume) for safety.

Directly in line with the current study, Hartanto, Grigolon, van Maarseveen, and Brussel (2017) developed a bikeability index specifically for TOD, to help promote the bicycle as a feeder mode to PT. The index includes indicators about traffic conditions, connectivity, infrastructure, environment, topography, and bicycle parking. While the study focuses on the bikeability of TOD (without considering other land use and transport factors characterizing TOD), the proposed index can serve as a basis to develop a TOD typology oriented on bikeability. The bikeability index of Hartanto et al. (2017) was developed for 21 stations in the Arnhem-Nijmegen region in the Netherlands, and the results suggested that suburban stations scored higher in bikeability than urban regions. With an extensive list of indicators regarding bikeability, this index provides a more detailed characterization of the cycling environment, in a context where the bicycle is a feeder mode to PT.

Nevertheless, bikeability measures are still not effectively integrated into TOD typologies. Some TOD typology studies have considered specific indicators such as the length or density of bicycle infrastructure or the presence of bicycle parking in the PT station areas (Chen & Lin, 2015; Han et al., 2021; Huang et al., 2018; Niu et al., 2021; Singh et al., 2017). These studies, however, did not comprehensively assess the quality of the cycling environment around PT stations. The typology proposed by Liu et al. (2020) is the one that includes, in a bicycle facilities score, the most variables regarding bikeability (bikeshare system, bicycle routes and parking shelter density). However, Liu et al. (2020) included 64 representative static and dynamic variables to better assess the spatiotemporal dynamics of activity at PT stations, which means that the cycling environment is not emphasized over the other variables in that study.

In the present study, we aim to comprehensively assess the contribution of the cycling environment in the context of TOD, by considering the complexity of the bikeability in the classification of PT station areas. This research seeks to explore how to develop bicycle-focused TOD typologies that consider the key bikeability components of TOD. In the context of the Montreal CMA, this classification of PT station areas allows to better assess the bikeability potential of these environments, in order to contribute to station development and support bicycle and PT use.

3. Case Study Area

The study area, shown in Fig. 1, is the Montreal CMA, which is divided into eight regions. Around 4.3 million people live in the CMA, on a territory of 4,259 km². The Montreal CMA includes two rapid mass transit networks: the metro and the commuter rail. The four metro lines, operated by the *Société des Transports de Montreal* (STM), mainly serves the central and peri-central neighborhoods (Montreal (Center) in Fig. 1. Montreal Census Metropolitan AreaFig. 1), where there is a greater population density. For all lines, the time interval of the metro varies from three to five minutes during peak hours, four to ten minutes during off-peak hours and five to twelve minutes on weekends. The region's commuter rail is operated by the regional PT operator (EXO). The five lines cover low-density suburbs at the periphery of the territory and converge towards Montreal (Downtown), where the highest concentration of employment of the region is located. The frequency of this service is one to two times an hour on peak hours, and it offers a few off-peak passages. Six stations are intermodal stations, servicing both the regional train and the local metro.

In the Montreal CMA, the modal share over a 24h period (in the fall period) is 64.0% for cars, 18.9% for PT, 10.6% for walking and 1.9% for cycling (Enquête Origine-Destination, 2018). Montreal (Center) has a 5.0% modal share for cycling with the highest modal share of 13.0 % in some neighborhoods (Vélo Québec, 2020). With the bikeshare system, highly valued by the housing market in Montreal (El-Geneidy, van Lierop, & Wasfi, 2016), the continuous development of the bicycle network, and the administration in place that sends a positive message surrounding bicycle infrastructure and new PT, Montreal takes the 18th place in the Copenhagenize Index (2019), a well-known index that ranks the most bicycle-friendly cities in the world, based on fourteen components of bikeability (Schmid-Querg et al., 2021).

The *Communauté métropolitaine de Montréal* (CMM) is the public planning body responsible for the planning, coordination, and strategic financing in the region. Its main land use planning objective is to direct at least 60% of new households into TOD– type neighbourhoods, by 2031 as a strategy to increase the modal share of transit (Communauté métropolitaine de Montréal, 2012). TOD is therefore instrumental in achieving the planning objectives of the Montreal CMA. Yet, the Montreal CMA presents important challenges for the successful implementation of TOD. The characteristics of PT station areas vary importantly across the territory, and the lack of appropriate planning tools complicates the integrated planning of land use and transport, and the development of cycling infrastructure. Further, the relatively low and medium density in which several PT stations are located and the CMA's efforts to support cycling call for integrated PT and cycling planning. Accordingly, the development of a TOD typology oriented on bikeability, in the case of Montreal, can shed light on the applicability of the methodology to inform transport planning and policies.

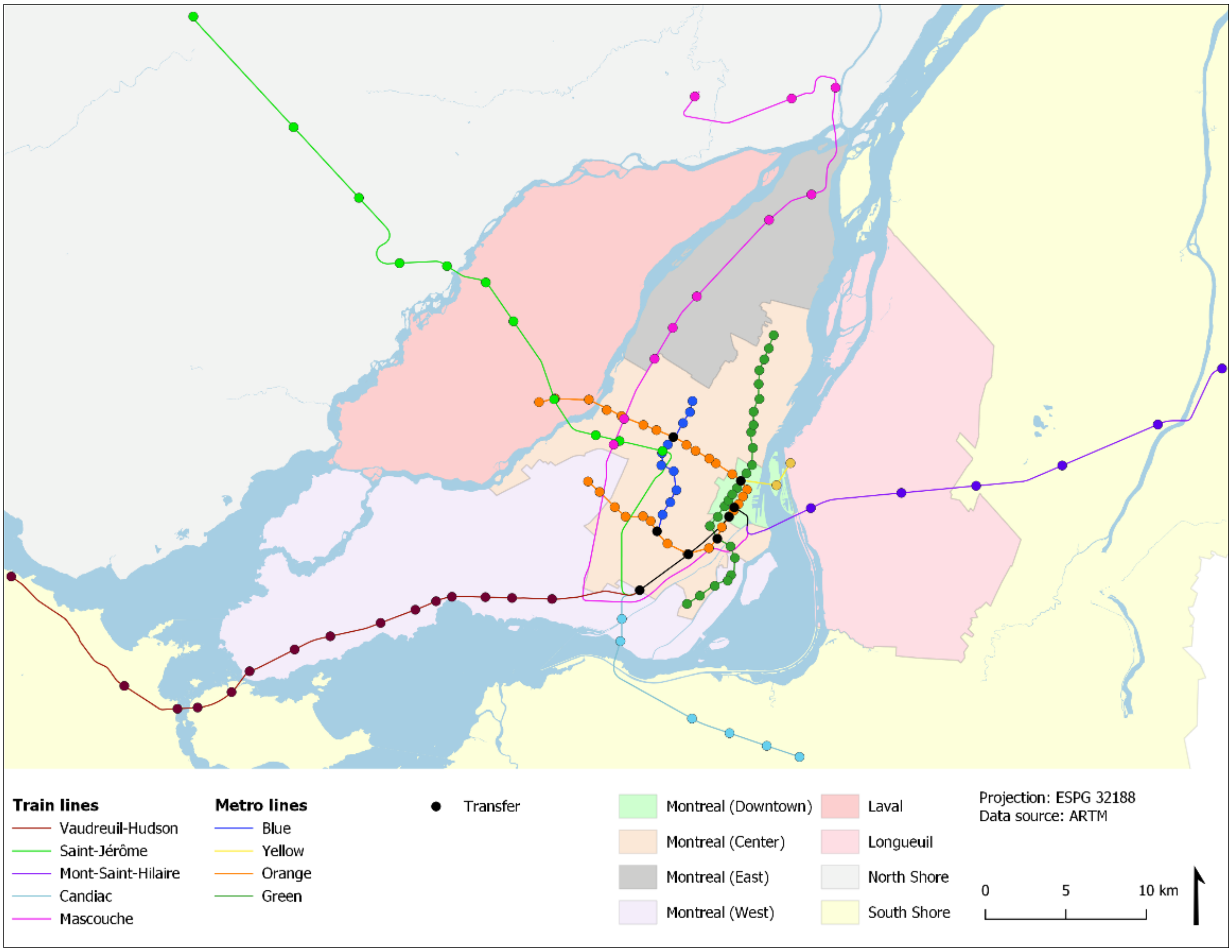

Fig. 1. Montreal Census Metropolitan Area

4. Methodology

4.1. Data and indicators

The PT stations selected for the study were the Montreal CMA metro and train stations that were in operation at the moment of the data collection (Summer 2022). The stations of the light rail network of the Réseau express métropolitain (REM), under construction at the time of the study, were not included in the analysis. Indicators were calculated for the 114 PT station areas at the PT node level, obtained from the GTFS data (EXO, 2022; STM, 2022), or inside a circular buffer area of 1,200 m radius around it. The 1,200 m threshold represents a five-minutes bicycle ride with a 15 km/h average speed in an urban area, as calculated by El-Geneidy, Krizek, and Iacono (2007) in Montreal. This threshold considers the larger catchment area that cycling can provide (Forouhar & van Lierop, 2021; Lee et al., 2016), while minimizing the overlap of the buffer areas. For the six intermodals stations (metro and train), the node of the metro station were selected as the centroid of the buffer area, since the metro is more important in terms of frequency of trips and number of users than the train (EXO, 2022; STM, 2022).

The selection of the indicators used in the present study is based on the literature review presented above, the data availability, and the knowledge of the context of the Montreal CMA. The selection is inspired by the node-place-pedestrian model (Vale, 2015), combined with context-specific bikeability indicators developed for the purpose of this study. In Table 1, the 14 selected indicators, their measurement method and data sources are presented. Building on Vale (2015), these are grouped into four criteria: land-use (place), public transport (node), walkability and bikeability.

The land use indicators describe the density and the diversity of the area around PT stations with five indicators. Population, job and points of interest (POI) density are used as a proxy to measure the activity density, while considering the diversity. Intersection density and motorway length are included to characterize the road network and its connectivity, as done by Park, Kang, and Choi (2014). Population and employment quantities are obtained at the dissemination area (DA) scale, from the 2016 Canadian census. The measures of density were, therefore, calculated in proportion to the space occupied by the DA within the buffer area. Otherwise, the exact location of POI and intersections were obtained. The intersections were retrieved from the OpenStreetMap (OSM) road network considering all segments from trunk, primary, secondary, tertiary roads, and residential streets, in order to capture the permeability of the street grid. The density indicators are all measured as the variable of interest per unit of area of the 1,200 m radius buffer area. The length of motorway considers both ways of motorways and trunks identified in OSM.

The PT criteria characterizes the inter-modality of the station, based on two indicators: bus frequency and capacity of Park and Ride. The frequency of buses sums up all bus trips that allow a transfer at the PT node (i.e., within 100m of the PT node) on a regular weekday during summer, based on the GTFS data of the different bus operators. The capacity of the Park and Ride considers all parking spots reserved for PT users around the PT node.

The walkability criteria is measured with the pedshed ratio, as done by Vale (2015), to assess the accessibility of destinations around the PT node and the connectivity of the street network. The walking service area is calculated using the shortest route algorithm from the pgRouting extension of PostGIS (pgRouting contributors, 2022). The pedestrian network considered to calculate the shortest route includes all segments of the OSM street network, except for motorways.

For the bikeability criteria, six indicators are selected: the traffic disruption along the cycling network, the type of cycling infrastructure, the topography, the presence of blue and green spaces along the cycling network, and the number of bicycle racks and bikeshare stations. The traffic disruption indicator is a weighted score that assesses the potential level of traffic disruption along the network on which cyclists are allowed to ride, which includes every segment of the street network, except highways. As indicated in the formula in Table 1, level of traffic is defined using OSM data: low traffic street segments correspond to alleys, residential and services streets, moderate traffic street segments include the secondary and tertiary links, and high traffic street segments include the trunk and primary roads. The indicator is used as a proxy for the level of traffic on the streets of the buffer area, knowing that the level of traffic influences cycling use in different ways (e.g., increasing travel time, reducing perceived and actual safety, increasing noise and air pollution). The cycleways indicator is a single score based on the cycling network only, meaning all segments tagged as cycleways in OSM. This indicator evaluates the quantity as well as the quality of the cycling infrastructure: a weighted average score based on the length of the cycleways is calculated, assigning a score of 1 for bicycle paths and 0.5 for bicycle lanes. The topography is assessed by a slope indicator that calculates the average slope (%) of the cycling network inside PT areas. The mean is weighted according to the length of every segment that a cyclist can legally ride on. The presence of bodies of water and vegetation along the network is evaluated as the proportion of the cycleways that has any blue or green area within a 10 m buffer around every segment of cycleways. The following categories and types of OSM polygons are considered for vegetation and bodies of water: natural (e.g., water, spring, bay, wetland, tree, wood), leisure (e.g., park, garden, golf course, nature reserve), land use (e.g., forest, grass, farmland, vineyard, basin). At the PT node level, the number of spaces in bicycle racks provided by PT operators are considered. Finally, bikeshare stations (with an average of a dozen bicycles available per station) capture the offer inside the 1,200 m buffer area.

Table 1. Presentation of the criteria and indicators included in the cluster analysis

Criteria	Indicator	Measurement method	Data sources
Land-use	Population density	Number of residents / km^2	(Statistics Canada, 2016)
	Job density	Number of jobs / km^2	(Statistics Canada, 2016)
	Points of interest	Number of points of interest / km^2	(DMTI Spatial Inc., 2020)
	Intersection density	Number of intersections / km^2	OSM
	Motorway length	Length of motorway (km)	OSM
Public Transport	Bus frequency	Frequency of buses at PT station	(EXO, 2022), (STM, 2022), (STL, 2022) and (RTL, 2022))
	Capacity of Park and Ride	Number of parking spaces in Park and Ride	(EXO, 2022; Thibault, 2017)
Walkability	Pedshed ratio	Ratio of walking service area on buffer area of PT station	OSM
Bikeability	Traffic disruption	$\frac{0.33\text{length}_{\text{low traffic}} + 0.67\text{length}_{\text{moderate traffic}} + \text{length}_{\text{high traffic}}}{\text{total length of street network in buffer area}}$	OSM
	Cycleways	$0.5\text{length}_{\text{bicycle lane}} + \text{length}_{\text{bicycle path}}$	OSM
	Slope	$\frac{\sum_i \text{slope percentage}_i * \text{length}_i}{\text{total length of cycling network in buffer area}}$	OSM and (Government of Canada, 2017)
	Water and green spaces	Proportion of cycling network along waterbody or vegetation	OSM
	Bicycle racks	Number of bicycle racks at PT nodes	(EXO, 2022) and (STM, 2022)
	Bikeshare stations	Number of bikeshare stations in buffer area	(BIXI, 2022)

4.2. Cluster analysis

A cluster analysis, based on the 14 selected indicators, was conducted to develop a TOD typology oriented on bikeability. The cluster analysis allows classifying PT stations into distinct groups that share common characteristics. The Partitioning Around Medoids (PAM) approach, also known as K-medoids, was used to proceed with the cluster analysis. K-medoids uses an actual observation (in this case a specific PT station) as the centre of a cluster. This central observation, referred to as the medoid of a cluster, is defined as the station which has the minimal average dissimilarity in the cluster. K-medoids overcome the sensitivity to outliers and to the data order and thus proposes a robust alternative to the classic K-means method, which uses the mean of all observations as the cluster centre (Jin & Han, 2010).

To validate the choice of the variables for the cluster analysis, a stepwise approach was adopted to test the stability of the clusters and the contribution of the different variables. First, the stepwise approach consisted of slightly varying the selection of indicators included in the analysis. The resulting distribution of the clusters was then assessed based on knowledge of the territory. The Hopkins statistic along with the average silhouette method also contributed to validate the selection of this indicator. Second, the stepwise approach consisted of changing the type or units of selected variables and testing the results based on this change, in the same way as adding/removing an indicator.

Fourteen variables and seven clusters were determined to generate an optimal classification of the PT station areas. To determine and visualize the optimal number of clusters, the average silhouette method is used. Two extremums could be observed in the silhouette shape: three (maximum) and seven (local maximum) clusters. Following that, the scaled data allowed to distinguish the extremums more clearly than the ordinal data and the choice of seven clusters allowed to better exploit and highlight all the variables related to bikeability. It is also more relevant to scale the data, since there are a lot of variables that do not have the same units and scale. Finally, the Hopkins statistics measured a value of 0.78, meaning that the data is highly clustered since its approaching 1.

ANOVA tests were conducted to analyse the difference between the mean values of each indicator, for all clusters. Tukey tests were then used to realize pairwise mean comparisons (between each pair of clusters) for each indicator.

5. Results

5.1. Typology of the public transport station areas

The cluster analysis resulted in seven clusters. This section first presents the spatial distribution of the clusters, followed by the distribution of the indicators across the seven clusters. It then concludes with a synthesis of the key characteristics of each cluster and a ranking of the clusters in terms of bikeability.

The spatial distribution of the clusters is presented in Fig. 2, where the medoid (most representative PT station of each cluster) is indicated. The distribution of the clusters shows a strong spatial component. Clusters 1 to 4 are concentrated in Montreal (Center). More specifically, Cluster 1 stations are mostly concentrated in central neighbourhoods, along the orange metro line (between the crossings with blue and green lines). The stations from Cluster 2 are all located close to each other, in Montréal (Downtown) core. The stations from Cluster 3, which is the largest cluster of all, are mostly located at the extremity of metro lines, in peri-central neighbourhoods. Interestingly, Cluster 4 is concentrated around the Mount Royal, a large urban park which has an elevation of 233 m. In contrast to Clusters 1 to 4, Clusters 5 to 7 are dispersed outside Montreal (Center). Cluster 5 is the most divided between metro and train stations. Stations from Cluster 6 and Cluster 7 are almost all located outside Montreal (Center) and Montreal (Downtown), along train lines.

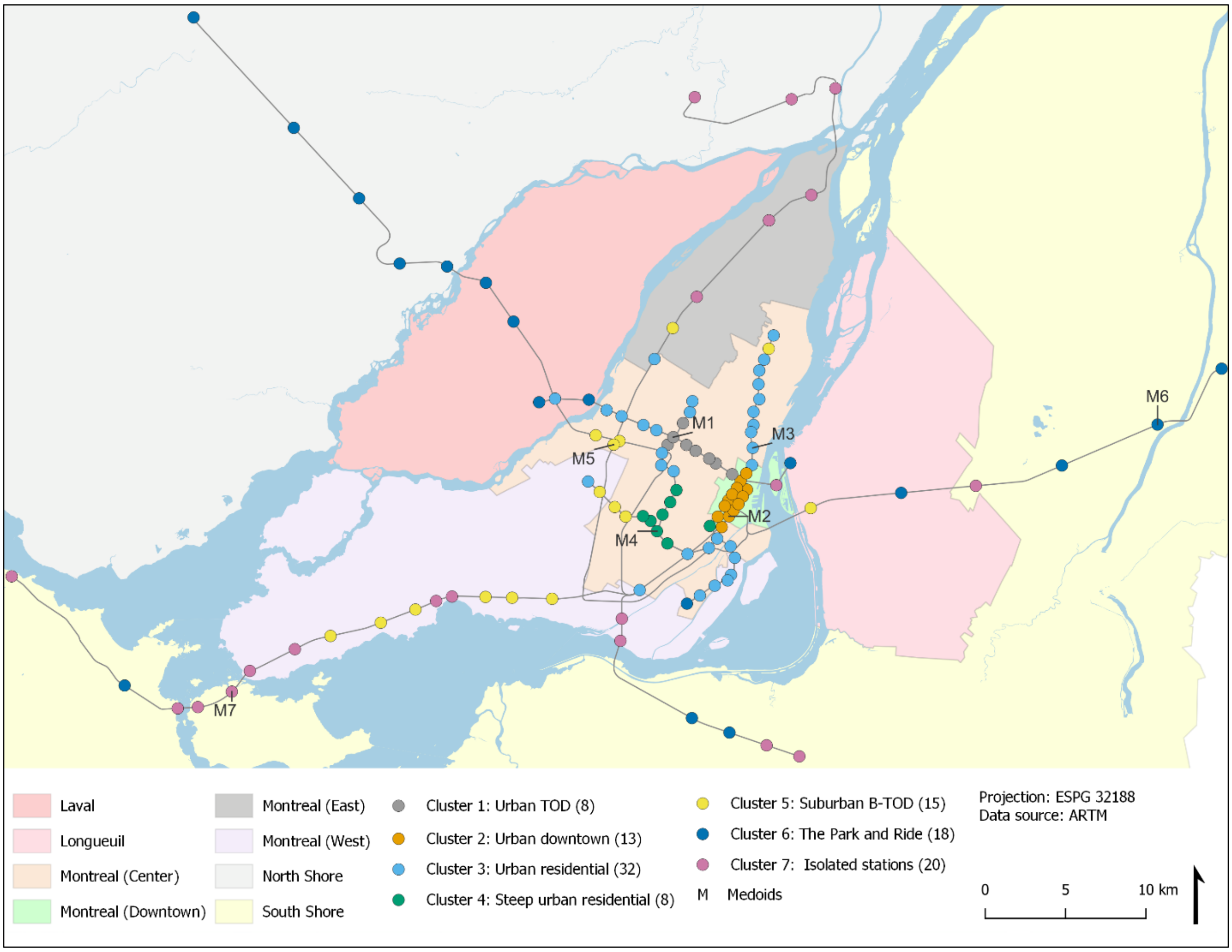

Fig. 2. Geographic distribution of the seven clusters

Fig. 3 presents the distribution of each indicator across the seven clusters. Original values, and not scaled values, are presented in the boxplots for ease of interpretation. Further, Table 2 presents mean and standard deviation values for each indicator and cluster. The ANOVA tests indicated that there was a significant difference between the mean values of clusters for each indicator. A multiple pairwise-comparison, with Tukey HSD tests, allowed to specifically identify which clusters differ significatively from each other, for each indicator, with a 95% confidence interval. Clusters that significantly differ from all others are indicated with an asterisk in Table 2.

Starting with the land use criteria, Fig. 3 shows a decrease in population density from Cluster 1 to Cluster 7, with the exception of Cluster 4. Population density is significatively higher for Clusters 1 to 4 as compared to Clusters 5 to 7. As for jobs and POI density, they are, by far, higher for Cluster 2. Some variations are visible across the other clusters, with namely the lowest job and POI density for Clusters 6 and 7.

Intersection density is also significantly higher for Cluster 2, otherwise we see an overall decrease from Clusters 1 to 7. As for the motorway length, the values are more dispersed inside the clusters, but when looking at the median, Clusters 2, 4, 5, and 7 present higher values.

With respect to PT, the bus frequency also appears to be higher for Clusters 1 to 4, especially for Clusters 3 and 4. Clusters 2 and 3 exhibits a large dispersion of values, revealing the presence of stations with a high frequency, and others with a low frequency of buses. For the Park and Ride capacity, the value is null for almost all stations in Clusters 1 to 4, capacities are greater for Clusters 5 to 7, and the capacities seen in Cluster 6 are significantly higher.

In line with the population density and intersection density, the pedshed ratio decreases steadily from Cluster 1 to Cluster 7. Cluster 1 has the highest pedshed ratio (significatively different from all other clusters' means), followed by Clusters 2 to 4 having a similar median. It then decreases importantly from Cluster 5 to Cluster 7, with the largest dispersion of values found inside these clusters.

Finally, looking at the bikeability criteria, we see that traffic disruption varies slightly through all clusters, but Cluster 2 stands out with the highest traffic disruption. It is followed by Cluster 7, which has the largest dispersion of values. For the cycleways, Cluster 1 presents the highest scores by far, followed by Clusters 2 and 3. The stations from Cluster 4 presents the highest average slope (median of 2.80%), followed by Cluster 2 (median of 1.51%), whereas the other clusters have significatively lower values, between 0 and 1. As for the water and green spaces and number of bicycle racks, they vary across the seven clusters, without a clear pattern. Finally, the number of bikeshare stations is significantly higher for Clusters 1 and 2 compared to all other clusters, and mostly null for stations in Clusters 5 to 7.

Fig. 3. Dispersion of the indicators across the seven clusters

Table 2. Indicators mean values and standard deviation

Indicators		Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5	Cluster 6	Cluster 7
Population density (/km^2)	**Mean**	*11694.03	8099.03	7307.66	9118.93	3542.42	2113.11	1141.91
	Std	707.14	1581.90	1879.67	2177.23	1948.58	929.38	780.67
Job density (/km^2)	**Mean**	6810.91	*36008.53	3216.63	4957.11	2261.89	835.56	581.56
	Std	2690.73	13655.60	1577.11	2395.48	1534.60	656.24	432.24
POI density (/km^2)	**Mean**	836.42	*3388.56	314.89	425.18	227.28	107.64	64.18
	Std	146.846	1447.66	138.71	215.38	159.84	95.44	51.19
Intersection density (/km^2)	**Mean**	73.78	*110.42	64.67	57.70	53.93	44.63	26.11
	Std	13.27	12.07	13.09	16.19	12.19	13.49	9.28
Motorway length (km)	**Mean**	0	4.61	2.14	2.73	4.99	1.80	4.71
	Std	0	0.62	2.62	2.27	1.93	2.84	2.62
Bus frequency (trips/day)	**Mean**	479.00	610.92	840.47	653.00	378.53	561.28	224.40
	Std	307.55	499.61	535.95	318.77	451.22	854.75	318.64
Capacity of Park and Ride (parking spots)	**Mean**	0	0	7.25	0	159.53	*699.11	285.25
	Std	0	0	28.75	0	205.23	358.91	227.67
Pedshed ratio (km^2/km^2)	**Mean**	*0.82	0.76	0.73	0.73	0.62	0.52	0.36
	Std	0.03	0.04	0.07	0.04	0.08	0.14	0.16
Traffic disruption score	**Mean**	0.41	*0.54	0.44	0.43	0.43	0.44	0.47
	Std	0.01	0.02	0.04	0.04	0.04	0.06	0.07
Cycleways score	**Mean**	*19.79	10.74	10.01	4.71	4.50	7.49	4.44
	Std	4.20	1.81	3.03	1.17	2.31	2.92	3.15
Slope (%)	**Mean**	0.72	*1.65	0.79	*2.74	0.54	0.58	0.79
	Std	0.33	0.52	0.33	0.73	0.28	0.35	0.64
Ratio of bicycle network along water and green space	**Mean**	0.17	0.27	0.24	0.21	0.15	0.22	0.28
	Std	0.05	0.03	0.09	0.9	0.08	0.07	0.18
Bicycle rack (bicycle hoops at stations)	**Mean**	87.50	6.77	53.69	25.00	37.93	70.72	27.75
	Std	84.53	7.34	40.92	32.83	26.06	58.15	19.11
Bikeshare stations (stations inside catchment area)	**Mean**	57.63	65.85	17.56	13.88	2.13	0.83	0.65
	Std	16.20	12.63	10.25	6.66	2.23	1.72	1.60

* p value < 0.05 (Cluster's mean significantly different from all other clusters)

5.2. Bikeability ranking in the context of TOD

The developed typology enables the assessment of the current bikeability of all 114 PT stations of Montreal CMA, in the context of TOD. Fig. 3 ranked the seven clusters on a TOD bikeability scale, according to the mean values and standard deviation of indicators seen in Table 2, supported by the authors' knowledge of the study area. Clusters are named based on their most predominant characteristics and are divided in two distinct groups based on their level of density (i.e., low- and high-density area). Key common attributes from the four criteria are also specified in Fig. 4, as following: Land-use (LU), transport (PT), walkability (W), and bikeability (B).

Clusters 1 to 4 display characteristics of a denser environment, with the highest land use density values. Those clusters are also characterized by a high pedshed and are oriented towards PT services. As for the bikeability criteria, they typically exhibit characteristics of a bikeable environment, with however important variations between the clusters.

Cluster 1 is characterized by eight metro stations. As shown in Table 2, this cluster has the highest population density, pedshed ratio, and score for cycleways, as well as the lowest traffic disruption. The cluster is also characterized by high POI and intersection densities, by high numbers of bicycle racks and bikeshare stations, and by the absence of motorway and Park and Ride. Cluster 1, called the *"urban TOD"*, is placed first on the TOD bikeability scale, since it presents the best balance between all TOD features in the case of the Montreal CMA. Further, from a bikeability standpoint, this cluster stands out from the others as it provides the highest quality urban environment for cycling. In addition, the absence of motorways in those areas reduces the presence of breaks in the urban fabric caused by the road network.

Cluster 2 is composed of 13 metro stations (including intermodal stations) and stands out with the highest job, POI, and intersection densities. This cluster also exhibits a high population density, high pedshed ratio, the absence of Park and Ride, but is characterized by lower scores for the bikeability criteria (namely with the highest traffic disruption). Cluster 2 is the *"urban downtown"* cluster, with key characteristics of central business districts in North America. Montréal (Downtown) area acts as a major destination area, with its employment centre and its cultural hub. Given the urban fabric in which these stations are located, the current bikeability is assessed to be lower than for Clusters 1 and 3.

Clusters 3 and 4 include mostly metro stations and present similar characteristics for the first three criteria (high population density and pedshed ratio, average POI and job densities, presence of motorways, high bus frequency and low capacity of Park and Ride), but differ with respect to the bikeability criteria. Cluster 3, which is the largest cluster with 32 stations, is referred to as the *"urban residential"* cluster. It is rated with a higher bikeability than Cluster 4, because it has a higher score for cycleways and more bicycle racks and bikeshare stations. This cluster is ranked in second place on the bikeability scale, as it is characterized by features of land use and bikeability that are in line with the TOD concept (higher population density and score for cycleways, higher presence of bicycle parking and bikeshare stations).

Cluster 4, named the *"steep urban residential"*, differs in one major aspect: the topography, which explains its lower ranking. It presents the highest elevation around its eight metro stations. This cluster also confers features that are less suitable for cycling (higher presence of motorways, lower score for cycleways, and lower numbers of bicycle racks). Cluster 4 is, therefore, ranked below Cluster 2 in terms of bikeability, as the topography acts as an important barrier to a greater uptake for cycling for all population groups.

Cluster 5 to 7 are all defined by lower land use densities, a lower frequency of buses, and a lower pedshed ratio, together with a higher traffic disruption. Cluster 5 comprises 15 stations. Regarding the land use, transport, and walkability criteria, Cluster 5 is the one that has the most similarities with Clusters 1 to 4 (higher densities, greater pedshed ratio and more bikeshare stations). For that reason, it is referred to as the *"suburban TOD"* cluster. Even if this cluster has the lowest score for cycleways (with a high variability for stations inside the cluster), it is placed higher than cluster 6 and 7 on the current TOD bikeability scale. This is explained by its similarities with higher density clusters, which confer land use features that are more suitable for a bicycle-oriented TOD.

Cluster 6 is *"the Park and Ride"* cluster, with 14 train stations and four metro stations. It stands out by the largest capacity of its Park and Ride and bicycle parking. Although it has a greater score for cycleways than Clusters 4 and 5, the low rank for TOD bikeability aligns with a lower density imposed by the size of the Park and Rides, which makes distances on average farther.

Cluster 7 has 20 stations, of which only one is a metro station. This *"isolated stations"* cluster is a particular case that stands out from the other clusters by having the lowest score in every TOD component. This is why it is ranked last on the TOD bikeability ranking. They are distinguished by minimum values for density indicators and the lowest pedshed ratio, but a greater presence of blue and green spaces.

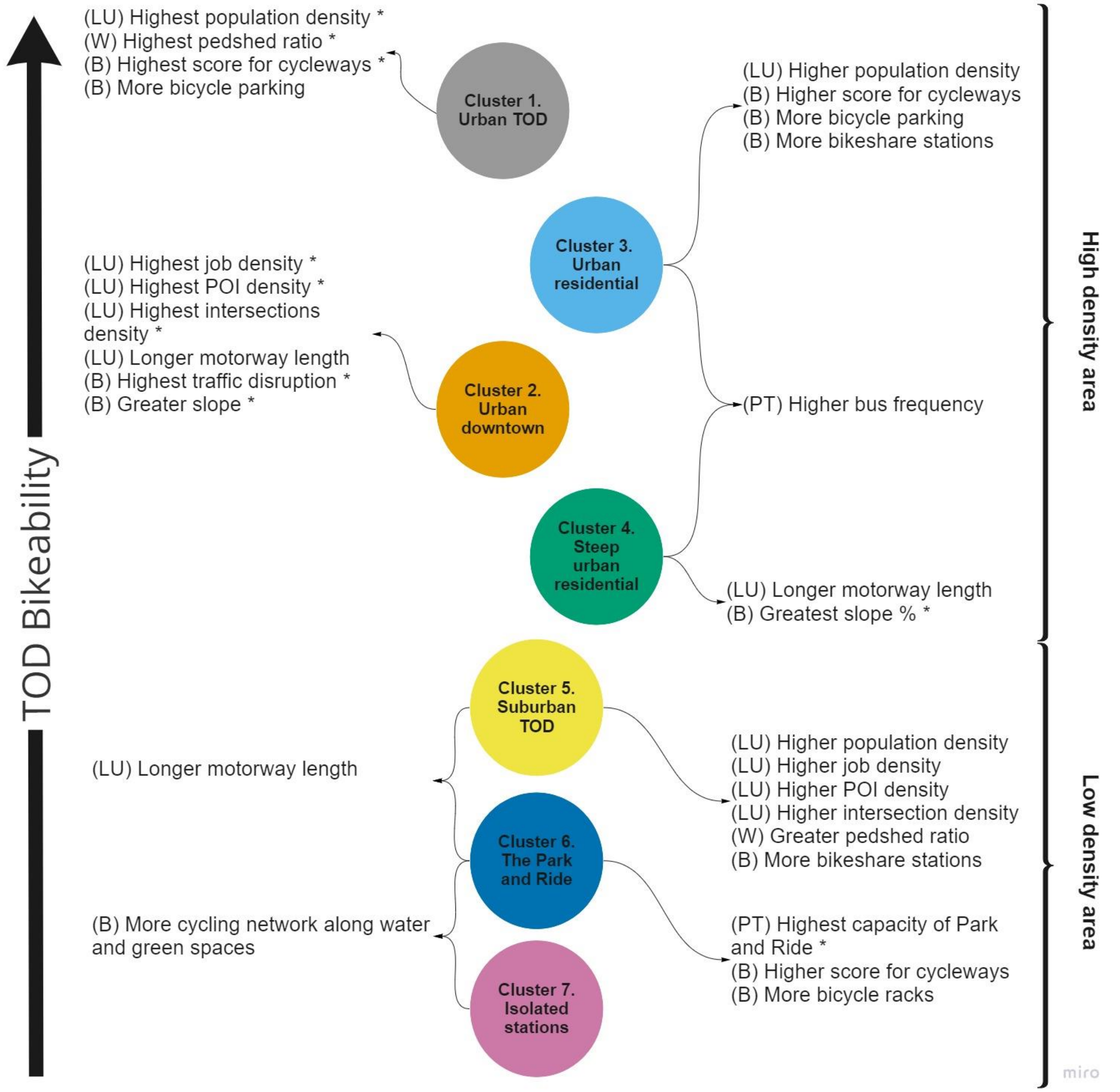

Fig. 4. TOD Bikeability ranking for the seven clusters

6. Discussion

This research aimed to adapt classic TOD typologies to provide a classification of PT station areas based on the current bikeability, which cannot be done on the basis of the classic typologies that consider walking as the predominant (and often single) mode of transport around TOD. The new proposed typology helps discriminate stations according to a bikeability criterion, while considering land-use, transportation, and walkability criteria.

Results showed that a convenient cycling environment is associated with higher scores for TOD characteristics, taking the *"urban TOD"* cluster as an example. In other words, a successful cycling environment is often associated with a successful TOD, in the case of the Montreal CMA. This is also often the case for walkable environment (Jeffrey et al., 2019; Vale, 2015; Vale et al., 2018; Woo, 2021).

By examining all types of stations in the Montreal CMA, it is possible to clearly distinguish the high-density PT station areas (clusters 1 to 4) from the low-density PT station areas (clusters 5 to 7). Clusters 1 to 4 are grouping the stations whose general characteristics (i.e., 3D: density, diversity, design) most closely match those representatives of traditional TOD and are supportive of walkable and bikeable environments. Accordingly, these clusters are ranked with a higher overall bikeability. Clusters 5 to 7 group stations that tend to be located further away from the central business district (downtown area), are characterized by significantly lower land use density, and provide a lower quality environment for walking, cycling and PT. In terms of bikeability, those clusters are more similar to one another than the first four clusters. Since these stations provide lower density of destinations (jobs and POI), individuals need to travel longer distances to get to destinations. Their bikeability is accordingly assessed lower than for the previous clusters. Indeed, density, land-use diversity, and connectivity positively impact the use of both walking and cycling (Muhs & Clifton, 2016), and provide high multimodal accessibility conditions (Vale, 2015).

However, other factors come into play when it comes to providing a high quality-cycling environment. In addition to level of density, land-use diversity, and connectivity, cycling environment are also characterized by the quality of the network, its completeness and connectivity, its level of separation from motorized traffic, and elevation (Muhs & Clifton, 2016). By considering only the indicators that walking and cycling environment have in common, classification of stations would be based mainly on walkability, as it neglects important features of bikeability. Such typologies have been presented in previous research, as done by Vale (2015) and Jeffrey et al. (2019). With the inclusion of a bikeability criteria, PT stations can be distinguished based on the quality of the cycling environment, while still considering the density of the area. This typology is specifically relevant for regions aiming to jointly support cycling and TOD development.

6.1. Targeted interventions and prioritization according to the bikeability potential

In addition to assessing the bikeability of PT station areas, the results of the typology presented in the results can serve as a framework to identify specific and targeted interventions for stations with similar characteristics. It also illustrates how the typology can be used to develop strategic and organized planning, and to establish priority of interventions, based on current bikeability and future bikeability potential. Depending on the planning objectives identified by a region, the typology enables to identify which clusters are to be prioritized.

Table 3 presents an example of prioritization scheme and summarizes the proposed interventions for each cluster, for short- and long-term planning. The prioritization scheme aims to identify which stations should be targeted in terms of investments and interventions. The criteria used to develop the prioritization of the clusters and to identify the key interventions are: (i) the planning objectives prioritized by the City of Montreal (Ville de Montréal, 2022), and (ii) the expected impact of the interventions (short-term and long-term) on the associated planning objectives.

Territorial equity

As an example, within the Montreal CMA, a particular emphasis is placed on ensuring "*territorial equity"* when upgrading and consolidating bicycle paths (Ville de Montréal, 2022). "*Territorial equity"*, in this case, reflects the desire to improve cycling environments outside central areas to reduce discrepancies across the territory. The aim is to support a more equitable distribution of cycling infrastructure across all boroughs. With this in mind, the City of Montréal wants to allow more citizens to travel by bicycle throughout the territory, namely by introducing new bicycle paths in outlying boroughs and by increasing the connectivity between sectors (Ville de Montréal, 2022).

At the metropolitan scale, prioritizing Clusters 3, 4 and 5 would be aligned with that objective. First, to extend the widespread use of cycling outside of the central core of Montreal CMA, improvements around the *"urban residential (3)"* and *"steep urban residential (4)"* clusters could be prioritized. Clusters 3 and 4 group together stations that are more likely to be the origin of travel, with high population density and lower POI density. These clusters also have a relatively higher bus frequency, providing PT service to peri-central neighbourhoods that are not served by the metro. The typology proposed in this study allows to differentiate those two clusters of stations based on their cycling environment, that otherwise appear similar according to the classic TOD features.

These clusters are ranked second and fourth on the bikeability scale and are located outside the central areas, so there is potential for improvement. Interventions are likely to contribute to providing high-quality cycling environment outside the core, therefore improving *"territorial equity"*, while ensuring that the interventions support higher rates of cycling. As it is the case for the *"urban TOD (1)"* stations, PT stations from *"urban residential (3)"* and *"steep urban residential (4)"* areas are located along metro lines leading to main activity centers. Therefore, improvements regarding cycleways (e.g., construction of new cycling highways along these segments of the metro network) and bikeshare stations availability around these stations are required, for them to shift to the *"urban TOD (1)"* cluster. These improvements could lead to the expansion of bicycle use, as seen after the construction of the REV cycling highway (eco compteur, 2022). More specifically, within these two clusters, stations with a higher density of POI could be prioritized for short-term bikeability interventions, since they are more likely to include destinations and thus improve accessibility. In the longer term, efforts to increase the density of activities around all stations in these clusters would be relevant. It is important to note that the environment that surrounds *"steep urban residential (4)"* PT stations presents steep slopes that may limit the positive effects of improvements to the cycling environment. Nonetheless, electric bikes (e-bikes), which in recent years have become more popular and a common site on city streets, could play an important role in removing the barriers to use a bicycle, which are often experienced in steeper areas, because of the physical effort it is requiring (Castañon & Ribeiro, 2021; Vale, Saraiva, & Pereira, 2016). Further, providing more high-quality bicycle parking and bikeshare stations near PT nodes could offer an interesting option for bimodality (cycling and PT) to limit the negative aspect of slopes on longer trips.

Also aligned with the objective of "*territorial equity"*, interventions in suburban areas could contribute to a more equitable distribution of cycling infrastructure across the region, although the results in terms of cycling uptake may be more limited than for the previous clusters. Based on this limitation, Cluster 3 and 4 are prioritized over these clusters. Nonetheless, in these less dense areas, integrated TOD and bikeability planning could act as a catalyst to improve the bikeability and support the use of the bicycle. Considering the results presented in Fig. 3 and its similarities with clusters 1 to 4, the cluster *"suburban TOD (5)"* have a lot of potential for improvement and could be prioritized for interventions regarding bikeability among clusters located in suburban areas (5, 6 and 7). As such, PT stations could act as catalysts to promote cycling in these environments. Improvements to the cycling environment (i.e., development of cycleways and strategies to reduce traffic disruption together with the addition of bikeshare stations) could improve the bikeability potential and the potential to make cycling to stations more attractive, knowing that walking is often not considered an option because of the more important travel distances to the stations. Furthermore, bicycle parking and secured bicycle parking would be required, as these have been shown to be essential to promote bicycle as a feeder to PT (Jonkeren & Kager, 2021), and to reduce concerns about theft or vandalism (Schmid-Querg et al., 2021). At the same time, by densifying and diversifying land use around stations, it could support cycling around the PT stations, by increasing the density of destinations. Since the *"suburban TOD (5)"* stations are in general further from downtown and central areas, but share similar pedshed ratios and intersection densities to the clusters located in denser areas (Clusters 1 to 4), planning strategies should take advantage of the more grid-street pattern to incorporate more cycleways along the street network. With these kinds of improvements, some *“suburban TOD (5)”* stations could eventually move to the *“urban residential (4)”* cluster, for instance.

On the other hand, interventions regarding bikeability of the *“Park and Ride (6)”* cluster could be planned under a longer term, so that stations with a higher density can later shift to the *“suburban TOD (5)”* cluster. Even if the current bikeability of these PT station areas is higher than for Cluster 5, the bikeability potential is evaluated as being lower. As long as individuals have access to a car, cycling is less likely to be the most attractive way to get to the station, as found by Park et al. (2014) in their research on determinants of walking, cycling and driving to access the PT stations in Mountain View, California. As of now, given the design and sizes of the Park and Ride and surrounding environments (namely major roads), they act as important barriers to access stations by bicycle, and to support cycling in the area. Planners may want to add more bicycle paths that connect to these parking lots, add more secured bicycle parking at these stations. They may also consider other uses for parking outside peak hours, while rethinking the configuration and size of the Park and Ride lots.

Modal share

Even with the highest scores for the bikeability criteria, there is still room for improvement for the *“urban TOD (1)”*, knowing that the bicycle mode share in the neighbourhoods surrounding these stations is 13 %, representing the highest cycling mode share in Montreal CMA. This cluster is ranked lower in terms of priority, as it does not align with the *“territorial equity”* objective put forward by the City of Montreal. Nonetheless, interventions around these clusters would likely significantly contribute to increasing the modal share of cycling. PT station areas from cluster 1 are aligned with each other along the orange metro line leading directly to Montréal (Downtown) and are located along the new *Réseau express vélo* (REV), the only cycling highway in Montréal. This infrastructure represents the safest kind of urban bicycle path in Montreal, while connecting with multiple other cycle paths and lanes. It therefore contributes to improving safety and connectivity, which are the two most important components of a good cycling environment according to Muhs and Clifton (2016). This high-quality cycling environment, combined with high residential density and a relatively high diversity of land-use (i.e., high jobs and POI density), provides the most suitable bicycle-oriented TOD environments in the Montreal CMA. This combination is indeed known to encourage cycling trips inside stations catchment area (Singh et al., 2017). Therefore, in this case, cycling provides a high potential as a mean to move towards the biggest employment/activity center of the region, either through the REV or as a feeder mode to the metro stations. In the short term, increasing the availability of the bikeshare system around metro stations of the *“urban TOD (1)”* cluster to fit the high demand could help increase cycling modal shares. On the long term, the neighbourhoods surrounding the stations to the east would benefit from more direct bicycle lanes to the metro stations and the REV, which would contribute to support cycling around these stations and to a greater use of the metro and the REV.

Safety

Cluster 2 provides a built environment that is convenient for cycling, but the current bikeability and the bikeability potential are being reduced by the traffic disruption that is significantly higher than for the other clusters, raising important safety concerns. This is consistent with the findings of Hartanto et al. (2017), where urban stations scored lower than suburban stations in their bikeability index applied to Arnhem-Nijmegen region in the Netherlands, because of the traffic conditions, the high density of intersections, and the infrastructure that presented less segregated cycling paths. There is also a high density of stations in Montréal (Downtown) area, with the orange and green lines running parallel in this portion, suggesting that walking may be more convenient to get from stations to destinations in this area, due to shorter distances, and high traffic disruption and density of intersections (Jeffrey et al., 2019; Vale, 2015). While greater intersection density can shorten the travel distance, they also increase the travel time in bicycle, because of the crossing time (Muhs & Clifton, 2016).

As of now, the modal share for PT and walking is already high for this cluster. 74% of trips to work/school in Montréal (Downtown) area in morning rush hour are made by PT, illustrating that trips towards this direction are mainly made by PT (Enquête Origine-Destination, 2018). Therefore, this cluster is not necessarily to be prioritized regarding bikeability interventions. However, it is important to maintain a high number of bikeshare station at PT nodes, mostly at intermodal stations. Since there are fewer train stations, individuals who take the train might have to walk longer distances or transfer with the metro to get to their destination. It could be relevant for these individuals to rely on the bikeshare system to cover that last mile trips. On the longer term, knowing that residential density is constantly increasing in Montréal (Downtown) area, focusing on the safety component of the cycling environment could lead to an improvement of the cycling potential in this area, more specifically by reducing the traffic disruption (e.g., reduced vehicles speed limits, reduced lane width).

Specific cases

Finally, based on the proposed framework, interventions regarding *"isolated stations (7)"* do not appear as a priority since those stations are not necessarily planned as TOD. When analyzing the stations from a contextual point of view, the specific location of these PT stations seems to be the reason why they are grouped together (e.g., in the middle of a park, shopping center, or industrial zone, in vast or empty areas, at the junction of highways, adjacent to waterways or vast green spaces). Overall, most of these stations are segregated from the urban fabric, which limits the development of these stations as TOD and at the same time the potential for improving bikeability. An individualized consideration would be required since the context varies greatly across stations. For example, one of these stations is located on a small island dedicated to vast nature and leisure activities (e.g., an amusement park, a car racing track, a festival area), where the development of a TOD is not desirable. Another one is located at the junction of multiple highways, which would require significant changes in the regional land use and transport systems before it can be developed as a TOD and support cycling.

Table 3. Example of prioritization scheme ranking the clusters and proposing short-term and long-term interventions

Priority	**Clusters**	**Short-term planning**	**Long-term planning**	**Planning objective**			
				Territorial equity	Modal share	Safety	Specific cases
1	3. Urban residential	Develop safe cycling infrastructure along stations with higher POI density Increase the number of bikeshare stations	Increase density of activities	X	X		
2	4. Steep urban residential	Develop safe cycling infrastructure along stations with higher POI density Increase the number of bikeshare stations, by prioritizing electric bicycle	Increase density of activities	X			
3	5. Suburban TOD	Increase the number of bikeshare stations at PT stations and inside a larger catchment area Increase the number and the safety of bicycle parking at stations Develop cycling network to stations Reduce traffic disruption	Increase residential density Increase density and diversity of activities	X			
4	6. The Park and Ride	Increase the number and the safety of bicycle parking at stations Add more bicycle paths that connect to the stations	Re-design and re-size parking lots Increase residential density Increase density and diversity of activities	X			
5	1. Urban TOD	Increase availability of bikeshare system at stations based on the demand	Add more direct cycling lanes to the stations Increase safety and connectivity of the cycling network		X		

6	2. Urban downtown	Increase safety of the cycling network Reduce traffic disruption (e.g., speed limits and lane width)	Improve bikeshare station’s distribution	X	
7	7. Isolated stations	Individual considerations	Individual considerations		X

Overall, in addition to shedding light on which interventions are required to support bicycle use around different types of PT station areas, the framework provides insight on how these interventions are aligned with the objectives established by a region, whether it is to support the widespread use of bicycle in central areas or to support the use of bicycle as a feeder mode to PT stations in suburban areas. This can help regions establish priorities in terms of land use and transport interventions, and to develop short, medium and long terms policies.

7. Conclusion

While TOD planning remains a challenge (Curtis et al., 2009; Thomas et al., 2018), TOD typologies have been recognized as a useful diagnostic method to develop targeted interventions around stations with similar characteristics (Ibraeva et al., 2020). The bikeability in the context of TOD has been neglected in the literature or often evaluated in the same way as walkability. To adequately consider bikeability in the context of TOD, this paper proposed a framework that explicitly assesses bikeability throughout a TOD typology. The method proposed 14 indicators, of which six are related to bikeability, to evaluate the performance of PT station areas, specifically with respect to their bikeability potential. The typology applied to the Montreal CMA groups the 114 PT stations into seven clusters. The results show that the addition of a bikeability criteria to a TOD typology helps discriminate the different types of station, based on their cycling environment. Findings also suggest that PT stations providing a convenient cycling environment also present characteristics of a successful TOD, in the case of Montreal CMA. This approach allows recommending more targeted interventions, mainly oriented on bikeability, to station development.

Performing a TOD typology is relevant when land use and transport policies aim to develop TOD around existing PT stations, as it is the case in Montreal. The application of this method could be extended to validate the choice of the location of a new PT station or better understand the context in which a future station is to be implemented. Planners could simulate the location of a new station, propose a frequency of buses at the station, and calculate the indicators to see in which cluster the new station would fit. This would also allow a better integration and planification of the cycling infrastructure around the new PT stations.

There are nonetheless some limitations to this study. The limited number of variables describing the performance of the PT is explained by the fact that the focus of the study is on bikeability and not on the relationship between PT performance and bikeability around TOD. Therefore, we considered that the performance of the PT is consistent along the structural transport network. A specific land use mix indicator was also not included in the typology, because the data available was not able to capture the diversity of the land use at a small scale (e.g., data were available for whole blocks only) and at a vertical scale (e.g., a commercial building at the first floor of a housing tower). It was also chosen not to specify the mode (metro or train) of the node in the final typology, to limit the effect of imposing this feature on the other variables. When including this variable, the ideal number of clusters, according to the first maximum of the silhouette shape and to the interpretability of the results, was three, and the clusters could be distinguished as: downtown stations, other metro stations and train stations. It is then the second maximum of the silhouette shape (seven clusters) that allowed the other variables to weigh in the classification of the stations and differentiate clusters based on bikeability. Despite these limitations, the authors are confident that the proposed framework and resulting typology contribute to identifying distinct clusters of stations that are relevant to better identify the necessary bikeability interventions for more strategic and targeted development of PT stations.

Future research could compare the cluster results with actual travel behaviour around those stations. This would provide more insights on the potential influence of PT station area characteristics on cycling and PT use. The cluster results could also be combined with socio-demographic variables to propose a prioritization of intervention that takes equity into consideration. The methodology could also be adapted to focus on specific types of bicycles (e.g., e-bikes, bikeshare, cargo bikes, etc.). This would namely bring considerations related to the size of the catchment area and the influence of the slope. Future research could also investigate the application of the method in different geographic contexts in an attempt to observe the impact of external factors (e.g., bicycle culture, political, individuals, weather constraints) on the assessment of the bikeability potential and targeted interventions.

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