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Anna Ibraeva

TRANSIT-ORIENTED DEVELOPMENT

Tese no âmbito do Programa Doutoral em Planeamento do Território orientada pelo Professor Doutor António Pais Antunes, Professor Doutor Gonçalo Homem de Almeida Correia e Professora Doutora Cecília Silva e apresentada ao Departamento de Engenharia Civil da Faculdade de Ciências e Tecnologia da Universidade de Coimbra

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Anna Ibraeva

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Resumo

Esta tese de doutoramento explora o potencial do *Transit-Oriented Development (TOD)* na redução do uso do automóvel e na promoção de modos sustentáveis de transporte no longo prazo. *Transit-Oriented Development* é um conceito do planeamento urbano que implica a concentração dos principais polos de atração (governamentais, comerciais e outros) na proximidade das estações de transporte público juntamente com a densificação e diversificação dos usos de solo na área adjacente. Esta configuração pretende facilitar o acesso aos principais destinos de viagem através de modos de transporte sustentáveis ao mesmo tempo que reduz as distâncias percorridas mediante a instalação de equipamentos e serviços dentro do bairro onde os utilizadores residem. Deste modo, espera-se que as viagens mais longas sejam geralmente efetuadas por transporte público e os afazeres diários dentro do bairro sejam feitos à pé ou de bicicleta.

Esta tese é composta por quatro artigos que abordam um tópico transversal: o efeito do metro e do *TOD* no comportamento dos viajantes. Uma revisão extensiva da literatura sobre o conceito de *TOD*, os principais efeitos do *TOD* e as questões do respetivo planeamento permitiu identificar as maiores lacunas de investigação na área. Focando-se nas lacunas relacionadas com o comportamento dos viajantes e recorrendo a uma abordagem longitudinal, esta tese tem como objetivo avaliar o efeito da implementação de uma rede de metro no peso (*share*) do transporte individual nas deslocações e o modo como esse efeito potencial varia consoante o ambiente construído em torno das estações e em função do tipo das estações – *TOD, transit-adjacent development (TAD)* ou *Park & Ride*. O Metro do Porto é usado nesta tese como estudo de caso, abrangendo uma região de análise composta por sete municípios que passaram a ser servidos por metro nos anos 2002-2011.

A tese começa com uma análise ao nível da freguesia para um período de dezassete anos, e subsequentemente procede-se a uma análise mais fina ao nível da secção estatística. No início, os efeitos da implementação do metro sobre os pesos do automóvel e do autocarro – os dois principais modos na região antes do metro – são analisados ao nível da freguesia e dos pares origem-destino usando modelos beta autorregressivos. A seguir, os efeitos do metro são analisados com uma maior precisão tomando em conta as características socioeconómicas e do ambiente construído em cada freguesia usando um modelo de *difference-in-differences*. Na parte final é apresentada uma análise detalhada ao nível da secção estatística recorrendo a *first difference estimators.*

Os resultados destas análises mostram sistematicamente a importância do Metro do Porto para a redução das viagens de carro, com os efeitos do metro a propagarem-se até áreas bastante distantes. Comparativamente com as estações dos outros tipos, estes efeitos para as estações *TOD* têm a tendência de ser mais fortes em intensidade e extensão espacial, enquanto as estações *Park & Ride* revelam a menor influência sobre a redução das viagens de automóvel. Estes resultados vão no sentido da introdução de medidas *TOD* (tais como diversificação e densificação dos usos de solo e a melhoria do ambiente pedonal), e, em termos mais gerais, favorecem a prossecução de estratégias *TOD* em cidades e regiões metropolitanas.

Palavras-chave: Transit-Oriented Development, sistemas de metro, estação de metro, repartição modal, ambiente construído, efeito transbordamento, estudo longitudinal, modelos de regressão.

Abstract

The research developed in this thesis explores the long-term potential of Transit-Oriented Development (TOD) in the reduction of car use and promotion of sustainable transport modes. Transit-oriented development is an urban planning concept that implies the concentration of major facilities (governmental, commercial and others) in proximity to transit stations together with the densification and diversification of land-use in station areas. Such configuration is intended to make main destinations easily accessible by sustainable transport modes, and at the same time reducing trip distances by providing amenities and services within the neighborhood. Thus, it is expected that longer trips would be regularly made by public transport and daily errands within the neighborhood by walk or bicycle.

Four articles are compiled in this thesis addressing the same transversal topic: the effect of metro and TOD on travel behavior. An extensive literature overview that covers the concept of TOD, major TOD effects and TOD planning issues allowed the identification of main research gaps existing in the field. Focusing on the gaps related to TOD and travel behavior, this thesis aims to evaluate using a longitudinal approach whether and to what extent metro implementation affects the shares of car trips and how these potential effects may vary depending on different station environments. As such, the effects from commonly identified station types like transit-adjacent development (TAD) or Park & Ride are also assessed, framed in a broad network-wide analysis. The Metro do Porto light-rail transit system is used in this thesis as a case study involving an area of analysis comprised by seven municipalities that received this metro service in 2002 – 2011.

The thesis starts from the civil parish level of analysis covering a large time interval (seventeen years), subsequently narrowing down to the census tract level. At first, the effects of metro implementation on the shares of car and bus trips – the two main modes in the region before metro – are analyzed at a parish level and at an origin-destination pair level using beta autoregressive models. Then, the effects on metro are analyzed with greater detail accounting for the built environment and socio-demographic characteristics of each parish using a difference-in-differences approach. Finally, a fine-grained analysis at the census tract level is performed exploring the importance of station proximity on the number of car trips using first difference estimators.

The results of the analyses consistently demonstrate the importance of the Metro do Porto system for car trips reduction, with metro effects propagating to rather distant areas. Overall, for TOD stations this effect tends to be larger in magnitude and spatial extent than for other station types, with Park & Ride stations having the weakest influence on car trip reduction. These findings provide support for the application of TOD-inspired measures in station areas (like mixed land use, densification or pedestrian-friendly environment) and, in a more general context, motivate to pursue TOD strategies in the cities and metropolitan regions.

Keywords: Transit-Oriented Development, metro systems, station areas, mode shares, built environment, spillover effects, longitudinal research, regression models.

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List of acronyms

Abbreviation	Definition
AHP	Analytic Hierarchy Process
APTA	American Public Transportation Association
BRT	Bus Rapid Transit
CAOP	Carta Administrativa Oficial de Portugal
CBD	Central Business District
CLPM	Cross-lagged Panel Model
DID	Difference-in-Differences Model
FAR	Floor Area Ratio
FE	Fixed-Effects
INE	Instituto Nacional de Estatística
LRT	Light Rail Transit
MCDA	Multi-criteria Decision Analysis
MdP	Metro do Porto
MNL	Multinomial logistic regression
OD	Origin-Destination
OLS	Ordinary least squares
OSM	Open Street Map
P&R	Park&Ride
PMA	Porto Metropolitan Area
PTAL	Public Transport Accessibility Level
R+P	Rail and Property Mechanism
RLM	Robust Lagrange Multiplier
SAR	Spatial autoregressive model
SDID	Spatial Difference-in-Differences Model
SEM	Spatial Error Model
SMCA	Spatial Multi-Criteria Analysis
SUTVA	Stable Unit Treatment Value Assumption
TAD	Transit-adjacent Development
TOD	Transit-oriented Development
VMT	Vehicle miles of travel

1. INTRODUCTION

This introductory chapter is intended to outline main research topic of this thesis. For the purpose, it is divided into four sections. In the first section, the research framework of the thesis is provided to broadly contextualize the concept of Transit-Oriented Development. In the second section, main thesis objective is stated and main research questions are specified. The third section describes the thesis structure. Finally, the fourth section presents the research dissemination approach and results.

1.1. Research Framework

Ever since massive motorization growth made urban sprawl possible, highlighting the intrinsic relationship between the spatial organization of urban settlements and their transport infrastructure, the creation of more sustainable forms of urban living became a critical concern for planners and local authorities, stimulating research on land use and transport interaction. Comparing mobility patterns in compact dense areas with sufficient transit supply versus in sparse and automobile-dependent areas, several early findings reported generally more sustainable mobility patters in the former case (Newman and Hogan, 1987; Newman and Kenworthy, 1989; Cervero, 1995; Newman and Kenworthy, 1996). The concept of Transit-Oriented Development (TOD) emerged in this context (Calthorpe, 1993).

Inspired by classic urban planning concepts like the Garden City and the Linear City, TOD proposes to organize settlements around public transport nodes as centers of urban life and in a certain way reverse cities back to public transport. Facilitating access to transport terminals by sustainable transport modes, densification of immediate station areas and diversification of their functional composition appear to be main elements that ensure successful implementation of a TOD project. Applying these measures to the whole transport network should balance the distribution of transport supply and urban facilities in the whole city as the concentration of activities would be centered around transit. Within each TOD local commerce, service and employment opportunities are expected to reduce the need for long-distance trips and local trips would be primarily made by sustainable transport modes due to pedestrian friendly-design, traffic calming measures and parking limitations. Intra-urban trips between different TODs would be secured by fast and reliable transit.

However, as TOD projects started to surge around the world, it became evident that TOD performance depends on a wide variety of factors such as the socio-demographic composition of a neighborhood, habits and long-established preferences of the residents, regional accessibility, and others. The variability of TOD outcomes reflects the complex and multi-faceted nature of contemporary urban agglomerations, providing a challenging field of research. In the context of increasing levels of urbanization worldwide and major infrastructure investments like the Grand Paris Project in France or the Moscow Central Circle in Russia, this is a highly relevant topic.

Although TOD is a promising concept for urban planning, several obstacles to its implementation may arise. Because of leapfrog development, greatly facilitated by highway networks and car availability, peripheral areas of many modern cities are characterized by scattered low-rise suburbs where implementation of a rapid transit line may not be financially viable and where simultaneously the demand for high-rise and dense development is low, therefore potential TOD introduction is compromised. Quite commonly these suburban areas are provided with a Park&Ride stations in an attempt to incline local population, normally car drivers, to make at least part of their journey by a sustainable transport mode. Park & Ride facilities are intended to reduce congestion in the areas of high travel demand by providing parking lots at stations where drivers can leave their cars for little or no cost and make the rest of the trip by transit. Therefore, for the drivers these facilities might allow to reduce travel time and costs (including vehicle maintenance or vehicle deprecation costs), for transit providers Park&Ride have the potential to increase ridership levels, and the overall benefits for the society include potential decrease in the levels of congestion, pollution, energy consumption and parking demand in urban centers (Noel, 1988). In practice, however, there are certain concerns regarding Park&Ride stations, for example, the risk that Park&Ride might be underused if the advantages of using it are not so obvious to the drivers (Karamychev and Van Reeven, 2011; Bos et al., 2004), might increase and/or redirect traffic to other places (Parkhurst, 1995; Parkhurst, 2000) and/or incline people who would otherwise walk, cycle or go by bus to drive to the station (Parkhurst, 1995; Dijk and Parkhurst, 2014). Nevertheless, Park&Ride stations are rather common in most modern transit networks.

Sometimes locating stations in the middle of a consolidated urban area and developing a TOD might be compromised by existing regulations or other obstacles like expensive right-of-way. In these cases, transit-adjacent development (or TAD) stations can be identified in the network as stations located in proximity to urban settlements, but poorly articulated with them and lacking favorable access conditions (sidewalks, lighting, security, etc.). These stations often appear in low-density suburbs with segregated land-uses, surface parking lots, automobile-oriented facilities like car dealerships, motor vehicle services, etc. (Renne, 2009). With dedicated policies aimed at densification, land use mix and pedestrian-friendly environment these stations have the potential to become TODs in the future, and this scenario, especially in cities with growing population numbers, appears to be a rather natural evolution. Otherwise, TADs may demonstrate the effect of transit improvement when very little effort was made to increase the attractiveness of a station area.

In the end, the resulting transit network is often a compilation of different station areas, some being TOD, others TAD or Park&Ride, however, they all pursue the same goal of maximizing ridership in a specific setting. Given the complexity of modern cities, it is essential to evaluate and compare the performance of different station types and identify factors that affect this performance.

1.2. Thesis Objective

The main objective of this thesis is to identify and evaluate the outcomes of LRT metro implementation on mode choice and determine whether and how these outcomes vary depending on different station types and station environments using longitudinal research design. The choice of the objective was based on an extensive analysis of the available literature dedicated to TOD influence on mode choice and successive identification of existing research gaps.

The introduction of Metro do Porto light-rail transit system, a relatively recent large-scale infrastructure project, is used in this thesis as a case study. There are several reasons for this choice: first, detailed data for pre-metro and post-metro periods were available, allowing to perform before/after analyses; second, Metro do Porto serves a very heterogeneous territory, providing an excellent opportunity to study the impacts of different station types introduced in various settings (urban, suburban, rural); third, little is known about TOD interventions in Southern Europe, so using Metro do Porto as a case study could enrich existing evidence.

To achieve this general objective, three specific research questions were defined as follows:

1. On a macro scale, what was the influence of metro introduction and different station environments over time on the mode share (namely, the shares of car and bus trips) considering trip generation and trip distribution?
2. On a macro scale, how did the metro implementation affect the number of car trips over the years?
3. How did the influence of metro on the number of car trips manifest on a micro scale and what was the magnitude of the spillover effect for different station types over a ten-year period?

To answer the first question, in the third chapter a series of autoregressive models is developed for trip generation (at a parish level) and trip distribution (at an origin-destination pair level) using as dependent variables the share of car trips and the share of bus trips. Since, before metro, car and bus were the main transport modes in thestudy area, this approach allows to understand whether and to what extent these two modes were affected by the new metro service. The influence of metro on the shares of car and bus trips for OD pairs with metro at both ends, at only one end, and no metro service is analyzed. Besides, having information about station environments at different trip ends allows to evaluate the influence of TOD stations at both trip ends on the respective shares.

To answer the second question, in the fourth chapter a spatial difference-in-differences model is applied to evaluate the changes in the number of car trips associated with metro implementation at a parish level. Using Census data allows to control for potentially important socio-demographic variables, as well as built environment characteristics such as building density and land use mix. Since metro users were reported not only in the directly served parishes, but also in the adjacent ones, the model accounts for metro spillover effects. Furthermore, the model also accounts for the predominant station type in each parish and assess the corresponding spillover effects.

To answer the third question, in the fifth chapter the results of an aggregated-level analysis (at a parish level) are complemented with a disaggregated analysis at a census tract level. Using detailed data allows to properly distinguish between the effects of different station types and compare the respective spillover effects, while still controlling for socio-demographics and built environment characteristics.

While these questions to a certain degree have already been addressed in the literature, this thesis contributes to the existing research findings providing new insights through a longitudinal approach that allows to control for travel behavior patterns in the pre-metro period and to separate them from the metro effect. Since metro did not exist in the study area before 2002, the selected case study can be considered a natural experiment, providing a rare opportunity to analyze travel behavior before and after metro implementation. Given the longitudinal and experimental nature of this research, it is expected that the demonstrated results will provide strong and reliable evidence on the possible outcomes of metro implementation as well as different station types. These findings could guide the practitioners involved in spatial/transport planning and reinforce further research in the field.

1.3. Thesis Structure

This thesis is divided into six chapters. Following this introduction, Chapter II aims to illustrate the current state of the art in TOD research, providing a broad comprehensive analysis of the existing findings and highlighting the main research directions. Starting from the concept of TOD and its relation to other urban planning concepts such as the Garden City or the Linear City, the chapter then covers two major topics that make up a substantial part of TOD-related literature: TOD effects and TOD planning. In the first case, TOD effects on travel behavior, real estate prices, residential location choices, urban form and community life are considered. In the second case, focus is on the issues of planning policy (including policy transferability, stakeholders' perspectives, implementation problems and solutions and value capture mechanisms) and planning decision support tools. Eventually, this broad analysis allows to identify major research gaps regarding TOD effects and TOD planning, some of which are addressed in the following chapters.

Chapter III is an attempt to evaluate the impact of a Metro do Porto LRT on the share of car and bus trips applying a longitudinal research approach to two distinct types of analyses: trip generation and trip distribution. In the first case, the analysis addresses changes in the shares of car and bus trips reported by the parishes of the metro-served area. In the second case, changes in the shares of car and bus trips that occurred on major origin-destination pairs are examined. First, the descriptive statistics and visual analysis of trip generation are provided, then the same techniques are applied to trip distribution analysis. Afterwards, a series of autoregressive models for both trip generation and distribution is developed, followed by the discussion of the obtained results.

In Chapter IV, the effect of metro implementation on the number of car trips between 2001 and 2011 is analyzed, using the spatial difference-in-differences approach that is specifically appropriate for a before/after analysis and allows to control for spatial spillover effects. Starting from the general characterization of the study area and the evolution of car trips over the years (1991-2011), the chapter subsequently provides the model formulation, followed by a section dedicated to results where special attention is given to the evaluation of changes in parishes with different predominant station types (TOD, TAD or Park & Ride).

In Chapter V, macro and micro-level analyses of changes in the number of car trips between 2001 and 2011 are developed. First, the motivation for the research is provided, and followed by a description of the methodological approaches used at each level of analysis. In the results section, the macro-level model estimations are reported first, then the outputs from a more detailed section-level model are presented. The latter are divided into two subsections: in the first one, overall metro proximity is analyzed, whilst in the second one the proximity to different station types (TOD, TAD or Park&Ride) is evaluated.

In Chapter VI the findings are summarized and some concluding remarks are provided. Also, several limitations of this study are reported and potential directions for future research are discussed.

1.4. Research Dissemination

The dissemination of the results reported in the present thesis consisted essentially in journal articles (each chapter of this thesis is a research article published or under revision in the academic journals) and conference presentations. This dissemination strategy allowed to raise awareness on the subject, inform professionals, researchers, students, and general public, promote further interest in the field and gather valuable feedbacks from different audiences that eventually helped to improve the contents of this thesis. The articles and presentations are listed below.

Published journal articles

Ibraeva, A., de Almeida Correia, G. H., Silva, C., Antunes, A. P., 2022. Mobility impacts of a new metro system with transit-oriented development features. Transportation Research Part D: Transport and Environment, 109, 103357, DOI: 10.1016/j.trd.2022.103357.

Ibraeva, A., Van Wee, B., de Almeida Correia, G. H., Antunes, A. P., 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, 103036, DOI: 10.1016/j.jtrangeo.2021.103036.

Ibraeva, A., de Almeida Correia, G. H., Silva, C., Antunes, A. P., 2020. Transit-oriented development: A review of research achievements and challenges. Transportation Research Part A: Policy and Practice, 132, 110 – 130, DOI: 10.1016/j.tra.2019.10.018.

Journal articles under evaluation

“Impacts of Transit-Oriented Development upon car use over a 10-year period in Porto, Portugal: from macro- to micro-analysis”.

Conference presentations

- "Post-Metro Mode Choice Changes: from Macro- to Micro-Analysis", European Colloquium on Theoretical and Quantitative Geography (ECTQG2021), 2021, Manchester, UK

- “Changes in car use resulting from a TOD-type project: longitudinal macro-analysis of the case of Metro do Porto (Portugal)”, 24th EURO Working Group on Transportation Meeting, EWGT 2021, Aveiro, Portugal
- “TOD research achievements, planning tools, and challenges”, TRB Webinar: Retrospective, Perspective, & Prospective of Transit-Oriented Development, 2021.
- “Macro-analysis of mobility transitions over a 10-year period with the introduction of the light-rail system in the Oporto Metropolitan Area”, Third “accessibility and connectivity” UERA Thematic Working Group workshop, 2019, Munich, Germany.
- “The Transit-Oriented Development Urban Planning Concept: Achievements and Research Gaps”, PLURIS 2018 - 8º CONGRESSO LUSO-BRASILEIRO para o Planeamento Urbano, Regional, Integrado e Sustentável, 2018, Coimbra, Portugal.

Participation in lectures/workshops

- "Trip generation, distribution and mode choice impacts of a new metro system with TOD features: A beta regression analysis of 2000 and 2017 mobility surveys' data for Porto (Portugal)", WaveLab Networking Seminar (University of Bergamo), 2021, Bergamo, Italy
- “Transit-Oriented development (TOD) research”, University of Coimbra, 2021, Coimbra, Portugal
- “Transit-oriented development”, University of Porto, 2018, Portugal

2. TRANSIT-ORIENTED DEVELOPMENT: A REVIEW OF RESEARCH ACHIEVEMENTS AND CHALLENGES*

The present chapter aims to provide a broad and systematized literature review of major research topics related to TOD. Besides reporting main research outcomes and commonly used methodological approaches this chapter intends to identify main research gaps and discuss future research directions.

Among the attempts made worldwide to foster urban and transport sustainability, transit-oriented development (TOD) certainly is one of the most successful. Since the TOD concept appeared in the late 1980s, it has received increasing attention from researchers and practitioners as a way to merge together transport engineering and planning, land-use planning, and urban design for providing comprehensive solutions to contemporary urban problems. This attention has notably led to the publication of over 300 articles explicitly concerned with TOD in Web of Science journals, as well as to many implementations of the concept, some already completed and others underway (as, for example, the Grand Paris Project in France and Moscow Central Circle in Russia). Essentially, TOD can be described as land-use and transport planning that makes sustainable transport modes convenient and desirable, and that maximizes the efficiency of transport services by concentrating urban development around transit stations. However, as TOD projects started to be implemented worldwide, it became evident that their outcomes could be quite diverse, revealing that in practice the results of a project would depend on a wide variety of factors, trends and complex interrelations between them. In this chapter, we aim to provide a comprehensive, systematic and up-to-date review of TOD research achievements and challenges. We start by presenting the TOD concept, framing it in the theory of urban planning, and by describing the different typologies of TOD proposed in the literature. Then, we review the vast research dedicated to the study of TOD effects, distinguishing impacts on travel behavior, real-estate prices, residential location, urban form, and community life. The next subject we look at is TOD planning, focusing separately on policy issues and decision-support tools. In the final part of the chapter, based on the analysis of previous literature, we identify the main gaps and challenges that TOD research needs to address in the future.

2.1. Introduction

Achieving sustainable development is one of the major goals of urban policies. Since transport is an essential part of cities' activity, many attempts have been made to foster the use of sustainable transport modes, including (public) transit, which have not been entirely successful. In this context, exploring transit-oriented development (TOD) appears to be promising: even though

* This chapter - with slight adaptations - corresponds to the article: Ibraeva, A., de Almeida Correia, G. H., Silva, C., Antunes, A. P., 2020. Transit-oriented development: A review of research achievements and challenges. Transportation Research Part A: Policy and Practice, 132, 110 – 130.

several of its principles had been applied in the early post-war years in Denmark and Sweden, the very idea of TOD only became conceptualized in the late 1980s, making it a relatively new notion in urban planning. Inspired by classic concepts like the Garden City and the Linear City, TOD proposes to organize settlements around transit nodes as centers of urban life and in a certain way reverse our cities back to transit after the post-war decline (for example, in the United States the number of unlinked trips by bus and surface rail decreased by 3 to 9 times in the years 1946-1974, remaining steadily low after that; see APTA, 2018). Facilitating access to sustainable transport and transit stations, densification of immediate station areas and diversification of the functional composition of these areas appear to be critical elements of the successful implementation of a TOD project. However, as TOD projects started to surge around the world, it became evident that their performance depends on a wide variety of factors such as the socio-economic level of a neighborhood, habits and long-established preferences of residents, and regional accessibility conditions. Therefore, TOD performance reflects the complex and multi-faceted nature of contemporary urban agglomerations, providing a challenging field of research. In the context of increasing levels of urbanization worldwide and major infrastructure investments like the Grand Paris Project in France or the Moscow Central Circle in Russia, this is a highly relevant topic.

Since the 1990s, accompanying the emergence of TOD projects worldwide, the number of journal articles dedicated to this subject has been progressively growing (Figure 2.1). Analyzing the 330 articles registered in the Web of Science until the end of 2018 (using the search phrase "transit-oriented development" and considering only the journal categories "transportation", "urban studies", "transportation science and technology", "development studies" and "regional urban planning"), it is evident that the vast majority of research on the subject of TOD originates from the United States, in particular from the University Systems of California, Minnesota, and Texas. In Europe, TOD research is mostly present in Dutch universities, especially in the University of Amsterdam and in the Delft University of Technology. In addition to this, there is also a growing interest in TOD in the Asia-Pacific region, notably in Beijing University and in the Universities of Hong Kong, Melbourne, and Queensland. Overall, it is clear that, despite the unquestionable preponderance of the United States on this matter, TOD-related studies are becoming internationally widespread.

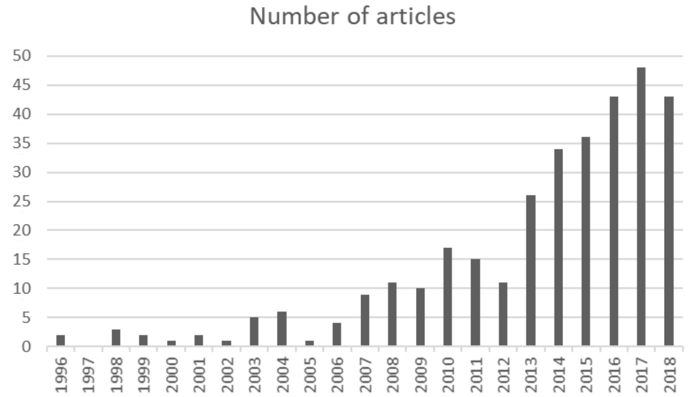

Figure 2.1 – Number of articles on TOD registered in the Web of Science*

In this context, we found opportune to perform a comprehensive, systematic and up-to-date review of TOD research achievements and challenges. Despite several articles offer related reviews (Ewing and Cervero, 2001; Hess and Lombardi, 2004; Ewing and Cervero, 2011), they tend to be more specific than we are with respect to thematic and/or geographic scope, and do not cover the considerable efforts developed to explore TOD in recent years.

Two essential directions are pursued in this chapter. First, we present and discuss what we believe to be the main research results achieved since the TOD concept was introduced. For this, we have performed an in-depth analysis of the literature listed on the main bibliographic databases (Web of Science, Scopus, and Google Scholar), providing special attention to the most impactful articles according to the total and the annual average number of citations they received so far. Second, based on the opinions of the many authors who have written on the subject and on our own analysis, we try to identify the main gaps in the literature, as well as the ensuing research challenges (and opportunities).

The remainder of the chapter is structured in five sections. The first of these sections focuses on the definition(s) of the TOD concept, on its connections with previous urban planning concepts, and on its best-known early implementations. Then, we look into the efforts that have been made to establish TOD typologies capturing the main dimensions of the concept. The next section deals with the existing knowledge on TOD effects considering five different (but not completely independent) domains: travel behavior, real-estate prices, residential location, urban form, and community life. This is followed by the identification of policy issues raised by TOD planning and a discussion of advanced tools specifically designed to support planning decisions. Our views on TOD research gaps, challenges and opportunities appear afterward. The last section briefly concludes the chapter.

* Recent query to the Web of Science database confirms the growing number of articles as follows: total of 58 articles in 2018, 68 articles in 2019, 90 articles in 2020.

2.2. TOD Concept(s)

In the 1980s, observing the shortcomings of suburban gridlock and car-oriented developments, urban planners and researchers started to look for alternatives, getting inspired by traditional neighborhood design, new urbanism and successful developments around transit stations. As noted by Cervero and Kockelman (1997), the main objectives of the research agenda at that time were: reduction of motorized trips and especially solo-driving; shortening of motorized trip length; and increase of non-motorized trips like cycling and walking.

The concept of TOD was then introduced by architect and urban planner Peter Calthorpe, who, in his book The Next American Metropolis, urged for planning for pedestrians and transit, "not to eliminate the car, but to balance it" (Calthorpe, 1993). His ideas were closely associated with the notion of "pedestrian pocket" (a neighborhood layout which facilitates walking trips, offering a variety of available routes and shortening travel times for pedestrians) introduced a few years earlier. In that book, Calthorpe specifically defined TOD as a "mixed-use community within average 2000-foot [AN: 600 meters] walking distance of a transit stop and core commercial area. TODs mix residential, retail, office, open space, and public uses in a walkable environment, making it convenient for residents and employees to travel by transit, bicycle, foot, or car". Major commercial and employment areas should be located in close proximity to a station ("primary area"), and nearby public space should ensure neighborhood vitality. A residential zone should be developed in the remaining area, with densities gradually decreasing (yet remaining in the range of 25-62 units per hectare, depending on the surroundings). Additionally, a "secondary area" related to TOD might appear at the maximum distance of 1.6 kilometers from the core zone, where low-density housing, vast park areas, schools and other facilities for local community could be placed. The street network of this outer area should secure easy, fast and direct access to the core, especially by bicycle, and provide park-and-ride lots. By contrast to the secondary area, which could have larger building blocks and lots, constructions in the primary area should ideally occupy less surface, thus allowing for higher street connectivity. Having a variety of available routes, users are expected to choose local streets for their short displacements, instead of using arterial axes. The initial version of the concept focused mostly on neighborhood organization, yet later the importance of TOD on a larger regional scale was emphasized, mixing issues of local neighborhood arrangement with more ambitious public transport strategies.

The idea of TOD was clearly inspired by previous urban planning concepts, notably the Garden City. In his famous Three Magnets Diagram, Ebenezer Howard attempted to reconcile rural countryside and a city by proposing town-country features, mixing the environmental quality and comfort of a rural area with the opportunities and income levels of a city (Howard, 1902; Hall and Tewdwr-Jones, 2011). Similarly, TOD is an effort to infuse a suburb with elements of a city core, supposedly making an area less busy, congested and chaotic than the downtown, yet still vivid and functional. Furthermore, both concepts promote dense, compact and walking-scale settlements. However, there are certain differences between the two concepts with regard to the spatial arrangement of a settlement. Firstly, the location of major employment sites in the Garden City is at the edge of the agglomeration while in TOD employment is concentrated in the central area. Such difference stems from the fact that, when the Garden City concept was proposed, a large number of people was working for heavy industries, which should be isolated from residential areas. Currently, the tertiary sector has assumed primary importance, whereas heavy industries almost disappeared in many cities of the developed world and their location is not considered in TOD. Secondly, life in the Garden City was organized around the main square (which also hosted health, administration and cultural venues) with radial boulevards originating from it, while the center of TOD is a transit station, revealing the major importance ascribed to the transport infrastructure.

Interestingly, the idea of organizing urban settlements adjacent to transport infrastructure remits to another planning concept: the Linear City, elaborated by Arturo Soria y Mata in a series of articles published in 1882. Acknowledging transport as a major challenge for urban planning, Soria y Mata suggested arranging urban settlements along a public transport corridor, tramway or railway, thus achieving a linear form of urbanization instead of the traditional radiocentric city layout (Boileau, 1959; Hall and Tewdwr-Jones, 2011). Rectangular shaped buildings had to guarantee comfortable circulation with easy access to the central avenue. On a wider scale, the Linear City would serve as a link between two larger cities, complementing a transport corridor and concentrating urban growth next to it, what clearly resonates with the TOD concept.

As industrialization and first systems of mass transit were expanding in traditional compact cities, cars were still unaffordable to the majority of people. Public transport service was essential for the community, and linear urbanization patterns along tramways or railways were introduced in many cities: Ciudad Lineal in Madrid, streetcar suburbs in the USA, Stalingrad, and Magnitogorsk in the Soviet Union, etc. In contrast, later on, with the proliferation of private cars, scattered forms of settlement became fairly widespread since the 1960s. Functional segregation was common for these settlements, creating residential neighborhoods and retail or business centers as clusters, interconnected by roads.

Notwithstanding, several cities managed to partially divert from these trends despite the prevailing diffusion of car-oriented developments elsewhere. For example, in Copenhagen, urban growth concentrated mostly along rail corridors in the absence of better alternatives for commuting as massive motorization had not occurred yet. In these circumstances, locating new settlements in proximity to a rail line was considered a very suitable solution (Knowles, 2012). In Stockholm, rail-based urbanization was facilitated and supported by the city council, which managed to acquire land around the city, giving the authorities the freedom to decide upon the organization of new satellite towns (Cervero, 1995). In both cases, functional mix was incorporated in the plans: in Copenhagen, businesses were allowed to settle at a maximum distance of one kilometer away from rail stations, and stations received park-and-ride facilities; in Stockholm’s new towns, the number of companies had to be proportional to the number of residents and, at the same time, main points of attraction like shopping centers have been located near rail stations. Furthermore, an influential study by Newman and Kenworthy (1996) identified several cities which have been successful at directing their development towards public transport. Overall, the initiatives which allowed for a reduction in car use involved the implementation of parking restrictions (in cities such as Freiburg, Toronto and Zurich), the expansion of the public transport network (Freiburg, Portland, Toronto, Vancouver and Zurich), the limitation of land available for development (Freiburg and Portland), and the revitalization and infill of the inner city (Portland, Toronto and Vancouver). Eventually, these sporadic examples of coordinated land-use and transport policies served as empirical evidence for the shaping of TOD principles.

To sum up, broadly, the concept of TOD may be defined as "careful coordination of urban structure around the public transport network" (Hickman and Hall, 2008). More detailed definitions introduce soft modes: "TOD can be described as land-use and transportation planning that makes cycling, walking, and transit use convenient and desirable, and that maximizes the efficiency of existing public transit services by focusing development around public stations, stops, and exchanges" (Thomas and Bertolini, 2015). In contrast to these definitions, which highlight the primary importance of transit for local neighborhoods, TAD (transit-adjacent development) is defined as a development which "lacks any functional connectivity to transit, whether in terms of land-use composition, means of station access, or site design" (Cervero et al. 2002). Besides, some definitions highlight the regional importance of TOD, describing it as "an approach to station area projects which reaches further than single-locations, and aims at the re-centering of entire urban regions around transport by rail and away from the car" (Bertolini et al. 2012). As noted by Ewing and Cervero (2001), compact and dense developments would produce only minor effects on travel behavior if they were not properly incorporated into a wider regional transport network. Behind these theoretical considerations stands the assumption that by planning accurately and accounting for the effects of land-use and spatial organization on people's behavior and choices, one can shape travel demand.

2.3. TOD Typologies

Various authors have attempted to classify TODs according to various features of stations and adjacent areas. Typically, the criteria for evaluation of a station area involve density, diversity, and design, the 3Ds identified by Cervero and Kockelman (1997) as the main features of a TOD. Based on indicators that reflect the relative importance of these components, the resulting typologies contribute to a better understanding of how the concept is implemented. Furthermore, they are useful to support TOD planning processes, as grouping stations allows to diagnose common problems and design targeted policies for specific station types (see Section 5).

Probably, the best-known approach leading to a TOD typology is the node-place approach (or "model"), developed by Bertolini (1996; 1999). The approach basically translates into an XY-diagram, where the Y-axis represents the accessibility of a node (the "node-index", describing the variety and frequency of transit supply) and the X-axis the characteristics of a place (the "place-index", describing the functional mix of the station area). The stations are positioned on the diagram depending on their performance on both indexes. Balanced stations with reasonable transit supply and land-use diversity around stations will appear in the middle of the diagram (with approximately 0.5 for both indexes), while stressed stations with considerable passenger flow and extremely intense use of adjacent area will be placed near the upper right corner (where both indexes achieve the maximum value of 1). Applying the node-place model to Amsterdam and Utrecht, Bertolini (1999) concluded that most stations are relatively balanced, except Amsterdam Sloterdijk (low place-index) and Amsterdam and Utrecht Central Stations (both stressed stations). Thus, the node-place approach provides a means to simultaneously evaluate the transport supply and land-use characteristics of a site, and since these two elements are fundamental for the TOD concept, various studies used it as a basis for the classification of TOD, either with or without modifications (Reusser et al., 2008; Monajem and Nosratian, 2015; Chen and Lin, 2015; Groenendijk et al. 2018).

An extension of the node-place model was suggested by Vale (2015), who concentrated on the walkability and pedestrian comfort of the station areas by adding a pedestrian shed ratio, measured as the proportion of walkable area inside a 700-meter buffer from a station. Based on the node-place indexes and the pedestrian shed ratio, transit terminals in the Lisbon Metropolitan Area were classified into seven clusters. Transit supply was found to be limited for a significant part of the analyzed stations. Simultaneously, the pedestrian comfort measure represented a considerable improvement in the evaluation of the station areas as some stations qualified as "balanced" by the original model were not pedestrian-friendly, suggesting that these are more likely to be TAD than TOD.

Among the studies where modifications were proposed, we highlight the attempt made by Lyu et al. (2016) to incorporate design characteristics in the node-place approach. These authors suggested classifying metro stations in Beijing using a set of indicators that correspond to the three dimensions hidden behind the acronym TOD: "transit", "oriented" and (urban) "development". The "oriented" dimension included indicators like average block size, the average distance from a station to jobs/residences, and intersection density, among others. This approach allowed to group stations that lacked transit elements (like high transit frequency), "oriented" elements or development elements (like mixed uses and high density). Using this typology, Beijing metro stations were grouped into six clusters. As might be expected, stations located in the city core were highly ranked on all criteria, while distant peripheral stations did not score much, however, for the stations located in-between these two extremes, the typology managed to produce quite sophisticated results, accounting for nuances between different stations (like the degree of walkability or the diversity of station areas).

A different perspective on a TOD typology was proposed by Singh et al. (2014), who, focusing on urban agglomerations as a whole, classified TOD according to their actual TOD index and their potential TOD index. The first index is meant to assess existing TOD levels in locations already served by transit, whereas the second one aims to identify sites with already high levels of TOD (in terms of the built environment, density, etc.) but lacking the "transit" element. The approach was tested on the Arnhem Nijmegen City Region (in the Netherlands), and the authors focused on the potential TOD index, identifying appropriate sites for future TOD based on the levels of 3Ds and economic activity (number of business establishments). A grid cell of 300×300 meters was selected as unit of analysis and potential TOD index values (from 0 to 100) were obtained using spatial multi-criteria analysis (SMCA). For the selected area, the highest value of a potential TOD index reached only 60 points, meaning that the demand for TOD in the region might not be very strong. The majority of sites with high scores were found in proximity to urban areas.

Motivated by the fact that available TOD typologies were rarely validated against station's actual performance (in terms of ridership level, mode choice, auto ownership, etc.), Kamruzzaman et al. (2014) proposed a TOD classification and tested whether it reflected the travel behavior observed at the stations. Six indicators were used: public transport accessibility level (PTAL), net residential density, net employment density, land use mix, intersection density, and cul-de-sac density. Cluster analysis disclosed four types of station sites in Brisbane: residential TOD (high PTAL and intersection density, average land use mix), activity center TOD (high diversity level, high PTAL and net employment density), potential TOD (modest density levels, low PTAL), non-TOD areas (lacking both the transport and built environment features of a TOD). Subsequent validation of the typology confirmed higher probabilities of using transit in residential TODs. Curiously, the authors noted certain irregularity in the spatial distribution of TOD in the urban areas (some activity center TOD were located in the center but others were located in the periphery), arguing that such pattern invalidates geographical classifications based on TOD location in a city (central TOD vs suburban TOD for example).

A similar logic was adopted by Higgins and Kanaroglou (2016) who developed a TOD typology for the Toronto region and evaluated the performance of station types in terms of the modal split. Latent class analysis was applied to heavy rail, light rail, and bus rapid transit stations (existing and planned) and resulted in 10 different station types. The typology was based mostly on 3Ds criteria, but also included a destination accessibility measure accounting for employment and residential sites within a 10-minute walk from stations and for the travel times between stations. As opposed to the aforementioned case of Brisbane, in Toronto, stations with high TOD levels were concentrated in the city core, while stations in the outskirts could hardly be classified as TODs. Transit appeared as the preferred mode for traveling to work in the inner urban neighborhoods, except for residents of TOD located in central commercial areas who preferred to walk. The socio-demographic structure of central TOD was found to be quite specific, largely composed of young professionals and single-member households.

A different approach was used in a recent work by Huang et al. (2018) where station typology aims to reveal different roles of TOD in order to assess the relationship between them. As argued by the authors, differences between TOD are essential in order to achieve synergistic effects which appear once places differ from each other or provide access to different goods/services but still share the same geographical market. Using latent class cluster analysis and correspondence analysis for the case of the Arnhem Nijmegen City Region, the authors based the analysis on the following variables: population density, job density, business density, land-use diversity, mixed-ness of land uses, intersection density and length of bicycle and pedestrian networks. Results provided three types of TODs: urban mixed-core, urban residential and suburban residential. Probably, only three categories were distinguished because the network was relatively small and dominated by two central stations.

2.4. TOD Effects

A very substantial amount of research effort has already been devoted to estimating the impacts of TOD effects. Based on a detailed assessment of the literature, we have classified this research into five areas according to the types of effects, highlighting the most studied areas (size of squares) and the direction and intensity of the interactions between them (orientation and width of arrow lines) (Figure 2.2). The effects on travel behavior are the most studied (especially mode choice as could be expected, but also trip generation and parking), followed by the effects on real-estate prices in and around TOD areas. Other effects, less studied, are the ones concerning residential location (in both directions, i.e., effects of travel behavior on peoples' choice of where to live as well as the converse), urban form (i.e., effects on land use and on the spatial distribution and accessibility of activities) and community life. These various types of effects are addressed below in separate subsections.

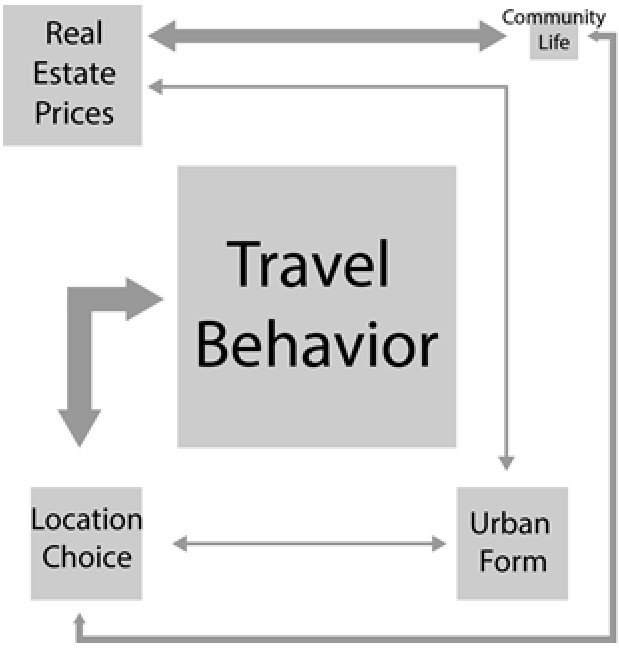

Figure 2.2 – Areas of study of TOD effects

2.4.1. Travel Behavior Effects

Amongst the articles dedicated to the effects of TOD, the ones dealing with travel behavior are certainly the most frequent. For this section, we selected articles that, besides being recurrently cited, may also complement each other, and provide an ample overview of research results on the matter. These articles are listed in Table 2.1. In this table, we specify the methodology adopted in each article and the case study to which it was applied (if any).

Allegedly, the quality and configuration of the surrounding built environment exerts influence on travel choices: according to Cervero and Gorham (1995), residents of a transit-oriented neighborhood commute 1.4% to 5.1% more by public transport than those living in a car-oriented neighborhood; and, according to Cervero and Radisch (1996), residents of traditional neighborhoods averaged 10% more leisure walking trips than residents of car-oriented suburbs. In Brisbane, the probability of using transit in non-TOD and potential TOD areas is 1.4 and 1.3 times lower compared to residential TOD, whereas walking and cycling are respectively 4 and 2.5 times less likely (Kamruzzaman et al. 2014). In central commercial areas of Toronto transit is competing with walking, as 41% of commute trips are made by foot (Higgins and Kanaroglou, 2016). Other works also point out that neighborhood characteristics may influence the modal split as well, e.g., Ewing and Cervero (2001), Handy et al. (2005), and Chatman (2013). It is believed that TOD, combining transit supply with a highly walkable built environment, may encourage more sustainable travel patterns, yet, for example, the degree to which car trips decrease with TOD varies in different studies.

Table 2.1 - Selected articles on the effects of TOD on travel behavior

Reference	Methodology	Case study
Cervero and Gorham (1995)	Descriptive statistics/OLS regression model	San Francisco Bay Area, Los Angeles Area
Cervero (1995)	Historic overview/descriptive statistics	Stockholm Area
Cervero and Radisch (1996)	Comparative analysis/discrete choice modeling (binomial logit)	San Francisco Bay Area
Ewing and Cervero (2001)	Literature review	n/a
Lund et al. (2004)	Descriptive statistics/comparative analysis	California
Handy et al. (2005)	OLS regression model/discrete choice modeling (ordered probit)	California
Cervero (2007)	Discrete choice modeling (nested logit)	California
Cervero and Arrington (2008)	Descriptive statistics - comparative analysis/OLS regression model	Philadelphia, Portland, Oregon, Washington, D.C., San Francisco Bay Area
Cervero and Day (2008)	OLS regression model/discrete choice modeling (binomial logit)	Shanghai
Loo et al. (2010)	OLS regression model	NYC, Hong Kong
Chatman (2013)	OLS regression model/discrete choice modeling (logit regression)	New Jersey
Kamruzzaman et al. (2014)	Cluster analysis/OLS regression model	Brisbane
Nasri and Zhang (2014)	Comparative analysis/multilevel mixed-effect regression	Washington, D.C., Baltimore
Higgins and Kanaroglou (2016)	Latent class method	Toronto
Pan et al. (2017)	Spatial analysis/OLS regression model	Shanghai
Ewing et al. (2017)	Descriptive statistics - comparative analysis	Denver, Los Angeles, San Francisco, Seattle, Washington, D.C.
Tian et al. (2017)	Descriptive statistics	Seattle region
Park et al. (2018)	Discrete choice modeling/negative binomial model	Regions of Atlanta, Boston, Denver, Miami, Minneapolis-St.Paul, Portland, Salt Lake City, Seattle
Pongprasert and Kubota (2018)	Factor analysis/structural equation modelling	Bangkok

One of the early attempts to analyze the effects of TOD on modal split was made by Cervero (1995). He analyzed the case study of Stockholm rail-served satellite towns, where half of all workers and a third of the residents commute by public transport (Tunnelbana). The towns showed higher levels of transit use than a typical "control" suburb also served by a rail line and with similar income levels, yet characterized by a market-led development. As a descriptive study based on aggregate data for each studied urban area, it provided a general overview of mobility patterns in these settlements, however, without trying to explain the factors influencing them.

A more detailed analysis of TOD effects on travel behavior is provided by Cervero (2007) using data from a one-day travel diary of residents of 26 TOD housing projects in California. Public transport ridership levels in neighborhoods within walking distance (800 m) from a station were compared to those in farther areas, considering heavy rail, light rail, and commuter rail. Attempting to attenuate the influence of self-selection (people's willingness to reside in locations where they can continue using their usual transport mode, transit in this case; see also Subsection 4.3) in travel patterns, only interviewees who did not reside in TOD before and whose workplace did not change were selected for the analysis. This group of respondents reported a 4 USD decrease in average daily commute costs and a mean increase in job accessibility of 6.5%. Among residents living at a distance between 800 meters and 4.8 kilometers of a station, the share of public transport reached only 7%, while for those living within 800 meters the equivalent figure was 27% with 85% of them traveling to the station by non-motorized modes. This led the author to conclude that greater public transport patronage levels could be reached by intensifying housing supply near stations and offering accommodation for smaller households with fewer cars which tend to reside in proximity to transit. Chances of using public transport were estimated to be 41.6% higher if a person lived close to a station, other factors held constant. However, significant differences existed in terms of urban design and pedestrian comfort between the selected sites, as noted by Lund et al. (2004), and mixing station areas with rather different characteristics made the findings difficult to interpret.

A similar risk is present in another influential study by Cervero and Arrington (2008) that analyzed 17 multi-family residence projects varying considerably in densities. Selected TOD were located in proximity to either heavy rail, commuter rail or light rail in different parts of the United States, all mostly mono-functional (only 6 of the 17 projects hosted commerce or services at the ground floor). The majority of developments were 3- or 4-floor high, excluding four projects in Washington, which ranged in height from 16 to 21 floors. On average, each dwelling unit was provided with 1.16 parking spaces. Compared to the estimations made in the national guidelines, TOD areas were generating 70% to 90% fewer car trips per domicile in central areas and 15% to 25% in suburban areas. Moreover, it was found that an increase in densities was accompanied by a decrease in car trips.

While the selection of study areas in the aforementioned works was based mostly on distance to a station, a work of Nasri and Zhang (2014) comparing TOD vs. non-TOD areas in Washington D.C. and Baltimore is an interesting example of defining TOD through quantitative indicators: residential or employment density of a TOD had to be the same or higher than the metropolitan average, mixed-use level should be at least 0.30 (according to an entropy measure), and maximum distance to transit should be half-mile. It was revealed that, in terms of socioeconomics, TOD residents had smaller households, lower levels of car ownership, and higher rates of zero-car households. In Washington, the results concerning trip characteristics confirmed that people make less use of cars in TOD areas both for work and non-work trips. Yet, in Baltimore, several outcomes were quite unexpected: work trips by public transport/walking/bike turned out to be approximately 5% more in non-TOD areas, whereas the use of cars was found to be almost the same (73.61% in TOD and 73.45% in non-TOD). The authors suggested that such phenomena might be explained by the fact that many people commute to Washington from Baltimore and the public transport links are quite poor between the two cities. Estimated elasticities of vehicle miles traveled (VMT) in Washington was 37.7% lower in TOD areas than in non-TOD areas, and 20.9% lower in Baltimore, all else being equal. Considering the physical layout of selected areas, land-use parameters (residential and employment density, mixed-use) were found to negatively affect VMT levels. On the contrary, distance to CBD and street connectivity increased VMT.

These results were further confirmed in a work of Park et al. (2018), who analyzed data from eight metropolitan areas in the United States. Detailed data availability allowed to analyze origin-destination pairs and the influence of regional accessibility on travel behavior. Regional job accessibility was found to negatively affect VMT by car, at the same time increasing the probabilities of using public transport or walking. Regional compactness (predominantly compact built environment form as opposed to sprawling) were also favoring transit use and walk trips.

A comparative study by Loo et al. (2010) aimed to explore common factors that contribute to high levels of public transport in Hong Kong and New York. Data from a typical weekday rail usage for 80 stations in Hong Kong and 468 in New York were used to create a combined model (meaning that both cities were included in a single model and not considered in two separate models) for two cities with data weighting to compensate for the difference in the number of observed stations. Results showed that mixed land use was associated with transit patronage especially because it created bi-directional travel patterns. Highest levels of transit use were recorded on interchange stations and stations/lines which have been in operation since a long time ago (these are typically centrally located). Bus service connectivity that increases the catchment area of a railway station was also found important in attracting passengers. Similar results were provided by Pan et al. (2017) in a study of passenger volume in Shanghai, adding that longer trips are more likely to be made by transit due to lower travel cost and time. Employment opportunities in a 500-meter buffer zone, the presence of a district commercial center, possibility of line transfer in a station, and opening year of a station were found to be statistically significant. Seemingly, Asian cities, and Shanghai in particular, are attracting much attention in the context of TOD due to high-density levels and population dynamics: as the inner city of Shanghai is gradually ceded to offices, public sector or retail, households are moving from the historical center to suburban areas that are mostly represented by single-use superblocks and poor walking environment, which potentially may increase car use.

In order to understand how a change in residential location may affect modal split, Cervero and Day (2008) analyzed the results of a survey of 900 households conducted in four neighborhoods in the outskirts of Shanghai, of which two are served by a metro line and the other two by bus service only. A large part of the respondents (46%) used to live in more central areas before moving into the neighborhoods studied, so, in general, they have experienced an increase in distance to work and lower regional accessibility. Changes in modal split were considered only for household heads' and only in cases where the previous travel mode was a non-motorized mode or the bus. People were found to maintain the same transport mode they had used before relocation (58.8%), or switch from non-motorized modes to bus (8.2%) or from bus to metro (8.0%) (Cervero and Day, 2008). As noted by the authors, relocating population to areas served by transit allows minimizing the risk of an increase in car-ownership rates.

Another issue related to travel behavior in TOD is parking supply. This issue was in particular addressed by Chatman (2013) in a study for New Jersey. Advocating for a more detailed approach to factors other than rail access, the author analyzed the correlations between car ownership/car use and factors like type and age of housing, parking supply, trip purpose, and demographics. The study considered 10 railway stations, and their buffer areas were intentionally increased to 3 kilometers in an attempt to control for spatial autocorrelation as travel behavior of residents within 650 meters was compared to travel behavior observed in the areas beyond walking distance to the station. Limited on- and off-street parking availability surged as the most significant predictor for a lower probability of car ownership or car commuting, whereas rail distance did not have a significant influence on car ownership rates. Car commuting was shown to decrease by 60% in station areas with limited parking supply compared to other sites. Similarly, limited parking availability was related to a 25% decrease in using a car for secondary trips. Several other factors were significant as the number of bus stops, smaller apartments, and functional mix, leading the author to conclude that simple rail proximity might not be a decisive factor in lower levels of car use, instead, it is the combination of factors that makes a difference.

Subsequent studies show that even limited parking in station areas is frequently underused. Ewing et al. (2017) analyzed this issue from a user's perspective, using data obtained from counting people on site entering or exiting the buildings and briefly interviewing them, in addition to registration of parking occupancy. TOD were defined as master-planned sites that possess multi-story buildings (density), mixed uses and a walking-friendly environment and are well conjugated with transit stations, while the approach for site selection was mostly qualitative (direct observations, interviews with stakeholders, imagery analysis). Five sites were selected, with one (Redmond, a city near Seattle) being only served by bus and the others also by rail. At peak-hour time, maximum parking occupancy in selected TOD was 84%, being worth noting that these areas already have at least two times less parking than the national guidelines prescribe. Besides, the number of car trips amounted to a maximum of 37.4% of the threshold in the national guidelines. Redmond was found to generate only 65% of the average residential parking demand and 27% of the commercial parking demand estimated in the national guidelines (Tian et al., 2017). Studied

TOD areas required less parking space than the national guidelines would suggest, putting at risk site's attractiveness as an oversupply of parking might induce car trips and worsen pedestrian environment. Such risk could probably be minimized introducing demand management to enable different drivers to use the same parking lots (most sites had only dedicated parking for residents or visitors), liberating area for other amenities like green spaces or cycle lanes.

It should be noted that most studies are concerned with the travel choices of TOD residents living within approximately 800 meters from the station. Station proximity is likely to be the most influential factor in mode choice. Other frequently mentioned transit-related variables include station opening year (Loo, et al. 2010; Pan et al. 2017), distance to CBD (Cervero and Arrington, 2008; Nasri and Zhang, 2014; Pan et al. 2017) and number of bus stops (Chatman, 2013; Loo et al. 2010; Nasri and Zhang, 2014; Park et al. 2018). Most frequent sociodemographic variables are car ownership (Cervero, 2007; Cervero and Day, 2008; Nasri and Zhang, 2014) and household income (Cervero, 2007; Cervero and Day, 2008; Chatman, 2013; Park et al. 2018; Pongprasert and Kubota, 2018). The weight and importance of other TOD components, for example residential density (Cervero and Arrington, 2008; Chatman, 2013; Loo et al. 2010; Nasri and Zhang, 2014; Pan et al. 2017), employment density (Chatman, 2013; Loo et al. 2010; Nasri and Zhang, 2014; Pan et al. 2017) and retail (Chatman, 2013; Loo et al. 2010; Pan et al. 2017) in station areas have started to be evaluated more recently. The conclusion is that their effect on travel behavior seems to be moderate, at least for commuter trips which have been the focus of most studies. Still, when considered together with other TOD-related factors like diversity or urban design, the effect might be more visible, particularly in terms of access mode to transit. Comfortable and safe access to transit is quite important for TOD residents (Pongprasert and Kubota, 2018). Therefore, accurate selection of station areas is paramount: station areas need to adequately correspond to TOD characteristics in terms of urban design and walkability, otherwise, final results may be misleading.

2.4.2. Real-Estate Price Effects

Most of the studies on this topic use hedonic price models to deconstruct the price of real estate parcels based on its characteristics, including those not directly inherent to the property itself, like the surrounding environment (Table 2.2). Data for these studies can be obtained both through a revealed preference approach, i.e., the analysis of empirical evidence on commercial transactions, or through a stated preference approach based on surveys aiming to measure respondents' willingness to pay for a particular good (Bartholomew and Ewing, 2011).

Table 2.2 – Selected articles on the effects of TOD on real-estate prices

Reference	Methodology	Case study
Bowes and Ihlanfeldt (2001)	Hedonic price model/random-effects regression models	Atlanta region
Hess and Almeida (2007)	Hedonic price model	Buffalo
Atkinson-Palombo (2010)	Hedonic price model	Phoenix
Bartholomew and Ewing (2011)	Literature review	n/a
Duncan (2011a)	Hedonic price model	San Diego
Duncan (2011b)	OLS regression model/2SLS	San Diego, Carlsbad, San Marcos
Mathur and Ferrell (2013)	Hedonic price model	San Jose
Kay et al. (2014)	Hedonic price model	New Jersey
Renne et al. (2016)	Factor analysis/multilevel regression model	USA
Xu et al.(2016)	Hedonic price model/spatial autoregressive model/spatial error model	Wuhan, China
Yu et al. (2018)	Hedonic price model/spatial Durbin model/geographically weighted regression	Austin

Overall, in theory, proximity to a station and subsequent accessibility benefits should be reflected in the price premium. However, in reality, the relationship between the two factors may not be so straightforward. For example, it is possible that the effect on property values differs depending on the type of transport infrastructure (heavy rail or light rail), property type (commercial or residential) and neighborhood income level (Bowes and Ihlanfeldt, 2001; Hess and Almeida, 2007). Furthermore, a study in Atlanta showed that residential property values in immediate metro station areas (radius of up to 400 meters) are likely to decrease in value due to congestion, noise and potential increase in crime rates, but tend to increase beyond this limit, reaching a maximum at a distance of 1.6 to 4.8 kilometers, and then decrease again. Moreover, there is a price increase (4.7%) for properties located beyond the 4.8-kilometer limit if the nearest station has a parking lot, but for houses located closer to the station it may be insignificant (Bowes and Ihlanfeldt, 2001).

The discussion concerning factors affecting house prices in station areas was supported by Kay et al. (2014) in a case study involving eight station areas in New Jersey, five of which were providing direct access to Manhattan, New York City. House prices around stations without direct access to Manhattan were decreasing with distance (properties located within 800 meters of a station showed a 6.3% premium compared to those 1.6 kilometers away) before starting to increase again at a 3.2-kilometer distance. The authors suggest that a slight increase at a 3.2-kilometer distance can be partially related to the presence and influence of another station. Interestingly, for stations providing direct access to Manhattan, the price premium decreased steadily with distance (properties within 800 meters valued 10.6% more than those 3.2 kilometers away). This makes clear that a price increase in station areas and its distribution may depend not only on the distance but also on the service coverage and attainable destinations. Controlling for spatial autocorrelation and other potentially important factors for property values, an additional surplus in value was discovered in high-income neighborhoods.

Similar conclusions were drawn from the evaluation of the effects of light rail transit (LRT) in Buffalo (New York), where transport improvements were introduced as part of a wider revitalization strategy for central areas. Hess and Almeida (2007) used hedonic regression models to assess variations in residential property prices in buffers of approximately 800 m around LRT stations. Two types of distance measurements were considered: network distance and straight-line distance. Residential property values were found to increase by $0.99 every 30 meters closer to the station using network distance and $2.31 using straight-line distance, so straight-line distance was considered to be a more important factor, yet the increase in price was regarded as modest. Generally, the authors noted that a price premium was observed only in areas where access to LRT was highly valued and mostly in high-income areas located on the periphery, whereas in depressed central neighborhoods the effect of proximity to a station was limited, leading the authors to conclude that the introduction of LRT alone could hardly revitalize deprived areas.

Further exploring factors affecting property values in the vicinity of station areas, Duncan (2011a) compared condominium prices in neighborhoods with similar pedestrian amenities inside and outside of stations' catchment areas in San Diego. The author distinguished between TOD and TAD, focusing thus on the importance of neighborhood layout and pedestrian environment. It was observed that prices decreased significantly as distance to the station increased for areas with good pedestrian environment, suggesting that residents of these neighborhoods highly value proximity to transit. The price premium could reach around 11% in poor pedestrian environments near stations and more than 15% in pedestrian-friendly environments. Attempting to further evaluate station-generated price premiums, Duncan (2011b) studied their magnitude based on allowable density levels. Controlling for the bidirectional influence between zoning and property prices, it was revealed that despite higher allowable densities are negatively associated with home values, this does not apply to station areas: limiting densities in station areas is unlikely to augment prices; on the contrary, property prices in station areas with permissive zoning tend to be higher. Yet, the cross-sectional model used in both studies did not allow to understand the causal influence of the rail system.

Addressing this challenge, Mathur and Ferrell (2013) analyzed the Ohlone-Chenyoweth area in San Jose using longitudinal data for three time periods (before, during and after TOD construction), comparing the same station area under different conditions. Hedonic regression models showed that, in the pre-TOD period and during TOD construction, distance to a station was statistically insignificant for house prices, however, after TOD was implemented, it became relevant, with a 50% decrease in the distance being associated to a price premium of 3.2% within 1.6 kilometers from a station. After TOD construction, house prices within approximately 200 m from the station increased by 11.2%.

As increases in TOD housing prices are frequently reported, concerns arise that they may repel low-income groups (potentially more prone to transit use than high-income residents) to settle in TOD areas. In this regard, Renne et al. (2016) analyzed housing expenditures together with transport expenditures in order to understand whether higher housing costs in TOD areas are compensated by transport savings. TOD areas were defined as station areas with a walk score of at least 70 (meaning that most amenities can be reached on foot) and a minimum density of 8 housing units per acre [AN: 4,047 square meters]. Stations that met only one of these criteria were regarded as hybrids, and stations not meeting any criteria were qualified as TAD areas. It was found that home values and rental prices in TOD used to be and were still higher than in hybrids and TAD areas (in the years 1996-2015) and that the disparity in price was increasing; in particular, rental prices in TOD areas registered a record increase of 45% in 2010-2015. At the same time, mean household income in TOD areas was lower than in TAD areas and the proportion of renters was higher (72% against 63% in hybrids and 45% in TAD areas). However, transport costs in TOD areas were the lowest (approximately 14% of income, compared to 17% in hybrids and 19% in TAD areas). Since TOD residents spent around 29% of income in housing (against 27% in hybrids and 28% in TADs), in sum they might end up paying less, yet these figures were taken from a database for the years 2008-2012, and thus might not reflect market conditions that have rapidly changed after 2012. Still, this work is worth mentioning for introducing the idea of evaluating property prices in TOD areas together with the potential reduction of transport expenditures.

In contrast to the majority of studies which addressed housing prices, Yu et al. (2018) evaluated price changes of commercial properties for the newly introduced rail and BRT systems in Austin. Controlling for spillover effects, the general impact of transit proximity on commercial properties was found to be modest, except around TOD stations where the synergistic effect of TOD produced additional price premiums of $9/ft2 within 400 m from a station, $8.3/ft2 within 400-800 m, and $5.6/ft2 for properties within 800-1200 m [AN: 1ft2 = 0.09m2]. Similar results were reported by Xu et al. (2016) for the city of Wuhan in China, where price premium for commercial properties located within 100-400 m from a station was approximately 8% and 16.76% inside a 100-meter buffer from a station.

Overall, evidence from other locations also shows that, in general, proximity to TOD leads to the increase in home prices and that the real-estate market switches towards pedestrian-friendly developments preferably served by transit (Bartholomew and Ewing, 2011).

2.4.3. Residential Location Effects

The attachment of TOD residents to their transport habits raises the discussion about the role of self-selection in observed mode choices, as one can doubt whether frequently reported higher levels of transit use in station areas are actually the result of TOD (causal relationship) or they simply reflect people's preference to reside in locations where they can continue to have the same travel behavior. This issue has been addressed in numerous studies, yet many do not distinguish between different station areas (TOD or non-TOD). In this section, we first review generic studies and then focus on a few articles concentrating specifically on TOD (Table 2.3).

Attempting to capture the impact of the built environment on travel behavior after accounting for self-selection effects, Mokhtarian and Cao (2008) and Cao et al. (2009) performed extensive analyses of, respectively, methodological issues and empirical evidence on the subject, concluding that the built environment does have an influence on travel choices even after controlling for those effects. However, the extent of this influence and the exact weight of specific components of the built environment are hard to assess as they may vary depending on the trip purpose, population segments and other factors sometimes omitted in the studies (like the location of a neighborhood inside a city or region). Using survey data, Kamruzzaman et al. (2015) analyzed the main neighborhood features that influence residential location, highlighting "accessibility and mobility of places", "natural environment", "child-centric facilities" and "ease of commuting" as determinant factors, yet without specifying the reasons to live in a TOD area.

Table 2.3 - Selected articles on the effects of TOD on residential location choice

Reference	Methodology	Case study
Lund (2006)	Discrete choice modeling (binary logit)	San Francisco Bay Area, Los Angeles, San Diego, USA
Cervero (2007)	Discrete choice modeling (nested logit)	California, USA
Mokhtarian and Cao (2008)	Literature review	n/a
Cao, Mokhtarian and Handy (2009)	Literature review	n/a
Bohte et al. (2009)	Literature review	n/a
Olaru et al. (2011)	Descriptive statistics - comparative analysis/discrete choice modeling (latent class and hybrid choice)	Perth, Australia
Cao and Cao (2014)	Comparative analysis/discrete choice modeling (ordered logit)	Minneapolis - St. Paul, USA
Kamruzzaman et al. (2015)	Comparative analysis/discrete choice modeling (binary logit)	Brisbane, Australia

Focusing specifically on TOD, Lund (2006) performed a stated preference survey aiming to analyze the residential location choices of TOD residents who changed their domicile in the last five years. As major reasons for their relocation, respondents mentioned "type or quality of housing (reported by 61%); the cost of housing (reported by 54%); and quality of neighborhood (reported by 52%)". However, the significance of these factors varies across socioeconomic groups; for example, the cost is primarily important for low-income residents, followed by "access to shops and services", since car availability in this population group might be limited and therefore proximity to commercial and service establishments is valued. The idea that cost is a fundamental factor for low-income groups was further explored by Olaru et al. (2011), who observed that, since prices tend to be higher near transit stations, the population in those groups is more likely to settle in areas further away from a station. Lund (2006) adds that these location choices might also be explained by the fact that industrial sites for low-paid jobs are likely to be easier to reach by bus or car, while station areas might be more attractive for medium or high-income residents since CBD and office employment centers are generally easily accessible by rail. High-income households and larger households were found to value mixed uses and "proximity to everything", and generally were more willing to pay for these neighborhood characteristics (Olaru et al., 2011). However, neither of the studies mentions access to transit among the top-three reasons for location decision. In Los Angeles, surveyed residents preferred living in TOD for highway proximity rather than for transit availability (21.2% against 19.3%), while respondents in San Diego rated both amenities almost equally (Lund, 2006). The survey by Olaru et al. (2011) was conducted slightly before the opening of a rail line, so probably self-selection had not fully manifested yet. In short, it appears that TOD may be responding to the needs of households with different income levels (for example, quick access to CBD for more affluent groups and proximity to shops and services for low-income residents) and that TOD features are important yet to a different degree for different population groups.

Similarly, Cervero (2007), evaluating the influence of self-selection using a nested logit model for a sample of random households selected in the suburbs of San Francisco, noted that people working within a mile from a station are likely to live in proximity to transit, however, families with children tend to opt for other locations. Only 19.6% of residents living within half-mile from a station commuted by transit with this rate falling down to 8.6% beyond this limit. According to the author's estimations, around 40% of the transit ridership bonus observed in station areas may be explained by self-selection.

The weight of self-selection in residential location choices remains an object of investigation, yet most academics agree that, in any case, it is important to provide people with the possibility of living close to a station in order to support users' loyalty to sustainable transport modes. Otherwise, as Bohte et al. (2009) and Cao and Cao (2014) underline in their studies, neighborhoods without proper transit or pedestrian/cycling infrastructure may not only "self-select" residents with car-friendly profile but would even deepen their attachment to cars.

2.4.4. Urban Form Effects

Inverting the logic of some studies aiming to understand how land-use characteristics affect TOD in terms of trip generation and modal split, several articles have analyzed how stations affect adjacent land use and overall urban patterns (Table 2.4). Indeed, "the changing cityscape should help define transport investment, and transport investment should help to define urban form" (Hickman and Hall, 2008).

Table 2.4 - Selected articles on the effects of TOD on urban form

Reference	Methodology	Case study
Hickman and Hall (2008)	Descriptive statistics	London
Papa et al. (2008)	Descriptive statistics/spatial analysis	Naples
Knowles (2012)	Descriptive statistics/descriptive analysis	Copenhagen
Ratner and Goetz (2013)	Descriptive statistics	Denver
Papa and Bertolini (2015)	Descriptive statistics - comparative analysis/spatial analysis	Amsterdam, Helsinki, Munich, Naples, Rome, Zurich
Dong (2016)	Descriptive statistics/2SLS regression model (Hausman-Taylor)	Portland
Loo et al. (2017)	Descriptive statistics	Hong Kong
Zhao et al. (2018)	Descriptive statistics/OLS regression model	Beijing

A work by Ratner and Goetz (2013) provides a detailed descriptive analysis of land-use changes in Denver as the city were intentionally pursuing a TOD policy by changing zoning regulations and allowing for densification and mixed uses in station areas. Considering the station typology elaborated by the city council, the authors detected a significant increase in TOD projects, both residential and non-residential, along the Central Corridor light-rail line (50% of new office spaces and 46% of new residential developments). Specifically, changes occurred around six stations in the city center, where 89% of government institutions, 62% of office buildings and 61% of cultural venues were located, accumulating 90% of all “office TODs”. Thus, the public transport system is now playing a relevant role as a principal attraction of new developments able to change the urban city form and potentially reduce car use once supported by planning authorities.

Promoted by the city council of Copenhagen, a major TOD was introduced in Ørestad, at the fringe of the city. As described by Knowles (2012), this development, initially planned for a variety of uses (residential, office, educational facilities) around a light-rail line with scarce and expensive parking, eventually became an alternative to over pressured CBD, also because of specific planning permissions (notably, approval of an out of town commercial center). Besides, its advantageous location allowing fast connection to Malmö (Sweden) helped to increase the competitiveness of the site and its catchment area. Though being a single site-specific study, this work analyzes TOD as a strategy for sustainable urban growth.

Somewhat contrasting results were reported in a quantitative study by Papa et al. (2008) presenting an analysis of economic and spatial changes around rail stations in the period of 1991-2004 in Naples (Italy). An overall decrease in population density along the metro line was reported, together with a significant increase in property values. These trends were particularly strong in central areas and around stations with high levels of network connectivity. At the same time, a population increase in suburban areas generally followed a new public transport line, suggesting that population spread might be arranged along a transport corridor. However, it is unclear whether local authorities actually promoted any TOD policy or the changes occurred naturally.

In Beijing, the effects of metro on land development also appear controversial (Zhao et al. 2018). Despite land parcels located within 3 kilometers from a station were quite actively seeded for urban development, densification and functional mix were not completely achieved. In the central area, the floor area ratio (FAR) for commercial and residential uses increased, yet in the suburban area an increase in industrial uses was registered. Besides, high FAR was positively associated with proximity to a highway instead of metro. The authors explain such discrepancies by specific local planning conditions and poor dialogue between involved authorities.

Focusing on the Portland metropolitan area, Dong (2016) examined changes in land-use associated with metro stations. In a buffer of approximately 400 meters from a station, proportional change of net residential density and change in the number of dwellings was evaluated in the years 2004 and 2014, differentiating between the stations opened before 2004 (mature stations) and newly opened stations. It was observed that a 7% increase in the housing stock registered in 2004-2014 was concentrated around mature stations and that 95% of this increase came from multifamily homes. Using a regression model, the author concluded that a 10% rise in ridership was correlated with 11.8% more dwellings every two years. Vacant land availability also appeared to be considerably significant and each acre was linked to approximately 4.4 more dwellings every two years. Generally, as zoning limitations were reducing the land available for development in the outer-city areas, development initiatives were channeled to already urbanized areas, including station areas, representing opportunities for urban infill. However, in some cases, insufficient supply of undeveloped land in these areas has obstructed those initiatives.

The use of TOD in the context of urban infill was further examined by Loo et al. (2017), who evaluated its implementation on greenfield and infill sites over a 10-year period in Hong Kong. Socioeconomic data used in the analysis showed that greenfield developments, which appeared on formerly non-urbanized lands, naturally experienced greater population and employment growth compared to infill developments, still, values of population or employment density on the infill sites were greater. All station areas demonstrated large growth in residential use. In terms of mobility, residents of greenfield developments used transit more than residents of infill sites, yet, in turn, the latter showed higher rates of walking trips, which may be explained by the lack of attractive sites at a walking distance in recent developments. This study is particularly interesting in a context where TOD is seen as a way to address and manage population growth and as part of an urban renewal strategy, a subject relatively unexplored in the literature.

Attempting to move away from site-specific limitations, Papa and Bertolini (2015) chose to analyze TOD impacts on accessibility in six European metropolitan areas in a cross-comparative study. Amsterdam, Helsinki, Munich, Naples, Rome and Zurich, with a population of 1 to 4 million people, were selected due to the great variety of land uses and transport infrastructure present in these cities. In all cases, the study area was a 30-kilometer radius circle drawn around the rail station with the higher connectivity level. All stations in the study area were subsequently evaluated using the “node-place” index to estimate the level of TOD. Three main urban patterns were observed: “strong core structure” in Munich and Rome, “fully networked city-region” in Amsterdam, Zurich and Naples, and “corridor structure” in Helsinki. It was found out that TOD level is associated with cumulative rail accessibility which is higher when density and mixed-use levels correspond to the hierarchical level of a station (i.e., when density and mixed-use levels are higher in sites well-served by rail). As concluded by the authors, balancing the two components of TOD (by densifying land-use in rail-served areas or by improving transit supply in high-density areas) may significantly improve the accessibility conditions offered by a metropolitan area.

2.4.5. Community Life Effects

Apart from sustainable mobility patterns and dense built environment, generating a vibrant and lively community is also frequently mentioned in the TOD context, mostly as a consequence of TOD implementation. As stated by Currie and Stanley (2008), a variety of land-uses in TOD can “address problems associated with social exclusion and SC through creating proximate opportunities for access to activities and social networks” [AN: SC denotes social capital]. It is believed that TOD features provide favorable conditions for vivid street life, hence neighborhood community links should naturally follow. Despite research on this topic is still limited, there are a few works addressing it (Table 2.5).

Table 2.5 - Selected articles on the effects of TOD on community life

Reference	Methodology	Case study
Kahn (2007)	Comparative analysis/longitudinal analysis/binomial regression model (linear probability)	Los Angeles, Sacramento, San Diego, San Francisco, San Jose, Denver, Washington, Miami, Atlanta, Chicago, Baltimore, Boston, Portland, Dallas
Currie and Stanley (2008)	Literature review	n/a
Kamruzzaman et al. (2014)	Cluster analysis/simultaneous equation model	Brisbane

One of these works was carried out by Kamruzzaman et al. (2014), who investigated the levels of social capital in station areas in Brisbane (Australia), comparing TOD, TAD and conventional suburbs. Even though strong influence of self-selection was observed, it was still possible to find that TOD residents had stronger social links amongst themselves than TAD residents. However, it is important to note that independent variables (density, land use mix, PTAL) evaluated separately affected negatively social capital, meaning that improving only one variable may have adverse impacts on the community, as observed, for example, in highly dense areas where levels of social capital were frequently low.

A different perspective into the theme was brought by Kahn (2007), who concentrated on gentrification trends in TOD areas. Since TOD is likely to provoke a price increase in adjacent properties, there is some concern that low-income residents will be forced to leave an area, ceding it to well-off population groups. Potentially this shift may produce reverse effects on TOD efficiency in terms of transit use as high-income groups are frequently reported to have higher car ownership levels and drive more, so it is questionable whether they will use transit. In order to achieve more accurate results, the author differentiated between "park & ride" stations and "walk & ride" stations. The analysis of community dynamics in terms of property values and percentage of college graduates over a 30-year period in 14 cities of the United States revealed uneven gentrification patterns, since gentrification happened in some cities, for example in Washington D.C. and Boston, particularly around "walk & ride" stations, while it did not manifest in others (e.g., in Portland and Los Angeles). As the article focused only on population and real estate, it did not consider changes in commerce and services (like possible openings of new trendy shops). Interestingly, in most cities, "park & ride" station areas typically witnessed a decrease in the income level of residents.

2.5. TOD Planning

A thorough understanding of effects is certainly critical for the planning of TOD initiatives, but there is a number of other issues that need to be taken into account. We specifically address here, in successive subsections, planning policy issues and planning decision support tool issues.

2.5.1. Planning Policy

Articles that consider TOD in the planning policy context generally address three main topics: policy transferability; expectations and interests of stakeholders (in particular, local authorities and developers); and project implementation, including financing (Table 2.6).

Since the concept of TOD has gained international attention and has been applied in diverse national settings, the issue of transferability is inevitably raised. As shown in the previous sections, in the absence of a formal and widely accepted TOD definition, developments with quite different characteristics end up being considered TOD, complicating the perception of the concept and the evaluation of the outcomes of TOD implementation. Overall, most researchers recognize that there is a need to standardize and systematize existing knowledge about TOD in order to make the concept more understandable for the general public and to facilitate TOD implementation for local planners: "without standards and systems, successful TOD is the result of clever exceptionalism and beyond the reach of most communities or developers" (Dittmar et al. 2004).

Attempting to provide more precise bounds for TOD, Hale (2014) suggests the adoption a clear benchmark for these developments: sustainable transport modes have to account for at least 50% of the modal split in the station area, as sustainable modes have to be dominant in a TOD; otherwise, they should be classified as TAD. This radical measure is proposed by the author since it is expected to capture other elements of a successful TOD: if the majority of the population chooses walking, cycling or public transport, it is quite likely that an area itself corresponds to TOD standards in terms of built environment, meaning that there is not so much traffic or congestion, and streets are walking- and cycling-friendly. Such a classification criterion would significantly reduce the number of sites that can be designated as TODs, yet according to the author, this may be advantageous. The reason is that this would place the focus exclusively on "real" TOD and learn from them, eventually facilitating policy transferability. A possible shortcoming of such TOD differentiation is that it ignores the origin-destination pair. It is crucial to ensure that the destinations can, in fact, be reached by sustainable modes. Otherwise, there is a risk to underestimate site's performance because of exogenous factors that are out of planners' control. For example, a person may live in a TOD but may be forced to go to work by private vehicle since the workplace location is not served by transit. In this case, car commute can hardly be considered a development's failure. A similar issue arises if travel cost by transit is higher than by car. Therefore, it is uncertain whether such simple forms of distinction can actually work well for the concept of TOD.

Table 2.6 - Selected articles on TOD planning policy

Reference	Methodology	Case study
Cervero and Dai (2014)	Questionnaire analysis - descriptive statistics	Bogota (Colombia), Ahmedabad (India)
Cervero and Murakami (2009)	Cluster analysis/OLS regression model	Hong Kong
Dittmar et al. (2004)	Conceptual and policy discussion	n/a
Guthrie and Fan (2016)	Interview analysis	Twin Cities Region (USA)
Hale (2014)	Conceptual discussion	n/a
Lierop et al. (2017)	Interview analysis	USA, Canada, the Netherlands
Pojani and Stead (2014)	Policy discussion	Amsterdam, Stockholm, Vienna
Staricco and Brovarone (2018)	Policy discussion	Stedenbaan (the Netherlands), Bologna (Italy)
Thomas and Bertolini (2015)	Policy discussion (meta-analysis)	Tokyo, Perth, Melbourne, Montreal, Vancouver, Toronto, Naples, Copenhagen, Amsterdam-Utrecht, Rotterdam-Den Haag, and Arnhem-Nijmegen
Thomas et al. (2018)	Policy discussion	The Netherlands

The issue of policy transferability was also addressed in a work by Thomas and Bertolini (2015) who tried to define TOD success factors that altogether increase the chances of successful implementation in different national settings. The most important prerequisites were found to be "political stability, regional land use-transportation body, relationships between actors in the region, public participation, interdisciplinary implementation teams, and certainty for developers". Even though these desirable conditions might favor TOD planning and international examples of successful TODs might inspire local authorities, developing a site-specific approach to TOD is crucial to account for specific national contexts, local planning practices, built environment and cultural distinctions (Thomas et al. 2018; Staricco and Brovarone, 2018; Lierop et al. 2017). For example, in the Dutch context, this would mean planning TOD areas for cyclists due to population preferences and increasing TOD radius since bike trips can be longer than walking trips.

In order to understand planners' aspirations regarding the concept, Pojani and Stead (2014) performed a series of interviews with Dutch planners. The planning community showed particular interest in learning more about mixed uses and about means to achieve regular 24-hour use of a station area. The interviewees were also willing to be better informed about financial instruments that would allow reducing public investment and means to disseminate knowledge about TOD among the general public in order to minimize potential opposition from residents (densification plans may not be welcomed by local communities). The complexity of the concept, and only partially successful lobbying of TOD were identified by the interviewees as difficulties encountered in the promotion of a TOD policy. Even though being site-specific, this work is interesting as an effort to clarify the needs and demands of urban planners, revealing their attitude towards TOD from the practitioner viewpoint.

Another noteworthy contribution in this regard but from a different angle is the work of Guthrie and Fan (2016) in which interviews were done to reveal the attitude of developers towards

TOD in the Twin Cities region (Minneapolis and Saint Paul). Apparently, developers regarded transit access as an advantage, however, in the central areas better served by transit, the land price was high, land availability was scarce and building regulations were strict, preventing developers from choosing these sites. In spite of being attentive to network expansion plans, developers would decide to actually construct along a future transit link only if its opening were certain, expressing skepticism about transport plans elaborated for years ahead that could change over time. There was also interest in a collaborative approach to future developments: instead of simply prohibiting undesirable developments, local authorities could work together with developers on the preparation of more consensual plans. Besides, the majority of developers highly rated walkability, especially for residential developments, but they pointed out that the minimum parking requirements they had to comply with did not favor the creation of walkable neighborhoods as street space was ceded to parking. As a conclusion, the authors advocated for a more flexible planning since both parties (local authorities and developers) were apparently willing to create TOD areas, yet, to achieve such developments in practice, specific planning regulations might be needed (e.g., to lower minimum parking standards), as well as financial incentives to alleviate station area land costs.

Shifting to project implementation issues, Cervero and Dai (2014) surveyed evidence from 27 cities with BRT systems, to analyze the planning tools that accompanied TOD implementation and the barriers encountered in the process. The three most frequently used and top-rated tools included "infrastructure improvements", "zoning incentives/density bonuses" (for example, authorizing for higher densities if commercial establishments are introduced in the station area or increasing the allowable floor area ratio if a site hosts affordable housing) and "capital funds for TOD" (including elaboration of specific TOD plans and enhancement of station-adjacent public space). Simultaneously, the list of barriers to TOD started with the "lack of dedicated funding for TOD", "absence of TOD plan" and "lack of institutional coordination". The latter is also mentioned by Staricco and Brovarone (2018) as the main obstacle in delivering TOD in Bologna and Stedenbaan (The Netherlands), accompanied by difficulties in increasing transit frequencies (transit companies were poorly involved in the process). Regarding financial mechanisms, in both cities infrastructure investments were made by the government and property development was paid by private companies.

In contrast, in Hong Kong the Rail and Property (R+P) mechanism allowed taking advantage of the price premium generated by station proximity (Cervero and Murakami, 2009). In simple terms, the local transport company acquired development rights from the government before a rail line was built and subsequently resold them to developers for the price of rail-served parcels, thus raising funds for subsequent infrastructure improvements. R+P TOD stations resulted in a significant price premium (up to 34.2%) and in a 22% price premium for TOD sites not being R+P. Though this is a very specific example of a dense and spatially restricted metropole, it still might be beneficial for supporting TOD projects in other locations.

2.5.2. Planning Decision Support Tools

Our focus in this section is on tools (systems or models) specifically developed to support TOD decision processes whose application automatically provides clear indications on the most suitable decisions to make (Table 2.7). Approaches that just classify TOD areas, as the node-place approach and others mentioned in Section 3, are therefore not covered here (despite their possible usefulness in such processes).

Two main research directions have been explored up to now with respect to TOD planning decision support tools: multicriteria decision analysis (MCDA) and multi-objective optimization. MCDA is used to rank alternative decisions (or strategies, or courses of action) according to several predefined criteria (or success factors) and decision-maker preferences (possibly expressed by criterion weights). Multi-objective optimization is used to determine efficient solutions (i.e., decision variable values) considering a set of objectives while complying with a set of constraints, with both objectives and constraints expressed as functions of the decision variables. The outcome of their application is a Pareto front composed by the solutions that cannot be improved with respect to one of the objectives without being worsened with respect to at least one of the others (called non-dominated solutions). Finding the whole Pareto front is a complex task when the number of objectives is large (say, greater than three). The application of weights to the objectives converts multi-objective optimization into single-objective optimization problems, which are easier to tackle particularly when the functions representing the objectives and the constraints are linear and the decision variables are continuous. Nevertheless, it introduces the challenge of setting up the objective weights.

Table 2.7 - Selected articles on TOD planning decision support tools

Reference	Methodology	Case study
Banai (1998)	Multicriteria decision analysis / AHP	Memphis (Tennessee)
Banai (2005)	Multicriteria decision analysis / AHP	Piperton (Tennesse)
Lin and Gau (2006)	Multi-objective optimization	Taipei
Lin and Li (2008)	Multi-objective optimization /Grey TOPSIS method	Taipei
Strong et al. (2017)	Multicriteria decision analysis / AHP	Denver
Ma et al. (2018)	Multi-objective optimization / Genetic algorithm	Beijing
Sahu (2018)	Multi-objective optimization / Genetic algorithm	Naya Raipur (India)

Probably, Banai (1998) is the first author to have proposed an MCDA tool to be used for TOD planning purposes. More precisely, the tool (procedure) was aimed to "assess the suitability of land use around proposed light rail transit stations of a metropolitan area" by applying the Analytic Hierarchic Process (AHP) method in conjunction with a geographic information system. Four criteria were considered: mix of land uses; density; road network (street pattern); and proximity to a transit station. The application of the proposed tool was exemplified for Memphis.

Possible tool improvements to convert it into a decision support system were discussed by the same author in Banai (2005), this time using the example of a “land development concept plan” for a small city in the United States (Piperton, Tennessee).

Amongst the few other articles that also propose MCDA tools for TOD planning, we highlight Strong et al. (2017). The authors of this article recognized the “abundance of literature on TOD”, but their literature review noticed the lack of studies addressing the question of “how can a transit agency choose between alternative TOD sites to develop or build?”. In response to this question, they developed a decision support tool (framework) for making such choices “incorporating and assessing unique success factors and their weights”. Also, in this case, the AHP method was used but considering a very large set of criteria (18). In an application to Denver, and considering the opinion of experts, the most important ones were found to be “the quality and length of walking route to station”, the “number of mixed-use structures” and “the planned mixed-income housing”, whereas “parking supplies on site”, “existing or planned convenience or service retail store” and “existing or planned cultural or entertainment centers” were classified as the least important.

On the multi-objective optimization side, the first model explicitly aimed at assisting decision-makers in TOD planning has been presented by Lin and Gau (2006). These authors developed a linear continuous model considering three objectives: maximizing subway system ridership; maximizing living-environment quality; and optimizing the social equity of land development. The decision variables were the floor-space ratios for different land uses in subway station areas. The constraints included in the model accounted for restrictions on land use density, land use combinations, and level of service facilities. The application of the model was illustrated for the area surrounding the Chunghsiao-Fuhsing subway station in Taipei. The model was solved using the ε-constraints method and, presumably, off-the-shelf optimization software (the article is not clear in this regard).

Another article with the same first author, Lin and Li (2008), was published a couple of years later, also proposing an optimization model and involving a case study in Taipei. However, it differed from the previous one in several important respects. This time, the model was to be applied at the city-region level, and its decision variables represented the allocation of space to residential, employment and recreational activities, being of the mixed-integer linear-type (some decision variables were Boolean). Four objectives were considered: maximize environmental quality (i.e., minimize pollution treatment costs); maximize land-use variety; maximize the number of subway passengers; and maximize accessibility to non-residential activities. For handling the presence of uncertainty and the flexibility needed in practical planning, the inputs and outputs of the model could be grey numbers (ranges of possible values). The Grey TOPSIS method was used to solve the model.

Quite recently, two new multi-objective optimization models for TOD planning were proposed, respectively by Sahu (2018) and Ma et al. (2018), the former to decide the types and densities of land uses along a transport corridor and the latter around a transit station. The application of the models was illustrated for Naya Raipur (India) and Beijing, respectively. The objectives considered by Sahu (2018) were: maximize TOD characteristics (density of population and employment and diversity of land uses); shaping the skyline; minimize land use change; and making land uses compact. Ma et al. (2018) focused on the following objectives: maximize rail transit ridership; maximize land-use compactness (number of neighboring cells with the same land use); maximize accessibility (i.e. minimize "travel time around transit stations") taking into account congestion effects; minimize conflicts between the land uses of adjacent cells; and minimize environmental effects (measured by pollution treatment costs). In both cases, some objectives were expressed by nonlinear functions of (some) decision variables, thus making the models mixed-integer and nonlinear, and therefore very difficult (if not impossible) to tackle through exact optimization methods. Instead, both authors have resorted to genetic algorithm heuristics. However, there is an important difference in the methods they have applied, because Sahu (2018) applied weights to the objectives, thus converting the multi-objective model into a single-objective model, whereas Ma et al. (2018) truly tackled the multi-objective model, concentrating on the construction of the Pareto front and on the analysis of some non-dominated solutions.

Overall, it can be said that significant progress has been made toward the development of decision-support tools specifically designed to be used within TOD planning processes. The essential requirements that such tools should meet have been identified. Based on the knowledge and prototypes currently available, it should now be possible to build a truly user-friendly tool that planning agencies could effectively use to support their TOD initiatives.

2.6. TOD Research Gaps

Notwithstanding the considerable achievements of TOD research, there are still several gaps to address. Below, we identify the ones we consider to be the most relevant and challenging divided into two groups: gaps related to TOD effects and gaps related to TOD planning.

As stated before, the effects of TOD on travel behavior have been frequently studied in the literature, yet some aspects deserve to be further examined. In particular, the longitudinal research design often applied in the evaluation of urban form modifications is still rather rare in the analysis of the impacts of TOD on travel behavior. However, this type of analysis could be very useful since, when it comes to people's habits and preferences like the ones involving travel mode choices, significant changes hardly manifest themselves in short time periods. Instead, years may pass before the occurrence of significant changes in travel preferences or TOD-related features (mixed uses or density), and the frequently applied cross-sectional research design cannot capture these changes (Van de Coevering et al. 2015).

Analysis of modal split based on origin-destination pairs could also improve our understanding of TOD effects on travel behavior. The majority of studies uses data of TOD residents' travel choices which inform about the mode choice selected at a particular origin, yet they omit valuable information about the destination of the trips (whether it is easily reachable by car or transit, whether it is a mixed-use or a mono-functional site, etc.). The importance of a wider regional or metropolitan transport system cannot be neglected as it actually produces a significant impact on people´s choices, reducing the importance of neighborhood organization: "the form of the macro-region may be too auto-dependent for the micro-pattern of any particular neighborhood to matter. Islands of neotraditional development in a sea of freeway-oriented suburbs will do little to change fundamental commuting habits" (Cervero and Gorham, 1995). Potentially, this issue may be approached by studies which would consider origin-destination pairs, channeling the research into the domain of "accessibility-oriented development" (Deboosere et al. 2018).

Additionally, in this regard, it might be useful to distinguish between travel behavior of choice riders and captive riders (Lierop et al. 2017), and to understand which are the factors that determine the use of a particular transport mode in each situation. In the case of choice riders, analyzing the factors that determine the use of a particular transport mode might bring some insights into possible means to improve TOD performance (for example, if it happens that the proportion of choice riders in one TOD site is higher compared to others). In the case of captive drivers, such analysis might allow determining which OD pairs have poor transit connections.

Another common criticism of existing research is the focus on work trips and little interest in non-work trips which can account for several daily trips. In this regard, estimation of a site's attractiveness based on the number of jobs is sometimes considered as an oversimplification, since the distribution of activities that attract people is not necessarily limited to employment centers, especially in non-working hours (examples include schools, restaurants, bars, cultural venues, etc.). Research involving non-work trips is frequently entangled with limited data availability, but is certainly worth pursuing because the share of such trips is increasingly large.

Considering other TOD effects, research could better develop the issue of the potential benefits of TOD for community life at a micro-scale, for example in terms of safety and comfort, improved aesthetical appearance of an area, proximity to commerce or services, or other societal improvements, since the number of studies on these matters is still limited. Such evidence could support local authorities in the promotion of TOD and repel possible skepticism of residents towards new projects.

As evidenced in the previous section, the implementation of TOD projects may provoke a variety of changes in a number of aspects and simultaneous bi-directional dependence between trends may happen, as in the case of travel behavior and residential location (Estupiñán and Rodríguez, 2008) or transit supply and urban form (King, 2011; Xie and Levinson, 2010; Kasraian et al. 2016). The interdependence between these effects and their synergistic influence, particularly on the long term, could be better explored with appropriate techniques like two-stages least squares (instrumental variables) regression analysis or Granger causality analysis, which have rarely been used in TOD studies.

Turning now to research gaps related to TOD planning, one of the most relevant aspects to mention has to do with the uncertainty of TOD effects. The importance of planning in achieving successful TOD is still to be better explored, as one may question whether a specific policy direction should be pursued (for example, implementing mixed uses in a station area) or whether functional mix could appear naturally on its own as a consequence of increased accessibility and passenger flows.

On the other hand, market forces continue to produce a large impact on urbanization patterns, and if the logic of spatial organization promoted by the authorities does not coincide with market interests, the project is likely to deliver very moderate effect. According to Guthrie and Fan (2016), there is a certain interest from developers in TOD projects, which could favor their implementation if backed by local authorities. However, dialogue and interaction between these actors seem to be quite weak. Besides, as underlined by Staricco and Brovarone (2018), dialogue with transit companies (in terms of service frequency, route adjustments or multimodality) looks like being crucial for successful TOD implementation. However, it appears that these companies are often poorly involved in the planning process. In this sense, a decision-support tool that would facilitate and promote the participation of the different stakeholders (and particularly of developers, planners, and transit companies) in TOD planning processes would undoubtedly be of great utility.

2.7. Conclusion

Since the 1990s, research dedicated to TOD has been steadily increasing, and in recent years approximately 45 annual articles have been published in journals listed in the Web of Science database. This trend reflects a growing interest in this urban planning concept. However, as the number of studies rises, familiarizing with TOD may become difficult due to the extent and variety of the available literature. For this reason, in this chapter we have reviewed TOD research and systematized its results. Hopefully our review, together with the identification of the main research gaps, shall help researchers to get better acquainted with the subject and better informed on the challenges that lie ahead.

Thanks to the research efforts made in the past, it is now possible to understand rather well the many different effects produced by TOD implementations. Because the concept of TOD is multidimensional, it involves changes in different aspects occurring at the same time (but probably not at the same pace), eventually creating a complex network of mutually dependent interrelations. Summarizing the findings, it is possible to conclude that, in general, proximity to a station offering TOD features (density, land use mix and pedestrian-friendly design) increases the use of transit and simultaneously increases property prices in adjacent areas. In turn, an increase in property prices potentially leads to successive densification and/or gentrification of station areas, being doubtful whether public transport ridership levels remain high once high-income groups settle in a TOD. Normally, the aforementioned changes occur gradually with the course of time, hence it is possible that certain TOD effects take time to fully manifest themselves. Despite the progress achieved by previous research, there are still many open opportunities for TOD research and challenges to overcome. Part of these challenges arise in respect to TOD planning and to the development of user-friendly decision-support tools that can facilitate the preparation of TOD projects with the involvement of all relevant stakeholders.

CRediT authorship contribution statement

Anna Ibraeva: Conceptualization, Methodology, Formal analysis, Writing – original draft, Visualization. Gonçalo Homem de Almeida Correia: Resources, Formal analysis, Writing – review & editing, Supervision. Cecília Silva: Conceptualization, Writing – review & editing, Supervision. António Pais Antunes: Conceptualization, Resources, Formal analysis, Writing – review & editing, Supervision.

2.8. Addendum

Since the publication of the article "Transit-Oriented Development: a Review of Research Achievements and Challenges" in 2020 several new TOD-related publications became available. As of June 2022, papers dedicated to gentrification have raised particular interest (judging by the ranking of top-cited papers), which is quite natural as TOD effects on community life remain understudied. To summarize existing knowledge in the field, Padeiro et al. (2019) provided a systematic literature review on the relation between TOD and gentrification.

At the same time, TOD effect on mode choice continues to draw much attention from researchers. In this field, an article by Wang and Lin (2019) should be highlighted as an attempt to evaluate mode changes after residential relocation, distinguishing between the influence of the built environment, self-selection and travel preferences. The results demonstrate that the influence of travel preferences on residential location choice was insignificant. Instead, built environment significantly influences travel preferences. Another contribution to the longitudinal analysis of TOD effects is the work of Kamruzzaman et al. (2021), who used panel data to analyze attitudes reported by TOD residents during a ten-year period. As suggested by the authors, TOD environment affects personal attitudes, and among residents who initially disliked the built environment at TOD many start to favor it after some years, although in rare cases the opposite is also observed.

3. TRAVEL MODE CHOICE IMPACTS OF A NEW METRO SYSTEM WITH TOD FEATURES: A BETA REGRESSION ANALYSIS OF 2000 – 2017 MOBILITY CHANGES IN PORTO (PORTUGAL)*

The present chapter addresses the first research question, in particular, it aims to assess on a macro scale the influence of metro introduction and different station environments over time on mode share (namely, the shares of car and bus trips) considering trip generation and trip distribution.

Few studies have analyzed the impact of transit-oriented development (TOD) on mode choice using a longitudinal research approach, and even fewer incorporated origin-destination information in the analysis. In this chapter, we attempt to evaluate the impact of a metro system with TOD features on the share of car and bus trips applying that type of approach to two distinct types of analyses: trip generation and trip distribution. In the first case, we were concerned with mode shares registered at the parish level, in the second case, we focused on mode shares associated with different OD pairs. We based our analysis on the case of Metro do Porto (Portugal). Exploring data from two mobility surveys (2000 and 2017) using descriptive analysis and autoregressive beta modeling allowed us to detect changes in travel behavior accounting for the pre-metro mode shares. These shares were found to largely explain posterior mode shares, meaning that mode choice remained quite stable over time. Nevertheless, metro´s influence was found to be statistically significant in reducing the share of car trips. This effect was especially strong between OD pairs that had metro at both trip ends, and it intensified if the link was served by TOD stations. Metro influence on the share of bus trips varied from neutral to positive, suggesting that bus and metro complement each other rather than compete for passengers.

3.1. Introduction

In the last 25 years, Transit-Oriented Development (TOD) has been an increasingly prominent research theme both in urban planning and transport planning (Ibraeva et al., 2020). This concept, introduced by Calthorpe (1993), calls for mixed-use high-density urban developments around transit stations, as well as for parking limitations, traffic calming measures, and pedestrian/cycling-friendly local streets in nearby areas, in order to discourage the use of private cars. Numerous projects inspired by this concept have been emerging recently all over the world – e.g., FasTrack in Denver, U.S. (Ratner and Goetz, 2013), Stedenbaan, in The Netherlands (Spaans and Stead, 2016), and Corridors of Freedom in Johannesburg, South Africa (Harrison et al., 2019). The attention that researchers are devoting to TOD is, in this case, undoubtedly aligned with the

* This chapter - with slight adaptations - corresponds to the article: Ibraeva, A., de Almeida Correia, G. H., Silva, C., Antunes, A. P., 2022. Mobility impacts of a new metro system with transit-oriented development features. Transportation Research Part D: Transport and Environment, 109, 103357.

interest that TOD is attracting from both planning authorities and real estate development companies.

Amongst the frequently examined research topics, TOD impact on travel mode choices certainly, and naturally, is one of the most relevant. A vast body of knowledge concerning the effects of TOD projects particularly on car use is now available. Most of this knowledge has been assembled based on cross-sectional studies, i.e., TOD impacts were evaluated as a function of socio-economic, land-use, and transport service characteristics of different areas of the region/city under analysis in a given time period. In contrast, longitudinal research studies, wherein the evolution of such characteristics over time is taken into account, are quite rare, and even less common are studies that focus on the trips made between its different areas (including areas where transit stations are located). In fact, to the best of our knowledge, there are no studies that have analyzed whether and to what extent the implementation of a TOD project affected the modal origin-destination matrices of the region. This is precisely one of the main directions we pursue in this chapter, focusing on the Porto region, in northwest Portugal.

In the 1990s, this region, and especially Porto's city center as well as several radial highways, were suffering from severe traffic congestion and pollution problems for which the essential cause was largely consensual: the lack of a rapid transit solution in a densely populated area with around 1.2 million inhabitants. Metro do Porto (MdP), a light-rail system consisting of 67 km of double-track lines and 82 stations, was then launched to provide the foremost response to those problems. The construction works began in 1999, the first stations opened in 2002, and the last ones (to date) in 2011. With this chapter, we primarily aim to assess whether, and to which extent, this response was effective in decreasing the share of car trips. For this, we take advantage of data made available by two detailed mobility surveys carried out by Statistics Portugal (www.ine.pt) in 2000 and 2017; i.e., shortly before MdP started operations, and six years after the opening of the last stations, hence time enough for MdP to have fostered the changes in mobility patterns expected from its implementation.

More specifically, our first goal is to analyze the impact of MdP on the share of car trips performed in the Porto region considering the trips made from its 120 civil parishes (freguesias) and the trips between them; that is, we analyze both car trip generation and car trip distribution (origin-destination data). Besides, as there are always concerns about whether people switch to rapid transit from car (desired outcome) or from other transit modes, we also aim to evaluate the effects of MdP on bus ridership. Last but not least, it is also our goal to find whether the impact of MdP on mode choice varied across the types of stations included in the metro system. Indeed, the introduction of MdP was accompanied by numerous interventions in station areas (including traffic calming, sidewalk extension, cycle lanes, etc.). Depending on the nearby built environment, MdP stations can be classified as TOD (when a station is surrounded by a dense and lively area), transit-adjacent development/TAD (when a station is in proximity to an urban settlement but not properly articulated with it, especially in terms of access conditions) or park-and-ride/P&R (when a station is far away from any settlement and only equipped with a parking facility). We seek to evaluate the effect of TOD stations on mode choice as compared to other station types. From the methodological standpoint, the analyses we perform to achieve these objectives rely both on descriptive statistics and autoregressive models augmented with metro service variables.

An important trait of our analyses is their quasi-experimental nature. In fact, the road network and transit services of the Porto region went through major changes between 1985 and 2000, but after that and up to now (April 2021) practically all major infrastructure investments in the Porto region have been dedicated to the implementation of the metro system. Besides, changes to the main trip generators across the region were rather minor in this period. This is an ideal setting for applying a longitudinal research approach.

The remainder of the chapter is organized into five sections. The next one focuses on related literature and highlights the innovations we propose. Then, we provide essential information about the Porto region, its transport network and MdP. A descriptive analysis of the mobility changes induced by the new metro system appears afterwards. In the following section, we present the formulation of the autoregressive models and the results we have obtained through their estimation. To conclude the chapter, we summarize its main contributions and point out some promising research directions to explore in the future.

3.2. Related Literature

Mode choice is arguably one of the most studied subjects in Transport Planning: there are over 7,000 journal articles and reviews on the topic currently registered in the Web of Science, over 1,800 of which were published in the last two years (2019 and 2020). In this section, we refer and briefly discuss the ones that analyze mode choice in the context of TOD, particularly when they use origin-destination data or rely on a longitudinal research approach. Table 3.1 summarizes the main features of the articles selected.

Ever since TOD was conceptualized, the characteristics of the built environment in station areas (like street density, building density, and mixed-use) have been taken into account in the analysis of mode choice. In the early works of Cervero (1995), Cervero and Gorham (1995), and Cervero and Radisch (1996), the travel behavior of residents in pedestrian-friendly station areas with dense street networks was compared to the travel behavior of residents in automobile-oriented neighborhoods with curvilinear street networks and poor pedestrian environment. These initial works revealed that people with similar socio-economic characteristics living in locations with similar transit supply showed different travel preferences depending on the type of their neighborhood: those living in TODs were more likely to use transit compared to those living in automobile-oriented neighborhoods. These findings motivated a plethora of research on this topic, introducing new relevant factors such as parking availability (Chatman, 2013; Ewing et al., 2017; Tian et al., 2017), destination accessibility (Ewing et al., 2017; Park et al., 2018; Sung and Oh, 2011), intersection density (Sung and Oh, 2011) connection to buses (Chatman, 2013; Loo et al. 2010; Nasri and Zhang, 2014; Park et al. 2018; Sung and Oh, 2011), station characteristics like the opening year (Loo et al., 2010; Pan et al., 2017), or the possibility of transferring to another line

(Pan et al., 2017). In most studies, even after controlling for socio-economic and built environment characteristics, station proximity was generally reported as a significant predictor of mode choice (Cervero and Day, 2008; Crowley et al., 2009; Nasri and Zhang, 2014, etc.).

Much of the research effort has been dedicated to disclosing the importance of self-selection, i.e., the contribution of an individual's attitude towards a particular travel mode in his/her residential location choice, revealed, for example, when a person normally traveling by transit chooses to reside in an area with rich transit supply. Attitudes have proven to be important and statistically significant (Handy et al., 2005; Cervero, 2007; Cao, 2015), yet this does not dismiss the importance of the built environment. The relationships between attitudes, built environment, and mode choice tend to be rather complex, and travel preferences are not the only factor affecting residential location decisions (Guan and Wang, 2020). This can be confirmed by the behavior of dissonant residents – people that have pro-automobile attitudes but live in a TOD and vice versa (Cao, 2015). In this case, as shown by Brown and Werner (2008), attitudes matter if they are supported by the built environment, as pro-transit residents switched to transit only after a station was opened in the proximity. Similarly, Van de Coevering et al. (2016) demonstrated that people who have settled next to transit tend with time to use it more often. Attitudes seemed to be responsive to the surrounding environment: people living near railway stations developed favorable attitudes to public transport over time. In addition to the bidirectional influence of attitudes on residential location choices, there is evidence that travel destinations may also affect such choices: Cervero (2007) found out that people working within a mile (1.6 km) of a station tend to reside near transit. However, this does not necessarily mean that these residents would use transit: as shown by Khabazi and Nilsson (2021), the introduction of a transit service may shorten travel times for high-income groups living in station proximity as it prioritizes connections between dense urban neighborhoods and the CBD where high-wage residents are typically employed, yet these groups are frequently reported to use private vehicles rather than transit (Cervero and Gorham, 1995; Cervero and Radisch, 1996; Laham and Noland, 2017).

In this context, it is important to analyze TOD effect on mode choice from the perspective of OD pairs (considering both commute and leisure trips) thus accounting not only for residential location characteristics but also for the characteristics of frequent travel destinations (Wang, 2015). Guan and Wang (2020) noted that land use characteristics at a workplace affect the residential location choice (and vice versa) and indirectly affect mode choice. Furthermore, Choi et al. (2012) analyzed the influence of the built environment within a 500-meter station buffer on station-to-station ridership in Seoul for all trips on a weekday. The relationship between transit ridership and built environment varied depending on the trip end and departure time. For the morning peak hours, their results suggest that residential density at the origin and employment density at the destination increase transit ridership, yet the importance of residential density for metro ridership declines during midday and evening peak-hour periods. On the other hand, the number of feeder bus lines and a pedestrian-friendly environment were positively related to transit ridership in all time periods.

Table 3.1 - Selected articles on TOD and mode choice

Reference	Case study	Methodology	Data source	Timeframe	OD data
Cervero (1995)	Stockholm, Sweden	Historic overview/ descriptive statistics	Official data (Census)	One workday	No
Cervero and Gorham (1995)	San Francisco, Los Angeles, USA	Descriptive statistics/ Multiple linear regression (OLS)	Official data (Census)	One workday	No
Cervero and Radisch (1996)	San Francisco, USA	Comparative analysis/ discrete choice modeling (binomial logit)	Field/mail survey	One workday	Yes
Handy et al. (2005)	San Francisco Bay Area, USA	Discrete choice modeling (ordered probit)	Field/mail survey	Retrospective quasi-longitudinal	No
Cervero (2007)	San Francisco, USA	Discrete choice modeling (nested logit)	Household travel survey	One workday	Yes
Brown and Werner (2008)	Salt Lake City, USA	General linear model	Field/mail survey	Two years	No
Cervero and Day (2008)	Shanghai, China	Multiple linear regression (OLS)/ discrete choice modeling (binomial logit)	Field/mail survey	Before/after household's relocation	No
Crowley et al. (2009)	Toronto, Canada	Descriptive statistics	Household travel survey	1986 - 2001	No
Loo et al. (2010)	New York City, USA, Hong Kong, China	Multiple linear regression (OLS)	Smart card data	One workday	No
Sung and Oh (2011)	Seoul, South Korea	Multiple linear regression (OLS)	Smart card data/official data	Weekday/weekend; peak hour/non-peak hours;	No
Choi et al. (2012)	Seoul, South Korea	General linear model	Smart card data/official data;	One workday; peak/non-peak hours;	Yes
Chatman (2013)	New Jersey, USA	Multiple linear regression (OLS)/ discrete choice modeling (logit regression)	Field/mail survey	One week	No
Nasri and Zhang (2014)	Washington, D.C., Baltimore, USA	Comparative analysis/ multilevel mixed-effect regression	Household travel survey	One workday	No
Cao (2015)	Twin Cities, USA	Multiple linear regression (two-way ANOVA)	Field/mail survey	One week	No
Van de Coevering et al. (2016)	Amersfoort, Veenendaal, Zeewolde, the Netherlands	Cross lagged panel structural equation model	Field/mail survey	Seven years	No
Ewing et al. (2017)	Denver, Los Angeles, San Francisco, Seattle, Washington, D.C., USA	Descriptive statistics - comparative analysis	Field/mail survey	Five workdays	No
Pan et al. (2017)	Shanghai, China	Multiple linear regression (OLS)	Smart card data /official data	One workday	Yes
Tian et al. (2017)	Seattle, USA	Descriptive statistics	Field/mail survey	Two workdays	No
Park et al. (2018)	Atlanta, Boston, Denver, Miami, Minneapolis-St. Paul, Portland, Salt Lake City, Seattle, USA	Discrete choice modeling/negative binomial model	Household travel survey	One workday	Yes
Nasri and Zhang (2019)	Washington, D.C., Baltimore, USA	Multinomial logit (MNL)	Household travel survey	One workday	Yes
Guan and Wang (2020)	Beijing, China	Structural equation modeling (SEM)	Household travel survey	Two days	Yes
Khabazi and Nilsson (2021)	Charlotte, USA	Descriptive statistics, multiple linear regression (OLS)	Household travel survey	2002 - 2014	Yes

Similarly, Nasri and Zhang (2019) found out that transit ridership was affected not only by trip travel time, traveler's age and car ownership, but also by built environment characteristics at both the origin and the destination: TOD at both trip ends increased the probability of transit use or walk/cycle, even more so if TOD was at the destination, which could probably be explained by parking being typically limited at TOD sites. Overall, it was confirmed that high building densities and high street connectivity at both ends favored sustainable modes. However, the effect of land-use mix on transit was not significant.

Our research, inspired by the existing literature, is nevertheless quite different from the cited works. The fact that we had access to travel survey data for two years with a considerable time interval in-between (2000 and 2017) during which a new metro system was implemented allowed us to perform a quasi-experimental study of the evolution of mode choice over that period. In particular, this chapter offers what we believe to be the first attempt to combine a longitudinal research approach with OD data for analyzing the mode choice changes induced by the implementation of a metro system. The fact that this system involves stations with TOD features allows us to understand how this type of urban development can contribute to increase public transport ridership.

3.3. Porto Region

The region under study consists of the seven municipalities served by Metro do Porto – Gondomar, Maia, Matosinhos, Porto, Póvoa de Varzim, Vila do Conde and Vila Nova de Gaia (Figure 3.1, left). Though this region does not correspond to any administrative division, it approximately coincides with the Porto Metropolitan Area as defined when MdP was launched. The seven municipalities contain 120 civil parishes (*freguesias*), the smallest administrative units for which data are available in both mobility surveys (2000 and 2017). Acknowledging that mobility patterns and travel behavior may vary in urban, rurban and rural areas, the 120 civil parishes were grouped into six clusters according to their economic activity, land use and transport connection attributes (Figure 3.1, right):

(1) Metropolitan Core – municipality of Porto and central areas of Matosinhos and Vila Nova de Gaia, a continuous and well-connected urban fabric with diverse transport supply (including Porto municipal bus operator, STCP), high levels of density and land-use mix; numerous governmental institutions are located in this area.

(2) Rural North – large area predominantly agricultural with scattered settlements and low-rise buildings, poorly covered by public transport but easily accessible by car.

(3) Rurban North – area composed of residential zones, large shopping malls, industrial sites, and Porto airport, providing considerable employment opportunities. Well connected to Porto by car, yet public transport in 2000 was limited to private bus operators. Since 2006 the area is connected to the metro system, which eased access to the core area.

(4) Rurban Southeast – mostly residential low-rise area, poorly served by public transport but offering good expressway connections to the core area.

(5) Rurban Southwest – low-rise predominantly residential area with some large industrial sites, linked to Porto by several expressways, yet the access is constrained by frequent congestion

on the three main bridges connecting to Porto (*Ponte da Arrábida, Ponte do Infante D. Henrique* and *Ponte do Freixo*). The western part of the area is served by regular suburban trains.

(6) Urban North – continuous urban fabric of Póvoa de Varzim and Vila do Conde, two small towns that became important seaside resorts in Northern Portugal (their populations increase considerably in Summer).

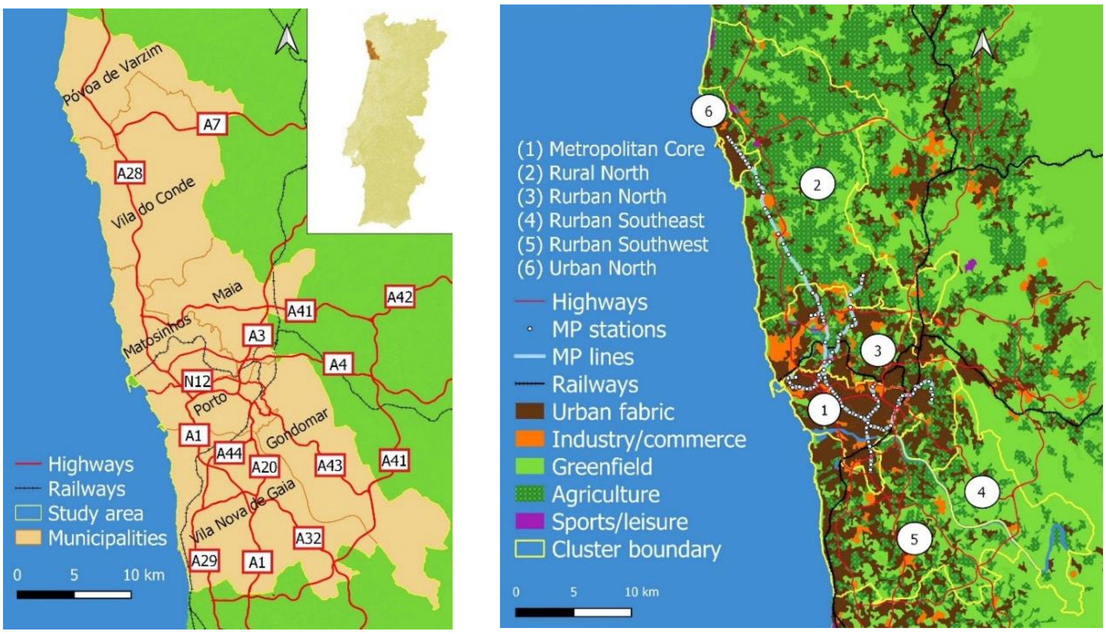

Figure 3.1 – Municipalities, road network and parish clusters of the Porto region

Table 3.2 summarizes the evolution of clusters concerning population and urbanization dynamics, between 2001 and 2011 (the latest population census years).

Table 3.2 – Cluster population and urbanization dynamics (2001-2011)

Cluster	№ of residents			Residential density (residents/km^2)		Building density buildings/km^2)	
	2001	**2011**	Var (%)	**2001**	**2011**	**2001**	**2011**
Metropolitan Core	391,302	368,580	-5.8	6,753	5,903	1,261	1,204
Rural North	107,772	113,686	5.5	458	486	132	151
Rurban North	323,183	344,954	6.7	2,669	2,831	551	564
Rurban Southeast	40,605	38,650	-4.8	476	454	117	130
Rurban Southwest	217,610	232,048	6.6	1,443	1,546	367	364
Urban North	62,503	65,731	5.2	3,813	3906	776	835
Porto Region	1,144,976	1,165,660	1.8	2,602	2,521	534	541

Source: Statistics Portugal (Population Censuses)

For years, Porto's surrounding municipalities specialized in industrial production and traditional craftsmanship, while Porto, as a regional capital, concentrated the main governmental, educational, and commercial facilities. As a result, most employment in Porto is offered in the service sector, meaning that the city attracts not only the working population, but also large numbers of consumers. The role of a regional leader in the tertiary sector results in an inevitable drawback: heavy traffic flows, which the city of Porto started to experience particularly in the 1990s. This was further aggravated by suburban growth around Porto: while Porto's central area was gradually losing residents and commerce, neighboring municipalities were increasingly attracting new residents.

The suburbanization was accompanied, if not determined, by a substantial investment in road infrastructure, particularly after the adhesion of Portugal to the European Union (then European Economic Community) in 1986. Consequently, since the early 2000s, the city of Porto is served by seven radial expressways (A28, A3, A4, A1, A43, A29 and A44) that intersect three circle expressways (A20, N12, and A41, respectively known as Via de Cintura Interna, Estrada da Circunvalação and Circular Regional Exterior do Porto) (Figure 3.1, left).

Though this investment was expected to greatly facilitate access conditions in the Porto region, it substantially increased congestion in the Metropolitan Core, where, on top of everything, the great majority of streets is quite narrow, hence, in the morning, flows coming from the expressways could not be distributed around easily, and the opposite happened in the evening. Moreover, to further worsen this situation, the motorization rate in Portugal almost tripled between the late 1980s and the 2000s, increasing from 125 to 335 cars/1000 inhabitants (Branco and Ramos, 2003; www.pordata.pt). Motorization rate growth in the period 2000-2017 for the study area is summarized in Table 3.3.

Table 3.3 – Motorization rates in the Porto region (2001-2017)

Motorization rate (/1,000 residents)	Metropolitan Core	Rural North	Rurban North	Rurban Southeast	Rurban Southwest	Urban North	Porto region
2001	433	282	472	231	366	453	373
2017	517	556	592	448	549	604	544

Source: Autoridade de Supervisão de Seguros e Fundos de Pensões

Between 2000 and 2017, the Rural North cluster experienced the greatest increase in motorization rates, followed by Rurban Southeast: additional 27 and 22 percentage points respectively ("percentage points" express the arithmetic difference between two percentages). Though motorization has grown mainly in peripheral areas, it still stays relatively low there compared to the rest of the region. Areas with the highest motorization rates (Urban North and Rurban North) showed a moderate increase of 12-15 percentage points (p.p.), while the Metropolitan Core only registered an 8 p.p. growth compared to 2000 values.

Traffic pressure in the Metropolitan Core was aggravated by the fact that train connections between this area and surrounding municipalities were quite poor: some lines were offering unreliable service and others had even been abandoned. Public transport supply within the region was mostly secured by a dense and extensive bus network. However, in the absence of dedicated lanes, bus service was also compromised by traffic congestion. Besides, routes were operated by a variety of companies (over 30) with timetables and ticketing systems poorly integrated, making bus use complex and often inconvenient.

In these circumstances, MdP surged as a project that could reduce road traffic in the region by taking advantage of existing railway infrastructure. Approximately 50 km of railway lines (at the time abandoned or underused) were repurposed for metro use, and this allowed to implement the metro system in just nine years: in 2002, the Porto-Matosinhos segment was inaugurated; this was followed, in 2006, by the launch of the Porto-Maia and Porto-Póvoa de Varzim segments, and that of the connections from Porto to the airport and to the main university campus; then, in 2008, the Porto-Vila Nova de Gaia segment was opened; and, at last, in 2011, the metro reached Gondomar (Figure 3.2). The implementation of the metro system certainly had implications on the bus service: several routes, especially in residential areas of Vila Nova de Gaia, were reconfigured to provide feeder service to metro stations.

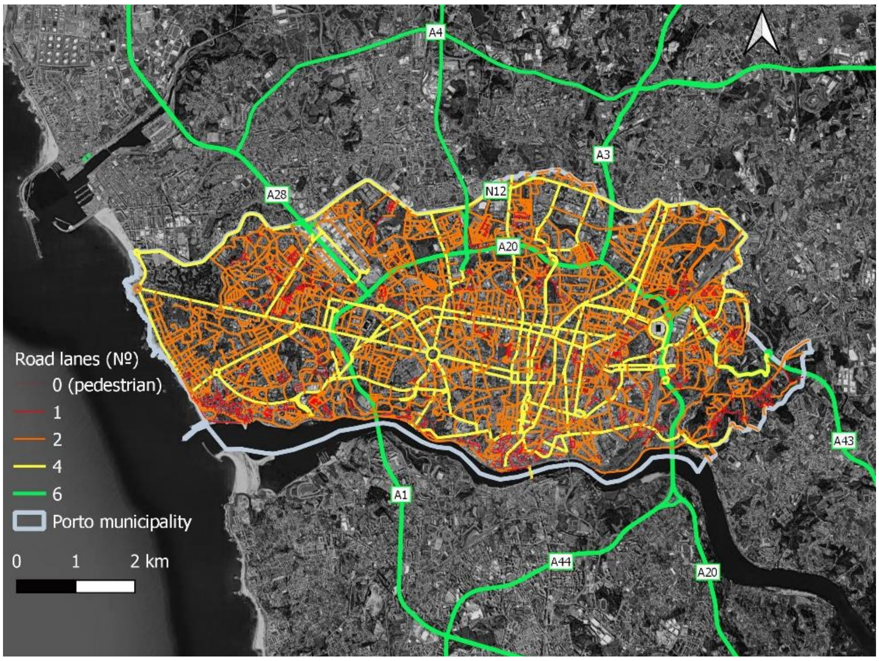

Figure 3.2 – Highway and street network of Porto

As the territory served by MdP is quite diverse in terms of land use and built environment, this has important implications in terms of station typology. In central urban areas of the Metropolitan Core, metro implementation was accompanied by significant investments in the surrounding area, including traffic calming measures, sidewalk extension, and urban design improvements like planting trees or better lighting. The introduction of metro in already dense and mixed-use urban areas, coupled with measures aimed to promote and favor metro use and access, transformed some station areas into TODs (Figure 3.4, left). However, in several cases (typically in more suburban environments) metro stations were placed at the fringe of the nearest settlements, with vacant lots in immediate station areas, hosting no commerce or service activities. Such stations were classified as transit-adjacent developments (TAD) (Figure 3.4, center). Finally, some stations mostly in rural areas are park-and-ride (P&R) (Figure 3.4, right). Naturally, in these different environments, frequencies also vary: whereas on the central station where all lines intersect (*Trindade*) trains leave on average every two minutes (workday), frequencies in non-central areas are considerably lower, with some stations of the Porto-Póvoa de Varzim segment having only two trains per hour (Figure 3.3).

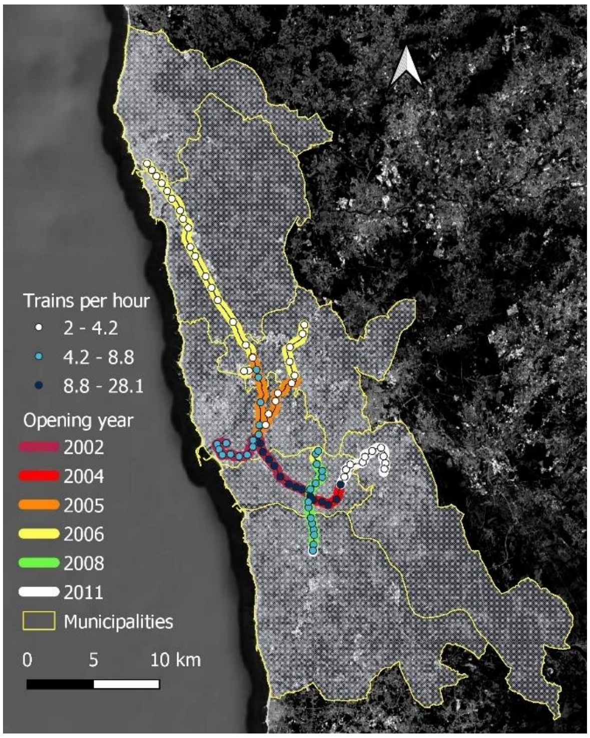

Figure 3.3 – MdP opening years and frequencies

Figure 3.4 – MdP station environments within a 400-meter buffer (TOD, TAD, and P&R station types)

3.4. Descriptive Analysis

The descriptive analysis we provide in this section, firstly concerning trip generation in the Porto region and, secondly, trip distribution, is based on the data collected by Statistics Portugal in the mobility surveys performed in 2000 and 2017 (based on 119 parishes, after one rural parish was omitted due to missing data in the 2017 survey). The respondents in both years were asked to describe all their trips (i.e., commute, leisure, personal, and shopping trips) on the day preceding the survey. Although the surveys differ in sample size and methodological approach, they both contain essential information about trip origins, destinations, and travel modes.

3.4.1. Trip generation

In this section, our focus is on trip generation by car and bus, by far the two major modes present in the Porto region during the whole period 2000-2017. Overall changes in the clusters in terms of trip generation per car, bus and metro are summarized in Table 3.4.

Table 3.4 – Mode shares in the Porto Region (2000-2017)

Indicator	Metropolitan Core	Rural North	Rurban North	Rurban Southeast	Rurban Southwest	Urban North	Porto region
Avg. change in car mode share (min-max range)	+26 p.p. [1, 41] p.p.	+41 p.p. [-4, 71] p.p.	+30 p.p. [13, 45] p.p.	+42 p.p. [32, 49] p.p.	+36 p.p. [4, 64] p.p.	+40 p.p. [38, 42] p.p.	+36p.p. [-5, 70] p.p.
Avg. change in bus mode share (min-max range)	-2 p.p. [-10, 6] p.p.	-3 p.p. [-13, 18] p.p.	-3 p.p. [-12, 5] p.p.	-5 p.p. [-8, 5] p.p.	-4 p.p. [-14, 13] p.p.	-2 p.p. [-5, 0] p.p.	-3 p.p. [-13, 18] p.p.
Avg. metro share in 2017 (min-max range)	6% [0%, 14%]	1% [0%, 17%]	2% [0%, 6%]	0%	0%	1% [0%, 2%]	2% [0%, 17%]

The share of car trips grew from 31% on average in 2000 to 67% in 2017 (i.e., 36 p.p.), while the use of bus declined from 10% to 7% on average. Overall, car mode share increased in all clusters, yet in a more pronounced manner in peripheral areas not served or poorly served by metro (Rural North, Rurban Southeast, and Urban North). The largest decreases in bus use (-5 p.p. in Rurban Southeast and -4 p.p. in Rurban Southwest) were registered in clusters that reported no metro trips, so probably former bus passengers switched to private cars. In clusters that reported at least some metro trips, the decrease in bus use was smaller. This could mean that car is a greater threat to bus use than the metro. However, further analysis is needed in this respect.

Analyzing the increase in car mode share more precisely, it is evident that, while in 2000 the use of private cars was quite homogeneous in the whole region, in 2017 this was no longer true (Figure 3.5). Namely, in the parishes of the Metropolitan Core, as well as in Porto-adjacent parishes of Rurban North served by metro, car use became less frequent. In 2017, the parishes with the higher car mode shares were generally peripheral, and either not served by metro or poorly served in terms of service frequency. At the same time, these areas also show a pronounced decline in the bus mode share (Figure 3.6). This contrasts with Porto and its more immediate suburban areas where this share mostly continued to be in 2017 at the same level as in 2000 or at a slightly lower level. Seemingly, in the case of Porto, the new metro system had a relatively limited impact on bus use, contrary to the widespread concern that with the new metro service residents might abandon buses and switch to metro (Figure 3.6). Probably, the reconfiguration of several bus routes to serve metro stations helped to secure bus ridership, as buses complement metro service rather than compete with it. Instead, in areas not served or poorly served by metro, the decrease in bus use was expressive, and very likely associated with the increase in motorization rates. Quite surprisingly, despite motorization growth, some parishes even in peripheral areas showed an increase in bus use in 2017, which likely can be explained by economic factors and not necessarily by changes in transport service levels, as suburban areas in Rurban Southwest and inland areas of Rural North are typically characterized by low income levels.

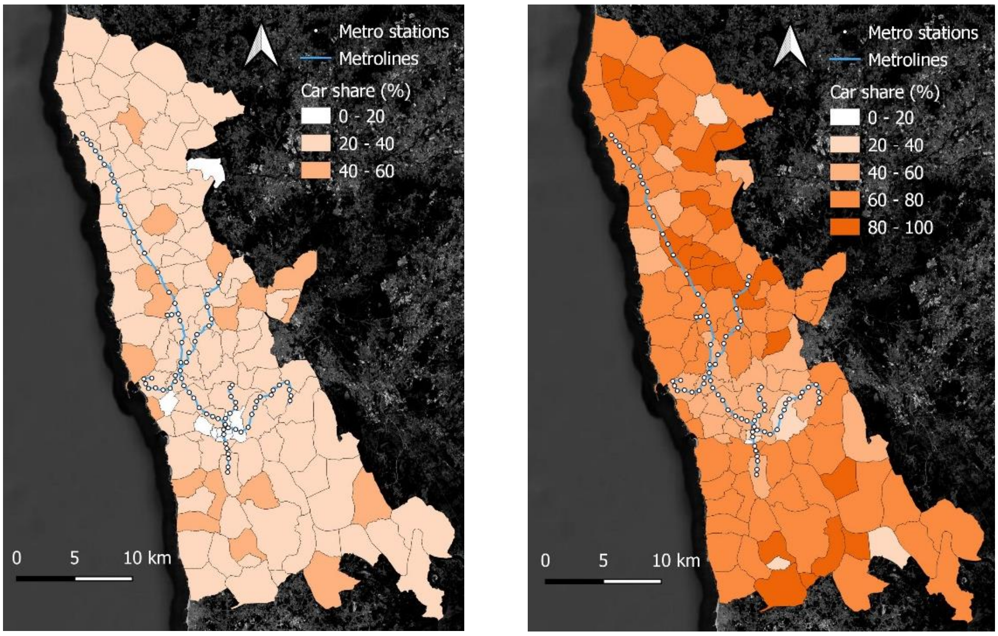

Figure 3.5 – Car mode shares in the Porto region in 2000 (left) and 2017 (right)

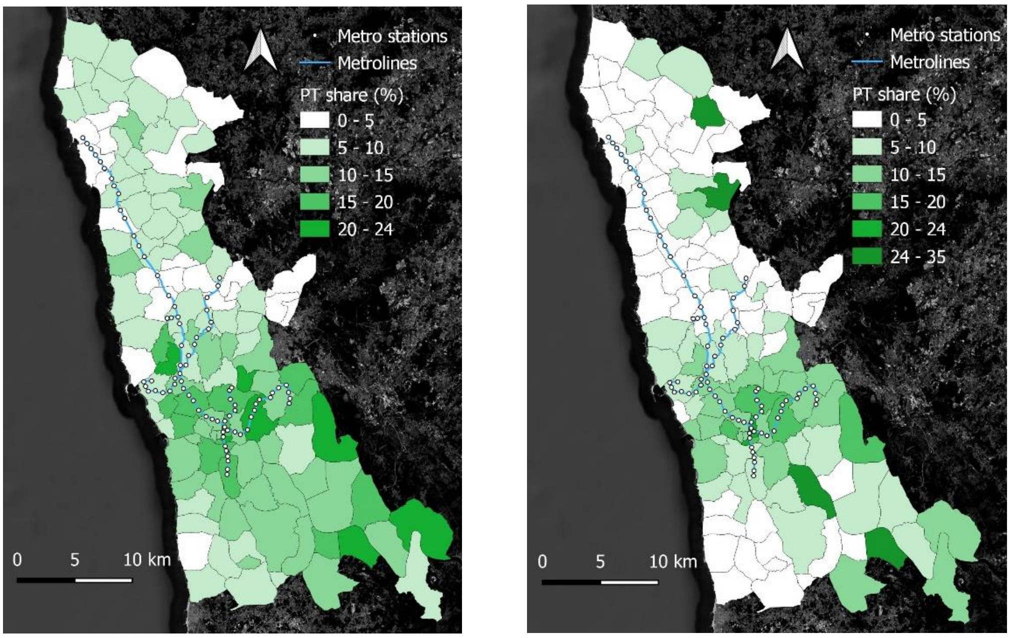

Figure 3.6 – Bus mode shares in the Porto region in 2000 (left) and 2017 (right)

3.4.2. Trip distribution

To perform a more precise parish-level analysis of trip distribution and mode choice on different OD pairs while ensuring representativeness of results, we selected pairs for which at least 20 trips were reported each way in the 2017 survey. The ensuing sample consists of a total of 222 bidirectional links covering the whole study region except Rural North, where–the number of respondents was too small to enable meaningful conclusions about local travel behavior.

The selected OD pairs were grouped into three categories: pairs with metro at both ends (61), pairs with metro at only one end (103), and pairs not served by metro (58). Table 3.5 summarizes the differences in travel behavior demonstrated by OD pairs in the different categories and the changes that occurred on these pairs in terms of mode choice between 2000 and 2017.

Table 3.5 – Mode shares in the Porto Region for the different OD pair categories

Indicator	No metro	Metro at one end	Metro at both ends
Avg. metro share	NA	NA	14%
Maximum metro share	14%	26%	65%
Av. difference in car mode share (2000-2017)	+33 p.p.	+31 p.p.	+24 p.p.
Minmax range in car mode change (2000-2017)	[-6, +54] p.p.	[-12, +67] p.p.	[-25, +50] p.p.
Av. difference in bus mode share (2000-2017)	-5 p.p.	-4 p.p.	-8 p.p.
Minmax range in bus mode change (2000-2017)	[-26, +13] p.p.	[-26, +19] p.p.	[-43, +26] p.p.

Naturally, the better the metro service provided to an OD pair, the higher the share of metro trips for that OD pair. Also, OD pairs with metro at both ends show a lower increase in the share of car trips between 2000 and 2017. At the same time, these OD pairs also registered the highest average decrease in bus use. However, quite strong within-group variations reflected in the minimum-maximum range values highlight the importance of potential explanatory factors other than metro service.

Trip distribution between clusters in 2000 and 2017 and the changes that occurred in the meantime are illustrated in Figure 3.7. To facilitate visualization, the maps on this figure only represent OD pairs that weight at least 5% of the total number of trips originating in a cluster, with arrow width reflecting the magnitude of the flow. Comparing the evolution of trip distribution in clusters between 2000 and 2017, it is noticeable that the proportion of inter-cluster trips increased, especially in Rural North and Rurban Southeast, where intra-cluster trips decreased by 20-26%. Residents of Rurban Southeast and Rural North started to make more trips to Rurban North, which for these two clusters is even more important than the Metropolitan Core. The Urban North is somewhat exceptional in this context, as the greatest share of trips involves only the neighboring Rural North cluster, without a significant number of trips to any other cluster.

The analysis of Figure 3.8 reveals how changes in mode share varied spatially in different areas. There was a quite homogeneous and solid increase in car use for almost all OD pairs in the Porto region, except those in the very central areas of the Metropolitan Core. Besides, the average length of OD pairs for which the majority (more than 50%) of trips were made by car decreased in 2017 in all groups (metro at both ends, metro at a single end, and no metro) by approximately 1.8 km, meaning that people are driving for shorter trips.

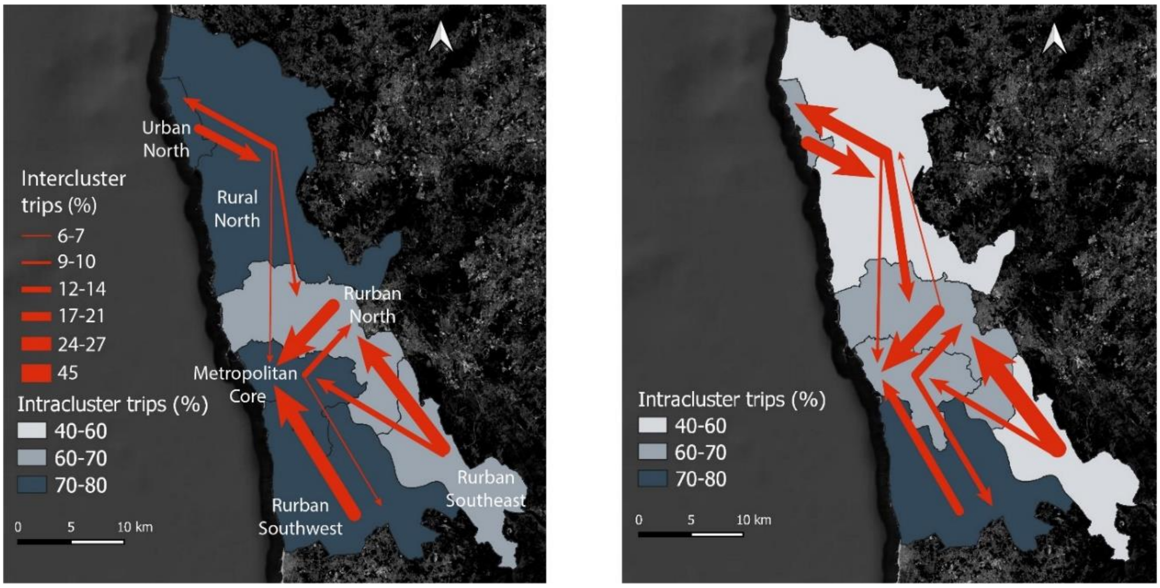

Figure 3.7 – Trip distribution in the Porto region in 2000 (left) and 2017 (right)

On the other hand, the difference in bus mode share was not so uniform across OD pairs (Figure 3.9). The greatest reduction in bus trips was observed in pairs linking the city of Porto and the central area of Vila Nova de Gaia. While the decline in bus patronage on pairs well served by metro was not surprising and could be attributed to the effect of metro, realizing that patronage decreased also on links connecting only rurban parishes was unexpected. In some cases, this decrease was associated with an increase in the share of car trips, and in others by a switch to metro. Apparently, for some people, taking metro to travel between parishes in the fringe of Porto was preferable to take a bus, even if implying a transfer in the city center. Nevertheless, as metro frequency varies over the region, bus ridership still experienced a major increase (up to 26 p.p. in comparison to 2000) between parishes that, being served by metro, did not have very frequent metro service (as between Porto's central area and Gondomar suburbs). Moreover, bus ridership increased quite significantly (up to 18 p.p. in relation to 2000) in Rurban North and Vila Nova de Gaia (Metropolitan Core). The majority of these links is served by metro at only one end and they often reflect trips to/from the municipal main town.

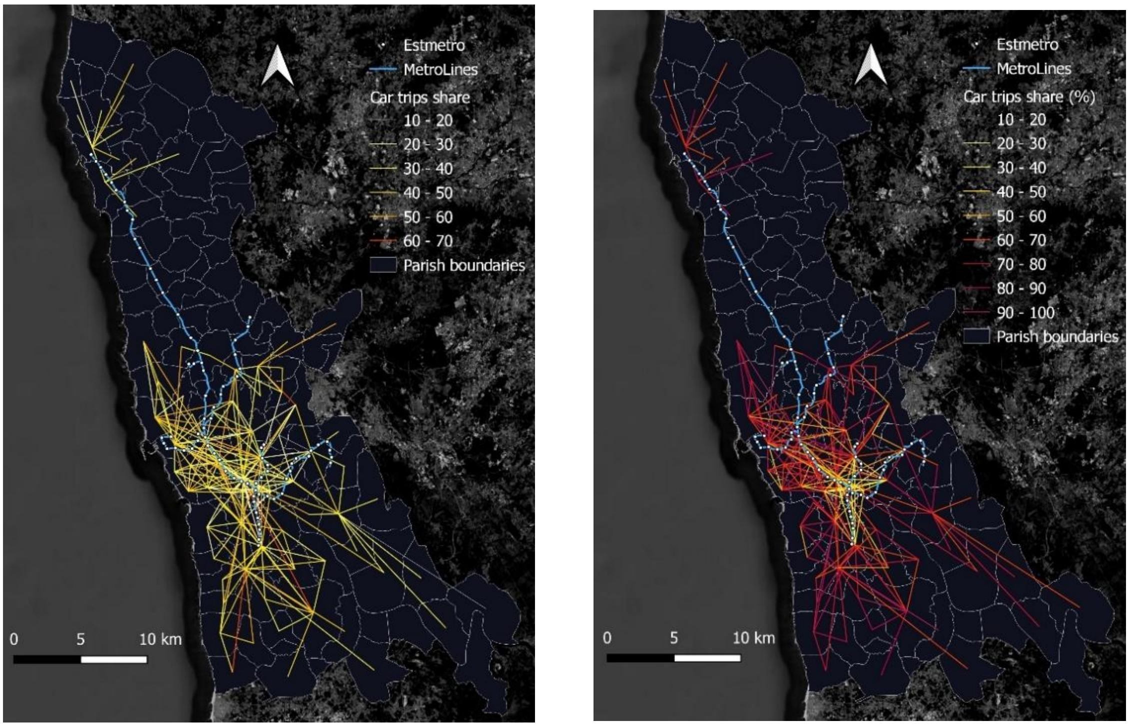

Figure 3.8 – Evolution of the car mode share in the main OD pairs of the Porto region in the period 2000-2017

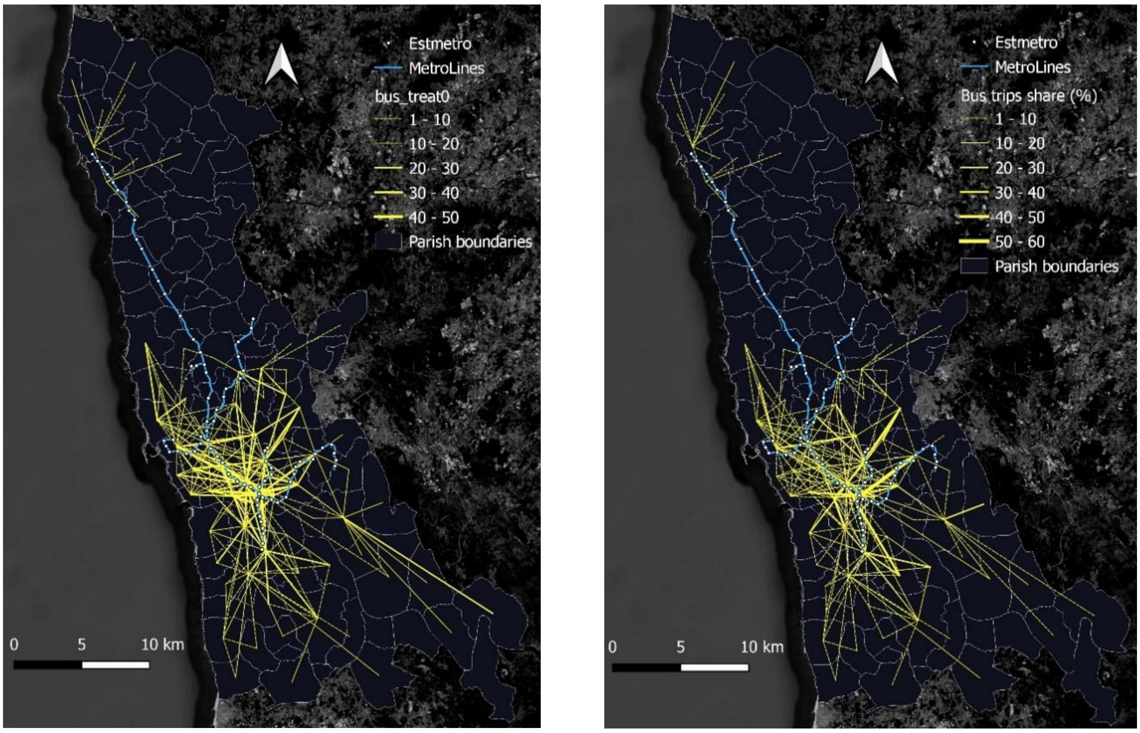

Figure 3.9 – Evolution of bus trip share on major OD pairs

To sum up, though there appear to be some common trends experienced by the majority of OD pairs (like increase in car use), the complexity and diversity of the study region and the different levels of service on the links make generalizations difficult. For this reason, the insights provided in this chapter on the potential effects of MdP on car use and bus use still need to be confirmed and validated by a systematic analysis based on statistical modeling.

3.5. Regression Models

In this section, the modeling approach we have developed to further analyze the impact of MdP on travel mode choice in the Porto region is described. In the first subsection, we justify the choice of a beta regression approach, describe the variables used and the formulation of two different models: one for trip generation analysis with parishes as units of analysis, and the other one for trip distribution analysis where the units of analysis are parish OD pairs. The second subsection is dedicated to discussing the results obtained through the estimation of both models.

3.5.1. Model formulation

Since we aimed to compare the effect of metro on two major modes (car and bus), the dependent variables of the trip generation and trip distribution models were, respectively, the share of car trips and the share of bus trips. We relied on autoregressive models, thus controlling for the pre-existing shares of each mode in 2000. This approach allows to separate the effect of metro from the pre-existing bus/car ridership levels. Furthermore, by considering mode shares in 2017 and 2000, the model will allow to indirectly detect potential self-selection: it is reasonable to expect that over a 17-year period some residents might have relocated choosing a residential location based on their attachment to metro. Unfortunately, with the data available (INE travel survey), it is not possible to measure the scope of these possible residential relocation effects during the study period. However, if residents relocated, following their preferences, to areas where they could take advantage of the recently introduced metro service, then the significance of the autoregressive coefficient should be low as shares in 2017 would tend to be quite different from shares in the pre-metro period. If, on the other hand, shares reported in 2017 are largely similar to those in 2000, this indicates that potential new residents ended up reproducing travel patterns that existed before metro, and in this case it is unlikely that metro availability affected significantly their residential location choices.

Given that the dependent variables are expressed as proportions (of car/bus use) and hence their values are limited to the [0, 1] interval, we decided to use beta regression for the estimation of the models. This type of regression analysis is specifically indicated for models where the dependent variable is a proportion (Kieschnick and McCullough, 2003), as it accommodates different density distributions of the dependent variable, non-constant variances, and skewness (Ferrari and Cribari-Neto, 2004). Therefore, this approach can be applied to modeling car and bus mode shares (though their distributions vary), which facilitates the comparison between the models.

The specific beta regression model we chose can be formulated as follows:

$$g(\mu) = \beta_0 + \beta_1 Y_{-1} + \sum_n \beta_{2n} X_n \tag{1}$$

where: μ is the mean of the dependent variable Y (in 2017 in our case); Y_{-1} is the one-period lagged dependent variable (in 2000); X_{tn} are n covariates, i.e., other variables that also influence the dependent variable; $\beta_0, \beta_1, \ldots, \beta_{2n}$ are regression coefficients; and g is a strictly monotonic and twice differentiable link function that maps (0, 1) into $\mathbb{R}$**.** The link function we used was the logit function, i.e., $g(\mu) = \ln\,[\mu/(1-\mu)] = \ln\,(\text{odds}\,\mu)$.

Beta regression models operate in the open (0, 1) interval, for this reason, scarcely occurring upper and lower bound values of 1 and 0 (representing 100% and 0% respectively) in our datasets were set to very close values of .001 and .998.

Table 3.6 – Beta regression model variables

Variable type	Variable designation	Variable description
Dependent and autoregressive	Car_share17	Share of car trips for a parish or OD pair in 2017
	Bus_share_17	Share of bus trips of a parish or OD pair in 2017
	Car_share_00	Share of car trips for a parish or OD pair in 2000
	Bus_share_00	Share of bus trips of a parish or OD pair in 2000
Covariates - Trip generation model	Metro_served	Equal to 1 or 0 depending on whether or not a parish is served by metro
	Metro_neighbor	Equal to 1 or 0 depending on whether or not a parish is a first-order neighbor of a parish served by metro
	High_freq	Equal to 1 or 0 depending on whether or not a parish is served by metro with a frequency higher than 15 minutes
	High_freq_neighbor	Equal to 1 or 0 depending on whether or not a parish is a first-order neighbor of a parish served by metro with a frequency higher than 15 minutes
	Low_freq	Equal to 1 or 0 depending on whether or not a parish is served by metro with a frequency lower than 15 minutes
	Δmotor_rate	Change in the motorization rate of a parish between 2000 and 2017
Covariates - Trip distribution model	Metro_1_end	Equal to 1 or 0 depending on whether or not one (and only one) of the parishes of an OD pair is served by metro
	Metro_2_ends	Equal to 1 or 0 depending on whether or not both parishes of an OD pair are served by metro
	TOD_2_ends	Equal to 1 or 0 depending on whether or not both parishes of an OD pair have TOD stations
	High_freq_link	Equal to 1 or 0 depending on whether or not the parishes of an OD pair are connected by metro with a frequency higher or equal to 15 minutes
	Wmotor_rate	Average motorization rate for the parishes of an OD pair weighted by the number of active residents in those parishes

The full list of variables included in the models is shown in Table 3.6. Besides analyzing changes in the share of car and bus trips in metro-served parishes, we also considered the potential spillover effect of metro in the neighboring parishes by introducing a variable that represents the first-order neighbors of the metro-served parishes. For evaluating the effect of TOD stations, several metro stations were classified as TOD. As some TOD criteria are difficult to quantify (like the neighbohood's orientation towards transit station or the perceived security level), a qualitative approach was deemed more appropriate. The classification of stations was therefore made based on the overall station's insertion in the surrounding built environment, its location related to the rest of the settlement, street density in the station area, and presence of high-rise buildings and service/commerce in the station area. Acknowledging that the share of car trips is largely dependent on car ownership, which in turn is strongly correlated with income levels, our models account for the evolution of motorization rates in the Porto region.

3.5.2. Model results

We present and discuss below in separate subsections the estimation results obtained for the trip generation models and the trip distribution models (based on the same 222 main OD pairs we considered in the previous section). The models were estimated using the “betareg” package for R (Cribari-Neto and Zeileis, 2009).

3.5.2.1. Trip generation

The estimation results for the global effect of metro on the share of car trips and bus trips are shown in Tables 3.7 and 3.8, respectively. Defined for beta regression models as the square of the sample correlation coefficient between the linear predictor and the link-transformed response (Ferrari and Cribari-Neto, 2004), the pseudo R^2 values for the models range around 0.37. Given a specific set of explanatory variables, these values are satisfactory and rather common in the context of mode choice modeling: for example, averaging regression results from the articles cited in Section 2 (“Related Literature”) gives a mean R^2 value of 0.42 for a total of 43 models with an average of 10 explanatory variables.

For both models, the lagged dependent variable was found significant and positively associated with the respective values in 2017, meaning that shares of car and bus trips in 2017 were strongly related to the respective shares of both modes in 2000. As such, even in the event of a shock (the new metro), the inertia to use the same travel mode was strong. This seems to confirm that residents’ habits to patronize a particular mode do not change easily.

The implementation of metro produced a negative impact on the share of car trips not only in the directly served parishes but also in their respective neighboring parishes, where the effect appears to be even stronger and more significant. Indeed, by transforming the log-odds estimates of model coefficients to mode share estimates, it can be concluded that the share of car trips decreased on average 8 p.p. in metro-served parishes and 13 p.p. in adjacent parishes*. Though this is somewhat surprising, the reason might be the small size of parishes in central areas and especially in Porto’s central area, which makes metro stations easily accessible to residents in metro-neighboring parishes.

The increase in the motorization rate in the period 2000-2017 was, as expected, positively related to the share of car trips, being every increase of 100 cars per 1000 inhabitants associated with a 2.6 p.p. increase in car mode share.

* This transformation is given by $\xi_i = \mu \times (1 - \mu) \times \beta_i$ where ξ_i stands for the derivative of μ (mode share) with respect to each explanatory variable i, and β_i is the regression coefficient of explanatory variable i. This formula is obtained through the differentiation of equation (1) when g is the logit link function.

Contrary to the effect on car mode share, the implementation of metro was associated with an increase of 2.2 p.p. and 2.4 p.p. in bus ridership for directly metro-served parishes and metro-neighboring parishes, respectively. Even if there were a decline in bus ridership during 2000-2017, it could hardly be attributed to metro. Rather, it could be caused by car ownership growth, as an increase of 100 cars per 1,000 inhabitants was associated with a 1 p.p. decrease in bus share in 2017.

Further exploring the change in car mode share, we assessed the impact of metro service frequency considering parishes without metro as reference. As expected, compared to non-served parishes, both the direct and the spillover effects of high-frequency metro on the share of car trips were strong and significant (Table 3.9), being linked with decreases of 13 p.p. and 13.5 p.p. respectively in metro-served and neighboring parishes. However, the effect of low-frequency metro was not significant, highlighting the importance of service frequency for metro ridership.

Table 3.7 – Estimation results for the car trip generation model

Variable	Coefficient	Marginal Effect	Std. Error	*z*-value	*p*-value
Intercept	-0.5699	n/a	0.2444	-2.332	0.0197 *
Car_share_00	4.4209	0.9587	0.6381	6.928	< 0.0001 *
Metro_served	-0.3500	-0.0775	0.1376	-2.545	0.0109 *
Metro_neighbor	-0.5674	-0.1263	0.1285	-4.415	< 0.0001 *
Δmotor_rate	1.2122	0.2628	0.5127	2.364	0.0181 *
Pseudo $R2$	0.373				
AIC	-161				
Log-likelihood	86.54 (*df* = 6)				

Note: * $p < 0.05$

Table 3.8 – Estimation results for the bus trip generation model

Variable	Coefficient	Marginal Effect	Std. Error	z-value	*p*-value
Intercept	-3.8707	n/a	0.2658	-14.564	< 0.0001 *
Bus_share_00	10.0634	0.4715	1.2942	7.776	< 0.0001 *
Metro_served	0.4451	0.0225	0.1906	2.335	0.01953 *
Metro_neighbor	0.4848	0.0244	0.1794	2.702	0.00689 *
Δmotor_rate	-2.1315	-0.0999	0.6984	-3.052	0.00227 *
Pseudo $R2$	0.3784				
AIC	-478.3				
Log-likelihood	245.2 (*df* = 6)				

Note: * $p < 0.05$

Table 3.9 – Estimation results for the extended car trip generation model

Variable	Coefficient	Marginal Effect	Std.Error	z-value	*p*-value
Intercept	-0.28310	n/a	0.26653	-1.062	0.28815
Car_share_00	3.96746	0.8589	0.65290	6.077	< 0.0001 *
High_freq	-0.56521	-0.1288	0.16420	-3.442	0.00058 *
High_freq_neibr	-0.59582	-0.1357	0.14692	-4.055	< 0.0001 *
Low_freq	0.03396	0.0073	0.17667	0.192	0.84757
Δmotor_rate	0.11661	0.0252	0.59285	0.197	0.84407
Pseudo $R2$	0.3717				
AIC	-161.3				
Log-likelihood	87.66 (*df* = 7)				

Note: * $p < 0.05$

3.5.2.2. Trip distribution

In Tables 3.10 and 3.11, we show the estimation results for the trip distribution models, which analyze car and bus trips for parish OD pairs, distinguishing pairs with metro at both trip ends and only at one end. The pseudo R^2 values obtained for these models range between 0.21 (bus share model) and 0.23 (car share model). These values of pseudo R^2 indicate that other factors are potentially important to further explain mode shares in 2017, and that predictions made based on these models must be taken with care. The already reported strong significance of pre-existing shares of car/bus trips in explaining their subsequent shares was also observed for OD pairs.

The effect of metro on the car mode share was strong for OD pairs with metro at both trip ends, being expressed by an average decrease of 10 p.p. in the share of car trips. Considering that the analysis focused on the OD pairs with the highest number of daily trips, the effect of metro is rather solid. For OD pairs that only have metro at one end, the effect was not significant. This means that, in contrast to the estimation results obtained for the trip generation models, these results clearly indicate that the simple presence of a metro station in a parish is not enough to bring on a decrease in the share of car trips. Surprisingly, the motorization rate of the parishes of an OD pair was not found to be significant.

Table 3.10 – Estimation results for the car trip distribution model

Variable	Coefficient	Marginal Effect	Std.Error	z-value	p-value
Intercept	-0.83698	n/a	0.59156	-1.415	0.1571
Car_share_00	3.82991	0.873	0.52083	7.354	< 0.0001 *
Metro_1_end	-0.08741	-0.0199	0.13259	-0.659	0.5097
Metro_2_ends	-0.44718	-0.1044	0.14736	-3.035	0.0024 *
Wmotor_rate	0.31346	0.0715	0.98962	0.317	0.7514
Pseudo $R2$	0.2327				
AIC	-149.1				
Log-likelihood	80.56 (df = 6)				

Note: * $p < 0.05$

Focusing now on the bus mode shares, OD pairs with metro at only one end were associated with a strongly significant increase of 4 p.p. in bus ridership. This probably happens because of the reconfiguration of the bus network, which improved the access to metro stations through feeder buses. At the same time, the share of bus trips did not appear to be affected in OD pairs with metro at both trip ends. Therefore, also in this case, it seems clear that metro and buses complement each other rather than compete. On the contrary, the motorization rate of the parishes of an OD pair had a significant negative influence on the bus mode share, indicating that every additional 100 cars per 1000 inhabitants were associated with an average decrease of 3 p.p. in bus ridership.

Table 3.11 – Estimation results for the bus trip distribution model

Variable	Coefficient	Marginal Effect	Std.Error	*z*-value	*p*-value
Intercept	-1.0646	n/a	0.7046	-1.511	0.1308
Bus_share_00	3.5032	0.332	0.7496	4.674	< 0.0001 *
Metro_1_end	0.4311	0.0416	0.1497	2.881	0.0039 *
Metro_2_ends	0.1221	0.0118	0.1701	0.718	0.4729
Wmotor_rate	-3.1108	-0.2948	1.1446	-2.718	0.0066 *
Pseudo $R2$	0.2121				
AIC	-555				
Log-likelihood	283.5 (df = 6)				

Note: * $p < 0.05$

Table 3.12 provides an extension of the car trip distribution model to demonstrate the influence of other potentially important variables, in this case, high metro frequency on a OD pair and TOD stations at both trip ends. In contrast to trip generation models, high-frequency service is not significant in OD pair models. Metro at both ends continues to be strongly significant, however, the coefficient changed slightly, this time suggesting a 8 p.p. expected decrease in car mode share compared to OD pairs not served by metro. The change in the coefficient might be explained by the moderate correlation of 0.25 between the "Metro_2_ends" variable and the "TOD_2_ends" variable. The latter manifested to be significant and even stronger in terms of the effect on the share of car trips than the "Metro_2_ends" variable, indicating a 22 p.p. decrease of that share in TOD-served parish OD pairs.

Table 3.12 – Estimation results for the extended car trip distribution model

Variable	Coefficient	Marginal Effect	Std.Error	*z*-value	*p*-value
Intercept	-0.04498	n/a	0.62961	-0.071	0.9430
Car_share_00	3.65340	0.8326	0.51183	7.138	< 0.0001 *
Metro_1_end	0.01841	0.0042	0.13567	0.136	0.8921
Metro_2_ends	-0.33913	-0.0788	0.15876	-2.136	0.0327 *
Wmotor_rate	-0.63968	-0.1458	1.01023	-0.633	0.5266
TOD_2_ends	-1.03127	-0.2153	0.49435	-2.086	0.0370 *
High_freq_link	0.67016	0.1576	0.50913	1.316	0.1881
Pseudo $R2$	0.2733				
AIC	-156.5				
Log-likelihood	86.26 (df = 7)				

Note: * $p < 0.05$

3.5.2.3. Final remarks

Several conclusions can be drawn from our findings. First, the impact of metro and TOD turned out to be much stronger for car use than for bus ridership, clearly suggesting that many of those who adhere to a new metro service are former car drivers and not bus riders. Second, lagged variables were strong predictors of future mode choice, so even if a new metro service is opened, people do not change their habitual modes quickly. This goes in line with findings reported by Cervero and Day (2008) and Van de Coevering et al. (2016). Our results also highlight the importance of a longitudinal research approach: by accounting for pre-existing mode choices, metro/TOD effects visible in the analysis are separated from pre-existing travel behavior and not confounded with it. Even though mode choice was found to be quite stable over time, it still can change, but the magnitude depends on proximity to metro and its frequency of service. Third, the analysis of OD pairs is extremely important in providing additional insights on factors influencing mode choice since characteristics at both trip ends are highly relevant, which also confirms previously reported findings (Choi et al., 2012; Nasri and Zhang, 2019). Mode shares for an OD pair can be quite different from those reported at the parish level: for example, our sample included two parishes connected directly (without transfers) by metro, one in the city center of Vila Nova de Gaia and the other hosting the main campus of the University of Porto, whose average share of metro trips was only 2%, yet metro share for the OD pair reached 65%. This demonstrates that ease of connection is highly relevant, and OD analysis can properly address this issue. Fourth, station environment, namely, TOD at both trip ends, can have a substantial impact on the share of car trips in an OD pair. Finally, the spillover effect of metro, especially that of high-frequency metro stations, can reach neighboring parishes and, in some cases, produce an impact on travel behavior comparable to the impact on metro-served parishes.

However, some shortcomings of our approach should be pointed out. Due to data limitations, we were not able to perform a more detailed analysis, based for instance on residential blocks. Also, the travel survey did not allow us to track new/old residents to properly control for self-selection and the importance of personal travel preferences in residential location decision. Finally, the dataset did not contain socio-demographic data associated with the OD matrices as well as any land-use information, but their inclusion in the model could certainly improve the results.

3.6. Conclusion

Transit-oriented development (TOD) impacts on travel behavior have been widely studied and discussed in the literature. Several studies have addressed this issue using a longitudinal research approach while other studies focused on destination characteristics using cross-sectional analysis. However, to the best of our knowledge, these two components (temporal dimension and destination characteristics) have not been analyzed together. This chapter aims to fill this research gap by investigating the impacts of Metro do Porto implementation on travel behavior after 17 years of operation including both trip end characteristics in the analysis. Moreover, since we perform a before/after metro analysis, our study is quasi-experimental in nature. Scarce presence of this type of studies in the literature makes the reported evidence especially valuable.

Two distinct issues were addressed: trip generation and trip distribution. In the first case, the unit of analysis was the parish, in the second it was the parish origin-destination (OD) pair. Since, in the absence of metro, residents of the study region largely relied on buses or cars in their daily routine, the effect of metro on the shares of these modes was analyzed and compared.

Although mode shares in 2000 could largely explain mode shares in 2017, the effects from metro implementation were nonetheless noticeable for both car and bus trips in 2017. The estimation of trip generation and trip distribution models pointed to the contribution of metro to decrease car use and to increase bus ridership. A detailed analysis for parish OD pairs provided additional insights: car mode share has clearly decreased in pairs that have metro at both trip ends, but the effect was neutral for pairs with metro at only one end. Compared to OD pairs not served by metro, having TOD stations at both trip ends resulted in a stronger effect on car mode share than having other types of stations, being associated with a decrease of 22 percentage points in that share. Considering bus mode share, the situation was found to be the opposite: metro at only one trip end was associated with an increase in bus ridership (probably reflecting the use of a bus to access a station), but no significant effects on bus share were observed for trips with metro at both ends. This evidence indicates that, quite likely, people switched to metro from cars rather than from buses.

These findings suggest several opportunities for future research. As characteristics at both trip ends are relevant, future studies could analyze in more detail (and at a micro scale) the influence of socio-demographic and built environment changes over the years on the changes in travel behavior. Besides, differentiating between trip purposes could provide additional insights since mode choice can also be affected by this type of factors. More precise results could be provided from studies that explicitly address self-selection and account for personal travel preferences in residential location choices. Expanding the analysis by adding more time periods could also help to understand the rate at which different people switch to a new service and why some switch faster than others. Eventually, these inputs could provide solid support for TOD planning and implementation, particularly in the process of identification of potential TOD sites.

CRediT authorship contribution statement
Anna Ibraeva: Conceptualization, Methodology, Software, Formal analysis, Writing – original draft. Gonçalo Homem de Almeida Correia: Conceptualization, Formal analysis, Writing – review & editing. Cecília Silva: Conceptualization, Writing – review & editing. António Pais Antunes: Conceptualization, Methodology, Formal analysis, Writing – review & editing, Supervision.

4. LONGITUDINAL MACRO-ANALYSIS OF CAR USE CHANGES RESULTING FROM A TOD-TYPE PROJECT: THE CASE OF METRO DO PORTO (PORTUGAL)*

The objective of this chapter is to provide an answer to the second research question: on a macro scale, how did the metro implementation affect the number of car trips over the years?

Transit-oriented development has been widely studied in recent years as a means to reduce car trips and promote sustainable transport modes. However, longitudinal studies on the matter are still rare. This chapter contributes to longitudinal research of Transit-Oriented Development (TOD) effects on travel behavior by analyzing the evolution of the number of car trips after the implementation of a light-rail metro system in the Porto region (Portugal). As Metro do Porto is a large infrastructure project (a metro network of 67 km), we relied on a macro-analysis performed at the civil parish level. Changes in the number of car trips are evaluated using a difference-in-differences model, extended to a spatial model to account for the metro's spillover effects. These effects became obvious as metro ridership is reported not only in the directly metro-served parishes but also in adjacent non-served parishes. Our results highlight the importance of the metro system in reducing the number of car trips, and this effect is visible not only in metro-served parishes but also in the neighboring ones, which are not directly served by the new transport system. Furthermore, we compare the performance of parishes predominantly served with TOD stations to those with transit-adjacent (TAD) and park-and-ride (P&R) stations. We conclude that both station types can reduce the number of car trips, yet only TOD parishes generate significant spillover effects. The importance of other potentially influential factors like building density or socio-economic characteristics is also discussed.

4.1. Introduction

Rapid urbanization has always been a major concern for urban planners challenged by the need to accommodate population growth and address increasing travel demand while preserving the environment and the quality of life. From a planning perspective, this challenge can be addressed through the concept of transit-oriented development (TOD), which aims to tackle traffic congestion and urban growth simultaneously by providing dense and mixed-used settlements around public transport nodes. Transit-oriented development is defined by American architect and urban planner Peter Calthorpe (1993) as a "mixed-use community within average 2000-foot [AN: 600 meters] walking distance of a transit stop and core commercial area. TODs mix residential, retail, office, open space, and public use in a walkable environment, making it convenient for residents and employees to travel by transit, bicycle, foot, or car". Since the 1990s, TOD has been

* This chapter - with slight adaptations - corresponds to the article: Ibraeva, A., Van Wee, B., de Almeida Correia, G. H., Antunes, A. P., 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, 103036.

gaining thrust, with TOD projects being implemented worldwide (like the Grand Paris project and the Corridors of Freedom Initiative in Johannesburg, respectively launched in 2010 and 2014). This growing trust is also reflected in a substantial increase of TOD-related publications in scientific journals (Ibraeva et al., 2020).

Since TOD is supposed to foster a reduction in car trips and the transition to sustainable transport modes, its influence on travel behavior has been the focus of numerous studies. The findings vary due to different national contexts and methods used for assessment, yet, in general, TOD is associated with fewer car trips and greater public transport patronage than in comparable automobile-oriented neighborhoods (see Section 2). Despite recent notable progress in the analysis of TOD effects on travel behavior (Ibraeva et al., 2020), studies addressing this issue using a longitudinal research approach are rare. Nevertheless, longitudinal analysis can bring several advantages compared to the typically adopted cross-sectional research design. First of all, a longitudinal analysis of panel data allows exploring more informative data and more variability, while still accounting for heterogeneity (Baltagi, 2005). Second, incorporating the temporal dimension in the analysis allows to detect the evolution occurring over the years, which is essential in the analysis of TOD influence on travel behavior: as a new public transport service is introduced, it takes some time for people to adjust their habits and mode choice to the new transport offer. The same applies to slowly occurring changes in the built environment of station areas.

In this chapter, we develop and apply a longitudinal research approach to analyze the impact of Metro do Porto – a metro system launched in Portugal in the early 2000s – on the use of private cars for commute trips (work or study). Introduced in just nine years on a territory that had no rapid transit service until then, Metro do Porto can be considered as a natural experiment in the sense that we analyze actual post-intervention changes in mode choice as opposed to preliminary project feasibility studies or studies based on stated preferences. To evaluate metro effects on mode choice, we have used a difference-in-differences (DID) model, i.e., a type of model that, to the best of our knowledge, has never been used before in the context of TOD travel behavior, but is highly appropriate for before/after analyses. A DID model estimates the effect of a treatment (in our case, the effect of the introduction of the metro) by comparing the average differences in an outcome variable (car trips) between a treated group and a control group (respectively, metro-served and non-metro-served civil parishes). To address potential bias from spillover effects and spatial autocorrelation, we also used a spatial DID (SDID) model.

The Metro do Porto network has a total length of 67 km and comprises 82 stations, of which 14 are underground (https://www.metrodoporto.pt). In addition to serving dense urban areas (notably the central area of Porto), it also serves residential suburbs and rural outskirts. In several cases, the introduction of metro was accompanied by the rehabilitation and/or renovation of adjacent areas to make them more attractive, safe, and vibrant (Pinho and Vilares, 2009). These interventions resonate with TOD principles, and this is why we classify Metro do Porto as a TOD-type project. Note, however, that Metro do Porto was not formally launched as a TOD project, and that, depending on the surrounding environment, station types vary: some of them ideally comply with TOD characteristics, while others can be better classified as transit-adjacent (TAD) – i.e., stations located in proximity to urban settlements but not properly articulated with them – or park & ride (P&R). In our analyses, we account for the difference between station types and compare their effects on mode choice.

In contrast to previous studies that have mostly concentrated on immediate station areas, this is a macro-analysis conducted at the level of the (civil) parish ("freguesia"), as one of our goals is to know whether the effect of a large TOD investment is visible not only in the proximity of stations but also on a wider scale. Our main research question is: to what extent did the introduction of metro affect the number of (private) car trips since, in the absence of metro, the car was the most convenient and fast mode of transport in the Porto region. We believe that a ten-year interval is appropriate for the purpose, as this period may encompass not only changes in residents' preferences but also emerging transformations in the built environment (Crowley et al., 2009; Dong, 2016). Thus, we also evaluate the influence of the additional covariates typically present in TOD research such as land-use and socio-economic variables.

The remainder of the chapter is structured as follows. The next section provides an overview of the existing literature on the effects of TOD on travel behavior, aiming to present existing research findings and some uncertainties (frequently associated with the lack of longitudinal research) that remain in this field. After that, we describe the case study, focusing on the socio-economic, urbanization, and travel mode trends observed in the Porto region. Special attention is given to the evolution of car use in metro-served and non-metro-served parishes. Our methodological approach is explained in the following section, where we provide a description of our DID model and its spatial extension. Subsequently, we present and discuss the modelling results we have obtained and provide a performance analysis of TOD- and TAD-served parishes. Finally, in the last section, we summarize our study and identify some directions for future research.

4.2. Literature Overview

This section is intended to provide an overview of the numerous studies addressing the influence of TOD on travel behavior. The resulting estimations of the TOD effects vary depending on the methodology applied, variables used, and national or urban context considered. Nevertheless, it is possible to generalize existing findings to some extent.

Considering transit-related variables, proximity to a transit station largely determines the attractiveness of transit use for residents (Cervero, 2007; Crowley et al., 2009; Lindsey et al., 2010; Zhang et al., 2017). Besides, a station's opening year is relevant, as older stations often perform better in terms of ridership than recently opened stations (Loo et al., 2010; Pan et al., 2017). While this could partially be explained by time-invariant characteristics (like the location of older stations in city centers where car use is restricted), a temporal dimension is also involved: with time, people get used to transit service and start using it more frequently and/or station areas gradually attract new residents that are predisposed to transit and are willing to use it (the latter phenomenon is called self-selection in the literature). Finally, the number of bus stops in a station area is considered important in several studies (Chatman, 2013; Loo et al., 2010; Nasri and Zhang, 2014; Park et al. 2018).

The physical characteristics of TOD are typically measured by street density, building density and/or intersection density, complemented by specific indicators aimed to capture the walkability of a location like a walk score (Renne et al., 2016). The functional performance of a neighborhood is typically estimated through residential density (Cervero and Arrington, 2008; Chatman, 2013; Loo et al., 2010; Nasri and Zhang, 2014; Pan et al., 2017), retail density, and/or employment density, or through composite mixed-use indexes (Chatman, 2013; Loo et al., 2010; Nasri and Zhang, 2014; Pan et al., 2017; Singh et al., 2014). When considered separately, the influence of land-use variables on transit ridership tends to be moderate, but their cumulative effect can be significant, especially for walking trips to a station. It has been empirically demonstrated that residents in walkable neighborhoods with a dense street pattern commute 1.4 to 5.1% more by public transport than residents of otherwise similar but automobile-oriented neighborhoods (Cervero and Gorham, 1995). Kamruzzaman et al. (2014) estimated that the probability of transit trips in residential TOD neighborhoods is 1.4 times higher than in non-TOD neighborhoods.

It is necessary to highlight that all the aforementioned studies account for socio-economic characteristics. Among them, household income stands out as particularly significant (Cervero, 2007; Cervero and Day, 2008; Chatman, 2013; Nasri and Zhang, 2014; Park et al., 2018; Pongprasert and Kubota, 2018), with higher income levels being associated with higher car ownership rates and a higher number of car trips. Admitting the overall importance of income level for travel behavior, several concerns remain. First, income does not always define mode choice. As shown in Cervero and Gorham (1995), comparable socio-economic groups may have different behavior in TOD and non-TOD environments. Similarly, the majority (83%) of residents in Subiaco TOD (Perth, Australia) reported a decrease in car use though the area was characterized by income levels higher than the regional average (Griffiths and Curtis, 2017). Second, even if some groups are predisposed to use the car for their trips, it is still necessary to encourage other transit-favorable groups to maintain their preferences, and, for that, it is essential to provide developments with convenient access to transit service. Third, young adults nowadays seem to be less car-oriented (lower levels of car ownership, use, and, sometimes, tenure of driving license) than equally aged adults in the past. While the underlying reasons for this phenomenon (‘peak car’) are still being debated (Goodwin and Van Dender, 2013; Klein and Smart, 2017; McDonald, 2015; Newman and Kenworthy, 2011), the trend is noticeable and may remain in the future.

While the majority of studies are cross-sectional, evaluating the influence of TOD on travel behavior at one moment in time, some authors have highlighted the need for a longitudinal approach, since mode choice, as a habit, does not change easily or quickly. A longitudinal approach is also extremely advantageous to control for residential self-selection (Cao et al., 2009; Wang and Lin, 2019), which has gained major attention in recent years. The potential effect of TOD on travel behavior has been questioned because it is unclear whether frequently reported increases of transit ridership are indeed due to the TOD characteristics of a neighborhood or due to the positive attitude some people have towards transit that eventually makes them settle in (self-select) that type of neighborhood. Van de Coevering et al. (2016) analyzed data from an internet questionnaire conducted in 2005 and 2012 for three Dutch cities (Amersfoort, Veenendaal, and Zeewolde) using a cross-lagged panel model (CLPM), and concluded that, with time, people well served by transit start to use it more often, while car use is reinforced with time amongst people living farther away from a transit station. Attitudes concerning certain mode choices were not found to be significant predictors of location choice; instead, they appeared as flexible and responding to changes in the environment: as people start to live close to a station, they become more favorable to transit. Similar findings were reported by Brown and Werner (2008), who included attitudes in their before/after analysis of changes in travel mode choices caused by the opening of an LRT station. Some residents had a positive attitude to transit even before the station's opening. However, though they could reach another station farther away, they were not using transit until a station was opened nearby (within a half-mile distance). This means that the influence of attitudes on mode choice may be limited if these attitudes are not sustained by the surrounding environment.

4.3. Porto Region Evolution

Focusing essentially on temporal changes, we provide in this section an overview of the dominant urbanization, transport system and travel mode trends in the Porto region, in the years before the launch of Metro do Porto and after the first nine years of its operation. For this purpose and, more broadly, for the analyses we conduct later in this chapter, we designate by Porto region the group of seven municipalities served by the metro system: Gondomar, Maia, Matosinhos, Porto, Póvoa de Varzim, Vila do Conde, and Vila Nova de Gaia (Figure 4.1). Altogether, these municipalities comprise 120 civil parishes (our units of analysis). The Porto region is located in the northwest of Portugal, being one of the two most important areas of economic activity and employment in the country (the other is Lisbon). It approximately coincides with the Porto Metropolitan Area (PMA) as delimited when Metro do Porto was launched (since then PMA boundaries were enlarged on several occasions through the incorporation of new municipalities). According to the latest census (2011), the total population of the Porto region was 1.2 million, remaining practically unchanged in the previous ten years.

Unless otherwise stated, all the data we used in our analyses come from population censuses conducted by Statistics Portugal (INE) and from the respective mobility information. The figures were elaborated based on publicly available information (CAOP - Carta Administrativa Oficial de Portugal and OpenStreetMap).

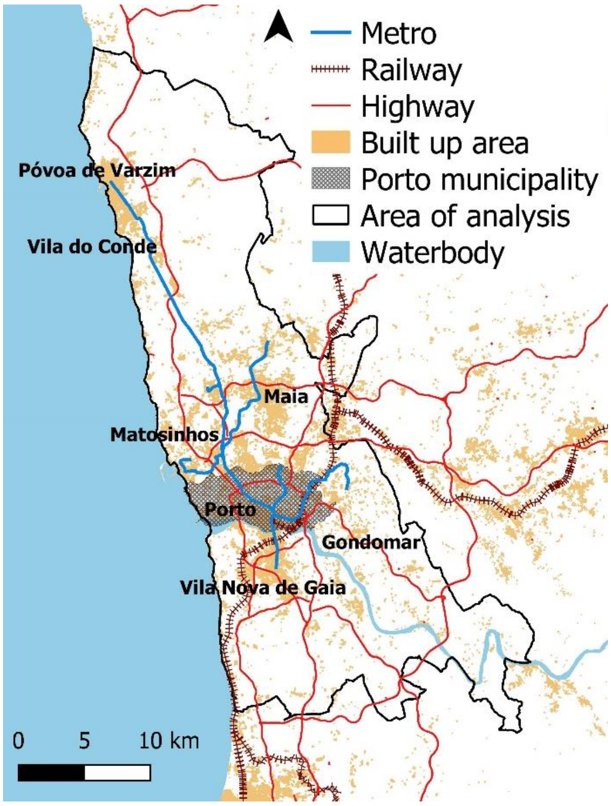

Figure 4.1 - Porto region

4.3.1. Urbanization and transport system trends (1950 – 2011)

The suburbanization process in the Porto region started in the 1950s with increasing motorization levels and dispersion of settlements, some already monofunctional (e.g., exclusively residential) (Breda Vázquez, 1992). This trend intensified over time: while in 1960 the number of residents in the five municipalities adjacent to Porto was 40% higher than in Porto municipality (around 422×103 in the periphery vs. 303×103 in Porto), in 1981 there were two times more residents in the periphery compared to Porto (641×103 in the periphery vs. 327×103 in Porto).

With the integration of Portugal in the European Union, which took place in 1986, a strong emphasis was put on the expansion of a road network that was still underdeveloped compared to other European countries like France (Padeiro, 2018). In the 1990s, major investments in the highway network were undertaken and, in 2009, this network became the 5th longest (in total length) of the European Union (PORDATA, https://www.pordata.pt/). As a consequence of these investments, Porto is now surrounded by three circle expressways (A20, N12, and A41, commonly known as Via de Cintura Interna, Estrada da Circunvalação and Circular Regional Exterior do Porto) which intersect with six radial expressways (A28, A3, A4, A1, A43, and A29).

In the years 2001-2011, employment in the region was mostly concentrated in the central areas of municipalities' main towns. Porto accumulated 8 out of the 10 most important (civil) parishes in terms of employment, with central business district (CBD) parishes offering 70% more employment than the regional average (Pinho, 2009). As Porto is mainly specialized in the tertiary sector (shops and offices), besides commuters, it also attracts numerous commerce and service consumers, together with a growing number of tourists. Matosinhos and Vila Nova de Gaia also provide significant employment opportunities, while the eastern municipality of Gondomar is largely residential, with population working mostly in the neighboring municipalities.

The Metro do Porto project was launched in this setting, with the opening of the first of its six lines connecting Matosinhos to Porto's central area in 2002. Other lines followed shortly (Figure 4.2, left), until at last in 2011 the municipality of Gondomar was connected to the metro system.

The implementation of the project significantly altered the pre-existent railway network: about 50km of the existing metro lines are former railway lines, abandoned or very little used. In other cases, railway segments were closed (connection Muro-Trofa) or started to co-exist with the metro (connection São Bento-Campanhã).

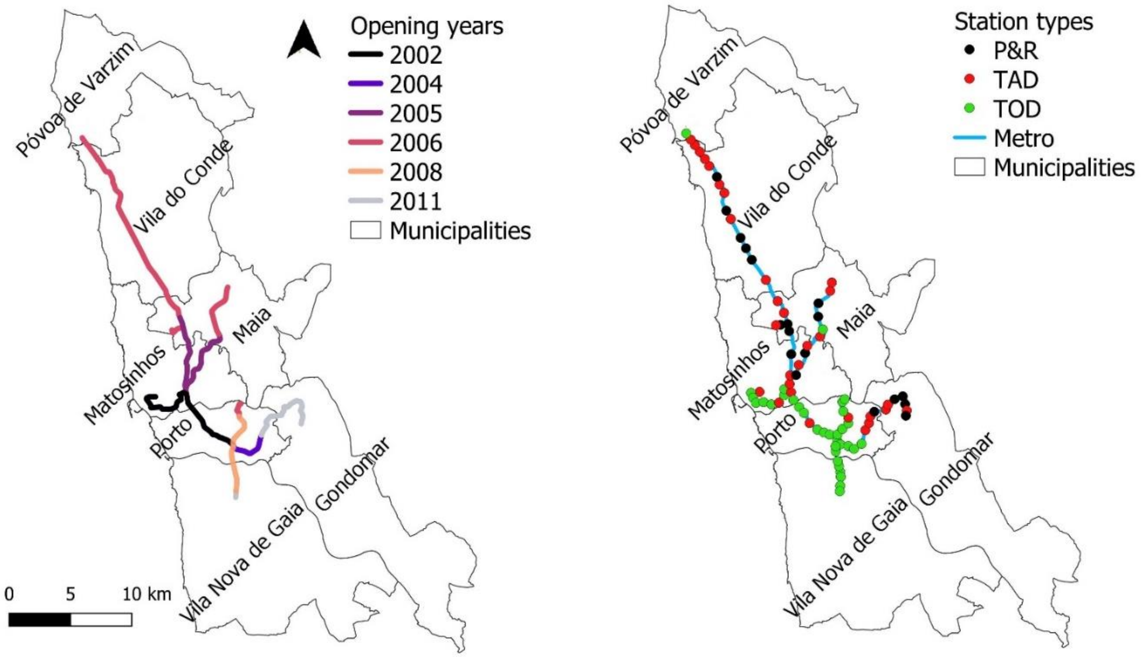

Figure 4.2 – Metro do Porto lines: opening years (left) and station types (right)

It is essential to highlight the heterogeneity of the metro-served parishes and, consequently, of the station environments. As shown in Figure 4.2 (right) and exemplified in Figure 4.3, some stations, located in dense and mixed-uses urban settings, are TOD, while others are transit-adjacent (TAD), simply placed in proximity to a settlement as an additional service, or park & ride (P&R).

It should be underlined that, while a TOD strategy was not openly assumed when Metro do Porto was launched, several measures have been taken in this sense during the project execution. Since, in many cases, metro was provided to already dense urban areas (often historic), major interventions (like large construction projects) were not possible. In these conditions, efforts were concentrated on improving the overall pedestrian and biking environment, and on implementing traffic calming measures. For instance, the upper deck of Dom Luís I bridge, connecting central areas of Porto and Vila Nova de Gaia (north and south bank of the river respectively), was closed off to car traffic and assigned to metro and pedestrian and bike use only. On Avenida da República, Vila Nova de Gaia's main avenue, the number of traffic lanes was substantially reduced, not only to accommodate metro lines (one each way) but also because sidewalks were substantially widened. Overall, Metro do Porto introduced 268×103 m2 of sidewalks, 179×103 m2 of green areas and 3.6×103 m2 of cycle lanes (Pinho and Vilares, 2009). In addition to the above measures, multimodality was promoted by the metro project, providing integrated ticketing for passengers of bus and metro and as well as a single ticket for metro trips and parking next to P&R stations.

Figure 4.3 – Different station environments within a 500-meter buffer

4.3.2. Mode choice trends (1991-2011)

In 1991, the majority (54%) of the trips to work or study in the Porto region was made by walking or bus. Globally, only 15% of the trips were made by car. These trips were most common in the suburban residential areas around Porto (Maia, Ramalde, Paranhos) and in high-income neighborhoods near the ocean (Foz do Douro, Miramar). The share of car trips increased substantially until 2001, reaching about 33% (i.e., it more than doubled in ten years), and then increased again, to 43%, in 2011. Thus, even though the region showed an average decrease of 7% in the overall number of trips (probably due to the economic crisis that severely affected Portugal after 2008), the share of car trips still increased. Instead, the share of other transport modes has diminished steadily in the period 1991-2011 (Figure 4.4).

The decline in bus patronage up until 2011 may be partially due to the Metro do Porto project. In fact, between 2001 and 2011 many bus routes were adjusted and linked to metro stations to facilitate intermodalism, and also several routes (with a length of 137 km in total) were eliminated thus affecting passenger flows. Although there is no data available about the mode choice changes in populations affected by the redesign of bus routes, we cannot exclude such changes and the impacts they could have had on travel behavior. The reduction of the bus ridership may appear to have been caused by passengers switching from buses to metro, yet this certainly was not the only reason. The share of bus trips was falling relatively uniformly in almost the entire Porto region, served or not by metro. Besides, in 2011, the metro was even weaker in terms of ridership than bus service, so even if it did attract some passengers from other buses, this attraction was certainly modest.

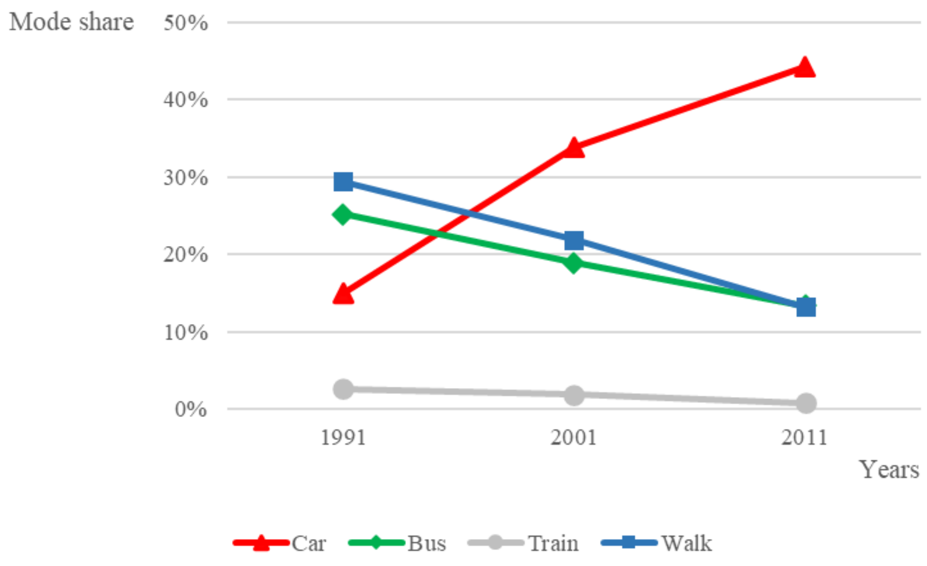

Figure 4.4 – Evolution of mode choice in the Porto region between 1991-2011

Analyzing the mode choice trends at the parish level, it is visible that the increase in car trips was especially noticeable in the northern rural areas, where the respective share went from below 10% to above 40%. This increase [of car use in northern rural areas] may be partially due to a 9% increase in the average number of trips to other municipalities for work or study in 1991-2011. Nevertheless, most trips were short distance, as the average trip time for the area increased from 15 to 17 minutes. The use of a car in these conditions might be explained by poor or absent public transport service. At the same time, it is visible how the central area and urban parishes, where car trips were frequent in 1991, gradually ceded the leadership in car trips to peripheral suburban parishes (Figure 4.5).

Bus service used to be quite important particularly in the municipalities of Vila Nova de Gaia and Gondomar, with 41-54% share of trips in some parishes in 1991, yet, even in those municipalities, the share went down to 23-28% in 2011 (still the largest share among the parishes in the region). This decline could be attributed to the introduction of metro, but it appears that the preference for the metro over the bus was limited to the centers of Porto and Vila Nova de Gaia (Figure 4.6).

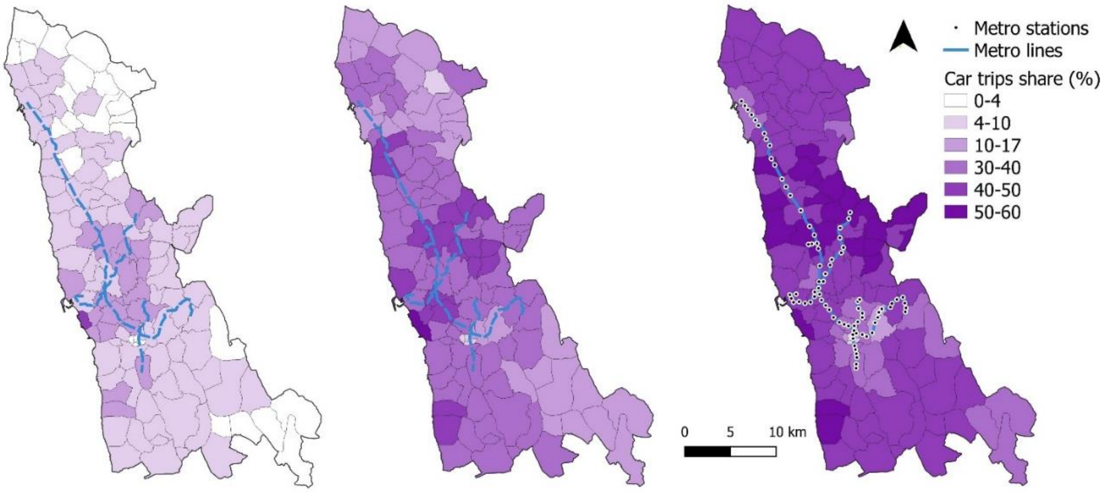

Figure 4.5 – Car trip shares in the Porto region in 1991 (left), 2001 (middle) and 2011 (right)

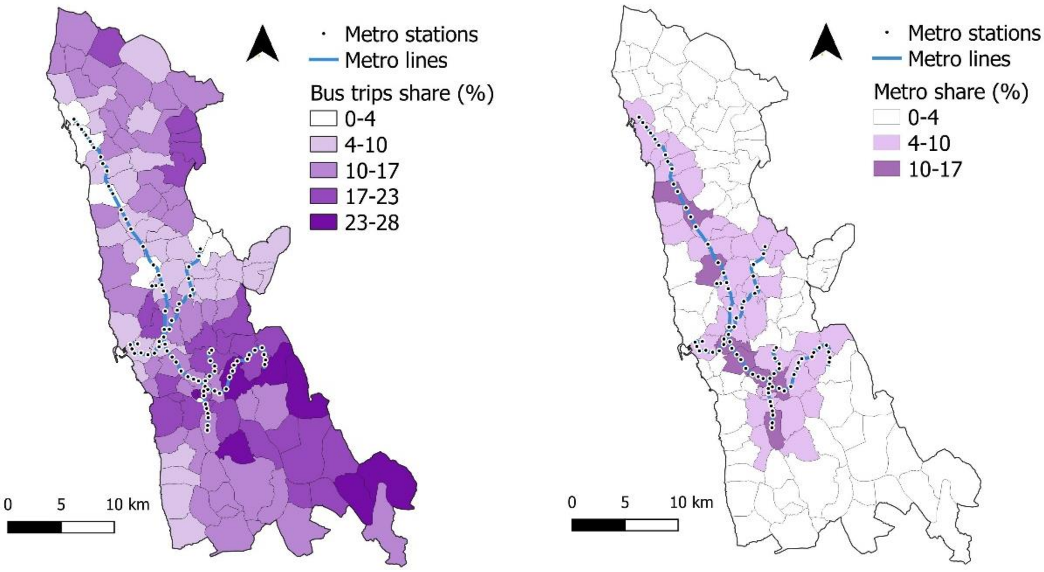

Figure 4.6 – Distribution of bus trips (left) and metro trips (right) in 2011

Although the share of metro in the directly served parishes is noticeable, this does not necessarily signify a decrease of car trips in these parishes. Based on car use data it is possible to analyze whether metro-served and non-metro-served parishes in the Porto region reveal different dynamics after the implementation of the metro. For this purpose, a parish was considered to be metro-served if it was covered by a 400 m buffer from a station. As a result, 37 parishes out of 120 were classified as metro-served. The analysis showed that the increase in car trips in metro-served parishes was markedly smaller in the period 2001-2011 than in non-metro-served parishes, even though the metro-served parishes had higher car trip shares in 1991 and 2001 (Figure 4.7). Between 1991 and 2001, both served and non-served parishes showed common trends. However, after the introduction of the metro, the trend for metro-served parishes declined, while for non-served parishes it remained quite stable. Thus, one can question whether metro, though unable to decrease the share of car trips, still contributed to decreasing the growth rate of car usage, and, if so, to which extent.

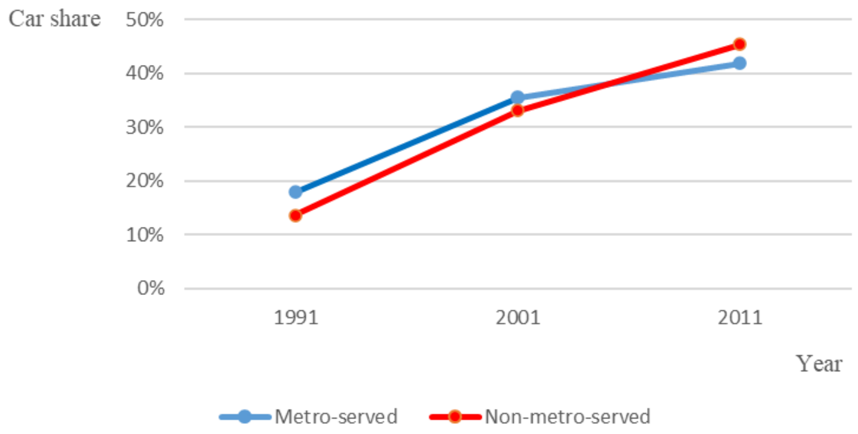

Figure 4.7 – Car trips share in the metro-served and non-metro-served parishes of the Porto region

4.4. Methodological Approach

In this section, we focus on the methodological approach adopted in our study (Figure 4.8). Once we decided to study the impact of Metro do Porto on travel mode choice, we looked for the data available. As stated before, the unit of analysis was the civil parish. After collecting the relevant data (population, land use, transport system, and mode choice), and performing a preliminary analysis to observe the mode choice trends for metro-served and non-metro-served parishes in the period 1991-2011, we decided to use a difference-in-differences model. This is a widely used approach to evaluate a treatment effect in a natural experiment setting (see, e.g., Abadie, 2005; Lechner, 2011; Strumpf et al., 2017; Vermeersch, 2007). It is especially appropriate when a treatment status is assigned externally, and only to a fraction of the units in a sample. The visualization of car use trends in the Porto region revealed a classic setup for the application of such an approach. Therefore, it should perfectly suit our needs, as we later were able to confirm.

Below, we first present the DID model upon which we have based our study. Then, we explain the extension of this base model to the spatial difference-in-differences (SDID) model that we have developed to account for heterogeneity and spatial correlation between the units of analysis. Finally, we describe all the variables included in the models.

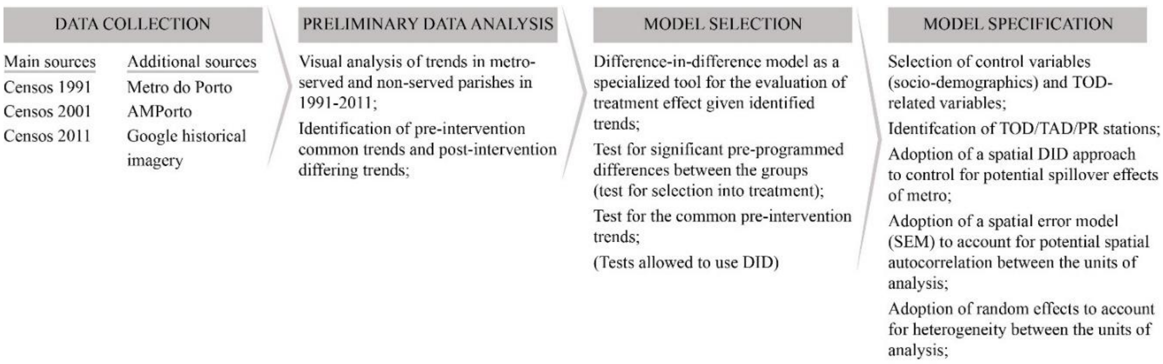

Figure 4.8 – Stages of the methodological approach

4.4.1. Difference-in-differences model

We have applied the DID model to a period defined by two census years: 2001 and 2011. The number of parishes and their boundaries remained intact in the study period, allowing to form a panel dataset. Since the metro was introduced in 2002 and the last stations were built in 2011, it is possible to perform a before-after analysis, considering metro implementation as a natural experiment. However, it should be emphasized that, since the metro was introduced gradually over the years, the estimates provided by the model mix long-, medium- and short-term effects. Since census data is available only once in ten years, this shortcoming is inevitable. Still, as the metro system was not fully complete until 2011, probably the influence of the metro, even in the older stations, did not manifest expressively. This was confirmed by a series of tests we have performed to check for the statistical significance of the impact of station age on the number of car trips.

In a DID model, the units of analysis are divided into a treatment group and a control group based on their exposure status. In our case, treated parishes were those served by metro, while other parishes served as controls. The model assumes that, in the absence of treatment (metro), both groups would follow the same trend. This common trends assumption limits the application of a DID model to cases where both treated and control groups follow the same trend in the pre-intervention period. Therefore, it is strongly recommended to visualize data for more than two periods to check if the assumption holds (Ryan et al., 2019; Strumpf et al., 2017). The outcome of the model is the evaluation of the treatment effect based on the comparison between the observed values and the hypothesized counterfactual values that treated units would show in the absence of treatment. The counterfactual values are estimated based on the trend of the control group (Figure 4.9). For this reason, the treatment status of a unit should not affect the outcome in other units; in other words, the stable unit treatment value assumption (SUTVA) has to hold (Angrist et al., 1996; Delgado and Florax, 2015).

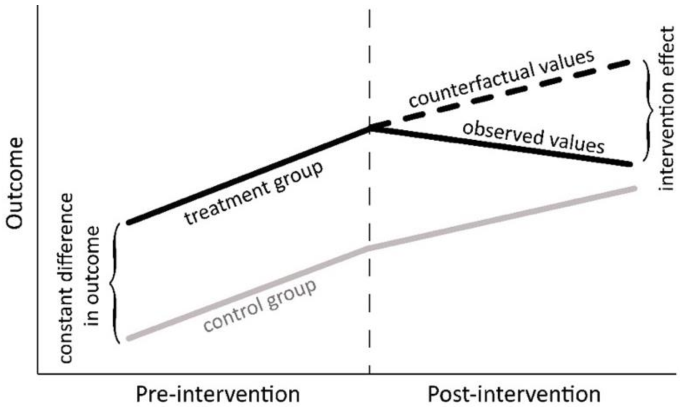

Figure 4.9 – Graphical representation of DID

A DID model is mathematically formulated in the following way (Abadie, 2005):

$$Y_{ijt} = \beta_0 + \beta_1 E_j + \beta_2 T_t + \beta_3 E_j T_t + \sum_n \beta_{4n} X_{ijtn} + \varepsilon_{ijt} \qquad (1)$$

where: Y_{ijt} is the dependent variable for unit i of group j in period t; $E_j = 1$ if j is the treated group, and $E_j = 0$ if j is the control group; T_t is a binary variable equal to 1 if t is the post-treatment period and equal to 0 if t is the pre-treatment period; E_jT_t is the interaction term between the group and time indicator (or the treatment variable); X_{ijt} are n covariates, i.e., other variables that also influence the dependent variable; $\beta_0, \beta_0, \dots, \beta_{4n}$ are regression coefficients; and ε_{ijt} is the error term.

The coefficient β_1 of variable E_j yields the average difference between the treated group and the control group, and controls for unobserved group effects (Angrist and Pischke, 2008). Ideally, regressing the dependent variable on E_j would result in a non-significant p-value, as this would mean that there are no significant pre-programmed differences between the treated group and the control group, so the groups are similar. Therefore, chances of receiving a treatment are also similar for both groups and there is no selection into treatment. The coefficient β_2 of variable T_t reflects the average common changes in both groups between the pre- and post-treatment periods. The β_3 coefficient of the interaction term E_jT_t discloses the time difference between the two groups (difference in differences), i.e., the treatment effect.

For the sake of simplicity, we will write equation (1) in matrix format (without subscripts) as follows:

$$\boldsymbol{Y} = \beta_0 + \beta_1\boldsymbol{E} + \beta_2\boldsymbol{T} + \beta_3\boldsymbol{E} \circ \boldsymbol{T} + \boldsymbol{\beta_4} \circ \boldsymbol{X_4} + \varepsilon, \tag{2}$$

where $\circ$ denotes element-by-element multiplication or Hadamard product.

Despite DID models account for time-invariant characteristics of both groups, omitting time-varying variables can bias the results. In the context of our study, the economic stagnation faced by Portugal after 2001 was a potential threat. This threat was controlled by including the unemployment rates in the model as a covariate. Other socio-economic variables were included because they are important for mode choice, allowing controlling for potential changes in the composition of both groups over the years (Lechner, 2011; Ryan et al., 2015). To address other possible time-varying confounders, an analysis of Google satellite imagery was performed to check whether significant changes happened in the period 2001-2011 in terms of street density and highway/railway networks. Other than the metro, few transport infrastructure developments were implemented in the region between 2001 and 2011: the road and rail networks were already well-established, so confounding effects from them were unlikely to exist. The same applies to street density: though certain changes took place in parallel with the Metro do Porto project, their effect was not (statistically) significant at our level of analysis. Furthermore, the set of main travel destinations in the region remained almost intact: one new shopping mall was opened (Vila do Conde Fashion Outlet) and the Asprela Campus of the University of Porto, located in the north of the city, was substantially expanded, yet again these changes were not found to be significant.

To test for selection into treatment (whether one group had greater chances to receive treatment than the other group), the number of car trips per 1000 inhabitants in 2001 (pre-treatment year) was regressed on the binary group variable E_j (treated vs non-treated parishes). The coefficient of the group variable was not significant, so even though there are preprogrammed differences between the treated and control parishes, they are still quite similar, which can be confirmed also in Figure 4.7: in 1991, the difference in car modal share between the treated and control parishes was quite clear, but in 2001 both groups were very close to each other. Since the difference between the groups narrowed between 1991-2001, the significance of the interaction term was also checked for the pre-treatment period. The interaction term for that period was not found to be significant, meaning that groups did not follow divergent trends (Ryan et al., 2015).

4.4.2. Spatial difference-in-differences model

Despite the ease of estimation and interpretation of a DID model, problems may arise in the presence of spillover effects from the treatment, since such effects would violate the SUTVA assumption. In the case of Metro do Porto, some spillover effects were already visible in Figure 4.6: metro trips are reported in several parishes that were not directly served by the metro. Since the metro attracted ridership from parishes adjacent to metro-served parishes, the adoption of a technique that would account for the spillover effects of the metro was necessary. Specifically, we selected the spatial DID (SDID) model proposed by Delgado and Florax (2015).

Extending the initial DID equation to SDID leads to the following equation:

$$\begin{aligned} \boldsymbol{Y} &= \beta_0 + \beta_1\boldsymbol{E} + \beta_2\boldsymbol{T} + \beta_3(\boldsymbol{I} + \rho\boldsymbol{W})\boldsymbol{E} \circ \boldsymbol{T} + \boldsymbol{\beta_4} \circ \boldsymbol{X_4} + \varepsilon \\ &= \beta_0 + \beta_1\boldsymbol{E} + \beta_2\boldsymbol{T} + \beta_3\boldsymbol{E} \circ \boldsymbol{T} + \beta_3\rho\boldsymbol{W}\boldsymbol{E} \circ \boldsymbol{T} + \boldsymbol{\beta_4} \circ \boldsymbol{X_4} + \varepsilon \end{aligned} \quad (3)$$

where: $\boldsymbol{I}$ is the identity matrix; ρ is the spatial autoregressive parameter, $\boldsymbol{W}$ is an $(NT \times NT)$ block-diagonal matrix combining spatial weight matrices ($\boldsymbol{W_N}$) of different time periods. In our case, the cross-sectional matrix remains the same for all time periods, so $\boldsymbol{W} = \boldsymbol{I}_T \otimes \boldsymbol{W}_N$ (where $\otimes$ denotes the Kronecker product) $\boldsymbol{W}_N$ is row-standardized, thus $\boldsymbol{WE} \circ \boldsymbol{T}$ "is the share of unit's i neighbors that are treated" (Bardaka et al., 2018; Bardaka et al., 2019; Delgado and Florax, 2015).

The average treatment effect (ATE) is the sum of the average direct treatment effect ($ADTE$) and the average indirect treatment effect ($AITE$):

$$ATE = \mathrm{E}[ATE(w)|\boldsymbol{WE}] = \beta_3 + \beta_3\rho(\bar{w}) = \beta_3(1 + \rho\bar{w}) \quad (4)$$

where $w \in \boldsymbol{WE},\ 0 < w \leq 1$, and $\bar{w}$ is the proportion of treated neighbors.

$ADTE$ is represented by the aforementioned interaction term $\boldsymbol{E} \circ \boldsymbol{T}$, while the $AITE$ for each unit is estimated based on the proportion of the treated units among the unit's neighbors. Since metro spillover effects on mode choice are consistently visible mostly in parishes directly adjacent to treated parishes, the spillover is estimated for the first-order neighbors (queen adjacency) of these parishes.

As nearby units of analysis frequently tend to be similar to each other in a number of ways, including travel behavior (positive Moran's I), we chose a spatial error model to control for spatially correlated errors (Bardaka et al., 2018; Bardaka et al., 2019; Croissant and Millo, 2019).

Additionally, random effects estimation was preferred since it also addresses unobserved random heterogeneity between units (Bardaka et al., 2018; Bardaka et al., 2019; Croissant and Millo, 2019).

To confirm the model specification, conditional Lagrange multiplier tests that detect spatially correlated errors even in the presence of random effects and vice versa were run, confirming the existence and significance of both spatially correlated errors and random effects (Baltagi et al., 2003). We used the Kapoor et al. (2007) model specification as it accounts for time-invariant and time-varying spillover effects (Baltagi et al., 2013), assuming the same spatial autocorrelation process in both individual effects and the remaining error components.

4.4.3. Model variables

The dependent variable in both models (DID and SDID) is the number of car trips per 1000 inhabitants: as the parishes differ in size, the total number of car trips had to be transformed to per capita values to allow for comparison. A summary of the independent variables is provided in Table 4.1. The principal data source of the variables was Statistics Portugal (INE).

Table 4.1 – Explanatory model variables

Variable type	Variable designation	Variable description	Data source
DID	“group”	equal to 1 for metro-served parishes, and equal to 0 for non-metro-served parishes	our classification
	“metro”	equal to 1 if in 2011 a parish was served by metro, and equal to zero otherwise	Metro do Porto
	“year”	equal to 1 in the post-treatment period (i.e., after the implementation of metro), and equal to 0 in pre-treatment period	n/a
Land-use	“buidense”	building density	INE, Census
	“landmix”	proportion of buildings with multiple uses	INE, Census
Location	“cbd_dist”	straight line distance from a parish (centroid) to Porto CBD	n/a
	“triptime”	average trip time in one direction for the main daily trip reported by the citizens	INE, Census
Parish	“TAD”	equals to 1 if the majority of metro stations in a parish are of the TAD-type, and equal to zero otherwise	our classification
	“TOD”	binary variable, equals 1 if the majority of metro stations in a parish are of the TOD-type, and equal to zero otherwise	our classification
Socio-economic	“education”	the proportion of people with complete secondary education (a proxy for income)	INE, Census
	“less13”	the proportion of people aged less than 13 years old	INE, Census
	“more65”	the proportion of people aged more than 65 years old	INE, Census
	“unemployed”	the proportion of unemployed per 1000 active residents);	INE, Census

Since metro stations also vary in their characteristics (Figure 4.3), we account for this variability with binary variables TOD, TAD, and Park and Ride (P&R). The last class is set as reference (and not included in the model) and is used to compare the performance of TOD and TAD relative to P&R. The TOD, TAD and P&R variables were defined initially based on the street density inside the 400-m buffer from a station. Street density inside the buffer was then classified into three groups. After that, a station-level analysis was made, evaluating other TOD elements such as the location of a station in the surrounding built environment, high- or low-rise development, the existence of mixed uses and local businesses, and availability of parking. A parish was classified as TOD, TAD or P&R based on the predominant station type in each case: if the majority of stations was TOD, then the parish was considered TOD. In three cases without a predominant station type, a classification was assigned to a parish according to the type of the station that had the largest passenger volume in that parish in 2011. The resulting classification is illustrated in Figure 4.10.

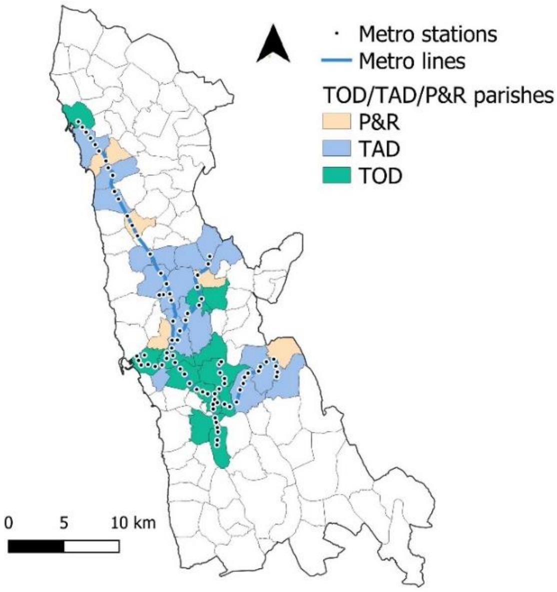

Figure 4.10 – Classification of the parishes of Porto region based on station types

4.5. Study Results and Discussion

In this section, we present, analyze and discuss the results obtained through the estimation of the models using the *splm* package of the R software (Millo and Piras, 2012). It is divided into two subsections, dedicated, respectively, to the DID model and the SDID model. In the last part of the second subsection, we focus on the performance of parishes depending on the predominant type of metro service (TOD, TAD, and P&R) they offer.

4.5.1. DID model

The results of the estimation of the DID model are presented in Table 4.2. The large value of the R-squared coefficient (0.81) and the preponderance of highly significant variables suggest that the model is quite strong in explaining the dependent variable. As can be seen for the "year" variable, the number of car trips increased over 10 years in both groups in a similar manner (as shown by the coefficient of the variable "group", the difference between treated and non-treated parishes is only 7 additional car trips per 1000 inhabitants on average).

The interpretation of the model is straightforward: the coefficients show the impact of a unit change in the different explanatory variables on the number of car trips per 1000 inhabitants between 2001 and 2011. The treatment effect of the metro was confirmed to be highly significant and associated with an average decrease of around 19.91 car trips per 1,000 inhabitants in the metro-served parishes. Among other TOD-related variables, building density was the most significant ($t = -8.44$), confirming the importance of a dense built environment for the promotion of sustainable modes and providing support for densification as a means to decrease the attractiveness of car use. In contrast, mixed uses appear to not have been a factor contributing significantly to the decrease in car use. It should be noted however that the respective variable ("landmix") is not very precise: it is based on all mixed-uses buildings, yet we had no information on whether these uses are local shops or large shops and office centers.

Table 4.2 – DID model estimation results

Variable	Estimate	Std.Error	t-value	p-value	
(Intercept)	238.46067	41.78831	5.706	3.57e-08	*
year	57.13790	9.24600	6.180	2.93e-09	*
group	7.02750	5.67564	1.238	0.216920	
triptime	-2.98380	0.39384	-7.576	8.85e-13	*
landmix	-10.52828	25.75519	-0.409	0.683083	
buidense	-0.05444	0.00645	-8.440	3.69e-15	*
education	1140.74170	78.33885	14.562	< 2e-16	*
unemployed	-0.32056	0.07443	-4.307	2.46e-05	*
more65	-0.35508	0.09753	-3.641	0.000336	*
less13	0.24968	0.15655	1.595	0.112118	
metro	-19.91631	7.06818	-2.818	0.005261	*
cbd_dist	-1.42877	0.32711	-4.368	1.90e-05	*
$R2$	0.8275				
Adjusted $R2$	0.8192				
Residual Std. Error	24.5 (df = 228)				
F statistic	99.42* (df = 11,228)				

Note: * $p < 0.05$

Regarding socio-economic variables, as expected, higher unemployment rates and greater proportions of the elderly population decrease the number of car trips. The proportion of young residents, though positively associated with car use, was not found to be significant. The only socio-economic variable significantly associated with an increase in car trips is the level of education (used as a proxy for income level) with extremely high influence on the dependent variable: an extra percentage point of residents with secondary education leads to 1.14 additional daily car trips per person. It should be noted that the highest income neighborhood of Porto (Foz do Douro) is not served by metro, so in this case the wealthiest residents naturally use a car.

Somewhat surprisingly, the number of car trips decreases as the distance to Porto CBD increases. Similarly, longer trip times are associated with less car use. Perhaps, this is the consequence of metro service being available in the distant northern parishes of Póvoa de Varzim and Vila do Conde, where people working in the central parishes of Porto, Matosinhos or Vila Nova de Gaia (with plenty of employment opportunities) could have switched to metro to avoid transport costs (including those corresponding to a loss of time caused by traffic congestion). Alternatively, in the distant parishes, that effect might also be explained by the use of buses/coaches or walking which, ceteris paribus, signifies longer trip times than travelling by car. Besides, residents in distant parishes might have less interaction with Porto CBD, mostly working in local businesses and thus being less dependent on the use of a car.

4.5.2. SDID model

The estimation of the SDID model with spatial errors, random effects and spillover effects (Table 4.3) confirmed the presence of significant individual heterogeneity (ϕ parameter) and spatially correlated errors (ρ parameter).

The average treatment effect (ATE) of metro implementation in the presence of spillover effects can be estimated using Equation (4) (Delgado and Florax, 2015):

$$ATE = \mathrm{E}[ATE(w)|\boldsymbol{WE}] = \beta_3(1 + \rho\overline{w}) = -22.06 + (-25.03 \times 0.3) = -29.57 \quad (5)$$

Thus, after accounting for both direct and indirect effects, the average treatment effect of metro increased compared to the DID model, consisting of a reduction of almost 30 car trips per 1000 inhabitants. With respect to the other variables, the direction of the relationships between the dependent and explanatory variables remained stable, and the coefficients changed only slightly.

Overall, the results confirm the potential of metro in limiting the number of car trips even when car trip rates were rapidly growing before the intervention. Considering the effect of metro implementation, it is evident that, even on a macro level of analysis, metro had a positive and significant effect on the evolution of the number of car trips. The same applies to the spillover effects of metro, though the indirect effect is naturally less significant than the direct one.

Table 4.3 – SDID model estimation results

Variable	Estimate	Std.Error	t-value	p-value	
(Intercept)	184.9039448	37.6552505	4.9104	9.087e-07	*
year	52.6443263	9.1347194	5.7631	8.258e-09	*
group	-4.0377630	5.5941124	-0.7218	0.4704248	
triptime	-1.3135456	0.5908249	-2.2232	0.0261996	*
landmix	-3.8481888	17.8659895	-0.2154	0.8294618	
buidense	-0.0349263	0.0075189	-4.6451	3.399e-06	*
education	991.8120649	72.9349486	13.5986	< 2.2e-16	*
unemployed	-0.1491637	0.0614796	-2.4262	0.0152566	*
more65	-0.3066042	0.0860939	-3.5613	0.0003691	*
less13	0.1975709	0.1251760	1.5783	0.1144866	
metro	-22.0680296	7.0946238	-3.1105	0.0018675	*
cbd_dist	-0.4022318	0.6020271	-0.6681	0.5040511	
spillover	-25.0335332	11.9811875	-2.0894	0.0366714	*
ϕ	1.327998	0.383650	3.4615	0.0005372	*
ρ	0.668218	0.063556	10.5138	< 2.2e-16	*
Pseudo - $R2$	0.7686659				

Note: * p < 0.05

Performance of TOD, TAD and P&R parishes

In order to analyze the performance of parishes considering the respective station environments, we estimated the SDID model with the inclusion of binary variables for TOD and

TAD parishes (Table 4.4). The inspection of this table reveals that both TOD and TAD parishes performed significantly better than P&R parishes: as attested by the regression coefficients, in TOD parishes this effect was more intense (additional decrease of 26.6 trips per 1,000 inhabitants) and more significant ($t = -3.6$), whereas in TAD parishes the additional decrease was just of 13.9 trips ($t = -2.2$). Moreover, TOD parishes were characterized by significant spillover effects ($t = -2.0$), as opposed to TAD parishes ($t = -0.9$). This is quite surprising, as it would be reasonable to expect that the spillover effect from TAD parishes would be noticeable since it is generally easy to park a car and leave it for the day next to TAD stations. Hence, in principle, TAD parishes could be expected to attract residents of neighboring parishes. The strength of the spillover effects of TOD parishes is possibly due to the fact that they offer a more developed bus network with greater geographical coverage than TAD parishes, which facilitates the use of metro by residents of neighboring parishes.

To sum up, and as could be expected, the influence of metro on mode choice is stronger in the parishes where metro service is offered, and it propagates to the neighboring parishes. The magnitude of the spillover effects also depends on parish types, as parishes where TOD stations are dominant reveal greater catchment potential than TAD or P&R parishes. This finding provides important support for TOD policies: TOD projects are often compromised by substantial investment costs (Cervero and Murakami, 2009; Searle et al., 2014, Tan et al., 2014; Yang et al., 2016) that are not so easy to justify if potential benefits are confined to a relatively small station area. Instead, if TOD projects, complemented by a bus network, can produce advantageous spillover effects in nearby parishes, then they might gain more support from both local population and authorities.

Table 4.4 – SDID model estimation results distinguishing parish types

Variable	Estimate	Std.Error	t-value	p-value	
(Intercept)	190.5992642	37.3905375	5.0975	3.441e-07	*
year	53.5398220	8.9134637	6.0066	1.894e-09	*
group	-5.8713394	5.3248665	-1.1026	0.2701894	
triptime	-1.3502034	0.5819435	-2.3202	0.0203321	*
landmix	-1.4595306	19.0530566	-0.0766	0.9389390	
buidense	-0.0323379	0.0074589	-4.3355	1.454e-05	*
education	994.0264672	72.0859764	13.7895	< 2.2e-16	*
unemployed	-0.1820588	0.0620645	-2.9334	0.0033529	*
more65	-0.3249594	0.0856314	-3.7949	0.0001477	*
less13	0.1963332	0.1250725	1.5698	0.1164720	
TOD	-26.5969383	7.3403817	-3.6234	0.0002908	*
TAD	-13.8937251	6.3511990	-2.1876	0.0287006	*
TODspill	-32.9865845	16.1647787	-2.0406	0.0412861	*
TADspill	-14.4419914	16.4029713	-0.8804	0.3786157	
cbd_dist	-0.4844707	0.5817444	-0.8328	0.4049634	
ϕ	1.270915	0.379173	3.3518	0.0008029	*
ρ	0.654524	0.066432	9.8525	< 2.2e-16	*
Pseudo - $R2$	0.7848339				

Note: * $p < 0.05$

4.6. Conclusion

In this chapter, we presented a study aimed to analyze the impact of Metro do Porto on the use of private cars for commute trips (work or study). The analysis extends over a ten-year period (2001-2011) and is essentially based on census data: 120 civil parishes ("freguesias") were selected as units of analysis to explore whether metro, as a large infrastructure project, produced effects noticeable on a macro scale. While the majority of studies about the effect of TOD on car use comes from the USA, our study diversifies the existing research by bringing evidence from a TOD-type project in southern Europe.

Given the natural experiment setting, a difference-in-differences model was selected as the most appropriate statistical approach. To our best knowledge, this is the first study where such approach was used to analyze the impact of TOD on travel behavior. Since metro usage was also reported in parishes not served by metro directly, the basic DID model was extended to a spatial DID model allowing to capture the spillover effects from metro. Our findings suggest that not only the direct metro effect is significant, but also the indirect metro spillover effect to neighboring units is clearly noticeable. Investigating the relative performance of TOD, TAD, and P&R parishes in explaining car use, we found that the influence of TOD parishes is significantly related to a lower number of car trips in the neighboring non-directly metro-served parishes. This finding may seem counter-intuitive at first because TOD stations are generally less accessible to cars compared to P&R stations. Therefore, it could be expected that their influence would be limited to areas close to stations (up to 0.8 - 1.6 km from a station). The fact that TOD parishes attracted passengers from areas farther out might be due to the reconfiguration of bus routes that was made specifically to make access to the metro easier. TAD and P&R stations probably have less connecting services, and this limits their spillover effects. Also, the spillover of TOD might be greater due to the overall attractiveness of the consolidated urban fabric, that provides a safer and more pleasant environment compared to relatively isolated TAD/P&R stations.

Certain policy implications can be derived from our results. TOD effects may not be limited to immediate station areas; instead, TOD spillover effects can be significant. As such, TOD investment in a given area can be beneficial not only for that particular area, but also for adjacent larger areas. To further exploit TOD spillover potential, increases in allowable densities and mixed-use settlements should be promoted, together with regular and reliable bus service linking the metro stations and adjacent parishes. The combination of these factors can significantly reduce the number of car trips even in situations where motorization rates are increasing. In the case of Metro do Porto, the planned expansion of metro lines to the southern municipality of Vila Nova de Gaia provides rich opportunities to develop new stations according to TOD principles. This expansion will possibly be reinforced by a bus rapid transit (BRT) system. The knowledge we acquired through our study can support the planning of BRT station areas as well.

As made clear above, our study already provided interesting conclusions concerning the impact of Metro do Porto on travel behavior. But we see several opportunities for future research. The first involves the application of the same methodological approach (difference-in-differences) to similar projects in other European countries to understand whether the results we have obtained are also observed in other geographical contexts – particularly in France, Italy and Spain, where numerous light-rail and fast-tram TOD-type projects were put in place in the last 25 years. Indeed, despite the growing interest that TOD is attracting in European countries, up to now the research efforts regarding its impacts on travel behavior are descriptive in nature (see, e.g., Bertolini, Curtis and Renne, 2012; Knowles, 2012; Pojani and Stead, 2018; and Paulsson, 2020). Another enticing research direction to pursue consists in the development of a micro-analysis of the impact of Metro do Porto, conducted at the census tract level ("secção estatística") to complement the macro-analysis we have performed at the parish level. This micro-analysis could provide more precise insights into the gradient of spillover effects (for example, using distance-decay functions), as well as into the relative performance of different types of stations. The main problem here is that census tract limits often change considerably from census to census, whereas parish limits stay essentially the same (another problem is that parish data are generally free while census tract data are expensive). This complicates the application of a longitudinal research design. Additionally, since our analysis was limited to work and study trips, it could be further developed in the future by also addressing other travel purposes (but this is not possible using census data in Portugal at this point). Finally, because the data from the 2021 census will become available soon, a study on the impact of Metro do Porto covering the period 2001-2021 based on panel data from three census years will be an interesting avenue for future research. Since practically nothing happened in Portugal in the last decade with respect to infrastructure investment (due to the "sovereign debt" crisis that severely affected the country and consequent bailout program), new data make it possible to study the long-term effects of the project, since these effects do not suffer from contamination of the effects of new lines or new line extensions.

CRediT authorship contribution statement

Anna Ibraeva: Conceptualization, Methodology, Software, Formal analysis, Writing – original draft, Visualization. Gonçalo Homem de Almeida Correia: Methodology, Formal analysis, Writing – review & editing, Supervision. Cecília Silva: Resources, Validation, Writing – review & editing, Supervision. António Pais Antunes: Conceptualization, Formal analysis, Writing – review & editing, Supervision.

5. IMPACTS OF TRANSIT-ORIENTED DEVELOPMENT UPON CAR USE OVER A 10-YEAR PERIOD IN PORTO, PORTUGAL: FROM MACRO- TO MICRO-ANALYSIS

In this chapter, the third research question is addressed, bringing evidence about the influence of metro on the number of car trips on a micro scale and the magnitude of the spillover effect for different station types over a ten-year period.

Transit-oriented development (TOD) as an urban planning concept that aims to promote sustainable transport modes has been actively studied in recent years, especially in the context of car trips reduction. However, longitudinal studies on the matter are still rare. In this chapter, we analyze the effects of the implementation of a new metro system in the period 2001-2011 focusing on how changes in the number of car trips were influenced by station type (TOD, TAD and Park&Ride). Specifically, we perform a before/after analysis of the impact of metro implementation in the Porto area (Portugal) both at a macro scale (civil parish) and at a micro scale (census tract). By considering these two levels of analysis it is possible to demonstrate the overall effect of metro, visible already at a macro scale, as well as more detailed effects only detectable at a micro scale. In particular, census tract-level data enables a comprehensive analysis of spatial spillover effects from different stations, comparing the extent (i.e., the distance range within which the effect of station proximity is visible) and the intensity (the reduction in the number of car trips) of the spillover in each case. Since modern urban agglomerations are rather complex structures and incorporate areas with distinct characteristics that define the metro service supply (dense urban centers, suburban residential neighborhoods, industrial sites, etc.), we control for the built environment and socio-demographic characteristics. The results of our analyses make clear that both direct and indirect metro effects are already visible at the macro scale, yet at the micro scale, it is observed that the magnitude and intensity of the spillover effects vary depending on station type. The effects of TOD stations on the reduction of car trips are the strongest and are felt at up to 2 km from a station, while TAD and Park & Ride effects are weaker and do not reach beyond 1.2 km.

5.1. Introduction

Transit-oriented development (TOD) is a manifold concept that intends to address current urban challenges like heavy traffic and associated pollution by providing dense, mixed-use, and lively neighborhoods in proximity to transit stations. A neighborhood centered around a station with a dense street network that facilitates access to transit and a variety of local retail and services is expected to discourage the use of a private vehicle. However, due to the complexity of modern cities, many factors such as socio-demographics, residential location choice and built environment characteristics at the destination may constrain the success of TOD in reducing car use. In the last ten years, accompanying the implementation of TOD projects in many countries around the globe, numerous attempts have been made to analyze and evaluate TOD's contribution to the reduction of car use and a switch to sustainable transport modes (Ibraeva et al., 2020). Notwithstanding the major progress made in this research area, several issues remain understudied.

More precisely, comprehensive micro level TOD studies (intending by "micro" census tract or census block level) are still rare. While there are numerous works developed at the individual or the household scale (Bardaka and Hersey, 2019; Chatman, 2013; Cervero and Radisch, 1996; Handy et al., 2005; Van Acker et al., 2007; Cervero and Day, 2008; Olaru and Curtis, 2015; Cao et al., 2007; Brown and Werner, 2008; Van de Coevering et al., 2016) or the neighborhood scale (Cervero and Gorham, 1995; Cervero and Kockelman, 1997; Cervero, 2007; Griffiths and Curtis, 2017; Nasri and Zhang, 2014), they are typically limited in terms of the sample size (being based on survey data) and/or geographical scope (being based on specific pre-selected station areas). City and region-wide micro-level studies relying on comprehensive census data are seemingly unavailable. Expanding the area of analysis may provide stronger evidence and, owing to greater variability, disclose phenomena that may not manifest themselves in a neighborhood-specific study, while using census data allows overcoming the limitations of a reduced sample size.

In recent years, longitudinal TOD studies have received particular attention because of the advantages they offer compared to cross-sectional studies. In fact, incorporating various time periods in the analysis allows revealing changes that occur over time, which in the TOD context is extremely beneficial given that modal shifts or changes in the built environment tend to occur slowly. Additionally, compared to cross-sectional studies, which reveal associations, longitudinal studies, under certain conditions (like precedence), provide stronger evidence of causality. Moreover, through longitudinal studies, it is possible to separate the intervention effects from the pre-existing situation if the latter is controlled for in the model. Finally, if a longitudinal dataset contains information about pre-existing personal preferences in terms of mode choice, it may also allow controlling for potential self-selection (i.e., when a person's mode choice is defined by long-established favorable attitudes towards a specific transport mode and does not depend on the surrounding built environment or transport facilities in proximity).

Existing longitudinal studies dedicated to travel behavior and TOD generally analyze the travel mode changes occurring after a residential relocation (Handy et al., 2005; Cervero and Day, 2008; Cao et al., 2007; Van de Coevering et al., 2016) or after an infrastructure/development improvement like a new station opening or the requalification of a station area (Griffiths and Curtis, 2017; Olaru and Curtis, 2015; Brown and Werner, 2008). Complementing these site-specific analyses, Ibraeva et al. (2021) describe a before/after analysis of a metro system implementation considering the whole system and assuming a macro level of analysis (civil parish).

In this chapter, we aim to further explore the link between travel behavior and TOD, addressing the shortcomings of the aforementioned works. In fact, in this chapter, we offer a detailed micro-level (census tract) analysis of changes in the number of car trips for work/study in a region that received a new metro service during a 10-year period of analysis (2001-2011). Since no other major infrastructure investment occurred during this period in the study area, our study design can be considered "a natural experiment". Moving from a parish level evaluation to a more detailed census tract level - in the Porto area, up to 77 census tracts are included in the same parish - allows to accurately estimate not only the direct effect of metro implementation but also its spillover effect and the gradient of the spillover intensity. The region of the analysis (Figure 5.1) is the territory of seven municipalities served by Metro do Porto (Gondomar, Maia, Matosinhos, Porto, Póvoa de Varzim, Vila do Conde and Vila Nova de Gaia).

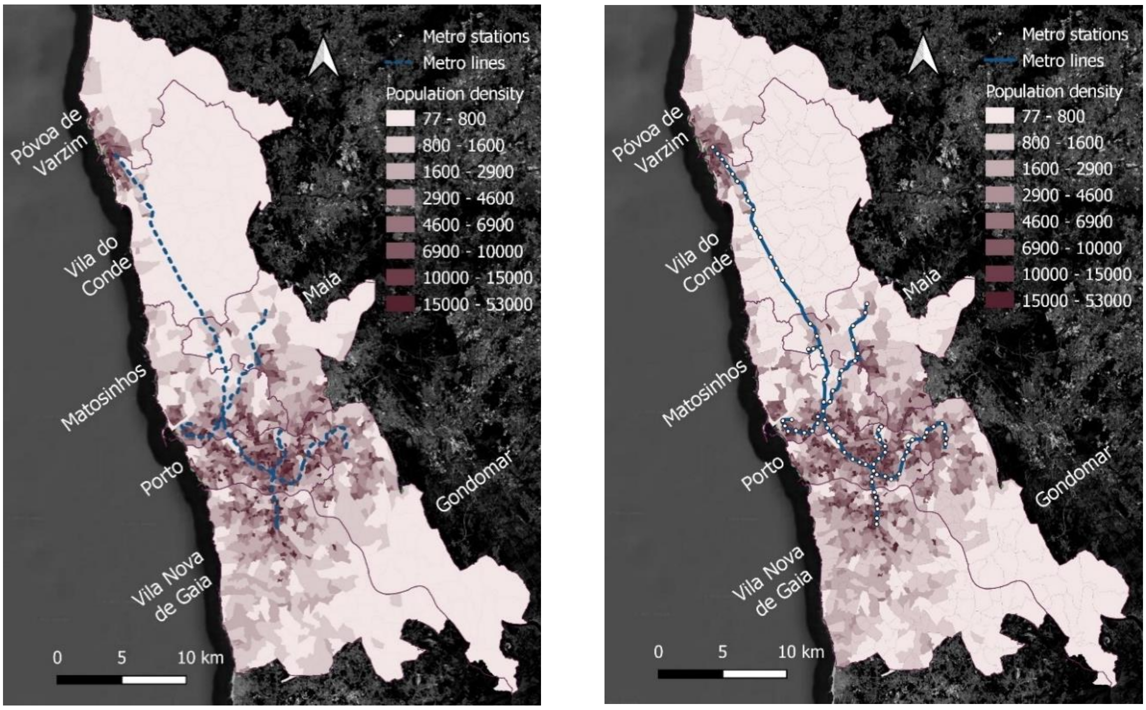

Figure 5.1 – Population density in the study area in 2001 (left) and 2011 (right)

Metro do Porto is an LRT system that opened in 2002 connecting the second-largest city in Portugal – Porto – with seven neighboring municipalities. Implemented in just nine years (the last stations of the existing network opened in 2011), this metro system operates in very diverse geographic environments: from dense urban areas to suburban and even rural areas. While historically Porto's CBD accumulates the main shopping areas and major governmental and service facilities, there are nevertheless numerous workplaces located in the neighboring municipalities. Given this configuration, the network of daily flows in the region is rather complex. In the absence of metro, daily movements in the area were essentially secured by private vehicles and, to a lesser extent, by buses. Metro implementation was associated with a reduction in the share of car trips on major origin-destination pairs (see Chapter 3) as well as overall reduction in car use for commuting trips in parishes served by metro (Ibraeva et al., 2021).

As station types vary depending on the surrounding environment, using census tract-level data allows us to compare the performance and spillover effects of different station types identified in the Metro do Porto network: TOD, TAD (transit-adjacent development) and P&R (Park&Ride). By contrast to TOD, TAD stations are located in the proximity but peripherally to a settlement, being poorly connected with it and lacking service/commercial/recreational facilities in the immediate station area. P&R are isolated stations in mostly rural areas provided with an adjacent parking lot.

The remainder of the chapter is structured as follows. In the next section, we describe the modelling approach, followed by an overview of the variables used in the analysis. Then we present the results of the models (parish-level and the census tract level) and discuss them. Finally, the last section summarizes the results and provides some final remarks.

5.2. Modelling Approach

In this section we explain the regression modelling approach adopted in this study. First, the general model formulation applied to both macro and micro scale analysis is provided. Second, a more detailed description of parish-level model and census tract-level model is given due to varying spatial specifications implemented in each case.

5.2.1. General model

To obtain the results between different scales of analysis and highlight details that only a more refined dataset can detect, an essentially similar approach was used in both cases. The Hausman test, applied to the initial OLS models at parish and census tract levels, supported the use of the fixed effects model (FE) in both cases. For an analysis with only two time periods, this model is identical to the first difference estimator and takes the following form:

$$\Delta Y_i = \beta_1 \Delta X_{i1} + \beta_2 \Delta X_{i2} + \ldots + \beta_k \Delta X_{ik} + u_i,$$

where ΔY_i is the difference in the dependent variable (number of car trips per 1000 inhabitants) between two time periods (2001 and 2011), ΔX_{i1}, X_{i2} ... X_{ik} are differences in the covariates, and Δu_i is the idiosyncratic error term. With this model formulation, it is possible to estimate whether/how changes in the explanatory variables affect changes in the dependent variable at the same time controlling for omitted unobserved effects that vary between the units but are constant over time.

While both models are based on the same equation, spatial structures at a macro and micro scale are naturally different (Figure 5.2). In the first case parishes, the smallest administrative units in Portugal, have the average area of 6 km^2 (ranging between 0.25 km^2 and 19.43 km^2) and population of 9680 in 2011. In the second case, statistical census tracts (subdivisions of parishes) have the average area of 0.46 km^2 (from 0.008 km^2 to 8 km^2) and population of 743 in 2011. Due to these differences, there are distinct patterns of spatial clustering in each case, and they need to be accommodated using different spatial specifications for the parish-level model and the census tract-level model which are explained next.

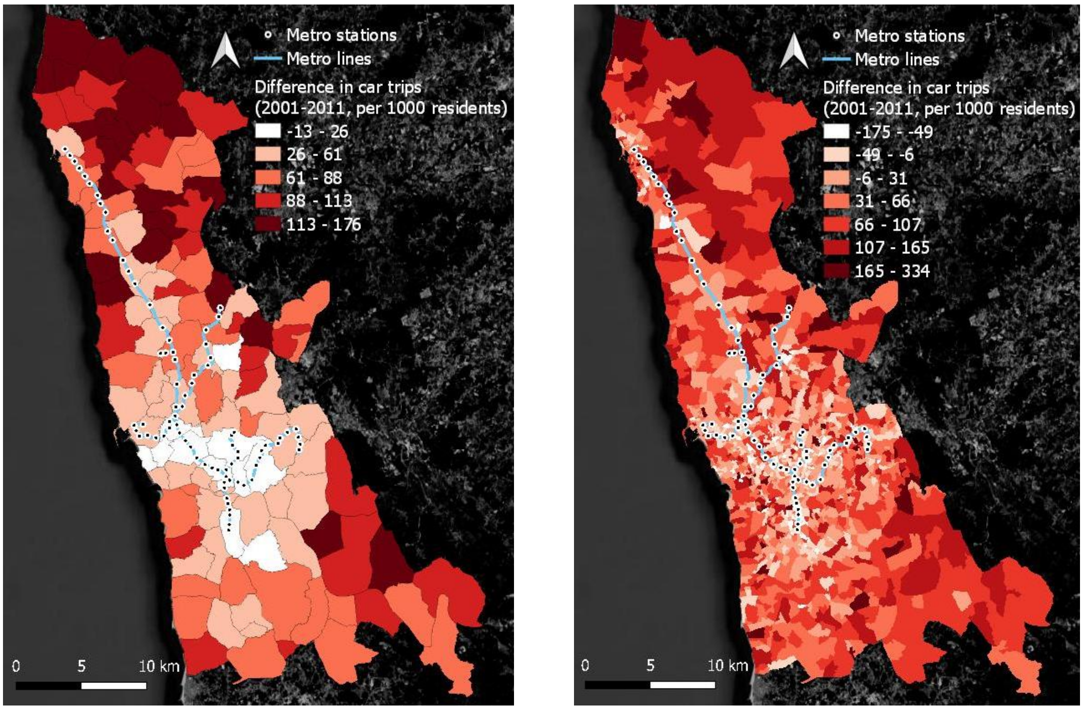

Figure 5.2 – Changes in car trips at macro (parish) and micro (census tract) level in 2001-2011

5.2.2. Spatial parish-level model

Visible spatial clustering and Moran's I statistic (statistic = 0.55, p-value = 0.001, calculated using queen contiguity) indicate quite strong spatial dependence between the parishes. Robust Lagrange Multiplier tests that allow detecting spatial error autocorrelation in the presence of a spatially lagged dependent variable and vice versa (Anselin et al., 1996) were performed to identify the source of spatial dependency. At the macro-level, RLM tests found appropriate the use of a spatial lag model. Thus, the parish-level spatial autoregressive (SAR) model takes the form:

$$\Delta Y_i = \rho(I_T \otimes W_N)\Delta y + \beta_1 \Delta X_{i1} + \beta_2 \Delta X_{i2} + \ldots + \beta_k \Delta X_{ik} + u_i,$$

where W_N is the $N \times N$ spatial weights matrix and ρ is the corresponding spatial parameter. The use of a spatially lagged dependent variable is justified when neighboring observations show similar values, which in the context of our study can reflect the natural clustering of urban, suburban or rural parishes. Besides, this specification is appropriate when one expects a value observed in a unit to be influenced by the values of its neighboring units. However, this is hardly the case in our sample since it is difficult to imagine that increase in the number of car trips in a parish would provoke increases in adjacent parishes. Alternatively, the use of a SAR model is justified in cases when endogenous interaction is possible so that "changes in one region/agent/entity set in motion a sequence of adjustments in (potentially) all regions in the sample such that a new long-run steady state equilibrium arises" (LeSage, 2014). In our case, Metro do Porto could potentially produce an effect in the directly-served parishes that propagated to their first-order neighbors, then second-order neighbors, etc., eventually reaching the whole study area, and in its turn, this global effect might have fed back into the directly-served parishes.

5.2.3. Spatial census tract-level model

Considering the census tract-level model, specification with spatially correlated errors (SEM) was the most appropriate (also supported by the RLM tests). According to Croissant and Milo (2019), "the spatial error is (…) appropriate when one expects the innovation relative to one observation to influence the outcomes of neighboring ones, as would be the case for an economic shock of some kind to a given region (fully) influencing the relevant dependent variable in that region and also propagating – with distance-decaying intensity – toward nearby ones". Since the implementation of a large-scale infrastructure project (Metro do Porto) can effectively be considered a "shock", this model specification should properly account for the spatial dependence in the error term possibly related to the metro introduction. The SEM model for the census tracts takes the following form:

$$\Delta Y_i = \Delta X_{i1} + \beta_2 \Delta X_{i2} + \ \dots + \beta_k \Delta X_{ik} + \ u_i, \qquad u_i = \lambda W u + \varepsilon,$$

where W is the $N \times N$ spatial weights matrix, λ is the corresponding spatial parameter and ε is the error term with $\varepsilon_i \overset{iid}{\sim} N(0, \sigma^2)$.

5.3. Model Variables

The main data source for our study is the Census data for 2001 and 2011 provided by Statistics Portugal (INE) that contains information related to socio-demographic characteristics of the residents, commuting mode choices, travel times and built environment characteristics at the origin. Information in both years was aggregated into the same units of analysis forming two panel datasets, one with 120 parishes and the other one with 1561 census tracts. The distribution of metro trips in 2011 was then mapped to establish a cut-off distance after which the shares of metro ridership become imperceptible (on average, 2 km from a metro station). Observations located beyond the metro's influence buffer were considered as the reference level in the regression models.

For all models presented in this chapter, the dependent variable is the difference between 2001 - 2011 in the number of car trips for work or study per 1000 inhabitants. Statistical summary of the dependent variable is provided in Table 5.1.

Table 5.1 – Summary statistics of the dependent variable

Variable	Mean	Std. Dev.	Min.	Max.
Δ number of car trips/1000 inhabitants	36.2	62.5	-175	334.5

Furthermore, variables that control for socio-demographic characteristics are also formulated in the same way for all models. These include variables reflecting the population composition by age, unemployment rate and the number of residents with completed secondary education or higher, serving as a proxy for the income level. Besides, average trip time is added since it certainly affects the mode choice as well as average train frequency.

Regarding the built environment characteristics, all models account for the land-use mix and dwelling density. However, the data reflecting the land-use mix is not very precise: the variable of land-use mix is represented as the share of mostly residential/mostly non-residential buildings as opposed to exclusively residential buildings. Therefore, it does not provide detailed information about the uses present in a building. Nevertheless, it can still differentiate between relatively mixed areas and monofunctional residential-only neighborhoods. To avoid multicollinearity, residential and building density were substituted by the dwelling density (highly correlated with both residential and building density). Besides, as census tracts' areas are rather small, residents likely work/study outside of the census tracts of their residence, having to travel through neighboring census tracts to get to places of their work/study, so characteristics of these adjacent tracts might also influence the mode choice. For this reason, spatial lag of the dwelling density was introduced to the census tract-level model.

Metro-related explanatory variables vary depending on the scale of the model. For the aggregated macro-level model, a parish was considered metro-served if a 400-meter buffer from a metro station at least partially overlapped a parish's area. For the micro-level model, census tracts whose centroids are located within a 400-m buffer and a series of consecutive distance ranges (400m – 800m, 800m - 1200m, 1200m - 1600m, 1600m - 2000m) from the metro stations were identified. The distance for the last buffer (2 km) was selected to cover the first-order neighbors of the metro-served parishes to evaluate the spillover effect as these indirectly served parishes also reported metro trips in 2011.

Finally, to evaluate the effect and spillover magnitude for different station types, a qualitative analysis was performed to identify TOD, TAD and P&R stations. The initial evaluation was based on the visual analysis of station areas using satellite imagery which allowed to assess street configuration in the area, access conditions and overall stations' insertion in the surrounding environment. More specifically, the aim was to see whether there was a dense street network in each station area and whether the network's configuration facilitated the reach of a station. Additionally, it was possible to evaluate the access conditions: existence of sidewalks, lighting and bus stops/parking lots in area. Finally, using Census and OSM data station areas were assessed considering the development type (high or low-rise) and presence of commerce/services. After determing different station types, network distance between metro stations and census tracts' centroids was calculated, finding the closest metro station for each census tract. Census tracts were then grouped into the categories that reflect the distance to the closest station and its type. Table 5.2 provides the summary and brief explanation of all used variables.

Table 5.2 - Variable description

Variable type	Variable designation	Variable description
Dependent variable	car_trips	Difference in the number of car trips per 1000 inhabitants between 2001 and 2011
Explanatory variables common for macro- and micro-level models	dwell_dens	dwelling density in 2001 and 2011
	lumix	share of mostly residential/mostly non-residential buildings in 2001 and 2011
	plus_65	number of residents aged 65 or more per 1000 inhabitants in 2001 and 2011
	sec_edu	number of residents having completed secondary education or more per 1000 inhabitants in 2001 and 2011
	triptime	average trip time in 2001 and 2011
	unemp	number of unemployed residents per 1000 inhabitants in 2001 and 2011
	below_13	number of residents aged 13 or less per 1000 inhabitants in 2001 and 2011
Explanatory variables specific to the macro-level model	metro	binary variable, equals 1 if a parish is served by metro in 2011 and zero otherwise
Explanatory variables specific to the micro-level model	dwell_dens_lag	spatial lag of the dwelling density variable
	PR400/ PR800/ PR1200/PR2000	binary variable, equals 1 if a census tract's centroid is located within a 400-meter buffer/within a range of 400 – 800-meters/within a range of 800 – 1200-meters/within a range of 1200 – 2000-meters from a park&ride station, being it the closest station as well
	TAD400/TAD800/ TAD1200/ TAD2000	binary variable, equals 1 if a census tract's centroid is located within a 400-meter buffer/within a range of 400 – 800-meters/within a range of 800 – 1200-meters/within a range of 1200 – 2000-meters from a TAD station, being it the closest station as well
	TOD400/TOD800/ TOD1200/ TOD2000	binary variable, equals 1 if a census tract's centroid is located within a 400-meter buffer/within a range of 400 – 800-meters/within a range of 800 – 1200-meters/within a range of 1200 – 2000-meters from a TOD station, being it the closest station as well
	trainhour	average workday number of trains per hour passing on the closest metro station
	up_to400/ up_to800/ up_to1200/ up_to1600/ up_to2000	binary variable, equals 1 if a census tract's centroid is located within a 400-meter buffer/within a range of 400 – 800-meters/within a range of 800 – 1200-meters/within a range of 1200 – 1600-meters/within a range of 1600 – 2000-meters from the closest metro station

5.4. Regression Results

This section reports the results obtained by all three models: at first, the parish-level model, then the census tract-level model that evaluates the overall effect of metro station proximity, and, finally, the census tract-level model that accounts for both proximity to a station and station type. All models were estimated using the "spatialreg" packages in R (Bivand and Piras, 2015).

5.4.1. Parish-level model

The results of the parish-level model are presented in Table 5.3. The autoregressive term (ρ) is statistically significant and positive, meaning that the number of car trips in a spatial unit (parish) increased as the number of car trips in its neighboring units also increased and vice versa. The effect of metro in the directly-served parishes, as well as metro spillover effects for the first-order neighbors of the directly-served parishes, are visible already at the macro scale. For the directly-served parishes, metro implementation was associated with a decrease of 24 car trips per 1000 inhabitants.

As expected, growth of the unemployment rate and the number of residents aged 65 or more was inversely related to changes in the number of car trips, while an increase in the number of residents with complete secondary education or higher (a proxy for income level) was associated with an increase in the dependent variable. Considering built environment controls, only the increase in the dwelling density was statistically significant in reducing the number of car trips at a 90% confidence level.

Table 5.3 – Parish-level model estimation results

Variable	Coefficient	Std.Error	z-statistic	p-value	
intercept	30.9507	12.423	2.4914	0.0128	*
lumix	0.002	0.0343	0.0572	0.9544	
below_13	-0.1193	0.1697	-0.7028	0.4822	
plus_65	-0.5496	0.1703	-3.2272	0.0013	*
sec_edu	0.4193	0.0918	4.5667	4.9558e-06	*
unemp	-0.0558	0.0213	-2.6123	0.0089	*
trip_time	0.5014	0.7607	0.6592	0.5097	
dwell_dens	-0.0031	0.0017	-1.7849	0.0742	.
metro	-24.4215	4.881	-5.0034	5.633e-07	*
ρ	0.5395	0.078	6.9103	4.8364e-12	*
Log likelihood	-547.3123				
AIC	1116.6				

Note: * $p < 0.05$, . $p < 0.1$

The results displayed above were obtained through the model that controls for spatial autocorrelation of the dependent variable, introducing a spatial lag as a covariate. By doing so, it is assumed that the value of the dependent variable in a given spatial unit depends on the values in the neighboring units, but also the value in that unit influences the values in the neighboring units. Faced with this feedback effect, a few analysts (LeSage and Pace, 2009; LeSage, 2014; Bivand and Piras, 2015) recommend estimating the direct, indirect and total effects taking into account the value of the spatial autoregressive parameter. The impact measures after correction for the spatial autocorrelation effects are reported in Table 5.4.

Table 5.4 – Impact measures for the parish-level model

Variable	Direct		Indirect		Total	
lumix	0.0021		0.0021		0.0042	
below_13	-0.129		-0.13		-0.259	
plus_65	-0.5944	*	-0.599	*	-1.1935	*
sec_edu	0.4535	*	0.45709	*	0.9106	*
unemp	-0.0603	*	-0.0608	*	-0.1212	*
triptime	0.5424		0.5466		1.089	
dwell_dens	-0.0034	.	-0.0034		-0.0068	.
metro	-26.4135	*	-26.6194	*	-53.033	*

Note: * $p < 0.05$, . $p < 0.1$

The coefficient for the average direct metro effect remained almost unchanged and similar to the coefficient for the average indirect effect. The average indirect effect coefficient reflects the global spillover from metro implementation for the whole area of analysis: metro introduction in one parish affects the number of car trips in it, and this affects the number of car trips in the first-order neighbors of the directly served parishes, then from the first-order neighbors the spillover moves on to subsequent neighbors, eventually covering the whole study area and feeding back to the directly-served parishes. As stated before, introducing a metro station in a parish led to an average decrease of 26 car trips per 1000 inhabitants in that parish, but it also influenced the non-directly served parishes, where the average decrease was almost identical. However, it should be highlighted that this estimation of the global spillover effect (i.e., the effect that affects the whole area, going beyond the neighborhood set of the directly-served units) relies essentially on the spatial autoregressive parameter and the spatial weights matrix. The resulting drawback of this model is that, for different variables, the ratio between the direct and the indirect effect is the same (Elhorst, 2014). Acknowledging that the magnitude of the indirect effect may vary depending on the distance to metro (i.e., local spillover effect can be revealed at a micro scale), in the following section (3.2) this issue is addressed in more detail.

Other covariates remained largely unchanged, yet it is interesting to note that only the direct and the total effects of the dwelling density were significant (at a 90% confidence level), meaning that at the parish level, changes in car trips were negatively affected by changes in the density levels at the origin but not by changes in the density levels of the origin's neighbors.

5.4.2. Census tract-level model (metro proximity)

The results of the census tract-level model that evaluates the effect of station proximity are presented in the Table 5.5.

At the micro-level, growth in the number of residents aged 13 or less (per 1000 inhabitants) and in the average trip time became significant and positively related to the growth of car trips. Both results were expected: having children is often associated with many additional trips (to day care, sport and leisure facilities, etc.) that are easier to make by car, as well as longer trips. Surprisingly, growth in the unemployment rate became positively related to the number of car trips in the census tract-level model. While this effect was not observed in the parish-level model, it is possible that on a micro-scale in certain census tracts unemployment increase coincided with an increase in car trips, for example, in the peripheral rural areas where car remained essential for daily trips and where unemployed could have relocated due to lower cost of life (notably, cheaper rents).

Regarding built-environment controls, switching from parish-level to census tract-level analysis shows how some of the factors that might be irrelevant on a macro scale turn out to be significant on a micro-scale. In the case of the dwelling density, both the variable and its spatial lag were found to negatively affect the number of car trips (the latter only at a 90% confidence level). Interestingly, though the spatial lag appeared less significant, spatial lag's coefficient was slightly stronger than the coefficient of the variable itself (-0.006 vs -0.003), meaning that on a micro scale densities in the neighboring units might be slightly more important in defining mode choice than densities in the census tract of residence. The land-use mix was not significant, however, as already mentioned, this variable did not provide much detail about existing land uses.

Metro station proximity was found to be significant within a 1.6 km range, being inversely related to the number of car trips, with decreasing influence on the dependent variable as distance increased. For census tracts located within a 400-meter buffer from a metro station, the opening of the station was associated with an average decrease of 43.5 in the number of car trips per 1000 inhabitants. This coefficient falls by about 10 car trips with each additional 400 meters until a 1200-meter limit from the station. Surprisingly, the coefficients for census tracts located within 800 – 1200 and 1200 - 1600-meter buffers are very similar (minus -23.5 and -21 trips, respectively). Probably, within 1200-meter buffer from a station a gradual decline in the influence of metro proximity´s reflected people´s willingness to walk to/from the station, while after 1200-meter they prefer to use buses so the influence of distance weakened for the range 1200 – 1600 meters. Unfortunately, available data do not allow to check this hypothesis.

Besides distance, the average daily train frequency on the closest station was significant, with each additional train being associated with an average decrease of 1.3 car trips per 1000 inhabitants.

Table 5.5 – Census tract-level model estimation results

Variable	Coefficient	Std.Error	z-statistic	p-value	
intercept	40.2649	6.0834	6.6188	3.621e-11	*
lumix	-0.006	0.0062	-0.9701	0.332	
below_13	0.31	0.0411	7.5393	4.730e-14	*
plus_65	-0.3315	0.035	-9.4731	< 2.2e-16	*
sec_edu	0.5611	0.0279	20.1119	< 2.2e-16	*
unemp	0.1041	0.0375	2.7790	0.0055	*
triptime	0.7540	0.3396	2.2207	0.0264	*
dwell_dens	-0.0036	0.0016	-2.2923	0.02189	*
lag_ dwell_dens	-0.0063	0.0036	-1.7462	0.0808	.
up_to400	-43.5742	3.5941	-12.1237	< 2.2e-16	*
up_to800	-31.5188	3.4348	-9.1764	< 2.2e-16	*
up_to1200	-23.573	3.8146	-6.1796	6.426e-10	*
up_to1600	-21.0795	4.1461	-5.0841	3.693e-07	*
up_to2000	-7.2903	4.668	-1.5618	0.1183	
trainhour	-1.2989	0.1907	-6.8114	9.666e-12	*
λ	0.1393	0.0403	3.453	< 6e-04	*
Log Likelihood	-8119.421				
AIC	16273				

Note: * $p < 0.05$

5.4.3. Census tract-level model (TOD/TAD/Park&Ride proximity)

The results of the census tract-level model that accounts for different station types are presented in Table 5.6. Overall, the coefficients are very similar to those in the previous model, except for the trip time and train frequency variables: the coefficient for the trip time increased from 0.75 to 1.06 and the coefficient for the train frequency changed from -1.3 to -0.94.

Considering the proximity to different station types, TOD stations revealed the strongest (in terms of distance) spillover effect with a significant negative influence on the number of car trips visible in census tracts located up to 2 km away. The significant influence of TAD was limited to a 1.2 km distance range. Besides, the influence of TOD stations was considerably stronger than other station types, especially for census tracts located within 400-800 meters from a station: within this range, TOD stations demonstrated a double decrease in the number of car trips compared to TAD stations (-41 car trips for TOD versus -21 car trips for TAD). TOD's influence decreased with distance: from -52.2 car trips in the immediate station area (up to 400 meters) to -21.5 car trips for census tracts located within 1200-2000-meter distances, falling relatively steady on average by 10 car trips every 400 meters. TAD stations on the other hand showed very little variation in coefficients for census tracts located within 400-1200-meter distances. Park&Ride was the only station type that did not show significant negative influence on the number of car trips in the immediate station areas (up to 400 meters from a station). This probably occurred because P&R immediate station areas were mainly scarcely populated census tracts with scattered private housing, where apparently station proximity did not change much people's habits. However, in some cases small relatively dense settlements are located within 400 – 1200-meter buffer from a P&R station and, apparently, for them station opening was important, even if the station area only had a parking lot and access options were limited in this case. Furthermore, it should be noted that the number of P&R stations within Metro do Porto system is rather small compared to other station types, so the results might differ for networks in which the representativeness of different station types is more balanced.

Table 5.6 – Census tract-level model estimation results including station types

Variable	Coefficient	Std.Error	z-statistic	p-value	
intercept	37.5686	6.0543	6.2053	5.460e-10	*
lumix	-0.006	0.0062	-0.9755	0.3293	
below_13	0.3132	0.0409	7.6624	1.821e-14	*
plus_65	-0.3345	0.0349	-9.5864	< 2.2e-16	*
sec_edu	0.5619	0.0277	20.2782	< 2.2e-16	*
unemp	0.1146	0.0374	3.0618	0.0022	*
triptime	1.0658	0.3431	3.1063	0.0019	*
dwell_dens	-0.0029	0.0016	-1.8694	0.06156	.
lag_ dwell_dens	-0.0055	0.0036	-1.5292	0.1262	
trainhour	-0.9448	0.2019	-4.6805	2.862e-06	*
TOD400	-52.2267	4.1523	-12.5778	< 2.2e-16	*
TAD400	-34.248	5.8382	-5.8662	4.458e-09	*
PR400	-11.511	10.8511	-1.0608	0.2888	
TOD800	-40.9818	4.2372	-9.6720	< 2.2e-16	*
TAD800	-20.961	5.0945	-4.1145	3.881e-05	*
PR800	-21.147	7.9483	-2.6606	0.0078	*
TOD1200	-28.3823	4.9268	-5.7608	8.371e-09	*
TAD1200	-20.6092	5.7543	-3.5815	0.0003	*
PR1200	-15.9153	8.0801	-1.9697	0.0489	*
TOD2000	-21.4905	4.4178	-4.8645	1.147e-06	*
TAD2000	-9.9235	6.3542	-1.5617	0.1184	
PR2000	-8.5991	7.509	-1.1452	0.2521	
λ	0.1239	0.0406	3.0495	0.0023	*
Log likelihood	-8107.045				
AIC	16262				

Note: * $p < 0.05$

Model validation

To assess the internal validity of the models and evaluate their performance on unseen data, a 5-fold cross-validation was performed using the “mlr3” package in R (Lang et al., 2019). For each fold, the dataset was randomly split into test data (20% of all observations) and train data (80% of observations), then the model was fit using train data and validated on the test data. Once the procedure was made for all folds, the model performance measures were averaged.

For the parish-level model, the averaged $R^2 = 0.58$ (for OLS model adjusted $R^2 = 0.66$), which means that overall the model performs relatively well on unseen data, though there is some decrease in the explanatory power. On the other hand, the average Spearman’s rank correlation coefficient (measure of correlation between true observed response and the predicted response) was rather high - 0.81.

Considering the census tract-level models, the resulting value of the $R^2 = 0.49$ (similar for both models), coincided with the adjusted R^2 value for OLS regression, meaning that this parameter remained stable during cross-validation. Average Spearman’s rank correlation coefficient was 0.68, suggesting strong correlation between the observed value and the predicted response.

5.5. Conclusion

The present chapter aimed to evaluate the effect of a metro implementation on a macro and micro scale, accounting for the different station types (TOD/TAD/P&R) and spatial spillover effects. The analysis, covering a 10-year period (2001 – 2011) in which metro was introduced, was performed for seven municipalities in the Porto area (Portugal) currently served by new system. At the macro-level, 120 civil parishes were used as units of observation and the sample for the micro-level consisted of 1561 statistical census tracts. Given the difference in number of observations that is also reflected in different spatial organization on a macro and micro level, different spatial specifications for the parish and census tract level models were adopted (spatial lag in the first case and spatial error in the second case).

The implementation of a large infrastructure project like Metro do Porto is expected to produce significant overall effect on the area and macro-level analysis allows to reveal it, highlighting general trends over a ten-year period. These results are complemented by a micro-scale analysis acknowledging that the smaller the unit of analysis is, the greater are the chances that its inhabitants have similar characteristics, therefore the results can reveal interrelations unnoticeable on a macro-scale. The results suggest that both direct and indirect effects of the metro implementation are visible already on a macro scale. However, switching to a micro scale allows to detect with greater precision the effect of the station proximity, demonstrating how the magnitude of effect changes with distance.

It was estimated that the effect of metro proximity, strongest in the immediate station area (up to 400-meter distance from a station), is decreasing at a rather constant rate until a 1200-meter limit from the station, then remains at a slightly lower level within 1200 – 1600-meter range and then falls sharply for census tracts located within 1600 – 2000-meter distance. While stable decrease of the spillover intensity until 1200-meter limit may reflect the effect of increased distance from a station, the fact that beyond this limit the intensity of metro spillover does not follow the same decrease rate might mean that factors other than distance influence the intensity of the spillover in those areas.

Suspecting that the spillover intensity might vary depending on the closest metro station type, we analyzed the performance of TOD, TAD and P&R stations. TOD stations showed the strongest negative influence on the number of car trips significant for all distance ranges as well as a relatively constant decrease rate. The influence of TAD stations, strongest in the 400-meter buffer, surprisingly almost did not change within 400 – 1200-meter distance. Another unexpected outcome was the insignificant effect of immediate proximity to P&R stations: P&R did show manifestly negative influence on car trips for census tracts located within a 400-meter buffer. Also, the extent of the spillover effect from P&R stations was the smallest compared to other station types, being limited to 400 – 1200-meter buffer from a station. Probably, with more detailed data it would be possible to examine the determinants of the spillover magnitude and knowing this could possibly allow to elaborate strategies to maximize station's influence.

These findings have important implications for both research and planners. Apparently, TOD stations reveal greater potential in reducing the number of car trips as compared to other station environments, therefore, the effect from the introduction of a metro system might be further reinforced by interventions in station environment and efforts should be made in this direction already at the planning stage. Depending on a station's type, surrounding built environment, and existing access options, station's influence may reach relatively remote areas. Compared to other station types, the decay of the spillover effect from TOD stations is more stable, suggesting that it might be easier to forsee and plan for the potential outreach of a TOD at a planning stage. The presence and magnitude of station's spillover is an indication that, probably, broader areas should be taken into consideration during the elaboration of urban/transport plans for a new station or evaluation of its effects.

These findings, besides confirming the negative influence of TOD on car trips, also give rise to several questions which may be addressed by researchers in the future. Even after controlling for the socio-demographics, built environment and metro service levels, there might be some understudied factors that influence the extent and intensity of spatial spillover from the infrastructure investment. In the future more detailed analysis could shed some light on these processes which would be extremely valuable for researchers and practitioners.

CRediT authorship contribution statement

Anna Ibraeva: Conceptualization, Methodology, Software, Formal analysis, Writing – original draft, Visualization. Gonçalo Homem de Almeida Correia: Methodology, Formal analysis, Writing – review & editing, Supervision. Cecília Silva: Resources, Validation, Writing – review & editing, Supervision. António Pais Antunes: Conceptualization, Formal analysis, Writing – review & editing, Supervision.

6. CONCLUSION

This final chapter aims to briefly summarize the contents of the thesis and provide some final remarks concerning the analyses performed, policy implications that derive from the reported results, and potential future developments on the matter. In the first section the development of the thesis and main findings are summarized. In the second section answers to the previously identified research questions are provided. Third section contains discussion about potential policy implications of the findings. In the last fourth section several possibilities for future research are outlined.

6.1. Summary

In this thesis, the focus was to evaluate TOD-related effects on mode choice framing them in the broader context of a large infrastructure investment in the Porto region. Given the exceptional research setting that allowed to perform longitudinal before/after analysis of Metro do Porto introduction, it was possible to evaluate the effects of metro on mode choice from different perspectives.

More precisely, in the context of TOD effects the lack of longitudinal studies addressing the evaluation of travel behavior is apparent. Besides, most studies focus on the built environment characteristics of the origin, and very few have included origin-destination information in the analysis (characteristics of the destination and overall ease of connection, especially by public transport, between both trip ends). Both longitudinal approach and origin-destination information are highly relevant for the purpose of the evaluation of TOD effects on travel behavior. A longitudinal research design, as opposed to the frequently used cross-sectional approach, allows to detect changes/evolution in the travel behavior rather than simple association. Besides, as changes in travel behavior may not occur easily or quickly, incorporating information from various years amplifies the analysis, demonstrating whether changes are rather quick or slow. Using origin-destination information is essential because obviously one's mode choice is defined not only by the characteristics of the origin, but also of the destination and by available transport options that exist between both trip ends. Motivated by the potential to expand the existing knowledge about TOD effects using longitudinal approach and information about both trip ends, present thesis addresses these major research gaps.

The second chapter provides the results of an extensive analysis of existing literature on the subject of TOD and provides an overview of existing research gaps in relation to TOD effects and TOD planning.

In the third chapter of the thesis changes in mode choice at a parish level (trip generation) and at a link level between different OD pairs (trip distribution) over 17 years (2000-2017) were analyzed using descriptive statistics and autoregressive models. The results suggest that the impacts of metro implementation and TOD on the share of car trips were significant and negative in for both trip generation (an average decrease of 8 p.p. in the directly served parishes and 13 p.p. in adjacent parishes) and trip distribution (an average decrease of 10 p.p. for pairs with metro at both trip ends). For OD pairs served by TOD stations at both trip ends the estimated reduction in car use reached 22 p.p. By contrast, the shares of bus trips were found to be positively associated with metro (average increase of 2.2 p.p. in metro-served parishes and 4 p.p. increase on links with metro at one end). These findings suggest that passengers of the new metro service were more likely to be former car riders than bus riders, and that bus and metro in the case of Porto complemented each other rather than competed. Despite these changes, it was also observed that people tended to maintain their habitual transport mode as autoregressive coefficients showed great significance in all models.

In the fourth chapter the effect of metro implementation was analyzed on a macro scale of a parish using census data for the years 2001 and 2011, right before and after the intervention, thus approaching it as a natural experiment. Visual analysis of the growth of car share in 1991-2011 demonstrated that metro-served and non-served parishes had similar growth rates in the pre-metro period, yet after metro was introduced this growing trend in metro-served parishes became weaker. Using a spatial difference-in-differences model allowed to detect the influence of metro and predominant station type while controlling for socio-demographics, built environment characteristics and metro spillover effects. It was found that both direct and indirect effects of metro implementation were strongly significant and negatively affected the number of car trips (the reduction in the directly served parishes constituted about 30 car trips per 1000 inhabitants). Comparing the performance of parishes with different predominant station types, the direct effect of TOD parishes on the number of car trips was almost two times larger than that of TAD parishes (-26.6 and -13.9 trips per 1000 inhabitants, respectively), both being significant. The indirect spillover effect was only significant for parishes with TOD as predominant station type. These findings suggest that direct and indirect metro effects were already visible on a macro scale. Besides, the influence of different station types (the direct effect of TOD and TAD parishes and TOD spillover effects) was noticeable even at an aggregated level.

In the fifth chapter the focus is placed on the importance of the scale of analysis, starting from the macro level (parish) and then switching to the micro level (census tract). This approach allowed to highlight the evidence that only micro-scale analysis could reveal, in particular, how metro influence on the number of car trips varies with the distance to the closest station and its type. The findings suggest that the number of car trips falls as distance to the station decreases (ranging from -43.6 to -21 car trips per 1000 inhabitants within 1600 meters from a station), but not at a constant rate. While it is possible that after a certain critical distance (1,600 meters) from a station people start to use cars much more often, it is also possible that the magnitude of the spillover effects depends on some other factors yet to be explored. Considering the influence of different station types, the micro analysis confirmed that TOD stations exercised strongest negative influence on the number of car trips in all distance ranges (from -52 to -21.5 car trips per 1000 inhabitants), followed by TAD (from -34 to -20 car trips within 1200-meter distance from a station), while proximity to P&R stations was less relevant and even non-significant for the first (up to 400 meters) and last (1600-2000 meters) distance ranges. Once again, it is noticeable that the magnitude of the spillover effect from different station types does not decrease at a constant rate with anincrease in distance.

6.2. Main Contributions

This thesis adopted a longitudinal approach to provide a long-term evaluation of the effect of Metro do Porto implementation on travel behavior. Major findings addressing the research questions identified are as follows:

1. On a macro scale, what was the influence of metro introduction and different station environments over time on the mode share (namely, the shares of car and bus trips) considering trip generation and trip distribution?

   Overall people tend to maintain their habitual transport mode, however, metro managed to reduce the share of car trips for both trip generation and trip distribution models. Metro's influence on the share of bus trips ranged from neutral to positive. The effect of TOD was noticeable when analyzing OD pairs: pairs with TOD at both trip ends showed greater reduction in car share than pairs simply connected by metro.

2. On a macro scale, how did the metro implementation affect the number of car trips over the years?

   The negative influence of metro on car trips is confirmed by longitudinal analysis. The results demonstrate that, even in the region with growing motorization rates and increasing car use, the implementation of metro managed to weaken these upward trends. TOD stations revealed greater catchment areas and greater reduction in car use as compared to TAD and P&R stations.

3. How did the influence of metro on the number of car trips manifest on a micro scale and what was the magnitude of the spillover effect for different station types over a ten-year period?

   The extension and the magnitude of the effect from metro implementation depend on station environment characteristics, and both were stronger in dense, mixed-use, pedestrian-friendly station areas (TOD). The spillover effects of metro in the case of the Porto region propagate to areas far beyond the immediate station areas, and spillover effects from TOD are visible up to 2 km from a station.

Overall, these results showed that the effect from metro introduction was reinforced in station areas with TOD features.

6.3. Policy Implications

The policy implication of this thesis is that TOD, demonstrating a stronger negative influence on car trips than other station types, can favor a shift to sustainable transport modes and therefore should be favored and promoted by local authorities. It must be stressed that the area served by Metro do Porto is rather heterogeneous and includes dense urban areas as well as rural territories, yet even in this case the results supported TOD, meaning that it is a valid strategy not only for highly compact and populated cities, but also for metropolitan territories with less uniform profile. The results also support the importance of socio-economic factors that ideally should be considered at the planning stage since certain population groups might be more inclined to switch to a new transit service and providing them with a reliable alternative to a private vehicle could strengthen sustainable mobility patterns. At the same time, it should be highlighted that TOD also shows potential to reduce car use as a destination for trips generated elsewhere, i.e., its implementation may lower car use not only in the immediate station area and adjacent neighborhoods, but also in more distant locations from where people travel to TOD. In addition to that, TOD stations demonstrated high spillover potential: they can amplify stations' influence making them reach quite distant areas. This effect should be supported and reinforced by appropriate measures aimed to ease station access, for example, introduction of feeder bus services and greater integration of sustainable transport modes. Overall, as TOD stations apparently have greater potential to reduce the number of car trips compared to other stations, policies should be aimed at adding TOD features (like improved access conditions by sustainable transport modes or greater land-use mix) to existing station areas and new station areas should be planned and organized in accordance with TOD principles.

6.4. Possibilities for Future Research

Several directions for future research evolved from this thesis. First, it might be interesting to conduct an in-depth analysis of the reasons why some people, provided with metro, discontinued car use and others did not. As can be seen from the findings, even for OD pairs with metro at both trip ends, the shares of car trips in 2017 are largely explained by the shares of car trips in 2000, so despite metro many people kept on using private vehicles and the analysis could not explain this behavior. Second, the analyses were performed using only two time intervals (ten and seventeen years), which allowed to identify long-term changes, but could not capture the continuous progression of occurring changes. Probably adding some interim data could reveal which population groups are more likely to switch faster to a new service and why, or which station types manage to attract new passengers faster than others. Third, further exploration is needed on the matter of station spillover effects and factors that influence them. In the case of Metro do Porto, the decrease in spillover effects does not occur at a constant rate with distance, suggesting that there might be some unknown factors that determine the magnitude of the spillover. Fourth, presented analysis of mode changes between different OD pairs was performed at a macro level of a parish, and more detailed approach using micro-level data of statistical subsection or census block could possibly improve the existing knowledge about the importance of the destination characteristics.

Although there are several research directions that might still deserve further exploration, overall existing evidence points to rather significant potential that TOD has in reducing car use and promoting sustainable transport modes. The results reported in this thesis in general also align with previously reported findings from other case studies, suggesting that the TOD may be successfully applied in different countries/cities. Nevertheless, the future of the concept will also depend on major societal and urban trends such as possible increase in remote work (and, consecutively, less commute trips), gentrification of TOD areas or others.

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