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POLYTECHNIQUE MONTRÉAL

affiliée à l'Université de Montréal

**Développement d'un outil de classification des zones TOD intégrant
l'évaluation de l'environnement cyclable**

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Mémoire présenté en vue de l'obtention du diplôme de *Maîtrise ès sciences appliquées*

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Développement d'un outil de classification des zones TOD intégrant l'évaluation de l'environnement cyclable

présenté par **Arianne Robillard**

en vue de l'obtention du diplôme de *Maîtrise ès sciences appliquées*

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RÉSUMÉ

Les villes sont conscientes qu'il faut encourager et faciliter l'utilisation de modes de transports plus durables pour contribuer à la transition écologique. Dans cet optique, la planification conjointe des transports et de l'aménagement du territoire est considérée comme centrale pour réduire la dépendance à l'automobile, l'étalement urbain et les émissions de gaz à effet de serre. Pour ce faire, les villes s'inspirent beaucoup du concept *Transit-Oriented Development* (TOD) pour la planification de leur territoire. Ce concept est reconnu pour favoriser la densité et la mixité du développement urbain autour des stations de transport en commun (TC). Cette configuration permet non seulement d'encourager l'utilisation des TC pour des déplacements de longues distances, mais aussi de rendre plus attrayante l'utilisation de la marche ou du vélo pour des déplacements de plus courte durée. Or, la mise en œuvre du concept TOD reste encore difficile en pratique en raison de la configuration actuelle des villes ou des défis de gouvernance.

Afin de favoriser la planification axée sur les TOD, différents outils d'analyse et de planification sont mis de l'avant. Notamment, les méthodes de classification des stations de TC, aussi connues sous le nom de typologies de TOD, sont utilisées pour mieux comprendre comment ce concept se manifeste (ou pourrait se manifester) dans les différentes régions du monde. Ces méthodes consistent à mesurer la performance des stations d'un réseau de transport selon des indicateurs portant sur les transports et l'utilisation du sol. Ensuite, les stations sont regroupées en quelques catégories, à l'aide de méthodes de *clustering*, selon leurs similitudes. Ces résultats permettent de fournir des recommandations ciblées pour le développement des stations.

Bien que les typologies TOD aient été largement explorées en recherche, d'importantes lacunes subsistent. D'une part, la marche est très souvent considérée comme le moyen principal de se déplacer vers et autour des stations de TC. Cependant, le vélo est également une composante importante de la théorie des TOD et semble être négligé dans la littérature sur les typologies de TOD. Si plusieurs typologies de TOD ont démontré que les stations de TC peuvent être classées en fonction de la qualité de l'environnement piéton, il serait donc possible de le faire en fonction de l'environnement cyclable aussi. D'autre part, il est encore difficile de connaître la portée de ces outils en pratique et de comprendre comment ils peuvent être utilisés dans d'autres contextes que pour ceux pour lequel ils ont été développés. En effet, les résultats des typologies de TOD présentés dans la littérature sont utiles pour tirer des conclusions pour les régions pour lesquelles ces

typologies sont appliquées. Cependant, les conclusions tirées sont peu pertinentes pour d'autres régions, à l'exception de s'inspirer des bonnes pratiques concernant la planification des TOD. Il a été démontré que le transfert des politiques en matière de TOD doit considérer le contexte géographique dans lequel elles s'inscrivent. L'hypothèse est donc que le même principe s'applique aux typologies de TOD.

Ce mémoire vise donc à répondre aux deux objectifs de recherche suivant :

- (1) Développer une méthodologie pour classifier les stations de TC de la région métropolitaine de Montréal, en fonction de la qualité cyclable de l'environnement qui les entoure.
- (2) Évaluer le transfert des outils de typologies de TOD à travers divers contextes géographiques.

Pour répondre au premier objectif de recherche, une revue de littérature sur les typologies de TOD et sur les indicateurs de « cyclabilité » dans le contexte des TOD est effectuée. Ensuite, les informations sur les stations de TC (métro et train de banlieue) du Grand Montréal sont récoltées dans les bases de données pertinentes et publiquement accessibles. Les stations sont évaluées en fonction de cinq indicateurs sur l'utilisation du sol, deux sur les transports, un sur la « marchabilité » et six sur la « cyclabilité ». Les stations sont ensuite classées avec la méthode de *clustering* K-medoids, selon leurs similitudes. Sept différents types de stations, présentant chacune un environnement cyclable bien particulier, sont révélés pour la région métropolitaine de Montréal. Il est possible de remarquer une composante spatiale importante. La partie plus dense de Montréal comporte un cluster couvrant les stations de métro de la ligne orange entre Jean-Talon et Berri-UQAM dont les caractéristiques s'apparentent à celles provenant de la définition des TOD et offrant un environnement cyclable favorable; un autre cluster comportant les stations du centre-ville, avec une forte circulation automobile et plus favorable pour les déplacements à pied; deux autres clusters à vocation plus résidentielle où le transport par autobus est plus présent, dont un d'eux est situé autour du Mont-Royal où il y a une grande variation de l'élévation. La partie moins dense de Montréal offre en général un environnement cyclable moins favorable, mais un trafic automobile réduit. Il est composé d'un cluster à vocation résidentielle moins dense, présentant un fort potentiel cyclable pour le déplacement vers les stations; un autre cluster de stations se démarquant par la présence de stationnement incitatif; et finalement un cluster de stations qui se retrouvent dans des milieux plutôt isolés (p. ex., en bordure d'autoroutes ou de cours d'eau, près d'un centre commercial ou dans des parcs publics). Finalement, des recommandations sont fournies

pour montrer comment l'outil peut être intégré au processus de planification afin d'améliorer la pratique du vélo autour des stations. Les interventions sont priorisées pour les stations possédant un fort potentiel cyclable.

Pour répondre au deuxième objectif, une revue de la littérature sur les méthodologies de typologies de TOD permet de détecter les tendances concernant le choix des stations à analyser, l'aire d'accessibilité et les critères/indicateurs choisis, ainsi que les méthodes de *clustering* utilisées. Par la suite, l'outil de classification développé au premier objectif pour la région de Montréal est adapté et transféré à la ville de Rotterdam aux Pays-Bas. Pour considérer le contexte de mobilité de Rotterdam et les données disponibles, les adaptations nécessaires à la sélection et au calcul des indicateurs sont expliquées dans la méthodologie. Parmi les adaptations nécessaires, il y a : un rayon de 800 m (plutôt que 1,200 m) pour la zone tampon; un indicateur de densité d'adresse (plutôt que densité d'emploi et de points d'intérêts); l'indication de la présence d'un stationnement sécurisé pour vélo à la station (plutôt qu'un décompte du nombre d'arceaux à vélo disponible à la station). Pour Rotterdam, on obtient cinq clusters de station. À la différence de Montréal, un cluster se démarque pour être composé de deux stations centrales et aucun cluster ne se démarque pour son offre de stationnement incitatif ni pour son élévation. Les conséquences des choix méthodologiques sur les résultats sont mises de l'avant. Cette étude a permis de proposer un cadre méthodologique en cinq étapes guidant le développement de typologie de TOD. En (1) définissant le contexte de la région à l'étude, il est possible de (2) sélectionner des indicateurs pertinents aux conditions de mobilité de celle-ci. Par la suite, (3) le choix de la méthode de clustering se fait principalement en fonction du type de variable, de la quantité de données et des ressources disponibles. (4) La présentation des résultats est importante pour visualiser la répartition des stations selon leur type et comprendre les distinctions entre chacun des types de stations. Finalement, il est suggéré de (5) discuter de l'intégration de l'outil de typologie de TOD au processus de planification de la région étudiée.

Les conclusions de cette recherche sont d'intérêts pour les chercheurs et les professionnels s'intéressant au développement des stations et au concept de TOD. Ce mémoire fournit un guide pour la conception de typologies de TOD permettant de répondre aux objectifs de planification ou de recherche spécifique aux différents contextes géographiques. Il inclut des exemples d'application concrets pour deux villes provenant du contexte occidental. Davantage de recherches sont nécessaires pour valider le cadre méthodologique en dehors du contexte occidental.

ABSTRACT

To contribute to the sustainable transition, cities are aware that they need to encourage and facilitate the use of more sustainable transportation modes. Integrating transport and land-use planning is central to reducing car dependency, urban sprawl and greenhouse gas emissions. In urban planning, cities increasingly try to implement the concept of Transit-Oriented Development (TOD). This planning concept promotes density and diversity of urban development around public transport (PT) stations. This configuration would not only encourage the use of PT for longer-distance trips, but also make it more attractive to walk or cycle for shorter trips. However, the TOD concept is still difficult to implement in practice due to the current configuration of cities or governance.

Various analysis and planning tools are used to promote TOD planning. Classification methods for TOD, also known as TOD typologies, help understand how the concept is implemented (or could be implemented) in different regions of the world. These methods consist in measuring the performance, related to land use and transport, of PT network stations. Then stations are grouped together based on their similitudes, with the use of a clustering method. These results can help propose targeted recommendations for station development.

Although TOD typologies have been widely explored in research, significant gaps remain. Walking is often considered as the per default mode to get to and around PT stations. However, cycling is also an important component of the TOD concept but seems to be neglected in the literature on TOD typology. If multiple TOD typologies demonstrated that PT stations could be classified based on the quality of the pedestrian environment, it should be possible to do the same based on the cycling environment.

On the other hand, it is still difficult to know how these tools can be applied in practice, and how they can be used in contexts other than those for which they were developed. The results of TOD typologies presented in the literature are useful for drawing conclusions for the regions for which these typologies are applied. However, the conclusions drawn are of little relevance to other regions, except for learning from good practices in TOD planning. It has been shown that the transfer of TOD policies must consider the geographical context in which they are embedded. The assumption is that the same principle applies to TOD typologies.

Therefore, this thesis aims to address the following two research objectives:

- (1) Develop a methodology for classifying PT stations in the Montreal metropolitan area, based on the bikeability of their surrounding environment.
- (2) Evaluate the transfer of TOD typology tools across distinct geographical contexts.

To answer the first research objective, a literature review on TOD typology and on bikeability index is then conducted. Next, information on PT stations (metro and suburban train) of Greater Montreal are collected in the relevant and open databases. Stations are evaluated on the basis of five indicators related to land use, two related to transportation, one on walkability and six on bikeability. Stations are then classified with the K-medoids clustering method, based on their similitudes. Seven different types of stations, all presenting a particular cycling environment, are revealed for the Montreal metropolitan region. There is a strong spatial component. The denser part of Montreal is composed of one cluster covering stations on orange metro line from Jean-Talon to Berri-UQAM with characteristics similar to the ones from TOD definition and offering a favourable cycling environment; another cluster group stations from the downtown area with high traffic disruption and more convenient for walking; two other clusters with a more residential vocation and a greater presence of bus transport, one of which is located around Mount Royal, where there is a steep elevation. The lower density part of Montreal, in general, offers a poorer cycling environment, but less traffic disruption. It is composed of one residential cluster of stations, with low density but high cycling potential for bicycle trips to the stations; another cluster distinguishes itself for the presence of Park and Ride; and finally, one cluster of stations located in rather isolated environments (e.g., along highways or waterways, near shopping malls or in public parks). Recommendations are provided to show how the tool can be integrated into the planning process to improve cycling around stations. Interventions are prioritized for stations with high cycling potential.

To answer the second research objective, a literature review on TOD typology methodologies allows to detect patterns in the choice of the stations to be analyzed, the catchment areas and criteria/indicators selected, and the clustering methods used. Following that, the classification tool developed in the first objective for the Montreal region is adapted and transferred to the city of Rotterdam in the Netherlands. To consider Rotterdam's mobility context and the data available, the adaptations needed to select and calculate the indicators are explained in the methodology. Adaptations include: a buffer radius of 800 m (rather than 1,200 m); an address density indicator (rather than employment and point-of-interest density); an indication of the presence of secure

bicycle parking at the station (rather than a count of the number of bicycle racks available at the station). For Rotterdam, five clusters of stations are revealed. Unlike Montreal, one cluster stands out for being composed of two central stations, and no cluster stands out for its park-and-ride facilities or its elevation. Consequences of methodological choices are put forward in the results section. This study proposed a five-steps methodological framework to guide the development of a TOD typology. By (1) defining the context of the region under study, it is possible to (2) select relevant indicators to its mobility conditions. Subsequently, (3) the choice of clustering method is based primarily on the type of variable, the size of the data and the resources available. (4) The presentation of results is important to visualize the distribution of stations by type and to understand the distinctions between each type of station. Finally, it is suggested to (5) discuss the integration of the TOD typology tool into the planning process of the study area.

The findings of this research are of interest for researchers and professionals focusing on station development and the TOD concept. This thesis provides a guide to the design of TOD typologies to meet the planning or research objectives of any region. It includes concrete application examples of two cities from the Western context. More research is needed to validate the conceptual framework outside the Western context.

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LISTE DES SIGLES ET ABRÉVIATIONS

TOD	Transit-Oriented Development
TC	Transport en commun
PT	Public Transport
SRB	Service rapide par bus
CMM	Communauté métropolitaine de Montréal
PMAD	Plan métropolitain d'aménagement et de développement
ARTM	Autorité Régionale des Transports Métropolitain
STM	Société des transports de Montréal

CHAPITRE 1 INTRODUCTION

1.1 Contexte et problématique

Afin de répondre aux enjeux liés à la dépendance automobile (p. ex., la congestion routière, les émissions de gaz à effet de serre, la sédentarité, etc.), plusieurs chercheurs et planificateurs urbains à travers le monde s'intéressent au concept de planification axée sur le transport en commun (TC). Ce concept est communément identifié par l'acronyme anglais TOD, désignant *Transit-Oriented Development*. Le concept TOD a originalement été défini par Calthorpe (1993), dans le contexte des États-Unis, comme étant un développement urbain dense à usage mixte donnant accès à une station de TC importante à l'intérieur d'un rayon de 400 à 800 m (5 à 10 minutes de marche). Cette configuration encourage donc la marche et le vélo pour les déplacements de courtes distances et favorise l'utilisation du réseau de TC pour les déplacements de plus longues distances. Bien que le terme TOD soit maintenant globalement utilisé, la littérature définit ce dernier de façon plus large. Le TOD est donc un concept de planification urbaine intégrant les transports et l'aménagement du territoire pour rendre les modes de transports durables tels que la marche, le vélo et le TC plus attrayants et pratiques, en concentrant le développement urbain autour de stations de TC (Ibraeva, de Almeida Correia, Silva, & Antunes, 2020; Thomas & Bertolini, 2017). En raison de son caractère malléable (Cournoyer-Gendron, 2017), l'implémentation du concept TOD demande d'accorder une importance au contexte dans lequel il s'inscrit (Thomas & Bertolini, 2017; Thomas et al., 2018; van Lierop, Maat, & El-Geneidy, 2017). En effet, plusieurs villes à travers le monde appliquent ce concept pour remplir différents objectifs de planification. En Amérique du Nord et en Australie, on s'en sert pour rediriger l'étalement urbain autour des stations de TC. En Amérique du Sud, c'est plutôt de relocaliser les centres urbains déjà très denses autour de nouveaux réseaux de TC, comme les services rapides par bus (SRB). En Europe, ce concept semble guider le redéveloppement des stations existantes, alors qu'en Asie, le concept TOD est plutôt utilisé comme stratégie pour contrôler la croissance rapide des populations en développant les nouvelles communautés le long des réseaux de TC (Lyu, Bertolini, & Pfeffer, 2016). De ce fait, les critères de succès d'implémentation des TOD varient en fonction du contexte géographique.

Afin d'évaluer et de mieux comprendre comment le concept TOD s'implante à travers différentes régions, plusieurs chercheurs s'intéressent à classifier les stations de TC en fonction de différents attributs. Les résultats de ces classifications sont présentés sous forme de typologies de TOD

permettant d'établir des politiques de planification plus ciblées en fonction des différents types de stations. Par exemple, Higgins and Kanaroglou (2016) a développé une typologie de TOD présentant 10 différents types de stations de TC pour Toronto. Des exemples de types de stations sont : les stations dans le noyau urbain commercial, dans les quartiers résidentiels urbains, dans les quartiers résidentiels suburbains et les stations servant l'aéroport. Cet outil de planification permet donc de fournir des recommandations plus stratégiques et plus ciblées au type de stations, quant à leur développement (Ibraeva et al., 2020). Plusieurs auteurs ont proposé différentes typologies de TOD pour des régions d'études spécifiques. Ceci contribue d'abord à l'amélioration de la méthodologie de classification de stations de TC, mais aussi à partager les bonnes et les moins bonnes pratiques en matière de TOD. Les régions souhaitant appliquer le concept de TOD peuvent donc s'inspirer de ces diverses politiques, en prenant soin de les adapter à leur propre contexte. Bien qu'appliquées à une région d'étude spécifique, les typologies de TOD sont généralement conçues pour être transférables d'un contexte géographique à l'autre (Higgins & Kanaroglou, 2016; Lyu et al., 2016). Cependant, aucune étude n'a spécifiquement démontré ni discuté la manière de transférer ces méthodologies vers un contexte différent.

Sans équivoque, en tant que région métropolitaine issue d'un contexte nord-américain, Montréal s'est donc inspiré d'un tel concept pour continuer le développement de son territoire. En 2011, la Communauté métropolitaine de Montréal (CMM) a mis en place le Plan métropolitain d'aménagement et de développement (PMAD) du Grand Montréal. Ce plan concentre ses actions selon trois orientations : l'aménagement, le transport et l'environnement. L'objectif premier en lien avec l'aménagement est d'orienter 60% des nouveaux ménages dans des quartiers TOD, d'ici 2031 (Communauté métropolitaine de Montréal, 2012). Selon Roy-Baillargeon (2016) et Cournoyer-Gendron (2017), la CMM se sert du concept TOD comme outil de gouvernance pour répondre aux objectifs de densification résidentielle, tout en conservant le principe de suburbanisation. Malgré que certaines régions d'Europe comme les Pays-Bas sont reconnus pour leur implémentation exemplaire du concept TOD, le Canada connaît aussi du succès dans cette pratique, notamment à Vancouver (van Lierop et al., 2017). Sachant que Montréal appuie sa planification urbaine sur le concept de TOD, il est pertinent de se demander comment ce concept se profile à travers cette vaste région métropolitaine canadienne. Son contexte urbain nord-américain fait en sorte qu'il est peut-être plus difficile de percevoir les zones répondants aux principes de TOD dans le Grand Montréal, contrairement aux Pays-Bas par exemple. C'est pourquoi il est important de développer des

typologies de TOD adaptées au contexte géographique, en tenant compte des particularités régionales, afin de classer les stations de TC en fonction de leur environnement spécifique.

Par ailleurs, dans la planification de TOD, la marche est souvent considérée comme le principal mode d'accès aux stations de TC, elle reçoit donc beaucoup d'attention, contrairement au vélo (Lee, Choi, & Leem, 2016; Vale, 2015). En effet, l'évaluation de la qualité de l'environnement cyclable dans la classification des quartiers TOD est, pour la plupart du temps, négligée ou très peu considérée. Pourtant, aux Pays-Bas, là où le concept TOD se manifeste de façon exemplaire, le vélo est un mode d'accès aux stations de transports en commun très courant (Forouhar & van Lierop, 2021; Hartanto, Grigolon, van Maarseveen, & Brussel, 2017). Dans cette lignée, il est d'ailleurs important de noter qu'aux États-Unis et au Canada, la planification selon le principe TOD se concentre surtout sur l'amélioration des réseaux de transports actifs, tandis qu'aux Pays-Bas, elle se concentre surtout sur le développement de pôles multimodaux et la réduction du temps de déplacement en transport sur rail (van Lierop et al., 2017). La ville de Montréal a récemment dévoilé sa vision vélo 2023-2027 sous le thème de l'équité territoriale et de la connectivité, qui vise à développer plus de 200km de nouvelles voies cyclables d'ici cinq ans (Ville de Montréal, 2023).

1.2 Objectifs de recherche

Ce mémoire vise à mieux considérer l'évaluation de l'environnement cyclable dans les typologies de TOD et à comprendre davantage le transfert méthodologique des classifications de stations de TC à travers différents contextes géographiques, tout en considérant davantage. Il répond donc aux deux objectifs de recherche suivant :

- (1) Développer une méthodologie pour classer les stations de TC de la région métropolitaine de Montréal, en fonction de la qualité cyclable de l'environnement qui les entoure.
- (2) Évaluer le transfert des outils de typologies de TOD à travers divers contextes géographiques.

Le premier objectif porte sur le développement d'un outil de typologies de TOD permettant de classer les stations de TC principalement en fonction de leur environnement cyclable. Cet outil est appliqué aux stations de métro et de train de banlieue de la région métropolitaine de Montréal. Ceci vise à mieux comprendre comment l'environnement cyclable autour des stations diffère entre elles, tout en considérant les caractéristiques de l'aménagement, des transports et de l'environnement piéton. Les résultats de cette classification permettent de fournir des recommandations ciblées en

fonction du type de stations et des objectifs de planification de la ville de Montréal, en proposant un ordre de priorité d'interventions stratégique. Cette méthodologie peut aussi être appliquée à d'autres contextes, comme il sera démontré dans le deuxième objectif.

Le deuxième objectif est construit sur la base du premier objectif. Il concerne la conceptualisation d'un cadre méthodologique pour transférer des outils de typologies de TOD d'un contexte géographique à un autre. Le développement de ce cadre est basé sur une revue exhaustive de la littérature et sur la démonstration du transfert de la méthodologie de classification des stations de TC développé pour Montréal, vers la ville de Rotterdam aux Pays-Bas. Montréal et Rotterdam ont été choisis comme régions d'études puisqu'elles présentent toutes les deux des objectifs de planification axés sur les TC et le vélo, mais des contextes de mobilité très différents. L'infrastructure cyclable de Rotterdam est plus développée que celle de Montréal, ce qui se traduit par une part modale du vélo considérablement plus élevée dans cette ville. Les résultats de cette étude sont synthétisés et généralisés à l'intérieur d'une figure conceptuelle servant de guide pour le développement d'outil de classification de stations de TC. Ce cadre peut être appliqué au développement d'une typologie de TOD pour toute région géographique, peu importe l'objectif de recherche ou de planification visé par cette typologie. Il permet ainsi d'accroître l'accessibilité de cet outil de planification pour en faciliter son utilisation en pratique.

1.3 Organisation générale du mémoire

Le corps de ce mémoire est composé de deux articles scientifiques répondant chacun à l'une des deux questions de recherches citées plus haut.

Le chapitre 2 détaille la démarche de l'ensemble du travail de recherche. Les grandes étapes du travail de recherche sont décrites, en commençant par la phase exploratoire qui a permis d'identifier le premier objectif de recherche, et éventuellement le deuxième objectif. Ensuite, cette section survole les méthodologies utilisées et développées pour répondre aux deux objectifs de recherche.

Le chapitre 3 aborde la revue de la littérature réalisée dans le cadre de ce projet de recherche. Une revue de littérature détaillée est présente dans chacun des articles de ce mémoire. Les constats soulevés lors de la revue de la littérature se trouvent donc divisés entre les chapitres 4 et 5 de ce mémoire. Le chapitre 3 présente ainsi de façon succincte les principaux thèmes abordés dans chacune des revues de la littérature et la complémentarité de celles-ci.

Le chapitre 4 présente l'article scientifique « Transit-oriented development and bikeability: Classifying public transport station areas in Montreal, Canada », publié le 15 janvier 2024 dans le journal *Transport Policy*. Cet article a aussi été présenté à la *World Conference on Transport Research Society* qui s'est tenue à Montréal en juillet 2023. Cet article a été rédigé par l'auteure de ce mémoire en collaboration avec la directrice de recherche Geneviève Boisjoly et la co-directrice Dea van Lierop. Cette étude répond au premier objectif de recherche en présentant le développement d'une méthodologie de classification de stations de TC, en fonction de l'environnement cyclable. L'article présente une revue de la littérature en deux parties. La première survole les différents critères et indicateurs typiquement utilisés dans les outils de typologies de TOD et permettant de caractériser les stations de TC et l'environnement qui les entoure. La deuxième partie explore plutôt l'évaluation de l'environnement cyclable dans le contexte des TOD. La méthodologie propose de combiner des indicateurs mesurant la « cyclabilité » de l'environnement entourant les stations de TC aux indicateurs traditionnellement utilisés pour les typologies de TOD (c.-à-d., des indicateurs caractérisant l'utilisation du sol, les transports et la « marchabilité »). Les résultats de cette classification démontrent que l'ajout d'indicateurs TOD évaluant la « cyclabilité » de produire une typologie de TOD distinguant les différents types de stations de la région métropolitaine de Montréal, principalement en fonction de leur « cyclabilité ». L'article se termine par une discussion proposant différentes interventions à prioriser, selon les objectifs de la programmation cyclable de la Ville de Montréal, sous le thème de l'équité territoriale (Ville de Montréal, 2022).

Le chapitre 5 comprend l'article scientifique « A Methodological Framework for the Development of Transit-Oriented Development (TOD) Typologies » soumis à la fin du mois de mars au journal *Cities*. L'article a été rédigé par l'auteure de ce mémoire, sous la codirection de Dea van Lierop et Geneviève Boisjoly. L'article commence par une revue de la littérature sur les méthodologies permettant la création de typologie de TOD. Ensuite, la méthodologie développée au chapitre 4 pour Montréal est appliquée et adaptée au contexte de Rotterdam, une ville néerlandaise. Dans ce chapitre, la section expliquant la méthodologie détaille les adaptations nécessaires pour développer une typologie de TOD orientée sur la « cyclabilité », en fonction du contexte de mobilité et de la disponibilité des données. Les résultats sont présentés sous la forme d'une comparaison entre les tendances spatiales et les caractéristiques typiques des différents clusters de station pour les deux régions (Montréal et Rotterdam). Cette section aborde aussi l'influence des choix méthodologiques

sur les clusters de stations obtenues. Les résultats de cet article discutent et proposent ensuite un cadre méthodologique, en cinq étapes, généralisant la méthodologie de développement d'outil de typologie de TOD. Cette fois-ci, cette section discute des résultats et de l'influence des choix méthodologiques à travers la démarche complète. L'exercice de transfert méthodologique entre Montréal et Rotterdam sert donc de preuve de concept. En conclusion, les limites et les perspectives de recherche sont présentées.

Le chapitre 6 discute de façon générale de l'apport des deux articles. Il met en commun les résultats obtenus afin de mettre en valeur la contribution de ce mémoire dans la recherche sur les outils de planification pour le développement des stations.

Le chapitre 7 conclut ce mémoire avec un rappel des résultats principaux, les limitations de la présente recherche ainsi que les futures avenues de recherche possibles en lien avec le sujet.

CHAPITRE 2 Démarche du travail de recherche

Cette section présente la démarche intégrale du travail de recherche poursuivie dans ce mémoire (voir Figure 2.1). Elle décrit les étapes de recherche permettant l'atteinte des objectifs identifiés plus haut. Dans le cas échéant, la démarche est présentée de façon linéaire, mais il faut comprendre que les objectifs de recherche se sont précisés tout au long de l'avancement du travail de recherche.

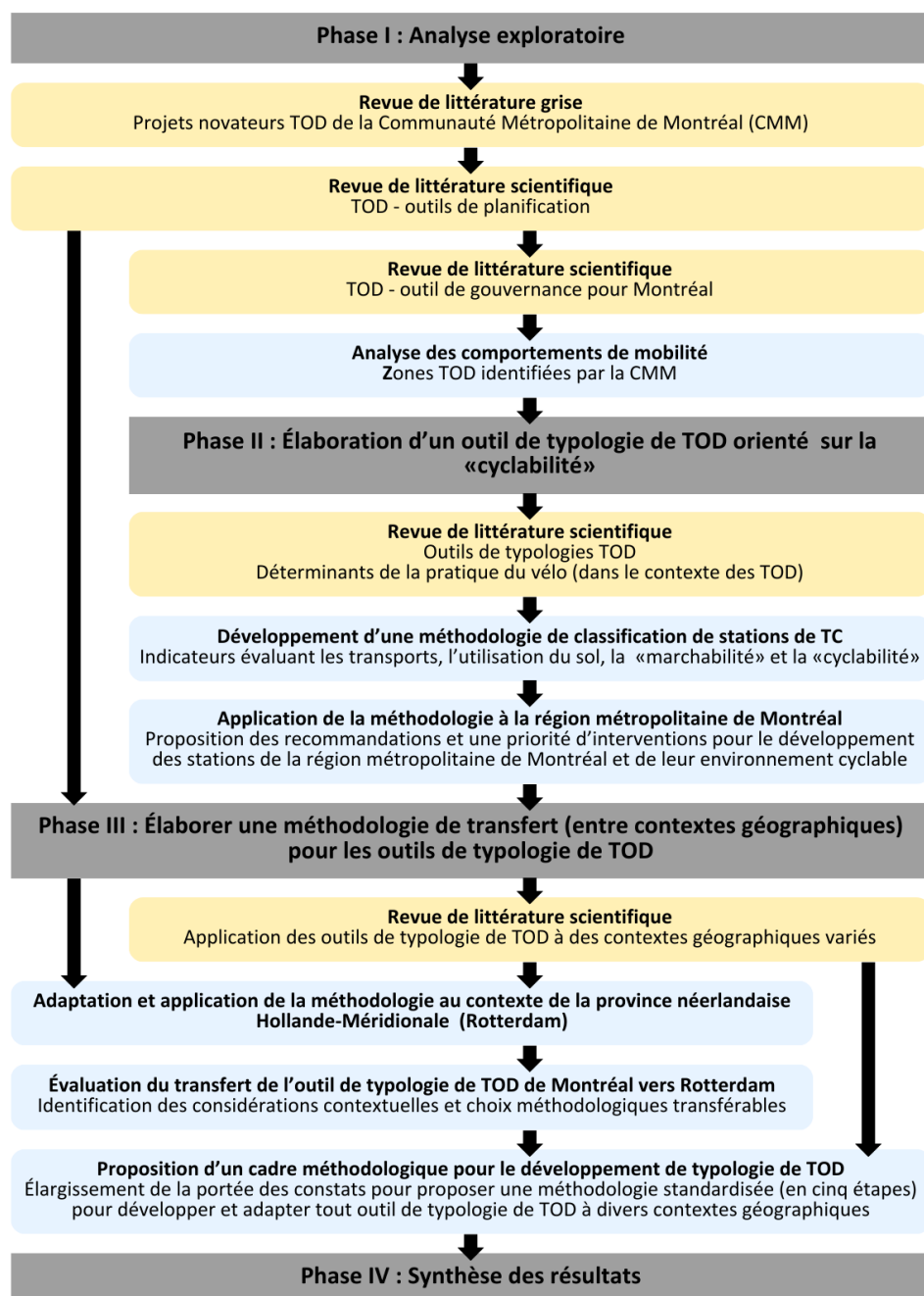


Figure 2.1. Schéma de la démarche du travail de recherche

2.1 Phase I : Analyse exploratoire

Le travail de recherche a d'abord débuté par une analyse exploratoire de la littérature grise, pour mieux comprendre comment le concept TOD se manifeste dans la région de Montréal. Une lecture du PMAD produit par la CMM a permis de reconnaître l'importance accordée au concept TOD pour le développement de la région métropolitaine de Montréal. En effet, l'objectif principal de l'orientation « aménagement » du PMAD est d'orienter 60% des nouveaux ménages dans les quartiers TOD, d'ici 2031 (Communauté métropolitaine de Montréal, 2012). La CMM a d'ailleurs publié un guide d'aménagement des aires TOD, à l'intention des municipalités du Grand Montréal (Communauté métropolitaine de Montréal, 2011). Il permet de comprendre comment le concept prévoit être implémenté dans la région, en fonction des types de stations. Ce dernier propose les lignes directrices en termes d'aménagement (p. ex., densité, diversité, infrastructure de transport).

L'analyse exploratoire s'est poursuivie avec un survol de la littérature scientifique portant sur les TOD, en considérant les études réalisées spécifiquement sur le cas de Montréal. Depuis que la CMM a établi cet objectif d'aménagement, des chercheurs du Québec se sont surtout penchés sur la question de gouvernance de ce concept de planification (Cournoyer-Gendron, 2017; Roy-Baillargeon, 2016).

Par la suite, une analyse exploratoire des comportements de mobilité des résidents du Grand Montréal à l'intérieur des aires TOD a été effectuée. Ce sont les données sur les déplacements des résidents provenant de l'enquête Origine-Destination récoltées par l'Autorité régionale des Transports métropolitains (ARTM) en 2018 (Enquête Origine-Destination, 2018), conjointement avec les données sur les limites des aires TOD fournies par la CMM, qui ont été analysées. La Figure 2.2 illustre les différents types d'aires TOD identifiés par la CMM. Les aires TOD ont un rayon variant entre 500 m pour les stationnements incitatifs et terminus d'autobus et 1000 m pour les gares et les stations de métro et de train. Ce sont donc toutes les stations de TC (métro et train de banlieue), et plus encore, qui devraient être planifiées en tant que TOD selon les objectifs de la CMM.

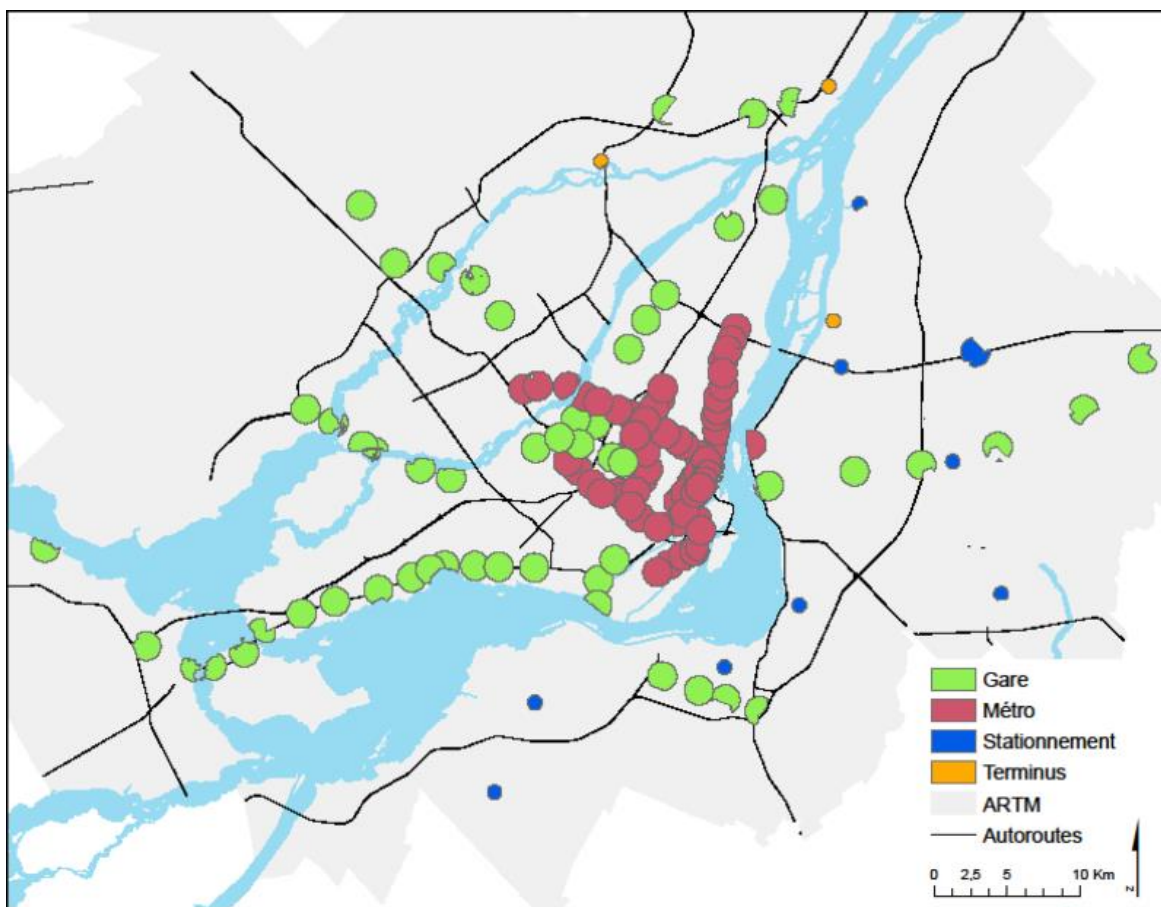


Figure 2.2. Aires TOD identifiées par la CMM pour la région du Grand Montréal

La Figure 2.3 montre les parts modales des déplacements dont l'origine se situe à l'intérieur des aires TOD, en fonction des différents types d'aires TOD. On remarque que c'est seulement à l'intérieur des zones TOD entourant les stations de métro que les comportements de mobilités diffèrent remarquablement des zones hors TOD. La part modale pour le TC (~30%) et la marche (~15%) sont donc visiblement plus élevées qu'ailleurs. C'est aussi près des stations de métro que le vélo est utilisé en plus grande proportion. L'ambition de la CMM est de développer chacune des stations de TC se trouvant sur son territoire en aire TOD. Sachant que les comportements de mobilité attendus pour un TOD sont seulement perceptibles près des stations de métro, on voit la pertinence d'explorer davantage le processus de planification de ces aires TOD. Ce travail de recherche contribue donc à l'avancement des connaissances sur les outils de planification des aires TOD. Plus encore, ce mémoire témoigne de la pertinence d'exploiter les données sur les transports et l'utilisation du sol (p. ex., géospatiales, horaires de TC, déplacements, etc.), dans le domaine de la planification des transports.

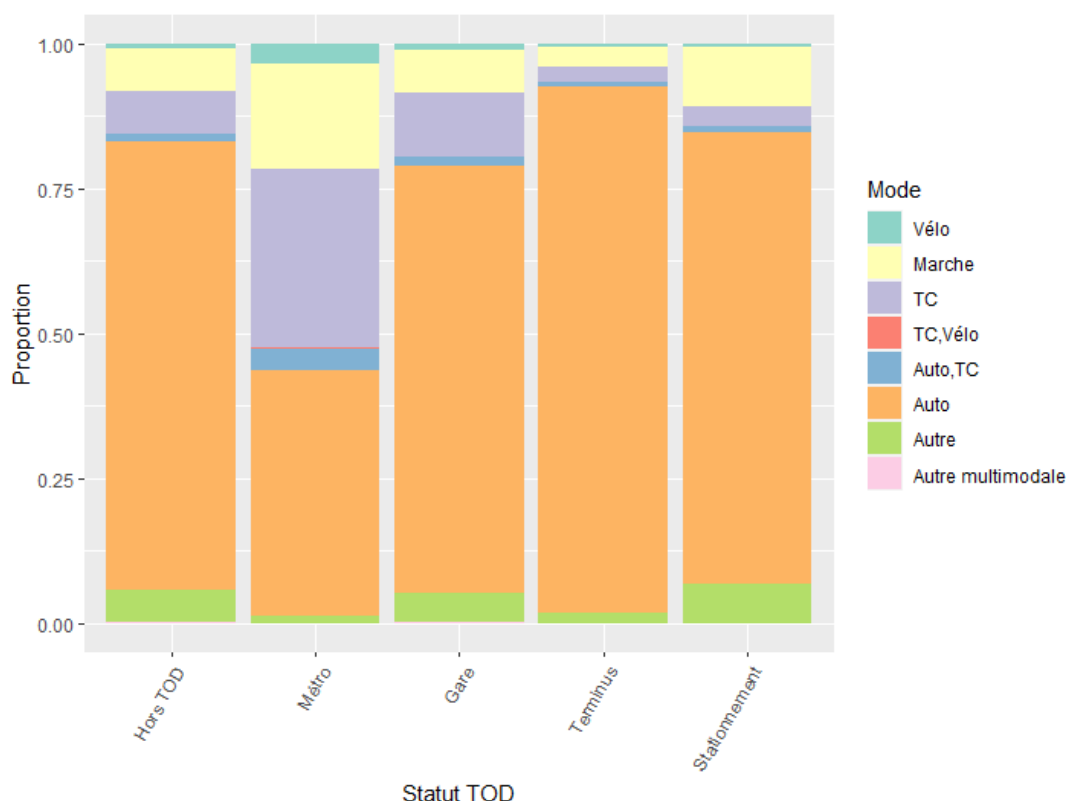


Figure 2.3. Parts modales des résidents du Grand Montréal, en fonction des différents types d'aires TOD

La complétion de l'analyse exploratoire de la littérature scientifique s'est donc concentrée sur les outils de planification et d'aide à la décision pour la planification des TOD, dans le domaine du génie des transports, de l'urbanisme et de l'aménagement du territoire. Il s'avère que les outils de typologies de TOD reçoivent une attention particulière dans la littérature scientifique, depuis quelques années (Ibraeva et al., 2020). Une typologie de TOD est le fruit d'une classification des stations de TC, dans le but de comprendre comment le concept TOD s'implante dans une région spécifique. Les aires TOD (stations de TC) sont donc classées selon différents types, en fonction de leur performance qui est mesurée par une série d'indicateurs principalement en lien avec les transports, l'utilisation du sol, l'accessibilité et la mobilité (Liu, Singleton, & Arribas-Bel, 2020). Son utilité a été démontrée par sa capacité à fournir une analyse détaillée des aires TOD, selon les données disponibles, permettant ainsi de proposer des recommandations d'interventions ciblées en fonction des types de stations de TC / aires TOD.

Dans la littérature, la marche à pied est typiquement le mode de transport privilégié pour se déplacer vers les stations de TC. Les méthodologies pour classer les stations mesurent généralement les indicateurs de performance des TOD à l'intérieur d'un rayon accessible à pied. Certains articles présentant même des typologies de TOD concentrant leur contribution sur des mesures de « marchabilité » (Jeffrey, Boulangé, Giles-Corti, Washington, & Gunn, 2019) ou d'accessibilité piétonne (Vale, 2015). Ce n'est pas la même attention qui est accordée au vélo dans l'étude sur les typologies de TOD, et pourtant, c'est un mode de transport privilégié dans certaines régions où les TOD sont implémentés avec succès, comme les Pays-Bas. En effet, le vélo permet de parcourir une plus grande distance pour un même temps donné à la marche (Forouhar & van Lierop, 2021; Hartanto et al., 2017; Lee et al., 2016). Le vélo a donc un potentiel d'améliorer l'accessibilité aux transports en commun et de devenir un mode de transport de choix pour les déplacements de courtes durées à l'intérieur des zones TOD. Afin de mieux intégrer la pratique du vélo dans la planification des TOD, il est essentiel de mieux intégrer l'évaluation de l'environnement cyclable dans les outils de typologie de TOD.

2.2 Phase II : Élaborer un outil de typologie de TOD orienté sur la « cyclabilité »

D'après les constats relevés dans l'analyse exploratoire, il est possible d'identifier le premier objectif de recherche. Celui-ci consiste à développer une méthodologie pour classer les stations de TC de la région métropolitaine de Montréal, en fonction de leur environnement cyclable. Cet objectif fait l'objet de l'article scientifique « Transit-oriented development and bikeability: Classifying public transport station areas in Montreal, Canada ».

D'abord, cet article met en contexte la marginalisation de l'évaluation de l'environnement cyclable dans le contexte des typologies de TOD. Une revue de la littérature explore les différentes typologies de TOD, en examinant plus particulièrement les critères et indicateurs choisis, les méthodes de classification utilisées et l'implication des résultats pour le processus de planification des TOD. Cette revue s'intéresse aussi aux déterminants de la pratique du vélo en général, et plus spécifiquement dans le contexte des TOD. Les choix méthodologiques expliqués dans cet article ont donc été influencés par cette revue de la littérature. L'existence d'un indice de « cyclabilité »

dans le contexte des TOD (Hartanto et al., 2017) a servi d'inspiration pour la sélection des indicateurs mesurant la qualité de l'environnement cyclable.

Parallèlement à la revue de la littérature, la collecte de données a aussi permis de concrétiser les choix méthodologiques. En effet, la disponibilité des données influence le type d'analyse qui peut être effectuée. Il est donc question de regrouper les données pertinentes provenant des bases de données telles que le portail de données ouvertes du gouvernement provincial du Québec (Gouvernement du Québec, 2022) et GéoIndex (plateforme partagée de données géospatiales et de photographies aériennes par l'Université Laval). La manipulation de ces données a permis de développer une méthodologie permettant de classer les stations de TC (stations de métro et de trains de banlieue) selon des indicateurs évaluant les transports, l'utilisation du sol, la « marchabilité » et la « cyclabilité ». La méthodologie développée est finalement appliquée à la région métropolitaine de Montréal.

La typologie de TOD proposée dans cet article est donc la présentation des résultats de la classification des stations de TC. Les résultats démontrent que la méthodologie développée permet de classer les stations de TC en fonction de l'environnement cyclable actuel et du potentiel cyclable. Pour le cas spécifique de Montréal, des recommandations pour le développement des stations sont proposées, en concordance avec les objectifs de la programmation cyclable (Ville de Montréal, 2022). La typologie permet de cibler les interventions en matière d'infrastructure cyclable, en fonction du type de station. Une analyse des priorités d'interventions a d'ailleurs été effectuée.

L'atteinte de ce premier objectif a mis la table pour l'élaboration du deuxième objectif de recherche. D'abord, la revue de la littérature a permis de constater que plusieurs études abordent la possibilité de transférer les méthodologies proposées vers différents contextes géographiques (Higgins & Kanaroglou, 2016; Kumar, Sekhar, & Parida, 2020; Lyu et al., 2016), mais qu'aucune n'est consacrée à évaluer le processus de transfert. La deuxième phase de ce mémoire a aussi permis de constater que les résultats obtenus de la classification des stations de TC sont propres à Montréal et qu'ils sont spécifiques à ce contexte. Alors, d'autres régions pourraient s'inspirer des résultats en notant les bonnes et les moins bonnes pratiques, mais c'est principalement Montréal qui peut tirer des leçons des résultats de sa propre typologie de TOD. Il y a donc une composante

contextuelle bien importante à l'élaboration de typologies de TOD, tout comme pour sa planification, tel que démontré par Thomas et al. (2018).

Il a donc été naturel de se pencher sur la question de transfert des méthodologies de développement de typologies de TOD entre divers contextes géographiques. D'autres contextes géographiques pourraient effectivement bénéficier d'appliquer un outil de typologie de TOD orienté sur la « cyclabilité ». Il est donc pertinent de réfléchir à ce qu'il faut prendre en considération pour transférer une telle méthodologie, développée spécifiquement pour le contexte montréalais, à une autre région géographique présentant un contexte culturel et politique complètement différent.

2.3 Phase III : Élaborer une méthodologie de transfert (entre contextes géographiques) pour les outils de typologie de TOD

Pour répondre au deuxième objectif de recherche, la phase III propose d'élaborer une méthodologie générale de transfert d'outil de typologies de TOD entre divers contextes géographiques.

Pour y arriver, une revue exhaustive de la littérature analyse les articles scientifiques qui ont produit des typologies de TOD. La récolte des articles s'est faite dans les bases de données *Web of Science* et *Compendex*. Une attention particulière est portée à la façon dont chacun des articles a considéré le contexte géographique dans l'élaboration de leur méthodologie. En outre, les méthodologies développées sont examinées, plus précisément les indicateurs choisis, les méthodes de calculs et de classification (*clustering*) utilisés, ainsi que la forme de la présentation des résultats.

Ensuite, il a suffi d'appliquer la méthodologie développée pour Montréal durant la phase II à un autre contexte géographique, soit celui de la région de Rotterdam aux Pays-Bas. Un stage de recherche à l'Université d'Utrecht aux Pays-Bas a permis de se familiariser avec le contexte de mobilité du pays, pour lequel les TC et l'infrastructure cyclables sont très développés. Le transfert méthodologique a nécessité des adaptations afin de considérer les particularités du contexte des Pays-Bas. Une analyse terrain, sous la supervision d'une professeure étudiant les transports et la planification spatiale dans le contexte des Pays-Bas, a permis d'identifier les adaptations méthodologiques nécessaires. Les apprentissages tirés de la revue de la littérature ainsi que ceux découlant de ce transfert méthodologique ont été synthétisés dans un cadre méthodologique. Ce cadre méthodologique présente donc une méthodologie standardisée pour développer et adapter tout outil de typologie de TOD à divers contextes géographiques.

2.4 Phase IV : Synthèse des résultats

Pour terminer, les constats relevés des deux articles constituant ce mémoire sont mis en commun pour déterminer ce qui rend une méthodologie de typologie de TOD transférable d'un contexte géographique à l'autre. L'application de la méthodologie développée pour Montréal au premier objectif ainsi que le transfert de celle-ci à Rotterdam fournit donc deux exemples concrets démontrant le cadre méthodologique proposé au deuxième objectif. Le mémoire conclut en établissant les limites de l'étude et les perspectives de recherche.

CHAPITRE 3 Revue de littérature

La revue de la littérature effectuée dans le cadre de ce travail de recherche est répartie dans les deux articles présents dans ce mémoire. Il y a donc une revue de littérature spécifique à chaque objectif de recherche, bien que les deux revues soient interreliées.

Dans le chapitre 4, la revue de littérature se concentre sur les principaux indicateurs utilisés dans le développement de typologies de TOD. C'est le modèle « *node-place* » développé par Bertolini (1999) qui sert d'inspiration pour la plupart des typologies de TOD présentes dans la littérature. Cette revue de la littérature souligne plus spécifiquement les efforts qui ont été mis pour inclure des indicateurs relatifs à la « marchabilité » (Jeffrey et al., 2019; Vale, 2015). Une lacune par rapport à la présence d'indicateurs sur la « cyclabilité » et de typologie spécifiquement orientée vers la « cyclabilité » a ensuite été identifiée. La revue de littérature aborde donc les déterminants de la pratique du vélo en général et dans le contexte des TOD.

Dans le chapitre 5, la revue de littérature examine les articles présentant des typologies de TOD sous un autre angle. Cette revue s'intéresse à comprendre comment les auteurs ont pris en considération le contexte géographique à l'étude (c.-à-d., comment ils ont adapté et/ou transféré les choix méthodologiques aux spécificités de la région étudiée). Un tableau synthèse est développé afin de synthétiser les résultats de la revue. Pour chaque article, le Table 5.1 identifie donc la région à l'étude, le système de transport analysé, les critères d'évaluation TOD, la zone tampon des stations, les étapes principales de la méthodologie et les contributions scientifiques. Cette revue de la littérature contribue à répondre au deuxième objectif de recherche en permettant d'identifier l'approche méthodologique typiquement empruntée pour développer des typologies de TOD.

CHAPITRE 4 ARTICLE 1: TRANSIT-ORIENTED DEVELOPMENT AND BIKEABILITY: CLASSIFYING PUBLIC TRANSPORT STATION AREAS IN MONTREAL, CANADA

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Abstract

Transit-oriented development (TOD), characterized by a dense 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

4.1 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 et al., 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 et al., 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 et al., 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 et al., 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.

4.2 Literature review

4.2.1 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 et al. (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 et al., 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 Nosrati (2015) added spatial indices to the node-place model to evaluate the quality of the local street network in Tehran; Y. 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; L. Yang & Song, 2021), pedshed ratio (Singh et al., 2017; Vale, 2015; Vale, Viana, & Pereira, 2018; L. 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 bikeability has been developed.

4.2.2 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. Castañón 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 et al. (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.

4.3 Case Study Area

The study area, shown in Figure 4.1, 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 Figure 4.1), 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.

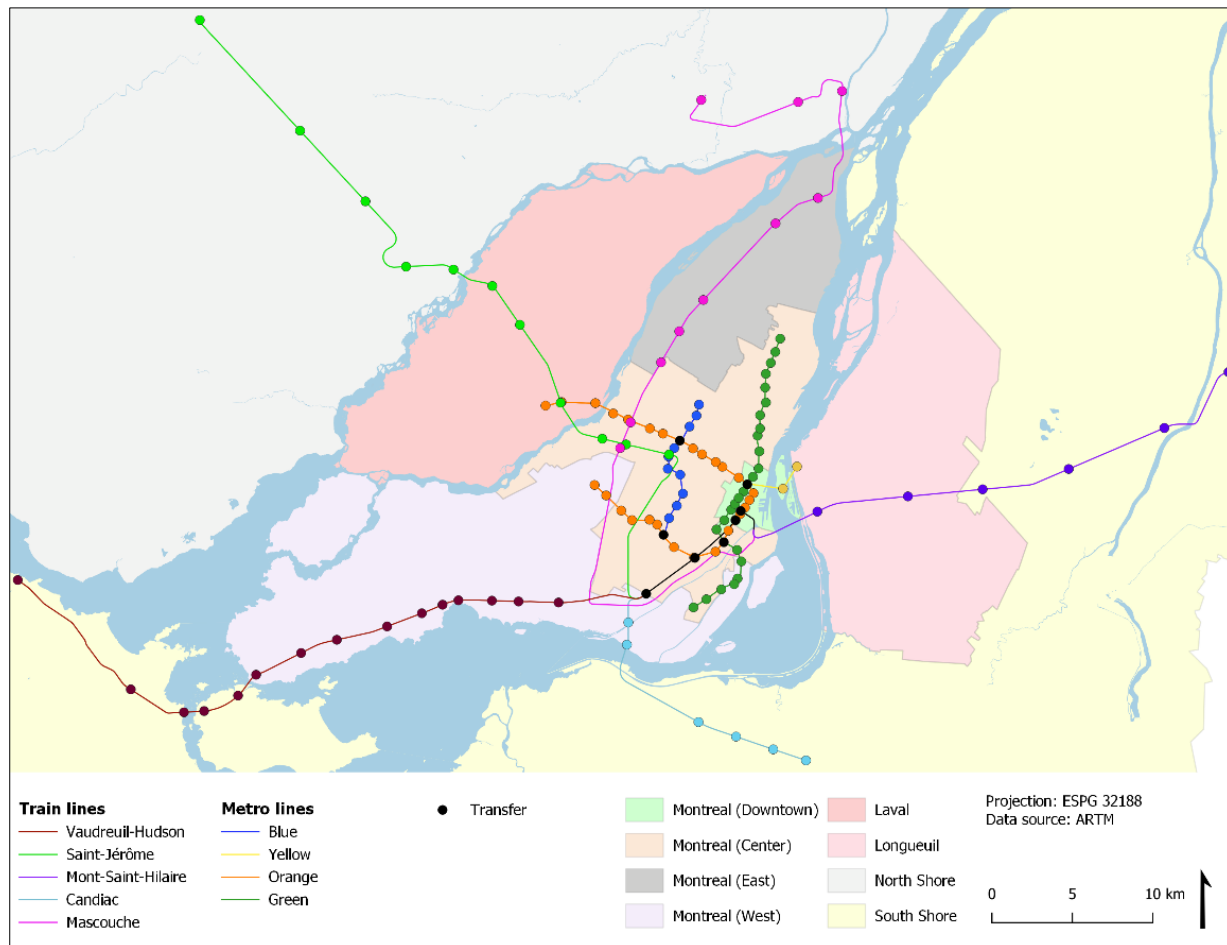


Figure 4.1. Montreal Census Metropolitan Area

4.4 Methodology

4.4.1 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 4.1, 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 (water body and parks and other 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 4.1, 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 4.1. 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)

4.5 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 it is 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.

4.6 Results

4.6.1 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 Figure 4.2, 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.

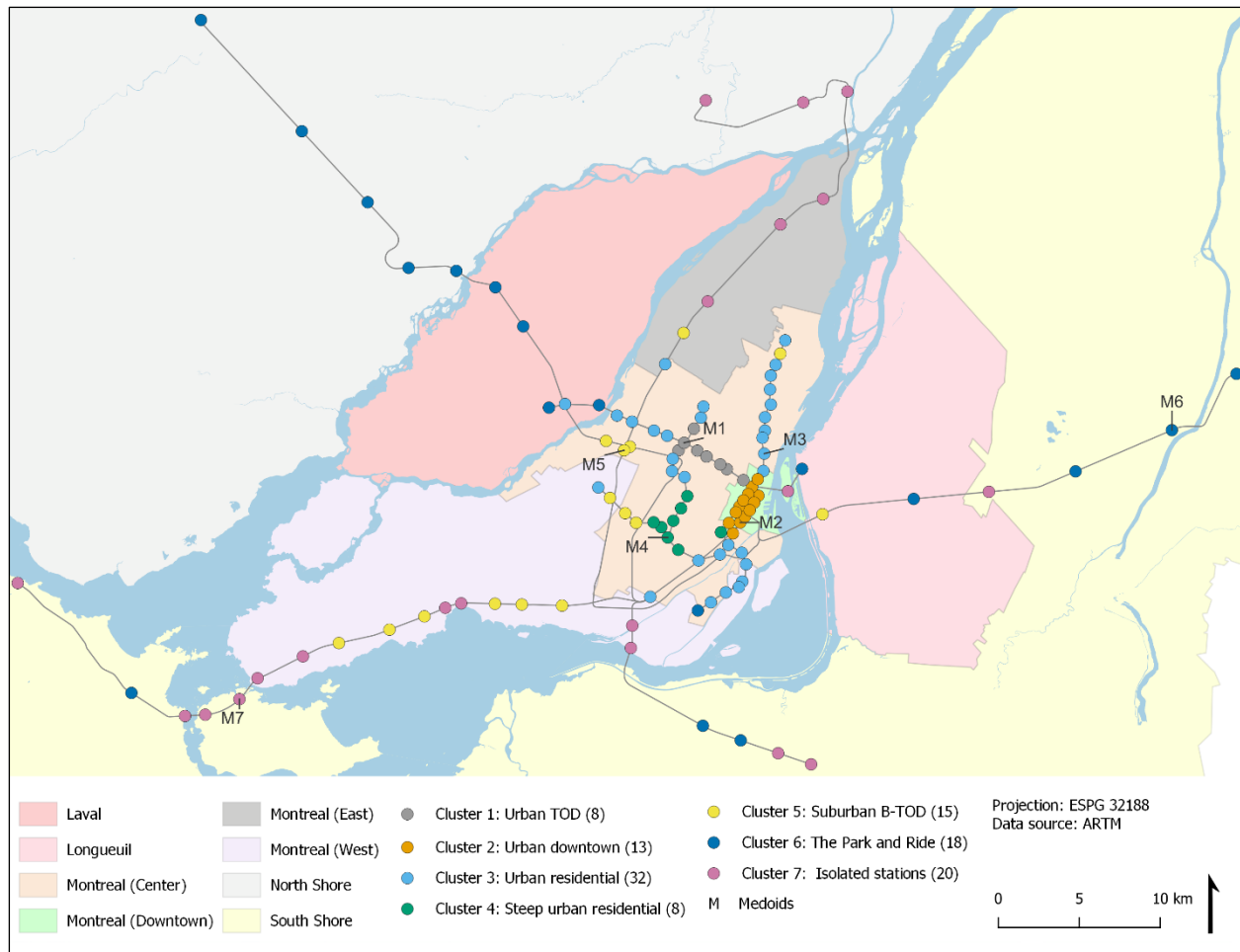


Figure 4.2. Geographic distribution of the seven clusters

Figure 4.3 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 4.2, 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 significantly 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 4.2.

Starting with the land use criteria, Figure 4.3 shows a decrease in population density from Cluster 1 to Cluster 7, with the exception of Cluster 4. Population density is significantly 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 (significantly 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 significantly 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.

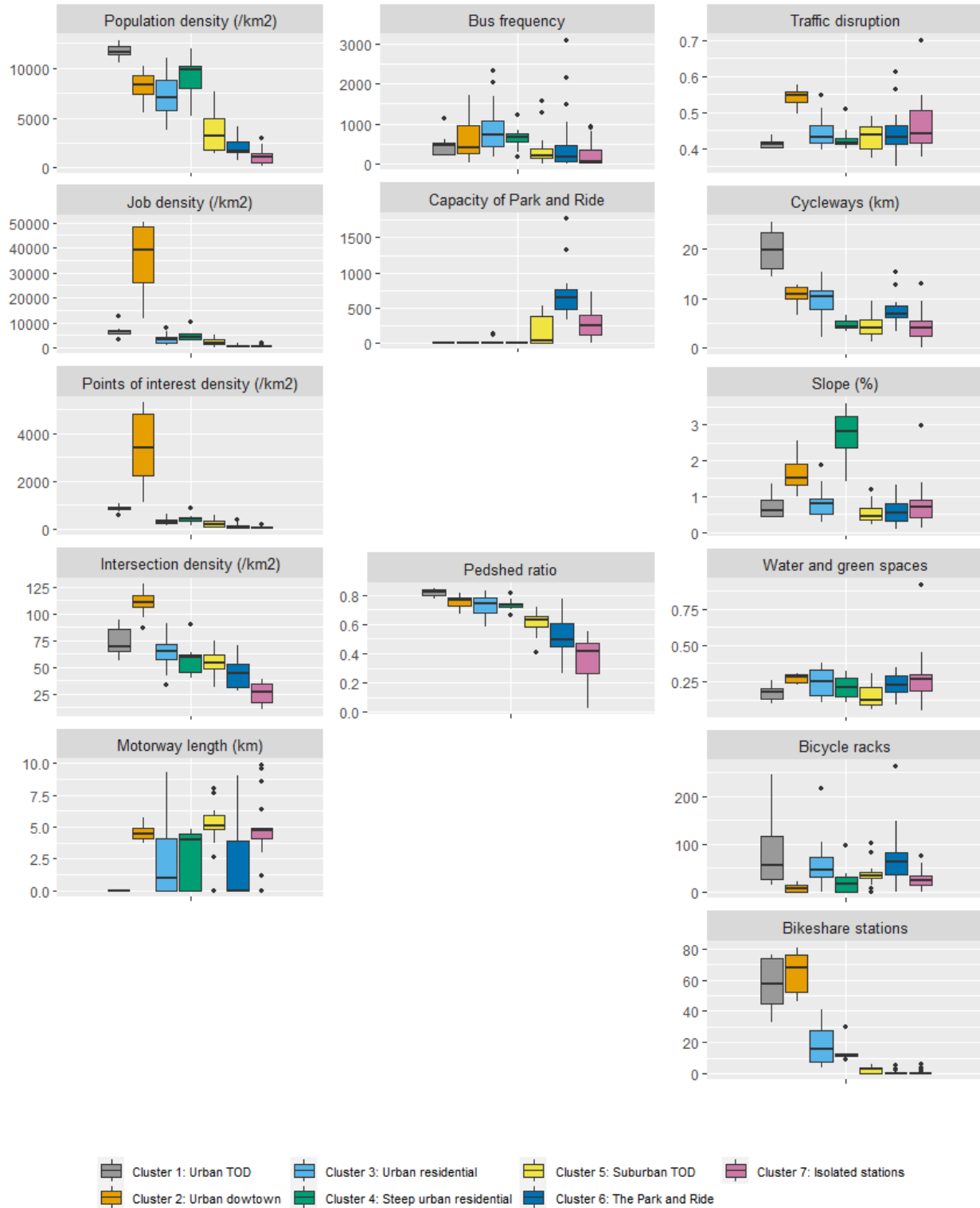


Figure 4.3. Dispersion of the indicators across the seven clusters

Table 4.2. 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

Table 4.2. Indicators mean values and standard deviation (suite)

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

4.6.2 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. Figure 4.4 ranked the seven clusters on a TOD bikeability scale, according to the mean values and standard deviation of indicators seen in Table 4.2, 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 Figure 4.4, 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 4.2, 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.

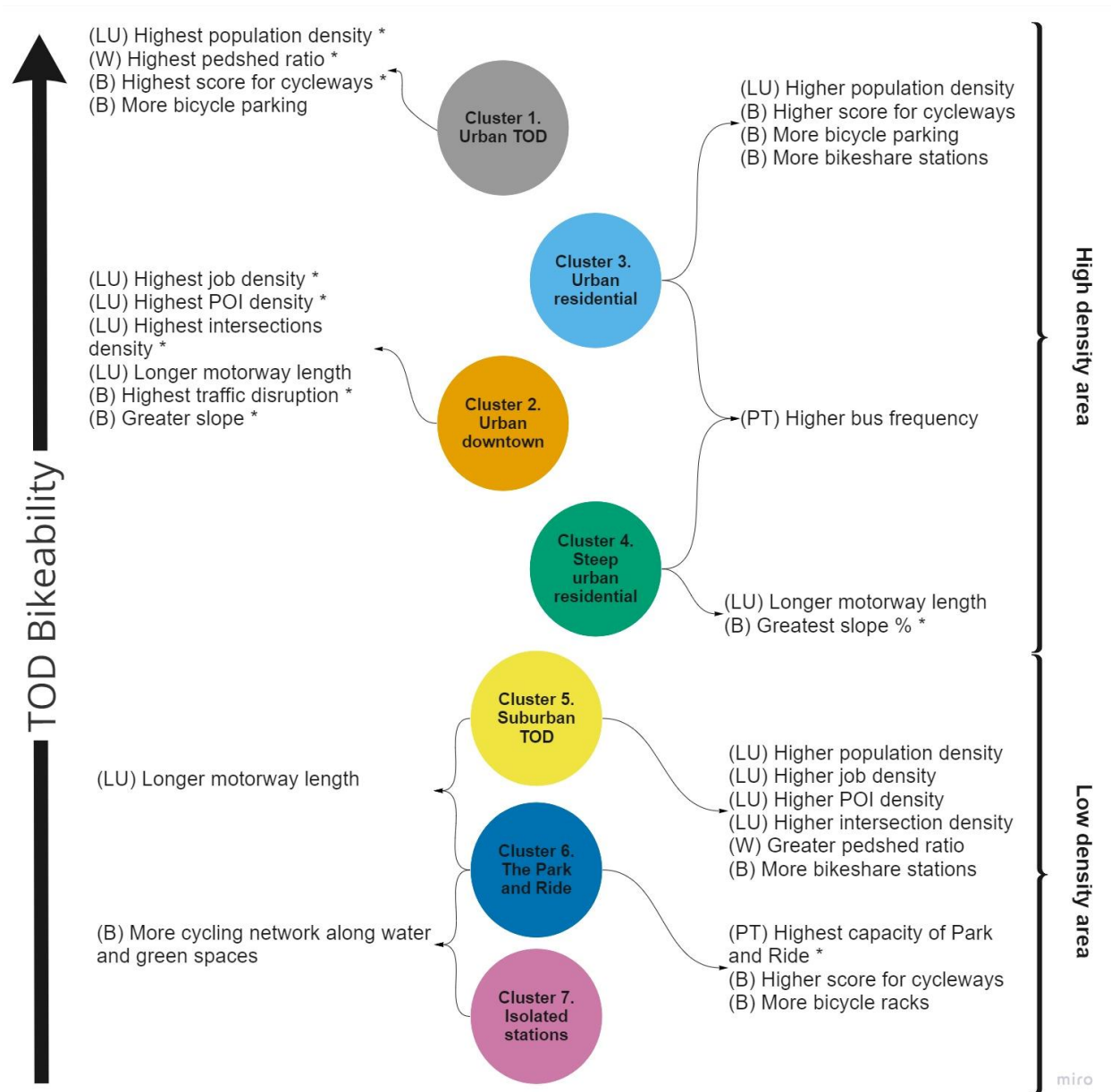


Figure 4.4. TOD Bikeability ranking for the seven clusters

4.7 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 environments 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 environments 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.

4.7.1 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 4.3 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.

4.7.1.1 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 (Castañón & 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 Figure 4.4 and its similarities with clusters 1 to 4, the cluster “*suburban TOD (5)*” has 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 longer 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 the use of bicycles 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 over 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 and restraints on its use are not significant (e.g., congestion, cost), 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.

4.7.1.2 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.

4.7.1.3 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 during the 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 stations 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. In the longer term, knowing that residential density is constantly increasing in the Downtown Montréal 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).

4.7.1.4 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 4.3. 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			

Table 4.3. Example of prioritization scheme ranking the clusters and proposing short-term and long-term interventions (suite)

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.

4.8 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.

CHAPITRE 5 ARTICLE 2: A Methodological Framework for the Development of Transit-Oriented Development (TOD) Typologies

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Abstract

To support the implementation of transit-oriented development (TOD) in different cultural, political, and geographic contexts, researchers and planners increasingly use TOD typologies. This diagnostic planning tool clusters PT stations together based on their degree of similarity, by assessing the state of transport and land use. Targeted recommendations are made accordingly to enhance future stations and neighbourhood development. Since 2009, much methodological progress has been made to support the development of TOD typologies (e.g., development of new indicators, use of different clustering methods, proposition of different criteria for prioritizing

interventions). While TOD typologies are meant to be transferable across contexts, authors typically develop TOD typologies as specific case studies. As such, no studies explicitly provide insight on how to proceed to adapt it to other regions.

This paper sets out to determine which factors need to be considered when applying a TOD typology tool to any given region. To do so, this study builds on a bicycle-oriented TOD typology tool developed for the Montreal region (Robillard, Boisjoly, & van Lierop, 2023). It then details the process of adapting this existing methodology to another context: Rotterdam (Netherlands). Montreal and Rotterdam were selected as case cities to assess the transferability of a TOD typology tool between two regions in an industrialized western context with completely distinct mobility contexts and cultures; specifically, Montreal's cycling infrastructure is much less developed compared to that of Rotterdam. The proposed TOD typology tool evaluates the bikeability around PT stations through a series of indicators related to the cycling environment and other traditional indicators related to land use, transportation, and walkability. The transfer results in two distinct typologies, clustering stations mainly according to their bikeability, within the context of their respective region.

The findings of the study result in a methodological framework to guide the development of TOD typologies in diverse contexts, based on (i) a comprehensive review of the relevant literature, and (ii) a demonstration of an application of a bicycle-oriented TOD typology to distinct contexts. This five-step framework can serve as a practitioner's guide to develop or adapt TOD typology tools to various contexts. First, the identification of the study area consists of: selecting the PT stations to be included in the classification (e.g., metro stations for a local scale, train stations for regional/national scale), and defining the research or planning objectives underlying the development of the typology (e.g., supporting bicycle as a feeder mode to transit, extending transit network and use, adjusting transit system to rapid growth of cities). Next, TOD indicators and catchment area type are specified (e.g., circular or network buffer around stations, selection of distance based on the mode of transportation). This is followed by the selection of the classification methods (e.g., selection of the appropriate clustering method according to data format and size), the presentation of the clustering results, and a discussion on planning implications. The proposed framework enhances the accessibility of TOD typology tools for planners and practitioners. To refine this framework, future studies could conduct a systematic literature review on TOD typology, and test multiple clustering methods while developing a TOD typology. Moreover, this

framework needs to be validated in non-Western contexts to ensure its applicability across diverse urban settings.

Keywords: Transit-oriented development, TOD typology, Clustering, Classification, Station development, Bicycle

5.1 Introduction

Land use and transportation are two important components of urban planning. Cities across the globe often integrate the two through Transit-Oriented Development (TOD). The concept of TOD was introduced by Calthorpe (1993) as a planning approach to support the integration of public transport into community planning. In the context of the United States (US), Calthorpe (1993) formally defined this concept as the development of a community where residents could easily access a public transport (PT) station, and a core set of services and shops within a walking distance of 600 m (2,000 ft). Although the definition of the term “TOD” is commonly accepted, the integration of public transportation and land-use is planned differently across geographic regions (Thomas et al., 2018; van Lierop et al., 2017). However, even though TODs are planned differently around the world, they commonly focus on developing dense, compact, and mixed-use neighbourhoods around stations that are integrated into rapid mass transit systems. In all geographic contexts, these transit-oriented liveable communities are pedestrian and bicycle-friendly and help to reduce dependence on the automobile (Curtis et al., 2009).

In research and planning, developing a TOD typology is a well-known and increasingly used strategy to understand and evaluate how the concept of TOD is implemented in a region. A TOD typology is a classification of PT stations. Indicators related to land-use and transportation are measured for every station composing a transportation network in a region and stations are clustered together based on the degree of similarity of their indicators. Results from the classification allow for the identification of more targeted policy recommendations for different types of stations and neighborhoods, and to plan for new stations or for improvements of existing ones (Ibraeva et al., 2020). In the literature, several papers propose different approaches leading to TOD typologies. While presenting PT stations classification specific to their studied city, authors of TOD typology’s paper usually propose innovations to the current classification methodologies, related to the calculation of the indicators or the clustering methods. They generally conclude with an interpretation of the results and a discussion of the planning implications. Apart from identifying

best practices and learning from mistakes, other regions can only learn limited lessons from the results and policy recommendations of another region's TOD typology (Ibraeva et al., 2020; Su et al., 2021). Indeed, “in order to be successful, TOD implementation must be specific to the urban forms, political and planning contexts, and cultural preferences. International examples should only be used as inspiration” (Thomas et al., 2018).

Since TOD typologies are useful for identifying best practices of TOD applications, the methodologies that determine TOD typologies should be shared and reproducible in contexts other than the one in which it was applied. This is why many authors often claim that their TOD typologies methodology “is applicable beyond the context of the case study” (Monajem & Nosratian, 2015; Reusser, Loukopoulos, Stauffacher, & Scholz, 2008), “is easily transferable” (Higgins & Kanaroglou, 2016), “can be extended to other geographic contexts” (Su et al., 2021), or “is made as transparent and replicable as possible” (Lyu et al., 2016). Several authors have even sought to create standardized/normative typologies (Higgins & Kanaroglou, 2016; Jeffrey et al., 2019).

However, despite claiming that TOD typologies are reproducible in multiple contexts, what can be seen from the literature is that no TOD typology methodology has been identically replicated to another distinct context. Even if the node-place model (Bertolini, 1999) is an inspiration for a majority of TOD typology methodologies, authors that wanted to apply it had to adapt it (Chen & Lin, 2015; Chorus & Bertolini, 2011; Ivan, Boruta, & Horák, 2012) or extend it (Lyu et al., 2016; J. Ma et al., 2022; Su, Wang, Li, & Kang, 2022; Vale, 2015; Y. Yang, Zhong, & Gao, 2022) to their case of study, with respect to contextual specificities or data availability. Knowing that the context-specific component is central to the development of TOD typologies, it evidently begs the question of the relevance of applying exactly the same methodology of TOD typology to distinct regions. Rather than proposing one and only one good way to perform a TOD typology, the use of a standardized and more general methodology would provide more flexibility for developing robust TOD typologies across geographic and cultural contexts. With this in mind, the following research questions are generated: (1) What makes a TOD typology transferable and replicable? (2) What needs to be considered when applying any of the proposed TOD typologies in the literature, which are applied to a specific region, to another region with a distinct context?

To answer these questions, we propose a methodological framework that generalizes the design of context-specific TOD typologies tools. The methodological framework results from a comprehensive literature review on TOD typologies and the process of adapting a bicycle-oriented TOD typology (Robillard et al., 2023) to two regions with different geographical, sociocultural, and political contexts: Montreal (Canada) and Rotterdam (Netherlands).

The paper is structured as follows. After the literature review (Section 2), the methodology explains how we apply and adapt the TOD typology methodology to the two cities (Section 3). Then, the results and discussion section (Section 4) is twofold: (i) the clustering results for both Montreal and Rotterdam are presented and discussed, and (ii) findings are summarized into a methodological framework to guide the development of TOD typologies. This framework is of relevance for further research on TOD typologies and for any practitioners wishing to perform a TOD typology for its specific region and planning objectives.

5.2 Literature review

This literature review focuses on the different methods of stations classification, with a specific focus on geographic and contextual considerations. The reviewed TOD articles on TOD typology are presented in Table 5.1, with details about the study area, the selection of criteria/indicators and catchment area, the methodology and the contributions.

5.2.1 The node-place model

The node-place model, by Bertolini (1999), is one of the first station classification methodologies to analyze and compare TOD projects. It was applied to 31 railway stations in the Amsterdam and Utrecht regions in the Netherlands. It measured the accessibility to the PT stations (node-index), and the intensity and diversity of activities within a 700 m walkable radius of the stations (place-index). Node-index comprised the calculation of the number of directions and daily frequency of train, tram, underground, and bus, number of train stations within 45 minutes, parking capacities for car and bicycle, closest distance from motorway access and the number of freestanding bicycle paths. Place-index calculated the number of residents, the number of workers from different sectors and the degree of functional mix. Both indices were calculated, by means of a multicriteria analysis. PT stations were scattered into a 2D diagram (place-index as a function of node-index), and then visually divided into five clusters. The model suggests that in the long term, interventions regarding

land-use and transport at PT stations should tend to a linear relationship between the node and place indices, (i.e., the two indices tend to balance out), to eventually form one balanced cluster of PT stations.

5.2.2 Applications of the node-place model

From 2008 to 2015, TOD typologies that followed the development of the node-place model were designed to make recommendations to enhance station development in their region of application. Most of these studies have mainly attempted to apply and adapt the node-place model to their context of study, to meet different research objectives while proposing minor innovations to the classification methodology, as presented in Table 5.1.

In many cases, applying the node-place model required adapting TOD indicators according to context and/or data availability (Chorus & Bertolini, 2011; Ivan et al., 2012; Monajem & Nosratan, 2015; Reusser et al., 2008; Vale, 2015). TOD indicators are often categorized into criteria to simplify the methodology. For a list of all possible criteria, one should refer to Table 5.1. For instance, Reusser et al. (2008) and Zemp, Stauffacher, Lang, and Scholz (2011) both adapted the selection of the TOD indicators based on interviews with experts, to better consider the Swiss context in the measurement of TOD performance. In the case of Ostrava (Czech Republic) and Lisbon (Portugal), bicycle-related indicators were removed from the node-index because cycling remains unusual in these regions (Ivan et al., 2012; Vale, 2015). Additionally, Ivan et al. (2012) also included indicators on land prices and rates of unemployment in the place-index, because houses near stations are often inhabited by socially disadvantaged people in Ostrava.

Other authors have opted to analyze only a subset of stations from the entire transport network to address specific research objectives. For an overview of all transportation systems that underwent a TOD typology, Table 5.1 lists the number of stations that are part of the classification. For instance, Chorus and Bertolini (2011) only considered the 99 stations that fulfill a regional role in their TOD typology of the Tokyo, Japan railway network. Whereas Chen and Lin (2015) applied the node-place model to only one station in Shanghai (China), to evaluate the development of the Hongqiao business district that surrounds the multimodal Hongqiao Hub station. Instead of using the classic 700 m network buffer, they used the whole Hongqiao business district as the catchment area, to assess the influence of the station for the whole district. To identify neighborhoods with the potential to host a station and become a TOD, Kamruzzaman et al. (2014) adapted the node-

place model in this sense to Brisbane (Australia). Indicators were then calculated within an 800 m network buffer from the centroid of the census collect districts. This 800 m, corresponding to a 10 min walk was selected, as suggested by Queensland policy documents. Other examples of choice of catchment area are described in Table 5.1.

In short, to meet their research objectives, all studies described above had to adapt parts of the node-place model to their geographical context. Whether it was through the selection of the indicators, the definition of the catchment area, or the choice of stations to be included in the classification.

5.2.3 Extended versions of the node-place model

From 2015, many “extended versions” of the node-place model were proposed, as initiated by Vale (2015) and Lyu et al. (2016). These mainly relate to the addition of one or two criteria to the classification of PT stations. In Table 5.1, these new criteria appear after classics ‘node’ and ‘place’ criteria, in the appropriate column.

To develop a typology specific to the metro network of Beijing (China), Lyu et al. (2016) extended the node-place model by adding a third dimension, and named it the transit’ (‘node’), ‘oriented’, ‘development’ (‘place’) model. L. Yang and Song (2021), Liao and Scheuer (2022) and Qiang, Zhang, and Huang (2022) further applied this specific methodology, with small modifications, to Ningbo, Beijing and Shanghai respectively, remaining in a Chinese context. Lyu et al. (2016) concluded that investigating the context-specific capability of TOD to satisfy urban transportation needs could help the development of Beijing and other Chinese cities.

To include the design aspect in the node-place model, Vale (2015) combined it with an evaluation of the pedestrian environment, by calculating the pedshed ratio of all ferryboat and rail stations in Lisbon Metropolitan area (Portugal). Based on the work of Vale (2015) and Lyu et al. (2016), Vale et al. (2018) formally developed the node-place-design model to adapt the original node-place model to a more local scale. They applied it to the subway stations in Lisbon (Portugal). As seen in Table 5.1, indicators and catchment areas were adapted to the context of subway stations to reflect the smaller scale of this transit network, compared to the railway system (e.g., smaller distance between stations). This set of two studies illustrates the needs to adapt the methodology to the context of the area of study, even if it is in the same city. The node-place-design model of Vale et al. (2018) was further applied to London (England) (Y. Zhang et al., 2019) and Shanghai’s

new towns (L. Zhang, Hou, & Qiang, 2022), with adaptations regarding catchment area and indicators.

From that moment, many other authors proposed extended versions of the node-place model to consider different specificities of the PT network under study. They added a third (and sometime a forth) criterion to the ‘node’ and ‘place’ criteria, such as ‘experience’ (Groenendijk, Rezaei, & Correia, 2018), ‘tie’ (Li et al., 2019; Rabiei et al., 2022), ‘functionality’ (Su, Wang, et al., 2022; Su et al., 2021), ‘network’ (Dou et al., 2021), ‘accessibility’ (Cummings & Mahmassani, 2022), ‘ridership’ (Amini Pishro et al., 2022), ‘socio-demographic’ (Su, Wang, et al., 2022; Su, Zhao, Zhou, Li, & Kang, 2022), ‘system support’ (J. Ma et al., 2022; L. Ma, Dill, & Mohr, 2014), and ‘vibrancy’ (Y. Yang et al., 2022).

With the emergence of these extended node-place model, it is possible to notice a desire to evaluate specific components of TOD instead of just its accessibility (node index) and land-use (place index), when performing a TOD typology. This also goes in line with adapting the classification of TOD to a specific geographic context with its own policies and strategies regarding development of stations and PT network.

5.2.4 Other TOD typologies

From 2016, some studies have instead tried to move away from the node-place model, by proposing different criteria for classifying indicators. Again, this was to better encompass the specificities of the contexts under study.

Few TOD typologies directly selected some of the 5D variables developed by Cervero and Kockelman (1997) and Ewing and Cervero (2010), to define their TOD indicators. The 5D’s are density, diversity, design, distance to transit and destination accessibility. Among these, Higgins and Kanaroglou (2016) focused on developing a TOD typology using a latent class clustering method applied to Toronto (Canada), which also inspired Huang et al. (2018) in their attempt to evaluate the complementarity between TOD nodes in their TOD typology of Arnhem and Nijmegen (Netherlands) rail stations. Jeffrey et al. (2019) also followed the 5D’s classification of indicators and measured the TOD potential in Melbourne (Australia), based primarily on walkability measures. Niu et al. (2021) developed a TOD typology especially for Green TOD built environment in Singapore, using indicators based on the 5D variables. These studies all encourage that other authors to apply their methodology to their geographic context, in order to develop a

standardized/normative method (Higgins & Kanaroglou, 2016; Jeffrey et al., 2019), to verify the replicability of it (Huang et al., 2018) or as a comparative purpose (Niu et al., 2021).

Finally, by looking at Table 5.1, a few studies also selected their own criteria for TOD evaluation and classification (Cucuzzella, Owen, Goubran, & Walker, 2022; Kumar et al., 2020; Liu et al., 2020; Rodriguez & Kang, 2020; Seo & Lee, 2021; Singh et al., 2017; Woo, 2021).

5.2.5 Contextualisation of TOD typologies

Many authors have proposed robust methodologies to perform TOD typologies in various geographic contexts. In addition, different TOD typologies can be developed for the same region, all answering different purposes. As reflected in Table 5.1, these different methodological choices include, among others, the selection of criteria and indicators, catchment areas, clustering methods, and validation measures.

Many authors are aware of the limitations of the transferability of their methodology outside the context of their study case (Higgins & Kanaroglou, 2016; Liao & Scheuer, 2022; Lyu et al., 2016). Other regions can draw inspiration from the clustering results but would benefit more from applying (and adapting) the methodology to their own context. This is why most studies try to produce TOD typologies that are “generalizable”, “transferable”, or “easily repeatable”. However, no studies explicitly provide insight on how to proceed to adapt it to other cities. There is an obvious gap in the research regarding contextualization and transferability procedures for TOD typologies.

Table 5.1. Literature review on TOD typologies

Authors	Region of application	PT system and number of stations	Catchment area	Criteria (number of indicators)	Method	Contributions and/or novelty
Bertolini (1999)	Amsterdam and Utrecht (Netherlands)	31 railway stations	700 m walkable buffer	Node (13) Place (8)	(1) Calculation of node and place indices by means of multicriteria analysis (2) Scatter plot of stations into a x (node) – y (place) diagram (3) Visually clustering of station	Development of the original node-place model.
Reusser et al. (2008)	Swiss	1,684 railway stations	700 m walkable buffer	Node (10) Place (7)	(1) Application of the node-place model (2) Cluster analysis - Operational classification with a two-steps clustering approach	Addition of indicators based on interviews with experts. Operational classification – Use of clustering algorithm

Table 5.1. Literature review on TOD typologies (suite)

Zemp et al. (2011)	Swiss	1,700 railway stations	700 m walkable buffer	10 indicators for quantification of context factors	(1) Identification of context factors, based on interviews with expert (2) Cluster analysis with Ward's method (3) Application of node-place model (4) Comparison of classes according to passenger frequencies, geographic distributions, and context dynamics	Interviews with experts to validate the choice of indicators. Comparison of clusters according to passenger frequencies, geographic distributions, and context dynamics to assess the performance of the different clusters of TOD.
Chorus and Bertolini (2011)	Tokyo (Japan)	99 railway stations	700 m walkable buffer	Node (4) Place (6)	(1) Application of the node-place model (2) Correlation analysis to determine the influence of factors on station development (3) Dynamic examination of stations developments in Tokyo	Case studies of stations for each cluster
Ivan et al. (2012)	Ostrava (Czech Republic)	11 railway stations	700 m radius buffer	Node (6) Place (7)	(1) Application of the node-place model	Adaptation of node-place model to the city's context

Table 5.1. Literature review on TOD typologies (suite)

Kamruzzaman et al. (2014)	Brisbane (Australia)	1,740 census collection districts	800 m walkable buffer	Node (1) Place (5)	(1) Calculation of node and place indices (2) Cluster analysis with two-step clustering approach (3) Validation of typologies with mode choice behaviour (multinomial logistic regression analysis)	Application of the node-place model at the neighborhood scale (from the centroid) Validation of typologies with actual mode choice behavior
Monajem and Nosratian (2015)	Tehran (Iran)	79 subway stations	700 m radius buffer	Node (6) Place (8)	(1) Application of the node-place model (2) Calculation of spatial indices (3) Correlation analysis to determine the influence of factors on station development (4) Case studies of station	Addition of spatial indices into the node-place model
Chen and Lin (2015)	Shanghai (China)	1 air-rail station	Hongqiao Business District limits	Node (10) Place (7)	(1) Application of the node-place model	Application of the node-place model on a single multimodal station

Table 5.1. Literature review on TOD typologies (suite)

Vale (2015)	Lisbon (Portugal)	83 ferryboat and railway stations	700 m radius buffer	Node (9) Place (6) Pedestrian (1)	(1) Application of the node-place model (2) Calculation of pedshed ratio for every station (3) Cluster analysis with minimum distance, maximum distance, between-groups distance and Ward's method and K-means, including the pedshed ratio	Inclusion of ferryboat stations Inclusion of a pedshed index in the cluster analysis
Lyu et al. (2016)	Beijing (China)	268 metro stations	700 m radius buffer	Transit (6) Oriented (6) Development (6)	(1) Selection and calculation of indicators (2) Cluster analysis with Ward's method (3) Scatter plot of stations into 'Transit', 'Oriented', and 'Development' dimensions	Addition of the 'Oriented' dimension to represent the functional and morphological interrelation between the node and place values

Table 5.1. Literature review on TOD typologies (suite)

Higgins and Kanaroglou (2016)	Toronto (Canada)	372 existing and planned transit stations	800 m radius buffer	5 indicators according to the D variables	(1) Calculation of indicators (2) Cluster analysis with latent-class method (3) Validation of clusters with statistical t-test to measure performance of TOD outputs	Use of a latent-class clustering method in the context of TOD typology
Singh et al. (2017)	Arnhem and Nijmegen (Netherlands)	21 train stations	800 m radius buffer	21 indicators distributed in 8 criteria	(1) Calculation of the indicators (2) Calculation of TOD index with Multiple Criteria Assessment (3) Sensitivity analysis of TOD index (4) Identification of criteria to be improved for each station	Proposition of a TOD index instead of cluster analysis Detailed strategy for planning station development

Table 5.1. Literature review on TOD typologies (suite)

Huang et al. (2018)	Arnhem and Nijmegen (Netherlands)	22 train stations	800 m radius buffer	Density (3) Diversity (1) Destination accessibility (1) Design (2)	(1) Calculation of the indicators (2) Cluster analysis with latent-class method (3) Validation of typologies with ridership (4) Correspondence analysis to evaluate the complementarity effects between TOD nodes	Evaluation of the complementarity between TOD nodes and the role it plays inside the PT network
Groenendijk et al. (2018)	Rotterdam (Netherlands)	32 transit nodes	[300 m, 3200 m] radius buffer	Node (3) Place (3) Experience (1)	(1) Identification of criteria (2) Evaluation of the weight value of the experience (3) Calculation of the indicators (4) Comparison between node-place and node-place-experience models	Addition of the experience of travellers into the node-place-model

Table 5.1. Literature review on TOD typologies (suite)

Vale et al. (2018)	Lisbon (Portugal)	50 subway stations	500 m radius buffer	Node (7) Place (8) Design (3)	(1) Calculation of node, place, and design indices (2) Scatter plot of the three indices value (3) Cluster analysis with minimum distance, maximum distance, between-groups distance and Ward's method and K-means (4) Balance evaluation between the three indices for each cluster of stations	Addition of the design dimension into the node-place model to better consider the walkability of the environment at a more local scale
Y. Zhang et al. (2019)	London (England)	270 metro station	960 m radius buffer	Node (7) Place (4) Design (3)	(1) Application of the node-place-design model (2) Cluster analysis with K-means method (3) Network criticality analysis of each station	Addition of a network dimension to the node-place-design model, by measuring the weighted betweenness centrality of each station

Table 5.1. Literature review on TOD typologies (suite)

Jeffrey et al. (2019)	Melbourne (Australia)	230 train stations	800 m radius buffer	Design (2) Diversity (2) Density (1) Destination accessibility (6) Transit accessibility (3)	(1) Calculation of indicators (2) Cluster analysis with two-step clustering approach (3) Validation of clusters using knowledge of the case study and patronage data by mode	Development of a TOD typology based on walkability measures
Li et al. (2019)	Shanghai (China)	333 metro stations	15 min walkable buffer	Node (13) Tie (9) Place (2)	(1) Calculation of indicators (2) Cluster analysis with self-organizing maps (3) Selecting location for new metro stations with DBSCAN clustering	Addition of the 'tie' dimension Use of operational method to select new TOD location

Table 5.1. Literature review on TOD typologies (suite)

Kumar et al. (2020)	Delhi (India)	47 census community blocks	1,200 m radius buffer	8 TOD factors	(1) Calculation of indicators (2) Cluster analysis with two-step clustering approach (3) Validation of TOD typology “through the analysis of significant differences in terms of socio-demographic, and travel behavior variables”	Development of a method to identify neighborhood that are likely to become TOD
Liu et al. (2020)	New-York (United-States)	472 subway stations	800 m walkable buffer	Socioeconomic & demographic Location & accessibility Land use & built environment Transit-related	(1) Calculation of indicators (2) Cluster analysis with self-organizing maps (static features) (3) Temporal cluster analysis with self-organizing maps (dynamic features) (4) Comparison between statical and dynamical clustering	Integration of spatiotemporal dynamics of activity variables evaluated at stations

Table 5.1. Literature review on TOD typologies (suite)

Rodriguez and Kang (2020)	Seoul (Korea)	287 metro stations	500 m radius buffer	Place (7) Location (4) Integration (6) Value (2)	(1) Calculation of indicators (2) Exploratory factor analysis (3) Cluster analysis with Ward's method (4) Validation of typologies with ridership	Addition of the value (land market) criteria to cluster analysis of stations
Dou et al. (2021)	Shanghai (China)	286 metro stations	600 m radius buffer	Network (2) Node (6) Place (11)	(1) Calculation of indicators (2) Scatter plot of stations for node-place-network values (3) Cluster analysis with K-means (4) Comparative analysis between node-place and node-place-network model	Addition of the 'network' dimension
Niu et al. (2021)	Singapore	23 rail stations	500 m radius buffer	Density (2) Diversity (2) Design (7) Destination (1) Distance to transit (1)	(1) Calculation of indicators (2) Factor analysis (3) Cluster analysis with K-means method	Development of a typology especially for Green TOD built environment

Table 5.1. Literature review on TOD typologies (suite)

Su et al. (2021)	Beijing, Shanghai, Shenzhen, Hangzhou and Wuhan (China)	405, 415, 182, 202 and 90 metro stations	800 m radius buffer	Node (7) Place (8) Functionality (13)	(1) Calculation of indicator values and weights (2) Determination of TOD degree with analytic hierarchy process (3) Cluster analysis with two-step clustering approach (4) Scatter plot of stations for node-place- functionality values (5) Comparison of results for the five megacities	Addition of the 'functionality' dimension Comparison of typologies applied to multiple cities (comparative context)
Seo and Lee (2021)	Korea	34 national railway stations		Land use Transit accessibility Spatial structure	(1) Calculation of the three indices (2) Cluster analysis with K-means method (3) Evaluation of the relationship between clusters and locational characteristics with t- test	Determination of radius of influence (catchment area) with statistical analysis and not arbitrarily

Table 5.1. Literature review on TOD typologies (suite)

Woo (2021)	Seoul (Korea)	246 subway stations	500 m walkable buffer	Pedestrian accessibility (reach index) Building use index	(1) Calculation of the two indices (2) Cluster analysis with two-step clustering approach (K-means method)	Proposition of a different format for TOD indicators
L. Yang and Song (2021)	Ningbo (China)	63 subway stations	500 m to 1,500 m radius buffer	Transit (14) Oriented (7) Development (18)	(1) Calculation of the three indices (2) Cluster analysis with K-means method (3) Scatter plot of stations for transit-oriented-development values	Improvement of the 'oriented' dimension to consider the needs of the improvement project and the potential of the location to evolve
Amini Pishro et al. (2022)	Chengdu (China)	8 subway stations	500 m and 1,000 m radius buffer	Node (8) Place (9) Ridership (1)	(1) Calculation of the indices (2) Cluster analysis with K-means and Cube methods (3) Multiple linear regression to model relationships between node-place-ridership	Addition of the 'ridership' dimension, in function of the time

Table 5.1. Literature review on TOD typologies (suite)

Cucuzzella et al. (2022)	Montréal (Canada)	19 light-rail stations in construction	1,000 m walkable buffer	Socio-economic (4) Economic (5) Diversity (1) Development potential (3)	(1) Calculation of the three TOD index layers (2) Standardization of the three layers in the TOD index (3) Presentation of the overall TOD index for each station	Proposition of a new TOD index that combines the evaluation of socio-environmental characteristics, economic vibrancy, and development potential to encourage polycentric development
Cummings and Mahmassani (2022)	United-States	478 national railway stations	30 min car drive	Node (12) Place (14) Accessibility (4)	(1) Calculation of the three indices (2) Scatter plot of stations for node-place-accessibility values (3) Weighted multivariate regression to see effects of stations characteristics on ridership	Addition of the 'accessibility' dimension, to consider the large catchment areas of intercity rail
Liao and Scheuer (2022)	Beijing (China)	277 metro stations	700 m radius buffer	Transit (5) Oriented (6) Development (5)	(1) Calculation of the three indices (2) Cluster analysis with K-means method	Inclusion of the morphology and demand concepts into node-place indicators

Table 5.1. Literature review on TOD typologies (suite)

J. Ma et al. (2022)	Tianfu (China)	38 metro stations	500 m radius buffer	Node (4) Place (4) System support (3)	(1) Calculation of indicator values and weights (2) Scatter plot of stations for node-place- system values	Addition of the 'system support' dimension
Qiang et al. (2022)	Shanghai (China)	347 metro stations	500 m radius buffer	Transit (5) Oriented (5) Development (5)	(1) Calculation of the three indices (2) Cluster analysis with hierarchical clustering method (3) Correlation with ridership	Adaptation of the Transit Oriented Development TOD typology method to Shanghai

Table 5.1. Literature review on TOD typologies (suite)

Rabiei et al. (2022)	Montréal (Canada)	28 metro stations	400 m to 800 m radius buffer	Node (13) Place (5) Tie (4)	(1) Calculation of indicator values and weights (2) Cluster analysis with K-means method (3) Scatter plot of stations for node-place- tie values (4) Development of a typology by TOD index (5) Determination of the optimum amount of transit ridership and trip attraction to maximize public transport accessibility	Development of a multistage assessment method for TOD
Shin, Kim, and Kim (2022)	Seoul (Korea)	46,864 bus stops 354 subway stations	400 m walkable buffer for subway and 200 m for buses	Activity start time Activity duration Type of Land-Use	(1) Clustering of passengers' activity trip-chain with hidden Markov model (2) Cluster analysis of stations type with K- means method	A TOD typology based on activity trip-chain of the passengers (with smart-card activity)

Table 5.1. Literature review on TOD typologies (suite)

Su, Wang, et al. (2022)	Shanghai (China)	508 metro stations	800 m walkable buffer	Node (11) Place (8) Functionality (28) Sociodemographic (6)	(1) Processing of metro smart-card data (2) Variable selection based on node-place-functionality model (3) Random forest regression to predict metro-ridership indicator (4) Cluster analysis with affinity propagation clustering algorithm	Development of a machine learning clustering method with high computational feasibility
Su, Zhao, et al. (2022)	Hangzhou (China)	70 metro stations	800 m walkable buffer	Node (8) Place (23) Sociodemographic (4) Feedback (1)	(1) Processing of metro smart-card data (2) Variable selection based on node-place model (3) Geographically temporally weighted regression to analyse effect on metro-ridership (4) Cluster analysis with K-means	Development of a modeling approach to understand the relative contribution of TOD structural factors to metro ridership

Table 5.1. Literature review on TOD typologies (suite)

Wei and Wang (2022)	Yangtze River Delta (China)	123 high speed rail stations	1,500 m radius buffer	Node (11) Place (8)	(1) Calculation of indicator values and weights (2) Cluster analysis of stations type with K-means method (3) Scatter plot of stations for node-place-system values	Adaptation of the node-place model to Yangtze River Delta area in China
Wu and Divigalpitiya (2022)	Hefei (China)	77 subway stations	500 m walkable buffer	Node (8) Place (6)	(1) Application of node and place model (2) Identification of TOD development priority with silhouette method	Development of an operational method to determine priority of TOD with silhouette method
Y. Yang et al. (2022)	Guangzhou and Shenzhen (China)	224 and 237 metro stations	700 m radius buffer	Node (5) Place (8) Design (5) Vibrancy (3)	(1) Calculation of the three indices (2) Scatter plot of stations for node-place-design-vibrancy values (3) Cluster analysis with Ward's method (4) Calculation of overall TOD performance with cube method for comparative analysis between cities	Addition of a 'compactness' and a 'vibrancy' dimension Inter-city comparative analysis

Table 5.1. Literature review on TOD typologies (suite)

L. Zhang et al. (2022)	Shanghai's new towns (China)	23 metro stations	600 m walkable buffer	Node (5) Place (5) Design (5)	(1) Calculation of the indicator values (2) Classification of stations with Latent Dirichlet Allocation and hierarchical cluster analysis (3) Evaluation of the TOD performance based on node-place-design indices	Use of a latent Dirichlet Allocation method to identify dominant topic for each cluster
(Uddin & Roy, 2023)	Dhaka (Bangladesh)	17 metro stations	800 m radius buffer	9 indicators based on 4D's	(1) Calculation of indicators values (2) Cluster analysis with Latent Class, K-means, and hierarchical methods	Presentation of results of TOD typology from the use of multiple clustering techniques.
(Zheng & Austwick, 2023)	Greater Manchester (England)	177 rail stations	700 m radius buffer	Node (7) Place (4) Design (3)	(1) Calculation of indicators values (2) Cluster analysis with K-means ++	Addition of system centrality indicators and green space indicators
(Moyano, Solís, Díaz-Burgos, Rodrigo, & Coronado, 2023)	Madrid (Spain)	56 rail stations	800 m radius buffer	Urban planning (2) Public space (4) Land-use and intensity (5)	(1) Calculation of the variables (2) Cluster analysis with K-means	Development of a two-fold clustering analysis

5.3 Methodology

The aim of this study is to analyze the transfer of a TOD typology from one region to another. To achieve this, this paper builds on a bicycle-oriented TOD typology methodology formerly developed and applied to PT stations in Montreal (Canada) (Robillard et al., 2023). The specific details of data and methods underlying the development of the TOD typology can be found in this paper (Robillard et al., 2023). For the purpose of the current study, this section primarily focuses on presenting the methodological approach developed to adapt this methodology to PT stations in Rotterdam (Netherlands). First, this section presents the two case cities (Montreal and Rotterdam) and their mobility contexts. Second, it explains the procedure used to transfer the methodology developed for Montreal to Rotterdam, by addressing the selection and calculation of the different TOD indicators and the clustering method.

5.3.1 Case cities

The typology, previously applied to Montreal, is adapted to the Rotterdam area, to assess its transferability. The application of a bicycle-oriented TOD typology to Montreal and Rotterdam is in line with the policy objectives of both regions. They aim to integrate transportation and land-use through TOD planning policies, and to increase bicycle, walking and PT mode shares (Thomas & Bertolini, 2017). Further, both cities have a strong focus on planning bicycle-friendly initiatives (Gemeente Rotterdam, 2023; Ville de Montréal, 2022). While Montreal and Rotterdam share similar planning objectives, they present different mobility contexts and cultures. Table 5. summarizes the planning objectives and specificities of the two regions together with the methodological choices (PT stations, catchment area and TOD indicators).

5.3.1.1 Montreal (Canada)

Montreal is the second largest city in Canada, with roughly 1.8 million residents, and the Greater Montreal region (Montreal CMA) is home to over four million people. Montreal's population grew rapidly after its incorporation as a city in 1832, leading to the creation of suburbs and the expansion of its downtown area. This development eventually encouraged dependence on the car. The city then enjoyed a prosperous period, marked by the development of its metro network, the presentation of the International World Exposition in 1967 and the hosting of the 1976 Olympic Games. Downtown Montreal, an important economic and cultural center, is fed by a metro network,

a suburban system, and a bus service. In the Montreal CMA, the modal share over a 24 hour period (in the fall) is 64.0% for cars, 18.9% for PT, 10.6% for walking and 1.9% for cycling (Enquête Origine-Destination, 2018). The transportation networks under study for Montreal CMA is described in Table 5., there is the metro and the suburban train within the regional areas of the cities and extending to neighboring towns.

5.3.1.2 Rotterdam (Netherlands)

Rotterdam is also the second largest city in its country, the Netherlands, with approximately 600,000 inhabitants. It is part of the Randstad region, which includes other major centers of the Netherlands easily accessible by the national train and highway network: Amsterdam (~80km away), The Hague (~25km) and Utrecht (~55km). From a fishing village in the 13th century to a major international distribution center, Rotterdam now is home to the largest port in Europe. A large part of the city was destroyed during the Second World War and has been completely rebuilt with modern, avant-garde architecture and with a particular focus on land-use and transportation planning. Rotterdam is no exception to the bicycle culture in the Netherlands, with a modal share of 31% for bicycle (Knowledge Institute for Mobility Policy (KiM), 2017). It offers favorable conditions for cycling such as flat topography and little snow accumulation compared to Montreal, where winters are more arduous. Moreover, the modal share for cars is 29% and 16% for PT (Knowledge Institute for Mobility Policy (KiM), 2017). For Rotterdam, as stated in Table 5., only the local metro network of Rotterdam extending to The Hague is included in the analysis, since the train network extends across the entire country.

5.3.2 Method for transferring the typology (from Montreal to Rotterdam)

5.3.2.1 Selection and calculation of TOD indicators

In TOD typology, various indicators are calculated to measure the performance of PT stations, as shown in Table 5.1. These stations are then grouped together with a clustering method, based on the value of these indicators. In this study, the final selection of the indicators for both regions (presented in Table 5.) is adapted to the mobility context, and data format and availability.

Indicators were calculated within a 1,200 m circular buffer around the stations for Montreal and 800 m for Rotterdam. This decision considers the distance between stations (closer stations in Rotterdam), to reduce the overlap between the catchment areas.

As presented in Table 5., the TOD indicators for this typology are split into four criteria: land-use, public transport, walkability and bikeability. Details regarding the selection and definition of indicators can be found in a previous paper (Robillard et al., 2023).

For the land use criteria, population and job density are aggregated at the dissemination area scale for Montreal, and population and address density at the PC4 (first four digits of postal code) for Rotterdam. For Rotterdam, job, and points of interests (POI) density were not available, so address density acts as a proxy to assess the degree of urbanization (Statistics Netherlands, 2023).

For the PT criteria, only bus frequency at PT stations was calculated for Montreal. GTFS data for train do not follow a schedule but are rather based on frequencies. We decided to focus on scheduled PT in this case. For Rotterdam, all GTFS data were available in scheduled format. This approach made it possible to easily calculate the frequency of all PT at stations, which corresponds to the frequency of metro, buses, tramway, and trains connecting to the metro stations.

For the bikeability criteria, indicators related to traffic disruption, cycleways and water and green spaces were calculated in the same way for both cities, using data in the standardized format of OpenStreetMap (OSM). Slope assessment has been omitted for Rotterdam, as the Netherlands has an essentially flat topography, in contrast to Montreal. As cycling is more embedded in the habits and city culture in the Netherlands, parking facilities cannot be evaluated in the same way as in Montreal. In the Netherlands, bicycles tend to be parked almost anywhere, even if there are no official parking facilities. Therefore, it is most relevant to assess the presence of a secured bike parking at the station instead of counting the number of bicycle racks. For Montreal, secured bicycle parking is rare. As for bikesharing, only the most popular bikeshare systems with docking stations was considered for each region. For Montreal, people rely largely on the bikeshare system *Bixi* for their everyday commute, and stations are distributed across the region. For Rotterdam, *OV-fiets* is a well known bikeshare service across the Netherlands, that is operated by the national train system. There are other private bike-sharing systems in Rotterdam, with or without stations, but the reliability and availability of their data is not always known.

Table 5.2. Study areas and TOD indicators

	Montreal Census Metropolitan Area (CMA)	South Holland province – Rotterdam region
Study areas and objectives		
PT networks and stations	Metro network (68 stations) – operated by STM Suburban train (52 stations) – operated by EXO From those 120 stations, six of them are intermodal (metro and suburban train)	Metro network (70 stations) – operated by RET From those 70 stations, five of them are intermodal stations (metro and national train)
Research objective	Develop a bicycle-oriented TOD typology	
Planning objectives	Orient 60% of new households in TOD neighborhood, by 2031 (Communauté métropolitaine de Montréal, 2012) Cycling program focused on territorial equity (Ville de Montréal, 2022)	Accommodate for the growing number of cyclists and PT users Connect first and last mile trips to PT (Balz & Schrijnen, 2016)
Specificity of regions	Vast territory – monocentric organization Varied topography throughout the territory Strong political will to improve cycling at Montreal city level High modal share for automobile Winter with heavy snowfalls (five months / year) Vertical and horizontal residential density Aging population	Polycentric territorial organization Mostly flat topography Country is world leader in bicycle culture High modal share for public transport and bicycle Frequent rainfall all year round Mostly horizontal residential density Aging population

Table 5.2. Study areas and TOD indicators (suite)

TOD indicators		
Catchment area	1,200 m radius buffer	800 m radius buffer
Criteria and indicators	Land-use	Land-use
	Population density	Population density
	Job density	Address density
	Points of interest	
	Intersection density	Intersection density
	Motorway length	Motorway length
	Public transport	Public transport
	Bus frequency	Public transport frequency
	Capacity of incentive parking lot	Capacity of incentive parking lot
	Walkability	Walkability
	Pedshed ratio	Pedshed ratio
	Bikeability	Bikeability
	Traffic disruption	Traffic disruption
	Cycleways	Cycleways
	Slope	
	Water and green spaces	Water and green spaces
	Bicycle racks	Presence of secured bicycle racks
	Bikeshare stations	Self-serve bicycle (dock station)

5.3.2.2 Clustering analysis

The most widely used clustering method in TOD typology are described in Table 5., based on their strengths and weaknesses. This review of the most used clustering methods in the case of TOD typologies act as a justification for the choice of K-medoids. Partitional clustering methods are widely used in TOD typology, for there ease of implementation (Amini Pishro et al., 2022; Dou et al., 2021; Liao & Scheuer, 2022; Rabiei et al., 2022; Shin et al., 2022; Vale, 2015; Wei & Wang, 2022; Y. Zhang et al., 2019), but they are sensitive to initial values and parameters (Aggarwal & Reddy, 2014). Hierarchical methods are also popular in TOD typologies because they do not require the number of clusters to be predefined (Li et al., 2019; Liu et al., 2020; Lyu et al., 2016;

Rodriguez & Kang, 2020; Vale, 2015; Y. Yang et al., 2022; Zemp et al., 2011), however they are more computationally demanding (Aggarwal & Reddy, 2014; Norušis, 2012; Xu & Wunsch, 2005). Last, probabilistic methods such as two-steps clustering approach (Jeffrey et al., 2019; Kamruzzaman et al., 2014; Kumar et al., 2020; Reusser et al., 2008; Su et al., 2021; Woo, 2021) latent class method (Higgins & Kanaroglou, 2016; Huang et al., 2018; L. Zhang et al., 2022) are mostly used for larger datasets and categorical variables respectively.

Table 5.3. Strengths and weaknesses of TOD typology clustering methods

Approach	Clustering method	Strengths	Weaknesses
Partitional clustering	K-means	Ease of implementation and interpretation Most widely use clustering method	Sensitive to initial values Sensitive to outliers Pre-determination of number of clusters Only suited for numerical data
	K-medoids	Ease of implementation and interpretation More resilient to outliers Handle both numerical and categorical variables	Sensitive to initial values Pre-determination of number of clusters
Hierarchical clustering	Ward's algorithm	Deterministic method	Computationally demanding Sensitive to outliers Tend to find same size clusters
	Self-Organizing map	Suited for high dimensional dataset Handle non-linear relationships in the data	Computationally demanding Sensitive to the choice of initial parameters Risk of overfitting

Table 5.3. Strengths and weaknesses of TOD typology clustering methods (suite)

Probabilistic models	Two step clustering	Designed for large dataset Suited for both numerical and categorical variables Quickly available in most statistical software (e.g., SPSS) Combines feature of partitional and hierarchical clustering	Sensitive to initial values Same limitations as partitional and hierarchical clustering
	Latent class	Accommodates for unstandardized/unscaled data and multiple types of variables Better performance when dealing only with categorical data	Difficulties when there is not the same amount as categorical vs numerical variables Assume local independence of variables

To classify PT stations, the K-medoids clustering method was used. This method uses an actual observation (in this case a specific PT station) as the center (medoid) of a cluster. This method is known to be more resilient to outliers than the classical K-means method (Hennig, Meila, Murtagh, & Rocci, 2015).

As explained in the TOD typology developed by Robillard et al. (2023), a step-wise approach was used, consisting of testing the stability of the clustering results, as well as validating the ideal number of clusters and the indicators to include, with the Hopkin statistic and the average silhouette method.

5.4 Results and discussion

5.4.1 Clustering results for Montreal and Rotterdam

Results and observations from the clustering analysis for Montreal and Rotterdam are contextualized based on the cities' characteristics and the values of the indicators. The relevance of classifying PT stations according to the bikeability of TOD was previously demonstrated by Robillard et al. (2023) with Montreal as a case study. Therefore, this section focuses on identifying

similarities and differences in clustering results between Montreal and Rotterdam, following the transfer of the methodology.

Classification of stations resulted in seven clusters for Montreal and five clusters for Rotterdam, suggesting a higher variability in station types for Montreal, regarding the cycling environment.

Clustering results show a strong spatial component respectively for the two regions (see Figure 5.1 and Figure 5.2). Similar patterns for both regions can be detected, even if the scale of the transportation system is double the size for Montreal compared to Rotterdam.

In the city center of Montreal, there are four distinct types of stations (Cluster 1 to 4), all exhibiting different type of cycling environments. Additionally, a specific cluster of stations is concentrated in the downtown area. Conversely, in Rotterdam's city center, only two types of stations (Cluster 1 and 2) are observed: one “central station” and “urban TOD” stations. This suggests a higher level of homogeneity in station types within Rotterdam's center compared to Montreal's.

Different patterns are observed as you get further away from both city centers. For the Montreal CMA, there is an alternation between five out of seven types of stations outside the city center, meaning that two types of stations are only located in Montreal center. Results shows a monocentric organization, where smaller municipalities are feeding the city center. Even larger municipalities, such as Laval or Longueuil, do not present stations showing characteristics of downtown area. In contrast, results for Rotterdam show the polycentric organization in the Netherlands. Indeed, all five different types of stations are present outside Rotterdam center. When looking at the metro line going North in Figure 5.2, the closer you get from The Hague center, another important city in the Netherlands, the pattern of stations seems to repeat the one in Rotterdam center (i.e., one central station surrounded by “urban TOD” stations). It is possible to observe that the smaller geographic scale of the Netherlands allows an organization around multiple centers, with commuters often travelling between cities. This is also a manifestation of the nuance between “downtown” area in the North American context and the “city-center” in the European context. In the Netherlands, “city-center” is often associated with the historical center while in Canada both “downtown” and “city-center” are used to describe the economical center.

In both cases, isolated stations form a cluster of stations that are at proximity of waterways or highways.

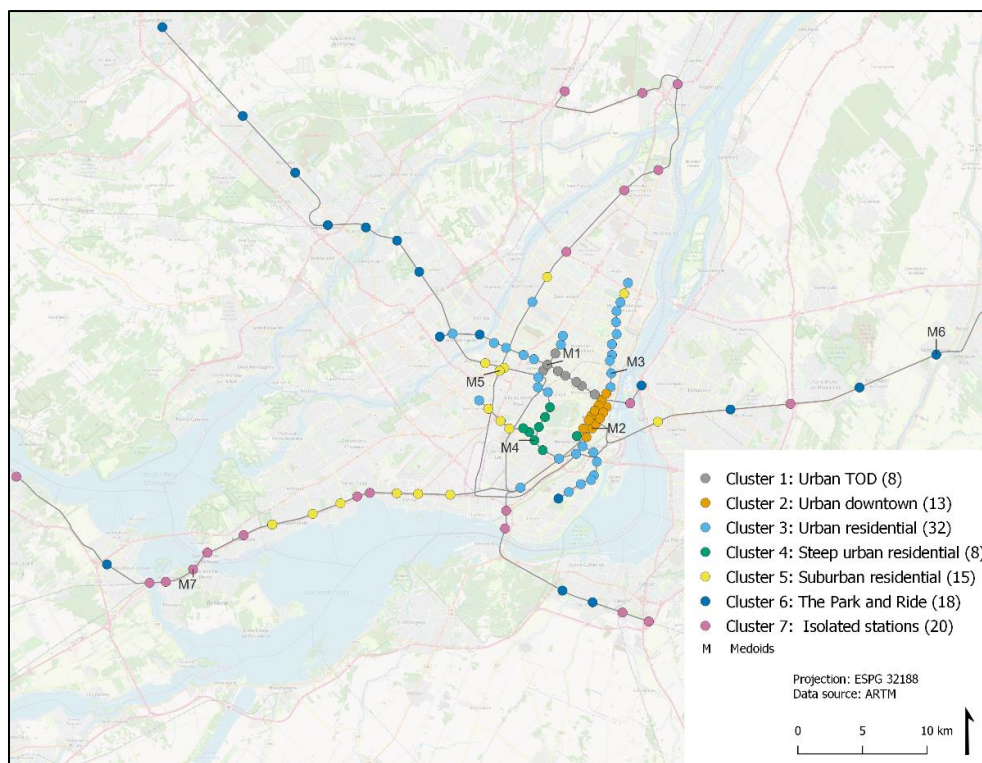


Figure 5.1. Map of clusters for Montreal CMA

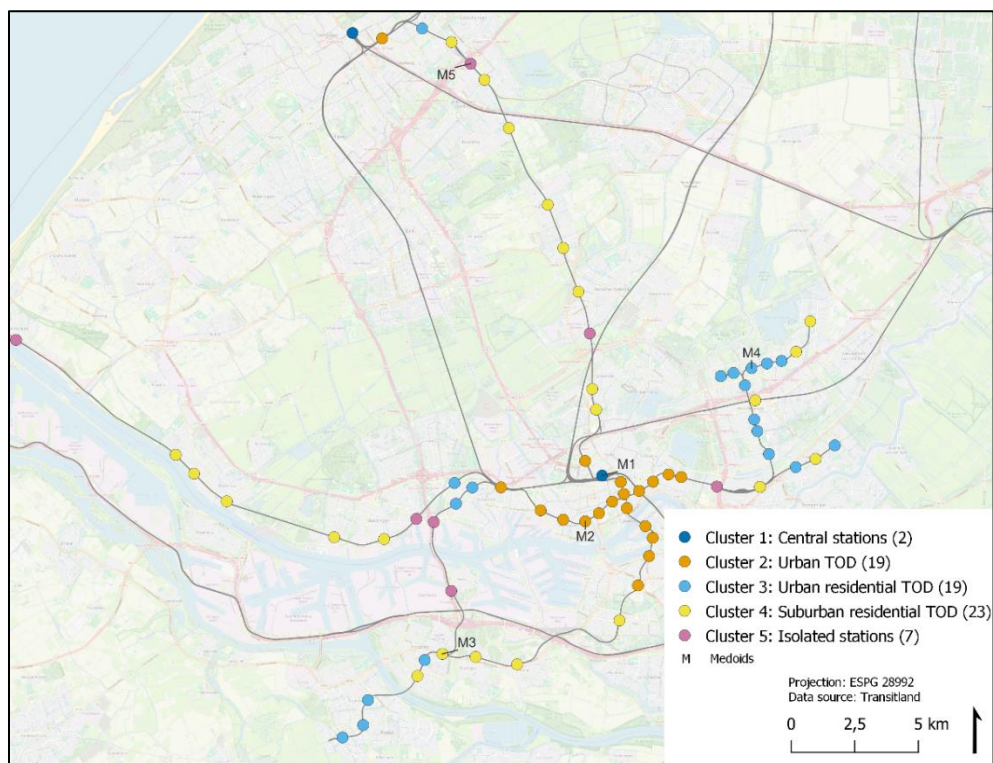


Figure 5.2. Map of clusters for South-Holland province (Rotterdam)

Figure 5.3 presents the Z score for each indicator across the seven clusters for Montreal and the five clusters for Rotterdam. Clusters with similar characteristics are found in both cities, demonstrating the existence of commonalities in the application of the TOD concept. Additionally, clusters with unique characteristics suggest that the implementation of TOD concept differ based on contextual factors, which in this case is shown by the differences in cycling environments around PT stations.

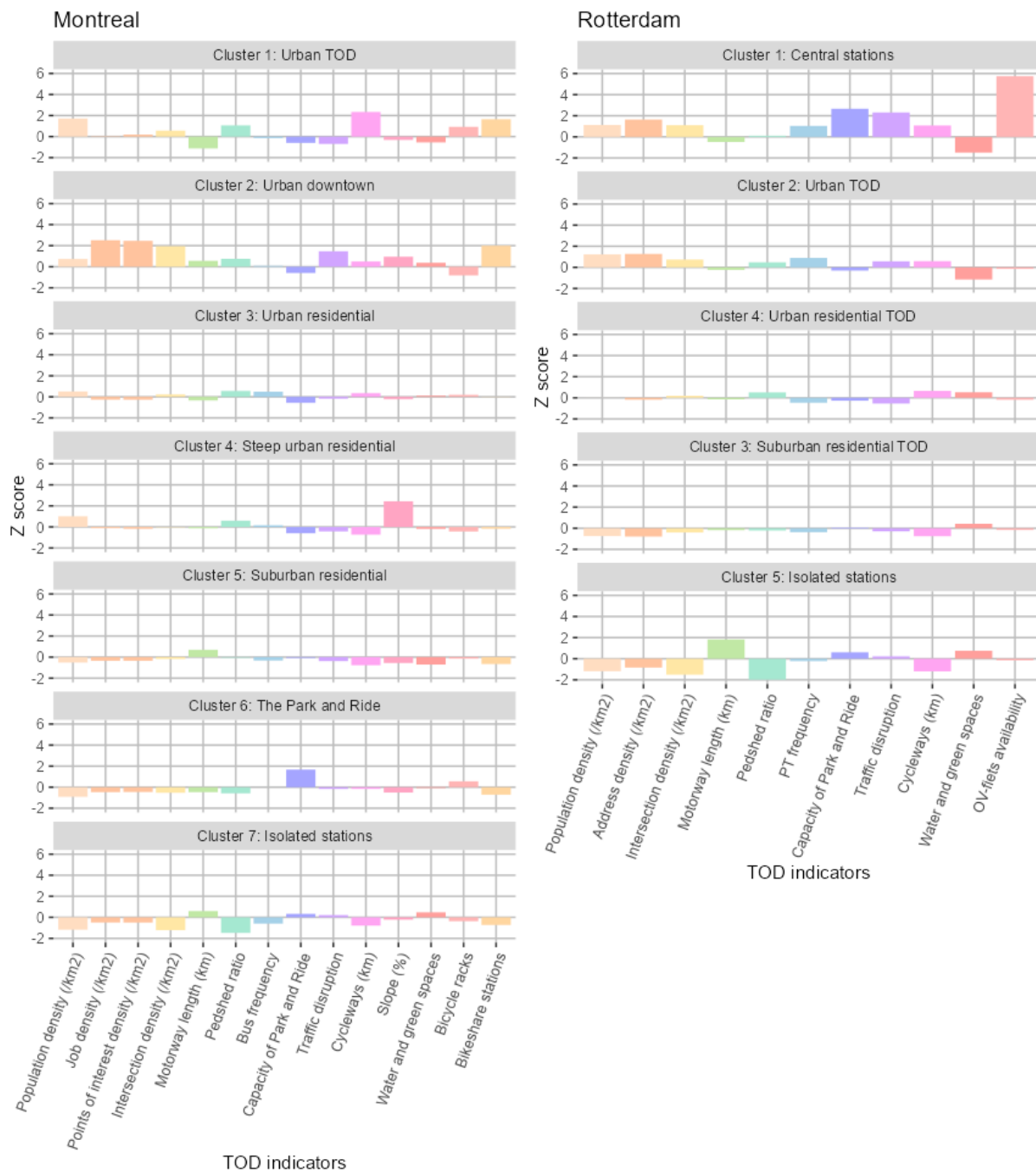


Figure 5.3. Dispersion of the indicators across the seven clusters for Montreal and the five clusters for Rotterdam.

5.4.1.1 City centers

Both city centers present more than one type of station. The two clusters of stations within Rotterdam center present a lot of similar characteristics, such as high density for population, addresses and intersections; as well as similar motorway length, pedshed ratio, PT frequency, and water and green spaces. They mostly differ on capacity of park and ride, traffic disruption, cycleways score and *OV-fiets* (Dutch bikeshare option) availability. In contrast, the four clusters in Montreal center are very different from one another. Cluster 1 stands out for its high population density and its better performance regarding cycling environment; Cluster 2 for its high job and POI density and high traffic disruption; and Cluster 3 and 4 are similar to each other regarding density and performance of cycling environment, but Cluster 4 distinguishes itself for its steep slopes. This shows the importance of including a slope indicator for Montreal, when analysing the cycling environment. To sum up, results imply that Montreal center has more different types of station compared to Rotterdam, including some that perform worst in terms of cycling.

5.4.1.2 Central stations

Central stations are classified in different clusters for each city. In Rotterdam, the two central stations (Rotterdam Central and The Hague Central) form one cluster of stations. They stand out for their high capacity of parking spaces and self-serve bicycle availability. These two stations also present the highest traffic disruption for the Rotterdam region, while still having the highest score for cycleways. This indicates the importance of central stations in the connection with other rail networks in the European context, and even with the bicycle network in the context of the Netherlands. Montreal also has a central station, but instead of forming a cluster in itself, it is part of the “urban downtown” cluster, where traffic disruption is at the highest level for Montreal. Indeed, this central station is central for the suburban train where multiple lines are built around this station, whereas it does not appear to be the case for the metro network.

5.4.1.3 Peripheral areas

A large variability in types of stations is seen outside the central areas of both cities. Fulfilling a similar role in each city, we have for Montreal, the “Urban residential” and “Suburban residential” clusters; and for Rotterdam, the “Urban residential TOD” and “Suburban residential TOD” clusters. The term TOD was added to these cluster’s name for Rotterdam, because they present a better

balance between overall TOD characteristics; such as higher population, addresses and intersection density, as well as high pedshed ratio and high score for cycleways (see Figure 5.3).

Outside Montreal's center, one type of station that emerges from the bicycle-oriented TOD typology is the "Park and Ride" cluster of stations. In Montreal CMA, people living in suburbs are encouraged to use public transport by accessing it by cars, to cover the longer travel distances. This configuration makes it harder to use bicycle as a feeder mode to transit, because parking is easily available and travel distances to stations are longer. This demonstrates the importance of measuring the access to the stations by various modes of transportation, either through TOD indicators or through the catchment area.

Clusters of "Isolated stations" for both regions present some similar characteristics: lowest densities for population and addresses/jobs/POI; lowest pedshed ratio; greater presence of motorway; low traffic disruption and bikeshare availability; high presence of water and green spaces; and lowest score for cycleways. This suggests that in different contexts, some stations are not built to become TOD, but are still part of the PT network and can serve as other purposes.

5.4.2 Methodological framework for the development of TOD typologies

The clustering results for Montreal and Rotterdam confirmed that the proposed TOD typology can be applied to the two regions despite their distinct mobility and geographical contexts. In this section, we present how these findings can be extended to any region aiming to build a more organized and structured planning approach for the implementation of TOD. Therefore, we propose a methodological framework to design any TOD typology tool. The methodological framework is generalized in Figure 5.4 and includes five steps: (1) define study area and objectives, (2) select TOD indicators, (3) choose classification methods to identify clusters, (4) present and validate results and (5) discuss planning implications. This framework builds on the literature review and the transfer of the TOD typology from Montreal to Rotterdam. Nonetheless, the framework is meant to be applicable to any region in the industrialized Global North, specifically in areas with high-quality open data.

5.4.2.1 Step 1: Define study area and objectives

As illustrated in Figure 5.4, the first step consists in defining the geographical limits of the region and the transportation network to be analysed, the research and/or planning objectives underlying the development of a TOD typology, and the specificities of this region.

Commencing with the boundaries (i.e., the extent of the territory and the public transport system to be analyzed), the literature has shown that TOD typologies have been implemented at different scales, for example, for a whole country (Cummings & Mahmassani, 2022; Niu et al., 2021; Reusser et al., 2008; Seo & Lee, 2021), a metropolitan area (Chorus & Bertolini, 2011; Vale, 2015), a city (Kamruzzaman et al., 2014), multiple cities (Bertolini, 1999; Su et al., 2021; Y. Yang et al., 2022) or simply a single neighborhood/district (Chen & Lin, 2015). As for the transport system, TOD typologies available in the literature may classify railway stations (Huang et al., 2018; Jeffrey et al., 2019), subway/metro stations (Chorus & Bertolini, 2011; Lyu et al., 2016), or a combination of different PT systems, such as buses and subway stations (Shin et al., 2022), rail and ferryboat stations (Vale, 2015) or rail and metro stations (Groenendijk et al., 2018). Further, only specific stations of the network can be selected for evaluation. For instance, stations with regional roles (Chorus & Bertolini, 2011) or stations from only one metro line (Rabiei et al., 2022) can be evaluated if only certain stations are built under the TOD concept. There is also the possibility to classify projected stations (Cucuzzella et al., 2022; Higgins & Kanaroglou, 2016), to support TOD implementation as soon as new transport lines are conceptualized.

As demonstrated in the case of Montreal and Rotterdam, the boundaries are intrinsically tied with the planning or research objectives underlying the development of the TOD typology, as well as the specificities of the region (e.g., geographical, political, cultural, and demographical characteristics). For Montreal and Rotterdam, these specificities are listed in Table 5.. From a planning perspective, both regions share similar planning objectives that aim to jointly support PT and TOD through the development of the bicycle network. As a result, it is of interest for the two regions to perform a TOD typology oriented on bikeability. For Montreal, the TOD policies as well as the broad transport and land use guidelines are developed at the metropolitan scale for all Greater Montreal municipalities (Communauté métropolitaine de Montréal, 2012), whereas the bicycle networks are under the responsibility of each municipality. Given that, both the territorial boundaries (metropolitan region) and the PT system to be analyzed (metro and train stations) were

based on the CMM planning objectives, which identified all stations to be planned as TOD (Communauté métropolitaine de Montréal, 2011). For Rotterdam, while the TOD guidelines are developed at the national level, the definition of the boundaries was based on the transport network of the Dutch province of South Holland (Balz & Schrijnen, 2016). It also makes sense for the transfer of the typology from Montreal CMA to Rotterdam region, to ensure consistency. The cases of Montreal and Rotterdam illustrate how the research or planning objectives underlying the development of the typology as well as the identification of the specificities of the region under study enable the definition of the study area, regardless of the distinction between the regions.

Other examples of research or planning objectives related to TOD typologies in the literature are: informing future planning and development of high-speed rail stations due to rapid urbanization (Wei & Wang, 2022); measuring the performance of the built environment based on Green TOD concept (Niu et al., 2021); identifying rail stations with the potential to become TOD, using walkability measures (Jeffrey et al., 2019); comprehensively understanding which TOD components influence and structure the redevelopment of stations (Chorus & Bertolini, 2011). The proposed methodological framework helps bring to life TOD planning objectives by basing methodological choices on these planning and/or research objectives.

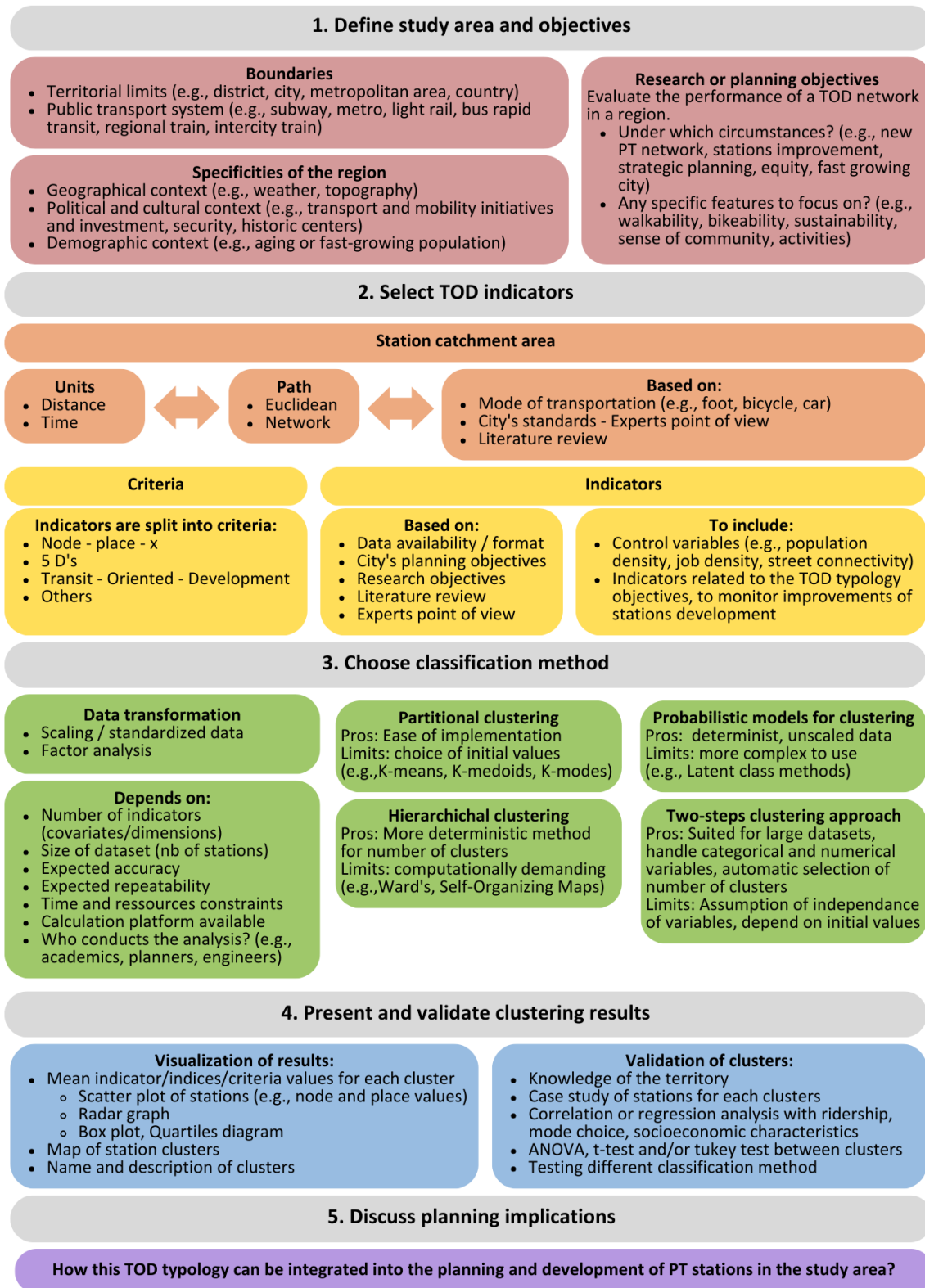


Figure 5.4. Methodological framework for TOD typology development

5.4.2.2 Step 2: Select and calculate TOD indicators

Once the study area is characterized, the second step (see Figure 5.4) aims to select indicators enabling the evaluation of the TOD's performance as a function of the area's objectives. The selection of indicators is a critical step in the development of a TOD typology, because PT stations are grouped together based on the level of similarity of these indicators. TOD indicators should at least reveal transport and land use information. They are usually calculated inside a catchment area around PT stations.

In the literature, studies usually separate indicators into criteria, either for methodological purposes (e.g., factor analysis, indices calculation) or to facilitate the interpretation of the results. Table 5.1 lists possible criteria taken from the literature. Most cases either includes the node and place criteria (Bertolini, 1999; Chorus & Bertolini, 2011; Kamruzzaman et al., 2014; Reusser et al., 2008) with the various extensions (Groenendijk et al., 2018; Vale, 2015; Vale et al., 2018; Y. Zhang et al., 2019), the 5D criteria (Huang et al., 2018; Jeffrey et al., 2019), or others (Liu et al., 2020; Rodriguez & Kang, 2020; Seo & Lee, 2021). Given that the definition of TOD is malleable and context-dependant, variables to measure PT stations performance vary between studies.

Authors of TOD typologies stated that the selection of TOD indicators is usually based on the literature, experts' interviews (Reusser et al., 2008; Zemp et al., 2011), contextual factors (Ivan et al., 2012; Lyu et al., 2016; Vale, 2015), and mostly on data availability and format (Chorus & Bertolini, 2011; Monajem & Nosratian, 2015). To calculate these indicators, choices related to the catchment area are usually justified based on the transportation mode (e.g., larger catchment area for rail stations (Cummings & Mahmassani, 2022)) and smaller for metro/bus stations (Vale et al., 2018)) or city's objectives and/or standards (Huang et al., 2018; Kamruzzaman et al., 2014; Singh et al., 2017; Su et al., 2021). The full range of possibilities is listed in Table 5.1, under the "catchment area" column.

For this study, the TOD indicators and catchment areas are different for Montreal and Rotterdam. Some adaptations have been made depending on data availability and contextual factors. For instance, indicators related to land-use and PT frequency were calculated differently for both cases, because of data availability. Also, the slope indicator calculated for Montreal was identified as not relevant in the case of Rotterdam, since the topography is flat. The clustering results for Montreal validated the pertinence of adding a slope indicator, by revealing a cluster specifically grouping

PT stations based on their steep elevation. Another example of adaptation is the indicator related to bicycle parking. As stated in the methodology, it is not relevant to count the amount of bicycle racks in Rotterdam, as it is done for Montreal, since bicycles are often parked almost anywhere, and there is an abundance of both private and public bicycle parking areas. To continue, a different buffer size was selected for the two contexts, because distances between stations are smaller in Rotterdam compared to Montreal. Calculating the indicators with the same buffer size for both regions was tested but did not lead to relevant results. These specific adaptations require knowledge of the territory under study, and therefore highlight the necessity to characterize the study area beforehand, as explained in first step.

5.4.2.3 Step 3: Choose classification method

Following the selection of the TOD indicators, the fourth step consists in the classification of PT stations through a clustering method (see Figure 5.4). In the recent literature on TOD typologies, authors generally classify PT stations using operational clustering methods, as detailed in the methodology section (see Table 5.). Partitional clustering methods, such as K-means are used for their ease of implementation (Amini Pishro et al., 2022; Dou et al., 2021; Liao & Scheuer, 2022; Rabiei et al., 2022; Shin et al., 2022; Vale, 2015; Wei & Wang, 2022; Y. Zhang et al., 2019). Hierarchical clustering methods in TOD typologies are also widely used, such as Ward's criterion (Lyu et al., 2016; Rodriguez & Kang, 2020; Vale, 2015; Y. Yang et al., 2022; Zemp et al., 2011) and self-organizing maps (Li et al., 2019; Liu et al., 2020). Many authors of TOD typology have also chosen probabilistic methods for clustering (Jeffrey et al., 2019; Kamruzzaman et al., 2014; Kumar et al., 2020; Reusser et al., 2008; Su et al., 2021; Woo, 2021), because it is a robust and quick method available on multiple statistics platforms. According to them, it also performs better when dealing with multiple types of variables (i.e., normal, ordinal, and continuous variables). Alternatively, some studies conducted factor analysis before clustering the stations (Niu et al., 2021; Rodriguez & Kang, 2020), because some clustering methods performs better when data are transformed (Aggarwal & Reddy, 2014).

For this TOD typology oriented on bikeability, a K-medoids clustering algorithm was chosen for both contexts (Montreal and Rotterdam). K-medoids is in the same family of methods as K-means, which is the most widely use approach in clustering, for its ease of implementation (Aggarwal & Reddy, 2014). It was chosen over K-means for its better suitability with outliers. As we see from

the clustering results for Rotterdam, central stations act as outliers and form one cluster of two central stations. Additionally, it can deal with both numerical and categorical variables, allowing to better consider the contextual differences between bicycle parking in both regions.

As presented in the method section, the selection of the clustering method depends on several factors, such as the size of the dataset or its number of dimensions as well as the time and resource constraints. The strength and weakness of each clustering methods currently used in TOD typology studies are stated in Table 5. and summarized in the methodological framework in Figure 5.4. The latter illustrates how the clustering step builds on the definition of the study area and TOD indicators to be calculated.

5.4.2.4 Step 4: Present and validate resulting clusters

Next comes the presentation and the validation of the results, which can take different forms as indicated in Figure 5.4. In the literature, almost every TOD typology presents the clustering results on a map of the region. In addition, other strategies include the scattering of node and place values indices (or its extended version) on a 2D or 3D scatterplot (Bertolini, 1999; Lyu et al., 2016). It is also common to see a section or a table describing each cluster individually to explain the distinctions between them and how they perform according to the different indicators selected earlier (Higgins & Kanaroglou, 2016; Reusser et al., 2008).

The validation of the results, namely due to the nature of clustering approaches, is also typically presented together with the results. For instance, Chorus and Bertolini (2011) and Monajem and Nosrati (2015) presented case studies for each type of stations. Other studies compared their extended model with the original node-place model (Dou et al., 2021; Liu et al., 2020; Reusser et al., 2008). Some studies also compared their clusters by looking at the correlation or regression with ridership (Amini Pishro et al., 2022; Cummings & Mahmassani, 2022; Huang et al., 2018; Qiang et al., 2022; Rodriguez & Kang, 2020; Zemp et al., 2011), or travel behaviors (Jeffrey et al., 2019; Kamruzzaman et al., 2014), and even with other sociodemographic characteristics (Kamruzzaman et al., 2014; Kumar et al., 2020) or land use characteristic (Huang et al., 2018). This is also a way to see which factors have the greatest influence on the ridership or on the classification of PT stations.

This paper mainly focuses on presenting a map of stations showing the resulting clusters for Montreal and Rotterdam, to observe the geographical patterns. For Montreal and Rotterdam, the

resulting clusters from the TOD typology have been validated based on the knowledge of the territory, doing fields visits and using Google Maps, inspired by Jeffrey et al. (2019). Next, the selection and calculation of indicators were adjusted based on the clustering results and silhouette method, as explained for Montreal in the previous paper (Robillard et al., 2023). However, to avoid cluster results from being too subjective, ANOVA and Tukey tests were conducted to identify significant differences between clusters index values and validate that there are significant distinctions between the clusters, as done by Robillard et al. (2023), building on previous studies (Higgins & Kanaroglou, 2016; Seo & Lee, 2021). Although the methodological framework is presented as a linear process, all the steps are linked, and an iterative approach is required to validate the stability of the clustering results.

5.4.2.5 Step 5: Discuss planning implications

If the objective underlying the development of a TOD typology is to design targeted policies for specific station type, as it is often the case (Ibraeva et al., 2020), the last step of the methodological framework emphasizes the need to discuss the policy implications of the results. Namely, avenues for reflection on how to include the TOD typology results into the planning process are to be considered.

An example of this kind of strategy in the literature would be one proposed by Singh et al. (2017), where they present a table with pictograms of TOD characteristics that could be improved for each station (local scale). By visually grouping stations with similar needs, a more global vision of station development is developed (regional scale). The bicycle-oriented TOD typology previously developed by Robillard et al. (2023) also proposes a way to integrate the typology results into planning strategies to facilitate its use in practice. In brief, clusters are placed on a bikeability scale and further ranked based on priority of interventions, according to the planning objectives of the city. This enables to build a more strategic and targeted approach to station development, regarding bikeability in this case. This is not yet something that is often done in TOD typologies. It could serve both as a description of the current situation and as a vision for future TOD planning.

5.5 Conclusion

This study conducted a comprehensive literature review on TOD typology and evaluated the transfer of an existing TOD typology methodology developed for Montreal, Canada to another

geographic context: Rotterdam, the Netherlands. This process entails discussing the insights gained on factors to consider when transferring a TOD typology tool from one context to another. The operational methodology starts by (1) setting and describing the study area and its planning objectives (2) selecting and calculating TOD indicators (3) perform the classification of PT stations with a clustering method (4) present and validate the clustering results and (5) discuss the integration of the developed TOD typology tool into the land-use and transport planning of the region. However, the findings suggest that only certain elements of TOD typology tools are transferable from one context to another. Since the definition of the study area is crucial to the development of a TOD typology, the methodological choices are highly context dependent. Although most TOD indicators (e.g., the ones related to density, PT frequency or parking capacity) are transferable from one context to another, important adaptations are required to fit the planning objectives and data availability. The same applies for the size of the catchment area. The use of the clustering method can be consistent when transferring TOD typology tools, but data format needs to be considered. Even though clustering results of PT stations will be different for each region, the presentation of the results can follow the same form. Depending on the validation method, some adaptations based on data availability or contextual factors need to be made. Finally, the process of integrating the TOD typology tool developed into the planning process is unique to the region.

While this paper focused on transferring the typology tool from Montreal to Rotterdam, it is expected that the tool can be applied to any region. For example, quickly expanding cities in the Global South with growing bicycle mode shares might be particularly interested in applying this methodology with the goal of identifying ways to promote cycling and cycling-public transport integration.

There are two main limitations to this study. First, although an exhaustive literature review was conducted, some information may have eluded analysis due to the lack of a systematic approach in reviewing the literature. Future studies could compile the entire body of work on TOD typology through a systematic literature review to refine the proposed conceptual framework. Second, despite the overview of the various clustering methods, only one method was tested for the TOD typology methodology used as a proof of concept. Future work could consider testing and analysing the different clustering techniques, to suggest a more appropriate selection of the method according to the study context. More efforts are also warranted to examine the applicability of the framework to contexts with more notable geographic, cultural, and political differences (for example, in non-

Western contexts). Nonetheless, this study presents a robust framework that can be built upon to develop, adapt and enhance TOD typologies regardless of the context.

CHAPITRE 6 DISCUSSION

De façon générale, ce mémoire contribue à faire progresser la recherche sur les outils de planification des TOD. En effet, il a permis d'adresser certaines lacunes dans la littérature concernant les méthodes de classification de stations de TC (outils de typologie de TOD) en s'intéressant d'une part, à l'intégration d'indicateurs liés à la « cyclabilité » et d'autre part, à la transférabilité des outils TOD d'une région à une autre.

D'abord, le chapitre 4 propose une méthodologie permettant de classer les stations de TC, principalement en fonction des qualités cyclables de l'environnement qui les entoure. Habituellement, les outils de typologies de TOD incluent l'évaluation de l'utilisation du sol, de la performance des transports et de l'environnement piéton. Seulement quelques articles incluent l'évaluation de l'environnement cyclable autour des stations (Chen & Lin, 2015; Han et al., 2021; Huang et al., 2018; Liu et al., 2020; Niu et al., 2021; Singh et al., 2017). Cependant, aucun d'entre eux ne le fait de façon systématique, en incluant un critère de performance évaluant uniquement l'environnement cyclable. L'article 1 se base donc sur les nombreuses typologies de TOD précédemment développées et sur un indice mesurant la « cyclabilité » dans le contexte des TOD (Hartanto et al., 2017), pour inclure un critère sur la « cyclabilité » comportant six indicateurs (trafic automobile, infrastructure cyclable, topographie, espaces verts et bleues, arceaux à vélo et stations de vélopartage).

Cette étude démontre que la méthodologie élaborée permet de raffiner les typologies de TOD existantes, contribuant ainsi à la progression de la littérature sur les typologies de TOD. Les résultats démontrent qu'il est possible de distinguer le type de stations de TC, en fonction de la qualité de l'environnement cyclable qui les entoure, comme il est possible de le faire en fonction de la qualité de l'environnement piéton (Jeffrey et al., 2019; Vale, 2015; Vale et al., 2018). De plus, les résultats obtenus confirment l'importance de certaines composantes de l'environnement cyclable reconnu comme étant des déterminants à la pratique du vélo. Par exemple, un des clusters de stations, se situant autour du Mont-Royal, se démarque par de fortes variations d'élévation autour des stations. Comme l'ont auparavant démontré Castañon and Ribeiro (2021) et Muhs and Clifton (2016), l'élévation impacte négativement l'utilisation du vélo. Dans le même sens, un cluster de stations situées dans le centre-ville de Montréal se démarque par une forte perturbation de trafic automobile. Évidemment, la sécurité des déplacements à vélo, un déterminant important

de la pratique du vélo (Castañon & Ribeiro, 2021; Muhs & Clifton, 2016), est fortement influencée par le niveau d'interaction avec les automobiles (Mekuria, Furth, & Nixon, 2012). Il a été montré que la pratique du vélo est un critère de succès dans l'implémentation des TOD. Il est donc essentiel de mieux intégrer l'évaluation de l'environnement cyclable dans les outils de planification des TOD, comme le fait la méthodologie proposée dans le chapitre 4 de ce mémoire.

Comme démontré dans le chapitre 4, les critères d'évaluation et des indicateurs choisis pour performer une typologie de TOD influencent les résultats obtenus. Il a aussi été démontré que les zones TOD peuvent être classées en fonction des caractéristiques de leur environnement cyclable. Alors, en fonction des critères et des indicateurs choisis, il est donc possible de répondre à des objectifs de recherche et de planification conjointement établies. Dans le cas de Montréal, l'objectif était de développer une typologie de TOD orientée vers la « cyclabilité » pour planifier plus stratégiquement les réseaux de transport et l'aménagement du territoire afin de favoriser l'orientation de la majorité des nouveaux ménages dans ce type de quartier (Communauté métropolitaine de Montréal, 2012) et l'utilisation des modes actifs et collectifs. Ce travail démontre comment le développement permet de répondre au programme cyclable de la ville de Montréal, dont le thème est l'équité territoriale (Ville de Montréal, 2022). La priorité des interventions proposées suggère de concentrer les efforts d'interventions en matière de « cyclabilité » autour des stations dont la qualité de l'environnement cyclable pourrait être améliorée et dont le potentiel cyclable est élevé. Par exemple, on peut penser aux stations de type « urbaines résidentielles » ou « suburbaines résidentielles » présentant une densité résidentielle importante, dont l'environnement, et l'achalandage est propice à l'augmentation de la pratique du vélo. En effet, dans la littérature, plusieurs typologies de TOD sont présentées pour répondre à des objectifs de planifications bien précis. Par exemple, Niu et al. (2021) a développé une typologie de TOD pour Singapour afin de proposer des interventions pour améliorer la performance globale des « TOD verts ». Additionnellement, L. Zhang et al. (2022) se penchent plutôt sur la question de la croissance rapide de la population à Shanghai en Chine et du développement des stations dans les nouvelles villes.

Le chapitre 5 se sert de la méthode développée au chapitre 4 pour comprendre comment adapter une telle méthodologie à un contexte géographique différent. Pour ce faire, le chapitre 5 présente les choix méthodologiques permettant d'adapter l'outil de typologie de TOD appliqué à Montréal, au contexte de Rotterdam. Le processus d'adaptation ci-contre et une revue exhaustive de la

littérature permettent de comprendre ce qui rend ce type de méthodologie transférable d'un contexte à l'autre. Ceci permet d'appuyer les affirmations de certains auteurs de typologies de TOD de vouloir développer des méthodologies « facilement transférables/répliquables » (Higgins & Kanaroglou, 2016; Lyu et al., 2016) ou « applicables dans d'autres contextes » (Monajem & Nosrati, 2015; Reusser et al., 2008; Su et al., 2021). Cependant, les résultats de cet article montrent qu'il n'est peut-être pas pertinent de développer des méthodologies standardisées/normalisées, comme le souhaiteraient certains auteurs (Higgins & Kanaroglou, 2016; Jeffrey et al., 2019). Le simple fait que le format et la disponibilité des données ne sont pas uniformes entre les différents contextes géographiques rend la standardisation des méthodologies impossible. Le chapitre 5 argumente plutôt qu'il faut développer des typologies propres au contexte dans lequel elles s'appliquent, tout comme le développement des politiques pour l'implémentation de TOD (Thomas et al., 2018; van Lierop et al., 2017).

Toutefois, afin de tirer profit des outils existants, le chapitre 5 se penche sur l'évaluation du transfert d'un outil de typologie TOD d'une région à une autre. Si la nuance est subtile, le chapitre 5 de ce mémoire permet de démontrer que les outils de typologie de TOD sont transférables d'un contexte géographique à un autre, tout en mettant de l'avant qu'ils doivent être adaptés en fonction de la région à l'étude, comme l'ont déjà mentionné Liao and Scheuer (2022) et Lyu et al. (2016).

C'est pourquoi une démarche globale de développement de typologie de TOD est proposée, par l'entremise d'un cadre méthodologique comportant cinq étapes. Les étapes permettent de (1) définir le contexte de la région à l'étude, (2) identifier les critères et les indicateurs TOD, (3) déterminer une méthode de *clustering*, (4) présenter les résultats de la classification des stations et (5) discuter de l'intégration de l'outil de typologie développé au processus de planification. Ce guide contribue à faciliter l'utilisation de ce type d'outil en pratique. Il peut aussi répondre à la lacune en matière de recherche sur les typologies de TOD identifiée par Ibraeva et al. (2020), qui proposent d'analyser quelles typologies sont utiles pour la planification des zones TOD. D'après les résultats du chapitre 5 de ce mémoire, toutes les typologies peuvent être utiles, à condition qu'elles soient développées de façon spécifique au contexte dans lequel elles s'inscrivent.

CHAPITRE 7 CONCLUSION

7.1 Rappel des travaux et des contributions de la recherche

En somme, ce mémoire contribue à l'avancement des connaissances en ce qui a trait à la classification des stations de TC dans une perspective de TOD. Par le fait même, ce mémoire contribue au développement d'outils d'aide à la décision pour la planification des aires TOD afin de favoriser l'utilisation des modes de transports actifs et collectifs. Ce type d'outil guide surtout la planification intégrée de l'aménagement et du transport dans les zones TOD. La classification des stations de TC permet de développer des politiques plus stratégiques et plus ciblées en fonction du type de stations.

Il est d'abord question de concevoir une méthodologie de classification de stations de TC intégrant l'évaluation de l'environnement cyclable autour de celles-ci. Plus précisément, cet outil de typologie de TOD permet de distinguer les stations de TC en fonction de la qualité cyclable de l'environnement qui les entoure, tout en considérant les caractéristiques liées à l'utilisation du sol, aux transports et à l'environnement piéton. Appliquée à la région du Grand Montréal, cette méthodologie résulte en une typologie des stations de TC pour l'intégralité du réseau de métro de la STM et du réseau de train de banlieue opéré par EXO. En proposant une priorité des interventions en matière de « cyclabilité », en fonction du type de stations, cet outil pourrait donc contribuer au suivi des objectifs établis par la CMM et de la ville de Montréal. Bref, cet outil de typologie de TOD permet de s'intéresser à la pratique du vélo dans l'évaluation du concept TOD, un élément qui est encore négligé dans la littérature sur le sujet.

Il s'ensuit de l'élaboration d'un cadre méthodologique guidant la conception d'outils de typologie de TOD pour une région géographique donnée. Une revue de littérature exhaustive sur les typologies de TOD est effectuée. De plus, l'outil de typologie TOD orienté sur la « cyclabilité » qui a été développé pour Montréal est transféré à la ville de Rotterdam aux Pays-Bas. Cette démarche de transfert est analysée et supporte l'élaboration du cadre méthodologique proposé, tout en servant de preuve de concept. Les constatations de cette recherche permettent de démontrer quels éléments doivent être considérés pour transférer un outil de typologie de TOD d'un contexte géographique à un autre. En d'autres mots, le cadre méthodologique guide tout professionnel cherchant à développer une typologie de TOD, en spécifiant les choix méthodologiques qui doivent être adaptés en fonction du contexte géographique. Il propose cinq étapes pour concevoir de façon

systématique un outil de typologie de TOD adapté aux objectifs de planification d'une région et/ou à des objectifs de recherches spécifiques. Il aborde entre autres le choix des indicateurs, de la zone de tampon, de la méthode de clustering et de la présentation des résultats de la classification des stations de TC. Au début du travail de recherche, des lacunes en lien avec le transfert et la standardisation des outils de typologie de TOD entre contextes géographiques ont été identifiées dans la littérature. Ce cadre méthodologique permet donc d'amorcer le travail dans cette direction.

De façon générale, les travaux de recherche constituant ce mémoire mettent en valeur les données disponibles publiquement relatives à la mobilité et à l'aménagement. Ces données sont intégrées dans un outil d'aide à la planification pour un développement des stations de TC plus stratégique, intégrant la pratique du vélo. Ce mémoire contribue aussi à faciliter l'usage des outils d'aide à la décision dans la pratique. Il propose une démarche plus générale et moins restrictive pour le développement de typologies de TOD, en incluant les approches reconnues dans la littérature.

7.2 Limites et contraintes

Les méthodes développées et constats établis dans le cadre de ces travaux de recherches ne sont pas sans limites. Développer des outils de typologies de TOD requiert l'utilisation de données. La qualité des résultats dépend donc souvent de la disponibilité des données et de la qualité de celles utilisées. Le transfert méthodologique a aussi amené son lot de défi. Le manque d'uniformité dans la présentation, la disponibilité et le format des données entre les différentes régions ou pays fait en sorte qu'il est impossible de reproduire des méthodologies de façon exacte. Le cadre méthodologique développé permet justement d'aborder les limites sur la disponibilité et le format de données de façon systématique.

De plus, les méthodes de *clustering* nécessitent de choisir certains paramètres et certaines variables. Bien que l'information soit disponible pour faire des choix éclairés concernant la méthodologie, il reste toujours une part de subjectivité qui peut influencer les résultats obtenus. Par exemple, dans le cas précis du développement de la typologie pour Montréal, avoir choisi d'inclure seulement les stations de métro plutôt que toutes les stations de TC (métro et train de banlieue) auraient pu donner des résultats légèrement différents. D'ailleurs, la connaissance du territoire peut contribuer à valider les résultats pour assurer une représentation plus fidèle de la réalité, tout en s'assurant qu'elle ne biaise pas les résultats.

Le cadre méthodologique a été conçu sur la base du transfert méthodologique entre Montréal et Rotterdam. Cette contrainte fait en sorte que le modèle n'a été testé seulement que pour deux régions et les constats ne peuvent pas être généralisés pour tous les cas. Plus de tests sont donc nécessaires pour valider le cadre méthodologique dans un contexte différent de celui de l'Amérique du Nord ou de l'Europe, par exemple.

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7.3 Perspectives de recherche

L'évaluation de l'environnement cyclable reste complexe et dépend de plusieurs facteurs. L'évaluation fournie dans le cadre de ce mémoire n'est pas exhaustive, notamment en raison des données disponibles et de la portée de la recherche. Alors que cette recherche s'est concentrée sur les données disponibles publiquement, d'autres études pourraient se concentrer sur une collecte de données plus étendue, et pourraient inclure d'autres variables déterminantes pour la pratique du vélo, telle que la qualité de la chaussée, la canopée, les îlots de chaleur, le taux de criminalité (vol), etc. Il est important de considérer que ces variables doivent être développées dans le contexte de la pratique du vélo dans les aires TOD. Il pourrait aussi être intéressant d'analyser la relation entre le type de stations et les comportements de mobilité autour de ces stations. Ce serait d'ailleurs une façon de contribuer à l'évaluation de la contribution de chacune des variables. En d'autres mots, il serait important de vérifier l'influence que chacune des variables sur la « cyclabilité » pose sur la classification des stations en fonction leur environnement cyclable. Cela contribuerait à l'élaboration de recommandations encore plus appropriées en fonction du type de station.

Des recherches additionnelles sont aussi nécessaires pour raffiner le cadre méthodologique développé. Une revue de littérature systématique sur les typologies de TOD pourrait être effectuée afin d'améliorer le cadre méthodologique, en s'assurant de considérer l'ensemble des études réalisées sur le sujet. De plus, de futures études évaluant le transfert d'un outil TOD dans différents

contextes géographiques seraient des plus pertinentes afin de peaufiner le cadre méthodologique et d'assurer une transférabilité plus générale.

Par ailleurs, dans la démonstration de l'utilisation du cadre méthodologique pour Montréal et Rotterdam, une seule méthode de *clustering* a été testée. En utilisant les mêmes données, il serait intéressant de tester plusieurs méthodes de *clustering* pour mieux comprendre leur influence sur les résultats dans le contexte des typologies de TOD. Il est donc primordial de détailler l'exploration et l'analyse des données en amont, afin de bien adapter l'ensemble de données à la méthode utilisée.

Finalement, étant donné que l'utilisation des outils de typologie de TOD en pratique n'est que très peu documentée, les futures recherches pourraient s'intéresser à l'utilisation de ce cadre méthodologique dans le domaine de la planification. Par exemple, il pourrait être intéressant de faire une analyse qualitative du processus de planification d'une région s'inspirant du concept TOD, qui utiliserait le cadre méthodologique développé dans le cadre de ce mémoire. Cela permettrait de fournir des recommandations afin de mieux intégrer les outils de typologies de TOD à la planification en aménagement et en transport.

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