

**Multistage Transit-Oriented Development (TOD) Assessment: Integrating
Sustainability Analysis and Disaster Mitigation**

Nasim Rabiei

A Thesis

In the Department of
Building, Civil, and Environmental Engineering

Presented in Partial Fulfillment of the Requirements
for the Degree of

Doctor of Philosophy (Building Engineering) at

Concordia University

Montreal, Quebec, Canada

© Nasim Rabiei, 2025

CONCORDIA UNIVERSITY
School of Graduate Studies

This is to certify that the thesis prepared

By: Nasim Rabiei

Entitled: Multistage Transit-Oriented Development (TOD) Assessment

Method: Integrating Sustainability Analysis and Disaster Mitigation

and submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy (Building Engineering)

complies with the regulations of the University and meets the accepted standards concerning originality and quality.

Signed by the final Examining Committee:

_____	Chair
Dr. Chunyan Lai	
_____	External Examiner
Dr. Yizhao Yang	
_____	External to program Examiner
Dr. Govind Gopakumar	
_____	Examiner
Dr. Samuel Li	
_____	Examiner
Dr. Ciprian Alecsandru	
_____	Supervisor
Dr. Fuzhan Nasiri	
_____	Supervisor
Dr. Ursula Eicker	

Approved by

Dr. Po-Han Chen, Graduate program director

Dr. Mourad Debbabi, Dean of Faculty

ABSTRACT

Multistage Transit-Oriented Development (TOD) Assessment Method: Integrating Sustainability Analysis and Disaster Mitigation

Nasim Rabiei

Concordia University, 2025

Transit-oriented development (TOD) is a compact, mixed-use, and pedestrian-friendly form of sustainable development centered around transit stations, which mitigates the problems associated with auto-oriented development (AOD), including traffic congestion, air pollution, and uncontrolled low-density sprawl. In river cities like Montreal, fragmented urban development and disaster planning strategies exacerbate these problems as the city expands into vulnerable areas, such as the floodplain.

In addressing these issues, researchers have employed various assessment methods, each intended to achieve one of the TOD goals. These include achieving a balance in land use and transportation development, enhancing urban sustainability, and promoting sustainable accessibility. However, the existing literature lacks a comprehensive approach that addresses all the aforementioned goals while mitigating the risks associated with compacting people and activities around stations. The objective of this research is to develop a novel assessment methodology that integrates TOD assessment and disaster mitigation, improves existing methodologies, and addresses TOD goals through the sub-objectives of the following sequential steps.

The first stage of the TOD assessment proposes an enhanced node-place model for station area typology based on the supply and demand of access to public transit service. To achieve balanced land use and transportation development, the proposed

node, place, and tie model utilizes weighted indicators and canonical scores to define viable station areas for increasing density and diversity. The second stage aims to achieve sustainable development by using the TOD index to evaluate station areas in line with sustainable land use criteria. The improved TOD index is the result of comparing different weighting and aggregation methods, as well as modifications to the calculation of selected criteria and indicators, and assessing the efficiency of station areas for compactness using data envelopment analysis. To achieve the goal of sustainable accessibility, the third stage of TOD assessment uses linear programming to maximize local and network public transport accessibility through land use development.

The second section presents a comprehensive approach to disaster mitigation, encompassing the reduction of vulnerability to meteorological hazards and the enhancement of urban resilience. In the first stage, a novel vulnerability assessment methodology is developed using the ArcGIS fuzzy overlay tool to integrate exposure, sensitivity, and adaptive capacity indices. This is followed by proposing a conceptual resilience model to mitigate the impact of disasters in densely populated TOD areas in the second stage. Applying this method in the Montreal Metro case study aims to draw the attention of policymakers and urban planners toward adopting more coordinated land use, transport, and disaster mitigation planning strategies.

Dedicated to my beloved mother, Ms. Azita Bayat, in recognition of her lifelong devotion, love, and unwavering support.

ACKNOWLEDGEMENTS

First and foremost, I express my heartfelt gratitude to the divine radiant source of life and love and its ever-constant shining lights.

I would like to express my sincere gratitude to my supervisors, Dr. Fuzhan Nasiri and Dr. Ursula Eicker, for their invaluable guidance and support throughout my research, particularly their understanding, which enabled me to complete this thesis despite the challenges I encountered. I would also like to thank my committee members for their valuable input and precious time.

I sincerely thank my beloved parents, Ms. Azita Bayat and Mr. Mansoor Rabiei, and my dear uncle, Mr. Naser Rabiei, for their support and love.

I want to honor the memory of my late grandparents, Ms. Malihe Amini Hajbashi and Mr. Abas Rabiei, whose care and attention continue to inspire me, as well as the memory of Mr. Shams Aldin Haeri, whose guidance laid the foundation for this journey.

I extend my appreciation to Dr. Mojtaba Rafieian for introducing me to the concept of Transit-Oriented Development and to my dear friends and family, Ms. Sepinood Meysami, Dr. Mitra Rahavard, Mr. Gene Strangio, and Dr. Mahnoosh Shahinrad.

TABLE OF CONTENTS

LIST OF FIGURES.....	ix
LIST OF TABLES	iii
CHAPTER 1: INTRODUCTION	1
1.1 Background	1
1.2 Problem Statement	4
1.3 Objective	6
1.4 Research Significance	7
1.5 Thesis Organization	8
CHAPTER 2: LITERATURE REVIEW	10
2.1 Introduction	10
2.2 Transit-Oriented Development (TOD)	11
2.2.1 Conceptual Framework	14
2.2.2 TOD Assessment Methods	16
2.2.3 Key Steps of TOD Assessment Methods.....	28
2.2.4 Accessibility and Transit-Oriented Development	34
2.3 Disaster Mitigation.....	38
2.3.1 Conceptual Framework	39
2.3.2 Disaster Mitigation Strategies.....	40
2.3.3 Disaster Mitigation Methods	44
2.3.4 Accessibility and Disaster Mitigation.....	53
2.4 Gaps in the Literature.....	55
CHAPTER 3: METHODOLOGY	60
3.1 Improved Transit-Oriented Development Assessment.....	63
3.1.1 Enhanced Node-Place Model.....	65
3.1.2 Improved TOD Index.....	82
3.1.3 Optimization.....	102
3.2 Disaster Mitigation Strategies.....	104

3.2.1 Vulnerability Assessment	105
3.2.2 Road Network Resilience Assessment	109
CHAPTER 4: CASE STUDY OF MONTREAL METRO	112
4.1 Land use and transport Integration Assessment	115
4.2 Vulnerability Assessment	124
4.3 Sustainability Analysis.....	128
4.5 Maximizing Public Transport Accessibility	133
CHAPTER 5: CONCLUSIONS	135
5.1 Summary	135
5.2 Contributions.....	140
5.3 Limitations and Future Works	142
APPENDICES.....	143
Appendix A-1: Accessibility measures.....	143
A-1-1 Cumulative accessibility.....	143
A-1-2 Gravity-based accessibility.....	144
A-1-3 Connectivity	145
A-1-4 Person-based, infrastructure-based, and utility-based accessibility.....	146
A-1-5 Accessibility types.....	147
Appendix A-2: The role of accessibility in TOD literature	148
A-2-1 Accessibility and TOD performance assessment.....	148
A-2-2 Accessibility and assessment of the environmental impact of TOD	149
Appendix A-3: Impact of TOD on accessibility	150
A-3-1 Impact of TOD on travel demand	150
A-3-2 Impact of TOD on residents' travel behavior	151
Appendix B-1: Correlation analysis.....	152
Appendix B-2: Canonical scores.....	153
REFERENCES.....	154

LIST OF FIGURES

Figure 1-1 Problem statement and research questions	6
Figure 1-2 Research contributions in each stage of the methodology	8
Figure 1-3 Thesis organization.....	9
Figure 2-1 Literature review layout	10
Figure 2-2 Growing interest of scholars in TOD	11
Figure 2-3 TOD concept.....	12
Figure 2-4 Conceptual framework	16
Figure 2-5 Node-place model (Bertolini, 1999).....	19
Figure 2-6 The critical role of accessibility in 5D variables	36
Figure 2-7 Conceptual framework	40
Figure 2-8 Resilience attributes, adapted and modified from Simonovic and Arunkumar (2016)	42
Figure 2-9 Resilience diagram	43
Figure 2-10 Probabilistic resilience assessment adopted from Chang & Shinozuka (2004) and Nieves-Melendez & De La Garza (2016)	50
Figure 2-11 The critical role of accessibility in urban disaster mitigation.....	54
Figure 2-12 TOD assessment framework.....	57
Figure 3-1 Overview of the thesis methodology.....	61
Figure 3-2 Conceptual framework of the improved TOD assessment.....	63
Figure 3-3 Structure of the proposed method.....	64
Figure 3-4 Scatter plot of stations based on their node and place canonical scores	82
Figure 3-5 Steps of the proposed disaster mitigation planning.....	105
Figure 3-6 Schematic model of TOD resilience assessment.....	110
Figure 4-1 Montreal metro lines and the annual ridership report (RR)	113
Figure 4-2 Existing TODs and Montreal metro	114
Figure 4-3 Analysis area defined by 400m and 800m station buffers.....	115
Figure 4-4 Weighted and unweighted node, place, and tie indices	119
Figure 4-5 Node, place, and tie indices of the Montreal metro.....	120
Figure 4-6 Clustering by k-means.....	121
Figure 4-7 Feasibility analysis of land-use interventions.....	123
Figure 4-8 Adaptive capacity calculation.....	124

Figure 4-9 Montreal's main meteorological hazards 125

Figure 4-10 Vulnerability index calculation process..... 126

Figure 4-11 Vulnerability of Montreal metro stations..... 127

Figure 4-12 Correlation analysis of 5D variables 128

Figure 4-13 Existing and planned public transport accessibility 134

Figure 5-2 Overview of the proposed method process 136

Figure 5-3 Outcome of each stage of the proposed methodology..... 137

LIST OF TABLES

Table 1-1 Research questions, objectives, and sub-objectives.....	7
Table 2-1 Overview of TOD assessment methods	17
Table 2-2 Literature using the node-place model.....	21
Table 2-3 Literature using the node-place-functionality model	22
Table 2-4 Literature using the node-place-design model	23
Table 2-5 Literature using the node-place-tie model.....	24
Table 2-6 Literature using the TOD index	26
Table 2-7 TOD literature using DEA	28
Table 2-8 Methods of defining TOD area	29
Table 2-9 Relation between risk, vulnerability, and resilience.....	45
Table 2-10 Examples of the application of the SD model.....	52
Table 2-11. Compare simulation models for resilience assessment	53
Table 2-12 Overview of TOD assessment methods	56
Table 3-1 The role of accessibility in the proposed methodology	62
Table 3-2 Criteria and indicators of the proposed node-place-tie model	67
Table 3-3 Resource for indicators of the proposed node-place-tie model.....	68
Table 3-4 Node index calculation.....	71
Table 3-5 Place index calculation.....	73
Table 3-6 Tie index calculation	74
Table 3-7 Variables of canonical correlation analysis (CCA)	79
Table 3-8 Criteria and indicators of the proposed TOD index	85
Table 3-9 Resource for selecting criteria and indicators of the improved TOD index.....	86
Table 3-10 Destination accessibility (D1)	90
Table 3-11 Distance to transit (D2) and Design (D3).....	94
Table 3-12 Density (D4) and Diversity (D5).....	96
Table 3-13 Rescaling techniques.....	98
Table 3-14 The consistency ratio (CR).....	99
Table 3-15 Fuzzy overlay techniques used in this study	108
Table 4-1 Canonical correlations.....	116
Table 4-2 Standardized canonical coefficients	117

Table 4-3 Correlations between input variables and canonical variables	118
Table 4-4 The relative importance of the node, place, and tie indicators.....	118
Table 4-5 Result of clustering	122
Table 4-6 Typology of the feasible station area for further development	123
Table 4-7 Relative weights of criteria	129
Table 4-8 Relative weights of indicators.....	129
Table 4-9 Data preparation and aggregation methods.....	130
Table 4-10 Result of aggregation by different methods	130
Table 4-11 Correlation matrix of different preparation and aggregation methods.....	131
Table 4-12 Result of DEA.....	132
Table 4-13 Results of optimization	133
Table 5-1 Overview of tools and techniques used in this research	138

LIST OF ABBREVIATIONS

3D (Density, Diversity, Design)

5D (Density, Diversity, Design, Distance to transit, Destination accessibility)

AHP (Analytic Hierarchy Process)

ANP (Analytic Network Process)

AOD (Auto-Oriented Development)

CBD (Central Business District)

CCA (Canonical Correlation Analysis)

DEA (Data Envelopment Analysis)

DOT (Development Oriented Development)

FAHP (Fuzzy Analytic Hierarchy Process)

Improved IGA (Improved Immune-Genetic based Algorithm)

IPCA (Impedance Pedestrian Catchment Area)

IPCC (Intergovernmental Panel on Climate Change)

OLS (Ordinary Least Square)

PCA (Principal Component Analysis)

PCC (Pearson Correlation Coefficient)

PSM (Propensity Score Matching)

SD (System Dynamics)

TAD (Transit Adjacent Development)

UHI (Urban Heat Island)

VKT (Vehicle Kilometer Traveled)

VMT (Vehicle Mile Traveled)

WSM (Weighted Sum Method)

CHAPTER 1: INTRODUCTION

1.1 Background

Auto-oriented development has led to several challenges worldwide, including traffic congestion, air pollution, and uncontrolled, low-density urban sprawl. Montreal is one of the fastest-growing cities in Canada, with the private vehicle fleet growing twice as fast as the population (Morency et al., 2020). As a result, urban sprawl has accelerated more than 26 times since 1951 (Nazarnia et al., 2016a). In river cities such as Montreal, the fragmentation of land use, transportation, and disaster mitigation planning exacerbates the abovementioned problems as the city expands into the floodplain.¹

To offset the adverse consequences of auto-oriented development (AOD), it is necessary to implement integrated land use and transport sustainable planning. First, this integration can help reduce congestion by improving sustainable accessibility. This requires a shift towards sustainable modes of transport (including public transit, cycling, and walking) and land use planning that considers access to transit services, for example, by locating residential areas near transit stations (Bertolini et al., 2005). This is particularly evident when considering the Braess paradox², which states that adding new roads may not reduce congestion and may worsen travel times. This hypothesis holds even when drivers can access dynamic traffic information for route selection (Bittihn & Schadschneider, 2021). Second, among the various policies aimed at reducing greenhouse gas (GHG) emissions, the transition to sustainable modes of transport is the most prominent, which also requires integrating land use

¹ According to “Urgence Québec”, in 2019, spring flooding damaged 2,341 homes and forced around 1,200 residents to evacuate (FloodList-News, 2019).

² Braess Paradox introduced by Dietrich Braess in 1968 and later confirmed by other researchers.

and transportation planning³. "Sustainable transportation requires higher-density land use patterns that accommodate alternative modes and are developed around passenger rail systems" (Litman & Burwell, 2006). Conversely, using electric vehicles is ineffective in reducing greenhouse gas (GHG) emissions because most countries rely on fossil fuels for electricity generation (Loo & du Verle, 2017). It has also been argued that urban tree-planting programs are less effective than combined land use and transport development, projected to reduce 22% of CO₂ emissions by 2030 (Shepherd, 2014a). Additionally, integrating land-use and transportation planning strategies is an effective way to reduce urban sprawl. Using reactive strategies, such as early warning systems, and preventive strategies, such as implementing greenbelts, open space preservation, and restrictive zoning, will decrease the impacts of urban sprawl, especially in flood-prone areas. In this regard, risk awareness, emergency preparedness, and the prevention of construction in flood-prone areas in Montreal have been improved since 2014 (Olivier, 2019). However, coordinated land-use and transportation strategies are the most effective way to control urban sprawl. These include implementing dense and mixed-use zoning, providing incentives for infill development, and investing in public transportation systems to support inward urban development.

The aforementioned strategies can be achieved through a shift towards transit-oriented development. Calthorpe first introduced the concept of Transit-Oriented Development (TOD) in the early 1990s; subsequently, it became a significant area of research and practice, aiming to reverse the auto-oriented urban development paradigm and fragmented land use and transportation planning. In his book, "The New American Metropolis," Calthorpe proposed a mixed-use, high-density,

³ According to the United Nations Framework Convention on Climate Change (UNFCCC), the transportation sector, in general, contributed 72.06% of global GHG emissions in 2010 (P. Li et al., 2018)

pedestrian-friendly community development around transit stations (Calthorpe, 1993). The TOD concept was first implemented in Portland, USA, and has since been adopted as a sustainable approach to land use and transportation planning in metropolitan areas worldwide. In 2011, the Council of the Communauté Métropolitaine de Montréal, in accordance with the "Metropolitan Land Use and Development Plan,"⁴ identified TOD as the primary objective for future urban development (Nazarnia et al., 2016)⁵.

Several techniques and methods have been used in the existing literature to evaluate potential and actual TODs. These techniques can be categorized into three main types: multi-attribute, multi-objective, and single-attribute methods. Multi-attribute assessment techniques include the node-place model and the TOD index. The node-place model is employed to analyze and typology station areas regarding the extent of equilibrium between land use and transport development. The TOD index is used to evaluate station areas in terms of their alignment with sustainable criteria. Multi-objective methods, including data envelopment analysis and optimization techniques, are employed to identify the most efficient and optimal decision for land use and transport development. Single-attribute techniques involve applying various statistical methods and an accessibility index to analyze the impacts of TODs. Each of these methods addresses one of the key goals of TOD: achieving a balance between land use and transport development, enhancing sustainability, and

⁴ Plan Métropolitain d'Aménagement et de Développement (PMAD)

⁵ It is worth mentioning that some studies claimed that TOD has not been as effective as initially thought in reversing the problems associated with car-oriented development. For example, Chindapasirt et al. (2024) argued that implementing TOD did not reduce carbon dioxide emissions in Khon Kaen City, Thailand. TOD exhibited more urban heat island (UHI) effect than non-TOD areas in Brisbane, Australia (Kamruzzaman et al., 2018). It also resulted in the creation of ecological imbalances in the suburban areas of Tokyo (W. Yang et al., 2024). In addition, Chen (2019) showed that TOD did not significantly reduce urban sprawl in Beijing, China. However, these unfavorable results may be due to unreliable assessment techniques, a lack of consistency in the choice of indicators, or be case-specific.

improving public transport accessibility. However, a comprehensive assessment approach that considers all TOD goals and disaster mitigation is currently lacking.

This research addresses this gap by proposing a multi-stage risk-aware TOD assessment methodology. Applying this methodology to the Montreal Metro case study provides urban planners and municipalities with a model to enhance existing TODs and identify suitable locations for new ones.

This study focuses on the built environment, with a particular emphasis on the relationship between land use and transportation. The application of sustainable development's social and economic pillars is limited to specific indicators that affect residents' choice of public transit. This is a traditional planning approach that is constrained by the limitations of current data, does not consider dynamic strategies, and assumes a constant metro network and service.

1.2 Problem Statement

Methods for evaluating transit-oriented development (TOD) have been modified and refined through professional practice and research, but some areas still require further consideration, as outlined below and in Figure 1-1.

The complexity of the issue and the large number of parameters involved in TOD assessment have led researchers to pursue a diverse array of objectives, methodologies, and outcomes. Each method is designed to achieve a specific TOD objective. For example, the node-place model has been used to develop station typologies based on land use and transport development equilibrium. The TOD index evaluates and clusters station areas, with improving sustainability as the primary objective. Optimization techniques, such as genetic algorithms and data envelopment analysis, are employed to maximize public transport accessibility, another objective

of TOD. This inconsistency in objectives, evaluation methods, and indicators inevitably leads to discrepancies in the final results.

In addition, the fragmentation of urban development and disaster mitigation planning increases disaster risk by concentrating large populations in compact TOD areas. To facilitate pedestrian access, TOD advocates dense urban settlements with a diverse range of activities located near transit stations and accessible within a 15-minute walk. Some of these activities not only benefit the neighborhood but also draw people from throughout the city via public transportation every day. As a result, the risk of disasters, whether man-made or natural, is exacerbated by the exposure of more people. This compactness also hinders the implementation of recovery operations such as evacuation and the provision of emergency services.

This thesis was developed in response to the following questions from the abovementioned problems: (1) how to relate, integrate, and improve existing TOD planning methodologies, and (2) how to mitigate the risks associated with increasing population density in TOD areas.

To address the first question, this research investigates the potential for enhancing Transit-Oriented Development (TOD) planning by integrating existing methodologies. This comprehensive approach compensates for the shortcomings of a specific method with the strengths of others. For example, the node-place model is constrained by land use and transport indicators, whereas this is not an issue in the TOD Index assessment. Conversely, the TOD Index score does not consider the correlation between land use and transportation criteria. This integration requires forming around a common objective, such as accessibility, which is the ultimate goal of all land use and transportation planning approaches.

Regarding the second question, this study investigates methods to mitigate the impact of disasters in compact TOD areas. One possible solution is to reduce the exposure of people and infrastructure by avoiding vulnerable areas. The second possible approach is to increase resilience by planning for post-disaster recovery. The comprehensive approach to disaster mitigation, which considers reducing vulnerability and increasing resilience and its application to TOD, remains an open research problem.

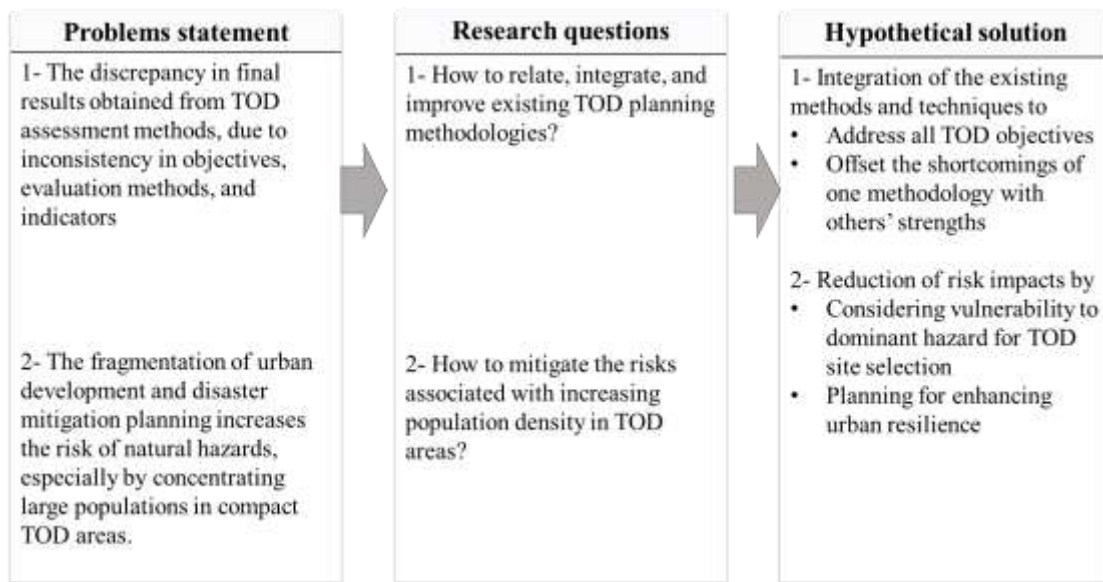


Figure 1-1 Problem statement and research questions

1.3 Objective

In accordance with the previously mentioned research questions, this thesis aims to propose an improved risk-aware TOD planning methodology that combines several stages, each addressing one of the research sub-objectives.

Regarding the first question, this research aims to integrate and improve existing TOD planning models by addressing three sub-objectives: balancing land use-driven demand and transport-driven supply by utilizing an enhanced nod-place-tie model (stage 3.1.1); enhancing the sustainability of the built environment by developing an

assessment model based on an improved TOD index (stage 3.1.2); maximizing accessibility to public transit by increasing the density and diversity of activities within the station area, which can be achieved through the application of linear optimization (stage 3.1.3). In addition, in response to the second research question, to reduce the risks associated with increasing population density in TOD areas, the following two steps are integrated into the proposed TOD model: reducing vulnerability by selecting station areas with lower vulnerability to the dominant hazards, which is achieved through the use of an improved vulnerability index (stage 3.2.1); and increasing road network resilience by proposing a framework for future resilience assessment and improvement through the introduction of emergency reserve lanes (stage 3.2.2). Table 1-1 summarizes the research questions, objectives, and sub-objectives corresponding to each stage of the proposed methodology.

Table 1-1 Research questions, objectives, and sub-objectives

Research questions	Objective	Stage of methodology	Research sub-objective
1) How can existing TOD planning methodologies be related, integrated, and improved?	An improved risk-aware TOD planning	3.1. Improved TOD	3.1.1 Balancing land use-driven demand and transport-driven supply
			3.1.2 Enhancing built environment sustainability
			3.1.3 Maximizing public transport accessibility
2) How can risks associated with increasing population density in TODs be mitigated?		3.2. Disaster mitigation strategies	3.2.1 Decreasing vulnerability
			3.2.2 Enhancing resiliency

1.4 Research Significance

The originality of this research lies in its holistic approach to TOD and disaster mitigation planning, as well as its contribution to enhancing existing methods at each stage (Figure 1-2).

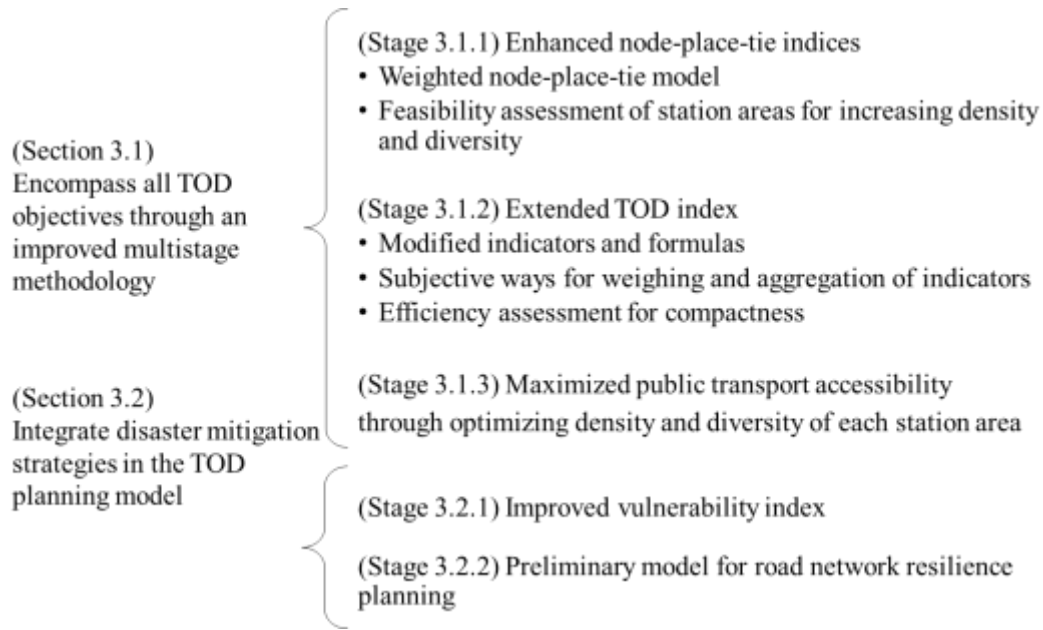


Figure 1-2 Research contributions in each stage of the methodology

1.5 Thesis Organization

This thesis comprises five chapters, as illustrated in Figures 1-3. The initial chapter functions as an introduction to the study, delineating the problem statement, research questions, objectives, and sub-objectives of this research. The second chapter is devoted to a literature review on TOD and disaster mitigation. The outcome of this chapter is a synthesis of the findings and gaps, which are then used to delineate the proposed methodology. The third chapter presents a novel risk-aware multi-stage TOD planning framework that integrates and improves upon previous methods. This is achieved through three stages of an enhanced TOD planning model and two stages of proposed disaster mitigation strategies. Chapter Four applies the developed models to the case study of the Montreal Metro. The concluding chapter, Chapter Five, summarizes the research, its contributions, and potential avenues for future research.

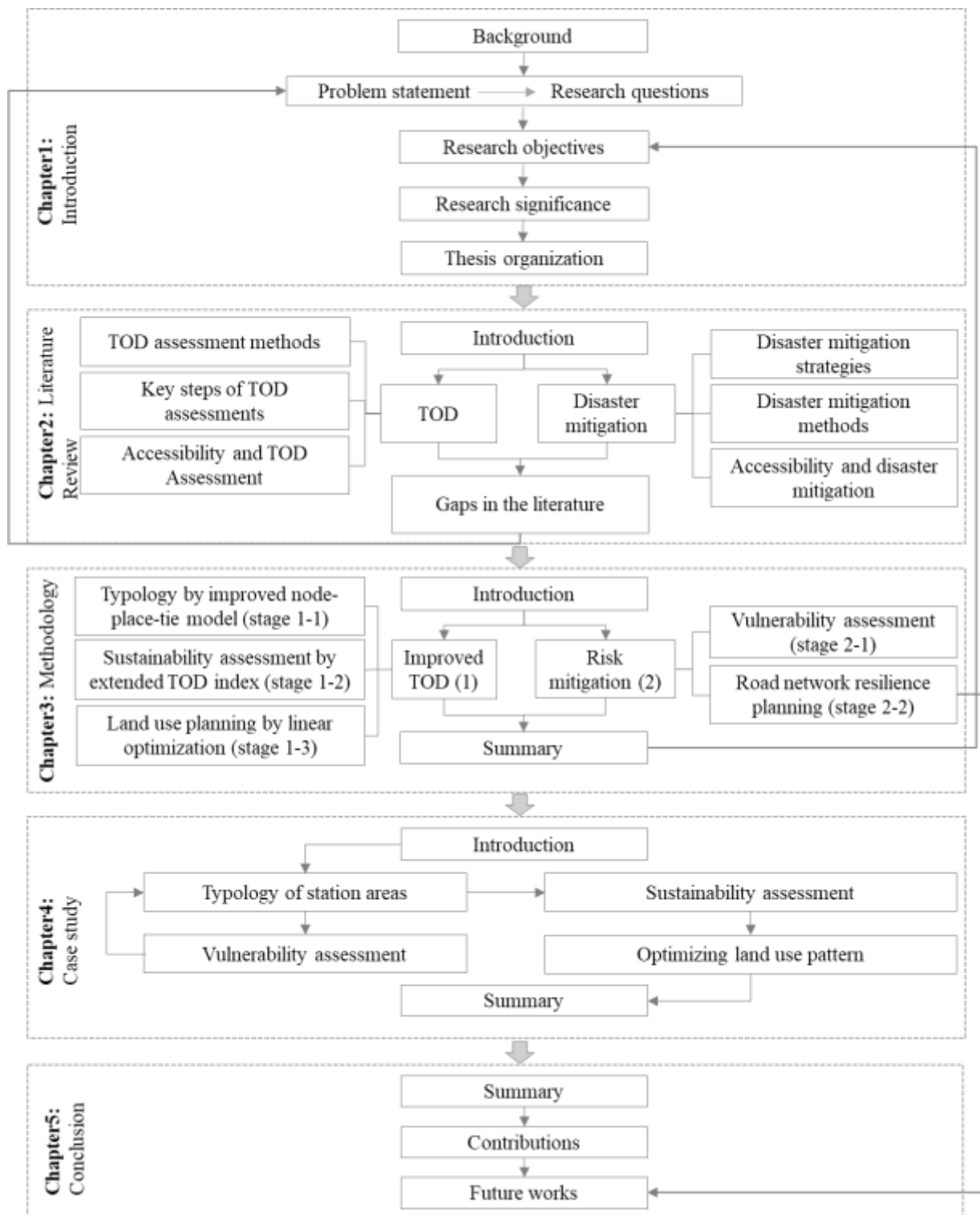


Figure 1-3 Thesis organization

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

Concerning the thesis objective of proposing improved risk-aware TOD planning, this chapter has developed a literature review on transit-oriented development (TOD) and disaster mitigation. The structure of the literature review is shown in Figure 2-1.

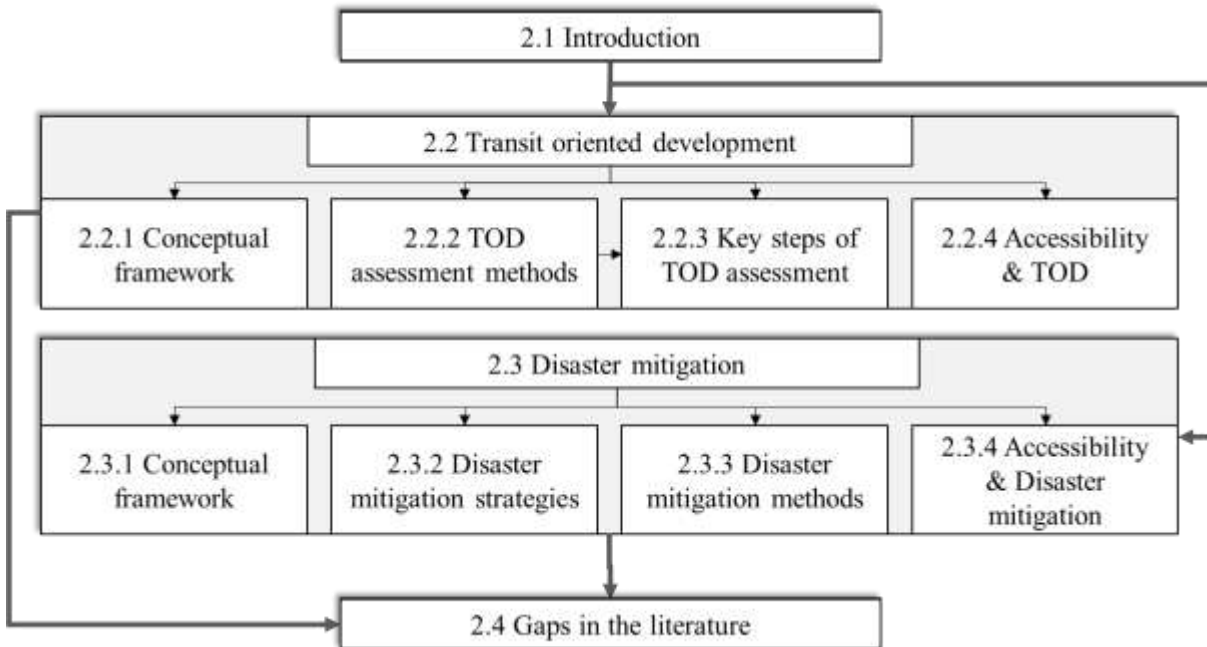


Figure 2-1 Literature review layout

As Figure 2-2 shows, scholarly attention to TOD has fluctuated but has increased exponentially. TOD has attracted growing interest from researchers in urban planning, environmental science, and transportation engineering. For this chapter, the scoping review methodology⁶ was initially employed to examine the scope and breadth of research on transit-oriented development (TOD) and disaster mitigation,

⁶The scoping review methodology consists of five iterative stages: the initial identification of research questions and sub-questions, scanning of the literature, selection of the most relevant studies, and categorization and synthesis. The scoping review is primarily concerned with conceptualizing the topic rather than the methodological approach and details of the literature (Arksey & O'Malley, 2005).

identifying the gaps in existing research, conceptualizing the research objective, and formulating the research questions and sub-questions. Subsequently, a more in-depth investigation was conducted on the reciprocal effect of accessibility and TOD⁷ using the systematic review⁸ methodology, using Scopus and Google Scholar databases.

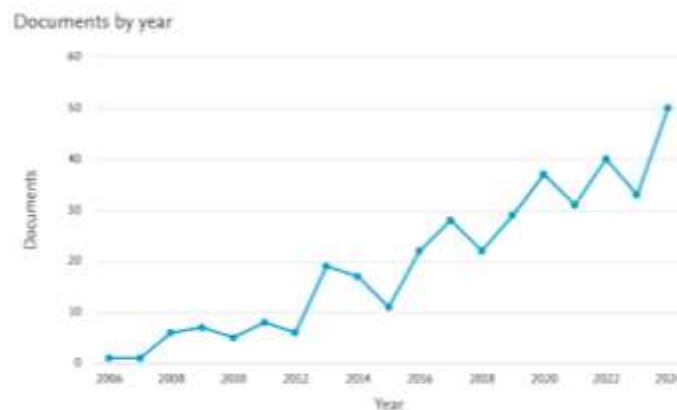


Figure 2-2 Growing interest of scholars in TOD

2.2 Transit-Oriented Development (TOD)

Calthorpe (1993), an architect and urban planner, first introduced the concept of Transit-Oriented Development (TOD), which has its roots in the Garden City movement. TOD integrates urban and transportation planning to transform low-density, auto-oriented development (AOD) into a dense, diverse, and walkable community around transit stations. Calthorpe envisioned TOD in three areas: the primary area in the vicinity of the transit station, including dense and mixed commercial and employment activity, supported by the central area of open and

⁷ Section 2.2.4 summarizes the systematic review of the relationship between TOD and accessibility. The full review was presented in a paper titled "Transit-Oriented Development and Accessibility: A Review and Conceptual Framework Proposal."

⁸ The systematic review is conducted in four stages: identification, screening, eligibility, and inclusion. It is performed based on a pre-defined and precise research question, which is then investigated through a critical analysis and synthesis of selected articles (Moher et al., 2009).

green urban space, and the second area, including housing, schools, and other neighborhood facilities, which gradually decreases in density (Figure 2-3).

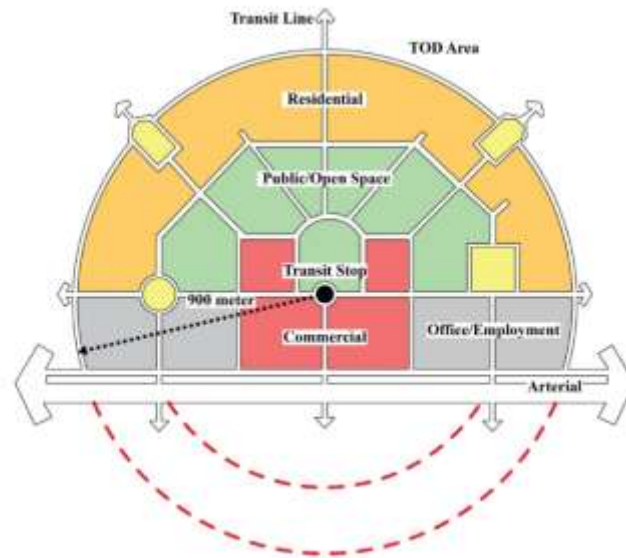


Figure 2-3 TOD concept

The "twenty-five-year biography of the TOD concept" by Jamme et al. (2019) showed that TODs shared certain aspects worldwide, including the development of compact, mixed-use, pedestrian-friendly communities in proximity to transit stations. This finding was confirmed by "a comparative analysis of the global implementation of TOD" conducted by Bhagwati and Kumar (2024). However, some characteristics of TOD vary according to the geographical context. For example, it can manifest as pedestrian-friendly neighborhood development in Europe, dense mixed-use development around transit stations in North America, or along transit corridors in Asian cities (Phani Kumar et al., 2020). The original purpose of the transit station, for example, in terms of serving commercial or residential areas, is also a significant factor (X. Huang et al., 2021).

The implementation of transit-oriented development has several advantages. TOD is an acceptable way to mitigate urban sprawl by directing urban growth toward transit stations and corridors (Hasibuan et al., 2014) and promoting a pedestrian-centric urban environment. Creating a pedestrian-friendly environment facilitates the development of sustainable and vibrant precincts near public transit stations (Olaru et al., 2019). The implementation of TOD also enhances public transport accessibility, which influences the mode choice of residents⁹. In light of these considerations, TOD may be regarded as a sustainable "accessibility-centered planning approach" (Bertolini, 1999). This concept also implies the integration of land use and transportation development, achieved through interweaving transit, pedestrian, and vehicular networks with dense and diverse land use. The alignment of urban and transportation planning will reduce travel distance, cost, and traffic congestion (Tamakloe & Hong, 2020). In addition to the aforementioned potential benefits, implementing TOD strategies offers a range of environmental, economic, and social advantages. These include reduced greenhouse gas emissions, increased property values, enhanced business growth, and improved quality of life.

Conversely, implementing transit-oriented development can pose some challenges. These include a high initial cost (Jain & Singh, 2019), barriers to integration with existing infrastructure (Hrelja et al., 2022), gentrification and displacement of residents due to increased property values (Jones & Ley, 2016), and intensification of risk factors associated with high population density. Ibraeva et al. (2020) provided a list of "implementation problems and solutions" of TOD from the perspective of planning authorities, transport operators, and developers.

⁹ As evidenced by an increase in transit ridership and/or a reduction in vehicle miles travelled.

In summary, the success of TOD implementation depends on these challenges being well addressed through appropriate planning and coordination. In order to address the inter-sectoral relationships, a system dynamic model can be employed, as demonstrated by Cox et al. (2017). Furthermore, the adaptation of incentives for "public participation" (Savvides, 2017) and "institutional coordination" for regional TOD planning (Staricco & Vitale Brovarone, 2018) is essential to ensure the resolution of conflicts of interest. Hasibuan et al. (2021) also highlighted the significance of the "environmental carrying capacity" of the proposed TOD location.¹⁰ Additionally, integration with risk mitigation planning is crucial to the sustainability of TOD areas, which is one of the study's objectives.

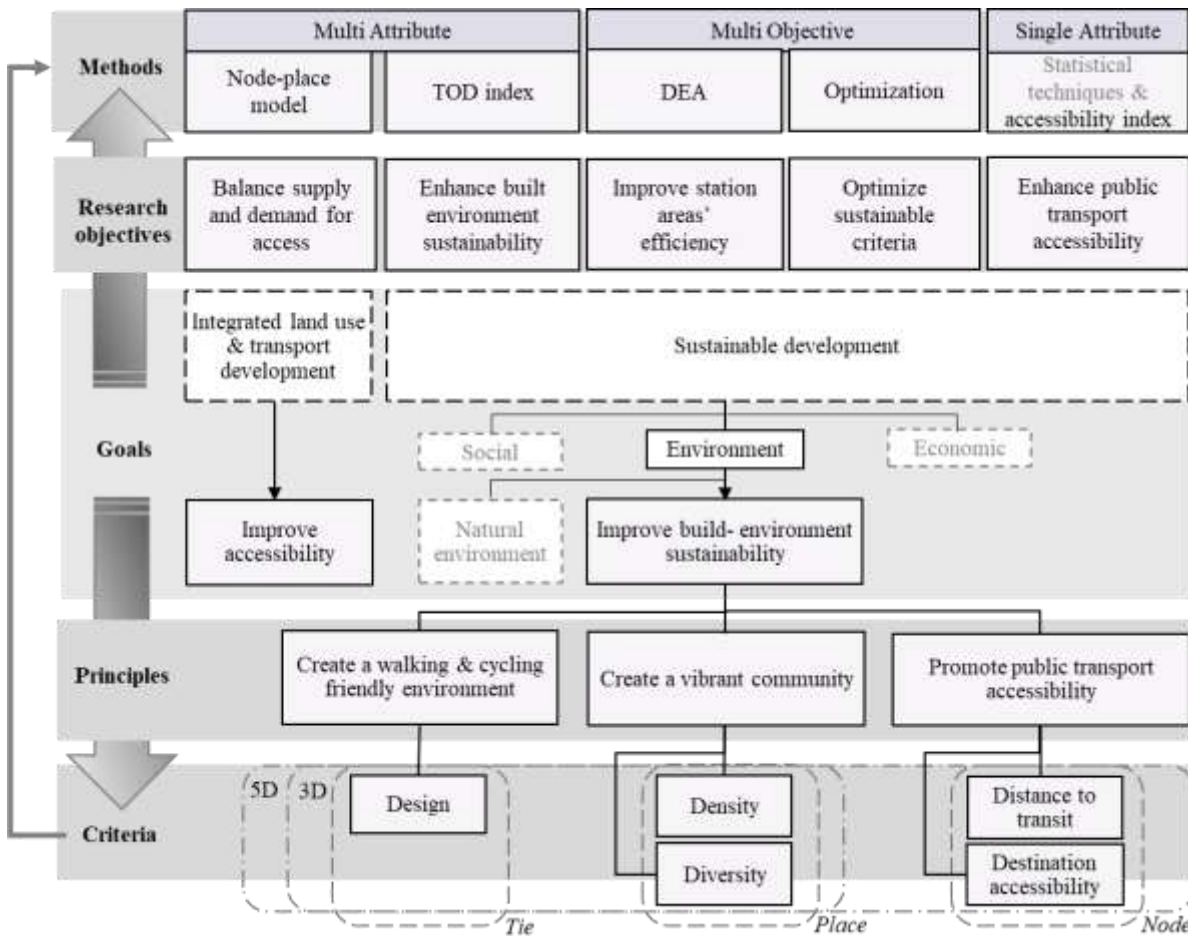
2.2.1 Conceptual Framework

For a better understanding of the concept of TOD, it is necessary to distinguish between Transit-Adjacent Development (TAD), Development-Oriented Transit (DOT), and Transit-Oriented Development (TOD). Transit-adjacent development (TAD) refers to a land use development around existing transit stations. TAD is a "station area that is not compact, mixed-use, or pedestrian-friendly" (Appleyard et al., 2019). Conversely, development-oriented transit (DOT) is where a transit station is built, or the transit network is expanded following the development of land use to serve new suburbs (J. Wang et al., 2024). This classification of station areas as TOD, TAD, DOT, or even Park and Ride is related to the performance of other station areas and the surrounding built environment (Ibraeva et al., 2021). According to Searle et al. (2014), "to achieve TOD rather than TAD, development needs, in particular, to be significantly denser than normal in that area. In addition, TOD should be assessed

¹⁰ In terms of land use capacity, water availability, socio economic and greenery

and planned from a network system perspective, as a transit node may exhibit different performance levels as an individual or within the network (Huang et al., 2018). Concerning this, Papa et al. (2013) advocated the concept of “network TOD” (NTOD). To differentiate between TOD, TAD, and hybrid station areas, researchers have employed the D variables, including the 3Ds (Density, Diversity, and Design) and the 5Ds (Density, Diversity, Design, Destination accessibility, and Distance to transit).

Transit-oriented development aims to achieve sustainable and integrated development in the land-use and transportation sectors. This is achieved by implementing built environment sustainability principles identified by the 3D and 5D criteria. TOD principles can be defined as follows: 1- The creation of a dynamic and vibrant community through the concentration of population and diverse activities in the vicinity of public transit stations, as evidenced by density and diversity indicators; 2- The creation of a pedestrian-friendly environment through urban design criteria that encourage residents to utilize active and public modes of access within the station catchment area; 3- The promotion of public transport accessibility in terms of destination accessibility and distance to transit stations. The aforementioned goals and principles are achieved through objectives and methods outlined in Figures 2-4. The topics in the dashed rectangles fall partially within the scope of this thesis, whereas those in the gray font are outside the study's scope.



Note: Topics in the dashed rectangles fall partially within the scope of this thesis, and those with gray font are outside the study's scope.

Figure 2-4 Conceptual framework

2.2.2 TOD Assessment Methods

We categorized the methodologies applied for TOD assessment into three main groups: multi-attribute, multi-objective, and single-attribute (Table 2-1). The term single attribute encompasses various statistical techniques used to analyze non-composite factors, which can also be applied in conjunction with multi-attribute techniques. Multi-attribute methods aggregate several indicators to form a composite indicator, such as node, place, and TOD indices. Multi-objective methods, however, employ multiple attributes as the objectives of an optimization.

Table 2-1 Overview of TOD assessment methods

Assessment technique		Authors
Single attribute	Regression analysis	Kamruzzaman and Wood et al. (2014), Nasri and Zhang (2014), Faghri and Venigalla (2014), Dou et al. (2015), Laaly et al. (2017), Kamruzzaman et al. (2018), Lyu et al. (2019), Nyunt and Wongchavalidkul (2020)
	Statistical techniques	
	Laten class	Higgins and Kanaroglou (2016)
	Principal axis factoring	Choi & Guhathakurta (2024)
	Principal component analysis	Nyunt & Wongchavalidkul (2020)
	Propensity score matching	Park et al. (2018), Nasri et al. (2018a), X. Li et al. (2022)
	Logit model	Nasri & Zhang (2019)
	Accessibility index	S. Lee et al. (2013), Rahmat et al.(2016), Deboosere et al. (2018), Conesa (2018), Cong et al. (2024)
Multi-attribute	TOD index	Singh et al. (2014), Singh et al. (2017), Motieyan & Mesgari (2017), Budiati et al. (2018), Huang et al. (2018), Taki & Maatouk (2018), D. Ma & Chen (2019), Ke et al., (2021), Ibrahim et al., (2023), H. Chen et al. (2024)
	Node- place	Bertolini (1999), Papa et al. (2013), Kamruzzaman and Baker et al. (2014), Papa and Bertolini (2015), Monajem et al. (2015), Vale (2015), Nurlaela et al. (2019), Olaru et al. (2019), W. Wu and Divigalpitiya (2022), Nemroudi et al. (2024), J. (Brian) Lee and Salih, (2024)
	Node- place- tie	Lyu et al. (2016), Vale et al. (2018), Z. Li et al. (2019), Nigro, Bertolini, Domenico, et al. (2019), Y. Zhang, Marshall, et al. (2019), Pezeshknejad et al. (2020), Cao et al. (2020), Su et al., (2022), Y. Yang et al. (2022), M. Zhang & Lee (2023), Pan & Huang (2024), Zhao et al., (2024)
Multi-objective	Deterministic optimization	Mixed-Integer Nonlinear Programming
		Liu et al. (2018)
		Bilevel programming
		J. Li et al. (2022)
		Linear programming
		Berawi et al. (2020b)
	Stochastic optimization	Genetic algorithm
		Sahu (2018), X. Huang et al. (2021), X. Ma et al. (2018)
		Gray programming
		J. J. Lin & Li (2006)
	Efficiency analysis	DEA
		Wey (2013), Wey (2015), Zhang & Guo (2017), Guo et al. (2018), E. H. Lee et al. (2019), Tamakloe & Hong (2020), T. Chen et al. (2023)

Single attribute assessment methods

Some researchers utilized non-composite variables, namely single-attribute assessment techniques, including accessibility indexes and statistical techniques, to analyze the TOD level of station areas.

Accessibility index have been used in several studies to evaluate the performance of TODs. For instance, Cong et al. (2024) used a "citywide rail transit accessibility index" to evaluate the effectiveness of TODs in Shenzhen, China, focusing on integrating land use and public transportation. Similarly, in the case study of Dhaka, Bangladesh, Rahman et al. (2022) used multiple regression analysis to examine the correlation between land use indicators and the public transport accessibility index. In a separate study conducted in Seoul, South Korea, S. Lee et al. (2013) categorize stations based on their value of the accessibility index. In addition, Conesa (2018) proposed a multiscale accessibility measure that incorporates both pedestrian accessibility at the local (station area) and public transport accessibility at the regional scale in Nord Pas-de-Calais, France.

In contrast, utilizing statistical techniques enables the simultaneous consideration of multiple attributes, albeit not in a composite form. The following examples represent the application of single-attribute methods in the TOD literature: To evaluate the impact of TODs on residents' mode choice, Langlois et al. (2015) employed a multilevel multinomial logistic regression model. Park et al. (2018), Nasri et al. (2018a), and X. Li et al. (2022) used the propensity score matching technique, while Nasri and Zhang (2019) employed the Logit model. In addition, Higgins and Kanaroglou (2016) employed a latent class model to assess the overall performance of a TOD area and to consider the relationship between TOD variables. Similarly, Nyunt and Wongchavalidkul (2020) employed principal component analysis to

investigate the correlation between transit ridership and density, diversity, and design criteria indicators.

Multi-attribute assessment methods

Regarding the TOD conceptual framework (Figures 2-4), multi-attribute assessment techniques, including the node-place model and the TOD index, address the first and second goals of TOD, respectively, achieving a balance between land use and transportation development and enhancing sustainability.

The initial node-place model, proposed by Bertolini (1999), was employed to create a typology of station areas based on the equilibrium between land use and transportation development. In the Bertolini model, the X-axis represents place indicators, namely the density and diversity of population and activities, and the Y-axis shows node indicators, namely accessibility and connectivity of transport stations. As illustrated in Figure 2-5, this model yields five typologies of stations: Dependency, Accessibility, Stress, Unsustained Node, and Unsustained Place.

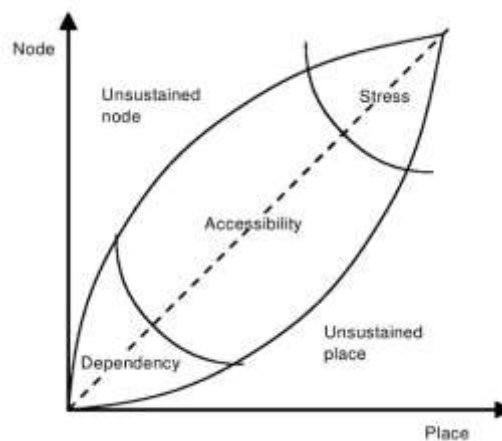


Figure 2-5 Node-place model (Bertolini, 1999)

The dependent, accessible, and stressed station areas exhibit a relatively balanced node and place distribution. The dependent station areas have weak nodes (transport

indicators) and weak places (land-use indicators), indicating a low level of supply and demand that requires development in both sectors. In contrast, the accessible station areas have medium to strong node and place features, indicating harmonious land use and transportation development. However, the node and place indicators are so developed in the stressed station areas that further development would be problematic.

On the other hand, station areas categorized as unsustained nodes and unsustained places are characterized by an imbalanced situation that can be addressed through strategic land-use and transportation planning interventions. The unsustained node represents station areas that are well-connected to a developed transit system but lack vibrancy and livability due to lower land use diversity and density. Conversely, the "unsustained place is characterized by strong place attributes and weak nodes, which refers to a station area with dense and diverse activities that are poorly connected to other station areas (Bertolini, 1999). Table (2-2) contains a list of literature on TOD that employs the node-place model.

Table 2-2 Literature using the node-place model

Author	Criteria and indicators		
	Node index	Place index	Tie index
J. (Brian) Lee and Salih, (2024)	Active and passive accessibility index	Residential and non-residential density, job density, intersection density, land use mix factor	-
Nemroudi et al. (2024)	Metro, bus, and car accessibility	Workforce, population, multi-functional mix	-
W. Wu and Divigalpitiya (2022)	Metro, bus, car, and bicycle accessibility	Number of residents and workers in different sectors and the degree of functional mix	-
Caset et al. (2020)	Feeder mode and railway accessibility in terms of frequency and number of services	Density of local and regional amenities, number of jobs and residents, the functional and spatial mix of land uses in the station area	
Nurlaela et al. (2019)	Frequency of service and type of public transit, length of travel, number of destinations served, and pedestrian connectivity	Land area ratio, floor space ratio, household and job density, degree of functional mix	-
Olaru et al. (2019)	Multi-modal and multi-scale accessibility, frequency of service, opportunity measure (number of employment), park and ride, and bike facilities	Density, diversity, socio-economic, and urban aesthetics	-
Papa and Bertolini (2015)	Closeness centrality	The average density of inhabitants and jobs	-
Monajem et al. (2015)	Proximity to the CBD, to-movement, through-movement	Population density, workforce density, degree of functional mix (diversity), to-movement, through-movement	-
Vale (2015)	Number of directions served by metro and bus, number of stations in 20 min travel, frequency of trains and bus, distance to the motorway access, parking capacity	Number of dwellings, number of employees in different sectors, and degree of functional mix	-
Papa et al. (2013)	"Closeness centrality index"	Average density of residents and jobs of each "accessibility zone (AZ)"	-

Subsequently, Lyu and his colleagues expanded the node-place model by incorporating the Z-axis for the tie index, which reflects the degree of "functional and morphological interrelation" of land use and transport indicators (Lyu et al., 2016).

A node, place, and tie model evaluates the performance of a TOD area to "balance between public transport-driven supply and land use-driven demand while simultaneously improving the pedestrian friendliness of the station areas" (Vale et al., 2018). The tie index plays such an important role in the typology of station areas, with the potential to decrease the class of a station area from TOD to TAD (transit adjacent development). TAD is a "station area that is not compact, mixed-use, or pedestrian-friendly"(Appleyard et al., 2019). Researchers have defined the tie index as functionality index (Table 2-3), design index (Table 2-4), and others (Table 2-5).

Table 2-3 Literature using the node-place-functionality model

Author	Criteria and indicators		
	Node index	Place index	Tie index
Pan & Huang (2024)	Public transport accessibility (metro nodes' infrastructure and service data), bus route density, metro network closeness centrality, and betweenness centrality)	Destination accessibility (topological data of station areas), place (land use diversity, POI density),	Functionality (intersection density, pedestrian shed ratio, shape index)
Su, Wang, et al. (2022)	Carrying capacity (number of entrances, metro, line, and direction), serving capacity (service duration), and connectivity capacity	Land use diversity, land use mixture	Functionality accessibility (average distance to different activities), serviceability, walkability, sociodemographic (age and income)

Table 2-4 Literature using the node-place-design model

Author	Criteria and indicators		
	Node index	Place index	Tie index
M. Zhang & Lee (2023)	number of directions served by metro, by bus, parking, and station platform, as well as frequency of metro	number of residents, number of workers in different sectors, number and variety of points of interest, and degree of functional mix)	Design (pedestrian and cycling network, pedestrian shed ratio, and cycling accessibility)
Pezeshknejad et al. (2020)	Frequency of train services, number of stations in 20 min, passenger frequency, proximity to CBDs	Population, number of workers in different sectors, degree of functional mix, possible destination points	Design (Street integration, betweenness, number of streets connected to a street, street density)
Y. Zhang, Marshall, et al. (2019)	Number of directions and station and frequency of service of metro and bus, parking, and distance to closest motorway access	Number of residents and workers, land use mix	Design (ped shed ratio, intersection density, accessible network length)
Vale et al. (2018)	Number of directions served by metro and other public transit, stations in 20 min, frequency of service, distance to the closest highway, availability of parking	Number of residents and workers in different sectors, degree of functional mix, number and variety of POIs	Design (Ped shed ratio, intersection density, accessible network length)

Table 2-5 Literature using the node-place-tie model

Author	Criteria and indicators		
	Node index	Place index	Tie index
Zhao et al. (2024)	Number of metro and bus routes, frequency of bus and metro, car ownership, street and sidewalk length	Population, jobs, area of residential, commercial, civic, and open space, as well as land use mix	People- vulnerability (number of ethnic, elder, foreign-born, low income, without car person)
Y. Yang et al. (2022)	Number of directions served by metro, metro and bus services, betweenness centrality and closeness centrality of metro network	Population, establishment facilities, leisure facilities, catering and restaurant facilities, administration facilities, education facilities, retail facilities, hotel facilities)	Vibrancy ¹¹ (daily inflow and outflow, nighttime activity) Design (morphology, compactness, pedestrian network, road intersection, and station functionality)
Su, Zhao, et al. (2022)	Number of metro station's entrances, lines, frequency of train services, number of stations in 20 min reach, connectivity of station in the network, closeness, average distance between stations	Density (populating, building, and road density), Diversity (land functional mixture, land use three-dimensional mixture, land use entropy)	Sociodemographic (proportion of educated, blue-collar, and employed people in catchment area) Design (average distance to different facilities, intersection density, street network betweenness, quantity of bus route and shared bicycle)
Cao et al. (2020)	Accessible opportunities, network centrality, and train service	Density, diversity, and design	Ridership
Nigro, Bertolini, Domenico, et al., (2019)	Number of directions served by metro, frequency, and presence of ticketing service	Residential and job density, number of students	Feeder transport indicators
Z. Li et al. (2019)	Metro station bearing capacity, service capacity, and connectivity	Land use diversity and mixture	Accessibility (distance to different facilities), walkability
Lyu et al. (2016)	Transit (number of directions served by metro and bus, and stations in 20 min, frequency of metro service, parking capacity, travel time to main activities by metro)	Development (number of residents, jobs, and workers in different sectors, degree of functional mix)	Oriented (walk score, average block size, the average distance from the station to jobs and residents)

¹¹ The concept of urban vibrancy, or vitality, was initially proposed by Jacobs (1961) as a measure of the interactions between residents and the urban environment. It can be defined as "the intensity of human activities and interactions" within a given urban setting (Y. Yang et al., 2022).

Another technique based on the assessment of multiple attributes is the TOD index. The actual and potential TOD indices have been employed to evaluate the built environment sustainability of existing TODs and identify potential areas for establishing future TODs, respectively (Singh, Martinez et al., 2015). The assessment uses the sustainability criteria within the stations' catchment area. Subsequently, the weighted or unweighted indicators are aggregated to obtain the TOD index, upon which the station areas are clustered and planning interventions are proposed.

Table 2-6 provides an overview of the application of the TOD index with different objectives and the indicators used by researchers. For instance, Motieyan and Mesgari (2017) employed a TOD index, a composite score comprising socioeconomic, density, diversity, and design indicators, to evaluate the TOD level. Subsequently, the model was validated for the case study of Tehran, Iran, by comparing the results with the level of public transit services and trip attractions in neighborhoods. In addition, a sensitivity analysis was conducted with different weights of the indicators obtained from the fuzzy AHP method. H. Chen et al. (2024) also employed a type of TOD index entitled the "comprehensive socio-economic development Index (CSEDI index)." This composite TOD score was obtained by normalizing and adding the selected indicators with equal weights for the Shanghai, China case study. Subsequently, the CSEDI index's site-specific effectiveness was validated using weighted sub-indicators with principal component analysis (PCA) and a regression analysis.

Table 2-6 Literature using the TOD index

Author	Objective	Criteria and indicators
Ibrahim et al., (2023)	Identify and rank the station areas with potential for TOD	Density, diversity, design, and economic development
Taki and Maatouk (2018)		Transportation-related, urban environment, economic development
Budiati et al. (2018)		Density, diversity, design, destination accessibility, distance to transit (5D)
Huang et al. (2018)	TOD typology to identify different roles of transit stations in the network	Density, diversity, destination accessibility, design
Motieyan and Mesgari (2017) and (2019)	Measure the green TOD level of neighborhoods.	Pollution, green infrastructure, energy optimum usage, density, diversity, urban design, and economic development
H. Chen et al. (2024)	Comparative assessment of the TOD level	Land use types, population, ridership, house price, POI
Ke et al. (2021)		Using socio-economic development index and urban big data: Transit efficiency, social, economic, and environmental indicators
Singh et al. (2017)		Density, diversity, design (walkability and cyclability), economic development, capacity of transit service, quality of transit system
Singh et al. (2014)		Density, diversity, economic development

Multi-objective assessment methods

According to Liu et al. (2018), "factors that do not have clear threshold but induce clear expectation can be categorized into objectives." This includes transit ridership and other indicators of accessibility. Multi-objective techniques can be employed to facilitate optimal decision-making concerning competitive objectives. For instance, a Genetic Algorithm-based optimization technique considers the trade-off between transportation and land use objectives to identify the optimal locations for station improvements (X. Ma et al., 2018; Sahu, 2018). The data envelopment analysis (DEA), initially proposed by Charnes et al. (1978), can also be employed in TOD literature to define the relative efficiency of station areas regarding sustainability indicators. DEA is a non-parametric and data-driven method employed to evaluate

the efficiency of decision-making units (DMUs)¹². A variety of DEA models have been employed for the assessment of TOD, using a ratio of a weighted sum of multiple outputs-inputs, such as TOD variables, in a manner that optimizes the efficiency of the target units, such as transit ridership (Guo et al., 2018; Tamakloe & Hong, 2020). The DEA models can be used to assess and compare TOD projects. It also supports planners and decision-makers in identifying the most efficient areas for improvement and prioritizing interventions.

Although different DEA model variables have been used in TOD literature (Table 2-7), the overall steps are as follows: 1. define decision variables (inputs and outputs) and decision-making units (DMUs), 2. "evaluate the weight coefficients of DMU input and output index," 3. define the efficiency of each DMU. It also may determine "slacks," which indicates the required improvement (increase in outputs or decrease in inputs) for each DMU to become efficient, in other words, to minimize the distance to an efficient frontier (Y. Zhang & Guo, 2017).

¹² The results of the DEA model are sensitive to the quality of the data and the context of the study; however, due to its non-parametric nature, it is less sensitive to outliers or data patterns.

Table 2-7 TOD literature using DEA

Author	Method	Input data	Output data
T. Chen et al. (2023)	Super efficiency & Bootstrap analysis	Land use indicators	Metro, bus, and bicycle ridership
Khare et al. (2020)	Super efficiency		BRT indicators
Tamakloe & Hong (2020)	CCR		Ridership
E. H. Lee et al. (2019)	CCR	Land use, socio-economic indicators	transit stations, lines, trips, energy generation of trips
Guo et al. (2018)	CCR		Ridership
Zhang & Guo (2017)	Slack-based CCR		Transit system
Wey (2013 and 2015)	DEA/AR (with assurance Region)	Land use indicators	Cost-effective development

2.2.3 Key Steps of TOD Assessment Methods

Delineation of TOD areas

The TOD area is delineated within the station influence area using both buffer-based and analytical methods. The circular buffer is the simplest method, typically defining TOD within a 400- to 800-metre radius or within a 5- to 10-minute walk of the public transit station. However, this method overlooks the impact of access barriers and overlapping areas in adjacent stations.

The analytical methods encompass network-based techniques, including service area and location-allocation GIS techniques. Andersen and Landex (2008) compared the station catchment area using the circular buffer and service area methods, concluding that the service area allows for a more detailed analysis, particularly when considering obstacles such as dead ends and intersections with traffic lights. The Ped Shed Ratio (Pedshed) is the ratio of the station pedestrian service area to the station circular buffer, which is used to assess a pedestrian network's connectivity (Schlossberg & Brown, 2004). Table 2-8 provides an overview of methods for defining the TOD area.

Table 2-8 Methods of defining TOD area

	Method	Reference
Analytical	Service area analysis	Conesa (2018), Lyu et al. (2019)
	Location and allocation	T. Lin et al. (2014)
	Thiessen polygons ¹³ with/without circular buffers	Liu et al. (2018), Khosravi et al. (2024), Liu et al. (2018), (Fan et al., 2022)
	Impedance Pedestrian Catchment Area	Ke et al. (2021)
	Combination of "Linear Referencing Method" and "Improved Huff Model" ¹⁴	Z. Zhu et al. (2021)
Euclidean (circular buffer)	400-500 m (5 min walking distance) for neighborhood	Faghri and Venigalla (2014); Loo and du Verle (2017); Papa et al. (2013); Wey et al. (2016)
	700-800 m radius (10 min walking distance) for community centers, CBD, or transit hubs	Budiati et al. (2018); Chorus and Bertolini (2016); Cournoyer-Gendron (2017); Huang et al. (2018); Kamruzzaman et al. (2018); Lyu et al. (2016); Nurlaela et al. (2019); Nyunt and Wongchavalidkul (2020); Renne et al. (2016); Santiago (2017); Searle et al. (2014)
	3000 m radius for E-TOD	Chatman (2013)
	3000 m radius for B-TOD	Lee et al. (2016)
	Within the area of the theoretical and "functional" buffer	Higgins and Kanaroglou (2018)
	Combination of 400m core, 800m catchment area, and 1600m influence area of metro stations	Jamaleddin et al. (2022)
	A mathematical model to define which TAZs ¹⁵ can be considered TODs in terms of population and employment density, entropy, and station buffer radius	Nasri & Zhang, (2014), Zamir et al. (2014), and Nasri et al., (2018a)

Selection and calculation of criteria and indicators

The built environment principles of TOD can be evaluated using the sustainability criteria of density, diversity, and design (3Ds), initially proposed by Cervero and Kockelman (1997) and subsequently extended to 5Ds by R. W. Lee and Cervero

¹³ The advantage of using the combination of the circular buffer and Thiessen polygon (Voronoi diagram) is that the catchment areas of the stations do not overlap.

¹⁴ Z. Zhu et al. (2021) employed the "Linear Referencing Method" for delineating the boundary of the station area and the "Improved Huff Model" for calculating the probability that a transit station is selected by residents, taking into account the Walk Score, the level of public transport accessibility, and the service quality score.

¹⁵ A Traffic Analysis Zone (TAZ) is a transport planning unit that contains information required for travel demand, including socio-economic, geographical, land use and transport infrastructure data.

(2007). These sustainability criteria encompass density, diversity, design, destination accessibility, and distance to transit. The 6th D was later introduced by Ogra and Ndebele (2013) and employed by Ewing et al. (2021) to refer to demand management. The 7th D was later proposed by Kapoor et al. to address the demographic dimensions that influence residents' mode choices. To measure these criteria, researchers typically draw indicators from literature reviews and expert judgment techniques, such as the Fuzzy Delphi method (Wey et al., 2016). The following provides a succinct overview of the 5D criteria and indicators.

The term density is defined as the number of people or the proportion of a specific land use type's area to the total area. It can be further subdivided into the following categories: population density, build-up area density, and residential density (Mahriyar & Rho, 2014), commercial density, the density of urban open spaces (Lokku & Prasad, 2018), and employment density as defined by Wey, Zhang, and Chang (2016).

Diversity can be defined as the heterogeneity of land use types within a given area, such as residential, commercial, industrial, and recreational uses. This can be quantified using the mixed-ness index (Singh, Lukman, et al., 2015) and the entropy measure (Cervero & Kockelman 1997; Budiati et al. 2018). A high population density, coupled with diverse land use and activities in a transit station area, results in compact urban development with a vibrant community, which is one of the fundamental principles of TOD.

The design criteria concern the physical and aesthetic quality of streets and urban open spaces, which impact residents' choices of walking and cycling to the station. This includes indicators such as walk score and bike score (Gilderbloom et al., 2015; Xia et al., 2019) and street connectivity (Motieyan & Mesgari, 2017). The design

criteria are intended to create a walking and cycling-friendly environment, which is the other principle of TOD.

Destination accessibility describes the ease with which key destinations can be reached from the station area via active, private, and public access modes. This includes "the potential for interaction," as indicated by population, employment, and public transit service indicators, as well as "the potential for interchange with other transit systems," as indicated by road network and transit network indicators (Budiati et al., 2018).

Distance to the transit station is also one of the five sustainable criteria (5Ds), as a shorter distance for residents to the station is typically associated with increased transit ridership and a reduction in car dependency. The combination of destination accessibility and distance to transit, in turn, promotes public transport accessibility, which represents the third principle of TOD.

Preparation and aggregation of data

The acquisition of data for the TOD area entails collecting data from both spatial and non-spatial databases. The primary data is then aggregated to calculate secondary data as a composite indicator, such as the TOD index and node, place, and tie indices. Generating a composite indicator involves several analytical procedures, including correlation analysis, data scaling, weighting, and data aggregation.

Researchers use different correlation analysis techniques to verify the relationship between variables. The Pearson Correlation Coefficient (PCC) identifies variables that demonstrate a high degree of correlation with one or more variables, which may decrease the reliability of the statistical analysis (Ewing et al., 2017; H. Chen et al., 2024). Principal Component Analysis (PCA) can generate new sets of uncorrelated variables (Lyu et al., 2016a; Nguyen et al., 2020; Nyunt & Wongchavalidkul, 2020).

Canonical Correlation Analysis (CCA) identifies the correlation between two sets of variables and their components (Nurlaela et al., 2019; Pezeshknejad et al., 2020).

Data scaling is a pre-processing technique used to adjust data values to a range of 0 to 1. Researchers used a variety of techniques, including the unit-based normalization method (R. Huang et al., 2018; Motieyan & Mesgari, 2017), z-score normalization (Lyu et al., 2019; M. H. Taki & Maatouk, 2018), and min-max rescaling technique (Singh et al., 2017). In the min-max technique, the correlation of the variables with the target variable, whether positive or negative, determines the rescaling formula. For example, since higher travel time results in lower accessibility (i.e., a negative correlation), it is rescaled by the cost formula. However, the better transit service results in higher accessibility, which is positively correlated, so the benefit formula is used.

Before aggregating indicators, it is also essential to define their relative importance in relation to the research objectives, past data, and expert judgment. A literature review reveals that subjective weighting methods are more prevalent than objective ones. The weighting methods may be grouped into the following categories. The initial category pertains to the weighting of variables according to expert judgment. This encompasses rank-order weighting (Budiaty et al., 2018; Roszkowska, 2013; Singh et al., 2017), ranking based on the expected value or range (Rahmat et al., 2016; M. H. Taki & Maatouk, 2018), as well as pairwise comparison including Analytic Hierarchy Process (AHP) (H. M. Taki et al., 2017), Fuzzy AHP (Motieyan & Mesgari, 2017; Ke et al., 2021), combination of AHP and entropy methods (W. Yang et al., 2024), Analytic Network Process (ANP) (Wey & Chiu, 2013), and Fuzzy ANP (Wey et al., 2016). The second category is weighting according to the perspective of TOD residents (Sohoni et al., 2017; Yap & Goh, 2017). However, some researchers have used objective weighting methods, whereby the weight

assigned to each indicator is defined in relation to a target variable. For example, Lyu et al. (2019) employed multiple regression analysis to determine the relative importance of TOD indicators according to their effect on the target variable (accessibility). Finally, indicators should be aggregated to produce a composite score in multi-attribute methods. The TOD index can be calculated using the weighted sum method (Rahmat et al., 2016) and the overlaying technique (Dou et al., 2016; Singh et al., 2014).

Data analysis

Depending on the type of data and the purpose of the analysis, different methods of data analysis, including descriptive, analytical, and spatial analysis, are used alone or in combination.

Descriptive statistics such as spider web diagrams, means, and standard deviations summarize and describe a data set's main characteristics (Budiati et al., 2018; Ehman et al., 2017; Singh et al., 2017). Analytical statistical techniques infer patterns and relationships between datasets. These include regression analysis (Faghri & Venigalla, 2014; Lyu et al., 2019) and clustering techniques such as two-step cluster analysis (S. Lee et al., 2013; Kamruzzaman et al., 2014; Olaru et al., 2019; Jeffrey et al., 2019), multi-step clustering (Lyu et al., 2016a), latent class clustering (C. D. Higgins & Kanaroglou, 2016; R. Huang et al., 2018), K-means clustering (S. Li et al., 2020), hierarchical cluster analysis (Lyu et al., 2016b), "self-organizing maps algorithm"(SOM), an unsupervised machine learning algorithm for clustering and outlier identification (Z. Li et al., 2019a).

Additionally, researchers employ spatial analysis techniques, including spatial clustering, hotspot analysis, and outlier detection, to identify spatial correlations between data points. In this regard, Singh et al. (2014) used " the Getis Ord Gi and Anselin Local Moran's I statistics" to identify the potential TOD areas by hot spot

analysis. Dou et al. (2016) evaluated the success of existing TODs regarding the correlation between population density and accessibility using a "geographically weighted regression model." They applied spatial cluster analysis and Getis-Ord Gi to detect changes in urban morphology and Anselin Local Moran's I to define "migration origins and destinations" that reflect accessibility and CO2 emissions. In other studies, Kamruzzaman et al. (2018) and Singh et al. (2017) applied the Global Moran's I to confirm the presence of clusters, followed by Anselin Local Moran's I for clustering and outlier analysis. Later, Pan & Huang (2024) applied a type of latent class clustering method (latent profile analysis) to cluster station areas and a machine learning algorithm, "gradient boosting decision trees," to investigate the possible non-linear relationships between TOD variables and metro station vibrancy.

2.2.4 Accessibility and Transit-Oriented Development¹⁶

Accessibility reflects "the interdependencies and trade-offs between land use and transport patterns" (Bertolini et al., 2005), which determine the form and direction of urban development. According to Deboosere et al. (2018), accessibility is "a comprehensive measure of the interaction between land use and transport" and "the ease of reaching destinations." Consequently, the quality of TOD analysis depends on the precision with which its accessibility is quantified, taking into account four elements: land use (including travel origin and destination), transport service and network, travel impedance (the cost and time of travel), and travelers' mode choice (active, public, and private).

Four types of accessibility measures were used to quantify accessibility: location-based, infrastructure-based, person-based, and utility-based (Conesa, 2018; Geurs &

¹⁶ Section 2.2.4 (Accessibility and TOD) summarizes the review paper by the same authors, titled "Transit-Oriented Development and Accessibility: A Review and Conceptual Framework Proposal," which has been accepted for publication by the International Journal of Sustainable Transportation.

Wee, 2004). Location-based accessibility measures have been commonly employed in the context of Transit-Oriented Development (TOD) literature, which focuses on the ability to access specific locations and activities. This access can be evaluated using graph theory (connectivity measure), the number of opportunities (accessible activities) as a cumulative opportunity measure, or by considering both the distance and attractiveness of destination opportunities through gravity-based measures. Infrastructure-based accessibility concerns the quantity and quality of services and transportation networks. However, person-based accessibility has been considered when analyzing residents' mode choices. They can also be used in the typology of station areas as indicators of node and tie indices, respectively. However, utility-based accessibility, which concerns the financial benefits of access to different locations, except Mudigonda et al. (2014), has typically been overlooked in TOD literature. For a tabular summary of the location-based, person-based, infrastructure-based, and utility-based accessibility measures, as well as the classification of accessibility types used in TOD literature, please refer to Appendix A-1. Having provided an overview of the various accessibility types and measures employed in TOD studies, the subsequent sections will examine the reciprocal impacts of TOD and accessibility.

The role of accessibility in TOD evaluation

Whether as one of the D-variables or in other forms, accessibility has consistently been the primary factor in TOD evaluation across various multi-attribute, multi-objective, and single-attribute methods.

The criticality of accessibility among D variables, such as 5Ds, is illustrated in Figure 2-6. Population density and land use diversity change the demand for travel and travel patterns. On the other hand, urban design factors and the distance to transit stations influence travelers' mode choice.

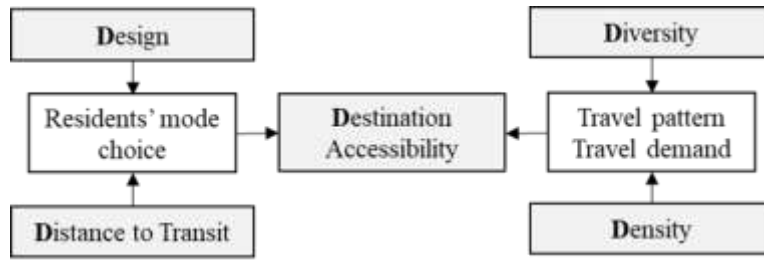


Figure 2-6 The critical role of accessibility in 5D variables

Accessibility is a key assessment factor in multi-attribute methods, such as the TOD Index and node, place, and tie indices. For instance, it was used in developing the TOD index by H. Chen et al. (2024) and Motieyan & Mesgari (2017), as well as in the development of the node index in the node-place model proposed by Bertolini (1999) that used by Nemroudi et al. (2024) and other researchers. It was also used in the subsequent modifications of the Bertolini model in the form of node, place, and design models by Vale et al. (2018), Pezeshknejad et al. (2020), and M. Zhang & Lee (2023), the node-place-orient model developed by Lyu et al. (2016a), and the node-place-functionality model by Su, Wang, et al. (2022) and Pan and Huang (2024).

In addition, to enhance sustainable accessibility, maximizing transit ridership has been considered one of the main objectives in different multi-objective methods conducted by researchers such as Berawi et al. (2020), X. Huang et al. (2021), X. Ma et al. (2018), and J. Li et al. (2022). In addition, the number of passengers using public transport was used as an indicator of the efficiency of TODs in the application of data envelopment analysis (DEA) by J. Guo et al. (2018) and Tamakloe & Hong (2020).

Furthermore, the accessibility index can serve as a primary metric for evaluating TODs. This includes the accessibility index proposed by S. Lee et al. (2013), the multiscale accessibility index developed by Conesa (2018), and the "citywide rail transit accessibility index" introduced by Cong et al. (2024).

In addition, accessibility has been used by researchers to evaluate the environmental impacts of TOD in terms of CO2 emission (Liu et al., 2018; Motieyan & Mesgari, 2019; Chindaprasirt et al., 2024), urban heat island (Kamruzzaman et al., 2018), urban sprawl (D. Ma & Chen, 2019), and other ecological effects (W. Yang et al., 2024). Please refer to Appendix A-2 for an overview of the role of accessibility in TOD literature.

Impact of TOD on accessibility

The concentration of population and activities following TOD principles inevitably affects accessibility, albeit not to the same extent. The studies by Lyu et al. (2019) and Papa & Bertolini (2015) showed that compactness, defined as the concentration of population and activities in the proximity of the transit station, has the most significant impact on accessibility. The impacts of TOD on station areas' accessibility can be identified in terms of travel demand and residents' travel behavior.

The travel demand of residents is directly influenced by land-use alterations, particularly by increasing the density and diversity of population and activities in the TOD area. Cervero & Kockelman (1997) posited that the effect of the built environment on travel demand could be measured by 3Ds, later improved to 5Ds by R. W. Lee and Cervero (2007). Nyunt and Wongchavalidkul (2020) also showed a strong relationship between transit ridership and land-use variables. In another study, Y. Wang et al. (2016) examined the impact of increasing population and employment density on travel demand.

Additionally, living in pedestrian-friendly environments and having access to adequate public transportation options influence residents' mode choices. The impact of TOD on residents' travel behavior can be quantified regarding the reductions in parking (Ewing et al., 2021; Tian et al., 2017) and car use in terms of "vehicle miles traveled" (Fan et al., 2022; Nasri & Zhang, 2014; Park, Ewing, Scheer, & Ara Khan,

2018) or "vehicle kilometers traveled" (F. Chen et al., 2017), as well as increases in transit ridership (S. Lee et al., 2013; Nyunt & Wongchavalidkul, 2020; Pan et al., 2017a; H. Zhu et al., 2024). Moreover, some studies have sought to compare the impact of land use and transportation factors on transit ridership (Amini Pishro et al., 2022; Cao et al., 2020; Su, Wang, et al., 2022; Su, Zhao, et al., 2022). Transit ridership can also be used to identify key TOD indicators, as noted by Li et al. (2016). For an overview of the impacts of TOD in terms of changes in travel demand and residents' travel behavior, please refer to Appendix A-3.

2.3 Disaster Mitigation

Disaster management is a multidisciplinary approach that includes pre-disaster preparedness and mitigation planning to prevent and reduce the adverse effects of disaster and its impacts, emergency response during a disaster, and post-disaster recovery for social and structural rehabilitation (Public Safety Canada, 2017).

The pre-disaster phase of emergency management encompasses preparedness strategies aimed at enhancing the capacity of society and communities to respond effectively when a disaster strikes, as well as mitigation strategies designed to prevent and mitigate the disaster's impact by reducing vulnerability and increasing resilience. Vulnerability characterizes a system's ability to prevent disasters, while resilience is its ability to resist, respond to, and recover from disasters (S. P. Simonovic & Peck, 2013). A systemic approach to disaster management focuses attention on a system's internal capabilities and interactions, rather than external factors beyond its control, such as hazards (S. P. Simonovic, 2015). Therefore, in addition to societal mitigation measures (e.g., increasing public awareness), which are beyond the scope of this study, efforts to identify and reduce system

vulnerabilities and increase resilience make the system inherently capable of coping with the hazard event.

It is also necessary to integrate disaster mitigation into urban development planning. As articulated by the United Nations Commission on Sustainable Development (2001), the objective of disaster mitigation is "to enable societies to be resilient to natural hazards while ensuring that development efforts do not increase the vulnerability to these hazards"(Godschalk, 2003). Also, the Institute for Catastrophic Loss Reduction (2011) stated that Canada's vision is "to develop a society that is more resilient to natural disasters, where sustained planning, investment and action result in more sustainable communities" (Dotto et al., 2010). This highlights the need to integrate disaster mitigation strategies with long-term urban development strategies such as TOD.

2.3.1 Conceptual Framework

This section focuses on mitigating disaster risks in the built environment and their impacts on structural damage and performance loss by reducing vulnerabilities and enhancing resiliency. It also highlights the role of accessibility in disaster mitigation (Figure 2-7).

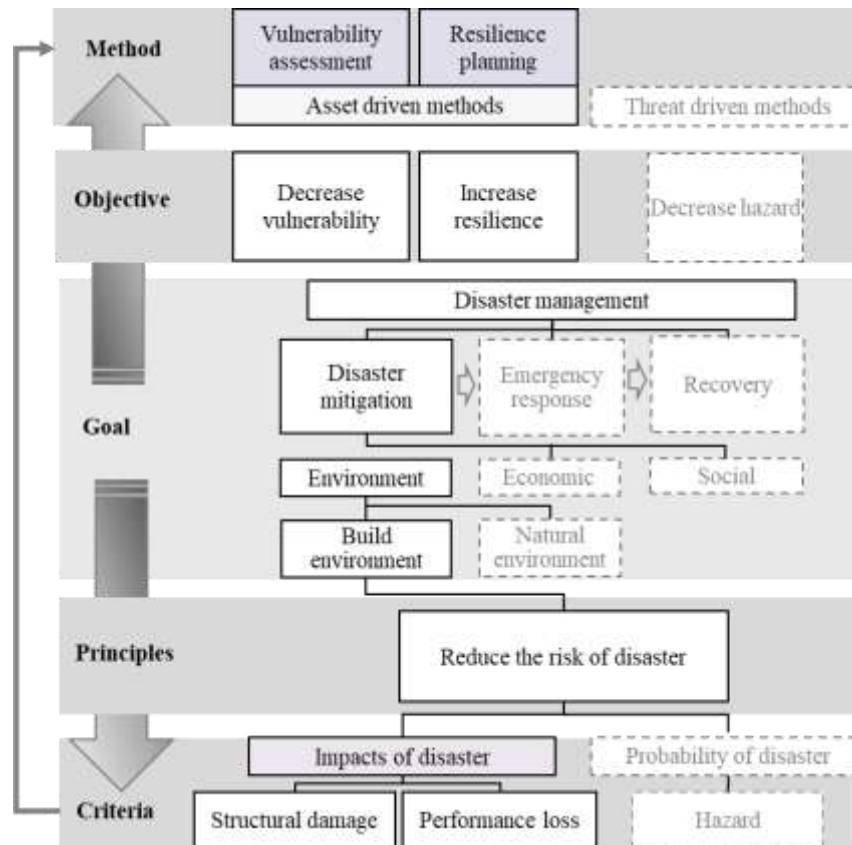


Figure 2-7 Conceptual framework

2.3.2 Disaster Mitigation Strategies

This section defines disaster risks and the primary strategies to mitigate them in terms of reducing urban vulnerability and enhancing resilience.

Risk of disaster

Risk can be defined as the likelihood of a hazardous event occurring and its potential negative consequences (Park & Lee, 2019). However, different interpretations of risk lead to different methodological approaches. Some researchers consider risk "the product of hazard likelihood, magnitude, and consequence" (Nelson et al., 2019). Hazards are unexpected events with high negative impacts, either natural or man-made. Natural hazards encompass meteorological hazards (e.g., floods, heatwaves, storms) and seismic hazards, which are increasing in frequency and intensity due to

climate change. Others, including this research, are concerned with the adverse consequences of disasters, shifting the focus from uncontrollable external factors such as hazards to the reduction of urban vulnerability and the enhancement of resilience

Urban vulnerability

In 2007, the International Panel on Climate Change (IPCC)¹⁷ defined vulnerability as "the degree to which a system is susceptible to and unable to cope with the adverse effects of hazards." Urban vulnerability is defined regarding the magnitude, frequency, and type of hazard, the characteristics of urban infrastructure (including structural integrity, criticality, and interdependencies), and the socioeconomic factors of the targeted community (Fakhruddin et al., 2015).

In 2014, the IPCC shifted its focus from external factors, such as hazards, to the inherent properties of the urban system, namely exposure, sensitivity, and adaptive capacity. Exposure is "the degree, duration, and extent in which the system is in contact with, or subject to the perturbation" (Lee, 2019). Sensitivity is the "characteristics of sectors, systems, and groups of people directly or indirectly influenced by threats"(M. Zhang et al., 2019). Exposure, together with sensitivity, determined the magnitude of damage. In contrast, adaptive capacity represents the ability of the urban area to withstand hazards, including the "adaptive capacity of the populations, functions, and structures"(Marcussen, 2018).

¹⁷ IPCC 2007, Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, and IPCC 2014, Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.

Urban resilience

In their review paper on "Defining Urban Resilience," Meerow et al. (2016) introduced resilience as the ability of a system affected by hazards to resist, respond, and recover promptly. In addition, Simonovic and Arunkumar (2016) emphasized the importance of past disaster experiences in preparing for more effective responses to disasters and revising disaster mitigation plans.

Resilience is characterized by four attributes, known as the 4Rs: robustness, resourcefulness, redundancy, and rapidity. The term "robustness" refers to the ability of a system to withstand stress or pressure. "Redundancy" refers to the extent to which the constituent elements of a system are substitutable. "Resourcefulness" describes a system's capacity to provide the necessary performance and resources. Furthermore, "rapidity" shows how a system can resume normal performance promptly after a disruption (Bruneau et al., 2003). Figure 2-8 illustrates how the risk of failure, or the likelihood that the system will perform below a desired level, can be reduced by increasing the resilience attributes. In this figure, p^* is the performance threshold for the system to have a normal function, and the triangle below this level and duration ($t_1 - t_2$), represents the failure of the system performance (risk of damage).



Figure 2-8 Resilience attributes, adapted and modified from Simonovic and Arunkumar (2016)

In the context of urban resilience, time is a critical factor, as opposed to risk and vulnerability (Bristow et al., 2014; Hay, 2013). The resilience of a system can be determined by identifying the following critical timeframes: the time of hazard occurrence (t_0), the duration the system can withstand pressure before failure ($t_0 - t_1$), the period requiring emergency actions to prevent further damage ($t_1 - t_2$), and the time needed to recover and resume a safe operational state ($t_2 - t_3$).

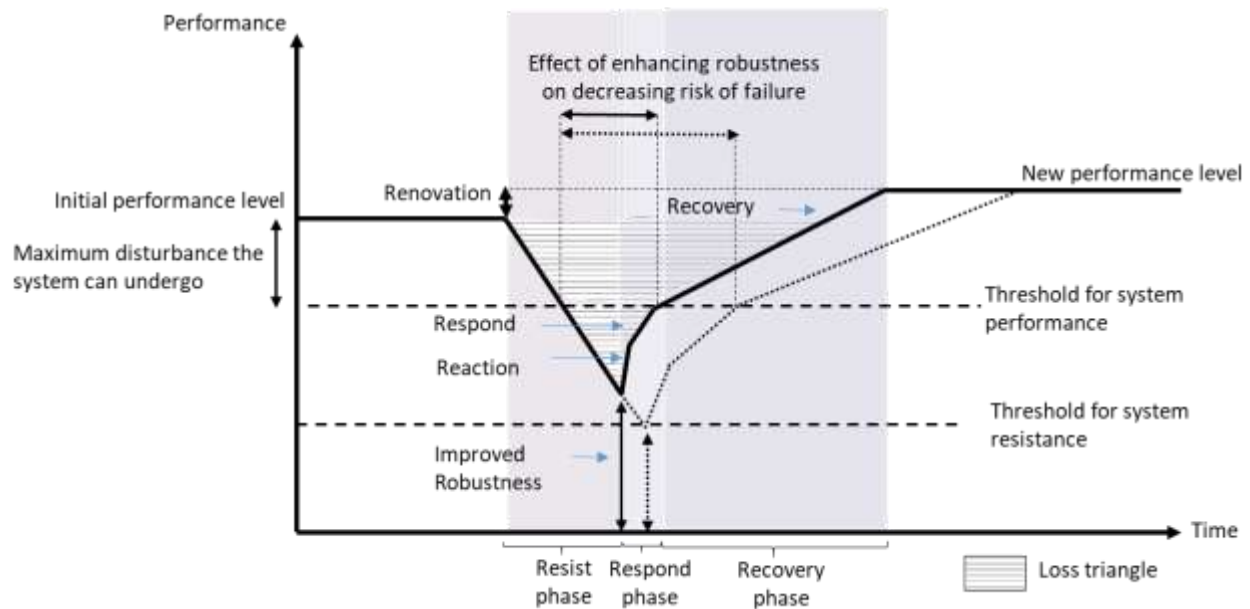


Figure 2-9 Resilience diagram

After facing a hazard event, urban systems —encompassing infrastructures, people, and organizations —experience three phases of resilience. The first phase of resilience depends on the reliability of the infrastructure, specifically its resistance to physical failure. Enhancing robustness and physical strength reduces the risk of failure. Second, the "respond" phase focuses on the emergency response that helps urban functions recover to their desired level of performance. For example, if there is redundancy in the road network (e.g., reserved lanes for emergency services) and emergency centers (e.g., hospitals and shelters), evacuation and emergency services

will be facilitated, resulting in reduced human and property losses. Finally, the third phase of resilience involves rehabilitation and recovery actions, which depend on resourcefulness, in other words, abundant social, economic, and organizational investments. In general, the total renovations enhance the performance of the infrastructure to a higher level than before the hazard attack, considering the usual deterioration that assets experience over time (Figure 2-9).

2.3.3 Disaster Mitigation Methods

Disaster mitigation involves risk identification to define the source and magnitude of hazardous events, followed by risk assessment to measure its likelihood and negative impacts (Theocharidou & Giannopoulos, 2015). It also involves the application of strategies to assess and manage urban vulnerability and resilience by considering the interdependencies among critical infrastructures (Seidelsohn et al., 2018). In recent years, there has been a significant shift in disaster mitigation from improving the resistance of infrastructures to resilience (Simonovic, 2016). Improving infrastructure resistance can postpone disasters, but it can also indirectly lead to more catastrophic consequences in the long run. For example, the construction of levees may delay the risk of flooding, but it may also result in greater damage during the flood event.

Risk assessment

White et al. (2014) categorized risk assessment methods into two groups: "threat-driven" and "asset-driven" approaches. The threat-driven approach focuses on the likelihood of risk occurrence, where risk is a function of factors such as hazard, vulnerability, exposure, and resilience (Table 2-9). However, the asset-driven approach focuses on mitigating the negative consequences of disasters, including socio-economic damage, structural failure, and loss of performance, which is also a common goal of risk, vulnerability, and resilience studies.

Table 2-9 Relation between risk, vulnerability, and resilience

Relation		Authors
Risk & Vulnerability	Risk is a function of vulnerability and exposure	(Park & Lee, 2019)
	Risk is a function of vulnerability and hazard	(Waghwalā & Agnihotri, 2019), (Y. Wu et al., 2015)
	Risk is a function of vulnerability, exposure, and hazard	(Asefa & Mindahun, 2019), (Lyle & Hund, 2017), (Lückerath et al., 2018), (Manna et al., 2019)
Risk & Resilience	Risk mitigation through resilience strategies	(Waghwalā & Agnihotri, 2019)
	Resilience is a function of risk impacts	(E. H. Lee & Kim, 2017), (Xian et al., 2018)
Risk & Resilience & Vulnerability	Risk is a function of hazard, exposure, vulnerability, and coping capacity	(E. Guo et al., 2014), (Rubio et al., 2019)

There are several tools and techniques for risk analysis, including the risk matrix, fault tree analysis, and risk assessment software. The risk matrix is a two-dimensional representation of risk in terms of relative risk impact and probability in both qualitative and quantitative methods (Theocharidou & Giannopoulos, 2015). The fault tree technique depicts the possibility of system failure in terms of the interdependencies of system components (Rausand & Hoyland, 2004). For example, Tang and Huang (2019) used a fault tree as a first step in analyzing the vulnerability of the road network to account for the interdependencies between path failures and the disconnectivity of the road network. In addition, there are software programs designed for hazard risk assessment, as presented by Lyle & Hund (2017) in a review of "risk assessment tools in Canada."

Vulnerability assessment

A vulnerability assessment is a process that involves several activities, including identifying critical hazards, assessing dimensions of vulnerabilities, and developing a vulnerability index or map.

The first phase of a vulnerability assessment involves identifying critical hazards and preparing a hazard map for the study area. The determination of the dominant hazard can be made using historical data and expert judgment by the application of decision-making methods such as the Analytic Hierarchy Process (AHP) (M. Zhang et al., 2019). The hazard map can be created using the HAZUS-Canada software, as was done by Tamima and Chouinard for the Montreal case study (Tamima & Chouinard, 2016), or by using different GIS datasets, as was done in Freetown, Sierra Leone, to create a multi-hazard map (Nelson et al., 2019).

Secondly, it is essential to define the type, scale, and factors of vulnerability assessment. A system or its components are subjected to a vulnerability analysis in the context of a single or multiple hazards. Furthermore, vulnerability can be evaluated at the national level, at the urban scale, or for specific critical infrastructure, for example, national-level vulnerability assessments to climate change (L. Li et al., 2019), a study in urban-scale of school-based flood emergency response in Shanghai, China (Yin et al., 2019), and considering interdependencies among critical infrastructure for vulnerability assessment in Taipei, Taiwan, concerning (Hsieh et al., 2014).

To conduct a vulnerability assessment, the Intergovernmental Panel on Climate Change (IPCC) introduced three key assessment factors: sensitivity, exposure, and adaptive capacity. The sensitivity measure reflects the question of "Who or what is at risk?" (Simonovic & Peck, 2013). The sensitivity index comprises social, economic, and physical indicators, including the structural condition of infrastructure

that renders it susceptible to failure, as well as the number of elderly, disabled, or low-income residents living in the area who may experience difficulties during the evacuation period following a disaster. The exposure index represents "the degree, duration, or extent to which the system is in contact with, or subject to the perturbation"(Lee, 2019). As noted by Dotto et al. (2010), urbanization can increase exposure to hazards due to the concentration of people and property. The location of assets also influences this, as reflected in the hazard map (Rowan et al., 2015). Adaptive capacity can be defined as "the capacity of populations, functions, and structures" to withstand the impact of a hazard (Marcussen, 2018). Some examples of adaptive capacity indicators include governance capacity and the capacity of early warning and drainage infrastructure (M. Zhang et al., 2019). In addition to the sensitivity, exposure, and adaptive capacity indices, some researchers consider other factors. For example, concerning the interdependencies among the IPCC assessment factors, Lee and Choi introduced three "intermediate" factors: potential impact, livelihood vulnerability, and internal factors (J. S. Lee & Choi, 2019). In another study, Alejandro and Santos employed the IPCC indicators, along with the damage index, to assess the vulnerability of people, homes, services, and infrastructure to flooding (Alejandro & Santos, 2018).

The third phase involves developing a vulnerability index or map at either the macro level (e.g., network performance) or the micro level (e.g., critical infrastructure). The existing literature can be divided into two categories based on the incorporation of probability analysis into vulnerability assessment (H. Zhang & Yao, 2019). The initial group of vulnerability assessment literature focuses on structural or performance failure and its consequences without considering the probability of failure. For example, Zhang et al. developed a "multidimensional vulnerability index" by aggregating the IPCC indicators weighted by the AHP for each dominant

hazard (M. Zhang et al., 2019). Case studies of vulnerability assessments in different hazard event scenarios, including the development of "flow-based" vulnerability metrics for road network performance loss in terms of travel time (Kim & Yeo, 2016) and "accessibility-based" vulnerability metrics for travel mode and cost (X.-Z. Chen et al., 2015). In contrast, the second group of literature considers vulnerability as a form of risk assessment, considering both the probability and the consequences of failure. For example, Tang and Huang employed fault trees and Bayesian network models to assess the probability of road connectivity failures and, consequently, the seismic vulnerability of the urban road network (Tang & Huang, 2019b).

Resilience assessment

A variety of qualitative and quantitative methods are used to assess urban resilience. Resilience could be measured by the degree to which it reduces the consequences of failure (system performance loss), the probability of failure, and the time required to recover (system recovery time) (Bruneau et al., 2003).

Resilience can be measured in terms of the cumulative performance loss. Simonovic introduces a "space-time dynamic resilience measure", in which the system resilience $r^i(t, s)$ is calculated with regard to the performance loss $\rho^i(t, s)$ at time (t) and location (s) for impact (i) , perturbation duration to time t , $(t - t_0)$, and initial performance (p_0^i) , Equation 2-1.

$$\text{Eq. 2-1} \quad r^i(t, s) = 1 - \left(\frac{\rho^i(t, s)}{p_0^i \times (t - t_0)} \right)$$

Performance loss $\rho^i(t, s)$ is measured by taking the difference between the initial performance (p_0^i) and the system performance for impact i at each time and location, $p^i(\tau, s)$, Equation 2-2.

$$\text{Eq. 2-2} \quad \rho^i(t, s) = \int_{t_0}^t [p_0^i - p^i(\tau, s)] d\tau, \text{ where } t \in [t_0, t_r]$$

The resilience, $r^i(t, s)$, would be maximum (equal to one) if there is no performance loss ($\rho^i(t, s) = 0$). In the other words, the initial performance (p_0) and performance at time and location of hazard occurrence $p^i(\tau, s)$ are equal.

Then, to calculate the total system resilience for multiple impacts of hazard (e.g., social resilience, economic resilience, engineering resilience, etc.), Equation 2-3 is introduced.

$$\text{Eq. 2-3} \quad R(t, s) = \left\{ \prod_{i=1}^M r^i(t, s) \right\}^{\frac{1}{M}}, (i \in M)$$

Where the total resilience of a system, $R(t, s)$, is the m-th root of the product of all of the system resilience for different hazard impacts (i) ranging from 1 to M , $r^i(t, s)$ (Simonovic, 2016).

Resilience could also be measured in a probabilistic framework (Figure 2-10), where the probability that a system is resilient in the face of an event A of magnitude i , $Pr(A|i)$, is equal to the probability that the system's performance after failure (r_0) is less than the maximum acceptable performance loss (r^*), and t_1 (when the system recovery is achieved) is less than the acceptable time (t^*). According to Equation 2-4, the total system resilience for multiple hazards (Z_A) is measured as the sum of the system resilience in each scenario multiplied by the probability of the hazard event, $Pr(i)$ (Chang & Shinozuka, 2004; Nieves-Melendez & De La Garza, 2016).

$$\text{Eq. 2-4} \quad Pr(A|i) = Pr(r_0 < r^* \text{ and } t_1 < t^*) \geq R^*, Z_A = \sum_i Pr(A|i) \times Pr(i)$$

Here, R^* is the minimum acceptable probability according to the system reliability goal for each scenario.

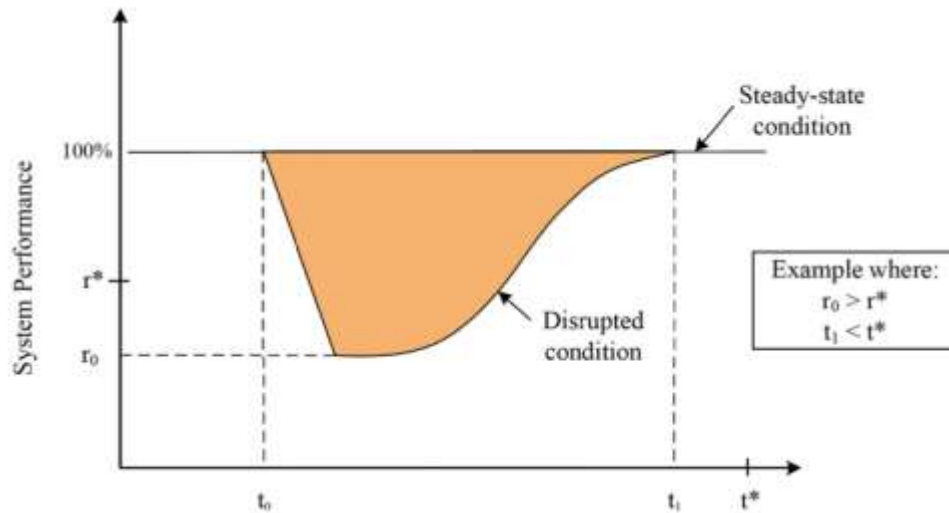


Figure 2-10 Probabilistic resilience assessment adopted from Chang & Shinozuka (2004) and Nieves-Melendez & De La Garza (2016)

Another way to measure resilience is in terms of recovery time, specifically the time it takes to return to the original level of performance. For example, Mojtahedi et al. predicted recovery time and transportation resilience to various natural hazards in New South Wales, Australia, considering the probability of recovery at the regional scale "using Cox's proportional hazards regression model" (Mojtahedi et al., 2017). In another example, Baroud and Barker (2014) measured resilience as "the time-dependent ratio of recovery to loss by applying Beta Bayesian and Kernel methods to the Mississippi River navigation system" (Baroud & Barker, 2014).

Additionally, other methods for assessing and managing resilience include scorecards, toolkits, indices, and models (Sharifi, 2016). The scorecard, which relies primarily on expert judgment, is the most subjective method of assessing resilience and was used by Chen et al. to evaluate the resilience of critical infrastructure in

Metro Vancouver, Canada (Chang et al., 2014). The Resilience Toolkit is a set of strategies, guidelines, and methods designed to help cities prepare for, respond to, and recover from various hazards. It incorporates both pre-and post-disaster resilience decisions (McDaniels et al., 2008). For example, the International Council for Local Environmental Initiatives (ICLEI-Canada) introduced five mitigation programs, including Building Adaptive Resilient Communities (BARC), in 2010. The resilience index is the result of aggregating weighted or unweighted indicators of evaluation criteria. For example, Lee and Kim developed a resilience index based on flood damage to drainage systems in Jeongup, Korea (E. H. Lee & Kim, 2017). Another example of the application of the resilience index can be found in the work of Gourbesville and Batica, where the "averaged weighted mean index method" is used to aggregate indicators of resilience phases (e.g., resist, respond, and recover phases) (Gourbesville & Batica, 2015). Finally, resilience models serve to simplify the complex nature of resilience assessment by transforming it into a mathematical algorithm in one or more scenarios in a static or dynamic model, such as the application of the graph model by Bristow and Hay (2016) for probabilistic resilience planning regarding the interdependencies between infrastructures that cause cascading and escalating failures. However, the system dynamics (SD) model better accounts for interdependencies among variables and cumulative, complex effects over time. The SD model includes two parts: qualitative (causal loop diagram) and quantitative (stock-flow diagram) (Simonovic & Peck, 2013). The SD model has been used in many disciplines, including disaster management, transportation, and urban development (Table 2-10).

Table 2-10 Examples of the application of the SD model

Application	Objective	Authors
Transportation	Simulate the interactions between transportation supply and demand	Abbas & Bell (1994)
	Review the application of the SD in transportation	Shepherd (2014)
	Estimate transportation supply-demand ratio	Wu et al. (2015)
Urban development	Simulate the interaction between transport, land use, and socio-economic development	Swanson (2003)
	Review the importance of SD in sustainable development	Hjorth & Bagheri (2006)
	Simulate the effect of policy-making on sustainable development	Duran-Encalada & Paucar-Caceres (2009)
	Integrate SD and CLUE ¹⁸ models for land-use scenario analysis	Luo et al. (2010)
	Integrate SD and GIS for assessing urban development	Guan et al. (2011)
	Simulate urban sustainable development	Tan et al. (2018)
	Simulate human behavior during flood emergency evacuation	Simonovic & Ahmad (2005)
Disaster management	Runoff modeling and flood assessment	Bazrkar et al. (2013)
	Investigate the reciprocal effect of physical and social systems on flood risk management	Baldassarre et al. (2015)
	Integrate SD and GIS for agriculture and disaster management	Simonovic (2015)
	Develop a dynamic flood resilience model	Simonovic (2016)
	Develop a dynamic vulnerability model	Woodruff et al. (2018)

SD model exhibits distinctive advantages over other simulation techniques for resilience assessment (Table 2-11). It is capable of simulating the causal relationships that exist between multiple systems and their components. Furthermore, it is an appropriate method for simulating system behavior and monitoring the effects of policies and strategies through causal feedback. SD has the potential to address the time lag between land use and transportation development. Additionally, it can be coupled with GIS for spatiotemporal simulation (Peck et al., 2014).

¹⁸ The CLUE model is a simulation tool that tracks the evolution of land use patterns in response to population growth, economic development, environmental change, and other factors.

Table 2-11. Compare simulation models for resilience assessment

Simulation model	Temporal		Deterministic	Stochastic	Advantage/disadvantage
	Continuous	Discrete			
Discrete Event simulation		√	√		Feasible to simulate different levels of detail and uncertainties with events that trigger system changes. It is not suitable for complex systems with a high degree of interaction.
System Dynamics (SD)	√		√		Capable of capturing causal relations between system elements, feedback, and future trends. Not appropriate to model individual behavior
Agent-Based simulation	√	√		√	Suitable for complex decision-making processes and the modeling of individual behavior. Challenging to undertake computation with many agents
Monte Carlo simulation				√	Capable of accounting for uncertainties and randomness in a time-independent manner. It is not appropriate for effective decision-making, as it relies on random sampling and generates a range of potential outcomes.

2.3.4 Accessibility and Disaster Mitigation

A shared consequence of natural disasters on land use and transportation is accessibility loss, which results from structural damage and a decline in road network performance. Therefore, as Figure 2-11 shows, accessibility measure has a critical role in urban disaster mitigation.

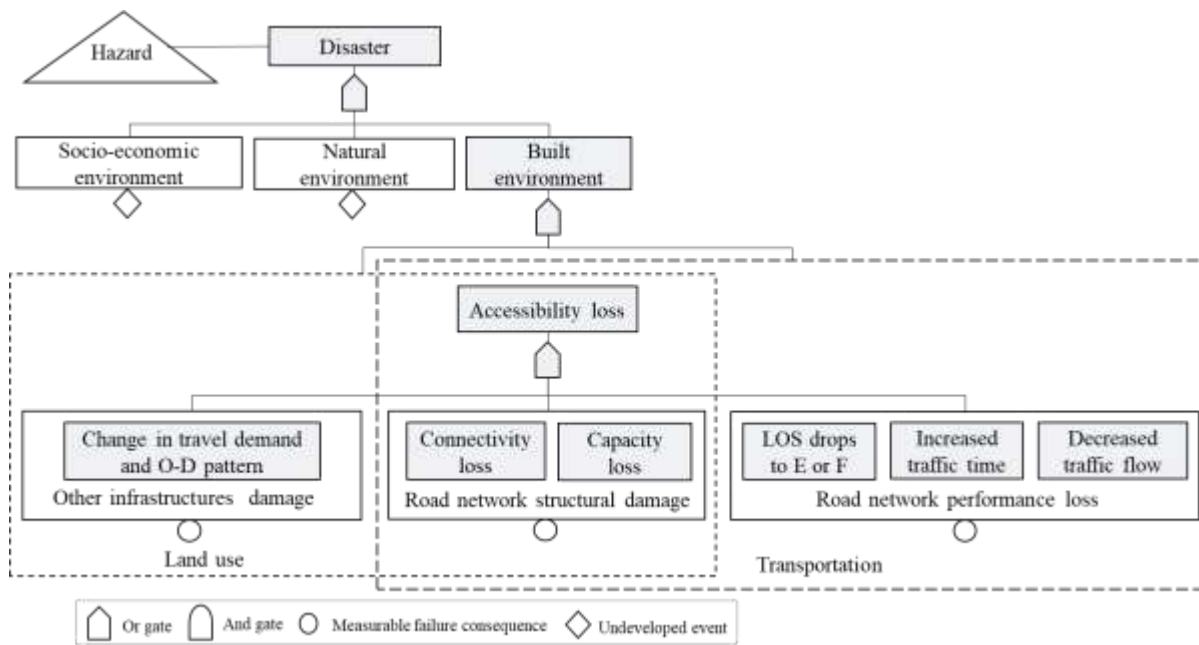


Figure 2-11 The critical role of accessibility in urban disaster mitigation

The impact of risk on the road network structure can be measured in terms of reduced capacity and connectivity. Capacity represents the maximum volume of vehicles a road can accommodate, or simply the number or fraction of available lanes, as Chen et al. (2015) considered when measuring road network capacity and defining disaster scenarios. On the other hand, the road network's robustness and redundancy (resilience attributes) can be measured by connectivity. Road network connectivity also represents its reliability and vulnerability, which are related, but the former does not consider the probability of failure (Reggiani et al., 2015). In this context, Tang and Huang evaluated the seismic vulnerability of bridges and urban road networks in terms of probabilistic connectivity measures using the Bayesian network and fault tree method (Tang & Huang, 2019b). When a road network experiences a reduction in its original capacity or connectivity due to partial or complete structural damage or the accumulation of debris, the level of accessibility is adversely affected.

The performance of the road network can also be affected by disasters, which can be quantified in terms of travel time (or its equivalent cost), traffic flow (measured in vehicles per hour), or in a more qualitative measure of level of service (LOS), which ranges from A (free flow) to F (congestion). Also, the loss of either connectivity or capacity of the road network can indirectly reduce the network's performance and accessibility. For instance, Chen et al. defined several flooding scenarios based on the capacity loss of the road network. They then analyzed the urban vulnerability of Hillsborough County, Florida, using an accessibility index formulated with regard to travel costs and different modes of access (X. Z. Chen et al., 2015).

Furthermore, any alteration in travel demand resulting from the disaster's impact on land use patterns will inevitably influence the accessibility measure. This is evident in the post-disaster period when the high demand for evacuation and emergency services negatively impacts the normal performance of the road network, which is, to some extent, disrupted or blocked by post-earthquake debris (Tamima & Chouinard, 2016).

2.4 Gaps in the Literature

The review identified two types of methodological and technical gaps: first, the lack of a comprehensive approach to TOD and risk mitigation planning; second, shortcomings in the assessment process.

The use of different variables and assessment methodologies results in inconsistent outcomes, a gap that needs to be addressed by proposing an integrated TOD assessment approach. Researchers have employed various methods to evaluate existing or potential TODs, each aligned with one of the TOD goals and objectives, as summarized in Table 2-12.

Table 2-12 Overview of TOD assessment methods

TOD goals	Integrated land use and transport development	Sustainable development			
Objective	Balance supply and demand for access	Enhance built environment sustainability	Evaluate the efficiency of station areas.	Optimize TOD criteria	Improve public transit accessibility
Method	Multi-attribute		Multi-objective		Single attribute
	Node-place-(tie) model	TOD index	DEA	Optimization	Statistical approaches & accessibility index

The extensive review of the TOD literature resulted in the classification of the main TOD assessment methods and their key steps, which are explained in Sections 2.2.2 and 2.2.3 of this chapter and combined and illustrated in Figure 2-12. The problem is that the scope, process, and results of applied multi-attribute, multi-objective, and single-attribute evaluation methods lead to different planning proposals.

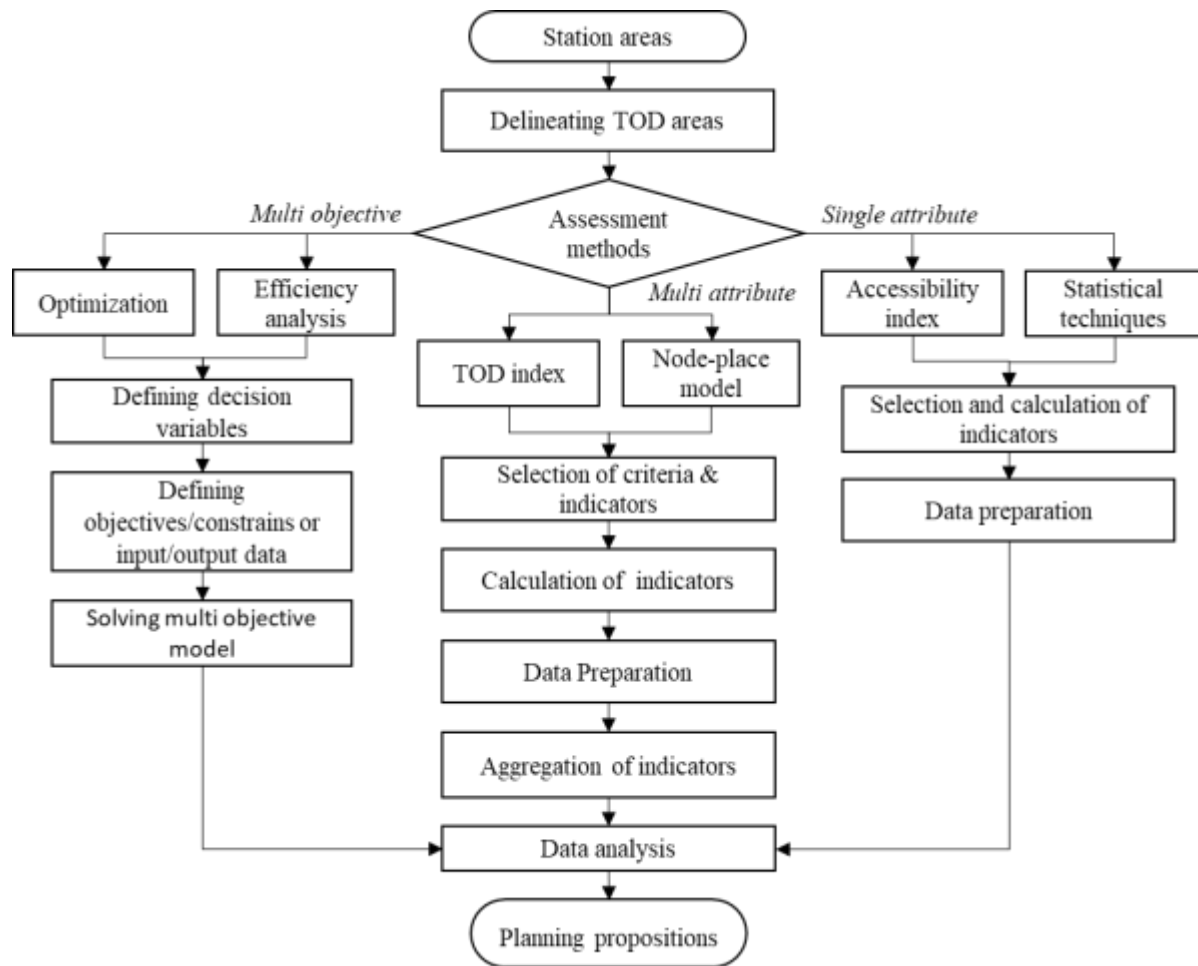


Figure 2-12 TOD assessment framework

Furthermore, it is necessary to integrate TOD and risk mitigation planning to address the risk associated with the concentration of people and activities in a confined area of TOD. This issue has not been considered in previous research, except Jamme et al. (2019), who mentioned the importance of integrating TOD with disaster mitigation strategies in their review paper.

Moreover, while there has been a recent shift in the literature from disaster vulnerability to resilience, a holistic approach to disaster mitigation has yet to be explored. To bridge this gap, it is necessary to integrate strategies for identifying and

reducing system vulnerability with increasing resilience, ensuring that a system becomes inherently capable of coping with hazardous events.

The second category pertains to shortcomings in the tools and techniques employed in the existing literature on TOD and disaster mitigation. In previous studies using the node-place model for station area typology, the relative importance of indicators and the feasibility of implementing land-use interventions (e.g., increasing density and diversity) without jeopardizing the balance between land use and transport supply and demand were not considered. Furthermore, the existing research that utilized the TOD index for comparative evaluation of station areas has not taken into account the potential for bias inherent in the process of weighting and aggregating indicators, the efficiency of station areas in terms of compactness, and the optimal level of density. Additionally, there is a lack of a multi-attribute vulnerability assessment method that accounts for inherent uncertainties.

This research aims to address the aforementioned gaps by proposing an improved TOD Assessment in the next chapter. However, this thesis does not address several additional shortcomings in the TOD literature, as follows. The utility-based accessibility measure, which examines the financial benefits of access to various locations, has not been considered in assessing the impact of TOD on residents' travel behavior, nor in evaluations using TOD index and the node-place model. Furthermore, although balancing land use and transportation is one of TOD's primary goals, there is a lack of research focused on developing dynamic and integrated models that can evaluate scenarios of different land use and transportation interventions in parallel. An exception is the study by Cox et al. (2017), which developed a preliminary system dynamics model to incorporate the causal effects of land use, transportation, energy, and the economic sectors. In addition, previous research on TOD has overlooked the application of multi-activity accessibility

measures that encompass multiple destination types, rather than focusing solely on employment destinations, which is the primary consideration among most researchers. Additionally, although the accessibility indicator reflects the variation in land use demand (density and diversity) and the supply of transport networks and services, in existing TOD planning models that use 5D criteria, destination accessibility has been considered in parallel with density and diversity indicators.

CHAPTER 3: METHODOLOGY¹⁹

As stated in Section 2.4, previous studies have not adopted a comprehensive approach to TOD evaluation. To bridge this gap, this research develops an enhanced risk-aware TOD methodology that integrates and enhances existing TOD evaluation methods (Section 3.1) and disaster mitigation strategies (Section 3.2). As presented in Figure 3-1, this methodology, with an accessibility-oriented approach, addresses all TOD goals through the objectives of its successive stages.

The primary objective of TOD, as well as other urban development approaches, is to improve accessibility through harmonized transportation and land use development. To this end, and regarding the node-place model of Bertolini (1999), the enhanced node-place-tie model is proposed in Stage 3.1.1 to determine which station areas are feasible for further development of the built environment without jeopardizing the balance between supply and demand for public transit access.

On the other hand, urban development aims to reduce the vulnerability of communities to disaster events. Therefore, the vulnerability of the candidate station areas to natural hazards is evaluated using historical data and the proposed model in Stage 3.1.3. Again, accessibility in terms of station areas' access to emergency centers plays a critical role in Stage 3.2.1.

Additionally, TOD is an anti-car-oriented development approach that seeks to enhance the built environment's sustainability through the realization of 5D criteria, which stand for density, diversity, distance to transit, and destination accessibility.

¹⁹ A version of Chapter 3 has been published by Rabiei et al. (2022) in a journal article entitled Multistage Transit-Oriented Development Assessment: A Case Study of the Montréal Metro System in the Journal of Urban Planning and Development, volume 148, issue 3, pages 1-17.

As explained in section 2.2.4 (Figure 2-6), destination accessibility plays a pivotal role among D variables. Therefore, in Stage 3.1.2 of this methodology, the sustainability of selected station areas from the previous stages is assessed using a TOD index, which is a modified and extended version of the model proposed by Singh et al. (2015).

Another TOD objective is to enhance public transport accessibility, which is realized by concentrating population and activities in the vicinity of public transit stations. In this regard, Stage 3.1.3 provides land use planning insights to optimize the demand for public transit access in terms of population density and diversity of activities, which is the outcome of Stages 2.1.1 and 2.1.2. This is particularly relevant in cities like Montreal, which have a well-developed public transit system but less-developed land use. Finally, Stage 3.2.2 assesses the potential impact of these planning interventions on road network resilience as a proposal for future research.

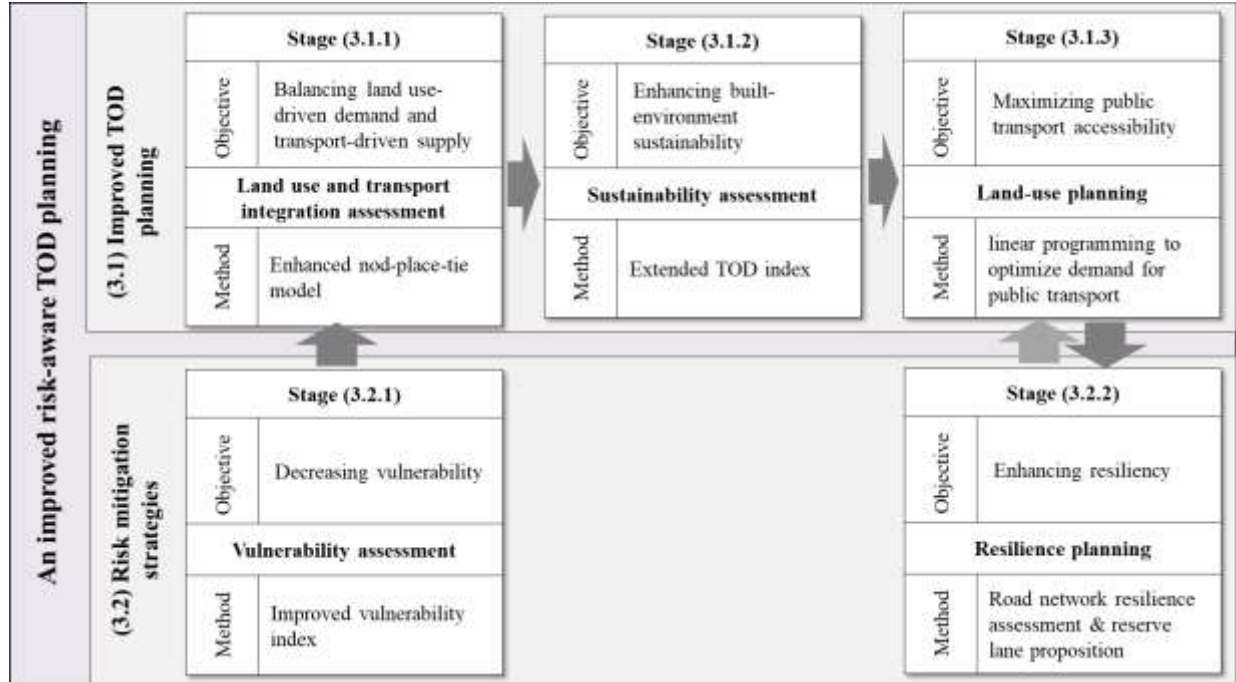


Figure 3-1 Overview of the thesis methodology

In this method, successive stages not only build upon the results of the previous stages but also share a common goal: enhancing accessibility. Stage 3.1.1 categorized station areas based on the supply and demand for public, private, and active accessibility. According to Bertolini's model (Figure 2-5), the accessibility type of stations is characterized by balanced land use and transport development. Stage 3.1.2 evaluates the TOD level of those station areas based on sustainable accessibility in terms of public transport, active (cycling and walking) modes of access, and other sustainable built environment criteria (5D). Stage 3.1.3 provides insights into enhancing public transport accessibility, including local and network station access through land-use interventions. In Stage 3.2.1, accessibility also plays a critical role in defining adaptive capacity regarding access to emergency centers and, consequently, the vulnerability of station areas. Stage 3.2.2 proposes a road network resilience model for future study, focusing on the accessibility of emergency services to TOD areas. Therefore, this research considers TOD as an "accessibility-centric planning approach"(Lyu et al., 2019), where accessibility plays an important role at all stages of the proposed methodology, as illustrated in Table 3-1.

Table 3-1 The role of accessibility in the proposed methodology

Stage	Role	Access mode
3.1.1	In Bertolini's node-place model (Bertolini, 1999), accessibility refers to a type of station with balanced land use and transportation development. The extended node-place model proposed in this thesis is also accessibility-oriented, particularly regarding indicator selection and calculation.	Public, Private, Active
3.1.2	Accessibility is a main sustainable built environment criterion (5D). This research extends it to encompass local and network transit accessibility in selecting and calculating the TOD index.	Public, Active
3.1.3	Maximizing local and network public transit accessibility is an objective of TOD planning.	Public
3.2.1	Accessibility to emergency centers affects the vulnerability of station areas.	Public, Private
3.2.2	Accessibility is a factor on which road network resilience is evaluated.	Public, Private

3.1 Improved Transit-Oriented Development Assessment

By definition, TOD is a sustainable and land-use-transport integrated development method; therefore, it can be said that its primary goal is to enhance sustainable accessibility. To achieve this goal, the following objectives must be realized: balancing transit-driven supply and land-use-driven demand for access, enhancing the sustainability of the built environment, optimizing the sustainability and efficiency of station areas, and improving public transport accessibility. As illustrated in Figure 3-2, this research integrates and enhances the methods currently used in the TOD literature, resulting in a more comprehensive approach than existing methods with limited objectives.

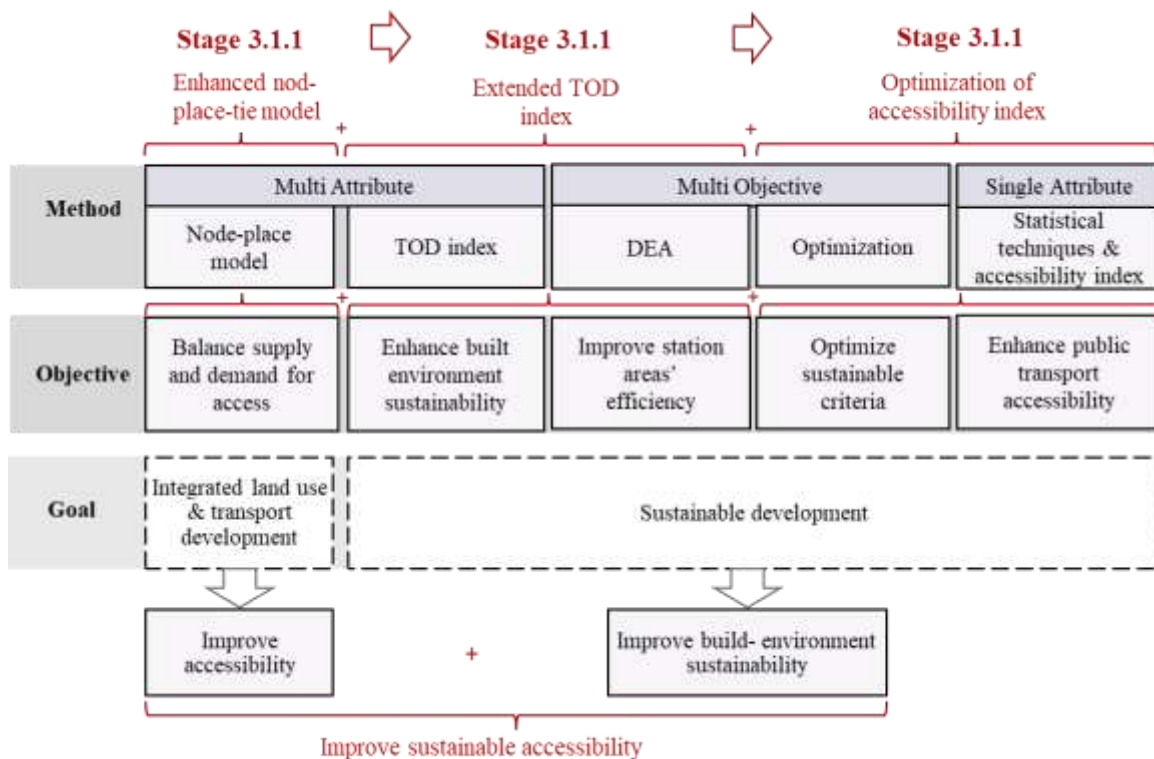


Figure 3-2 Conceptual framework of the improved TOD assessment

In pursuit of the goal of improving sustainable accessibility, each stage of the proposed method is developed based on the reorganized and modified key steps of

previous TOD assessment methods (Section 2.2.3) and some new steps (Figure 3-3). The enhanced node-place-tie model in Stage 3.1.1 and the proposed vulnerability analysis in Stage 3.2.1 provide a list of feasible station areas for land use development. These candidate station areas are then evaluated using an improved TOD index in Stage 3.1.2 to determine their ranking based on TOD level and efficiency for sustainable development. The results are subsequently utilized in Stage 3.1.3, which aims to maximize public transport accessibility by improving land use density and diversity. In conjunction with the resilience assessment proposal in stage 3.2.2, this process provides policymakers with planning insights.

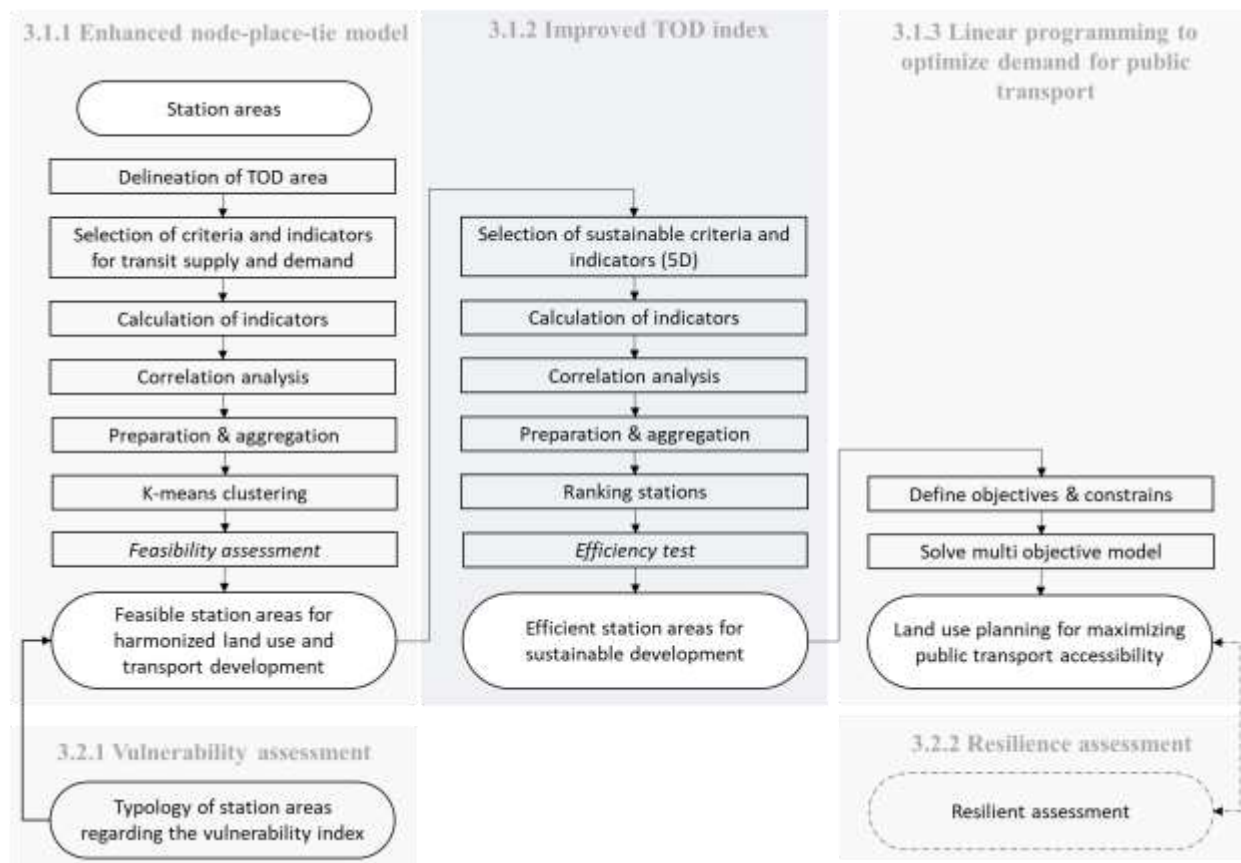


Figure 3-3 Structure of the proposed method

3.1.1 Enhanced Node-Place Model

One of TOD's goals is to ensure balanced land use and transportation development. The proposed node-place model in this stage builds upon the previous method of selecting and calculating criteria and indicators, as well as the correlation analysis between land use and transportation variables related to accessibility. The result of this stage is a list of balanced, accessible station areas that are feasible for further land-use development.

Delineation of TOD area

The delineation of TOD areas is the first step in all TOD assessment methods, based on which the required data are extracted. Among the delineation techniques discussed in Section 2.2.3, we use the 400-meter and 800-meter circular buffers around metro stations. This choice is not only due to the fact that the majority of previous TOD studies employed this method, but also because 2003 data from Montreal indicates that the average walking distance to the subway is approximately 800 meters (Ahmed et al., 2013).

This research utilized the location-based selection tool in ArcGIS to define 400 m and 800 m circular buffers, corresponding to 5-10 minute Euclidean walking distances to metro stations. The 400 m buffer is used to extract indicators that represent the travel destination, attracting people from outside the station catchment area. Conversely, the 800 m buffer is employed for indicators such as workforce density and transit captive users, representing the potential of the station area as an origin of travel.

Selection of criteria and indicators

This research builds upon previous models by striving to balance land use-driven demand with transport-driven supply. In this research, the criteria and indicators for the proposed enhanced node, place, and tie model are meticulously selected to ensure

that the node index reflects the supply of transportation access, the place index indicates the demand for access, and the tie index includes factors influencing both the supply and demand for access. Node indicators include the location, quality, and quantity of all transport infrastructure and services (public, private, and active modes of access). Place indicators encompass the density of potential travelers and the diversity of activities that serve as origins or destinations for travel via public and private access modes. Tie indicators reflect the factors that influence residents' mode choice.

These indicators are selected based on those used by other researchers, the availability of data, and the specific requirements of the case study. As noted by Yang et al. (2024), there is no generally accepted set of indicators that fully reflects the TOD concept. Reviewing the previous node, place, and tie indicators in Tables 2-2, 2-3, 2-4, and 2-5 confirms how they vary according to the researchers' perspectives. On the other hand, as Pezeshknejad et al. (2020) stated, increasing the number of indicators will not alter the final result if the effective indicators are selected through inquiries and correlation analysis. Therefore, with an accessibility-oriented approach and considering indicators used in prior studies and the spatial characteristics of this case study (such as Montreal's underground city and bicycle network), the criteria and indicators of the proposed model are selected and presented in Table 3-2.

Table 3-2 Criteria and indicators of the proposed node-place-tie model

Node-place- tie	Access mode	Indicators	Abbr.	
Node Index	Supply of access to public transport	Public, private and active	Spatial coupling	N-SCO
			Number of transit stations	N-NTS
			Bus route density	N-BLD
			Underground city access	N-ACC
			Frequency of transit service	N-FTS
			Number of directions served	N-NDS
			Level of comfort	N-LCO
			Interchange to other modes of access	N-IMT
			Parking	N-INP
			Road network connectivity	N-RNC
			Access to the highway	N-AHI
			Bike line density	N-BLD
			Bicycle stand	N-BST
Place Index	Demand for access	Public and private	Transit ridership	P_TRI
			Density of transit captive users	P_DTC
			Density of workforce	P_DWF
			Land use mixed-ness	P_LUM
			Trip attraction	P_TAT
Tie Index	Influential factors on supply and demand for access	Active	Safety	T_SAF
			Walkability	T_WAL
			Bike ability	T_BIK
			Pedestrian network connectivity	T_PNC

Note: If the study covers only one metro line, the frequency of transit service arrivals at all stations will be the same. Therefore, N-FTS will be omitted from the list.

Calculation of indicators

After defining the criteria and indicators, we need to establish a set of metrics to compare and classify the stations under study. Table 3-3 presents the references for the formula and data sources used in calculating the indicators, followed by Tables 3-4, 3-5, and 3-6, which provide an overview of the calculation of the node, place, and tie indices.

Table 3-3 Resource for indicators of the proposed node-place-tie model

Indicator		Data sources	References
N_SCO	Spatial coupling	Geoindex (2018) https://geoapp.bibl.ulaval.ca/login	Pan et al. (2017)
N_NTS	Number of stations	Montréal Données ouvertes (2021) http://donnees.ville.montreal.qc.ca/data	Pezeshknejad et al. (2020)
N_BLD	Bus route density	set	
N_ACC	Underground city access		-
N_FTS	Frequency of transit service		Vale (2015)
N_NDS	Number of metro directions	STM (2021) https://www.stm.info/en/info/networks/metro	
N_LCO	Level of comfort		Singh et al. (2017)
N_IMT	Interchange to other access modes		Vale (2015)
N_INP	Parking		
N_RNC	Road network connectivity	Montréal Données ouvertes (2021) http://donnees.ville.montreal.qc.ca/data	Patarasuk (2013)
N_AHI	Access to highways	Montréal Données ouvertes (2021) http://donnees.ville.montreal.qc.ca/data	Vale (2015)
N_BLD	Bike line density	set	-
N_BST	Bicycle stand	STM (2021) https://www.stm.info/en/info/networks/metro	Adopted and changed from Su et al. (2022)
P_TRI	Transit ridership		Singh et al. (2017)
P_DTC	Density of transit captive users	Montréal Données ouvertes (2021) http://donnees.ville.montreal.qc.ca/data	Adopted and changed from Su et al. (2022)
P_DWF	Density of workforce	Statistics Canada at https://www.statcan.gc.ca	Adopted and changed from Lyu et al. (2016)
P_LUM	Land use mixed-ness	Montréal Données ouvertes (2021) http://donnees.ville.montreal.qc.ca/data	Singh et al. (2017)
P_TAT	Trip attraction	Geoindex (2018) https://geoapp.bibl.ulaval.ca/login	Adopted and changed from Vale et al. (2018)
T_SAF	Safety	Montréal Données ouvertes (2021) http://donnees.ville.montreal.qc.ca/data	Adopted and changed from Lyu et al. (2016)
T_WAL	Walkability	WalkScore (2021) https://www.walkscore.com	Singh et al. (2017)
T_BIK	Bike ability		
T_PNC	Pedestrian network connectivity	Montréal Données ouvertes (2021) http://donnees.ville.montreal.qc.ca/data	Adapted from Patarasuk (2013) and changed according to Schlossberg and Brown (2004)

The node index represents the provision of access to public, private, and active modes. To measure public transport accessibility, we consider the location of stations within the urban layout, their position in the subway and bus networks, and the quality and frequency of subway service. This research also considers access to road and bicycle networks and services.

Public transport accessibility is influenced by the proximity of transit stations to points of interest (spatial coupling) and their access to the underground city. We adopted the spatial coupling index from Pan et al. (2017), which shows the "spatial distribution of rail transit stations and commercial centers". However, in this research, spatial coupling (N_SCO) refers to the proximity of stations to potential destinations and origins of travel, also known as points of interest (POI). According to Equation 3-1, the spatial coupling index of the station area i (SC_i) is defined in terms of the number of POIs near the station (δ_i) and their relative importance (w_i).

$$\text{Eq. 3-1} \quad SC_i = \frac{\sum_{i=1}^n \delta_i \times w_i}{\sum_{i=1}^n w_i}, \delta_i \begin{cases} 1, & \text{POIs are in buffer 50m} \\ & \text{(adjacent to station i)} \\ 0, & \text{otherwise} \end{cases}$$

In addition to land use around stations, it is also important to consider the availability of access to underground activities (N_ACC) for cities like Montreal, which have an active underground city.

The public transport accessibility is also affected by the stations' location in the subway and bus networks. To define the level of importance of stations in the metro network, we consider the number of metro directions passing through each station (N_NDS), the availability of bus terminals, intercity and suburban train stations (N_IMT), and parking facilities adjacent to metro stations (N_INP). Access to the bus network, on the other hand, is defined by the number of transit stations (N_NTS), which is determined by the number of metro entrances and bus stops within 400

meters of a metro station, and the bus line density (N_BLD), which is measured by the total length of the bus line in the buffer 800 meters from a station.

In addition, the quality and quantity of subway service impact public transport accessibility. Stations' level of comfort (N_LCO) depends on the quality of indoor temperature, ventilation, sanitation services, and the stations' physical and aesthetic aspects. For this thesis, the availability of an elevator is a determining factor for station accessibility. The other factors and the frequency of transit service in peak and non-peak hours (N_FTS) are the same for the stations in this case study.

This research also includes private car and active accessibility measures to calculate the node index. The level of private car accessibility is evaluated based on the number of highway exits within an 800m buffer of a metro station (N_AHI) and the road network connectivity (N_RNC). According to Equation 3-2, the road network connectivity of each station area (β) is measured by the total number of links (e) per node (v).

Eq. 3-2
$$\beta = \sum \frac{e}{v}$$

On the other hand, the number of bicycle stands in metro stations (N_BST) and the bike line density (N_BLD) indicate the active accessibility of station areas. Since all stations have an equal area (buffer 800m) in this study, the bike lane density is calculated in ArcGIS based on the total length of bike lanes.

Table 3-4 Node index calculation

	Indicator	Description	Abbr.
Public transit accessibility	Spatial coupling	The adjacency of points of interest (POI) to the station i $SC_i = \frac{\sum_{i=1}^n \delta_i \times w_i}{\sum_{i=1}^n w_i}$ $\delta_i = \begin{cases} 1, & \text{POIs are in buffer 50m (adjacent to station i)} \\ 0, & \text{otherwise} \end{cases}$	N-SCO
	Number of transit stations	Number of metro entrances and bus stops in the station area (buffer 400m)	N-NTS
	Bus route density	The total length of the bus route in the station area (buffer 800m)	N-BLD
	Underground city access	Availability of access to the underground city of Montreal	N-ACC
	Frequency of transit service	For peak hours, between 3-5 minutes, and a non-peak hour every 4-10 minutes (the same for all metro lines in Montreal)	N-FTS
	Number of directions served	Number of metro directions passing through the station	N-NDS
	Level of comfort	Availability of elevator	N-LCO
	Interchange to other modes	Availability of a bus terminal, an intercity train, and a suburban train station next to the metro station	N-IMT
	Parking	Availability of parking next to the metro station	N-INP
Private car accessibility	Road network connectivity	Total number of links per node in the station area I (buffer 800m) $\beta = \sum \frac{e}{v}$ β : road network connectivity e : number of edges in the station area i v : number of vertices in the station area i	N-RNC
	Access to highways	Number of highway exits in the buffer 800m	N-AHI
Active accessibility	Bike line density	The total length of bike lanes in the station area (buffer 800m)	N-BLD
	Bicycle stand	Number of stands for bicycles at the station	N-BST

The place index includes stations' land use characteristics that affect the origin and destination of travel. Considering station areas as origin of travel, the stations'

passanger volume is measured by the indicator of transit ridership (P_TRI), obtained from STM database, and the number of potential passengers with regard to the density of transit captive users (P_DTC) who, due to age or income, are more likely to use the metro and workforce (P_DWF) residing within the 400m buffer around stations.

Station areas also act as travel destinations for passengers from other regions. This can be measured by the land use mixedness (P_LUM) and trip attraction (P_TAT) indicators, representing stations' vibrancy and attractiveness. According to Equation 3-3 used by Singh et al. (2017), land use mixedness index of station i (LUM_i) shows the station's vibrancy in terms of the ratio of total non-residential land use (a) to the total land use area (A).

$$\text{Eq. 3-3} \quad LUM_i = \frac{a}{A}$$

This research also considers the ability of stations to attract people to the station area. As proposed in Equation 3-4, the level of station trip attraction of station i (TA_i) depends on the number of its points of interest (POI_k) and their relative importance ($WPOI_k$).

$$\text{Eq. 3-4} \quad TA_i = \sum_{k=1}^n POI_k \times WPOI_k$$

Table 3-5 Place index calculation

	Indicator	Description	Abbr.
Origin of travel	Transit ridership	Total number of passengers entering the station (in the year 2019)	P_TRI
	Density of transit captive users	The ratio of the number of people under 16 years, over 65 years, and with low income residing in the dissemination areas crossed by the outline of a circular buffer 400m to that area	P_DTC
	Density of workforce	The ratio of the number of workforces residing in the dissemination areas crossed by the outline of a circular buffer 400m to that area	P_DWF
Destination of travel	Land use mixedness	The ratio of non-residential area to the total area $LUM_i = \sum \frac{a}{A}$ LUM_i: land use mixedness index a: area of non-residential land use in the station area i A: area of all kinds of land uses in station area i	P_LUM
	Trip attraction	Number of POIs (destination points) in the station area (buffer 400m) and their degree of importance $TA_i = \sum_{k=1}^n POI_k \times WPOI_k$ TA_i: trip attraction station i POI_k: point of interest in the station area $WPOI_k$: weight of each point of interest (class 1- 3)	P_TAT

As mentioned, node and place indices indicate stations' land-use and transport characteristics that affect travel origins and destinations. However, the tie index includes factors that affect residents' choice to use public transit instead of their private cars; in other words, the level of pedestrian and cycling accessibility in the study area.

We used the Walkability (T_WAL) and Bikeability (T_BIK) indicators, commonly measured by Walk Score and Bike Score for real estate listings, to show how accessible a location is without a car. The Walk Score defines the quality of a neighborhood in terms of the average distance to amenities (points of interest) and block size. The availability of bike lanes, connectivity, and slope are the key factors

considered in the Bike score. We also consider the number of intersections with traffic lights, representing pedestrian access safety (T_SAF). In addition, we evaluated pedestrian access using the pedestrian network connectivity measure (T_PNC). According to graph theory, network connectivity (β) can be measured by Equation 3-5 regarding the total ratio of links (L) to vertices (V).

$$\text{Eq. 3-5} \quad \beta = \sum \frac{L}{V}$$

Here, having more route choices at each intersection means better road network connectivity, as opposed to having more dead ends (Patarasuk, 2013). However, from a pedestrian's point of view, ending at a freeway or major arterial is also a kind of dead end (Schlossberg & Brown, 2004). Therefore, we calculate pedestrian network connectivity in the non-impeded road network after excluding freeways and arterial roads from an 800 m buffer of stations.

Table 3-6 Tie index calculation

	Indicator	Description	Abbr.
Pedestrian-friendly	Safety	Number of intersections with traffic lights in the station area (buffer 800m), which represents the probability of an accident	T_SAF
	Walkability	Walk score represents pedestrian access to POIs in the station area i	T_WAL
Cycling-friendly	Bike ability	Bike score represents the cycling accessibility of the station area i	T_BIK
Pedestrian access	Pedestrian network connectivity	Total number of links per node in the non-impedance road network (after excluding freeways and arterial roads from an 800m buffer of station i) $\beta = \sum \frac{L}{V}$ β: pedestrian network connectivity L: number of links V: number of vertices (nodes)	T_PNC

Correlation analysis

After defining the primary and secondary data, the Pearson Correlation Coefficient (PCC) and Canonical Correlation Analysis (CCA) are used to assess the linear relationship between indicators and criteria. This thesis used Excel software and an Excel add-in named XLSTAT for statistical analysis.²⁰

The Pearson Correlation Coefficient (PCC) is represented by a value between -1 and 1 ($-1 < r < 1$) that indicates positive, negative, or null linear relationships between variables. A coefficient above 0.3 suggests a strong positive relationship, while one below -0.3 signifies a strong negative relationship between two indicators (Pezeshknejad et al., 2020). Moreover, when an indicator exhibits a high correlation with other indicators ($|r| > 0.75$), to prevent the multicollinearity effect that undermines the reliability of statistical results, we can remove that variable from the initial list of selected indicators, following Li et al. (2019)²¹ Therefore, performing a PCC to prevent bias toward a specific outcome is crucial, as it can distort the interpretation and statistical significance of analyses involving multiple variables, such as Canonical Correlation Analysis (CCA).

Then, Canonical Correlation Analysis (CCA) is utilized to explore the linear correlation between node, place, and tie indices and to identify the most effective variables in this correlation. This process involves the following steps:

1- Introducing new composite indicators derived from the original node, place, and tie indicators to ensure that each set contains an equal number of variables. Therefore,

²⁰ XLSTAT is an Excel add-in for statistical analysis (<https://www.xlstat.com/en/solutions/features/normality-tests>)

²¹ Another way to deal with multicollinearity is to combine the highly correlated variables through Principal Component Analysis (PCA).

the twenty-two indicators introduced in Table 3-2 are combined into three composite variables for each node, place, and tie index, as shown in Table 3-7.

2- Calculating canonical variates (variables) that are new composite variables created by canonical correlation analysis (CCA). Canonical variates are linear combinations of the original variables that maximize the correlation between the two sets of variables. XLSTAT utilizes the correlation circle to illustrate the relationship between the original variables (node, place, and tie indicators) and the canonical variates. The X and Y axes of the canonical circle represent the first and second canonical variates, while the arrows indicate the original variables; see Appendix B-1.

3- Calculating the canonical correlation coefficient demonstrates the role of each variable in the correlation between their respective sets. Most statistical software, including XLSTAT, standardizes data for correlation analysis. The software produces a table titled "Standardized Canonical Coefficient," representing the contribution of each original variable to the correlation between sets. A standardized canonical coefficient above 0.3 indicates the strength of a variable's effect on the correlation between sets, whereas a coefficient below -0.3 signifies an inverse relationship. The number of canonical correlation coefficients equals the number of variables in the smaller set.

4- Obtaining weights of node, place, and tie variables regarding the correlations between them and canonical variables, in contrast to previous studies, which assumed that all indicators play an equal role in the correlation between land use and transport. This research uses “the correlations between input variables and canonical variables”, obtained from XLSTAT, to determine the variables’ relative importance and weights.

5- Obtaining the canonical score for each station area, which indicates how land use and transport sectors correlate in that area. Based on the canonical scores of the stations, this research proposes a feasibility assessment for land use planning in the final step of the proposed enhanced node-place model.

Since Pearson Correlation Coefficient (PCC) and Canonical Correlation Analysis (CCA) assume that the variables are normally distributed, a normality test such as the Shapiro-Wilk test²² must first be performed to ensure the data fulfills the normality assumption. If the p-value is less than 0.05, it indicates that the data is not normally distributed, and the PCC results may be unreliable. Therefore, the nonparametric alternative to the PCC, known as Spearman's rank correlation²³, can be utilized, which works with the ranked values rather than raw data. The Shapiro-Wilk test can also be used to check the multivariate normality assumption of datasets in CCA. When canonical correlation analysis is inappropriate due to non-normality, we can use partial least squares (PLS) regression²⁴ to verify the relationship between two sets of variables, rather than using CCA.

This study utilized an Excel add-in, named XLSTAT, for statistical analysis to perform the Shapiro-Wilk test, PCC, and CCA.

²² The Shapiro-Wilk test was introduced by Shapiro, S. S. and M. B. Wilk (1965) in an article entitled "An Analysis of Variance Test for Normality" (<https://doi.org/10.2307/2333709>).

²³ "Spearman's correlation applies to ranks and so provides a measure of a monotonic relationship between two continuous random variables. It is also useful with ordinal data and is robust to outliers (unlike Pearson's correlation)." (<https://stats.stackexchange.com/questions/3730/pearsons-or-spearman-s-correlation-with-non-normal-data>). Python coding can be used for getting the correlation coefficient, and the p-value can be found in <https://www.includehelp.com/ml-ai/spearman-s-correlation-and-its-implication-in-machine-learning.aspx>

²⁴ PLS is used for cases involving high-dimensional data, situations where multicollinearity exists among variables, or instances when the data are not normally distributed. PLS maximizes covariance instead of correlation. It is important to note that covariance is scale-dependent, complicating its application in situations such as this study. Python coding for PLS regression can be found in https://scikit-learn.org/stable/modules/generated/sklearn.cross_decomposition.PLSRegression.html

Preparation and aggregation of data

It is generally accepted that CCA performs better when the subject sets have an equal number of variables. Therefore, the node, place, and tie indicators are reorganized to ensure each set contains an equal number of variables. Following this adjustment, the node index (N) includes the public transport, private car, and active transport variables; the place index (P) consists of the transit station, origin of travel, and destination of travel variables; and the tie index (T) is composed of the pedestrian-friendly, cycling-friendly, pedestrian access variables. Table 3-7 presents a list of CCA variables created from node, place, and tie indicators previously explained in the selection of criteria and indicators section.

The PCC analysis is unaffected by variable scale and units, whereas CCA relies on rescaled data. As we utilize XLSTAT, an Excel plug-in for statistical analysis that automatically standardizes the variables, additional rescaling is not needed at this stage.

Since "the most effective indicator is the one that enhances the correlation between two sets of variables" (Pezeshknejad et al., 2020), this research proposes obtaining the weights of node, place, and tie indicators regarding the correlations between input variables and canonical variables, one of the outputs of canonical correlation analysis with XLSTAT. This represents an improvement over previous research that used CCA for analyzing the results in terms of "identifying which transportation and land use dynamics are more effective in station areas when considering them together" (Monajem & Ekram Nosrati, 2015) and overlooked the weights of indicators when aggregating them to create node, place, and tie indices.

The weighted indicators are then aggregated using the weighted sum method (Equation 3-6) to develop node, place, and tie indices (I_N, I_P, I_T), where the sum of the weighted indicators ($W_j x_{ij}$) of each station (i) is calculated regarding the number

of indicators (j), the number of stations (j), and the weight (W_j) of station indicators (x_{ij}).

$$\text{Eq. 3-6} \quad I_{N, P, T} = \sum_{j=1}^m W_j x_{ij}$$

Table 3-7 Variables of canonical correlation analysis (CCA)

Node-place- tie	Indicators	Abbr.	CCA variables
Node index (N)	Supply of access to public transport	Spatial coupling	N-SCO
		Number of transit stations	N-NTS
		Bus route density	N-BLD
		Underground city access	N-ACC
		Frequency of transit service	N-FTS
		Number of directions served	N-NDS
		Level of comfort	N-LCO
		Interchange to other modes of access	N-IMT
		Parking	N-INP
		Road network connectivity	N-RNC
		Access to the highway	N-AHI
		Bike line density	N-BLD
Place index (P)	Demand for access	Bicycle stand	N-BST
		Transit ridership	P_TRI
		Density of transit captive users	P_DTC
		Density of workforce	P_DWF
		Land use mixed-ness	P_LUM
		Trip attraction	P_TAT
Tie index (T)	Influential factors on demand and supply for access	Safety	T_SAF
		Walkability	T_WAL
		Bike ability	T_BIK
		Pedestrian network connectivity	T_PNC

Clustering

K-means clustering is then used to group station areas based on the values of node, place, and tie indices. The K-means algorithm is an iterative method that identifies the optimal cluster of samples, ensuring that the distance between a sample and the mean value in each cluster is minimal while maximizing the distance between different clusters. It is widely utilized in land-use planning due to its ability to handle extensive and continuous geospatial data, as well as to create interpretable clusters that integrate seamlessly with GIS software. Because of its iterative approach, K-means is more flexible in finding an optimal solution than hierarchical clustering. However, the number of clusters must be defined in advance. According to Bertolini's node-place model, the number of clusters is initially set to five ($k=5$).

The K-means iterative algorithm aims to find the optimal solutions that minimize the error function. As presented in Equation 3-7, error function (E) is “the sum of the squared Euclidean distances between each data point ($x \in C_i$) and the centroid (mean vector) of cluster i (μ_i)” (Likas et al., 2003).

Eq. 3-7
$$E = \sum_{i=1}^k \sum_{x \in C_i} |x - \mu_i|^2$$

The process begins with the random selection of K initial centroids. Each data point (station) is then assigned to the nearest centroid. Subsequently, the centroids are recalculated as the mean of the data points in each cluster. This process is repeated until convergence, when no further changes occur in assignments or centroids (Zhao et al., 2024).

Feasibility assessment

This research proposes a feasibility analysis to assess which station areas can be considered for land use and transport development without jeopardizing the balance between supply and demand for access. According to Bertolini's node-place model,

the balance between transport and land use development is reflected in the correlation between node and place indices (Bertolini, 1999). Therefore, canonical correlation analysis (CCA) is conducted to evaluate this correlation.

The CCA provides us with the node and place canonical scores, which reflect the extent and direction of the correlation between the supply and demand for transit access in station areas. In the extended node-place model proposed by this research, the node index represents indicators of the supply of access to the transport system, while the place index represents land use variables that affect the demand for public transport in station areas²⁵. A positive canonical score for the place index indicates that land use development improves the overall land use-transport development; however, a negative canonical score for the place index adversely impacts the access supply-demand correlation in that station area. The same reasoning applies to stations' canonical score on the node index.

As shown in Figure 3-4, the final step of the enhanced node-place model involves plotting stations based on their node and place canonical scores on the X-axis, which indicates the demand for access, and on the Y-axis, which reflects the supply of access. In this scheme, only the stations in the upper right portion of the coordinate axis have a positive node and place canonical scores, meaning transport and land use development will enhance the access supply-demand correlation. However, based on the initial assumption of this research, for the case study of Montreal and other cities with relatively more developed public transport systems than land use, the stations located on the right side of the coordinate axis are candidates for planning

²⁵ See Table 3-3 for the main indicators of the proposed node, place, and tie model, and consult Table 3-8 for the secondary composite variables that were later developed for CCA.

development. Since these stations have a positive canonical score for land use variables (place), and the transportation variables (node) are assumed to be fixed.

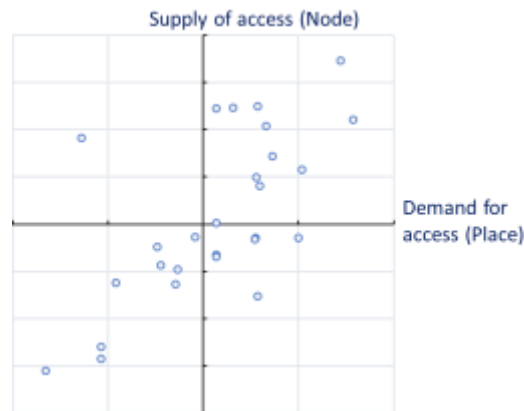


Figure 3-4 Scatter plot of stations based on their node and place canonical scores

3.1.2 Improved TOD Index

In the second stage, the proposed improved TOD Index focuses on assessing actual TODs in accordance with sustainability principles. Following an accessibility-oriented approach, this stage incorporates modifications to selecting criteria and indicators concerning supply and demand for access, calculation, rescaling, and weighting indicators. Additionally, it proposes an efficiency assessment of station areas for compactness.

Selection of criteria and indicators

In the second step, we select the criteria and indicators for the proposed TOD index, which evaluates the sustainability of station areas. These sustainable criteria, known as 5D, include destination accessibility (D1), distance to transit station (D2), design (D3), density (D4), and diversity (D5). Researchers used various indicators to measure the D criteria, as outlined in Table 2-6, where each criterion addresses exclusively one aspect of the built environment, and no meaningful relationship is found between them.

However, in this research, similar to the criteria and indicators chosen for the enhanced node-place model in section 3.1.1, the selection of criteria and indicators for the proposed TOD index is accessibility-oriented. We select 5D criteria and indicators based on their impact on public transport access supply at the local (station area) and urban scales (public transport network), the demand for sustainable access (public and active) within the station area, and the intermediate factors influencing supply and demand for sustainable accessibility.

This research defines destination accessibility (D1) through various types of accessibility, including location-based and infrastructure-based measures. Location-based accessibility encompasses the cumulative opportunity measure to assess local access to transit stations (D1_LA), connectivity metrics such as closeness centrality (D1_CC) and degree of centrality (D1_DC), which evaluate access to transit stations on a regional scale, along with the combination of gravity-based and cumulative opportunity measures to assess network accessibility (D1_NA). Infrastructure-based accessibility, on the other hand, concerns the public transit level of comfort (D1_LC) and the frequency of transit service (D1_FS)²⁶.

Distance to transit station (D2), which indicates pedestrian ease of access to stations, is generally considered within a 400- to 800-meter circular buffer around metro stations, defining the station's service area (D2_SS).

Design (D3) encompasses elements that influence residents' decisions to walk to transit stations, such as urban greenery (D3_UG), pedestrian network connectivity (D3_PN), and compactness (D3_CO). Urban greenery and pedestrian network

²⁶ As explained in Section 2.2.4 of the literature review, accessibility types include location-based (cumulative opportunity, connectivity, and gravity-based measures), infrastructure-based (concerning the quantity and quality of transport service and network), as well as person-based and utility-based accessibility types (concerning the influential factors on residents' travel mode choice, in common with D2)

connectivity contribute to a pleasant and safe environment, enhancing the pedestrian friendliness of the study area, while compactness reflects its livability. A higher level of compactness indicates less gray land use and, consequently, a more concentrated and developed station area, which ultimately minimizes urban sprawl and its negative environmental consequences on a metropolitan scale.

Density (D4) encompasses land-use and demographic data that influence the demand for sustainable access modes within the station catchment area. Density was first defined as one of the three main built environment criteria (density, diversity, and design) in terms of population density, employment (workforce) density, and accessibility to jobs (Cervero & Kockelman, 1997); though the latter was later considered as a separate criterion in the 5D framework by R. W. Lee and Cervero (2007). Ibraeva et al. subsequently highlighted that building density is the key factor in encouraging sustainable modes and facilitating densification (Ibraeva et al., 2021). Given this background and the origin-destination data of Montreal²⁷, this research evaluates the density of TOD areas through transit captive users (D4_DT), which includes low-income and very old or young residents, workforce density (D4_WD), referring to the number of daily commuters, population density (D4_PD), and building density (D4_BD), which represent urban concentration and the spatial distribution of the population. However, population density is expected to overlap with workforce density and the density of transit-captive users. This is later demonstrated through the correlation analysis conducted in Section 4.1 of the case study, where population density shows a high correlation with the other two factors and is subsequently excluded from the list of selected indicators.

²⁷ This is based on the 2003 Montreal origin-destination (OD) survey data from Agence métropolitaine de transport, in which 30.2% of public transport trips are for commuting to work and returning home, 21.7% are for school, 7.6% are for shopping, and 9.2% are for leisure activities (Ahmed et al., 2013).

Diversity (D5), unlike density, impacts the demand for access to the station catchment area from surrounding regions. Land use diversity (D5-LD) indicates the attractiveness of station areas as a travel destination. For example, the vibrancy and variety of land use in the residential peripheral regions are lower than in downtown areas, which exhibit greater land use diversity.

In summary, Tables 3-8 illustrate how the 5D criteria and indicators are defined within the context of sustainable supply and demand access.

Table 3-8 Criteria and indicators of the proposed TOD index

5D criteria		Access mode	Indicators	Abbr.
D1	Supply of access	Public transit Urban scale	Closeness centrality	D1_CC
			Degree of centrality	D1_DC
			Network accessibility	D1_NA
			Level of comfort	D1_LC
			Frequency of transit service	D1_FS
		Public transit local scale	Local access to the transit station	D1_LA
D2	Influential factors on residents' choice of sustainable access mode	local scale	Station service area	D2_SS
Active local scale		Urban greenery	D3_UG	
		Pedestrian network connectivity	D3_PN	
		Compactness	D3_CO	
		D4	Public transit local scale	Density of transit captive users
Workforce density	D4_WD			
Population density ²⁸	D4_PD			
Building density	D4_BD			
D5			Land use diversity	D5_LD

Calculation of indicators

Once we establish the criteria and indicators, it is essential to compile a set of metrics that enable us to compare and categorize the station areas. Table 3-9 presents the

²⁸ Population density is later omitted from the list of indicators because of its high correlation with the other two density indicators.

formula references and data sources used to calculate these indicators in this research.

Table 3-9 Resource for selecting criteria and indicators of the improved TOD index

Indicator		Data sources	References
D1_CC	Closeness centrality	Stm (2021) (https://www.stm.info/en/info/networks/metro)	Amini Pishro et al. (2022)
D1_DC	Degree of centrality	Montréal Données ouvertes (2021) (http://donnees.ville.montreal.qc.ca/dataset)	
D1_NA	Network accessibility	Stm (2021) (https://www.stm.info/en/info/networks/metro) Geoindex (2018) (https://geoapp.bibl.ulaval.ca/login)	Adapted and changed from Motieyan and Mesgari (2017)
D1_LC	Level of comfort	Stm (2021) (https://www.stm.info/en/info/networks/metro)	Singh et al. (2017)
D1_FS	Frequency of transit service		
D1_LA	Local access to the transit station	Montréal Données ouvertes (2021) (http://donnees.ville.montreal.qc.ca/dataset) Geoindex (2018) (https://geoapp.bibl.ulaval.ca/login)	Adapted and changed from Huang et al. (2018)
D2_SS	Station service area		Budiati et al. (2018)
D3_PN	Urban greenery	Montréal Données ouvertes (2021) (http://donnees.ville.montreal.qc.ca/dataset)	Patarasuk (2013) and Schlossberg & Brown (2004)
D3_CO	Pedestrian network connectivity		
D3_UG	Compactness	Open Street (2021) (https://www.openstreetmap.org)	Inspired by Aoki (2023)
D4_DT	Density of transit captive users	Montréal Données ouvertes (2021) (http://donnees.ville.montreal.qc.ca/dataset)	Adopted and changed from Cervero & Kockelman (1997) and Ibraeva et al (2021)
D4_WD	Workforce density	Statistics Canada	
D4_PD	Population density	(https://www.statcan.gc.ca)	
D4_BD	Building density	Montréal Données ouvertes (2021) (http://donnees.ville.montreal.qc.ca/dataset)	
D5_LD	Land-use Diversity	Can map (2021) (https://www.dmtispatial.com)	Motieyan and Mesgari (2017)

Destination accessibility (D1) encompasses indicators that influence the ease of access to the public transit networks and within the stations' catchment area, at urban and local scales, respectively (Table 3-10). This study measures ease of access to the

transit network by network centrality and network accessibility. According to Amini Pishro et al. (2022), the network centrality is evaluated using closeness centrality and degree centrality measures.

Closeness centrality (D1_CC) refers to the centrality of a station within the transit network. Closeness centrality of station i (CC_i) can be defined by the inverse aggregation of the shortest distance between station i and other stations (d_{ij}), representing the centrality of station i in the network (Equation 3-8).

$$\text{Eq. 3-8} \quad CC_i = \frac{1}{\sum_j d_{ij}}$$

Degree of centrality (D1_DC), or the importance of a station in the subway network, depends on the number of stations directly connected to it. Regarding Equation 3-9, exchange stations located at the intersection of two or more metro lines exhibit a greater degree of centrality (DC_i).

$$\text{Eq. 3-9} \quad DC_i = \sum_j a_{ij}, \text{ where } a_{ij} \begin{cases} 1, & i \text{ and } j \text{ are connected} \\ 0, & \text{Otherwise} \end{cases}$$

Network Accessibility (D1_NA) also impacts the ease of access for station residents to destinations in other station areas. As presented in Equation 3-10, network accessibility of station i (NA_i) can be calculated regarding the ease of access to employment opportunities in other station areas (O_j) and the impedance of travel as a function of travel cost $f(c_{ij})$ (Motieyan & Mesgari, 2017).

$$\text{Eq. 3-10} \quad NA_i = \sum_{j=1}^n O_j f(c_{ij})$$

On the other hand, to calculate the network accessibility of station i (NA_i), Higgins & Kanaroglou (2016) considered the ease of access of residents of station i (Pop_i) to the employment opportunities in other station areas (Emp_j) and travel time (TT_{ij}) as a travel impedance (Equation 3-11).

$$\text{Eq. 3-11} \quad NA_i = \ln \sum_{j=1}^n \frac{Pop_i \times Emp_j}{TT_{ij}^2}$$

Therefore, this research proposes a formula (Equation 3-12) that replaces employment opportunities in other station areas (O_j) with the trip attraction of other stations (TA_j), weighted by the transit ridership of station i (TR_i), instead of the total population of station i . In addition, applying the closeness centrality of station i (CC_i) as a travel impedance is more appropriate than travel time and cost, which are almost equal for different destinations in the metro network.

$$\text{Eq. 3-12} \quad NA_i = \sum_{j=1}^n \frac{TA_j \times TR_i}{d_{ij}}$$

Besides, the trip attraction of other station areas (TA_j) is not limited to employment opportunities, as noted in the previous literature. It also encompasses other points of interest (POI_k) such as health, education, office, and commercial, which are weighted according to their capacity to attract travelers (w), see Equation 3-13.

$$\text{Eq. 3-13} \quad TA_j = \sum_{k=1}^n POI_k \times w$$

Other factors that affect residents' ease of access to the transit network include the level of comfort ($D1_LC$) of the station, particularly regarding the availability of facilities such as elevators, and the frequency of transit service ($D1_FS$). The latter is nearly uniform across all stations, with service occurring every 3-5 minutes during non-peak hours on weekdays.

Local accessibility ($D1_LA$), on the other hand, signifies the ease of access to the station from its catchment area. This research proposes a formula for local accessibility, which indicates the ease of access of station i to the points of interest (POIs) in its service area. Here, the origin of the travel is station i , and the destinations are the POIs in its catchment area. As shown in Equation 3-14, local accessibility

(LA_i) is inversely related to the total distance between the POIs and the station i (d_k) and directly related to the number of points of interest (m) and the trip attraction of the station area i (TA_i), which is defined by the weighted sum of the points of interest in its station area.

$$\text{Eq. 3-14} \quad LA_i = \frac{m}{\sum_{k=1}^m d_k} TA_i, \text{ where } TA_i = \sum_{k=1}^n (POI_k \times w)$$

Table 3-10 Destination accessibility (D1)

		Indicator	Description	Abbr.
D1	Ease of access to the transit network	Closeness centrality	The centrality of a station in the network $CC_i = \frac{1}{\sum_j d_{ij}}$ CC_i : closeness centrality of station i d_{ij} : shortest distance between station i and j (in the Montreal metro network, including 68 stations) n : number of stations	D1_CC
		Degree of centrality	Number of stations that are in direct connection with a station $DC_i = \sum_j a_{ij}$ DC_i : degree of centrality station i in the Montreal metro network $a_{ij} \begin{cases} 1, & i \text{ and } j \text{ are connected} \\ 0, & \text{Otherwise} \end{cases}$	D1_DC
		Network accessibility	Ease of access for residents to other station areas $NA_i = \sum_{j=1}^n \frac{TA_j \times TR_i}{d_{ij}}$ NA_i : network accessibility of station i TR_i : transit ridership station area i TA_j : trip attraction of station j $TA_j = \sum_{k=1}^n POI_k \times w$ W : weight of points of interest POI_k : points of interest d_{ij} : shortest distance between station i and j ($i \neq j$)	D1_NA
		Level of comfort	Availability of elevator	D1_LC
		Frequency of transit service	Almost equal for all stations (every 3-5 minutes on weekdays at non-pick hours)	D1_FS
	Ease of access to the station area	Local access to transit station	Ease of access of station i to POIs in its service area $LA_i = \frac{m}{\sum_{k=1}^m d_k} TA_i$ TA_i : trip attraction of station area i $TA_i = \sum_{k=1}^n POI_k \times w$ m : number of points of interest d_k : distance of a point of interest k to station i	D1_LA

Distance to transit station (D2) and design (D3) include intermediate factors that influence the supply and demand for access (Table 3-11).

Distance to transit station (D2) is measured based on either the road network distance or the Euclidean distance from the transit station to the centroid of the dissemination blocks²⁹ in the station service area (D2_SS). The precision of this calculation depends on how the TOD area is defined.³⁰ For example, methods that consider the stations' service areas and network obstacles provide a more nuanced analysis than the circular buffer method. Like most previous research, this study uses the circular buffer method, resulting in a consistent distance-to-transit-station value for all stations.

Design (D3) encompasses aspects of the built environment that influence residents' choices of walking and cycling over vehicles to reach the metro station. In this research, only the land-use and transport factors that affect the supply and demand for public transportation are taken into account, including urban greenery (D3_UG), pedestrian network connectivity (D3_PN), and compactness (D3_CO)³¹.

Urban greenery (D3_UG) can be defined as the total area of open green space (e.g., parks, street green spaces), when a circular buffer delineates the TOD area (Budiati et al., 2018). However, in general, urban greenery (UG_i) is defined regarding the ratio

²⁹ The “hierarchy of standard geographic areas for dissemination, 2021 Census” can be found on the Statistics Canada website. (https://www12.statcan.gc.ca/census-recensement/2021/ref/dict/fig/index-eng.cfm?ID=f1_1)

³⁰ This involves considering factors such as pedestrian route connectivity, distance decay, neighborhood activity, public transport demand, and the distance between stations in the case study (Ahmed et al., 2013).

³¹ Other design factors (e.g., urban furniture, lighting, etc.) are left to be considered in an urban design study.

of the total green areas (S_g) to the service area of station i (S_i), as presented in Equation 3-15.

$$\text{Eq. 3-15} \quad UG_i = \frac{\sum S_g}{S_i}$$

Pedestrian network connectivity (D3_PN) also affects residents' decisions to walk to the station, although pedestrian perception of connectivity differs, as freeways and major arterial roads are viewed as obstacles to pedestrian access. Therefore, following Schlossberg & Brown (2004), we excluded freeways and major arterial roads from the network, which resulted in an increased number of dead ends and fewer pedestrian connectivity measures.

As presented in Equation 3-16, Pedestrian network connectivity (β) is measured regarding “the number of links in a given network (L) to the maximum number of links between nodes ($3 \times (v - 2)$), where v is the number of nodes”(Patarasuk, 2013).

$$\text{Eq. 3-16} \quad \beta = \frac{L}{3 \times (v - 2)}$$

Compactness (D3_CO) plays a crucial role in TOD as one of the design criteria within the 5D framework. It refers to the concentration of land use around transit hubs, which maximizes pedestrian accessibility at the neighborhood level and minimizes urban sprawl on a metropolitan scale. It can be measured by “density gradient³²”(Tong et al., 2018), by “the total number of adjacent cells with the same type of land use” (Ruan et al., 2021), by “the average height of buildings” (Y. Yang et

³² Tong et al. (2018) introduced “a geographical density gradient model to evaluate the density of facilities (points of interest) per 100 m circular area”.

al., 2022), or by floor area ratio (FAR) and building coverage ratio (BCR)³³. However, in this study, we were inspired by Aoki (2023) in applying Equation 3-17, where the compactness level of a station area i (COM_i) is defined by the ratio of the total built-up area (S_b) to the service area of the station i (S_i). The build-up area comprises buildings, roads, and other urban infrastructure, setting it apart from open spaces such as parks or vacant land (green and gray land uses).

$$\text{Eq. 3-17} \quad COM_i = \frac{\sum S_b}{S_i}$$

³³ The floor area ratio (FAR) measures the proportion of a building's total floor area to the land area, while the building coverage ratio (BCR) evaluates the ratio of the building's footprint to the land area. Vertical and horizontal compactness, which are indicators of the skyline and livability of an urban area, can be assessed by FAR and BCR, respectively.

Table 3-11 Distance to transit (D2) and Design (D3)

	Indicator	Description	Abb.
D2	Distance to transit station	The service area of a station	D2_SS
	Urban greenery	The ratio of the total green areas to the station area $UG_i = \frac{\sum S_g}{S_i}$ UG_i : urban greenery of the station area i S_g : total green areas in the station area i S_i : service area of the station i	D3_UG
D3	Pedestrian network connectivity	Total number of edges per node in the non-impedance road network (after excluding freeways and arterial roads from a station area) $\beta = \frac{L}{3 \times (v-2)}$ β : pedestrian network connectivity L : number of edges (links) in the non-impedance road network V : number of vertices (nodes) in the non-impedance road network	D3_PN
	Compactness	The ratio of the total built-up area to the station area $COM_i = \frac{\sum S_b}{S_i}$ COM_i : compactness level of the station area i S_b : total built-up areas S_i : service area of the station i	D3_CO

Density (D4) is defined in terms of the density of transit captive users (D4_DT), workforce density (D4_WD), building density (D4_BD), and population density (D4_PD), which is later discarded as explained in the section on selection of criteria and indicators. “Density is computed by dividing the variable of interest by the unit of area”(Motieyan & Mesgari, 2018). According to Equation 3-18, the density of residents (D_i) is calculated regarding the total number of residents in the dissemination areas (Res_i) in the service area of a 400m buffer (S_{DAj}).

$$\text{Eq. 3-18} \quad D_i = \sum \frac{Res_i}{S_{DAi}}$$

Building density (BD_i) is the mean value of building density and spatial distribution of the population in a 400 m buffer of station area i . As shown in Equation 3-19, it is calculated by knowing the total area of dissemination areas in station area i (S_{DA}) and their density indices ³⁴ (DI), as well as the total area of station area i (S_i).

$$\text{Eq. 3-19} \quad BD_i = \sum \frac{S_{DA} \times DI}{S_i}$$

Diversity ($D5$) reflects the extent of opportunities in the stations' catchment area for "initiating activities" (Nyunt & Wongchavalidkul, 2020) and attracting travelers from outside areas. Various methods and indicators have been used to evaluate land use diversity, including the dissimilarity index and entropy, which represent the proportion of dissimilar land uses in the study area. Entropy ranges from zero, indicating homogeneity where land uses are uniform, to one, representing heterogeneity (Cervero & Kockelman, 1997). According to the entropy measure, land use diversity in station area i (LUd_i) is defined regarding the share of each land-use type (Q_{LUj}), which is determined by the ratio of the area of each land use type (S_{LUj}) to the area of the station catchment area (S_i). In Equation 3-20, j represents a specific land use class and n is the total number of land use types in a station area.

$$\text{Eq. 3-20} \quad LUd_i = \frac{-\sum_j^n Q_{LUj} \times \ln(Q_{LUj})}{\ln(n)}, \quad Q_{LUj} = \frac{S_{LUj}}{S_i}$$

³⁴ The density index represents the number of people per square kilometer in dissemination areas, which serve as the units of data analysis in Statistics Canada's Census Geography. (<https://community.environicsanalytics.com/hc/en-us/articles/28614539576205-3-Statistics-Canada-s-Census-Geography>)

Table 3-12 offers an overview of the density and diversity indicators utilized in this study.

Table 3-12 Density (D4) and Diversity (D5)

	Indicator		Description	Abb.
D4	Density of transit captive users	The ratio of total residents under 16 years, over 65 years, and with low income/workforce/population to the total area of dissemination areas in a station area	$D_i = \sum \frac{Res_i}{S_{DAi}}$ D_i : density of transit captive users, workforce, or total residents in station area i Res_i : number of residents, workforce, or transit captive users in each dissemination area of station area i S_{DAi} : total area of dissemination areas (DA_i) within the service area of 400m from station i	D4_DT
	Workforce density			D4_WD
	Population density			D4_PD
	Building density		Mean value of building density of dissemination areas within a station area	$BD_i = \sum \frac{S_{DA} \times DI}{S_i}$ BD_i : building density in station area i S_i : total area of the station area i S_{DA} : area of each dissemination area DI : density index
D5	Land use Diversity	Based on the measure of entropy	$LUd_i = \frac{-\sum_j^n Q_{LUj} \times \ln(Q_{LUj})}{\ln(n)}$ $Q_{LUj} = \frac{S_{LUj}}{S_i}$ LUd_i : land use diversity in station area i S_i : total area of the station area i S_{LUj} : total area of land use type j Q_{LUj} : share of land-use type j n : number of land-use types	D5_LD

Correlation analysis

After the Shapiro-Wilk test ensures that the data fulfill the normality assumption, Pearson's correlation coefficient (PCC) is applied to verify the linear correlation between indicators. If the PCC result indicates that the indicators are highly related to each other ($|r| > 0.7$), they should be discarded to avoid the problem of

multicollinearity. For further explanation, please refer to section 3.1.1, subsection on correlation analysis to avoid redundancy.

Preparation and aggregation of data

This step involves examining various rescaling, weighting, and aggregating methods used in TOD literature to produce a combined evaluation index (TOD index) with less bias in the weighting and aggregating processes.

I. Rescaling

Data rescaling involves adjusting data to fit a specific range, thereby enhancing model performance, facilitating fair comparisons, and improving interpretability. A literature review reveals that specific data rescaling methods are frequently employed in particular contexts, regarding their limitations and abilities to address data distribution and scale issues. For example, linear max and linear sum are used as preprocessing steps in the analytic hierarchy process (AHP) and Entropy. In contrast, linear min-max is often utilized before using the weighted sum and CRITIC.³⁵ While vector normalization is reserved for the TOPSIS³⁶; see Table 3-13.

³⁵ CRITIC stands for the criterion importance through inter-criterion correlation.

³⁶ TOPSIS stands for the technique for order of preference by similarity to the ideal solution.

Table 3-13 Rescaling techniques

Rescaling techniques	Application	Formula		
		Benefit criteria	Cost criteria	
Linear max	AHP and Entropy	$\frac{x}{x_{max}}$	$1 - \frac{x}{x_{max}}$	Eq. 3-21
Linear sum		$\frac{x}{\sum x}$	$\frac{1/x}{\sum 1/x}$	Eq. 3-22
Linear min-max	CRITIC	$\frac{x - x_{min}}{x_{max} - x_{min}}$	$\frac{x_{max} - x}{x_{max} - x_{min}}$	Eq. 3-23
Vector normalization	TOPSIS	$\frac{x}{\sqrt{\sum x^2}}$	$1 - \frac{x}{\sqrt{\sum x^2}}$	Eq. 3-24

II. Weighting

Subjective weighting methods, such as the Analytic Hierarchy Process (AHP), have been extensively employed to determine the relative importance of criteria and indicators for developing the TOD Index. AHP is a structured method that includes creating a hierarchy of the decision alternatives, a pair-wise comparison of rescaled variables (r_{ij}) and deriving weights (w_j) (Equation 3-25), as well as checking their reliability by the consistency ratio (CR), Equation 3-26.

The consistency ratio (CR) checks the reliability of the judgments and weights regarding the "largest eigenvalue of the pairwise comparison matrix" (λ_{max}), random index (RI), defined in Table 3-14, and the matrix size (n). If the consistency ratio is less than one ($CR < 1$), the weights are valid (Saaty, 2008).

$$\text{Eq. 3-25} \quad w_j = \frac{r_{ij}}{\sum_{j=1}^n r_{ij}}$$

$$\text{Eq. 3-26} \quad CR = \frac{CI}{RI}, \text{ where } CI = \frac{\lambda_{max} - n}{n-1}$$

Table 3-14 The consistency ratio (CR)

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

This study aims to apply objective weighting methods that are more broadly applicable and less susceptible to bias in expert evaluations. While methods like entropy and criteria importance through inter-criterion correlation (CRITIC) have not yet been implemented in TOD literature, they have been used in other fields.

Entropy is an objective weighting technique focusing on the variability of the criteria and indicators' values among decision alternatives (stations). Consequently, indicators with more significant variability are given greater weight in decision-making (Y. Zhu et al., 2020). According to Equation 3-27, Entropy (E_j) is defined regarding the rescaled indicators' value of stations (r_{ij}) and a factor (h) that ensures $0 < E_j < 1$ for each station $i \in \{1, 2, \dots, m\}$ and indicator $j \in \{1, 2, \dots, n\}$.

$$\text{Eq. 3-27} \quad E_j = -h \sum_{i=1}^m r_{ij} \ln r_{ij}$$

The level of importance of each variable (w_j) is then calculated regarding the degree of divergence (d_j), Equation 3-28.

$$\text{Eq. 3-28} \quad d_j = 1 - E_j, w_j = \frac{d_j}{\sum_{j=1}^n d_k}$$

The CRITIC method also objectively determines the weights of criteria and indicators based on the variability of criteria and indicators' values among decision alternatives (stations) and the linear correlation between them. Therefore, highly

correlated variables with less variability get lower weights. The process involves rescaling data using the linear min-max normalization, calculating the standard deviation (σ_j), creating a correlation matrix to find the correlation coefficient of indicators (r_{jk}), and determining the CRITIC value of each variable (C_j) based on Equation 3-29. The weights of indicators (w_j) are then defined using Equation 3-30 (Diakoulaki et al., 1995).

$$\text{Eq. 3-29} \quad C_j = \sigma_j \sum_{k=1}^m (1 - r_{jk})$$

$$\text{Eq. 3-30} \quad w_j = \frac{C_j}{\sum_{k=1}^m C_k}, j \in \{1, 2, \dots, n\} \text{ and } k \in \{1, 2, \dots, m\}$$

III. Aggregating

At last, weighted indicators are aggregated using the spatial data aggregation methods in ArcGIS (Dou et al., 2016; Singh et al., 2014) and the weighted sum method (WSM) (Rahmat et al., 2016) to create a TOD index. As shown in Equation 3-31, the TOD index for each station area is obtained regarding the value of criterion j for station i (x_{ij}) and its weight (W_j).

$$\text{Eq. 3-31} \quad TOD\ Index_i = \sum_{j=1}^m W_j x_{ij}$$

Ranking stations

In TOD literature, stations are usually ranked based on the value of the TOD index. However, other methods, such as the technique for order of preference by similarity to the ideal solution (TOPSIS), have been applied in different fields of study (Tzeng & Huang, 2011). As depicted in Equation 3-32, TOPSIS ranks alternatives (stations) based on their performance score (P_j), which are defined regarding the Euclidean distance from the ideal best solution (D_j^+) and the ideal worst solution (D_j^-).

$$\text{Eq. 3-32} \quad P_j = \frac{D_j^-}{(D_j^+ + D_j^-)}$$

The Euclidean distance from the ideal best and worst solutions (D_j^+ and D_j^-) are defined by knowing the weighted normalized value (v_{ij}) as well as the indicators' maximum value (v_i^+) and minimum value (v_i^-), see Equation 3-33.

$$\text{Eq. 3-33} \quad D_j^+ = \sqrt{\sum_{i=1}^n (v_{ij} - v_i^+)^2}, D_j^- = \sqrt{\sum_{i=1}^n (v_{ij} - v_i^-)^2}$$

As shown in Equation 3-34, the weighted normalized value (v_{ij}) is defined by knowing the weight of indicators (w_i) and the rescaled indicator i for station j (x_{ij}), which is calculated by vector normalization for cost and benefit criteria presented in Equations 3-24.

$$\text{Eq. 3-34} \quad v_{ij} = x_{ij} \times w_i, i \in \{1, 2, \dots, n\}, j \in \{1, 2, \dots, m\}$$

To select the data preparation and aggregation method, the Pearson correlation coefficient (PCC) is then applied to compare the ranking results from different methods. In Equation 3-35, the correlation coefficient (r), calculated based on the corresponding data of each set (x_i, y_i) and their means ($\bar{x}, \bar{y}$), is then used to construct a similarity matrix.

$$\text{Eq. 3-35} \quad r = \frac{\sum (x_i - \bar{x})(y_i - \bar{y})}{\sum \sqrt{(x_i - \bar{x})^2 (y_i - \bar{y})^2}}$$

Efficiency test

This step addresses a TOD goal of compact and sustainable development around public transit stations. For this purpose, an output-oriented data envelopment analysis (DEA) is employed to maximize destination accessibility, design, density,

and diversity variables (D1, D3, D4, and D5) while maintaining a constant distance to transit (D2), representing the model's outputs and inputs, respectively.

We follow Wanke & Kalam Azad (2018) in employing an output-oriented DEA, a non-parametric method to assess the performance or efficiency of decision-making units (DMUs) based on their capacity to maximize outputs while maintaining constant inputs (Equation 3-36). DEA is defined regardless of data distribution and correlation in terms of the output data (y_{rk}), input data (x_{ik}), the weight of output data (u_r) and the weight of input data (v_i), as well as the number of input data (i), output data (r), and DMUs or stations in this study (j).

$$\text{Eq. 3-36} \quad g_{k=Max} \sum_{r=1}^s u_r y_{rk}, \sum_{r=1}^s u_r y_{rk} - \sum_{i=1}^m v_i x_{ik} \leq 0, \sum_{i=1}^m v_i x_{ik} = 1, \\ u_r, v_i \geq 0, i \in \{1, 2, \dots, m\}, r \in \{1, 2, \dots, s\}, j \in \{1, 2, \dots, k\}$$

It is recommended that the number of DMUs is at least twice the total number of input and output variables ($k \geq (m + s) \times 2$). In cases with too many variables, principal component analysis (PCA) can be applied to generate a new set of uncorrelated variables.

3.1.3 Optimization

Aligned with TOD's ultimate goal of enhancing sustainable accessibility, this stage focuses on maximizing public transport accessibility at each station. Assuming a sufficient and consistent supply of transport network and service, maximizing public transport accessibility relies on maximizing demand for public transport, which is defined by transit ridership and trip attraction. These factors determine the demand for access in each station catchment area.

Defining objectives and constraints

To maximize public transport accessibility of station i (AC_i), it is required to maximize the network accessibility of station i (NA_i) and its local accessibility (LA_i). This objective function is subject to constraints regarding each station area's current value (a and b) and the maximum value of all the stations (a_{max} and b_{max}), see Equation 3-37.

$$\text{Eq. 3-37} \quad \text{Max } AC_i = \text{Max } (NA_i + LA_i) = \text{Max} \left(\left(\sum_{j=1}^n \frac{TA_j}{d_{ij}} \right) TR_i + \frac{m}{\sum_{k=1}^m d_k} TA_i \right),$$
$$a TR_i + b TA_i \leq a_{max} TR_{max} + b_{max} TA_{max}, \quad a = \left(\sum_{j=1}^n \frac{TA_j}{d_{ij}} \right); \quad b = \frac{m}{\sum_{k=1}^m d_k}$$

Solving the multi-objective problem

To solve this linear programming problem, the network and local accessibility must be minimized. Network accessibility of station i (NA_i) is defined by Equation 3-38, considering the transit ridership of station area i (TR_i), trip attraction of other stations (TA_j), and the shortest distance between stations i and j (d_{ij}). It is noteworthy that the latter remains constant, based on the research assumption of a constant public transport service and infrastructure.

$$\text{Eq. 3-38} \quad NA_i = \sum_{j=1}^n \frac{TA_j \times TR_i}{d_{ij}}$$

Trip attraction of other stations (TA_j) is measured by Equation 3-39, considering the points of interest (POI_k) in station area $j \in \{1, 2, \dots, n\}$ and their weight (W).

$$\text{Eq. 3-39} \quad TA_j = \sum_{k=1}^m (POI_k \times w)$$

Local accessibility (LA_i) is defined according to Equation 3-40, in terms of the trip attraction of station i (TA_i), the number of points of interest (m), and the distance between points of interest k and station i (d_k).

$$\text{Eq. 3-40} \quad LA_i = \frac{m}{\sum_{k=1}^m d_k} TA_i, k \in \{1, 2, \dots, m\}$$

And the trip attraction of station i (TA_i), which is measured by Equation 3-41, relates to the points of interest within the local station area and their relative importance.

$$\text{Eq. 3-41} \quad TA_i = \sum_{k=1}^m (POI_k \times w)$$

3.2 Disaster Mitigation Strategies

Adopting a holistic approach to risk mitigation, this section presents a vulnerability assessment model and a proposal for future road network intervention planning to enhance resilience (Figures 3-5).

The proposed vulnerability assessment process (stage 3.2.1) aims to identify station areas at a higher risk of natural hazards and exclude them from the list of prospective land use developments. It involves extracting data, creating hazard maps, and developing indices for exposure, sensitivity, and adaptive capacity. It then aggregates these spatial data using the appropriate fuzzy overlay function in ArcGIS to produce a vulnerability index map.

The proposed methodology's stages and steps, as illustrated in Figures 3-1 and 3-3, are explained in two main sections: improved TOD planning (Section 3.1) and risk mitigation strategies (Section 3.2). However, it does not follow a linear path and involves some back-and-forth between its stages. In this regard, after defining the feasible station areas for land use development in Section 3.1.1, and before proceeding to Section 3.1.2 to evaluate the efficiency of those station areas for sustainable development, the areas showing high vulnerability to meteorological hazards are first identified and discarded in Section 3.2.1 (vulnerability assessment). At the final stage (3.2.2), we propose a schema for future research that integrates

system dynamics and traffic simulation models. This will help assess and predict how land use development affects the resilience of the road network in the study area.

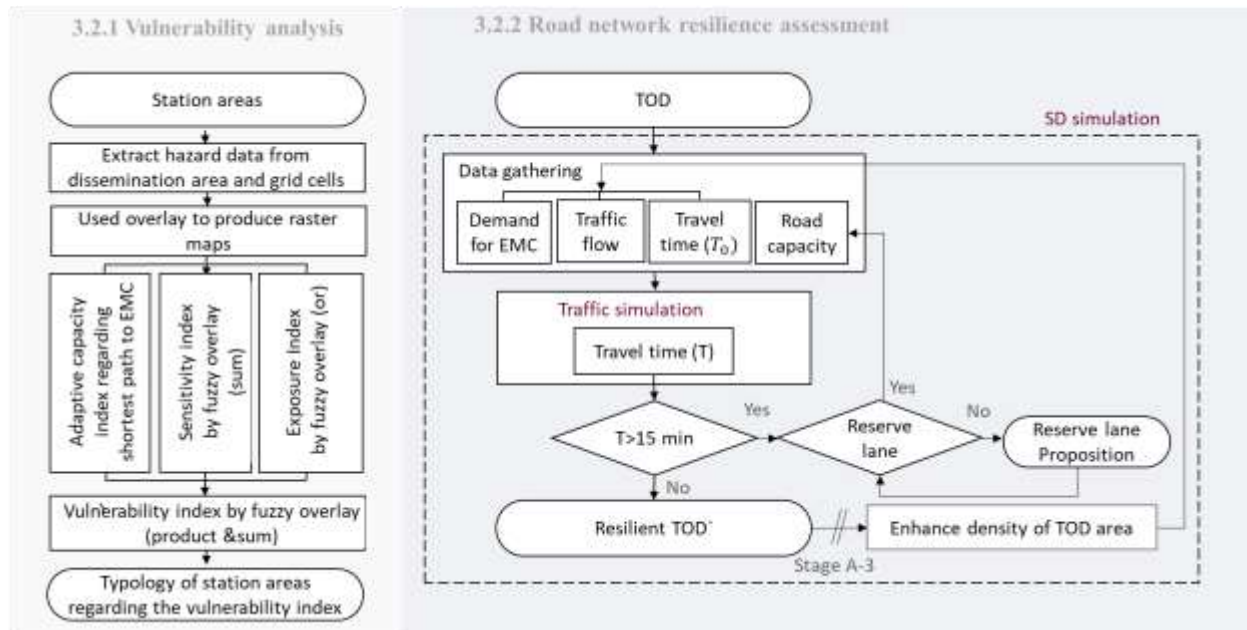


Figure 3-5 Steps of the proposed disaster mitigation planning

3.2.1 Vulnerability Assessment

After ensuring the balanced integration of land use and transport development in step 3.1.1, this step evaluates the vulnerability of station areas to meteorological hazards. Conducting a vulnerability assessment involves three steps: 1. Extracting hazard data to identify critical hazards and creating hazard maps for the study area; 2. Producing pre-processing maps that represent dimensions of vulnerability; and 3. Developing a vulnerability index.

Extracting hazard data

The data needed to identify critical hazards in Montreal and create hazard maps is obtained from the open data platform of the city of Montreal³⁷, along with population data obtained from Statistics Canada³⁸. This involves gathering data on the sensitive population (based on age and income characteristics) at risk of extreme meteorological events, the total population of dissemination areas exposed to Montreal's primary natural hazards (riverine and pluvial flooding, storms, and heat waves), and information on Montreal's emergency centers (hospitals, shelters, and fire stations).

Producing pre-processing maps

This step involves defining the dimensions of vulnerability and the spatial analysis methods employed.

To define dimensions of vulnerability, we follow the IPCC (2014),³⁹ which shifted its focus to inherent factors, including exposure, sensitivity, and adaptive capacity. Exposure refers to the extent to which the study area is in contact with hazards. Sensitivity includes the weaknesses that affect the degree of damage caused by hazards. In contrast, adaptive capacity represents the urban area's ability to withstand hazards.

ArcGIS spatial analysis techniques can be classified based on how they account for uncertainty. Former researchers employed expert judgment and the Analytic Hierarchy Process (AHP) to assign weights to indicators based on their importance,

³⁷ Ville de Montréal (2018). Données.Montreal. retrieved from [<https://donnees.montreal.ca/fr/dataset/vulnerabilite-changements-climatiques>]

³⁸ Government of Canada Publications (2018). Statistics Canada. retrieved from [<https://www.statcan.gc.ca>]

³⁹ The fifth assessment report of the Intergovernmental Panel on Climate Change (IPCC) in 2014

and then aggregated them through weighted sum or weighted overlay techniques to create hazard maps. This process was followed by the development of sensitivity, exposure, adaptive capacity, and ultimately, vulnerability indices (M. Zhang et al., 2019). Traditional overlay techniques, including weighted overlay and weighted sum, evaluate each cell based on specific criteria and class boundaries that can be challenging to define⁴⁰. In contrast, the fuzzy overlay analysis technique addresses scenarios where boundaries between classes (sets) are unclear by considering the possibility⁴¹ that a cell belongs to each set (degree of membership as defined by multiple criteria), rather than being confined to a specific set.

Fuzzy overlay techniques in ArcGIS, such as fuzzy OR, fuzzy sum, and fuzzy product, manage uncertainty in spatial analysis in various ways. Fuzzy OR selects the maximum value, Fuzzy SUM adds up all the input values, while Fuzzy PRODUCT multiplies the values, often resulting in a lower overall value (unless all factors have high values). “Choosing among them depends on whether the goal is to highlight strong suitability (OR), balance multiple influences (SUM), or enforce stricter conditions (PRODUCT)”⁴². Table 3-15 provides an overview of the fuzzy overlay techniques used in this study for creating pre-processing and vulnerability

⁴⁰ Traditional overlays include the weighted overlay, which “overlays several raster images using a common measurement scale and weights each according to its importance,” and the weighted sum, which “overlays several rasters, multiplying each by their given weight and summing them together”(ArcGIS help, an overview of the overlay toolset), retrieved from [<https://pro.arcgis.com/en/pro-app/latest/tool-reference/spatial-analyst/an-overview-of-the-overlay-tools.htm>]

⁴¹ Possibility, which comes from possibility theory and fuzzy logic developed by Lotfi Zadeh (1988), deals with vague or imprecise data, rather than the statistical likelihood of an event (probability).

⁴² Esri. (2020). ArcGIS Desktop: Release 10.8. Environmental Systems Research Institute. Retrieved from [<https://pro.arcgis.com/en/pro-app/latest/tool-reference/spatial-analyst/applying-fuzzy-logic-to-overlay-rasters.htm>]

maps, along with the proposed formula that will be explained in the following section.

Table 3-15 Fuzzy overlay techniques used in this study

Indicator	Fuzzy method	Combination logic	Formula
EI	OR	Union	$\text{Max} [(E_H \times W_H), (E_F \times W_F), (E_S \times W_S)]$
SI	SUM	Aggregative	$1 - [(1 - S_{LI}) \times (1 - S_A)]$
EI & SI	PRODUCT	Cumulative	$EI \times SI$
VI	SUM	Aggregative	$1 - [(1 - (EI \times SI)) \times (1 - ADI)]$

Note: In union, the highest input prevails. In aggregation, all factors influence the result in a combined way. In cumulative, any slight reduction in one input dramatically decreases the overall result and vice versa.

Creating the vulnerability index

The vulnerability index is developed based on the dimensions of vulnerability, including the study area's exposure to dominant meteorological hazards (exposure index), its socio-economic susceptibility (sensitivity index), and its ability to recover post-disaster in terms of access to emergency centers (adaptive capacity).

The adaptive capacity index (ADI) is defined based on each station area's ability to access emergency centers (EMCs). After allocating the population data to the centroid of each dissemination block using inverse distance weighted (IDW) interpolation, the shortest path from the centroid of each dissemination block to the nearest EMCs is determined in ArcGIS. The average of these shortest paths indicates the adaptive capacity of each station area.

The exposure index (EI) indicates the extent to which the study area is dominated by meteorological hazards, including heat waves (E_H), floods (E_F), and storms (E_S) by considering their relative importance in terms of the cost of damage (W_S , W_F , W_H).

The Or fuzzy overlay function is applied as the most severe hazard defines the exposure index, see Equation 3-42.

$$\text{Eq. 3-42} \quad EI = \text{Max} [(E_H \times W_H), (E_F \times W_F), (E_S \times W_S)], \quad \text{where } W_S + W_F + W_H = 1$$

The sensitivity index considers the population at risk and socio-economic factors. As equation 3-43 shows, the sensitivity index (SI) is created by overlaying the low-income population (S_{LI}) with the senior and junior population (S_A) using the Sum Fuzzy operation, as increasing the contributing factors aggregates the sensitivity index.

$$\text{Eq. 3-43} \quad SI = 1 - ((1 - S_{LI}) \times (1 - S_A))$$

Socioeconomic sensitivity determines the magnitude of hazards' impacts. Therefore, the fuzzy overlay product can measure the combined effect of sensitivity and exposure indices, where increasing the population at risk significantly affects the magnitude of damage caused by hazard exposure.

Finally, the vulnerability index is calculated based on the aggregated effects of all the aforementioned indices. As Equation 3-44 shows, the sum function is used for the fuzzy overlay of adaptive capacity, exposure, and sensitivity maps. This proposed method for assessing vulnerability to meteorological hazards (VI) incorporates the combined effects of sensitivity and exposure ($EI \times SI$) along with adaptive capacity (ADI), while incorporating uncertainties in spatial analysis.

$$\text{Eq. 3-44} \quad VI = 1 - [(1 - (EI \times SI)) \times (1 - ADI)]$$

3.2.2 Road Network Resilience Assessment

This stage proposes an approach to offset the adverse effects of increasing population density in TOD areas by focusing on the emergency response phase of disaster

mitigation. The effectiveness of emergency services depends on the accessibility of dissemination blocks to emergency centers (EMC) (e.g., hospitals, police stations, fire stations), which can be measured by travel time and, in turn, depends on the demand for access (factor of population), traffic flow, capacity of the road network, and distance to EMC. Therefore, resilience planning involves estimating the travel time from the centroid of each dissemination block to the EMCs in different development scenarios, including the current, five-year, and ten-year populations. If travel time to EMCs exceeds 15 minutes, the TOD area is not resilient to hazardous events, and planning interventions such as allocating a reserved lane for emergency services are recommended.

Since urban areas are dynamic systems that evolve due to population growth and new construction, system dynamics (SD) can be applied to simulate the effects of different urban system elements on their resilience. Figure 3-6 shows how population growth increases traffic flow, travel time, and demand for access to EMCs.

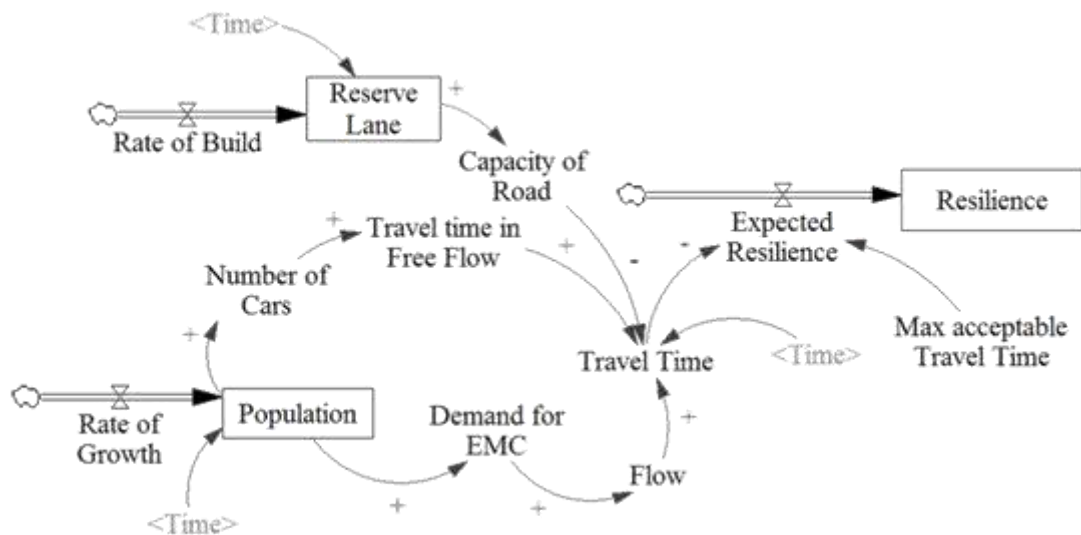


Figure 3-6 Schematic model of TOD resilience assessment

To mitigate the negative effects of population concentration in TOD areas, emergency access can be enhanced by designating reserve lanes. As shown in Equation 3-45, cumulative resilience for multiple hazards during the simulation period (ZA) is measured regarding the probability of hazard occurrence (Pr_i), which is considered constant, and the probability of meeting desirable performance in the face of hazards $Pr(A|i)$. Here, the desirable performance is defined as access to EMCs in less than 15 minutes ($T > 15$).

$$\text{Eq. 3-45} \quad ZA = \sum_i Pr(A|i) \cdot Pr(i), \quad Pr(A|i) = Pr(T > 15)$$

CHAPTER 4: CASE STUDY OF MONTREAL METRO⁴³

TOD is a component of Montreal's first regional plan, the plan métropolitain d'aménagement et de développement (PMAD), which is endorsed by all municipal representatives and therefore has the authority to facilitate local action (Cournoyer-Gendron, 2017). Since 2012, the PMAD, which can be translated as the Metropolitan Land Use and Development Plan, has been adopted "to create sustainable living environments in Greater Montreal, with the objectives of orienting 40% of future households towards transit-oriented hubs, both existing and proposed, throughout the region"(Lavoie & El-Geneidy, 2012). This inward urban development, along with the Quebec government's prohibition on building in flood-prone areas, prevents urban expansion into these areas, thereby satisfying the Canadian goal of "developing a society more resilient to natural disasters," as introduced by the Institute for Catastrophic Loss Reduction (Dotto et al., 2010). In addition, according to Public Safety Canada (2017), since 2015, emergency management in Canada has shifted its focus from preparedness and response to disaster prevention and mitigation.

In this study, the station areas of the Orange line of the Montreal Metro⁴⁴ were selected as a case study. With 68 stations, the Montreal metro is one of North America's busiest and oldest metro networks, after New York City, Mexico City, and the Toronto subway. The orange line of the Montreal metro, with 31 stations, runs through the center of the island of Montreal, where many existing TODs are located. In addition, according to metro ridership records (from 2019-2020) obtained from

⁴³ A version of Chapters 4 has been published by Rabiei et al. (2022) in a journal article entitled Multistage Transit-Oriented Development Assessment: A Case Study of the Montréal Metro System in the Journal of Urban Planning and Development, volume 148, issue 3, pages 1-17.

⁴⁴ Montreal Metro, namely the STM's Metro system, operated by the Société de transport de Montréal (STM).

the Société de transport de Montréal (STM), the orange line has the highest annual ridership (Figure 4-1).

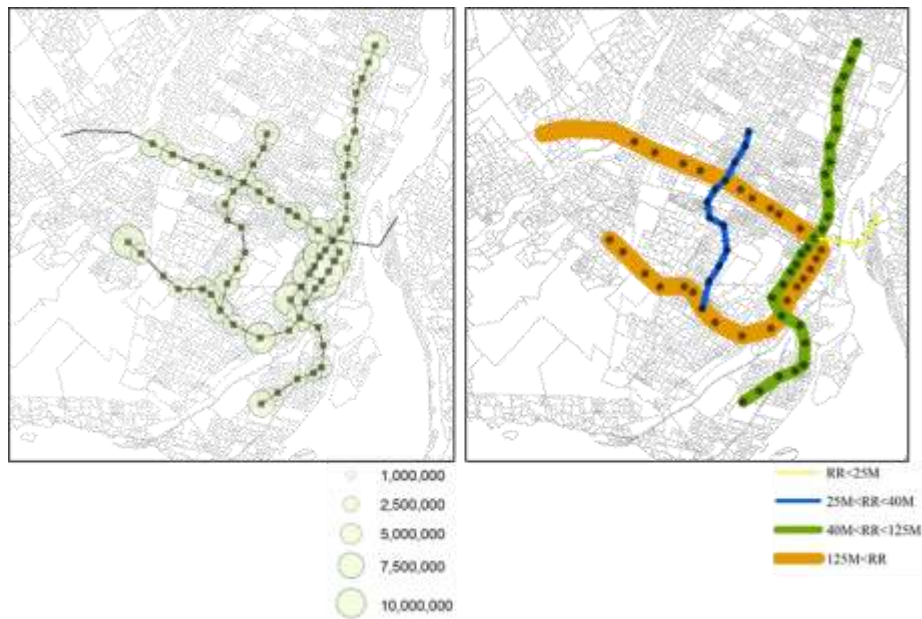


Figure 4-1 Montreal metro lines and the annual ridership report (RR)

Figure 4-2 shows the Orange Line and the existing TODs on the island of Montreal. Although the entire Orange line, with 31 stations, was used to calculate metro network indicators such as closeness centrality, degree of centrality, and number of metro directions, the case study and other indicators were limited to 28 stations on the island of Montreal.

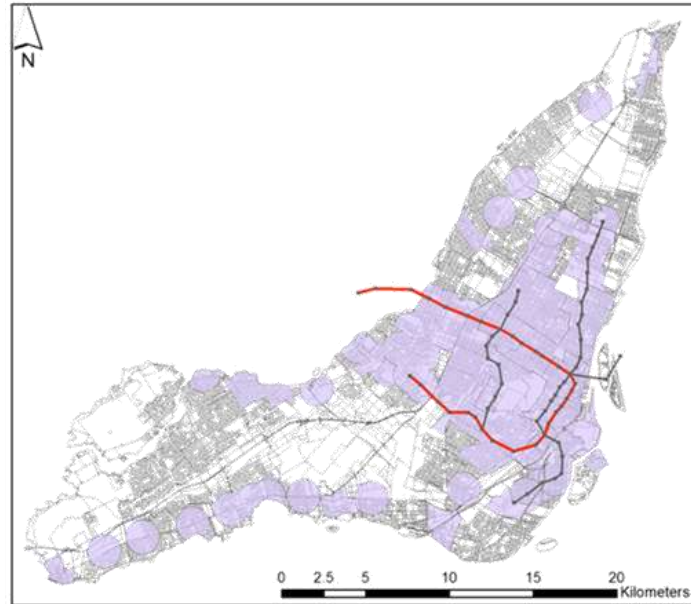


Figure 4-2 Existing TODs and Montreal metro

This study considered two circular buffers of 400m and 800m to analyze the TOD level of the station area. The metro stations of the Orange Line are closely located and pass through the Montreal city center, which has a high concentration of education, social, and commercial activities, especially between the two interchange stations, Berri-UQAM and Lionel-Groulx. Therefore, the 400-m buffer was used to calculate travel destination indicators, including land use mixedness and the number of points of interest that attract travelers from other stations. The 800-m buffer was used to obtain travel origin indicators, such as workforce and transit captive users' density (Figure 4-3).



Figure 4-3 Analysis area defined by 400m and 800m station buffers

4.1 Land use and transport Integration Assessment

Following the delineation of the TOD area for each station, the node, place, and tie indices are obtained from the databases presented in Appendix B-1. As the present study is confined to the Orange Line of the Montreal metro, the frequency of transit service (N-FTS) is equivalent for all stations and is therefore omitted from the list of variables. These variables are then calculated using the formulas and methods presented in Tables 3-4, 3-5, and 3-6.

Once the primary and secondary data have been defined, with consideration for the result of the normality test (a Shapiro-Wilk test conducted in Excel, where the p-value is greater than 0.05), the data are found to follow a normal distribution. Therefore, the assumption of linearity, a prerequisite for the Pearson correlation coefficient (PCC) and canonical correlation analysis (CCA) is satisfied.

PCC was applied to assess the linear relationship between variables and confirm the absence of risk of multicollinearity. As the correlation coefficient (r) was less than 0.7, none of the variables were discarded. CCA was then carried out using XLSTAT (an Excel add-in) to identify linear relationships among three sets of variables: node-place (N-P), node-tie (N-T), and place-tie (P-T). Here, node (N) refers to public transport, private car, and active transport variables. The place (P) contains the transit station, origin of travel, and destination of travel variables. The tie (T) includes pedestrian-friendly, cycling-friendly, and pedestrian-access variables. As shown in Table 4-1, the first canonical factor (F1) accounts for over 70% of the variability in the linear correlation of the node, place, and tie variables; therefore, the analysis is conducted based on F1.

Table 4-1 Canonical correlations

Set of variables	Variability (%) explained by F1	Variability (%) explained by F2	Variability (%) explained by F3	Canonical correlation on F1
Node-Place (N-P)	79.56	19.70	0.74	0.73
Node-Tie (N-T)	73.00	25.49	1.50	0.83
Place-Tie (P-T)	73.00	25.49	1.50	0.83

Most statistical software, including XLSTAT, standardizes data for correlation analysis. A standardized canonical coefficient above 0.3 indicates the strength of a variable's effect on the correlation between sets, whereas a coefficient below -0.3 signifies an inverse relationship. Table 4-2 illustrates the positive role of the origin of travel and pedestrian access variables in node, place, and tie correlation. In other words, enhancing the quality of land use development in station areas and improving pedestrian access to stations through urban design balances the supply-demand relationship between the land use and transport sectors. This finding highlights the importance of land-use development and urban design in Montreal, through which

enhancing pedestrian access (pedestrian network connectivity) and land-use density and diversity in the station area will positively affect the supply-demand correlation.

Table 4-2 Standardized canonical coefficients

Node-Place (N-P)					
Node	Public transport	-0.95	Place	Transit ridership	-0.90
	Privet car	-0.33		Origin of travel	0.12
	Active transit	-0.32		Destination of travel	-0.39
Node-Tie (N-T)					
Node	Public transport	-0.46	Tie	Pedestrian-friendly	-0.62
	Privet car	-0.48		Cycling friendly	-0.58
	Active transit	-0.91		Pedestrian access	0.26
Place-Tie (P-T)					
Place	Transit station	-0.95	Tie	Pedestrian-friendly	-0.75
	Origin of travel	0.55		Cycling friendly	-0.41
	Destination of travel	-0.23		Pedestrian access	-0.33

Then, the correlations between input variables (the composite variables of node, place, and tie indices) and canonical variables are obtained from XLSTAT for each node-place, node-tie, and place-tie (Table 4-3). The results of this table, which show the correlation between the input variables and the canonical variables, are then rescaled so that the total equals 1. Based on that, the relative importance of variables is derived and presented in Table 4-4.

The next stage involved aggregating the variables using the weighted sum method to calculate the node, place, and tie indices.

Table 4-3 Correlations between input variables and canonical variables

Node-Place	Place	Transit ridership	0.91
		Origin of travel	0.15
		Destination of travel	0.48
	Node	Public transport	0.91
		Privet car	0.18
		Active transit	0.22
Node-Tie	Node	Public transport	0.38
		Privet car	0.24
		Active transit	0.80
	Tie	Pedestrian-friendly	0.74
		Cycling friendly	0.80
		Pedestrian access	0.32
Place-Tie	Tie	Pedestrian-friendly	0.90
		Cycling friendly	0.52
		Pedestrian access	0.32
	Place	Transit ridership	0.82
		Origin of travel	0.28
		Destination of travel	0.30

Table 4-4 The relative importance of the node, place, and tie indicators

	Variables	Weight
Node	Public transport	0.65
	Privet car	0.21
	Active transit	0.51
Place	Transit ridership	0.87
	Origin of travel	0.21
	Destination of travel	0.39
Tie	Pedestrian-friendly	0.53
	Cycling friendly	0.66
	Pedestrian access	0.32

Figures 4-4 demonstrate that weighted and unweighted indicators significantly affect the resulting node, place, and tie indices. These graphs plot each station area based on its node, place, and tie values.

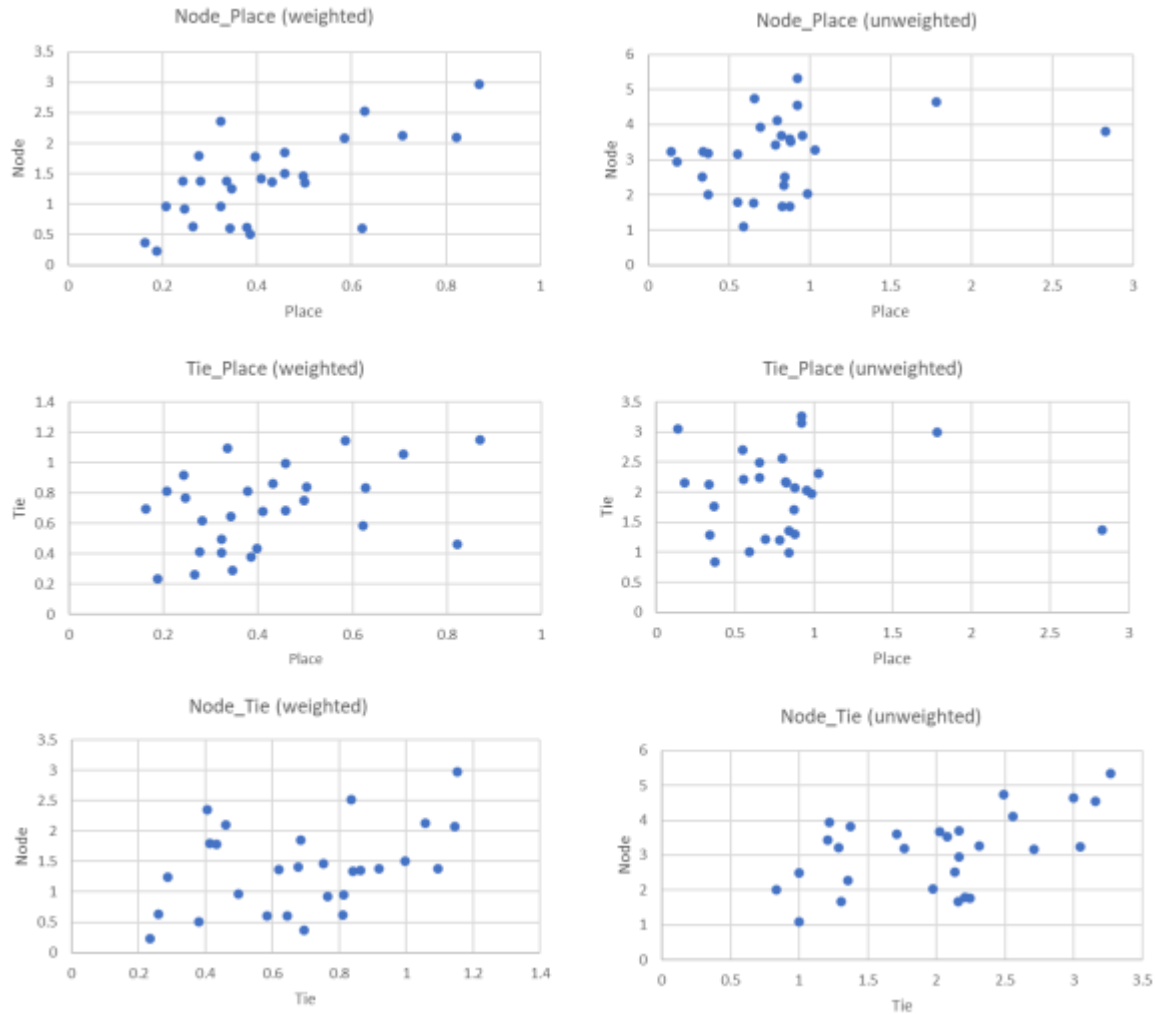


Figure 4-4 Weighted and unweighted node, place, and tie indices

Following the aggregation of variables using the weighted sum method and the calculation of the node, place, and tie indices, the accessibility of 28 station areas of the Orange line on the island of Montreal was compared in terms of their potential for access to public transport (node index), demand for access (place index), and the urban design factors affecting residents' choice of public transit mode (tie index). The result is represented in Figures 4-5.

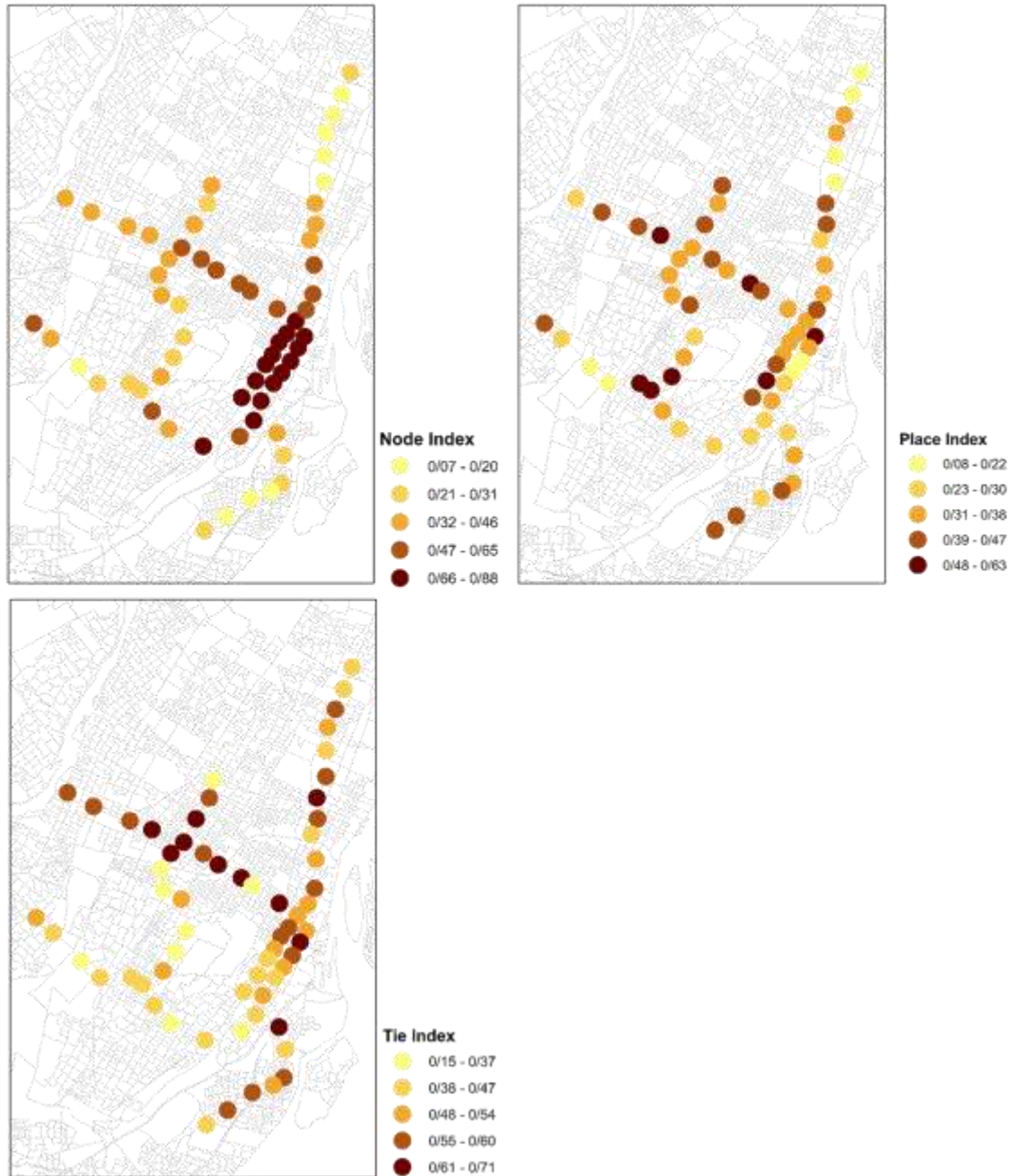


Figure 4-5 Node, place, and tie indices of the Montreal metro

The station area's typology was defined using K-means clustering (Figure 4-6). According to Bertolini's model, we initially opted for five clusters, and then four and three clusters were examined by XLSTAT. The optimal four clusters ($k=4$) were

identified to minimize the average inter-cluster distance and maximize the average distance from the center of each cluster to the other clusters.

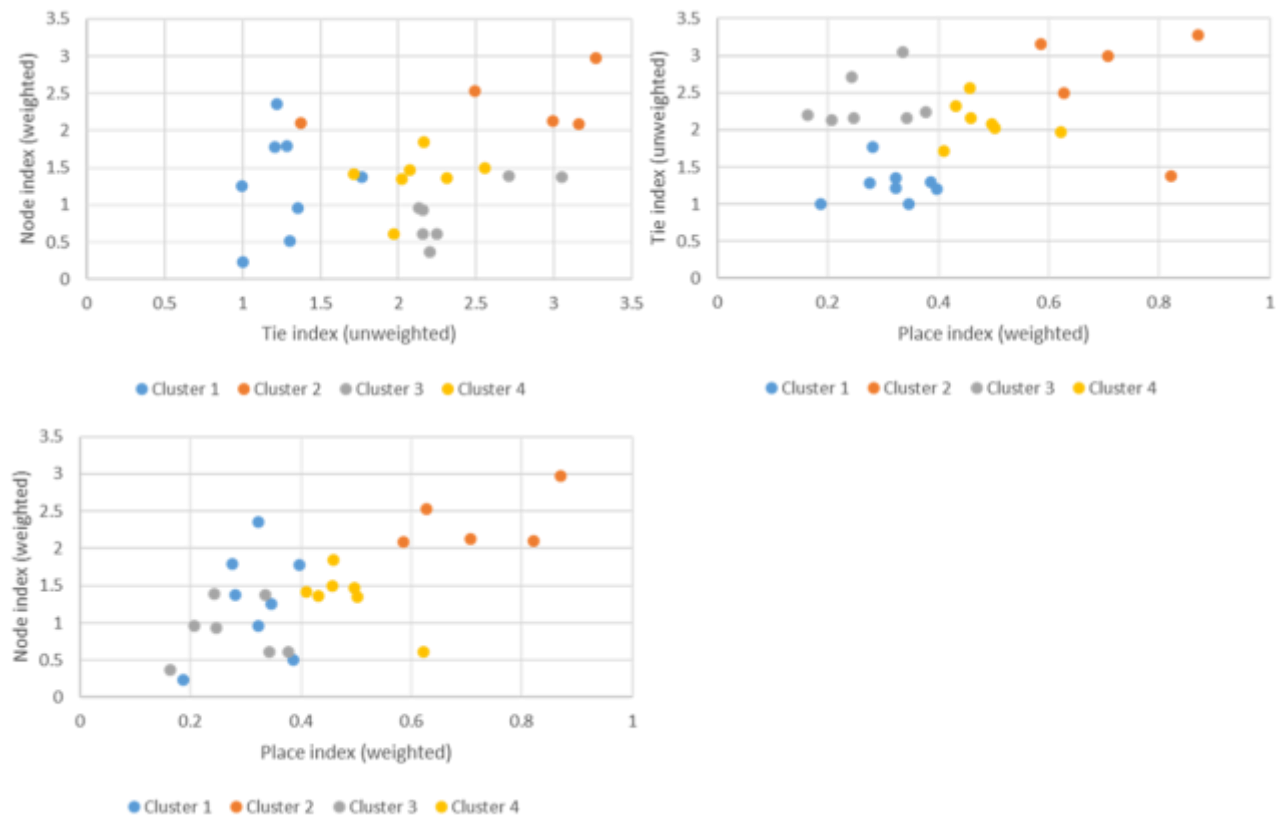


Figure 4-6 Clustering by k-means

Each cluster was then ranked based on the values of its node, place, and tie indices, which were assigned high (5), medium-high (4), medium (3), medium-low (2), and low (1). Accordingly, cluster one is considered unsustained, including stations with a medium-low node, medium place, and medium-high tie indices. However, clusters two to four have a balanced node and place with a medium to high tie index (Table 4-5).

Table 4-5 Result of clustering

Cluster	Station area	Node	Place	Tie
1	13-15-19-20-21-22-24-25	2	3	4
2	3-4-6-8-10-12-27	2	2	3
3	1-14-16-17-18	4	4	4
4	2-5-7-9-11-23-26-28	3	3	3

Ranking score: high (5), medium-high (4), medium (3), medium-low (2), and low (1)

Finally, we conducted a feasibility test regarding the node and place canonical scores in Appendix B-2. This indicates the correlation between each station area's transport and land use sectors. As illustrated in Figure 4-7, the stations' node and place canonical scores are plotted against the X-axis, representing demand for access, and the Y-axis for the supply of access. In this case study, assuming a fixed transport supply, the stations plotted in the top right (A) and bottom right (D) of the coordinate axis are considered feasible for further land use development, where enhancing land use variables positively impacts the equilibrium.

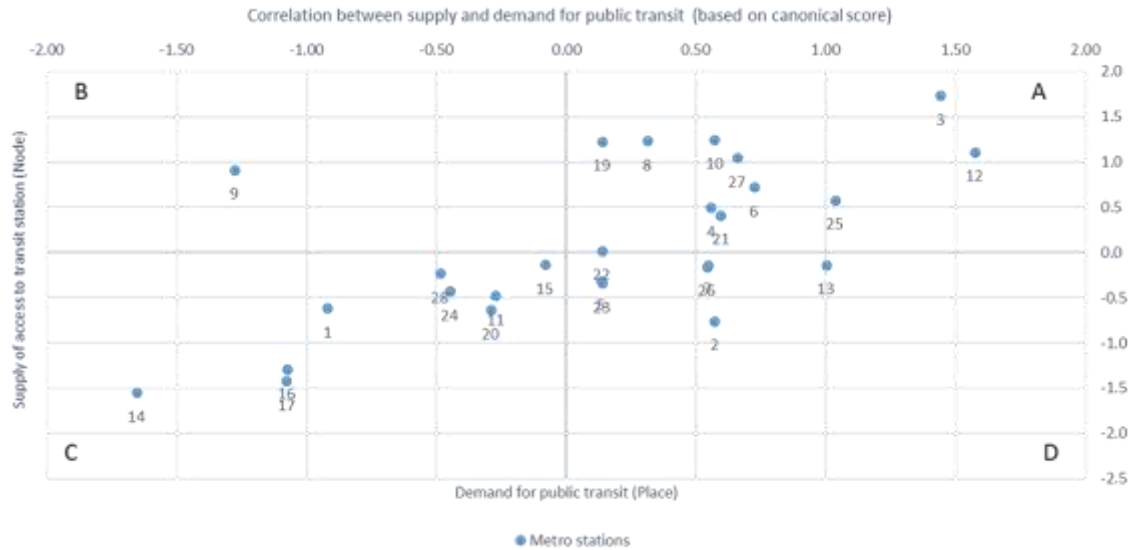


Figure 4-7 Feasibility analysis of land-use interventions

Following the feasibility analysis, 17 out of 28 stations were identified as suitable for enhancing density and diversity without compromising the balance between land use and transportation (Tables 4-6).

Table 4-6 Typology of the feasible station area for further development

Cluster	Typology	All stations	Feasible stations
1	Unsustained place (medium-low node and medium place)	13-15-19-20-21-22-24-25	13-19-21-22-25
2	Balanced (medium-low node and place)	3-4-6-8-10-12-27	3-4-6-8-10-12-27
3	Balanced (medium-high node and place)	1-14-16-17-18	-
4	Balanced (medium node and place)	2-5-7-9-11-23-26-28	2-5-7-23-26

The next stage will involve a vulnerability analysis of the feasible stations for further land use development.

4.2 Vulnerability Assessment

In this stage, balanced and feasible station areas for enhancing density, the outcome of the previous stage, were assessed in terms of vulnerability to dominant meteorological hazards, as obtained from historical data of Montreal. First, an adaptive capacity index map was produced regarding the shortest path from the centroid of each dissemination block to emergency centers, showing potential access to emergency services (Figure 4-8).

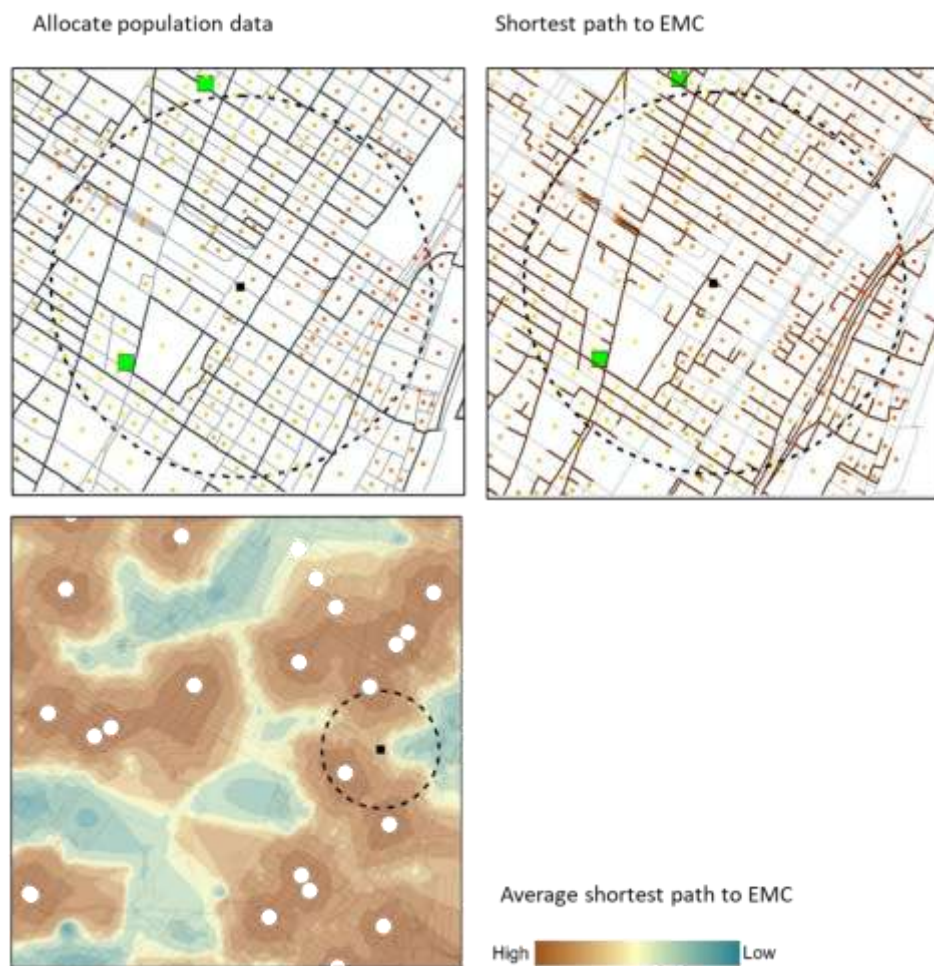


Figure 4-8 Adaptive capacity calculation

Then, hazard maps for Montreal's dominant meteorological hazards, including heatwaves, floods, and storms, were created, as presented in Figures 4-9.

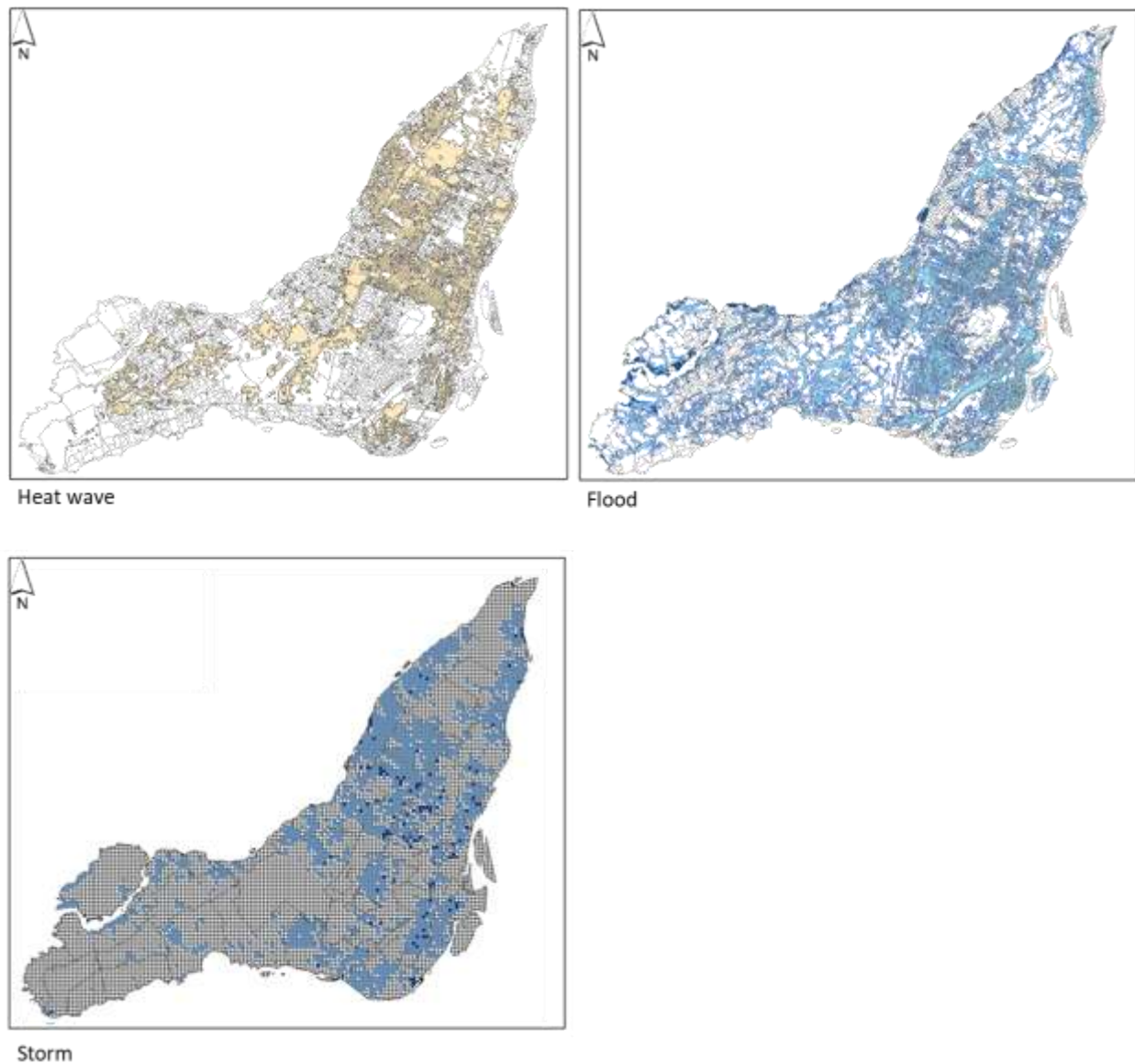


Figure 4-9 Montreal's main meteorological hazards

Then, sensitivity and exposure index maps were created using fuzzy overlay functions for socio-economic data, heatwave, flooding, and storm hazard maps according to the logic explained in section 3.2.1 (Figure 4-10).

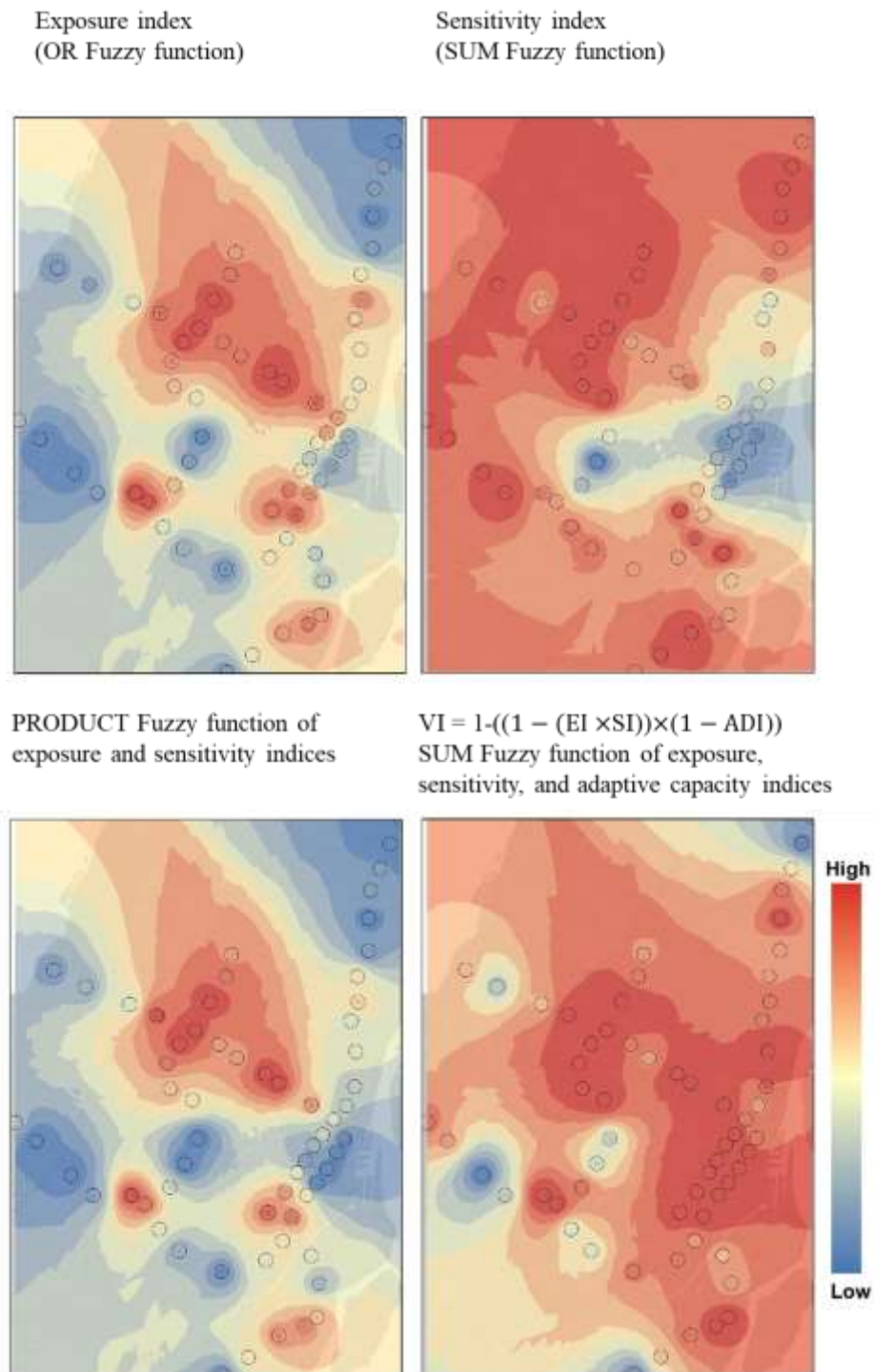


Figure 4-10 Vulnerability index calculation process

Finally, a fuzzy overlay of sensitivity, exposure, and adaptive capacity maps resulted in a vulnerability map that revealed stations 4, 5, 8, 9, 10, 13, 14, 15, 16, 17, 23, and 24 were highly vulnerable to meteorological hazards (Figure 4-11).

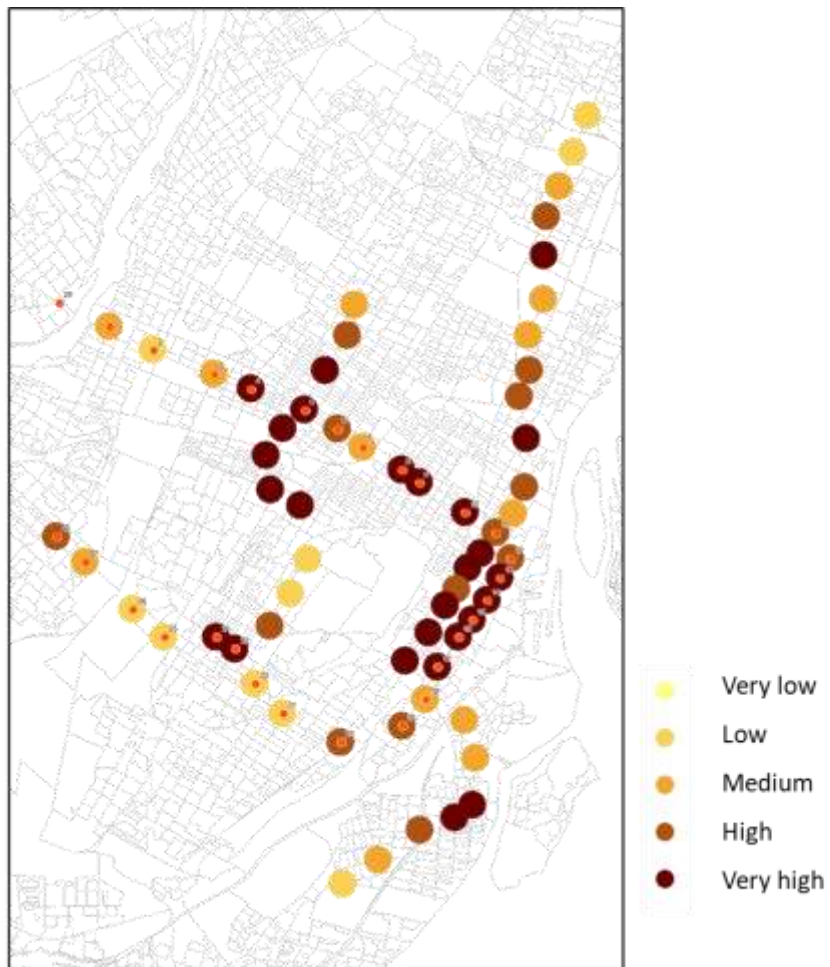


Figure 4-11 Vulnerability of Montreal metro stations

4.3 Sustainability Analysis

Following the calculation of 5D sustainable indicators, the Pearson correlation coefficient (PCC) test was conducted. This test demonstrated a high correlation between population density (D4_PD) and the density of transit captive users (D4-DT) and workforce density (D4-WD) ($|r| > 0.75$), see Figure 4-12. Therefore, population density ((D4_PD) was eliminated from the list of indicators to avoid the multicollinearity effect.

	D1_CC	D1_DC	D1_NA	D1_LC	D1_LA	D2_SS	D3_UG	D3_PN	D3_CO	D4_DT	D4_WD	D4_PD	D4_BD	D5_LD
D1_CC	1													
D1_DC	0.41	1.00												
D1_NA	0.26	-0.12	1.00											
D1_LC	0.01	0.17	0.37	1.00										
D1_LA	0.30	-0.02	0.89	0.27	1.00									
D2_SS	-0.19	0.01	-0.02	0.30	-0.08	1.00								
D3_UG	-0.01	-0.09	0.53	0.30	0.35	0.26	1.00							
D3_PN	0.11	0.07	0.14	0.16	0.08	0.27	0.15	1.00						
D3_CO	0.19	0.06	-0.08	-0.26	-0.07	-0.88	-0.20	-0.28	1.00					
D4_DT	0.21	0.14	-0.15	-0.30	-0.09	-0.24	-0.03	-0.57	0.27	1.00				
D4_WD	0.31	0.18	-0.17	-0.35	-0.07	-0.31	-0.17	-0.59	0.31	0.96	1.00			
D4_PD	0.23	0.15	-0.13	-0.30	-0.05	-0.22	-0.03	-0.57	0.24	1.00	0.95	1.00		
D4_BD	0.44	-0.02	0.23	0.19	0.13	0.10	0.06	0.20	-0.14	-0.35	-0.30	-0.34	1.00	
D5_LD	0.11	0.27	0.21	0.07	0.22	-0.36	-0.21	0.14	0.23	-0.27	-0.21	-0.28	-0.19	1

Figure 4-12 Correlation analysis of 5D variables

A comparison of Figure 4-12 and the indicators of the proposed TOD index (Table 3-8) reveals the reasons behind the negative correlation between D4_PD, D4_WD, D4_DT (population, workforce, and transit captive users' density that determine the demand for access) and D2_SS and D3_CO (station service area and compactness that influence demand for access) with the target variable D1_NA (network accessibility to public transport). With a constant supply of transportation, increasing these variables leads to higher travel demand and reduced potential accessibility to the public transport network. Given this negative correlation, the cost normalization formula was chosen for these variables, while the benefit normalization formula was applied to the other variables.

Different normalization and weighting methods were then examined on the dataset to select the most suitable method. Entropy, CRITIC, and AHP weights were calculated in Excel. The XLSTAT plugin of Excel facilitated defining the indicators' weights using AHP based on the judgment of five evaluators, and a consistency ratio of $0.086 \leq 0.1$ confirmed the validity of the results. The weights of the criteria and indicators, obtained from various subjective and objective methods, are presented in Tables 4-7 and 4-8.

Table 4-7 Relative weights of criteria

Criteria	Weight by AHP	Weight by Entropy	Weight by CRITIC
D1	0.28	0.71	0.38
D2	0.07	0.01	0.07
D3	0.13	0.12	0.22
D4	0.27	0.12	0.24
D5	0.25	0.04	0.09

Table 4-8 Relative weights of indicators

Indicators	Weight by AHP	Weight by Entropy	Weight by CRITIC
D1_CC	0.04	0.01	0.08
D1_DC	0.03	0.01	0.06
D1_NA	0.1	0.19	0.05
D1_LC	0.04	0.24	0.14
D1_LA	0.07	0.26	0.05
D2_SS	0.07	0.01	0.07
D3_UG	0.03	0.1	0.08
D3_PN	0.05	0.01	0.08
D3_CO	0.05	0.01	0.06
D4_WD	0.08	0.03	0.09
D4_PD	0.1	0.03	0.09
D4_BD	0.09	0.06	0.07
D5_LD	0.25	0.04	0.09

To select the most appropriate data preparation and aggregation methods, the four types introduced in Table 4-9 were calculated, and the results were then presented in Table 4-10.

Table 4-9 Data preparation and aggregation methods

Type	Normalization	Weighting	Aggregation
1	Min-Max	CRITIC	TOD index
2	Min-Max	AHP	TOD index
3	Vector	CRITIC	TOD index
4	Vector	CRITIC	TOPSIS

Table 4-10 Result of aggregation by different methods

Stations	Type 1	Type 2	Type 3	Type 4
1	16	22	17	10
2	17	23	13	9
3	27	17	27	24
4	28	24	28	28
5	24	27	18	13
6	18	20	16	15
7	8	14	8	8
8	22	21	24	25
9	25	18	25	26
10	19	25	20	21
11	3	4	3	4
12	10	13	11	16
13	14	6	15	19
14	4	19	5	3
15	15	16	10	12
16	7	9	6	6
17	7	9	6	6
18	2	3	4	5
19	13	10	19	22
20	12	5	9	11
21	11	11	14	18
22	5	8	7	7
23	23	15	21	20
24	9	2	12	14
25	21	26	22	17
26	20	12	23	23
27	26	28	26	27
28	6	7	2	2

Next, the pairwise comparison of different preparation and aggregation methods (Types 1 to 4) was conducted using the Pearson correlation coefficient (PCC). Table

4-11 shows a remarkable similarity between weighting by CRITIC and then aggregating and ranking by TOD index and TOPSIS in types 3 and 4, respectively. Their correlation coefficient of 0.938 is the second highest after that of types 1 and 3, both aggregated and ranked based on the TOD index. Therefore, Type 3 was selected, which rescaled the data using vector normalization, weighted with CRITICS, and then aggregated and ranked them with the TOD index. It is essential to note that the subsequent step in evaluating the efficiency of station areas using DEA is also based on 5D criteria and indicators, which are rescaled through vector normalization.

Table 4-11 Correlation matrix of different preparation and aggregation methods

	Type 1	Type 2	Type 3	Type 4
Type 1	1.000	0.731	0.944	0.840
Type 2	0.731	1.000	0.645	0.452
Type 3	0.944	0.645	1.000	0.938
Type 4	0.840	0.452	0.938	1.000

Subsequently, the efficiency of selected station areas in enhancing density and diversity was verified using an output-oriented data envelopment analysis (DEA) and MATLAB 7.1 software. In this particular case study, the number of DMUs (stations) and variables meets the recommended ratio (28 stations $\geq$ 2×14 variables); therefore, the same 5D variables were used.

As the DEA result in Table 4-12 shows, stations 3, 5, 7, 8, 10, 13, 22, 23, and 25 are not only balanced in terms of public transit supply and demand and feasible for further land use development, but they are also efficient for increasing density in confined TOD areas because their efficiency value (h) equals one. The results show

that other stations also demonstrate a high level of efficiency in land use development within the stations' circular buffer.

Table 4-12 Result of DEA

Feasible stations	U1	U2	U3	U4	V1	g	h (efficient)	Feasible, efficient, and not vulnerable stations
2	9.31	0	0	23.03	76.90	1.06	0.95	
3	0	0	0	35.92	88.18	1	1	3
4	7.22	15.01	0	18.01	95.83	1.42	0.7	
5	0	7.99	11.06	0	72.25	1	1	-
6	0	9.36	11.30	0.67	77.11	1.11	0.9	
7	13.52	0	0	0	75.95	1	1	7
8	0	12.40	8.06	20.23	92.88	1	1	-
10	0	19.90	0	0	85.39	1	1	-
12	0	10.18	6.61	16.60	76.20	1.03	0.97	
13	3.93	9.06	5.55	15.56	77.79	1	1	-
19	4.05	9.36	5.73	16.07	80.32	1.15	0.87	
21	1.04	9.43	11.61	0	80.73	1.11	0.9	
22	7.41	0	8.44	6.63	71.83	1	1	22
23	0	0	17.19	0.67	88.38	1	1	
25	0	0	14.53	0	74.67	1	1	25
26	0	11.09	7.20	18.09	83.02	1.2	0.84	
27	0	22.17	0	0	95.13	1.32	0.76	

Note: According to Equation 3-36, u_1, u_2, u_3 , and u_4 are the weights of the output data and v_1 is the weight of the input data. They defined in a way that maximizes outputs (destination accessibility, density, diversity, and design) while maintaining constant input (distance to transit). $H=1/g$, and $g=1$ shows efficient DMUs (stations)

4.5 Maximizing Public Transport Accessibility

To enhance public transport accessibility, the maximum local and network accessibility of the balanced stations that are feasible for improving land use density and diversity were defined at this stage. To solve the linear programming problem explained in section 3.1.3 of the methodology, we first determined the shortest distance between stations, existing transit ridership (TR), trip attraction (TA), and local and network accessibility (AC) for the selected stations. These factors are used to establish the objective function and constraints of Equation 3-37, which define the optimum values for transit ridership and trip attraction that maximize public transit accessibility at those stations. Table 4-13 shows the results of solving in Excel.

Table 4-13 Results of optimization

Feasible station i	Existing AC	Existing TR	Existing TA	Optimum TR	Optimum TA
2	2588450.60	3187169.00	31400.00	9291251.90	83635.8
3	1033570.17	1140620.00	36300.00	8328161.45	85601.28
4	2725499.57	2721639.00	20800.00	7535035.80	87219.86
5	4670286.94	4275310.00	32000.00	6907466.29	88500.58
6	2781441.22	2404527.00	23500.00	6523176.75	89284.82
7	5459238.32	4510487.00	50300.00	6234374.90	89874.19
8	4355749.75	3382119.00	20200.00	5858980.78	90640.28
10	3990765.73	2867001.00	24900.00	5420862.95	91534.37
12	1581459.49	1047247.00	18300.00	4996860.08	92399.66
13	3618307.96	2526024.00	69500.00	5268043.83	91846.24
19	6742528.25	4587301.00	92400.00	5133859.96	92120.08
21	7134603.35	4996694.00	64200.00	5284621.88	91812.41
22	5010278.40	3355489.00	21900.00	5053432.69	92284.21
23	5434764.00	3911042.00	57800.00	5430205.34	91515.31
25	4107804.52	3320365.00	32600.00	6099237.99	90149.98
26	4968999.84	4403658.00	38300.00	6687167.75	88950.15
27	4157348.14	4053264.00	15600.00	7356702.89	87583.79
Maximized AC	7545830.447				

By formulating transit network accessibility (NA) and local accessibility (LA) in relation to the demand for public transport, which is defined by transit ridership and trip attraction (see Equations 3-38 and 3-40), we can evaluate the potential of those stations for land use development, as shown in Figure 4-13.

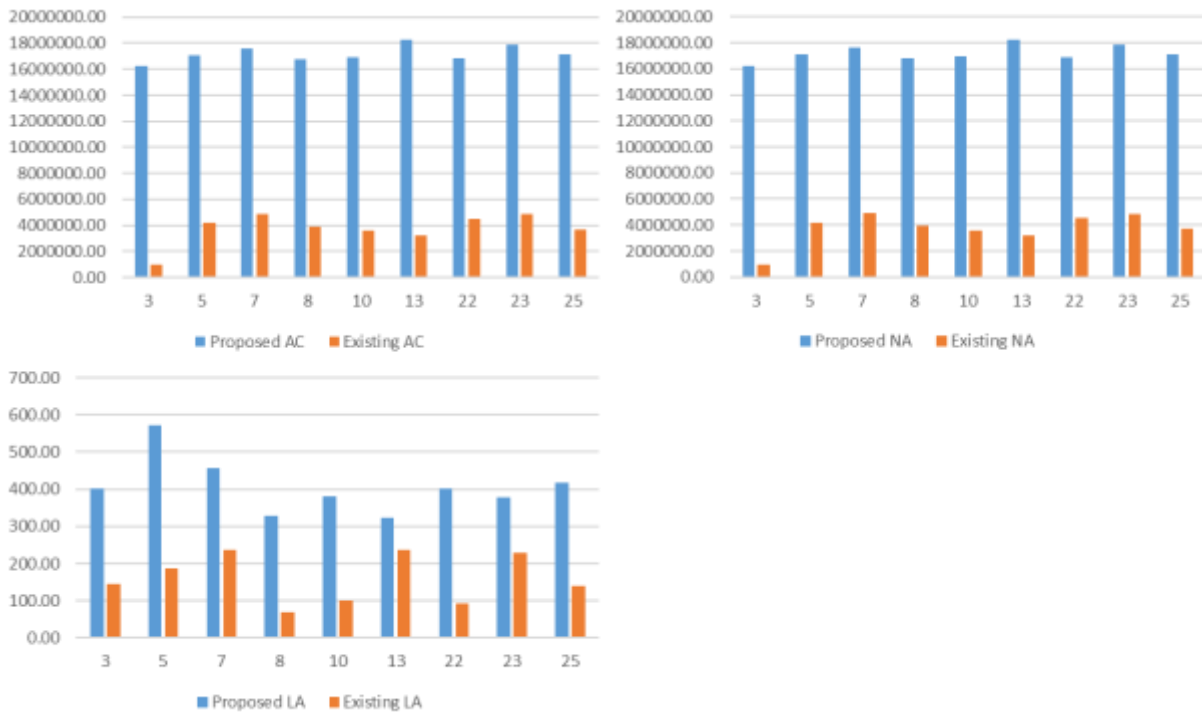


Figure 4-13 Existing and planned public transport accessibility

CHAPTER 5: CONCLUSIONS

5.1 Summary

This research proposed a comprehensive approach to TOD assessment and disaster mitigation by improving and integrating TOD assessment methods with disaster mitigation strategies. The proposed TOD assessment method addressed multiple TOD goals, including achieving a balance between land use and transportation development, promoting urban sustainability, and enhancing sustainable accessibility through successive stages. It included integrated land-use and transport assessment using an enhanced node-place-tie model (Stage 3.1.1), sustainability analysis with an improved TOD index (Stage 3.1.2), and providing insights for land-use planning through maximizing public transport accessibility via a linear programming problem (Stage 3.1.3). To achieve risk-aware TOD planning, this process was also integrated with disaster mitigation, including reducing the probability of disasters through vulnerability assessment (Stage 3.2.1) and decreasing the negative consequences of disasters by enhancing road network resiliency (Stage 3.2.2).

The common objective across all stages of the proposed method is to enhance public transport accessibility, though it was defined differently. Accessibility was defined as the balanced provision of transit supply and demand in the first stage, as the ease of access to transit stations in the second stage (one of the sustainable criteria, 5Ds, that shows the supply of public transit), and as the demand for local and network access to the public transport system in the third stage of the TOD assessment (reflected in stations' land use density and diversity). Accessibility also played a critical role in two stages of disaster mitigation, including vulnerability and resilience assessment. One aspect that defines stations' vulnerability to meteorological hazards is their adaptive capacity (access to emergency centers), which was measured as the

shortest distance to the nearest emergency centers. Timely access to emergency centers is also a gauge of how densely populated TOD areas are resilient in the face of disasters.

This research pursues the objective and sub-objectives outlined in Sections 1-3 through the risk-aware multi-stage TOD assessment process (Figure 5-2). Wherein, each stage is built upon the outcome of the previous stage and has specific outcomes that are illustrated in Figure 5-3.

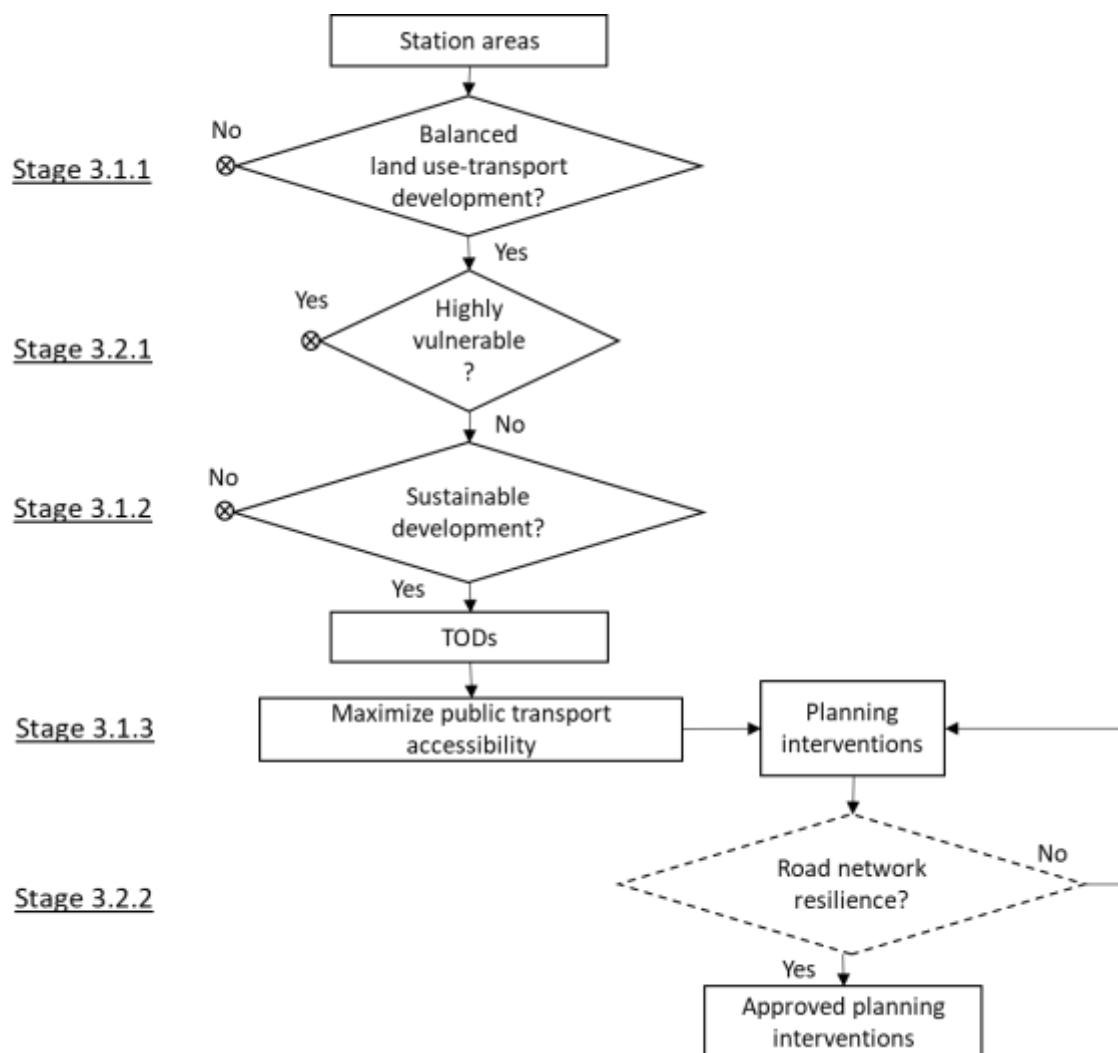


Figure 5-1 Overview of the proposed method process



Figure 5-2 Outcome of each stage of the proposed methodology

In addition to introducing a novel comprehensive approach to TOD and natural disaster mitigation, this research makes technical enhancements to the existing node-place and TOD index by modifying indicator selection and calculation, and by incorporating additional steps, such as a feasibility assessment and an efficiency test, in stages 3.1.1 and 3.1.2, respectively. It also introduces some novel vulnerability and resilience assessment techniques in stages 3.2.1 and 3.2.2. Table 5-1 summarizes the tools and techniques used in the stages of the proposed methodology.

Table 5-1 Overview of tools and techniques used in this research

Stage	Step	Tools and techniques	Description
3.1.1	Delineation of TOD area	Circular buffer	The location-based selection tool in ArcGIS is used to define 400 m and 800 m circular buffers as the basis for extracting indicators of the destination and origin of travel, respectively. These numbers are selected based on previous studies and the data from the case study.
	Selection of criteria and indicators	Accessibility-oriented selection of node, place, and tie indicators that balance land-use-driven demand with transport-driven supply.	Node indicators reflect the location, quality, and quantity of transportation infrastructure and services, representing the supply of access. Place indicators include the density of potential travelers and the diversity of activities that serve as the origin or destination of travel, defining the demand for access. Tie indicators, on the other hand, influence residents' mode choices, including those that affect both the supply and demand for access.
	Calculation of indicators	A set of metrics and formulas	Defining the primary and secondary data regarding the previous studies and the case study.
	Correlation analysis	Shapiro-Wilk test, Pearson Correlation Coefficient (PCC), and Canonical Correlation Analysis (CCA)	The Shapiro-Wilk test ensures that the data fulfills the normality assumption for PCC and CCA. PCC is used to assess the linear relationship between indicators and prevent bias toward a specific outcome. CCA is used to determine the correlation between node, place, and tie sets.
	Preparation and aggregation of data	CCA variables and weighted sum aggregation	The node, place, and tie indicators are redefined using CCA variables to ensure that each set contains an equal number of variables and are weighted, before aggregation, based on the correlations between input variables and canonical variables.
	Clustering	K-means clustering	According to Bertolini's node-place model, the initial number of clusters is set to five, and then the optimal clusters are identified iteratively.
	Feasibility assessment	Correlation Analysis (CCA)	The proposed feasibility assessment is based on stations' node and place canonical scores, which reflect the extent and direction of the correlation between the supply and demand for transit access.
3.1.2	Selection of criteria and indicators	Accessibility oriented selection of sustainable built environment factors (5D)	5D criteria and indicators are selected based on their impact on public transport access supply at both local and urban scales, the demand for sustainable access within the station area, and the intermediate factors that influence supply and demand for sustainable accessibility.
	Calculation of indicators	A set of metrics and formulas	It involves adapting and modifying the formula used in previous studies to meet the requirements of the case study.

	Correlation analysis	Shapiro-Wilk test and Pearson Correlation Coefficient (PCC)	After the Shapiro-Wilk test confirms that the data meet the normality assumption, PCC assesses the linear correlation between indicators and the risk of multicollinearity.
	Preparation and aggregation of data	Rescaling, weighting (AHP, Entropy, CRITIC), and weighted sum aggregation	Comparing different rescaling, subjective and objective weighting, and aggregation techniques.
	Ranking stations	TOD index and TOPSIS	Comparing ranking based on stations' TOD index and TOPSIS
	Efficiency test	Output-oriented DEA	Data envelopment analysis (DEA) is employed to analyze the efficiency of land use development (maximizing destination accessibility, design, density, and diversity variables) in a limited station area (a constant distance to transit), representing the model's outputs and inputs, respectively.
3.1.3	Optimization	Solving a multi-objective problem to maximize public transport accessibility	Assuming a sufficient and consistent supply of transport network and service, maximizing public transport accessibility relies on maximizing demand for public transport, which is defined by transit ridership and trip attraction.
3.2.1	Vulnerability assessment	ArcGIS fuzzy overlay tools	Creating a vulnerability index that incorporates sensitivity, adaptive capacity, and exposure indices while considering uncertainties.
3.2.2	Resilience assessment	Integrated traffic and system dynamics (SD) simulations	This stage suggests future research to address the negative impacts of increasing population density in TOD areas during the emergency response phase of disaster mitigation.

The proposed methodology was developed based on a meticulous literature review of TOD and disaster-mitigation assessment methods. The findings of this review were used to create a conceptual framework for TOD and disaster mitigation research, to categorize existing methods and techniques, and to identify commonalities in objectives, processes, and indicators. It also revealed conceptual gaps in prior studies, which served as inspiration for proposing this integrated, risk-aware TOD planning, as well as technical gaps, which were the subject of this research contribution at each stage.

This research sought to narrow the following conceptual and technical gaps in the literature and provide a foundation for further research in this area.

Conceptual gaps:

- Inconsistencies in the application of different TOD variables and assessment methods give rise to discrepancies in outcomes.
- The segregation of TOD and disaster mitigation has led to ignorance of the risks associated with the concentration of people and activities in a confined area of TOD and vulnerability to meteorological hazards.

Technical gaps

- The following deficiencies of the existing node, place, and tie model have been identified: first, the relative importance of the indicators; second, the feasibility of increasing the density and diversity of station areas without jeopardizing the balance between land use and transport supply and demand.
- Existing evaluation methods using the TOD index have shortcomings, including ignorance of the bias in subjective weighting and its effect on subsequent aggregation and ranking, the efficiency of station areas for compactness, and the optimal density level.
- There is a lack of a multi-attribute vulnerability assessment method that accounts for the inherent uncertainties.

5.2 Contributions

This study contributed to the literature by answering two research questions: (1) How can existing transit-oriented development (TOD) planning methodologies be linked, integrated, and improved? (2) How can the risks associated with increasing population density in TODs be mitigated?

In response to the first question, this research developed an improved TOD planning model by improving and integrating existing models in a multistage framework. In the first stage of the proposed methodology (Stage 3.1.1), an enhanced node-place-

tie model was introduced for the typology of stations regarding the correlation between demand and supply of access to public transport, namely land use and transport indicators. The novel aspect of this model is the application of canonical correlation analysis for two purposes: (1) to propose a weighted node-place-tie model and (2) to assess the feasibility of station areas for increasing density and diversity in the context of constant transportation systems. In the second stage (Stage 3.1.2), an improved TOD index was developed to assess the built environment sustainability of existing and potential TODs. This was achieved by (1) incorporating a modified set of indicators and formulas, (2) producing combined indicators with a lower degree of bias in the process of weighting and aggregating indicators, and (3) assessing the efficiency of enhancing land use indicators within 400–800 meter buffers of the metro station using DEA. In addition, the third stage (Stages 3.1.3) defined each station area's optimal density and diversity to achieve maximum local and network public transport accessibility.

Then, two disaster mitigation strategies were integrated into the proposed TOD planning to address the second research question. These strategies include reducing vulnerability to meteorological hazards and increasing resiliency by improving emergency response services. In the first stage of risk mitigation (Stage 3.2.1), a spatial multi-attribute analyst in ArcGIS, including different fuzzy membership functions, was used to assess the vulnerability of TOD areas to the dominant hazards in the Montreal case study. In addition, a conceptual model of road network resilience planning was proposed to facilitate post-disaster recovery activities such as evacuation and emergency services (Stage 3.2.2). The proposed model was tested on the Orange Line of the Montreal Metro, although it could be generalized to other case studies.

5.3 Limitations and Future Works

This study is based on the existing data and the assumption of a constant transport service and network. The proposed method is confined to the built environment and non-structural disaster mitigation strategies, although some socio-economic factors are considered in this research.

The multidisciplinary nature of urban research requires the involvement of researchers from other fields of study to enrich this model through a more in-depth consideration of socio-economic factors, including gentrification and cost-benefit analysis of TOD implementation.

In addition, the final stage of the proposed TOD planning (Stage 3.2.2) is limited to a conceptual framework for resilience assessment, with further development reserved for future research. Developing the road network resilience model proposed in the second stage of disaster mitigation entails traffic simulation and analysis, which requires the collaboration of a transport specialist.

APPENDICES

Appendix A-1: Accessibility measures

A-1-1 Cumulative accessibility

Author	Equation	Definition
Huang et al.(2018)	$LA_i = \sum \frac{L_{nr}}{(L_{nr} + L_r)}$	Local accessibility (LA_i) implies the possibility of access to opportunities (proportion of the non-residential area to the total area in station area) L_{nr} is the non-residential, and L_r is the residential land use area.
Lyu et al. (2019)	$ACC_{MS-i}^{1\ hour} = \sum_{Tim(MT-i, Cell-k) \leq 1\ hour} Job\ N_k + Inhabitant\ N_k$	Accessibility measured as a cumulative number of jobs ($Job\ N_k$) and inhabitants ($Inhabitant\ N_k$), in less than one hour distance from the centroid of the origin cell ($MT - i$) to destination cells ($Cell - k$) K is the number of 1 km ×1 km urban cells
Rahman et al., (2022)	$PTA = \frac{\sum ASC \times F}{AN}$	The public transport accessibility index (PTA) is defined in terms of the area covered by each bus station (ASC), the frequency of bus services (F) and the area of the neighborhood (AN)

A-1-2 Gravity-based accessibility

Author	Equation	Definition
Motieyan & Mesgari (2017) and (2019)	$NA_i = \sum_{j=1}^n O_j f(c_{ij})$	Network accessibility (NA_i) is the ease of access to facilities (attractions) in other station areas (O_i) by considering the function of travel cost $f(c_{ij})$ which entail travel time and mode of transport.
Higgins & Kanaroglou (2016), Budiati et al. (2018)	$NA_i = \ln \sum_{j=1}^n \frac{Pop_i \times Emp_j}{TT_{ij}^2}$	Network accessibility (NA_i) is the ease of access of residents in station i (Pop_i) to the employments in other station areas (Emp_j). Travel time (TT_{ij}) is inversely related to accessibility.
Pan et al. (2017)	$NA_i = \sum_{j=1}^n \frac{P_j}{T_{ij}}$	Network accessibility (NA_i) is the ease of access of residents from other stations (P_j) to station i regarding the travel time between them (T_{ij})
J. Li et al. (2022)	$A_i = \sum_{j=1}^n \frac{E_j}{T_{ij}}$	Accessibility of station i (A_i) is defined regarding the number of accessible opportunities in other station areas (E_j) and the travel impediment (T_{ij}). They calculated by the travel cost of each travel mode.
S. Lee et al. (2013)	$A_i = \frac{p_i}{T_i} + \sum_{j=1}^n \frac{p_j}{T_{ij}}$ $T_{ij} = t_{ij}^{boarding} + \sum_{h=1}^n t_{ijh}^{transfer} + \sum_{h=1}^{n+1} t_{ijh}^{in\ vehicle}$	Public transport accessibility index (A_i) is defined regarding the population or building floor area (p_i), internal travel time in station area (T_i), and travel time between stations i and j (T_{ij}), which is a combination of boarding time, transfer and in vehicle travel time.

A-1-3 Connectivity

Author	Equation	Definition
Zaheer et al. (2024)	$ISAI = \frac{L_A}{A_C}$	Pedestrian ideal station accessibility index (ISAI) is a proportion of the actual pedestrian accessible road length (L_A) to the area of circular buffer (A_C).
Cong et al. (2024)	$A_i = \alpha \times \frac{C_i - C_{min}}{C_{max} - C_{min}} + \beta \times \frac{D_i - D_{min}}{D_{max} - D_{min}}$ $C_i = \frac{1}{d_{i1} + d_{i2} + d_{i3}}$ $D_i = \sum_{j=1}^n X_{ij}$ $A_i = A_{i,min} \times \left(1 - \frac{D_{i,min}}{D_{max}}\right)$	Accessibility of grid cells containing transit station i (A_i) is composed of closeness centrality (C_i) and degree centrality (D_i) weighted by α and β. Where, d_{i1-3} is the distances from node i to other stations 1,2,3 and X_{ij} is a binary factor, $X_{ij} = \begin{cases} 1, & \text{node } i \text{ is directly connected to node } j \\ 0, & \text{otherwise} \end{cases}$ Accessibility of grid cells without transit station (A_i) is calculated regarding the accessibility of the closest station to grid i ($A_{i,min}$) and their distance ($D_{i,min}$), knowing the D_{max} is the distance from grid i to the farthest station.
Papa et al. (2013)	$NA_i^r = \frac{1}{\sum_j W d_{ij}}$	Weighted closeness centrality or the stations' network accessibility in the predefined radius r of station i (NA_i^r) is defined by the shortest path between station i and other stations d_{ij} , weight (w) of other stations (j) regarding their job opportunities.
Papa and Bertolini (2015)	$NI_{AZi} = \frac{N-1}{\sum_j^N d_{AZi, AZj}},$ N = number of nodes	Node index (NI_{AZi}) or centrality is measured as the inverse of the average sum of the distance from the centroid of each accessibility zone (AZ) to all other AZs, including walking distance to the station, and N is the number of nodes.
Tamakloe & Hong (2020)	$CC_i = \frac{1}{\sum_j d_{ij}}$ $BC_i = \sum_{j,k} \frac{P_{jk}(i)}{p_{jk}}$ $CE_i = \lambda^{-1} \sum_j a_{ij}$	Closeness centrality (CC_i) represents access of station i to other stations (j), considering their shortest path (d_{ij}). Betweenness centrality (BC_i) signify how many time station i is in the shortest path between two stations in the network. $P_{jk}(i)$ is the number of shortest paths between j and k which pass through station i. Eigenvector centrality (CE_i) shows degree of connectivity of station i to other highly central stations in the network. λ is an entry in the largest eigenvalue and a_{ij} is the adjacency matrix.
Z. Zhu et al. (2021)	$PTAL^* = \sum_{i=1}^l \frac{60}{t_{xi} + t_{yi}}$ $PTAL = \sum PTAL^*$ $t_{xi} = \frac{l_i}{v_m}, t_{yi} = \frac{1}{2} \times \frac{60}{r} \times k, k=1 \sim 2$	Public transport accessibility level (PTAL) is the aggregation of the accessibility of all modes ($PTAL^*$), which is a function of the walking time from path i (t_{xi}) and the waiting time (t_{yi}). Here, l_i is the i^{th} path walking distance, v_m is the mean walking speed.

A-1-4 Person-based, infrastructure-based, and utility-based accessibility

Author		Equation/method	Definition
Nguyen et al. (2020)	Person-based	Multinomial logit model	Taking into account the effect of socio-demographic characteristics of residents on mode choice
Park, Ewing, Scheer, & Ara Khan (2018)		Propensity score matching	
Nasri et al. (2020)		Node-place-tie model	The tie index reflects the effect of residents' socio-demographic characteristics and urban design factors on mode choice.
Zhao et al. (2024), Rabiei et al. (2022), M. Zhang & Lee (2023), Vale et al., (2018), Pezeshknejad et al. (2020)			
	Infrastructure-based	Node- place-(tie) model	The node index represents the quality and quantity of the public transport network and services that define the supply of public transport access.
Mudigonda et al. (2014)	Utility-based	Cost and benefit estimation	The NJRTM-E mode is employed for the estimation of trip generation by population relocation and mode choice. The ASSIST-ME was employed to estimate the direct and indirect costs.

A-1-5 Accessibility types

Accessibility type			Indicators	Authors
Accessibility type	Person-base		Sociodemographic, travel time, budget, and mode availability (indicating residents' mode choice)	Nguyen et al. (2020), Nasri et al. (2020), Park, Ewing, Scheer, & Ara Khan (2018)
			sociodemographic, urban design, and pedestrian access indicators (as part of the tie index)	Zhao et al. (2024), Rabiei et al. (2022), M. Zhang & Lee (2023), Vale et al., (2018), Pezeshknejad et al. (2020)
	Infrastructure-base		Number and frequency of metro trains (as part of the node index)	
	Utility-based		Travel time, driving and transit cost	Mudigonda et al. (2014)
	Location-base	Connectivity	Eigenvector, betweenness, degree, and closeness centrality	Zaheer et al. (2024), Cong et al. (2024), Papa et al. (2013), Papa & Bertolini (2015), Tamakloe & Hong (2020)
			Function of walking and waiting time	Z. Zhu et al. (2021)
		Gravity-base	Number of travel attractions (e.g., jobs and POIs) in destination and number of potential travelers in origin station areas, and travel cost/time	Motieyan & Mesgari (2017) and (2019), Higgins & Kanaroglou (2016), Budiati et al. (2018), Pan et al. (2017), J. Li et al. (2022), S. Lee et al. (2013)
			Cumulative opportunity	Opportunities in the station area (e.g., ratio of non-residential area to total area, or ratio of public transport coverage area multiplied by service frequency to total neighborhood area)
Access mode	Active	Local scale	Connectivity, walking and bike score, ped shed ratio, pedestrian root direction, ideal station accessibility index, passive accessibility score	X. Yang et al. (2023), Vale et al. (2016), Ke et al. (2021), Alawadi et al. (2021), Zaheer et al. (2024), J. (Brian) Lee and Salih (2024)
	Public transit		Urban and regional scale	Number and frequency of public services, location in the network, number of lanes and directions, transit ridership, connectivity, distributors
	Private vehicle	Number of parking, distance to the nearest highway (as part of the node index)		Nemroudi et al. (2024), Y. Zhang et al. (2019), Vale et al. (2018)
		VMT		Nasri & Zhang (2014), Fan et al. (2022)
		Number of parking		Ewing et al. (2021), Ewing et al. (2017), Tian et al. (2017)
	Multi modal	Street connectivity, metro, pedestrian and bicycle accessibility		Higgins and Kanaroglou (2016)
		Indicators of metro, car and bicycle accessibility (as part of the node index)		Wu and Divigalpitiya (2022)

Appendix A-2: The role of accessibility in TOD literature

A-2-1 Accessibility and TOD performance assessment

Methods for the evaluation of TOD performance	Accessibility indicator	Authors
Node-place	Node index or/and tie index	Nemroudi et al. (2024), Olaru et al. (2019)
Node-place-design		M. Zhang & Lee (2023), Vale et al., (2018), Pezeshknejad et al. (2020), Y. Zhang et al. (2019)
Node-place-ridership		Cao et al. (2020)
Node-place-accessibility		Z. Li et al. (2019a)
Node-place-orient		Lyu et al. (2016a)
Node-place-functionality		Su, Wang, et al. (2022), Pan and Huang (2024)
TOD index	Indicator of design or/and destination accessibility criteria	H. Chen et al., (2024), Motieyan and Mesgari (2017), Singh et al. (2017)
DEA	Output data	Metro and bus access
		E. H. Lee et al. (2019)
		Transit ridership
		Tamakloe & Hong (2020), Guo et al. (2018)
Optimization	Objective	Metro, bus, and bicycle access
		T. Chen et al. (2023)
		BRT access
		Khare et al., (2020)
		Maximize transit ridership, compactness, minimize travel time/traffic volume, conflict degree, environmental effects
		X. Ma et al. (2018)
		Maximize transit ridership
		Berawi et al. (2020), X. Huang et al. (2021)
		Maximize transit ridership, minimize VKT and travel cost/time
Accessibility index		J. Li et al. (2022)
		Maximize bicycle accessibility, minimize parking demand
		Liu et al. (2018)
Accessibility index	Citywide accessibility including closeness centrality, degree centrality, and weighted Manhattan distances to closest station	Cong et al. (2024)
		Walking distance to different urban facilities
		Rahmat et al.(2016)
Accessibility index, DEA	Multi-scale accessibility regarding walking and schedule/public travel time	Conesa (2018)
		Accessibility index (regarding population and total travel time), transit ridership
Regression analysis	Private and public travel time, number of jobs	S. Lee et al. (2013)
Laten class	Public transit (gravity measure) and pedestrian (connectivity measure) accessibility	Deboosere et al. (2018)
		Higgins and Kanaroglou (2016)

A-2-2 Accessibility and assessment of the environmental impact of TOD

Methods for evaluation of environmental impacts of TOD		Accessibility indicator	Authors
CO2 emission	Optimizing green TOD	Active accessibility, subway ridership	Liu et al. (2018)
	Green TOD index	Connectivity and gravity-based accessibility	Motieyan & Mesgari (2019)
	MTDM and scenario analysis	Public transport modal shares, VKT, travel time	Chindaprasirt et al. (2024)
Urban heat island (UHI)	Regression analysis	Public transport accessibility	Kamruzzaman et al. (2018)
Urban sprawl	Node-place-ecology	Node index	W. Yang et al. (2024)
	Cellular automata (CA)	Urban rail transit data	D. Ma & Chen (2019)

Note: Multimodal Travel Demand Model (MTDM), Vehicle kilometer traveled (VKT)

Appendix A-3: Impact of TOD on accessibility

A-3-1 Impact of TOD on travel demand

Method	Accessibility indicator	Authors
Nested logit model for mode and destination choice	VTMT, trip distance, destination, time/cost of mode of access	Y. Wang et al. (2016)
Principal component analysis	Transit ridership demand	Nyunt & Wongchavalidkul (2020)
Genetic algorithm	Maximize transit ridership, minimize travel time	X. Ma et al. (2018)
Generation-distribution joint model, user equilibrium model, logit function	Multimodal gravity-based accessibility (employment access, travel cost), travel flow	J. Li et al. (2022)

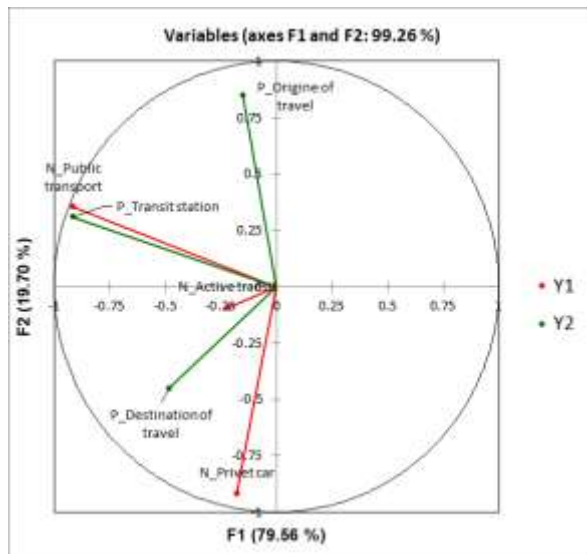
A-3-2 Impact of TOD on residents' travel behavior

Method	Accessibility indicator	Authors
Comparison with ITE manual	Number of parking and trip generation	Ewing et al. (2021), Ewing et al. (2017), Tian et al. (2017)
Regression analysis	Transit ridership	S. Lee et al. (2013), Pan et al. (2017), Pan et al. (2017), Zhu et al. (2024)
CCA and decision tree		Li et al. (2016)
Extended node-place model		Su, Zhao, et al. (2022), Cao et al., (2020), Amini Pishro et al. (2022) , Su, Wang, et al. (2022)
Node-place model		Olaru et al. (2019)
Modified fluid analogy		Limmonthol et al. (2020)
DEA and regression analysis		Tamakloe and Hong (2020)
Factor analysis and structural equation model	Acceptable walking distance and time for different residents' type	Pongprasert & Kubota (2019)
Mode choice model	Distanced travelled and number of trips per car, metro/bus, walking, and cycling for each scenario	Morency et al. (2020)
Heckman's sample selection model	VKT	F. Chen et al. (2017)
SDID model	Metro access/ service	Ibraeva et al. (2021)
Regression analysis	Distance travelled by metro/bus, car, walking/cycling modes	Kamruzzaman et al. (2014)
	Auto ownership and use	Chatman (2013)
	VMT	Nasri & Zhang (2014), Fan et al. (2022)
	VMT, number of auto, transit, and walk trips	Park, Ewing, Scheer, & Tian (2018)
Multinomial logit model	Ratio of travel time by transit to car	Nasri & Zhang (2019)
	Public, private, and active mode choice	Nguyen et al. (2020)
PSM and clustering	Public, private, and active mode choice	Park, Ewing, Scheer, & Ara Khan (2018)
PSM and regression analysis	Public, private, and active mode choice	Nasri et al. (2018a), Nasri et al. (2020)
	Number of bicycle and bus stations, connectivity	X. Li et al. (2022)

Note: ITE manual on trip and parking generation, Canonical correlation analysis (CCA), data envelopment analysis (DEA), Vehicle kilometer traveled (VKT) and Vehicle mile traveled (VMT) are calculated by multiplying the distance travelled in each origin-

Appendix B-1: Correlation analysis

The correlation circle in XLSTAT's Canonical Correlation Analysis illustrates the relationships between the original variables (node and place variables) and the canonical variates.



Original variables (arrows):

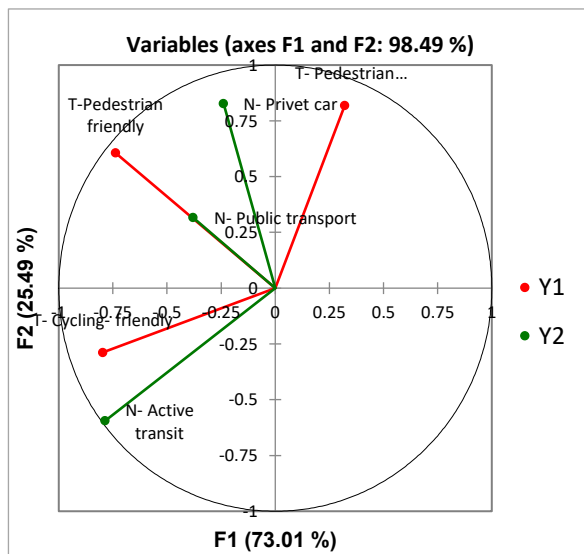
- Node variables (Y1) in red
- Place variables (Y2) in green

Canonical variates (circle axes):

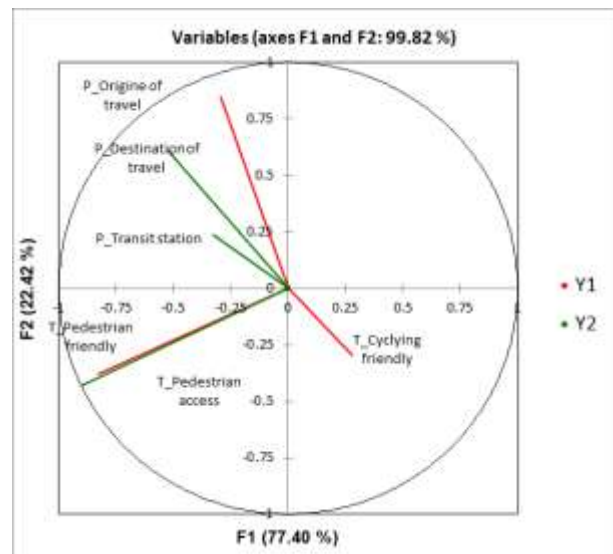
- F1 and F2

The arrows' direction and length show how the original variables are related to the canonical variates.

Correlation circle for node-place



Correlation circle for node-tie



Correlation circle for place-tie

Appendix B-2: Canonical scores

Canonical scores are the output of XLSTAT that demonstrates how transport and land use variables (as reflected in the node and place indices) positively or negatively affect the supply-demand equilibrium.

Stations	Canonical score for supply of access (Node)	Canonical score for demand for access (Place)
1	-0.62	-0.92
2	-0.76	0.57
3	1.73	1.44
4	0.49	0.56
5	-0.32	0.14
6	0.72	0.73
7	-0.14	0.55
8	1.23	0.31
9	0.91	-1.28
10	1.24	0.57
11	-0.48	-0.27
12	1.11	1.58
13	-0.14	1.00
14	-1.55	-1.65
15	-0.14	-0.08
16	-1.30	-1.08
17	-1.43	-1.08
18	-2.02	-3.13
19	1.23	0.14
20	-0.64	-0.29
21	0.41	0.60
22	0.01	0.14
23	-0.34	0.14
24	-0.43	-0.45
25	0.58	1.04
26	-0.16	0.54
27	1.04	0.66
28	-0.24	-0.48

REFERENCES

- Abbas, K. A., & Bell, M. G. H. (1994). System dynamics applicability to transportation modeling. *Transportation Research Part A*, 28(5), 373–390. [https://doi.org/10.1016/0965-8564\(94\)90022-1](https://doi.org/10.1016/0965-8564(94)90022-1)
- Ahmed, E.-G., Michael, G., Rania, W., Paul, T., & Julien, S.-L. (2013). New evidence on walking distances to transit stops: Identifying redundancies and gaps using variable service areas. *Transportation*, 41(1), 193–210. https://tram.mcgill.ca/Research/Publications/Transit_service_area.pdf
- Alawadi, K., Khanal, A., Doudin, A., & Abdelghani, R. (2021). Revisiting transit-oriented development: Alleys as critical walking infrastructure. *Transport Policy*, 100(November 2020), 187–202. <https://doi.org/10.1016/j.tranpol.2020.11.007>
- Alejandro, R., & Santos, M. (2018). *Vulnerability Assessment to Climate Variability and Climate Change in Tijuana , Mexico*. 1–21. <https://doi.org/10.3390/su10072352>
- Amini Pishro, A., Yang, Q., Zhang, S., Amini Pishro, M., Zhang, Z., Zhao, Y., Postel, V., Huang, D., & Li, W. Y. (2022). Node, place, ridership, and time model for rail-transit stations: a case study. *Scientific Reports*, 12(1), 1–16. <https://doi.org/10.1038/s41598-022-20209-4>
- Appleyard, B. S., Frost, A. R., & Allen, C. (2019). Are all transit stations equal and equitable ? Calculating sustainability , livability , health , & equity performance of smart. *Journal of Transport and Health*, 14, 1–15. <https://doi.org/10.1016/j.jth.2019.100584>
- Arksey, H., & O'Malley, L. (2005). Scoping studies: Towards a methodological framework. *International Journal of Social Research Methodology: Theory and Practice*, 8(1), 19–32. <https://doi.org/10.1080/1364557032000119616>
- Asefa, B., & Mindahun, W. (2019). *Geospatial Based Flood Risk Assessment : The Case of Kewet District , Amhara Region , Ethiopia*. December 2018, 0–10. <https://doi.org/10.5923/j.ajgis.20190801.01>
- Baldassarre, G. Di, Viglione, A., Carr, G., Kuil, L., Yan, K., & Brandimarte, L. (2015). Debates— Perspectives on socio-hydrology: Capturing feedbacks between physical and social processes. *Journal of the American Water Resources Association*, 5(3). <https://doi.org/10.1111/j.1752-1688.1969.tb04897.x>
- Baroud, H., & Barker, K. (2014). *Bayesian Kernel Methods for Critical Infrastructure Resilience Modeling*. 687–694. <https://doi.org/10.1061/9780784413609.070>
- Bazrkar, M. H., Fathian, F., & Eslamian, S. (2013). Runoff Modeling in Order To Investigate the System Dynamic Approach (Case Study: Tehran Watershed, Iran). *Journal of Flood Engineering*, 4(1), 39–56.
- Berawi, M. A., Saroji, G., Iskandar, F. A., Ibrahim, B. E., Miraj, P., & Sari, M. (2020a). Optimizing Land Use Allocation of Transit-Oriented Development (TOD) to Generate Maximum Ridership. *Sustainability*, 12, 1–20.
- Berawi, M. A., Saroji, G., Iskandar, F. A., Ibrahim, B. E., Miraj, P., & Sari, M. (2020b). Optimizing land use allocation of transit-oriented development (TOD) to generate maximum ridership.

- Sustainability (Switzerland)*, 12(9). <https://doi.org/10.3390/su12093798>
- Bertolini, L. (1999). Spatial development patterns and public transport: The application of an analytical model in the Netherlands. *Planning Practice and Research*, 14(2), 199–210. <https://doi.org/10.1080/02697459915724>
- Bertolini, L., le Clercq, F., & Kapoen, L. (2005). Sustainable accessibility: A conceptual framework to integrate transport and land use plan-making. Two test-applications in the Netherlands and a reflection on the way forward. *Transport Policy*, 12(3), 207–220. <https://doi.org/10.1016/j.tranpol.2005.01.006>
- Bhagwati, P., & Kumar, M. (2024). Transit-Oriented Development: Learnings from Global Examples. *LOGI - Scientific Journal on Transport and Logistics*, 15(1), 1–12. <https://doi.org/10.2478/logi-2024-0001>
- Bittihn, S., & Schadschneider, A. (2021). The effect of modern traffic information on Braess' paradox. *Physica A: Statistical Mechanics and Its Applications*, 571, 1–18. <https://doi.org/10.1016/j.physa.2021.125829>
- Bristow, D. N., & Hay, A. H. (2016). Graph Model for Probabilistic Resilience and Recovery Planning of Multi-Infrastructure Systems. *Journal of Infrastructure Systems*, 23(3), 04016039. [https://doi.org/10.1061/\(asce\)is.1943-555x.0000338](https://doi.org/10.1061/(asce)is.1943-555x.0000338)
- Bruneau, M., Chang, S. E., Eguchi, R. T., Lee, G. C., O'Rourke, T. D., Reinhorn, A. M., Shinozuka, M., Tierney, K., Wallace, W. A., & Von Winterfeldt, D. (2003). A Framework to Quantitatively Assess and Enhance the Seismic Resilience of Communities. *Earthquake Spectra*, 19(4), 733–752. <https://doi.org/10.1193/1.1623497>
- Budiati, W., Grigolon, A. B., Brussel, M. J. G., & Rachmat, S. Y. (2018). Determining the potential for Transit Oriented Development along the MRT Jakarta corridor. *IOP Conference Series: Earth and Environmental Science, The 4th PlanoCosmo International Conference*, 158, 1–15. <https://doi.org/10.1088/1755-1315/158/1/012020>
- Calthorpe, P. (1993). *The Next American Metropolis: Ecology, Community, and the American Dream*. Princeton Architectural Press. <https://books.google.ca/books?hl=en&lr=&id=WtKU5L0ajA8C&oi=fnd&pg=PA9&dq=1993,+Calthorpe+&ots=Fzwf2Cto7K&sig=xGpDsO6AuNscNAaU31uTgvkPDEg#v=onepage&q=1993%2C%20Calthorpe...>
- Cao, Z., Asakura, Y., & Tan, Z. (2020). Coordination between node, place, and ridership: Comparing three transit operators in Tokyo. *Transportation Research Part D: Transport and Environment*, 87(September), 102518. <https://doi.org/10.1016/j.trd.2020.102518>
- Caset, F., Blainey, S., Derudder, B., Boussauw, K., & Witlox, F. (2020). Integrating node-place and trip end models to explore drivers of rail ridership in Flanders, Belgium. *Journal of Transport Geography*, 87(July). <https://doi.org/10.1016/j.jtrangeo.2020.102796>
- Cervero, R. (2007). Transit-oriented development's ridership bonus: A product of self-selection and public policies. *Environment and Planning A*, 39(9), 2068–2085. <https://doi.org/10.1068/a38377>
- Cervero, R., & Kockelman, K. (1997). Travel demand and the 3Ds: Density, diversity, and design.

- Transportation Research Part D: Transport and Environment*, 2(3), 199–219. [https://doi.org/10.1016/S1361-9209\(97\)00009-6](https://doi.org/10.1016/S1361-9209(97)00009-6)
- Chang, S. E., McDaniel, T., Fox, J., Dhariwal, R., & Longstaff, H. (2014). Toward disaster-resilient cities: Characterizing resilience of infrastructure systems with expert judgments. *Risk Analysis*, 34(3), 416–434. <https://doi.org/10.1111/risa.12133>
- Chang, S. E., & Shinozuka, M. (2004). Measuring improvements in the disaster resilience of communities. *Earthquake Spectra*, 20(3), 739–755. <https://doi.org/10.1193/1.1775796>
- Charnes, A., Cooper, W. W., & Rhodes, E. (1978). Measuring the efficiency of decision making units. *European Journal of Operational Research*, 2(6), 429–444. [https://doi.org/10.1016/0377-2217\(78\)90138-8](https://doi.org/10.1016/0377-2217(78)90138-8)
- Chatman, D. G. (2013). Does TOD need the T? *Journal of the American Planning Association*, 79, 17–31. <https://doi.org/10.1080/01944363.2013.791008>
- Chen, F., Wu, J., Chen, X., Zengras, P. C., & Wang, J. (2017). Vehicle kilometers traveled reduction impacts of Transit-Oriented Development: Evidence from Shanghai City. *Transportation Research Part D: Transport and Environment*, 55, 227–245. <https://doi.org/10.1016/j.trd.2017.07.006>
- Chen, H., Zhao, K., Zhang, Z., Zhang, H., & Lu, L. (2024). Methods for the Performance Evaluation and Design Optimization of Metro Transit-Oriented Development Sites Based on Urban Big Data. *Land*, 13(8). <https://doi.org/10.3390/land13081233>
- Chen, T., Chen, Y., Zhou, Y., & Guo, J. (2023). Efficiency Assessment of Transit-Oriented Development Focusing on the 500-m Core Catchment of Metro Stations Based on the Concept of a Metro Microcenter in Beijing. *Journal of Transportation Engineering, Part A: Systems*, 149(12), 1–15. <https://doi.org/10.1061/jtepbs.teeng-7373>
- Chen, X.-Z., Lu, Q.-C., Peng, Z.-R., & Ash, J. E. (2015). Analysis of Transportation Network Vulnerability under Flooding Disasters. *Transportation Research Record: Journal of the Transportation Research Board*, 2532(1), 37–44. <https://doi.org/10.3141/2532-05>
- Chen, X. Z., Lu, Q. C., Peng, Z. R., & Ash, J. E. (2015). Analysis of transportation network vulnerability under flooding disasters. *Transportation Research Record*, 2532, 37–44. <https://doi.org/10.3141/2532-05>
- Chindaprasirt, P., Klungboonkrong, P., Jaensirisak, S., Faiboun, N., Long, S., Tippichai, A., & Taylor, M. A. P. (2024). Integrated Urban Transport and Land-Use Policies in Reducing CO2 Emissions and Energy Consumption: Case Study of a Medium-Sized City in Thailand. *World Electric Vehicle Journal*, 15(8), 1–19. <https://doi.org/10.3390/wevj15080349>
- Choi, Y., & Guhathakurta, S. (2024). Unraveling the diversity in transit-oriented development. *Transportation Research Part A: Policy and Practice*, 182(February), 104020. <https://doi.org/10.1016/j.tra.2024.104020>
- Chorus, P., & Bertolini, L. (2016). Developing transit-oriented corridors: Insights from Tokyo. *International Journal of Sustainable Transportation*, 10(2), 86–95. <https://doi.org/10.1080/15568318.2013.855850>

- Conesa, A. (2018). The accessibility assessment and the regional range of transit-oriented development: An application of schedule accessibility measures in the Nord Pas-de-Calais region. *Journal of Transport and Land Use*, 11(1), 119–141. <https://doi.org/10.5198/jtlu.2018.850>
- Cong, W., Zhou, J., & Lai, Y. (2024). The coordination between citywide rail transit accessibility and land-use characteristics in Shenzhen, China: An explorative analysis based on multidimensional spatial data. *Sustainable Cities and Society*, 113(December 2023), 105691. <https://doi.org/10.1016/j.scs.2024.105691>
- Cournoyer-Gendron, M. (2017). The Transit-Oriented Development Model in Montreal (Canada): Mobilizing a Concept and Negotiating Urban Development at the Local and Metropolitan Scale. *Environnement Urbain / Urban Environment [En Ligne]*, 12, 1–22.
- Cox, L., Bassi, A., Kolling, J., Procter, A., Flanders, N., Tanners, N., & Araujo, R. (2017). Exploring synergies between transit investment and dense redevelopment: A scenario analysis in a rapidly urbanizing landscape. *Landscape and Urban Planning*, 167(November 2016), 429–440. <https://doi.org/10.1016/j.landurbplan.2017.07.021>
- Deboosere, R., El-Geneidy, A. M., & Levinson, D. (2018). Accessibility-oriented development. *Journal of Transport Geography*, 70, 11–20. <https://doi.org/10.1016/j.jtrangeo.2018.05.015>
- Diakoulaki, D., Mavrotas, G., & Papayannakis, L. (1995). Determining objective weights in multiple criteria problems: The critic method. *Computers and Operations Research*, 22(7), 763–770. [https://doi.org/10.1016/0305-0548\(94\)00059-H](https://doi.org/10.1016/0305-0548(94)00059-H)
- Dotto, L., Duchesne, L., Etkin, D., & Elianna, J. (2010). *Canadians at risk : Canadians at risk : Our exposure to natural hazards- Canadian Assessment of Natural Hazards Project* (Issue February).
- Dou, Y., Luo, X., Dong, L., Wu, C., Liang, H., & Ren, J. (2016). An empirical study on transit-oriented low-carbon urban land use planning: Exploratory Spatial Data Analysis (ESDA) on Shanghai, China. *Habitat International*, 53, 379–389. <https://doi.org/10.1016/j.habitatint.2015.12.005>
- Duran-Encalada, J. A., & Paucar-Caceres, A. (2009). System dynamics urban sustainability model for Puerto Aura in Puebla, Mexico. *Systemic Practice and Action Research*, 22(2), 77–99. <https://doi.org/10.1007/s11213-008-9114-8>
- Ehman, E. C., Johnson, G. B., Villanueva-meyer, J. E., Cha, S., Leynes, A. P., Eric, P., Larson, Z., & Hope, T. A. (2017). *HHS Public Access*. 46(5), 1247–1262. <https://doi.org/10.1002/jmri.25711>.PET/MRI
- Ewing, R., Kim, K., Sabouri, S., Siddiq, F., & Weinberger, R. (2021). Comparative Case Studies of Parking Reduction at Transit-Oriented Developments in the U.S.A. *Transportation Research Record*, 2675(1), 125–135. <https://doi.org/10.1177/0361198120965558>
- Ewing, R., Tian, G., Lyons, T., & Terzano, K. (2017). Trip and parking generation at transit-oriented developments: Five US case studies. *Landscape and Urban Planning*, 160, 69–78. <https://doi.org/10.1016/j.landurbplan.2016.12.002>
- Faghri, A., & Venigalla, M. (2014). Measuring Travel Behavior and Transit Trip Generation

- Characteristics of Transit-Oriented Developments. *Transportation Research Board*, 2397, 72–79. <https://doi.org/10.3141/2397-09>
- Fakhruddin, S. H. M., Babel, M. S., & Kawasaki, A. (2015). Assessing the vulnerability of infrastructure to climate change on the Islands of Samoa. *Natural Hazards and Earth System Sciences*, 15(6), 1343–1356. <https://doi.org/10.5194/nhess-15-1343-2015>
- Fan, Z., Zhang, F., & Loo, B. P. Y. (2022). Rhythm of Transit Stations-Uncovering the Activity-Travel Dynamics of Transit-Oriented Development in the U.S. *IEEE Transactions on Intelligent Transportation Systems*, 23(8), 12503–12517. <https://doi.org/10.1109/TITS.2021.3115103>
- Geurs, K. T., & Wee, B. van. (2004). Accessibility evaluation of land-use and transport strategies: Review and research directions. *Journal of Transport Geography*, 12(2), 127–140. <https://doi.org/10.1016/j.jtrangeo.2003.10.005>
- Gilderbloom, J. I., Riggs, W. W., & Meares, W. L. (2015). Does walkability matter? An examination of walkability's impact on housing values, foreclosures and crime. *Cities*, 42, 13–24. <https://doi.org/10.1016/j.cities.2014.08.001>
- Godschalk, D. R. (2003). Urban Hazard Mitigation: Creating Resilient Cities. *Natural Hazards Review*, 4(3), 136–143. [https://doi.org/10.1061/\(asce\)1527-6988\(2003\)4:3\(136\)](https://doi.org/10.1061/(asce)1527-6988(2003)4:3(136))
- Gourbesville, P., & Batica, J. (2015). Methodology for flood resilience index FOOD RESILIENCE IMPLEMENTATION. ... *Conference on Flood Resilience ...*, October. http://icfr2013.ex.ac.uk/papers/C1_Batica.pdf
- Guan, D. J., Li, H. F., Inohae, T., Su, W., Nagaie, T., & Hokao, K. (2011). Modeling urban land use change by the integration of cellular automaton and Markov model. *Ecological Modelling*, 222(20–22), 3761–3772. <https://doi.org/10.1016/j.ecolmodel.2011.09.009>
- Guo, E., Zhang, J., Ren, X., Zhang, Q., & Sun, Z. (2014). Integrated risk assessment of flood disaster based on improved set pair analysis and the variable fuzzy set theory in central Liaoning Province, China. *Natural Hazards*, 74(2), 947–965. <https://doi.org/10.1007/s11069-014-1238-9>
- Guo, J., Nakamura, F., Li, Q., & Zhou, Y. (2018). Efficiency Assessment of Transit-Oriented Development by Data Envelopment Analysis: Case Study on the Den-en Toshi Line in Japan. *Journal of Advanced Transportation*, 1155, 1–10. <https://doi.org/10.1155/2018/6701484>
- Hasibuan, H. S., Sodri, A., & Harmain, R. (2021). The Carrying Capacity Assessment of Two MRT Stations Transit-Oriented Development Areas in Jakarta. *Indonesian Journal of Geography*, 53(1), 78–86. <https://doi.org/10.22146/IJG.51968>
- Higgins, C. D., & Kanaroglou, P. S. (2016). A latent class method for classifying and evaluating the performance of station area transit-oriented development in the Toronto region. *Journal of Transport Geography*, 52, 61–72. <https://doi.org/10.1016/j.jtrangeo.2016.02.012>
- Higgins, C., & Kanaroglou, P. (2018). Rapid transit, transit-oriented development, and the contextual sensitivity of land value uplift in Toronto. *Urban Studies*, 55, 2197–2225. <https://doi.org/10.1177/0042098017712680>

- Hjorth, P., & Bagheri, A. (2006). Navigating towards sustainable development: A system dynamics approach. *Futures*, 38(1), 74–92. <https://doi.org/10.1016/j.futures.2005.04.005>
- Hrelja, R., Olsson, L., Pettersson-Löfstedt, F., & Rye, T. (2022). Challenges of delivering TOD in low-density contexts: the Swedish experience of barriers and enablers. *European Transport Research Review*, 14(1), 1–11. <https://doi.org/10.1186/s12544-022-00546-1>
- Hsieh, C. H., Tai, H. H., & Lee, Y. N. (2014). Port vulnerability assessment from the perspective of critical infrastructure interdependency. *Maritime Policy and Management*, 41(6), 589–606. <https://doi.org/10.1080/03088839.2013.856523>
- Huang, R., Grigolon, A., Madureira, M., & Brussel, M. (2018). Measuring transit-oriented development (TOD) network complementarity based on tod node typology. *Journal of Transport and Land Use*, 11, 304–324. <https://doi.org/10.5198/jtlu.2018.1110>
- Huang, X., Liang, Q., Feng, Z., & Chai, S. (2021). A TOD Planning Model Integrating Transport and Land Use in Urban Rail Transit Station Areas. *IEEE Access*, 9, 1103–1115. <https://doi.org/10.1109/ACCESS.2020.3047207>
- Ibraeva, A., Correia, G. H. de A., Silva, C., & Antunes, A. P. (2020). Transit-oriented development: A review of research achievements and challenges. *Transportation Research Part A: Policy and Practice*, 132(October 2019), 110–130. <https://doi.org/10.1016/j.tra.2019.10.018>
- Ibraeva, A., Van Wee, B., Correia, G. H. de A., & Pais Antunes, A. (2021). Longitudinal macro-analysis of car-use changes resulting from a TOD-type project: The case of Metro do Porto (Portugal). *Journal of Transport Geography*, 92(July 2020). <https://doi.org/10.1016/j.jtrangeo.2021.103036>
- Ibrahim, S. M., Ayad, H. M., Turki, E. A., & Saadallah, D. M. (2023). Measuring Transit-Oriented Development (TOD) levels: Prioritize potential areas for TOD in Alexandria, Egypt using GIS-Spatial Multi-Criteria based model. *Alexandria Engineering Journal*, 67, 241–255. <https://doi.org/10.1016/j.aej.2022.12.053>
- Jain, A. D., & Singh, E. (2019). Transit oriented development in india: A critical review of policy measures. *International Journal of Recent Technology and Engineering*, 7(6), 745–751.
- Jamaledin, M., Ibrahim, H., Ferwati, M. S., Khamidi, M. F., & Indraganti, M. (2022). Pre-Transit Oriented Development Assessment Guidelines for Assessing Metro Station Dependent Component Area. *Designs*, 6(3). <https://doi.org/10.3390/designs6030056>
- Jamme, H. T., Rodriguez, J., Bahl, D., & Banerjee, T. (2019). A Twenty-Five-Year Biography of the TOD Concept: From Design to Policy, Planning, and Implementation. *Journal of Planning Education and Research*, 39(4), 409–428. <https://doi.org/10.1177/0739456X19882073>
- Jones, C. E., & Ley, D. (2016). Transit-oriented development and gentrification along Metro Vancouver's low-income SkyTrain corridor. *Canadian Geographer*, 60(1), 9–22. <https://doi.org/10.1111/cag.12256>
- Kamruzzaman, M., Baker, D., Washington, S., & Turrell, G. (2014). Advance transit oriented development typology: Case study in brisbane, australia. *Journal of Transport Geography*, 34, 54–70. <https://doi.org/10.1016/j.jtrangeo.2013.11.002>

- Kamruzzaman, M., Deilami, K., & Yigitcanlar, T. (2018). Investigating the urban heat island effect of transit oriented development in Brisbane. *Journal of Transport Geography*, 66, 116–124. <https://doi.org/10.1016/j.jtrangeo.2017.11.016>
- Ke, L., Furuya, K., & Luo, S. (2021). Case comparison of typical transit-oriented-development stations in Tokyo district in the context of sustainability: Spatial visualization analysis based on FAHP and GIS. *Sustainable Cities and Society*, 68(September 2020). <https://doi.org/10.1016/j.scs.2021.102788>
- Khare, R., Villuri, V. G. K., & Chaurasia, D. (2020). Urban sustainability assessment: The evaluation of coordinated relationship between BRTS and land use in transit-oriented development mode using DEA model. *Ain Shams Engineering Journal*, xxxx. <https://doi.org/10.1016/j.asej.2020.08.012>
- Khosravi, H., Abrishami, M., Mehrian, M. R., & Chamberlain, B. (2024). The positive impact of transit-oriented-development characteristics on Metro Station usage: A case study of Tehran's metro stations and TOD index calculation. *Cities*, 148(June 2022), 104840. <https://doi.org/10.1016/j.cities.2024.104840>
- Kim, S., & Yeo, H. (2016). A Flow-based Vulnerability Measure for the Resilience of Urban Road Network. *Procedia - Social and Behavioral Sciences*, 218, 13–23. <https://doi.org/10.1016/j.sbspro.2016.04.006>
- Laaly, S., Jaihani, M., & Lee, Y. J. (2017). A multiscale, transit-oriented development definition based on context-sensitive paradigm. *Transportation Research Record*, 2671, 31–39. <https://doi.org/10.3141/2671-04>
- Langlois, M., Van Lierop, D., Wasfi, R. A., & El-Geneidy, A. M. (2015). Chasing sustainability do new transit-oriented development residents adopt more sustainable modes of transportation? *Transportation Research Record*, 2531(2531), 83–92. <https://doi.org/10.3141/2531-10>
- Lavoie, M., & El-Geneidy, A. (2012). *Characterizing Land use and Transportation for Transit-Oriented Development in the Montreal Metropolitan Region*. http://digitool.library.mcgill.ca:80/R/-?func=dbin-jump-full&obj_id=122527&silo_library=GEN01
- Lee, E. H., & Kim, J. H. (2017). Development of resilience index based on flooding damage in urban areas. *Water (Switzerland)*, 9(6), 1–15. <https://doi.org/10.3390/w9060428>
- Lee, E. H., Shin, H., Cho, S.-H., Kho, S.-Y., & Kim, D.-K. (2019). Evaluating the Efficiency of Transit-Oriented Envelopment Analysis. *Energies*, 12, 1–15.
- Lee, J. (Brian), & Salih, S. H. (2024). Passive transit accessibility: Modelling and application for transit gap analysis and station area assessment. *Journal of Transport Geography*, 114(October 2023), 103757. <https://doi.org/10.1016/j.jtrangeo.2023.103757>
- Lee, J., Choi, K., & Leem, Y. (2016). Bicycle-based transit-oriented development as an alternative to overcome the criticisms of the conventional transit-oriented development. *International Journal of Sustainable Transportation*, 10, 975–984. <https://doi.org/10.1080/15568318.2014.923547>
- Lee, J. S., & Choi, H. Il. (2019). applied sciences Comparative Analysis of Flood Vulnerability

- Indicators by Aggregation Frameworks for the IPCC 's Assessment Components to Climate Change. *Applied Science*, 9(2321).
- Lee, R. W., & Cervero, R. (2007). *Research Basis for Proposed Criteria of the TOD Housing Program. The effect of housing near transit stations on vehicle trip rates and transit trip generation. A review of available evidence. California: University of California, Insitute of Urban and Reg.*
- Lee, S., Yi, C., & Hong, S. P. (2013). Urban structural hierarchy and the relationship between the ridership of the Seoul Metropolitan Subway and the land-use pattern of the station areas. *Cities*, 35, 69–77. <https://doi.org/10.1016/j.cities.2013.06.010>
- Li, J., Luo, X., Wang, H., Qiu, Y., & Fan, W. (2022). Bilevel Programming Model for Park-and-Ride Versus Transit-Oriented Development: A Case Study of Chengdu City, China. *Journal of Urban Planning and Development*, 148(1), 1–14. [https://doi.org/10.1061/\(asce\)up.1943-5444.0000786](https://doi.org/10.1061/(asce)up.1943-5444.0000786)
- Li, L., Cao, R., Wei, K., Wang, W., & Chen, L. (2019). Adapting climate change challenge: A new vulnerability assessment framework from the global perspective. *Journal of Cleaner Production*, 217, 216–224. <https://doi.org/10.1016/j.jclepro.2019.01.162>
- Li, P., Zhao, P., & Brand, C. (2018). Future energy use and CO2 emissions of urban passenger transport in China: A travel behavior and urban form based approach. *Applied Energy*, 211(October 2017), 820–842. <https://doi.org/10.1016/j.apenergy.2017.11.022>
- Li, S., Lyu, D., Huang, G., Zhang, X., Gao, F., Chen, Y., & Liu, X. (2020). Spatially varying impacts of built environment factors on rail transit ridership at station level: A case study in Guangzhou, China. *Journal of Transport Geography*, 82, 1–14. <https://doi.org/10.1016/j.jtrangeo.2019.102631>
- Li, X., Liu, Y., Gao, Z., & Liu, D. (2016). Decision Tree Based Station-Level Rail Transit Ridership Forecasting. *Journal of Urban Planning and Development*, 142(4), 04016011. [https://doi.org/10.1061/\(asce\)up.1943-5444.0000331](https://doi.org/10.1061/(asce)up.1943-5444.0000331)
- Li, X., Xiao, Q., Zhu, Y., & Yang, Y. (2022). Influence of TOD Modes on Passenger Travel Behavior in Urban Rail Transit Systems. *Urban Rail Transit*, 8(3–4), 175–183. <https://doi.org/10.1007/s40864-022-00179-6>
- Li, Z., Han, Z., Xin, J., Luo, X., Su, S., & Weng, M. (2019a). Transit oriented development among metro station areas in Shanghai, China: Variations, typology, optimization and implications for land use planning. *Land Use Policy*, 82, 269–282. <https://doi.org/10.1016/j.landusepol.2018.12.003>
- Li, Z., Han, Z., Xin, J., Luo, X., Su, S., & Weng, M. (2019b). Transit oriented development among metro station areas in Shanghai, China: Variations, typology, optimization and implications for land use planning. *Land Use Policy*, 82(129), 269–282. <https://doi.org/10.1016/j.landusepol.2018.12.003>
- Likas, A., Vlassis, N., & J. Verbeek, J. (2003). The global k-means clustering algorithm. *Pattern Recognition*, 36(2), 451–461. [https://doi.org/10.1016/S0031-3203\(02\)00060-2](https://doi.org/10.1016/S0031-3203(02)00060-2)
- Limmonthol, A., Rudjanakanoknad, J., & Bunditsakulchai, P. (2020). The Examination of the

- Effects of Land Use Development on the Balance of Mass Transit Ridership. *Engineering Journal*, 24, 1–17. <https://doi.org/10.4186/ej.2020.24.2.1>
- Lin, J. J., & Li, C. N. (2006). A grey programming model for regional transit-oriented development planning. *Papers in Regional Science*, 87(1), 119–138. <https://doi.org/10.1111/j.1435-5957.2007.00146.x>
- Lin, T., Palmer, R., Xia, J., & Mcmeekin, D. A. (2014). Automatic generation of station catchment areas: A comparison of Euclidean distance transform algorithm and location-allocation methods. *2014 11th International Conference on Fuzzy Systems and Knowledge Discovery, FSKD 2014, December 2016*, 963–967. <https://doi.org/10.1109/FSKD.2014.6980969>
- Litman, T., & Burwell, D. (2006). Issues in sustainable transportation. *International Journal of Global Environmental Issues*, 6(4), 331–347. <https://doi.org/10.1504/IJGENVI.2006.010889>
- Liu, J. H., Pai, J. Te, & Lin, J. J. (2018). Planning Strategy for Green Transit Oriented Development Using A Multi-objective Planning Model. *International Review for Spatial Planning and Sustainable Development*, 6A, 35–52. https://doi.org/10.14246/irspsd.6a.1_35
- Lokku, P. S., & Prasad, C. S. R. K. (2018). Framework for Establishing Feasible Transit Oriented Development Locations: a Case Study in Hyderabad, India. *International Journal for Traffic and Transport Engineering*, 8, 228–240. [https://doi.org/10.7708/ijtte.2018.8\(2\).07](https://doi.org/10.7708/ijtte.2018.8(2).07)
- Loo, B. P. Y., & du Verle, F. (2017). Transit-oriented development in future cities: towards a two-level sustainable mobility strategy. *International Journal of Urban Sciences*, 21, 54–67. <https://doi.org/10.1080/12265934.2016.1235488>
- Lückerath, D., Bogen, M., Rome, E., Sojeva, B., Ullrich, O., Worst, R., & Xie, J. (2018). *The RESIN climate change adaptation project and its simple modeling approach for risk-oriented vulnerability assessment*. March.
- Luo, G., Yin, C., Chen, X., Xu, W., & Lu, L. (2010). Combining system dynamic model and CLUE-S model to improve land use scenario analyses at regional scale: A case study of Sangong watershed in Xinjiang, China. *Ecological Complexity*, 7(2), 198–207. <https://doi.org/10.1016/j.ecocom.2010.02.001>
- Lyle, T. S., & Hund, S. V. (2017). *GEOLOGICAL SURVEY OF CANADA OPEN FILE 8255 Way forward for risk assessment tools in Canada*.
- Lyu, G., Bertolini, L., & Pfeffer, K. (2016a). Developing a TOD typology for Beijing metro station areas. *Journal of Transport Geography*, 55, 40–50. <https://doi.org/10.1016/j.jtrangeo.2016.07.002>
- Lyu, G., Bertolini, L., & Pfeffer, K. (2016b). Developing a TOD typology for Beijing metro station areas. *Journal of Transport Geography*, 55, 40–50. <https://doi.org/10.1016/j.jtrangeo.2016.07.002>
- Lyu, G., Bertolini, L., & Pfeffer, K. (2019). How does transit-oriented development contribute to station area accessibility? A study in Beijing. *International Journal of Sustainable Transportation*, 10, 1–11. <https://doi.org/10.1080/15568318.2019.1578841>

- Ma, D., & Chen, Y. (2019). Research on TOD Planning of Urban Rail Transit Based on Cellular Automata. *4th International Conference on Electromechanical Control Technology and Transportation (ICECTT) Research*, 332–335. <https://doi.org/10.1109/ICECTT.2019.00082>
- Ma, X., Chen, X., Li, X., Ding, C., & Wang, Y. (2018). Sustainable station-level planning: An integrated transport and land use design model for transit-oriented development. *Journal of Cleaner Production*, 170, 1052–1063. <https://doi.org/10.1016/j.jclepro.2017.09.182>
- Mahriyar, M. Z., & Rho, J. H. (2014). The Compact City Concept in Creating Resilient City and Transportation System in Surabaya. *Procedia - Social and Behavioral Sciences*, 135, 41–49. <https://doi.org/10.1016/j.sbspro.2014.07.323>
- Manna, P., Anis, M. Z., Das, P., & Banerjee, S. (2019). Probabilistic Modeling of Flood Hazard and its Risk Assessment for Eastern Region of India. *Risk Analysis*, 39(7), risa.13333. <https://doi.org/10.1111/risa.13333>
- Marcussen, M. (2018). *CITY OF CHICO CLIMATE CHANGE VULNERABILITY ASSESSMENT CLIMATE CHANGE VULNERABILITY ASSESSMENT*. 1–46.
- McDaniels, T., Chang, S., Cole, D., Mikawoz, J., & Longstaff, H. (2008). Fostering resilience to extreme events within infrastructure systems: Characterizing decision contexts for mitigation and adaptation. *Global Environmental Change*, 18(2), 310–318. <https://doi.org/10.1016/j.gloenvcha.2008.03.001>
- Meerow, S., Newell, J. P., & Stults, M. (2016). Defining urban resilience: A review. *Landscape and Urban Planning*, 147, 38–49. <https://doi.org/10.1016/j.landurbplan.2015.11.011>
- Mojtahedi, M., Newton, S., & Von Meding, J. (2017). Predicting the resilience of transport infrastructure to a natural disaster using Cox's proportional hazards regression model. *Natural Hazards*, 85(2), 1119–1133. <https://doi.org/10.1007/s11069-016-2624-2>
- Monajem, S., & Ekram Nosratian, F. (2015). The evaluation of the spatial integration of station areas via the node place model; an application to subway station areas in Tehran. *Transportation Research Part D: Transport and Environment*, 40, 14–27. <https://doi.org/10.1016/j.trd.2015.07.009>
- Morency, P., Plante, C., Dub, A., Goudreau, S., Morency, C., Bourbonnais, P., Eluru, N., Louis-françois, T., & Hatzopoulou, M. (2020). The Potential Impacts of Urban and Transit Planning Scenarios for 2031 on Car Use and Active Transportation in a Metropolitan Area. *Environmental Research and Public Health*, 17, 1–15.
- Motieyan, H., & Mesgari, M. (2017). Towards Sustainable Urban Planning Through Transit-Oriented Development (A Case Study: Tehran). *ISPRS International Journal of Geo-Information*, 6, 1–16. <https://doi.org/10.3390/ijgi6120402>
- Motieyan, H., & Mesgari, M. S. (2018). Development of a TOD Index through Spatial Analyses and HFIS in Tehran, Iran. *Journal of Urban Planning and Development*, 144(4), 04018038. [https://doi.org/10.1061/\(asce\)up.1943-5444.0000484](https://doi.org/10.1061/(asce)up.1943-5444.0000484)
- Motieyan, H., & Mesgari, M. S. (2019). A novel spatial index using spatial analyses and hierarchical fuzzy expert system for obtaining green TOD: a case study in Tehran city. *Geocarto International*, 34, 1–22. <https://doi.org/10.1080/10106049.2017.1353644>

- Mudigonda, S., Ozbay, K., Ozturk, O., Iyer, S., & Noland, R. B. (2014). Quantifying transportation benefits of transit-oriented development in New Jersey. *Transportation Research Record*, 2417, 111–120. <https://doi.org/10.3141/2417-12>
- Nasri, A., Carrion, C., Zhang, L., & Baghaei, B. (2018a). Using propensity score matching technique to address self-selection in transit-oriented development (TOD) areas. *Transportation*, 47, 359–371. <https://doi.org/10.1007/s11116-018-9887-2>
- Nasri, A., Carrion, C., Zhang, L., & Baghaei, B. (2018b). Using propensity score matching technique to address self-selection in transit-oriented development (TOD) areas. *Transportation*, 1–13. <https://doi.org/10.1007/s11116-018-9887-2>
- Nasri, A., Carrion, C., Zhang, L., & Baghaei, B. (2020). Using propensity score matching technique to address self-selection in transit-oriented development (TOD) areas. *Transportation*, 47(1), 359–371. <https://doi.org/10.1007/s11116-018-9887-2>
- Nasri, A., & Zhang, L. (2014). The analysis of transit-oriented development (TOD) in Washington, D.C. and Baltimore metropolitan areas. *Transport Policy*, 32, 172–179. <https://doi.org/10.1016/j.tranpol.2013.12.009>
- Nasri, A., & Zhang, L. (2019). How urban form characteristics at both trip ends influence mode choice: Evidence from TOD vs. Non-TOD zones of the Washington, D.C. metropolitan area. *Sustainability (Switzerland)*, 11(12). <https://doi.org/10.3390/SU11123403>
- Nazarnia, N., Schwick, C., & Jaeger, J. A. G. (2016a). Accelerated urban sprawl in Montreal, Quebec City, and Zurich: Investigating the differences using time series 1951–2011. *Ecological Indicators*, 60, 1229–1251. <https://doi.org/10.1016/j.ecolind.2015.09.020>
- Nazarnia, N., Schwick, C., & Jaeger, J. A. G. (2016b). Accelerated urban sprawl in Montreal, Quebec City, and Zurich: Investigating the differences using time series 1951–2011. *Ecological Indicators*, 60, 1229–1251. <https://doi.org/10.1016/j.ecolind.2015.09.020>
- Nelson, A., Lindbergh, S., Stephenson, L., & Halpern, J. (2019). *Coupling Natural Hazard Estimates with Road Network Analysis to Assess Vulnerability and Risk: Case Study of Freetown , Building Disruption Simulations in Hydrometeorological Risk Areas in Data-Scarce Sierra Leone*. <https://doi.org/10.1177/0361198118822272>
- Nemroudi, R., Ortuño, A., Flor, M., & Guirao, B. (2024). Application of the Node–Place Model in Algiers (Algeria). *Sustainability (Switzerland)*, 16(15). <https://doi.org/10.3390/su16156428>
- Nguyen, T. M. C., Kato, H., & Phan, L. B. (2020). Is Built Environment Associated with Travel Mode Choice in Developing Cities ? Evidence from Hanoi. *Sustainability*, 12, 1–16.
- Nieves-Melendez, M. E., & De La Garza, J. M. (2016). A Comparison of Two Quantitative Frameworks for Measuring the Resilience of Ground Transportation Systems. *Construction Research Congress*, 1373–1382.
- Nigro, A., Bertolini, L., Domenico, F., & Moccia, F. D. (2019). Land use and public transport integration in small cities and towns: Assessment methodology and application. *Journal of Transport Geography*, 74, 110–124. <https://doi.org/10.1016/j.jtrangeo.2018.11.004>
- Nurlaela, S., Nadya, A., Zuhdi, A. Y., Handayani, K. D. M. E., Fakhrianto, I., Nurkhariza, A. R.,

- & Yusuf, L. (2019). Qualitative comparative assessment by fsQCA for Transit Oriented Development (TOD) area comparison. *IOP Conference Series: Earth and Environmental Science*, 340, 1–13. <https://doi.org/10.1088/1755-1315/340/1/012037>
- Nyunt, K. T. K., & Wongchavalidkul, N. (2020). Evaluation of Relationships Between Ridership Demand and Transit-Oriented Development (TOD) Indicators Focused on Land Use Density, Diversity, and Accessibility: A Case Study of Existing Metro Stations in Bangkok. *Urban Rail Transit*, 6, 56–70. <https://doi.org/10.1007/s40864-019-00122-2>
- Ogra, A., & Ndebele, R. (2013). The Role of 6Ds : Density , Diversity , Design , Destination , Distance , and Demand Management in Transit Oriented Development (TOD). *Neo-International Conference on Habitable Environments, May 2013*, 539–546.
- Olaru, D., Moncrieff, S., Mccarney, G., Sun, Y., Reed, T., Pattison, C., Smith, B., & Biermann, S. (2019). Place vs . Node Transit : Planning Policies Revisited. *Sustainability*, 11, 1–14. <https://doi.org/10.3390/su11020477>
- Pan, H., & Huang, Y. (2024). TOD typology and station area vibrancy: An interpretable machine learning approach. *Transportation Research Part A: Policy and Practice*, 186(December 2023), 104150. <https://doi.org/10.1016/j.tra.2024.104150>
- Pan, H., Li, J., Shen, Q., & Shi, C. (2017a). What determines rail transit passenger volume? Implications for transit oriented development planning. *Transportation Research Part D*, 57, 52–63. <https://doi.org/10.1016/j.jtrangeo.2016.02.012>
- Pan, H., Li, J., Shen, Q., & Shi, C. (2017b). What determines rail transit passenger volume? Implications for transit oriented development planning. *Transportation Research Part D: Transport and Environment*, 57(September), 52–63. <https://doi.org/10.1016/j.trd.2017.09.016>
- Papa, E., & Bertolini, L. (2015). Accessibility and Transit-Oriented Development in European metropolitan areas. *Journal of Transport Geography*, 47, 70–83. <https://doi.org/10.1016/j.jtrangeo.2015.07.003>
- Papa, E., Moccia, F. D., Angiello, G., & Inglese, P. (2013). An accessibility planning tool for Network Transit Oriented Development: SNAP. *Urbanism*, 2, 1–9.
- Park, K., Ewing, R., Scheer, B. C., & Ara Khan, S. S. (2018). Travel Behavior in TODs vs. Non-TODs: Using Cluster Analysis and Propensity Score Matching. *Transportation Research Record*, 2672(6), 31–39. <https://doi.org/10.1177/0361198118774159>
- Park, K., Ewing, R., Scheer, B. C., & Tian, G. (2018). The impacts of built environment characteristics of rail station areas on household travel behavior. *Cities*, 74, 277–283. <https://doi.org/10.1016/j.cities.2017.12.015>
- Park, K., & Lee, M.-H. (2019). The Development and Application of the Urban Flood Risk Assessment Model for Reflecting upon Urban Planning Elements. *Water*, 11, 1–17.
- Patarasuk, R. (2013). Road network connectivity and land-cover dynamics in Lop Buri province, Thailand. *Journal of Transport Geography*, 28, 111–123. <https://doi.org/10.1016/j.jtrangeo.2012.11.011>
- Peck, A., Neuwirth, C., & Simonovic, S. P. (2014). *Coupling System Dynamics with Geographic*

- Pezeshknejad, P., Monajem, S., & Mozafari, H. (2020). Evaluating sustainability and land use integration of BRT stations via extended node place model, an application on BRT stations of Tehran. *Journal of Transport Geography*, 82, 1–14. <https://doi.org/10.1016/j.jtrangeo.2019.102626>
- Phani Kumar, P., Ravi Sekhar, C., & Parida, M. (2020). Identification of neighborhood typology for potential transit-oriented development. *Transportation Research Part D: Transport and Environment*, 78, 1–20. <https://doi.org/10.1016/j.trd.2019.11.015>
- Pongprasert, P., & Kubota, H. (2019). TOD residents' attitudes toward walking to transit station: a case study of transit-oriented developments (TODs) in Bangkok, Thailand. *Journal of Modern Transportation*, 27, 39–51. <https://doi.org/10.1007/s40534-018-0170-1>
- Public Safety Canada. (2017). *An Emergency Management Framework for Canada: Ministers Responsible for Emergency Management - Third Edition*. May, 1–23.
- Rabiei, N., Nasiri, F., & Eicker, U. (2022). Multistage Transit-Oriented Development Assessment: A Case Study of the Montréal Metro System. *Journal of Urban Planning and Development*, 148(3), 1–17. [https://doi.org/10.1061/\(asce\)up.1943-5444.0000836](https://doi.org/10.1061/(asce)up.1943-5444.0000836)
- Rahman, M. H., Ashik, F. R., & Mouli, M. J. (2022). Investigating spatial accessibility to urban facility outcome of transit-oriented development in Dhaka. *Transportation Research Interdisciplinary Perspectives*, 14(October 2021), 100607. <https://doi.org/10.1016/j.trip.2022.100607>
- Rahmat, A., Endot, I. R., Ahmad, Z., Ishak, Z., & Ibrahim, C. K. I. (2016). Development of Transit Oriented Development (TOD) Model for Malaysia. *Built Environment, Technology and Engineering*, 1, 36–47.
- Rausand, M., & Hoyland, A. (2004). *System reliability Theory* (Second). A JOHN WILEY & SONS, INC., PUBLICATION.
- Reggiani, A., Nijkamp, P., & Lanzi, D. (2015). Transport resilience and vulnerability: The role of connectivity. *Transportation Research Part A: Policy and Practice*, 81, 4–15. <https://doi.org/10.1016/j.tra.2014.12.012>
- Renne, J. L., Tolford, T., Hamidi, S., & Ewing, R. (2016). The Cost and Affordability Paradox of Transit-Oriented Development: A Comparison of Housing and Transportation Costs Across Transit-Oriented Development, Hybrid and Transit-Adjacent Development Station Typologies. *Housing Policy Debate*, 26, 819–834. <https://doi.org/10.1080/10511482.2016.1193038>
- Roszkowska, E. (2013). Rank Ordering Criteria Weighting Methods a Comparative Overview. *Optimum. Studia Ekonomiczne*, 65, 14–33. <https://doi.org/10.15290/ose.2013.05.65.02>
- Rowan, E., Kafalenos, R., Rodehorst, B., Gye, A., Hyman, R., Snow, C., Asam, S., & Choate, A. (2015). Indicator Approach for Assessing Climate Change Vulnerability in Transportation Infrastructure. *Transportation Research Record: Journal of the Transportation Research Board*, 2459, 18–28. <https://doi.org/10.3141/2459-03>

- Ruan, Z., Feng, X., Wu, F., Ding, C., & Hua, W. (2021). Land Use and Transport Integration Modeling with Immune Genetic Optimization for Urban Transit-Oriented Development. *Journal of Urban Planning and Development*, 147(1), 04020063. [https://doi.org/10.1061/\(asce\)up.1943-5444.0000658](https://doi.org/10.1061/(asce)up.1943-5444.0000658)
- Rubio, C. J. P., Yu, I., Kim, H., Kim, S., & Jeong, S. (2019). An Investigation of the Adequacy of Urban Evacuation Centers Using Index-based Flood Risk Assessment. *Journal of the Korean Society of Hazard Mitigation*, 19(2), 197–207. <https://doi.org/10.9798/kosham.2019.19.2.197>
- Saaty, T. L. (2008). Decision making with the analytic hierarchy process. *Services Sciences*, 1(1), 83–98. [https://doi.org/10.1016/0305-0483\(87\)90016-8](https://doi.org/10.1016/0305-0483(87)90016-8)
- Sahu, A. (2018). A methodology to modify land uses in a transit oriented development scenario. *Journal of Environmental Management*, 213, 467–477. <https://doi.org/10.1016/j.jenvman.2017.12.004>
- Santiago, R. (2017). *The Role of Urban Infrastructure in Supporting Transit-Oriented Development*.
- Savvides, A. L. (2017). Smart growth through joint highway air rights and transit-oriented development. *International Journal of Sustainable Development and Planning*, 12(7), 1142–1154. <https://doi.org/10.2495/SDP-V12-N7-1142-1154>
- Schlossberg, M., & Brown, N. (2004). Comparing Transit-Oriented Development Sites by Walkability Indicators. *Transportation Research Record: Journal of the Transportation Research Board*, 1887(1), 34–42. <https://doi.org/10.3141/1887-05>
- Searle, G., Darchen, S., & Huston, S. (2014). Positive and Negative Factors for Transit Oriented Development: Case Studies from Brisbane, Melbourne and Sydney. *Urban Policy and Research*, 32, 437–457. <https://doi.org/10.1080/08111146.2014.931280>
- Seidelsohn, K., Voss, M., & Krüger, D. (2018). Researching milieu-specific perceptions of risk, (in)security, and vulnerability—A conceptual approach for understanding the inequality and segregation nexus in urban spaces. In *Urban Book Series*. https://doi.org/10.1007/978-3-319-68606-6_21
- Sharifi, A. (2016). A critical review of selected tools for assessing community resilience. *Ecological Indicators*, 69, 629–647. <https://doi.org/10.1016/j.ecolind.2016.05.023>
- Shepherd, S. P. (2014a). A review of system dynamics models applied in transportation. *Transportmetrica B*, 2(2), 83–105. <https://doi.org/10.1080/21680566.2014.916236>
- Shepherd, S. P. (2014b). A review of system dynamics models applied in transportation. *Transportmetrica B*, 2(2), 83–105. <https://doi.org/10.1080/21680566.2014.916236>
- Simonovic. (2016). From risk management to quantitative disaster resilience - A paradigm shift. *International Journal of Safety and Security Engineering*, 6(2), 85–95. <https://doi.org/10.2495/SAFE-V6-N2-85-95>
- Simonovic, P. S., & Arunkumar, R. (2016). Comparison of static and dynamic resilience for a multipurpose reservoir operation. *Journal of the American Water Resources Association*, 52, 20. <https://doi.org/10.1111/j.1752-1688.1969.tb04897.x>

- Simonovic, S., & Ahmad, S. (2005). Computer-based model for flood evacuation emergency planning. *Natural Hazards*, 34(1), 25–51. <https://doi.org/10.1007/s11069-004-0785-x>
- Simonovic, S. P. (2015). Systems Approach to Management of Disasters – A Missed Opportunity. *Journal of Integrated Disaster Risk Management*, 5(2), 70–83. <https://doi.org/10.5595/idrim.2015.0099>
- Simonovic, S. P., & Peck, A. (2013). Dynamic Resilience to Climate Change Caused Natural Disasters in Coastal Megacities Quantification Framework. *British Journal of Environment and Climate Change*, 3(3), 378–401. <https://doi.org/10.9734/bjecc/2013/2504>
- Singh, Y. J., Fard, P., Zuidgeest, M., Brussel, M., & Maarseveen, M. van. (2014). Measuring transit oriented development: A spatial multi criteria assessment approach for the City Region Arnhem and Nijmegen. *Journal of Transport Geography*, 35, 130–143. <https://doi.org/10.1016/j.jtrangeo.2014.01.014>
- Singh, Y. J., Lukman, A., Flacke, J., Zuidgeest, M., & Van Maarseveen, M. F. A. M. (2017). Measuring TOD around transit nodes - Towards TOD policy. *Transport Policy*, 56, 96–111. <https://doi.org/10.1016/j.tranpol.2017.03.013>
- Singh, Y. J., Lukman, A., He, P., Flacke, J., Zuidgeest, M., & Maarseveen, M. Van. (2015). Planning for Transit Oriented Development (TOD) using a TOD index. *Transportation Research Board 94th Annual Meeting*, 27(15–2132), 1–20.
- Singh, Y. J., Martinez, J., Flacke, J., Flacke, J., Zuidgeest, M., & van Maarseveen, M. (2015). Planning for Transit Oriented Development (TOD) Using a TOD Index. In *GIS in Sustainable Urban Planning and Management* (Issue January). <https://doi.org/10.1201/9781315146638-15>
- Sohoni, A. V., Thomas, M., & Rao, K. V. K. (2017). Application of the concept of transit oriented development to a suburban neighborhood. *Transportation Research Procedia*, 25, 3220–3232. <https://doi.org/10.1016/j.trpro.2017.05.135>
- Staricco, L., & Vitale Brovarone, E. (2018). Promoting TOD through regional planning. A comparative analysis of two European approaches. *Journal of Transport Geography*, 66(November 2017), 45–52. <https://doi.org/10.1016/j.jtrangeo.2017.11.011>
- Su, S., Wang, Z., Li, B., & Kang, M. (2022). Deciphering the influence of TOD on metro ridership: An integrated approach of extended node-place model and interpretable machine learning with planning implications. *Journal of Transport Geography*, 104(129), 103455. <https://doi.org/10.1016/j.jtrangeo.2022.103455>
- Su, S., Zhao, C., Zhou, H., Li, B., & Kang, M. (2022). Unraveling the relative contribution of TOD structural factors to metro ridership: A novel localized modeling approach with implications on spatial planning. *Journal of Transport Geography*, 100(129), 103308. <https://doi.org/10.1016/j.jtrangeo.2022.103308>
- Swanson, J. (2003). The Dynamic Urban Model: Transport and Urban Development. *Proceedings of the 21st International Conference of the System Dynamics Society*.
- Taki, H. M., Maatouk, M. M. H., & Qurnfulah, E. M. (2017). Re-Assessing TOD index in Jakarta Metropolitan Region (JMR). *Journal of Applied Geospatial Information*, 1, 26–35.

- Taki, M. H., & Maatouk, M. M. H. (2018). Spatial Statistical Analysis for Potential Transit Oriented Development (TOD) in Jakarta Metropolitan Region. *Geoscience, Engineering, Environment, and Technology*, 3, 47–56. <https://doi.org/10.24273/jgeet.2018.3.01.1091>
- Tamakloe, R., & Hong, J. (2020). Assessing the efficiency of integrated public transit stations based on the concept of transit- oriented development. *Transportmetrica A: Transport Science*, 16, 1459–1489. <https://doi.org/10.1080/23249935.2020.1753849>
- Tamima, U., & Chouinard, L. (2016). Development of evacuation models for moderate seismic zones: A case study of Montreal. *International Journal of Disaster Risk Reduction*, 16, 167–179. <https://doi.org/10.1016/j.ijdr.2016.02.003>
- Tan, Y., Jiao, L., Shuai, C., & Shen, L. (2018). A system dynamics model for simulating urban sustainability performance: A China case study. *Journal of Cleaner Production*, 199, 1107–1115. <https://doi.org/10.1016/j.jclepro.2018.07.154>
- Tang, Y., & Huang, S. (2019a). Assessing seismic vulnerability of urban road networks by a Bayesian network approach. *Transportation Research Part D*, 02(003), 1–13. <https://doi.org/10.1016/j.trd.2019.02.003>
- Tang, Y., & Huang, S. (2019b). Assessing seismic vulnerability of urban road networks by a Bayesian network approach. *Transportation Research Part D: Transport and Environment*, xxxx, 1–13. <https://doi.org/10.1016/j.trd.2019.02.003>
- Theocharidou, M., & Giannopoulos, G. (2015). Risk assessment methodologies for critical infrastructure protection . Part II : A new approach Risk assessment methodologies for critical infrastructure protection . Part II : A new approach. In *European Commission Joint Research Centre-Institute for Protection and Security of the Citizen*. <https://doi.org/10.2788/621843>
- Tian, G., Ewing, R., Weinberger, R., Shively, K., Stinger, P., & Hamidi, S. (2017). Trip and parking generation at transit-oriented developments: a case study of Redmond TOD, Seattle region. *Transportation*, 44(5), 1235–1254. <https://doi.org/10.1007/s11116-016-9702-x>
- Tong, X., Wang, Y., Chan, E. H. W., & Zhou, Q. (2018). Correlation between transit-oriented development (TOD), land use catchment areas, and local environmental transformation. *Sustainability (Switzerland)*, 10(12). <https://doi.org/10.3390/su10124622>
- Tzeng, G.-H., & Huang, J.-J. (2011). Multiple Attribute Decision Making. In *Multiple Attribute Decision Making*. <https://doi.org/10.1201/b11032>
- Vale, D. S. (2015). Transit-oriented development, integration of land use and transport, and pedestrian accessibility: Combining node-place model with pedestrian shed ratio to evaluate and classify station areas in Lisbon. *Journal of Transport Geography*, 45, 70–80. <https://doi.org/10.1016/j.jtrangeo.2015.04.009>
- Vale, D. S., Saraiva, M., & Pereira, M. (2016). Active accessibility: A review of operational measures of walking and cycling accessibility. *Journal of Transport and Land Use*, 9, 209–235. <https://doi.org/10.5198/jtlu.2015.593>
- Vale, D. S., Viana, C. M., & Pereira, M. (2018). The extended node-place model at the local scale: Evaluating the integration of land use and transport for Lisbon’s subway network. *Journal of Transport Geography*, 69, 282–293. <https://doi.org/10.1016/j.jtrangeo.2018.05.004>

- van Lierop, D., Maat, K., & El-Geneidy, A. (2017). Talking TOD: learning about transit-oriented development in the United States, Canada, and the Netherlands. *Journal of Urbanism*, 10, 49–62. <https://doi.org/10.1080/17549175.2016.1192558>
- Waghwal, R. K., & Agnihotri, P. G. (2019). Flood risk assessment and resilience strategies for flood risk management: A case study of Surat City. *International Journal of Disaster Risk Reduction*, April, 101155. <https://doi.org/10.1016/j.ijdr.2019.101155>
- Wang, J., Tan, W., & Huang, J. (2024). Extending TOD through the interrelationship between transport and land use: A case study of Beijing. *Land Use Policy*, 144(September 2023), 107257. <https://doi.org/10.1016/j.landusepol.2024.107257>
- Wang, Y., Welch, T. F., Wu, B., Ye, X., & Ducca, F. W. (2016). Impact of transit-oriented development policy scenarios on travel demand measures of mode share, trip distance and highway usage in Maryland. *KSCE Journal of Civil Engineering*, 20(3), 1006–1016. <https://doi.org/10.1007/s12205-016-0618-y>
- Wanke, P., & Kalam Azad, M. A. (2018). Efficiency in Asian railways: a comparison between data envelopment analysis approaches. *Transportation Planning and Technology*, 41(6), 573–599. <https://doi.org/10.1080/03081060.2018.1488928>
- Wey, W. M. (2013). Smart Growth Principles Combined with Fuzzy AHP and DEA Approach to the Transit-oriented Development (TOD) Planning in Urban Transportation Systems. *Energy Technologies and Policy*, 3, 251–258.
- Wey, W. M. (2015). Smart growth and transit-oriented development planning in site selection for a new metro transit station in Taipei, Taiwan. *Habitat International*, 47, 158–168. <https://doi.org/10.1016/j.habitatint.2015.01.020>
- Wey, W. M., & Chiu, Y. H. (2013). Assessing the walkability of pedestrian environment under the transit-oriented development. *Habitat International*, 38, 106–118. <https://doi.org/10.1016/j.habitatint.2012.05.004>
- Wey, W. M., Zhang, H., & Chang, Y. J. (2016). Alternative transit-oriented development evaluation in sustainable built environment planning. *Habitat International*, 55, 109–123. <https://doi.org/10.1016/j.habitatint.2016.03.003>
- White, R., Boulton, T., & Chow, E. (2014). A computational asset vulnerability model for the strategic protection of the critical infrastructure. *International Journal of Critical Infrastructure Protection*, 7(3), 167–177. <https://doi.org/10.1016/j.ijcip.2014.06.002>
- Woodruff, S., BenDor, T. K., & Strong, A. L. (2018). Fighting the inevitable: infrastructure investment and coastal community adaptation to sea level rise. *System Dynamics Review*, 34(1–2), 48–77. <https://doi.org/10.1002/sdr.1597>
- Wu, W., & Divigalpitiya, P. (2022). Assessment of Accessibility and Activity Intensity to Identify Future Development Priority TODs in Hefei City. *Land*, 11(9). <https://doi.org/10.3390/land11091590>
- Wu, Y., Zhong, P. an, Zhang, Y., Xu, B., Ma, B., & Yan, K. (2015). Integrated flood risk assessment and zonation method: A case study in Huaihe River basin, China. *Natural Hazards*, 78(1), 635–651. <https://doi.org/10.1007/s11069-015-1737-3>

- Xia, T., Song, X., Song, X., Lu, M., Huang, S., Shibasaki, R., & Kim, K.-S. (2019). From walkability to bikeability: A GIS based analysis of integrating bike sharing service in Tokyo TOD system. *Abstracts of the ICA*, 1, 1–2. <https://doi.org/10.5194/ica-abs-1-409-2019>
- Xian, S., Yin, J., Lin, N., & Oppenheimer, M. (2018). Influence of risk factors and past events on flood resilience in coastal megacities: Comparative analysis of NYC and Shanghai. *Science of the Total Environment*, 610–611, 1251–1261. <https://doi.org/10.1016/j.scitotenv.2017.07.229>
- Yang, W., Yan, W., Chen, L., Wei, H., & Gan, S. (2024). Developing a TOD assessment model based on node–place–ecology for suburban areas of metropolitan cities: A case in Odawara. *Environment and Planning B: Urban Analytics and City Science*, 51(4), 839–853. <https://doi.org/10.1177/23998083231202880>
- Yang, X., Zheng, X., Cao, Y., Chen, H., Tang, L., & Yang, H. (2023). Connectivity analysis in pedestrian networks: A case study in Wuhan, China. *Applied Geography*, 151(December 2022), 102843. <https://doi.org/10.1016/j.apgeog.2022.102843>
- Yang, Y., Zhong, C., & Gao, Q. L. (2022). An extended node-place model for comparative studies of transit-oriented development. *Transportation Research Part D: Transport and Environment*, 113(October), 103514. <https://doi.org/10.1016/j.trd.2022.103514>
- Yap, J. B. H., & Goh, S. V. (2017). Determining the potential and requirements of transit-oriented development (TOD): The case of Malaysia. *Property Management*, 35(4), 394–413. <https://doi.org/10.1108/PM-06-2016-0030>
- Yin, J., Jing, Y., Yu, D., Ye, M., Yang, Y., & Liao, B. (2019). A vulnerability assessment of urban emergency in schools of Shanghai. *Sustainability (Switzerland)*, 11(2). <https://doi.org/10.3390/su11020349>
- Zaheer, M., Muhammad, K., Khan, A., Muzzamil, M., Khattak, H., & Faisal, M. (2024). *walking accessibility using an actual street network*.
- Zamir, K., Nasri, A., Baghaei, B., Mahapatra, S., & Zhang, L. (2014). Effects of transit-oriented development on trip generation, distribution, and mode share in Washington, D. C., and Baltimore, Maryland. *Transportation Research Record*, 2413, 45–53. <https://doi.org/10.3141/2413-05>
- Zhang, H., & Yao, Y. (2019). An Integrative Vulnerability Evaluation Model to Urban Road. *Wireless Personal Communications*, 107(1), 193–204. <https://doi.org/10.1007/s11277-019-06248-7>
- Zhang, M., & Lee, J. (2023). Make TOD More Bicycling-Friendly: An Extended Node-Place Model Incorporating a Cycling Accessibility Index. *Buildings*, 13(5). <https://doi.org/10.3390/buildings13051240>
- Zhang, M., Liu, Z., & van Dijk, M. P. (2019). Measuring urban vulnerability to climate change using an integrated approach, assessing climate risks in Beijing. *PeerJ*, 7, e7018. <https://doi.org/10.7717/peerj.7018>
- Zhang, Y., & Guo, L. (2017). *Study on coordinated relationship between urban rail transit and land-use*. 1–5. <https://doi.org/10.1109/liss.2016.7854339>

- Zhang, Y., Marshall, S., & Manley, E. (2019). Network criticality and the node-place-design model : Classifying metro station areas in Greater London. *Journal of Transport Geography*, 79, 1–10. <https://doi.org/10.1016/j.jtrangeo.2019.102485>
- Zhao, Y., Hu, S., & Zhang, M. (2024). Evaluating equitable Transit-Oriented development (TOD) via the Node-Place-People model. *Transportation Research Part A: Policy and Practice*, 185(December 2023), 104116. <https://doi.org/10.1016/j.tra.2024.104116>
- Zhu, H., Peng, J., Dai, Q., & Yang, H. (2024). Exploring the long-term threshold effects of density and diversity on metro ridership. *Transportation Research Part D: Transport and Environment*, 128(December 2023), 104101. <https://doi.org/10.1016/j.trd.2024.104101>
- Zhu, Y., Tian, D., & Yan, F. (2020). *Effectiveness of Entropy Weight Method in Decision-Making*. 2020, 1–5. <https://doi.org/10.1155/2020/3564835>
- Zhu, Z., He, Y., Guo, X., Zhang, Y., & Chen, J. (2021). Improved Huff Model for Estimating Urban Rail Transit Station Catchment Areas considering Station Choices. *Journal of Advanced Transportation*, 2021. <https://doi.org/10.1155/2021/6374724>