UNIVERSIDAD POLITÉCNICA DE MADRID
Escuela Técnica Superior de Arquitectura

ANÁLISIS DE LA PROXIMIDAD PEATONAL RESIDENCIAL: MÉTRICAS Y PATRONES DE APOYO A LA TOMA DE DECISIONES URBANÍSTICAS

TESIS DOCTORAL

Presentada para optar al título de Doctor por:

Manuel Benito Moreno
Arquitecto. Máster en Planeamiento Urbano y Territorial.

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Programa de Doctorado: Doctorado en Sostenibilidad Y Regeneracion Urbana

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ANALYSIS OF PEDESTRIAN RESIDENTIAL PROXIMITY

Patterns and Metrics to support Planning Decisions

A mi padre. Cada día que no estás, el mundo pierde un poco de luz.

A mi hijo. Cada día, desde que llegaste, el mundo retoma un poco de brillo.

Not all those who wander are lost.
J. R. R. Tolkien

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III. Abstract

This work addresses the problem of informational needs for urban proximity policies through empirical research. Urban proximity has emerged in the planning literature as a key strategy for sustainable urban development. In short, it is a strategy of facilitating urban configurations that minimize the need for travel and ensure access to basic urban functions, promoting local walking (or cycling) to achieve targets such as non-polluting mobility and healthy lifestyles.

Understanding which characteristics conform these urban configurations is informative for planning having local walking in mind. In this work, combinations of these characteristics will be reviewed and explored in the Metropolitan Region of Madrid, by examining walking travel behavior at varying short distances and purposes. Trip distance, built environment features like density, diversity, design, or destination accessibility, and demographic attributes, are rather consensually believed to exert significant effects on local mode choice.

This way, the research context of this work is the empirical study of local mode choice in relation to the built and social environment. Mode choice has been empirically approached through utility theories of consumer choice, formalized as linear models that correlate built environment metrics with travel mode decisions, controlling for social and trip characteristics, and accounting for their spatial nature. This tradition has helped policy makers evaluate the return of investing in improving conditions for local walking. However, their complexity and limitations often lead to subjective modelling which can hinder their informational validity.

The present work addresses two main questions. On one hand, it presents a scoping review which focuses on recent empirical studies dealing with urban proximity, but also situates them in the broader context of the study of mode choice and the built and social environment. This way, the state of the art both in the goals of proximity policies, and their associated research support, is addressed. On the other hand, the present work presents an empirical study of the case study of the Metropolitan Region of Madrid, leveraging recent methodological advances in the field. This study underpins the opportunity to experiment with new ways of exploring patterns of association between walking, and the social and built environment, in a context of growing demand for “urban proximity” policies. To do so, it leverages machine learning

approaches to predict walking against other modes, exploring accuracy and predictors' importance across an array of combinations of distance and purpose controls.

The empirical experiment addresses a subset of trip data that balances availability and detail, and attempts to capture the philosophy of urban proximity policies which focus on residential areas: travel survey data on home-based trips is analyzed, applying filters that include trip distance thresholds ranging from 600 to 1,500 meters and non-work purposes. A broad portfolio of social and built environment metrics is prepared and tested for modeling in multiple configurations and grouping strategies which help cross-validating the reliability of the final models, and evaluates different possible scenarios of data availability. The analysis is based on feature selection, which are workflows for attaining well specified machine learning models, removing sources of bias, selecting relevant features, and controlling overfitting.

Results suggest that even small changes in distance thresholds exert a great impact in all the model performance metrics; some purposes were the most easily predicted, sociodemographic variables are slightly more important overall, though some questions on their endogeneity to transport arise. Among built environment predictors, average building age, along with other street layout characteristics, pervasively obtain fairly accurate predictions too. While the effects of proximity thresholds and purpose have been proven very sensitive for the models, the sets of characteristics suggested are sometimes misleading, and still need further inspection.

Policy implications of the results rest in the fact that activities like Care and Study are very predictable in local active proximity, both using socioeconomic characteristics (such as household size and structure, driving license status, or activity status), configurational metrics that differentiate regional structure and typologies of urban tissue (captured through measures of road network centrality and mean age of buildings), and accessibility to specific purposes. These metrics are fairly easy to obtain and compute, could help perform accurate predictions on policy impacts, and adds nuances to the complex phenomenon of local travel beyond the more extended accessibility metrics. Other purposes struggle in the generalization of the problem, commonly overfitting, yet also pointing at similar characteristics that increase the accuracy of the models: household size, centrality measures, and accessibility to specific purposes.

As a general conclusion, the proposed approach shows promising signs of being able to identify important features of the social and built environment in understanding local active travel for purposes relevant to proximity policies, yet many questions remain unanswered regarding methodological aspects and informational power.

IV. Resumen en español

Este trabajo aborda el problema de las necesidades informativas para políticas de proximidad urbana mediante investigación empírica. La proximidad urbana ha surgido en la literatura sobre planificación como estrategia clave para el desarrollo urbano sostenible. En resumen, es una estrategia que promueve configuraciones urbanas que minimicen la necesidad de desplazamientos y garanticen el acceso a funciones urbanas básicas, promoviendo los trayectos a pie (o en bicicleta) para alcanzar objetivos como la movilidad no contaminante y estilos de vida saludables.

Entender las características de estas configuraciones urbanas es informativo para la planificación local en materia de caminabilidad. En este trabajo, se revisan y exploran combinaciones de estas características en la Región Metropolitana de Madrid, analizando el comportamiento de los viajes a pie en distancias cortas y con distintos propósitos. La distancia del viaje, las características del entorno construido (como densidad, diversidad, diseño o accesibilidad a destinos) y los atributos demográficos son elementos que, de manera bastante consensuada, se considera que influyen significativamente en la elección del modo de transporte local.

De este modo, el contexto de investigación de este trabajo es el estudio empírico de la elección del modo de transporte local en relación con el entorno construido y social. La elección del modo de transporte se ha abordado empíricamente mediante teorías de utilidad basadas en la elección del consumidor, formalizadas como modelos lineales que correlacionan métricas del entorno construido con la elección modal, controlando características sociales y del viaje, y considerando su naturaleza espacial. Esta línea ha ayudado a evaluar el retorno de invertir en mejorar las condiciones para la caminabilidad. Sin embargo, su complejidad y limitaciones a menudo conducen a una modelización subjetiva que puede comprometer su validez informativa.

El presente trabajo aborda dos preguntas principales. Por un lado, presenta una revisión exploratoria que se centra en estudios empíricos recientes sobre proximidad urbana, pero también los sitúa en el contexto más amplio del estudio de la elección del modo de transporte y el entorno construido y social. De esta manera, se aborda el estado del arte tanto en los objetivos de las políticas de proximidad como en su respaldo investigador asociado.

Por otro lado, este trabajo presenta un estudio empírico del caso de la Región Metropolitana de Madrid, aprovechando avances metodológicos recientes en el campo. Este estudio respalda la oportunidad de experimentar con nuevas formas de explorar patrones de asociación entre los desplazamientos a pie y el entorno social y construido, en un contexto de creciente demanda de políticas de proximidad urbana. Para ello, se aprovechan enfoques de machine learning para predecir los desplazamientos a pie frente a otros modos, explorando la precisión y la importancia de los predictores en diversas combinaciones de controles de distancia y propósito.

El experimento empírico trata de equilibrar la disponibilidad y detalle de la información disponible, y capturar la filosofía de políticas de proximidad centradas en áreas residenciales: se analizan datos de encuestas de viajes con origen en el hogar, aplicando filtros que incluyen umbrales de distancia de viaje entre 600 y 1.500 metros y propósitos no laborales. Se construye y prueba un amplio espectro de métricas del entorno social y construido para su modelización en múltiples configuraciones y estrategias de agrupación, lo que ayuda a validar la fiabilidad de los modelos finales y evalúa distintos escenarios posibles de disponibilidad de datos. El análisis se basa en la selección de características (feature selection), que son flujos de trabajo para obtener modelos de machine learning bien especificados, eliminando fuentes de sesgo, seleccionando características relevantes y controlando el sobreajuste.

Los resultados sugieren que incluso pequeños cambios en los umbrales de distancia tienen un gran impacto en todas las métricas de rendimiento del modelo; algunos propósitos (como los cuidados o el estudio) son más fácilmente predecibles; las variables sociodemográficas son ligeramente más importantes en general, aunque surgen dudas sobre su endogeneidad respecto al transporte. Entre los predictores del entorno construido, la antigüedad media de los edificios, junto con otras características de configuración de la trama urbana, obtienen predicciones bastante precisas de manera persistente. Si bien los efectos de los umbrales de proximidad y el propósito han demostrado ser muy sensibles para los modelos, los conjuntos sugeridos a veces son contraintuitivos y aún requieren interpretación, y futura inspección.

Las implicaciones de los resultados en la capacidad informativa para políticas de proximidad giran en torno al hecho de que algunos motivos de desplazamiento más relevantes para las mismas, como los cuidados o el estudio, son predecibles a través de métricas sociodemográficas (como la estructura y tamaño del hogar, la ocupación, o la tenencia de permiso de conducir), configuracionales (métricas de centralidad de red, o época del tejido urbano), o de accesibilidad específica a equipamientos relacionados. Éstas métricas son razonablemente fáciles de computar,

y añaden matices a la complejidad de la movilidad local, más allá de los estudios de accesibilidad. El resto de motivos de los viajes muestra persistentes problemas de sobre ajuste y mala generalización, aún también apuntando a combinaciones similares de características del entorno social y construido como palancas a la precisión de los modelos.

Como conclusión general, la aproximación propuesta muestra algunos signos prometedores para la identificación de características del entorno social y construido, relevantes para comprender la movilidad local activa para propósitos importantes en políticas de proximidad. Pese a ello, muchas preguntas siguen sin respuesta en lo concerniente a la metodología para extraer conclusiones y su poder informativo.

V. Acknowledgments / Agradecimientos

Hace ya una década, que siento que ha pasado como una exhalación, decidí completar mis estudios de Arquitectura con un postgrado en Estudios Urbanos. Los últimos años de la carrera se había formado en mi cabeza un apego a su parte más Urbanística, en detrimento de todo lo demás. Quería saber más sobre las ciudades, los territorios, los paisajes. Sobre su complejidad, sobre la cantidad de preguntas que surgen cuando uno no se conforma con un trazo que "cumple la norma". Con los años, en investigaciones, en el trabajo, en mi tiempo libre, en mis experiencias, fui desarrollando habilidades, y adquiriendo conocimientos, que me permitieron abarcar las preguntas. Siento que ésta tesis ha ido más allá de su contenido, y me ha brindado un patrimonio incalculable para continuar queriendo responderlas. Éste trabajo, como no podía ser de otra manera, está dedicado a mi gente más próxima. A mi pareja, a mi familia, a mis amigos, a aquellos que han mostrado (o fingido) interés, a quienes han dedicado su tiempo para construir mi espacio de estudio. También a quienes lo han desdeñado, a ellos les debo buena parte de mis ganas de continuar. A mi círculo académico, a quienes lo han cuestionado incansablemente, para hacerlo crecer. A la ciudad de Madrid, que tantos años me ha maravillado al caminar sus calles.

A decade ago —how did that happen—I decided to complement my Architecture studies with a postgraduate degree in Urban Studies. During the final years of my degree, I had developed a growing attachment to its urban planning aspects, to the detriment of everything else. I wanted to learn more about cities, territories, and landscapes—about their complexity, about the countless questions that arise when one is not satisfied with a design that merely "complies with regulations." Over the years, through research, work, free time, and personal experiences, I developed skills and acquired knowledge that allowed me to grapple with those questions. I feel that this thesis has gone beyond its content, granting me an invaluable foundation to keep seeking answers. As could not be otherwise, this work is dedicated to those in proximity—to my partner, my family, my friends, to those who have shown (or feigned) interest, and to those who have devoted their time to shaping my study space. It is also dedicated to those who dismissed it—to them, I owe much of my drive to keep going. To my academic circle, to those who tirelessly challenged it, helping it grow. And to the city of Madrid, which has filled me with wonder for so many years as I walked its streets.

1. Introduction

One of the strategies the EU has pursued for achieving sustainable and smart urban mobility is facilitating "active-modes" through "land-use proximity", an approach which some state members' strategies simply describe as "facilitating urban proximity". Urban proximity, as a wider concept, has been mostly addressed as a particular case of residential-centered and local-range geographic accessibility, with recent epistemological, methodological, and empirical discussion. The concept stems from planning trends such as the Compact City, Accessibility Planning, the Walkable City, or the 15-Minute City, which have become quite popular among scholars and policy-makers worldwide. Despite its popularity, the way in which this "urban proximity" can alter individual travel behavior still needs clarification and further empirical investigation to better inform the public debate. This work is an outcome of that particular reflection.

> *For every pizza ordered over the Internet there is a pizza baked, delivered, and consumed in the material world, and for every telecommuter working out of her electronic cottage in the woods there is a plumber who needs to have access to the very material block in her sewer line.*
>
> Helen Couclelis (Couclelis, 1996)
>
> *Planning instruments are still devoted to urban expansion, development, sectoral, or logistic strategies. We do not have neither tools nor knowledge to rebuild the complexity of daily urban life (...) that fundamental substrate of diverse economies and innovations which feeds on proximity, not on mobility, and ties everything together.*
>
> Fernando Roch (Fariña Tojo, 2016)

1.1 Motivation

Over the past 30 years, the EU has pursued sustainable and smart mobility through key policies spanning from the Green Paper on the Urban Environment to the Sustainable and Smart Mobility Strategy (SSMS) or the New Urban Mobility framework.

Aimed at cutting transport emissions by 90% by 2050, the SSMS offers a roadmap for the transition to sustainable mobility across member states. In the SSMS, urban mobility plays a central role as it accounts for an important share of Greenhouse Gasses (GHG) emissions, but also displays the greatest transformative potential due to its higher concentration. (European Commission, 1990; 2020). The New Urban Mobility (NUM) framework, covered in documents like the European Strategy for Low-Emission Mobility and the Urban Mobility Package, guides the creation of Sustainable Urban Mobility Plans to meet mobility goals, and offers guidance to local adaptation of the SSMS core principles (European Commission, 2021).

The general line in which sustainable mobility is conceived in these local-scope documents revolves around city strategies for the shift towards low-carbon systems. In the NUM framework and the Climate Neutral Cities Mission, for instance, one can differentiate an energy-approach (principles to reduce fossil fuels and overall energy consumption, such as zone restrictions or Electric Vehicle incentives), a transit-approach (systems efficiency, coverage, and reliability of local and regional public transportation), and an active-modes approach, aiming at facilitating active travel through the provision of adequate conditions, reducing overall travel and shortening travel distances as a strategic development line.

Some member states and local planning strategies go further in this last strategy and point in the direction of urban development that naturally promotes the adoption of low carbon modes for local mobility, namely the idea of facilitating “urban proximity” (Ramírez-Saiz et al., 2022; Büttner et al., 2022).

Urban proximity, as a strategy for achieving sustainable mobility, revolves around the reduction of traveled distances and travel needs by design (Banister, 2008; 2011; Holden, 2020). On scale and speed premises, this strategy goes beyond a transportation problem and deals with the

nature of streets as the scenario of urban vitality (Jacobs & Appleyard, 1987; de Terán, 1996). On motivation and interaction premises, the strategy is closely connected to socio-spatial dynamics such as identity building (Urry, 2002); on spatial premises, urban proximity deals with the implications of design in urban vitality and place-making (Montgomery, 1998). Policy-wise, it diverges from mobility-oriented policy traditions (aimed at systems and infrastructure for faster modes) and focuses on land use and design (inherent to the tradition of spatial planning), aware of the need for being targeted to diverse individuals and groups (Fariña, 2019; Silva et al., 2023). This way, policy-making through proximity faces the complex problem of dealing with both urban and transportation issues, expecting to obtain outcomes in both, and the different individual agents involved.

Though the political direction of urban proximity seems reasonable, the complex mechanisms that tie together travel, society, and the built environment are not a new, nor a consensual field of knowledge. A scientific legacy exists around questions on the mechanisms by which the built environment influences general travel behavior (Ewing & Cervero, 2001; 2010; Stevens, 2017; Aston, 2020), and local travel behavior (Handy, 1992; 2017; 2020).

Upon review of recent literature on proximity as a built environment condition affecting travel behavior, different categories of studies can be found: a lively epistemological debate and its connection to practice, descriptive and/or methodological studies, and a trend of empirical efforts to understand the mechanisms by which proximity can trigger the desired outcomes. This work focuses on this last approach, reviewing research directions and methodological limitations, contributing to framing the study of proximity through the association of characteristics that affect local travel behavior, their relevance, and informative power.

The Metropolitan Region of Madrid is proposed as a case study for empirical experimentation. The region is a densely populated compound that -policy wise- mirrors the debate on national-level agendas in Spain, which are already promoting proximity as one of their levers to achieve a number of goals of sustainable development. This region also poses an opportunity for its large data availability regarding travel and the social and built environment, which enables a consistent and detailed level of analysis in a large and diverse urban set.

1.2 Objectives

The main two objectives of this thesis are learning about urban proximity by looking at local walking travel through a conceptual lens (reviewing epistemological and scientific implications), and an empirical experiment in the Metropolitan Region of Madrid (through predictive modeling) lens, in association through social and built features which can be targeted by policy.

- ➔ Objective 1: To understand the current political and epistemological set in which urban proximity is invoked as a tool to achieve several sustainability goals. To understand empirical approaches to the idea of urban proximity as a lever to attain mobility shifts towards sustainability, particularly by increasing the share of walking locally. To situate these recent empirical approaches to urban proximity in the broader context of the study of travel and the built environment, properly connecting methodological and theoretical aspects. This goal is pursued mainly through the Background and Framework sections.
- ➔ Objective 2: To perform an empirical experiment in line with the reviewed framework, in order to explore the hypothetical combined effects of the social and built environment on local mode choice. More specifically, to explore emergent ways of dealing with some of the methodological limitations of the study of travel and the built environment. To experiment with machine learning in the particular context of the thesis, as an emergent alternative approach, offering a critical review of its limitations and advantages. To explore the case study of the Metropolitan Region of Madrid in terms of proximity behavior, and expand local knowledge on the matter. Results for this goal are mainly reported in the case study subsections of the Framework section, the Methodology section, and the Results.

1.3 Reading this thesis

The text has been arranged to allow two levels of reading depth. Every section contains a text which summarizes its key takeaways. However, in order to allow for a deeper dive into the concepts and the reviewed literature, Annex I provides extended summaries and reflections for most sections and sub-sections. In this annex, sections display a colour code in the left margin that indicates their topic:. Red tones indicate that the text revolves around broad ideas on the relationship between Travel and the Built Environment; Yellow tones indicate that the detailed text concerns the explicit exploration of the idea of Urban Proximity and. In the rest of the text, Blue tones in the left margin indicate the exploration of the Case Study, as an illustration of concepts and ideas. As it will be used before the detailed presentation in the Methodology section, a brief summary provided beforehand.

- ➔ Background: Defining Urban Proximity. Introduces the concept of urban proximity within the planning context, discussing socio-spatial approaches, contemporary strategies like the 15-minute city, and epistemological and empirical approaches to urban proximity.
- ➔ Framework: Travel and the Built Environment. Explores research on the relationship between travel behavior and the built environment, outlining different research strategies and theoretical approaches. It also defines key outcome variables, alongside influencing characteristics, methodological approaches and data constraints.
- ➔ Methodology: Feature Selection Approach. Details the methodological approach, including case study constraints, proposed workflow, and expectations. It specifies how data is collected and aggregated, defines key features influencing travel behavior, and outlines the methodological constraints of the study.
- ➔ Results and Discussion. Presents the accuracy and composition of the final models, particularly through permutation feature importance, and discusses the findings in relation to the theoretical framework and expectations.
- ➔ Conclusion. Summarizes key research outcomes, reflecting on methodological insights and theoretical contributions, and suggests future research directions for improving the understanding of urban proximity and travel behavior.

1.4 Review Methodology

This review process has not been strictly linear. The work started with a review of the idea of urban proximity throughout the history of planning, so as to understand the evolution of the concepts in urban theory and practice, and establish a first lineage with travel behavior, in order to guide the review of recent works. The review of recent works was guided by this first iteration, which yielded search terms later introduced in Scopus and Google Scholar, filtered for works published from 2010 on, and combined with the term Proximity.

This search returned works that were snowballed in search for theoretical or epistemological inputs, on one hand, and empirical approaches, on the other. A third class of papers, the "compliance metrics", was a first outcome of this iteration, and an indicator of the recent relevance of the 15-minute trend in proximity-centred works. The terms used are a basic set of keywords that refer to the main topic and outcomes targeted by sustainable mobility strategies, and the features commonly associated with it, in light of the first review on the context. This way, the term Proximity was coupled with the following terms: Travel, Mode Choice, Active Travel, Density, Diversity, Land Use Mix, Design, Accessibility, and Demographics.

In parallel, the review of the lineage on travel and the built environment also opened a wide and complex field of research, which was studied through review, discussion and meta-analysis works which, in particular cases, led to the review of other selected papers that emerged as relevant. This way, the review became a "review of reviews", attempting to search for both early and recent works (in order to grasp the evolution of thought).

In the second search iteration, the term Proximity and the publication year filter were removed from the search, resulting in a great number of articles, from which those review, meta-review, and discussion works were selected. If other works were found relevant, either in the search or in the references of these reviews, they were incorporated into the final list. Works were ordered by scientific impact, so as to identify impactful research in the last decades, but then a snowball effect, and a closer look to recent publications, led to the decision of completing the picture on this topic, regardless of impact metrics.

Thus, the methodological approach can be described as a scoping review. The first section identifies the definitions given to the concept of urban proximity, and selects the recent empirical works on the matter, following the loose approach of a panoramic review, suitable for a recent academic trend with a potential conceptual diversity. The second part goes through reviews, discussion, and meta-literature on travel and the built environment, following an umbrella review discourse. For each of the aforementioned research components, a general overview of trends and evidence was performed, a particular look at the recent literature on empirical studies of urban proximity, and an illustration of the concepts through the proposed Case Study. Figure 1 shows a diagram of the structure of this review.

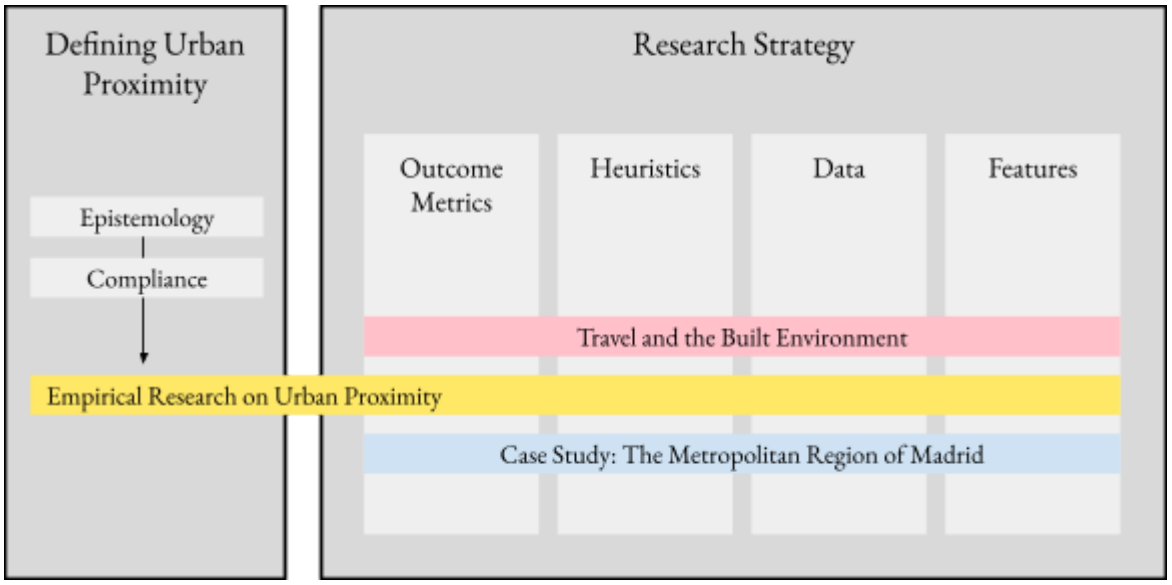


Figure 1: General Schema of the Review
The general schema for the review. It starts with an exploration the definition of proximity, which will later be a common thread for the general review of research strategy components in Travel and the Built Environment, and the Case Study

1.5 Summary of Research Strategy

This work reviews urban proximity both from a policy and an empirical standpoint. The review will lead to the definition of an empirical experiment around the concept, in light of the current state of art. Before proceeding, a brief summary regarding the latter is presented, giving the more informed reader a first conceptual understanding of the proposed experimental design, so as to introduce the concepts extracted from the general and particular literature.

As a policy approach, the informational needs of urban proximity have been understood in this work as ways of pointing at urban and social characteristics where there is a potential for a modal shift towards walking locally. This potential is addressed from the definition of observed trips in the case study, filtered by purpose and distance, capturing the "user defined" nature of proximity. The focus is put on daily residential-centred trips, which are the main target in policy and empirical advances reviewed. These definitions become a boolean filter for the data targeted in the experiment, and the spatial window to calculate the built environment metrics.

The research strategy has aimed at choice modeling. It has built a predictive model which targets two classes: walking, and all other modes. Predictions will be based on social and built environment characteristics, controlling for varying distances and trip purposes, so as to find whether certain metrics (or patterns of metrics), seem more informative to identify potential for modal shift. The models have used a disaggregate travel survey, enriched by other environmental metrics, using an isochrone spatial window, related to the proximity distance thresholds.

This work has drawn inspiration from utility and complexity theory. Hierarchically addressing the influence of the social and built environment in travel behavior has been explored from the former, facing theoretical and practical challenges. Also, the literature calls for experimentation on better capturing the complex interplay between these phenomena, borrowing ideas from complexity about emergent data behaviors rather than impositions on the form of the problem. This work has attempted to make a contribution in the common ground of both theories, using emergent techniques of explainable Machine Learning to test the proposed features against mode choice. In Figure 2, a brief summary of the research strategy is presented.

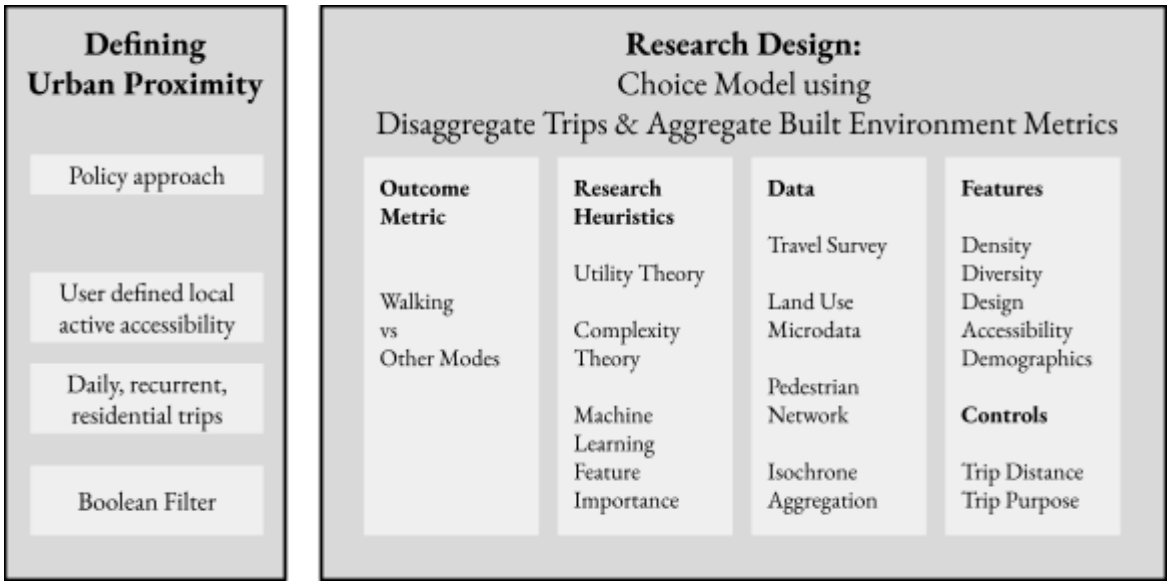


Figure 2: General Schema for Empirical Experiment Design

The general schema for the empirical experiment design. After reviewing definitions of urban proximity, a specific filtering on the data is set, preparing the datasets for modeling. The final research strategy is selected after reviewing possibilities on outcome metrics, heuristics, data sources and targeted features.

1.6 Case Study and Summary of Datasets

The case of the Metropolitan Region of Madrid (Henceforth, MRM) is presented, as well as the datasets used to represent its relevant features, as it will serve to illustrate the findings of sections 2 and 3, and become the materials for the experiment presented in sections 4 and 5. Different definitions of the MRM exist, as classifications that target domain-driven conceptualizations. In a first stance, the classification of MRM in the travel survey used in this work was explored. This initial classification, however, does not have a definition beyond being "municipalities contiguous to Madrid and a high functional relationship with it", comprising 47 municipalities of a diverse nature in terms of form and functional relationship

As this work is exploring local travel behavior (which, a priori, should not pose a conflict with regional mobility, and most works on the nature of this metropolitan focus on its strong monocentric behavior), it uses a classification which, maintaining this structural idea, defines a tighter boundary that leaves the urban-rural fringe out, focusing on the most populated and denser core of the region. The classification selected is the one proposed in García Ballesteros & Sanz Berzal (2002), in the *Atlas of the Community of Madrid at the edge of the XXI century*.

The MRM, according to this work, integrates 28 municipalities, with a total population of 5,557,365 inhabitants as for 2017 (the reference year before the travel survey used in this work), and a total area of 193,588 hectares. MRM includes a wide variety of urban fabrics, with a diversity of density levels and land use combinations. Mixed-use town- and neighborhood-centers coexist with residential-only suburbs and specialized centralities, resulting in a very diverse caseload of urban tissue samples.

In Figure 3, a map of the MRM is shown, represented with the multiple elements which will later on be used to unfold this work, and reference it to its wider geographic context. The high availability and granularity of the data represents a great opportunity for detailed work on the micro-scale nature of the present matter of study, yet maintaining a certain regional perspective.

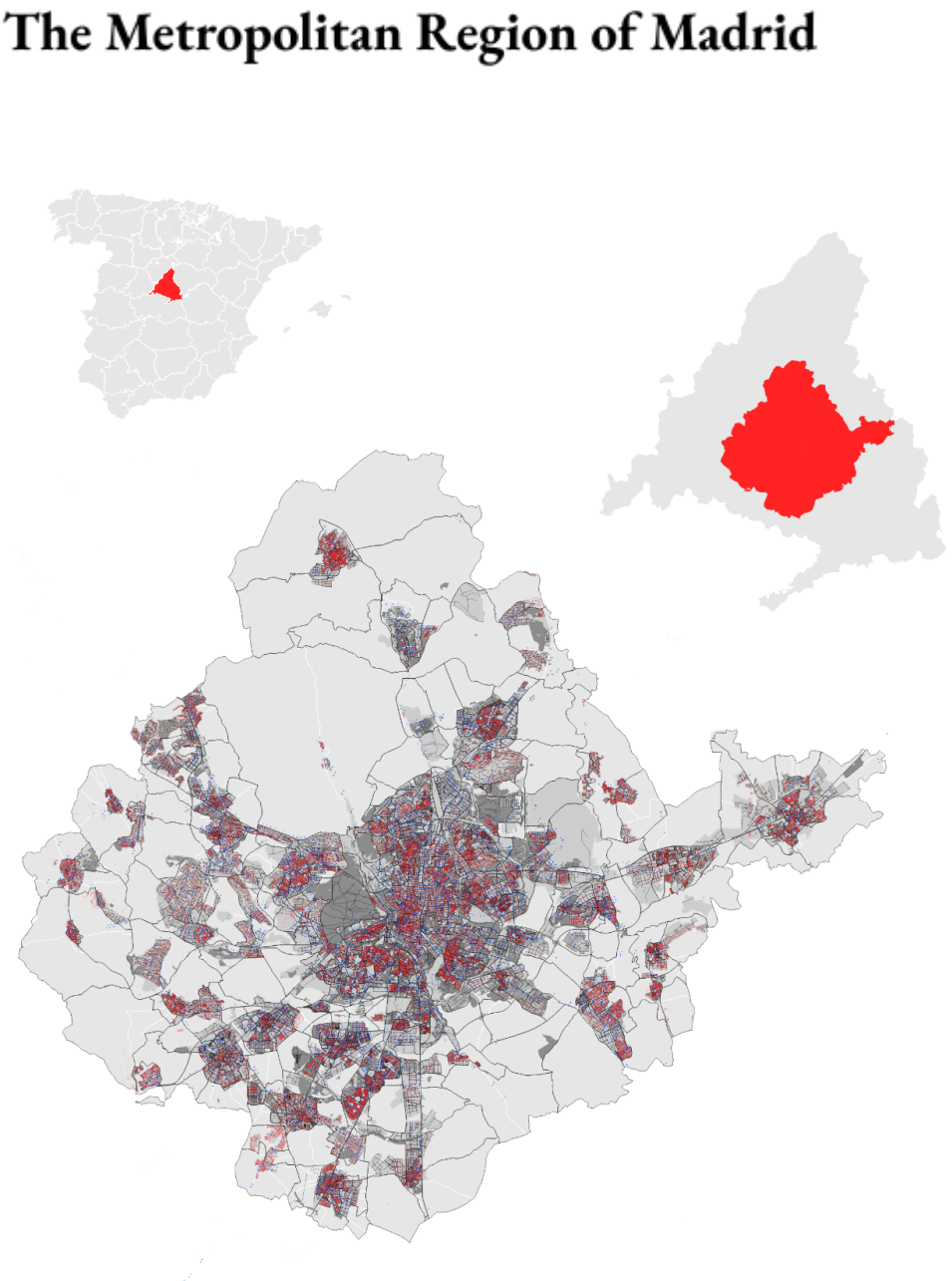


Figure 3: The Metropolitan Region of Madrid
The MRM in context. Upper left, the Spanish territory highlighting (in red) the Community of Madrid. Upper right, the Community of Madrid highlighting (in red) the MRM. Bottom, the MRM and all the spatial data layers used in this work.

The complete description of the datasets can be found in the Annex II. However, a brief summary is also provided, so as to be able to reference the different data sources throughout the Case Study exploration.

Cadastral Data - DGC

For land use data exploration, Cadastral data is. The data is available online from the Spanish Cadastral Direction (Dirección General de Catastro, 2017; henceforth DGC). It includes a full description of built surfaces and land uses registered at the parcel-level, and the official address assigned to each item.

OpenStreetMap - OSM

Another data source used for some land use and design metrics throughout this work is OpenStreetMap (henceforth, OSM), the most popular crowdsourced set of spatial data, from which additional land data which is not reported by DGC has been derived, namely green areas and pedestrian areas (Mooney & Minghini, 2017).

Public Transportation Data

The Consorcio Regional de Transportes de Madrid (Regional Transportation Consortium Madrid. Henceforth, CRTM) is the regional authority for multi-modal operation harmonization, planning, and research. This institution is also responsible for the publication of the travel data described below but, in this work, the spatial data representation of the public transportation infrastructure has also been used.

Sociodemographic and economic data - INE

For socioeconomic data, the Spanish Household Income Atlas (Atlas de Renta de los Hogares Españoles) has been used, an open dataset maintained by the Spanish Statistics Institute (Instituto Nacional de Estadística. Henceforth, INE), which holds data for socio-demographic and socio-economic variables at Census Tracts.

The Household Travel Survey in the Region of Madrid -EDM2018

Travel data is obtained from the Household Travel Survey 2018 (Encuesta Domiciliaria de Movilidad. Henceforth, EDM2018), published by the CRTM, which reports individual trips with their different stages, information on the individual travelers, and their household.

Road Network - RCL

Finally, these sources have been blended with the MRM Street Map, a road-center line (Henceforth, RCL) network geometry that includes the official names, validated and enhanced to sufficiently represent all possible pedestrian routes.

2. Background: Defining Urban Proximity

In this section, the scope of the review is established by framing recent efforts to define urban proximity. First, the section goes through the history of the concept in planning disciplines. Then, those works dealing with recent definition efforts are separated, and papers focusing on the "operational definition", or the identification of "states of proximity compliance", are inspected. Finally, the review of recent empirical studies is presented, to establish the state of the art around the idea of urban proximity as a sustainable mobility strategy.

> *Urban Planning can not be reduced to living, working, leisure and transportation. The whole city must be mainly conceived as the set for active citizenship, education, and a rich and autonomous personal life*
>
> Mumford (1961)
>
> *Most blocks should be short, this is, streets and chances for going around corners should be frequent. (...) Just like combinations of primary uses, crowded streets constitute an efficient element to generate diversity, just by the way they work. The means by which streets work (attracting wide combinations of users towards them) and the results they help achieve (growing diversity) are closely related. The relationship is reciprocal.*
>
> Jacobs (1961)

Following the academic and political discussion, a first attempt to define and understand the concept of urban proximity is presented. An historical perspective and a recent policy context is established, willing to better understand the informational needs of the political aspects of proximity. Then, the recent epistemological debate on proximity is addressed, both as an operational term to be targeted by policy, and as a definition of "compliance", an emergent trend of built environment quantification for political traceability.

Following this initial landing of the urban proximity concept, recent works of empirical nature are reviewed. In this work, "empirical approaches" imply those works that attempt to measure quantitative relationships between the travel outcomes targeted by policies which lever proximity, and other features (which, though are usually referred to as built environment, are also of a social, demographic and economic nature). Disentangling these specific works in their different research components (their background, methods, data, results, etc) will prepare the way to a meaningful connection with the wider literature.

The second main section of this review is the revisitation of the broad literature on travel and the built environment, under the lessons learned from the review on proximity. This literature is so vast that it will be addressed mainly through review, meta-review, and discussion papers along four prolific decades of research. The main theoretical lines and research strategies that frame empirical studies will be described, and four different relevant research components will be introduced: The outcome metrics targeted by empirical research (those measures of observed phenomena which are targeted by policy); the heuristics used to understand the mechanisms that operate in the targeted phenomena; the data sources and aggregation strategies involved in the research process and; and the features commonly associated with the outcome metrics, through the different heuristics and theoretical frameworks.


SPEAKS
FOR
JANE
JACOBS
NEEDS
HOMES
NOT
EXPRESSWAYS
NO ROAD
THROUGH
OUR
HOME
JANE JACOBS
DISRUPTS
COOPER
SUPPORTS
COOPER
DON'T
DRIVE


WHAT WOULD BETRAYAL AND DEVIOUS DECEIPT LOOK LIKE IF COMMUNISM IS THE END GAME?
THE 15 MINUTE W·E·F GHETTOS. ARE NOT ABOUT CLIMATE, IT'S TYRANICAL CONTROL!

2.1 Planning Context

Defining urban proximity may appear tautological, as urbanization historians often view human concentration as the foundational condition of urban settlements (see, for instance, Wirth, 1938 or Mumford, 1961), often nuanced by other dimensions of density (Glaeser, 2011), diversity and centrality (Conn, 2014). The need to redefine proximity has emerged as a reaction to recent global urban expansion and sprawling patterns, challenging the late 20th-century belief in the diminishing importance of physical distance (coined as the "death of distance" elsewhere) due to advancements in transportation and digital technology, as an alleged natural progression of economic growth, market expansion, and social democratization (Cairncross, 2002; Couclelis, 1996; Urry, 2002). A consistent wave of criticism (and planning alternatives) to this distance-free perspective has developed since then, exploring how proximity still matters in the relational plane of urban life, and it is not only a matter of distance.

A context on urban proximity will be given, showing that the explicit discussion in planning was triggered by a will of counteracting development philosophies that belittle distance through mobility-enabled strategies, around the turn of the century. A notion of the local physical arrangement and its role in well being has been present throughout the history of planning, and crystalized in the concept of the neighborhood (a predecessor to the term urban proximity).

Confronted with Modern zoning, the built environment features that these "neighborhood" approaches needed to trigger urban wellbeing were steadily pointed out. At a first stage, features included notions of land use mix and a more human scaled design as facilitators of outcomes of urban vitality and community building. Consecutive iterations added other features such as compactness, walkability, or accessibility, and targeted outcomes in sustainable transportation. In addition, current policy trends aim at detailed characteristics of those features and aim at outcomes in health, inclusion, and environmental sustainability.

2.1.1 Neighborhoods: a socio-spatial planning approach

Planning has implicitly dealt with urban proximity mostly through the neighborhood concept since the inception of the discipline. Even though this concept might now be totally incorporated into the general vocabulary, it was early planning approaches that gave the term a meaning as a coherent unit of urban tissue.

Early hygienist models like the Linear City and Garden City prescribed both regional design patterns, growth thresholds, and local ranges of proximity to retail, workspace (and regional transportation for longer commutes), public institutions and -particularly emphasized- to nature (Soria, 1882; Howard, 1898).

In these early models, tenancy and social mix strategies addressed the idea of social well-fare and community building in proximity, but it would be the Neighborhood Unit concept (Perry, 1929) that introduced an explicit notion of a *scheme for arrangement for the family-life community*. It conceived a cell-like modular arrangement that underlined curbing border-traffic (being one of the first traffic segregation proposals), and segregating it from retail, inner-pedestrian open space and facilities such as schools, playgrounds, and civic centers.

These early models had an implicit notion of proximity at work (Linear City drew a 300m residential buffer around a tram line; Neighborhood Units were conceived as ¼ mile radial shapes), yet they also set the basis for a dilution of the tridimensional space of traditional streets (de Terán, 1996). The advent of the Modern Movement and car-oriented culture brought a shift towards zoning and automobile infrastructure, diminishing attention to human-scale and volumetric enclosing of streets, according to later authors.

This tendency prompted reactions like Mumford (1965), who highlighted the loss of organic human-environment relations in modern suburbia; Jacobs (1961), who emphasized urban vitality and natural surveillance triggered by land-use mix and street permeability, hindered by zoning and the irruption of fast modes in local systems; Alexander (1965, 1979), who advocated for a more complex understanding of urban layout and function beyond the hierarchical Modern view; Lynch (1960) or Appleyard (1964), who criticised the loss of imageability (the set of elements people use to understand the environment) in the modern city; or Hagesträn

(1970), who advocated for bringing back the importance of human-centered temporal and spatial constraints into human geography and planning. In these works, proximity is addressed as a social question affected by urban design, and a critique to the Modern zoning paradigm.

A resurgence in neighborhood transport and urban planning concepts associated with proximity sparked in subsequent decades: Buchanan (1988) and Gehl (1989) explored place-making and the behavior and attachment of individuals with their immediate urban space; the New Urbanism movement (coining many concepts such as Neotraditional Development, Traditional Neighborhood Development, or Transit Oriented Development) (Calthrope, 1993), emerged as a reaction to the debate on urban sprawl, pointing at features such as density, land-use diversity, street connectivity, or pedestrian oriented design, also approaching planning from architectural implications of perspective, place-attachment and civic engagement.

These elements can be traced in posterior concepts like Smart Growth and Eco-Urbanism, which expanded upon the themes of efficiency and sustainability beyond mobility, community-building, and the idea of the Compact City (Pouyanne, 2004; Stevenson, 2016) as opposed to urban sprawl. These movements address proximity as both a threshold and design problem, expanding the earlier social critique and proposing thresholds (such as the quarter mile to transit and retail in the postmodern planning models) and design methodologies such as place-making. A review of neighborhood planning can be found in Sharifi et al. (2016).

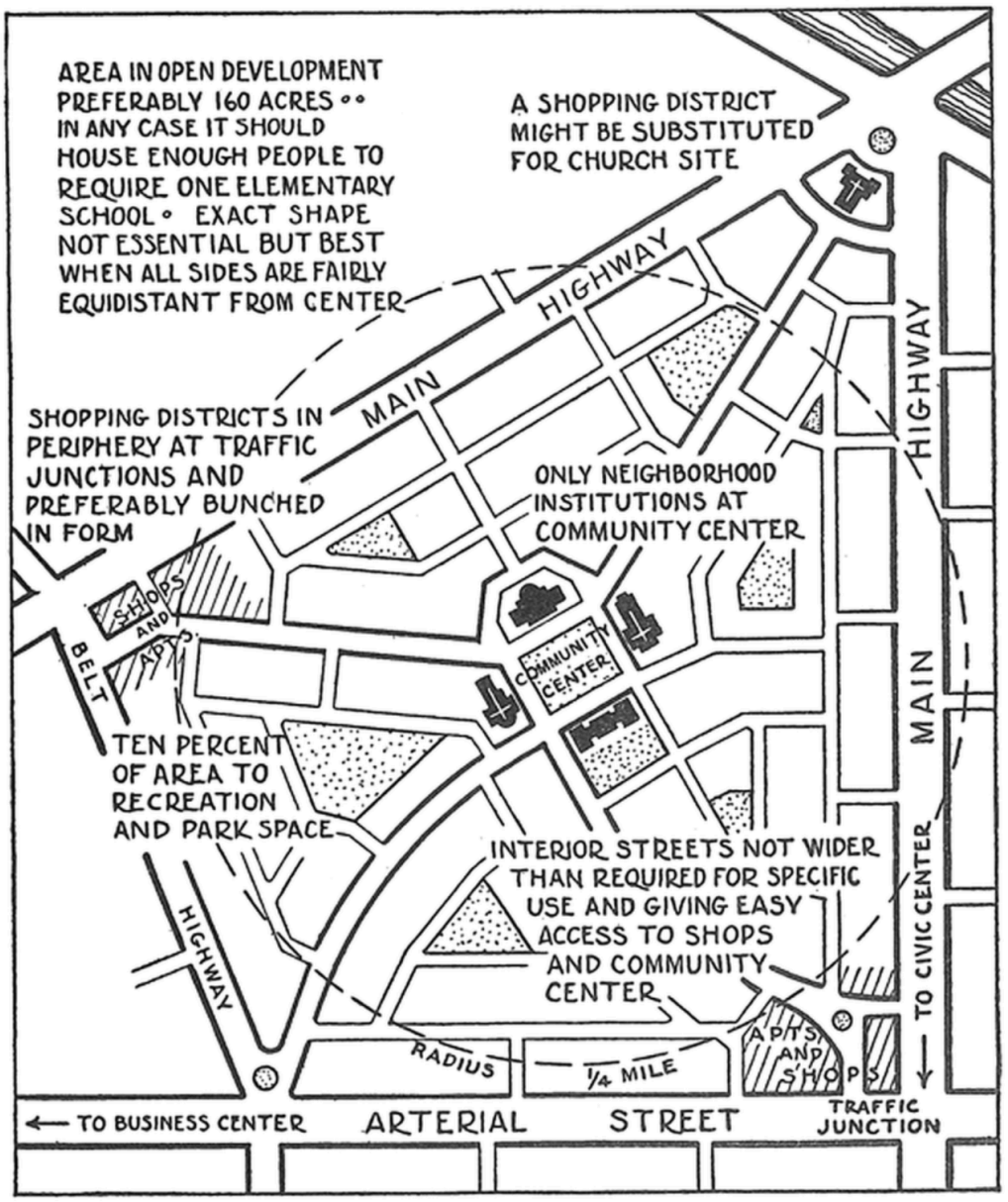


Figure 4: Clarence Perry. The Neighbourhood Unit

Clarence Perry's Neighborhood Unit Plan . From the original drawings of the idea, the many elements invoking an idea of proximity which would later be somewhat persistent in other approaches can be found: The distance threshold of ¼ mile from the community center; the shopping districts in the edge, connected to main surrounding streets; interior streets of a more pedestrian nature; and the space between the center and the border shops spotted with -ten percent- of recreation and park space.

2.1.2 Contemporary approaches dealing with proximity

Contemporary approaches to (or including) the idea of proximity are diverse in scope and philosophy: Accessibility Planning is an accessibility-based practical research on mobility and land-use planning. Its main philosophy is bringing the concept of geographic accessibility, -traditionally achieved through mobility- as harmonization of both domains. This line of thought emphasizes local accessibility by active mobility (which implies proximity) to counteract negative externalities of focusing solely on fast mobility as a facilitator of activity. Also, it explores the gaps between academic and decisional contexts, still siloed (Silva, 2017, 2019; Straatemeier, 2019; Pajares, 2019, 2021; Büttner, 2019).

Walkability -and the more general idea of the Walkable City- is a pedestrian-oriented attitude towards urbanity in planning, but also a complex quantitative field that has been core to recent planning tools dealing with proximity. It explores the features associated with cities in which walking becomes the core mode of transportation, and the implementation mechanisms and obstacles. This approach will be defined further in this work, but it is interesting to note that the term has triggered a consistent line on walkability as a measurable characteristic affecting pedestrian behavior (Southworth 2005; Pozueta, 2009; Speck, 2020).

The City of Care (Anzani & Scullica, 2022) and the Mobility of Care (Sánchez de Madariaga, 2013; Sánchez de Madariaga & Zucchini, 2020) are emergent concepts associated with a traditionally neglected subset of urban activity which deals with the care for other -dependent- population such as children, older adults, and people with hindered self sufficiency. These activities pose important challenges on the caretakers time budgets, and are mostly unveiled through gendered analyses of travel diaries, in which (although context dependent) women have been found to account for a bigger share of polygonal tours, and longer loops, to encompass working and caregiving. In this approach, proximity is valued as one of the most suitable strategies for alleviation of the impacts of care in time pressures (Valdivia, 2020)

The Inclusive City (Hanson, 2004; Ramírez et al., 2022) is the idea used to reflect on the needs of the older segments of the population and those with disabilities. It deals with the design of

urban space, but also with the very beginning and ends of trip tours, namely the adaptation of buildings to "access for all" conditions, as well as other means of transportation. The recent literature reflects on the advances in these situations, yet still with a limited consideration of proximity as the strategy to facilitate travel in limited conditions.

The Healthy City (de Leeuw, 2022) is also an emergent concept that points at urban proximity as a facilitator of well-being goals. Even though health has been a seminal target of urban planning as a discipline, this recent iteration mostly adds the idea that conditions of proximity can trigger a healthier lifestyle by promoting active modes for recreation and transport. Other derived outcomes targeted by health research pointing at urban proximity intersect with the broader strategies of sustainable mobility, such as the reduction of noise and air pollution. Place attractiveness and attachment has been associated with better mental health, and a less sedentary lifestyle. Also, the COVID-19 outbreak has placed local provision and access in the center of many recent environmental health studies (Capolongo, 2021).

These concepts are common in recent proximity policy making. Regarding the actual policy environment which directly affects the case study in the MRM, it is pertinent to understand both a national and local level of polices which refer to urban proximity. The most relevant policy framework for the present case study is The Spanish Urban Agenda (MITMA, 2023), which prescribes proximity from a double perspective of health and sustainability.

In this document, Target 5, named "Facilitate proximity and sustainable urban mobility", addresses two issues: "Facilitate land-use mix that reduces distance within the city' and "Prioritize as much as possible, continuous, safe, and responsible pedestrian paths, encouraging a healthier active lifestyle (...) developing pedestrian and cycling networks, ensuring pedestrian-friendly and safe trips, through specific policies". In its Target 2, "Avoid Urban Sprawl and revitalize the existing city", other specific issues are "Defining an urban model that encourages compactness, balance and the supply of basic services" or "Adopt planning measures to ensure balanced territories, encouraging development at adequate density (...) incrementing compactness if necessary, favoring higher building ratios, density, and adjusting over-sized facilities". Urban proximity appears in other parts of the text, all along assuming that these formal characteristics trigger the kind of sustainable mobility expected (Fariña, 2019). In the following subsection, the complete text of this document concerning urban proximity is

presented, along with the metrics proposed to monitor the Spanish cities' efforts to achieve SDGs associated with sustainable mobility through this particular strategy.

The Spanish Urban Agenda has already served as a vehicle for interesting proximity-based local policies in the country. Lamíquiz et al. (2024) review 5 spanish cities' approach to proximity concepts, and find consistent trends in some points: the spatial focus on the Neighborhood scale, but also in the SuperBlock concept (popularized by recent proximity policies in Barcelona and Vitoria-Gasteiz); the consistent leaning towards sustainable mobility planning, with the drawback of paying less attention to land use strategies; and the lack of clear governance and implementation strategies, in contrast with the explicit usage of the proximity concepts in the motivation of new planning actions.

2.1.3 The 15-minute city

Finally, the most popular contemporary approach in which proximity plays a core role is the 15-Minute City concept. Initially a proposed strategy within the candidature of Anne Hidalgo for the city of Paris, this approach gained prominence after being implemented, and hit the mainstream during the COVID-19 pandemics (which evidenced flails in proximity supply worldwide). The 15-Minute-City emphasizes planning around multi-accessibility (for different modes, users, motivations and schedules) of essential services within a short distance (Moreno, 2021), that acknowledges a threshold of hyper-proximity as a boolean condition, in contrast to measurements of accessibility.

The 15-minute trend (with other predecessors like the 20-minute neighborhood concept) has fueled an intensification of the discussion on urban proximity. It has already been conceptually expanded to meet different realities of implementation. For instance, a 30-Minute Territory approach has been proposed for those non-urban or low-density regions. Also, many authors already re-brand the concept to the X-Minute City, reflecting on the need to acknowledge a multiplicity of thresholds for different users and purposes. The specific 15-minute threshold is not the important idea, but the ideal of proximity and time-geography that lies behind it.

Khavarian-Garmsir (2023) sets this concept as a direct offspring of neighborhood planning trends along the past century, inheriting many of their contributions. To Pozoukidou (2021) or

Lamíquiz et al. (2022), the innovation of this concept is bringing forward local accessibility for resource allocation and governance. Megahed (2024) also presented strong connections between many contemporary sustainability goals. Bertaud (2022) or Marquet (2024) have also expressed some academic and political backlash of the 15-minute city concept, aiming at doubts on its viability and or frontal opposition to it as a constraint to residents' freedom. Papas et al., (2023) and Büttner et al. (2024) review recent policy inspired by the 15-minute city concept, finding a great acceptance in policy makers throughout europe, but also some gaps for bottom-up approaches to it (in terms of policy design, monitoring, and cost-effectiveness), and the consideration of social, governance, and logistic aspects, beyond spatial re-allocation.

2.2 Definitions of Proximity

In this section, recent works on urban proximity derived from the bibliographic search are presented. The different literature has been classified in epistemological, compliance (roughly associated with methodological definition of proximity states), and empirical works. The review has been constrained to papers published after 2012. The contemporary approach to proximity can be seen as a strategy to achieve accessibility which is somewhat opposed to mobility. This strategy assumes that certain formal parameters can trigger social travel behavior, yet this is assumed with caution, departing from determinism, acknowledging complexity and, in operational terms, mostly measured through accessibility in multiple user-tailored approaches.

These metric operationalizations conform to the second group of papers reviewed, those who explore how to correctly measure "states of proximity" through complex tuning of formal parameters, and call for objective ways of capturing the effects of proximity. The majority of works use accessibility metrics in combination with relevant frames for user definition such as choosing specific origin-destination pairs, and custom rules to calculate catchment areas; to later combine the measured proximity with other social or built environment features.

This, in fact, is the common denominator of most of the works reviewed in the section dedicated to empirical approaches. First, a certain definition of proximity is made, then a quantitative definition is elaborated (which can take the form of travel thresholds, or daily travel behaviors, or even a perceptual characteristic to be surveyed), and finally, other characteristics of society and the built environment are differentiated through this "labeling" of proximity.

2.2.1 Epistemological debate

Epistemological works address a proper definition of proximity when facing urban policy design, and span from academic to operational inputs. The review process searched for attempts to provide detailed nuances to the more general idea of urban proximity, especially concerning policy implementation, social implications, and built environment characteristics. A first conclusion is that operationally defining "urban proximity" is core to this research thread, as most studies will attempt to either fit their data to a certain definition, or some theoretical metric (such as accessibility), to investigate its relationship with observed travel behavior. The debate is multi-faceted. In defining proximity, each meaning of "distance" (it can be temporal, euclidean, geodetic, topologic), each pair of origin-destination (considering interactions), each mode constraints (speed and navigation); and each individual ability and perception; add unavoidable nuances to the definition. Temporal and experiential frameworks are stressed, to account for biological, perceptive, and symbolic constraints (Marquet, 2015).

When confronted with the need to operationally define proximity for policy-making, most works point at active accessibility as the main concept. In absence of a lack of consensus on the elements that comprise it, this active accessibility is defined not through fixed components (of distance, interaction, constraints, ability, etc.), but rather through arrays of possibilities (Gil-Solá, 2019; Büttner, 2022). In the latter efforts of wide definition by practitioners, another interesting proposition can be seen. Proximity can be treated as a strategy for accessibility, opposed to mobility, which exhibits a negative feedback loop or, in other words whenever long-range mobility is enhanced, proximity is hindered (Silva et al., 2023).

In summary, authors assume the role of urban form triggering societal change, but underpin the individual agency and ability to adapt to and transform the environment, influencing proximity back. In the reviewed works proximity is mostly seen beyond structuralist determinism, as a complex relationship of space, society, and individuals, in a range of combinations and directions. The most repeated concepts point at local accessibility and the search for consensus on the user-tailored approach, accounting for different abilities, thresholds and motivations.

2.2.2 Compliance metrics

Possibly due to the popularity of the 15-minute city, a number of recent works attempt to capture proximity as a measurable condition, or an identification of places or systems of places in a way of compliance with a theoretical model. The 15-minute city envisions hyper-proximity as the facilitator of quality of life; chrono-urbanism or linking planning to the natural pace of life; chrono-topia or adaptation of space to time frames; and topo-philia or supporting place attachment). Thus, according to the model's view, a proximity compliance definition will take into account a connection with time and activity, and the characteristics of space.

The 15-minute city uses an activity approach (live, work, supply, enjoy, learn and care, specifically omitting transportation); and urban levers (density, proximity, functional land use-mix, and digital ubiquity) in a time-geography like condition of a 15-minute accessible range (Moreno, 2020; Lamíquiz, 2022; Ramírez, 2022). Also, and most important for this section, it proposes to trace these conditions through geographic approaches (a traceability matrix), which may have prompted these works around measuring states of proximity (see a step-by-step implementation proposal in Büttner et al., 2022).

The idea of "compliance" is likely drawn from the traceability proposed by Moreno (2020), which can help practitioners and citizens engage in the construction of proximity-oriented policy. These are left out of the present empirical approach as they simply point at definitions without further exploration of related behaviors, however, they provide a good example of quantitative measurement of proximity. Most reviews on compliance compare accessibility approaches to reveal the x-minute city (the current preferred term for acknowledging a variety of thresholds and users). They reflect on ways in which a "state of proximity" can be mapped, and point to some metric and aggregation biases, on a general basis.

The most popular trend to measure compliance with urban proximity seems to be the use of accessibility metrics in combination with relevant frames for user definition, that involve both the use of particular rule-sets of origin-destination and establishment of movement rules to calculate catchment areas. In the recent literature, it is acknowledged that these metrics are extremely sensitive to changes in the origins and destinations selected, the concept dimensions accounted for, the modes and speeds considered, the reach thresholds and, of course, the

measures/metrics used (Carpio-Pinedo et al., 2021; Logan et al., 2022; Papadopoulos, 2023; Megahed, 2024).

The combination of these metrics with other social or built environment features is also somewhat of a common ground, either as control variables for user-tailored accessibility metrics, or as part of complex indexes of proximity or 15-minute city. Most works do focus on local scales, though some use regional dynamics either as alternative or baseline metrics, or in the form of regional conditions (such as distance to CBD, etc). Finally, the majority of approaches target active accessibility (walking and cycling) for framing these compliance states (Logan et al., 2022; Papadopoulos, 2023; Megahed, 2024).

2.2.3 Empirical studies

A definition for an empirical approach to travel and the built environment can be found in Cao et al. (2008): "it needs to meet a significant, non-spurious, time-precedent statistical relationship, with suggestions of causality". Works reviewed in this section are those taking such an approach to measure revealed outcomes of urban proximity. Particularly, the 15-minute city model has triggered a discussion on the low amount of evidence on the effects of local accessibility on travel behavior, the built environment, or sociodemographics (Abbiasov, 2023).

Proximity quantification in empirical research does exhibit correlation with local active travel, with geographic variations that point at different local built environment and regional characteristics, as well as sociodemographic variables. In empirical works around proximity, both qualitative (as an alleged preferred behavior) and quantitative (as an observed travel behavior) approaches are taken. A large number of different theoretical frameworks and disciplines intersect in the literature on travel and the built environment.

In the same way as compliance studies, empirical approaches first define a threshold of study for both proximity as a state of compliance (using one or various accessibility metrics with little exceptions), which is then studied through travel behavior or built environment characteristics. The idea of threshold is present, yet in these studies is extended through secondary statistical controls of the demographic or built environment kind, which add further nuances to the results. In most cases, the simple notion of proximity is not enough to fully predict outcomes in

local travel behavior and, in general, results on the mechanisms at work are inconclusive or simply labeled as complex. A summary of each of the selected works is presented. Later, Table 1 summarizes the 'proximity definitions' they propose.

- ➔ Haugen (2011) surveyed three dimensions of satisfaction with proximity: preferences for living close to everyday destinations, satisfaction with the proximity around their residential location, and a more general residential satisfaction. This work suggests that proximity preferences are structured by both practical and social rationales, and are largely affected by life situations: different states of proximity matter to different people, at different stages in a lifetime.
- ➔ In Haugen et al. (2012), the author studied a country-wide evolution of distances to different services and amenities in Sweden compared to actual behavior, in order to understand if it is population or services re-allocation which changes "proximity" states. The work reveals how a historical global decrease in access had not necessarily driven a reduction in overall travel, mostly due to individual preferences and increased mobility options.
- ➔ Marquet (2014; 2015) studied neighborhood-scale short daily pedestrian travel in Barcelona, and found an uneven spatial distribution, which could be fairly explained through differences in density and income levels.
- ➔ Kasraian et al. (2017) positively associated metrics of proximity to and accessibility by transport infrastructure, vicinity of urban areas, and spatial policies, to the possibilities of land being developed in the Randstad area in the Netherlands. In this work, a suggestion is made on the role of past and present spatial policies beyond proximity and accessibility.
- ➔ Searcy et al. (2018) performed a regression of mode choice of university students against commuting distance, and found a consistent threshold behavior in active modes.
- ➔ Gaglione (2021) aims at the geomorphological, physical (concerning both spaces and path networks), functional (distribution and location of services), socio-economic and settlement characteristics, to define "proximity states". The authors define different 15-minute accessible areas based on users' willingness to walk and the characteristics identified in each urban area.
- ➔ Li (2022) et al. tested the hypothesis that most people do not visit their closest grocery stores, and certain demographics make users go further than others. They argue that a

proximity threshold is not a good proxy for accessibility, and that peoples' behaviors differ widely by socio demographic traits, time, and type of amenity.

- ➔ Gil-Solá & Vilhemson (2022) explore the gendered dimension of proximity in densification strategies, by focusing on how women and men use nearby amenities in urban environments varying in amenity concentration. Their results indicate that the roles of gender and density vary with activity and gender, reflecting the dynamic relationship between proximity, inherent qualities of the activity, and individual values and conditions.
- ➔ Graels-Garrido et al. (2022) explore the spatial variations in the relationship between mobility and the provision of local amenities, and suggest people tend to visit neighborhoods with better access to certain classes of facilities. Locally, these and other features change in sign and magnitude through the different neighborhoods of the city in ways that are not explained by administrative boundaries, and that provide deeper insights regarding urban characteristics such as rental prices.
- ➔ Calafiore et al. (2022) propose a novel approach to identify where 20-minute neighborhoods might exist within a large city region and assess how their existence aligns with socio-spatial inequalities. They unveil spatial clusters of highly served areas as proxies of existing 20-minute neighborhoods, and perform an equity analysis by investigating global and local relationships between the accessibility score and socio-demographic and environmental variables.
- ➔ Bartzokas-Tsiompras & Bakogiannis (2022) construct a comparable index of walking performance of 121 European metropolitan areas and seven amenity types, and is able to demonstrate European-level disparities and statistically significant differences in 15-MWC performance due to GDP per capita differences.
- ➔ Knap et al (2023) underline the influence of density as a metric of regional structure, suggesting that the definition of short active access might not be suitable for sub urban or rural areas. They develop a metric, based on an accessibility framework and test it for cycling mode in the Utrecht region in the Netherlands. Travel data was used to determine input characteristics of the metric, such as the weight of destination types, which are weighted and aggregated into a composite metric that shows relative scores as an X-minute city. The intention of the metric is prioritizing neighborhoods to develop, set quantifiable goals, and evaluate planning scenarios.
- ➔ Poorthuis and Zook (2023) find how sub-urban areas are less prone to non-car proximity due to regional characteristics : They simulate a scenario which they use to study the

differences in reliance on cars in urban and non-urban areas; the differences in extra travel time across the urban-rural continuum if all car-based trips were replaced by public transport; and the effect of accessibility of goods and services on extra travel time if all car-based trips were replaced by public transport. They argue that practical implementations of the 15-minute city should take into account non-urban neighborhoods, especially in terms of car reliance.

- ➔ Birkenfeld et al. (2023) also surveyed local travel behavior qualitatively in a Canadian context, finding how urban proximity ideals rarely fit any household structure, as some non-local trips are always present in everyday travel behavior. The authors also conclude that household structure largely affects proximity behavior. They use a two-scale operationalization, and experiment with varying thresholds of "proximity compliance" , controlling by compositions of households, and find how few of them are able to conduct all their daily travel within close proximity, even if the built environment was substantially altered. They suggest that the x-minute city is not a one-size-fits-all model
- ➔ Abbiasov et al. (2023) regress a 15-minute accessibility state against 15-minute observed usage, finding it can explain circa 75% of the variation, also highlighting the role of spatial policy, and finding an interesting tradeoff of experienced segregation (15-minute access does not seem to trigger social diversity in the studied destinations).
- ➔ Aristizábal (2023) evaluate spatial-temporal coverage of economic poles in Manizales (Colombia) through a geographic accessibility model, considering the socioeconomic stratum of households, and apply a spatial regression model of pedestrian trips. Results show that proximity to urban economic poles is directly correlated with pedestrian trips.
- ➔ Elldér (2024) examines how key features of the built environment have influenced the development of the 15-minute city in Swedish cities through a 25-year period (1992–2017). The 15-minute city is operationalized as the proportion of the population in each city that can access a range of non-work urban social functions within a short distance from home, and show that population size has little significance, while density and mixed land use clearly contribute to this access, particularly in cities developed before mass motorization.
- ➔ Yu & Higgins (2024) regress sufficiency and intensity of accessibility (either meeting a minimum of accessible opportunities or measuring total accessible places) against car use and ownership, and find high negative correlation in both cases, yet more pronounced with intensity metrics. They calculate transportation accessibility -which they term access

intensity-, to five categories of daily necessities using walking, cycling, public transit, and driving; and a set of minimum access criteria to particular amenities to determine a set of binary access or sufficiency scores. They unveil spatial patterns of expected pockets of high and low access, and show that increases in 15-min accessibilities by walking, cycling, and transit are associated with decreases in driving for 15-min trips when they reach sufficient walking access to all five categories of necessities.

Table 1
Empirical studies reviewed and their definitions of Urban Proximity

Reference	Proximity Definition - Context
Haugen, 2011	Distance to everyday life needs
Haugen et al., 2012	Trips below 5 km. (local) or below 50 km. (regional)
Marquet & Miralles-Guasch, 2015	Active, working-day, non-work trips below 10 minutes
Searcy et al., 2018	(derived from results) 400 m. Walking. 800 m. Cycling
Kasraian et al., 2019	Adjacent Land Use within a 1.5 km. threshold
Graells - Garrido et al., 2021	Amenities reachable within 15 minutes walk
Bartzokas-Tsiompras & Bakogiannis, 2022	
Li, 2022	Visits to the nearest grocery store
Gil-Solá & Vilhelmson, 2022	Everyday life contexts: grocery shopping and leisure activities
Abbiasov et al., 2022	Trips below 15 minutes walk
Calafiore et al., 2022	Services, amenities and transport within 10 minute walks
Knap et al., 2023	Number of accessible destinations below 15 minutes cycling
Birkenfeld et al., 2023	Active trips below 15 and 30 minutes thresholds (includes public transport)
Poorthuis & Zook, 2023	Substitution of car trips below 10 km. by public transportation
Aristizábal et al., 2023	Distance and size of economic poles
Yu & Higgins, 2024	Non-work everyday trips under 15 min (calculated for each mode) for essential needs
Elldér, 2024	Basic, Full or Optimal services and amenities within a 15 minute walk (1 euclidean km.)

2.3 An Approach to sustainable urban mobility

What are, then, the initial implications of urban proximity policies for an empirical approach? In short, they need to be informative to the return or future functioning of their prescribed solutions, so as to strengthen their position in the public debate. This section discusses the review of the approach to proximity in planning research and practice for policy information.

Spatial thresholds and land-use schemes in planning history have had, among others, an intention of serving walking distances for ideal communities. However, as mobility oriented development never ceased to be the norm in most contexts, it was only the point in which infrastructure expansion became unfeasible, when a land-use alternative has gained interest as a political vector. To support urban proximity as a way towards sustainable mobility, both ideas of facilitating modal shift (increasing active modes and public transportation) and reducing distance traveled (by reducing the need for travel), are highlighted, as seen in Banister (2008; 2011). Empirical studies should focus on the benefits and the implications of these two changes.

This reduction is allegedly achieved by multi-dimensional arrangements of land use which facilitate this situation. However, measures taken in this direction are often unpopular, costly, or have spatial implications which result in interest conflicts (Marquet, 2024). An empirical approach to proximity should aim at policy-relevant metrics to understand how (and to which extent) each of the possible land use planning actions can drive travel change, and support the transition with evidence.

By quantifying a nuanced relationship between urban form features (and the relationships among them), sociodemographic characteristics, and overall travel, it should be possible to support a wider range of different policy approaches and scenarios (Handy, 1996). Also, results of empirical research need to be communicative enough to make their way into the public debate, so it is desirable that outcome metrics of research are intuitive to interpretation.

3. Framework: Travel and the built environment

To frame the quest for empirical support of proximity characteristics to achieve their desired outcomes, in this section, a brief history of the literature on travel and the built environment is given. Later, different components of the research body are addressed in depth: research strategies (a number of research strategies and particularities), research heuristics (a number of methodological approaches and related techniques), outcome variables (an overview of the common variables which are targeted by models), associated features (the "usual suspects" of influence, with a rich methodological debate), and data issues (limitations, operations, transformations, and aggregation scale).

3.1 Travel and the built environment revisited

The debate over New Urbanist claims sparked a wave of empirical research on land-use and its implications on travel behavior (Cervero, 1991; 2002; 2006), attempting to support the built environment characteristics listed by their advocates (which include the prior critiques to Modern planning) with evidence on their influence in the former. The approach comprises quantification of urban form and sociodemographic features, and their statistical association to travel outcomes, using models inherited from transportation planning.

Earliest transportation models -named the four-step models- were first used in the 1950s and evolved from simpler forecasts towards more grounded constructs, unveiling complex relationships of travel and the built environment with each iteration. The basic idea at this point was to link land use to trip generation, later assigned between zones using gravity relationships, and to modes and routes assuming travelers' cost rationality. (see Mitchell & Rapkin, 1954; Hansen, 1959; Lowry, 1964; McFaden, 1973; McNally, 2008, or Ortúzar & Willumsen, 2011). A general scheme of a 4-step model is shown in Figure 5.

These assumptions evolved in particular research lines to capture underlying processes at work on each stage, beyond notions of distance-time and mode availability as the only associated predictors (Acheampong, 2015). One of the most significant lines of forecast improvement involved the introduction of dimensions of the built environment in models of demand, choice, or trip distribution. As the debate on urban sprawl in the US went mainstream, methodological improvements generated a thread of its own, widening the scope of research (Cervero, 2006). Around this time, the approach was already consistently termed the Land Use Interaction Modelling (or LUTI) in transportation studies.

A vast portfolio of related characteristics have been tested since then. Predictors include notions of density (or intensity of activity in space), diversity (also called land-use mix, the complementarity of activity in space, facilitating interaction and short travel), accessibility (associated to the concept of geographical accessibility or the relationship between activity intensity and its separation, and a particular focus on transit nearness and regional structures), or design (both in terms of movement network layout, and the finer architectural materiality of public space) and, finally, demographic controls like age, income, or more complex behavioral or attitudinal variables (Ewing & Cervero, 2001; 2010, Stevens, 2017).

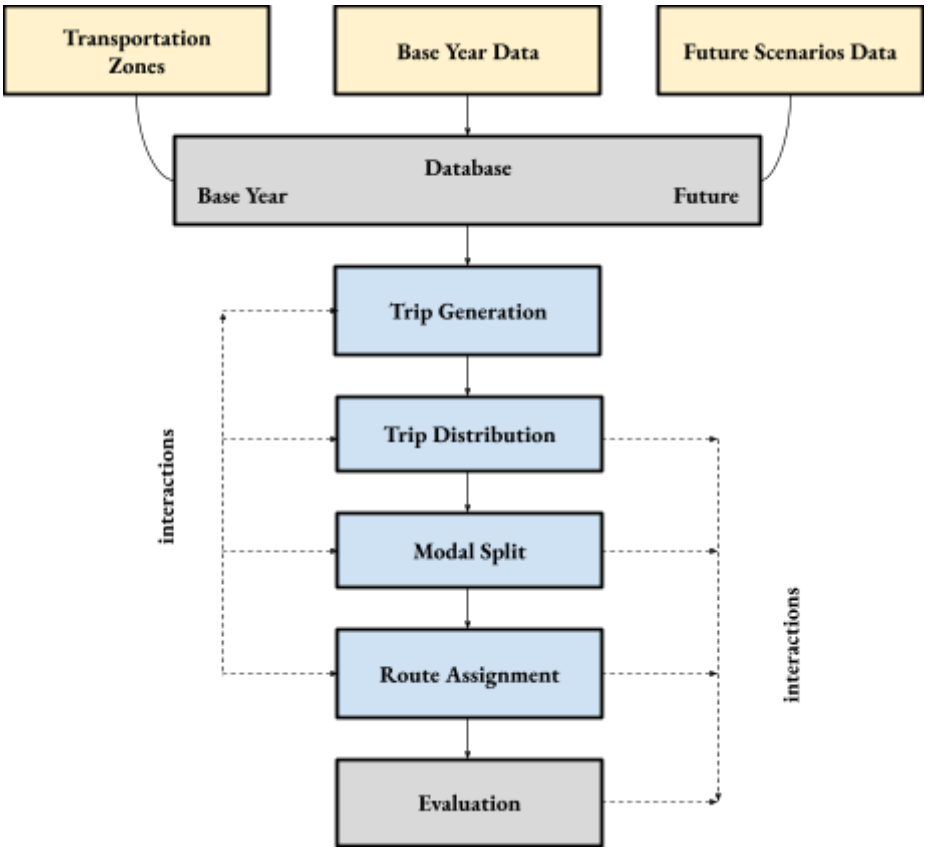


Figure 5: General Scheme of a 4-Step Model

General diagram of a 4-step model (after Ortúzar & Willumsen, 2011). Input data aggregated to Transportation Zones enters each of the 4 models sequentially and feeds every next step. The traditional approach of each model is: Trip Generation using statistical rates associated to land use quantities; Trip Distribution assuming a Gravity Model; Modal Split assuming Utility Maximization, and Route Assignment assuming Shortest Paths. All these four models have evolved into more theoretically grounded and complex models, but their order of application generally remains the same in contemporary models.

This approach has been termed as the "D's" approach, after the "branding" by Cervero & Kockelman (1997), triggering a range of works which have further tested the influence of urban form in travel behavior. However, it has also been recently criticized for having become a buzzword that is not helping researchers to actually inspire policies, as the number of "D's" tested continues to expand, further complicating their readability (Handy, 2018). In Table 2, a simple summary on the most commonly used "D's" is presented.

Table 2:
A summary of the "D's" in the reviewed literature

The "D's"	Refers to...
Density	Population, Households, Jobs, Land Use Categories (...) by Spatial Unit
Diversity	Land Use and Social Mix, Spatial Complementarity, Entropy, Dissimilarity (...)
Design	Street Network Configuration, Architectural Materiality, Aesthetics
Destination accessibility	Accessibility Metrics from-to relevant pairs of POIs
Distance to Transit	Commonly, Gravity-Based Accessibility to public transportation
Demand Management	Presence of Parkings, Level Of Service (...)
Demographics	Controls / Confounders

By the late 1990s, many empirical works were reviewed by Handy (1996), who detailed some of the seminal questions and the methodological constraints for this kind of approach, after a first confirmation that the measurement of urban form showed a relatively low level of explanation of travel behavior, and a high level of complexity.

This first wave of papers did not either confirm or reject the validity of approaching travel behavior through built environment characterisation, but rather arose that a lot needed to be explored and understood: few (if any) transparent relationships between form and travel could yet be understood; a relevant role of social behavioral predictors was starting to emerge (calling for cross-disciplinary knowledge) and; in general, results were not yet sound enough to predict the travel outcomes of new development, nor comparable enough to establish robust meta-research studies, and methodological and conceptual refinement was still needed (Crane, 2000; Stead & Marshall, 2001; Boarnet & Crane, 2001).

Later meta-research still showed mixed results. If, for instance, Boarnet & Crane (2001) claimed how traffic calming by design was the only feature with a solid statistical association, Leck (2006) highlighted the role of population density and land use-mix as the most relevant

predictors of travel choice, pointing at street patterns (one of the most measured characteristics of street design) as the weakest predictor of travel outcomes.

Ewing and Cervero (2010) argued that, though relationships of individual dimensions were low, their combination was quite significant and, among them, destination accessibility is the one that shows more predictive power (and as much as density, diversity, and design variables combined). To further complicate things, endogeneity and correlation between independent variables was commonly found in these features, making their statistical combination theoretically weak.

These disparate results exemplified how the "reduced form" approach did not allow a simple comparative framework, and how particular contexts, both concerning local planning and residents behavior, are key to understand what aspect of urban form affects what aspect of travel outcomes beyond regression, as a place-specific problem of planning, cities, and human experience (Boarnet, 2011). Moreover, the last decades have seen a growing interest in behavioral or activity based approaches, which highlight attitudinal, sociological, or psychological concepts (Aston, 2021).

One of these concepts is the residential self-selection problem, or the notion that residents plan their travel behavior before they choose neighborhood characteristics, meaning that there is endogeneity between the travel outcomes targeted and the built environment itself. When controlling for this issue, some researchers noted decreases in the soundness of the relationships inspected (Cao, 2009; Stevens, 2017), yet other authors, such as Levine (2006), saw this problem as a mechanism for actually achieving success in proximity policies.

Other behavioral approaches include the concept of lifestyle and familiar transitions (Van Acker et al., 2016) or intentions, habits and life-course events as triggers to travel behavior changes (Lanzini, 2017); or the role of descriptive and subjective norms, social signaling, status, and identity, as potential co-determinants of travel behavior (Javaid, 2020).

Recent research calls for more qualitative study. Naess (2015) argues against implicit assumptions of correlation and causality between the built environment and travel, and proposes a study of "tendences" that the built environment can exert -but not particularly trigger- in travel behavior. Handy (2018) argues that, even though better data and better methods seem to "improve" the correlations of the D's with travel behavior, they do not add

clarity for policy information, and using more "readable" and "comprehensive" metrics, such as accessibility, might be a wise next step.

In contrast, Aston (2021) updated the meta review by Ewing & Cervero (2010), with improved methodologies and more diverse geographies, finding similar general magnitudes of relationship. However, the work also reports higher elasticities for urban density and land use mix; and a decrease in reported elasticities for measures of local access.

The most recent review found is the bibliometric search by Gao et al. (2023), which followed this research trend for the period 1997 to 2023 and found an expansion from original studies in the US context, towards increasing research in China and Europe. The overall most used keywords concerning the D's metrics are design, accessibility, residential self-selection and density, in this order. Also, this review identified a shift from pure built environment features to a more holistic approach with attitudinal data, as well as an interest in integrating emerging technologies such as big data and machine learning.

Recent trends in the work by Gao et al. (2023) connect with the present review of empirical works around urban proximity. According to this last study, together with the growing attention to activity, behavior and technology, a clear emergence of active-modes research (also connected to topics of sustainable mobility and GHG emissions reduction) is seen to accelerate around the 2013-2015 period, peaking around the COVID-19 pandemic events.

Finally, other emergent topics such as last-mile delivery, particular focuses on children and older adults' travel behavior, or the use of data-centric approaches to the problem's complexity, are also well connected to the review framework. In the meta-review by Aston (2020), the use of accessibility approaches is shown to increase up to the point of discursive dominance in the field, consistent with the discourse in Handy (2018).

Next, the review decomposes this approach following the classifications found in an early (Handy, 1996) and a recent comprehensive review (Acheampong, 2015). Research strategies (theoretical frameworks of research), heuristics (methods to extract knowledge), targeted travel outcome variables, and their commonly associated features of the social and built environment, are all inspected for relevance in the broad field of travel and the built environment, and the particular recent empirical approaches to proximity.

3.2 Research Strategy

In a proximity-empirical context, the questions to ask, beyond compliance: "Can this place be considered a proximal environment?", can be adapted from early works reviewed such as Handy (1996), Crane (2000) and Krizek (2003): "What aspects or combinations of aspects of urban proximity influence travel? How many significant dimensions influence urban proximity? What is their significance and how do they relate to each other?"

Concerning urban proximity, these questions imply that a place that can be described as a proximal environment has differential attributes that can be measured and statistically related to travel behavior. However, dealing with such a complex set of phenomena, many authors like Boarnet & Crane (2001), Cao (2009), Boarnet (2011), or Naess (2015), call for taking statistical relationships carefully, as the direction in which causality is flowing is not completely clear, and correlation might not suffice to achieve empirical validity.

In empirical travel research, the attributes included, and the specification of the regression or classification models are the most critical decisions. The appropriateness and credibility of models depend on assumptions with regard to the form of the data and the structure of the underlying behavior. In both senses, the greatest challenge may be the explicit linkage of individual and land use measures to behavioral measures (Crane, 2000).

In the present review, the existing empirical research addresses many of these questions when designing the different approaches. Frameworks mostly gravitate around a notion of accessibility or threshold distances, yet in some cases other parameters such as density or diversity are explicitly mentioned. If, as shown by the present review, the accessibility approach is core, then it will be necessary to motivate the use of specific origins and destinations, rules of movement, and aggregation / specification of the final indexes used.

Anyway, beyond the selection of policy or behaviorally relevant components and statistical outcomes, questions to be answered can be as so: "Access to basic needs in proximity seems to

trigger a certain local kind of travel behavior, but, why and how much?" In this section, a classification of different research strategies which are helpful to obtain answers is given.

In the urban proximity review, works fall into most of the categories described by Handy (1996; 2002), Crane (2000), Ewing & Cervero (2001), Leck (2006) and Acheampong (2015), along with the additional category of spatial analysis (not found in these reviews), and are reviewed for relevance within the urban proximity topic and the found empirical works. Note that these categories are not exclusionary, and mixed designs are common ground in this line of research (Acheampong, 2015). Table 3 shows a summary of the strategies identified in the reviewed works.

Table 3
Research strategies of the empirical literature reviewed

Reference	Research Strategy
Haugen, 2011	Activity Based
Haugen et al., 2012	Activity Based
Marquet & Miralles-Guasch, 2015	Aggregate Analysis
Searcy et al., 2018	Disaggregate Analysis
Kasraian et al., 2019	Aggregate analysis
Graells - Garrido et al., 2021	Simulation Study
Bartzokas-Tsiompras & Bakogiannis, 2022	Aggregate Analysis
Li, 2022	Disaggregate Analysis
Gil-Solá & Vilhelmson, 2022	Activity Based
Abbiasov et al., 2022	Disaggregate Analysis
Calafiore et al., 2022	Spatial Analysis
Knap et al., 2023	Spatial Analysis
Birkenfeld et al., 2023	Activity Based
Poorthuis & Zook, 2023	Simulation Study
Aristizábal et al., 2023	Choice Model
Yu & Higgins, 2024	Choice Model
Elldér, 2024	Aggregate Analysis

3.2.1 Simulation studies

Simulation studies are those works that build predictions and/or implications of alternatives commonly based on previous assumptions of travel behavior, with limited or no prior empirical tests (Handy, 1996), and perform a simulation when one of the assumed parameters changes. For instance, the four-step model can be considered one of the first simulation models. In a broad sense, the idea of being able to "interactively" inspect how changes in certain parameters impact a whole system is what makes simulation studies different.

While not particularly suited for hypothesis testing in the travel-built environment context (Crane, 2000), simulations provide valuable insights into the complex effects of both realms. For example, street patterns have been a focus in micro-studies of walking and active modes (Handy, 2002; Leck, 2006), revealing how different designs impact movement and accessibility. Moreover, simulation approaches have been used to examine travel constraints and modal alternatives (Boarnet, 2011), also leveraging concepts from Complexity and General Systems Theory, which employ synthetic agents to simulate interactions within transportation networks (Acheampong, 2015). In the supplementary material, three examples of simulators are reviewed.

Simulation studies have been related to proximity and active travel modes, especially in modeling accessibility at both regional and local scales, and trajectory studies. Simulation in proximity considers route choice, network effects, and micro-scale urban features, helping in creating realistic proximity catchment areas (Vale et al., 2016), advancing the state of research on pedestrian navigation (Lee & Moudon, 2006) and urban interventions aimed at promoting active modes (Aldred, 2019).

In the review of empirical approaches, Poorthuis & Zook (2023), is the only example of a research oriented simulation. It focuses on the 30-minute territory concept (the regional version of the 15-minute city) to model the time viability of substituting automobile trips above 10 km. (observed) with a simulation of public transportation, attempting to achieve a 30-minute constraint in rural areas to finally use both mode travel times to analyze how a local accessibility metric fails to explain increased travel times in this hypothetical non-car scenario.

3.2.2 Disaggregate Analysis

Disaggregate analysis focuses on individual/household observed trips and their characteristics of influence (individual or environmental). It models the influence of the latter in the former by assuming mechanisms of choice flowing from the built environment towards individuals, and they have helped reveal behavioral complexities between communities (Handy, 1996).

In cases where detailed data on the built environment, travel routes, behavior, and socioeconomic characteristics of travelers are available, this approach is useful. It allows researchers to isolate different features and individual situations, helping to minimize the risk of ecological fallacy (incorrectly assuming that a particular spatial extent represents the mechanisms of effect on individuals). However, a major challenge for disaggregate analysis is balancing the level of detail and sample size. Detailed trip data is often limited by the need for expensive ad-hoc surveys, and while GPS data offers large datasets, it can lack critical information such as transportation mode or trip purpose due to privacy concerns (Aldred, 2019).

Trip chaining and multi-purpose trips pose further complexities in disaggregate analysis, as the inclusion of active phases like walking stages is often overlooked. Trip purpose is another critical feature especially for non-work, daily activities. The labeling of trips' purpose is essential to avoid uncertainty in analysis, and distinctions between walking and cycling for transport versus leisure are often blurred. This can lead to confusion when trying to understand some mobility outcomes.

In relation to urban proximity, disaggregate analysis has been widely applied to walking, cycling, and public transportation, with a focus on fine-grained features of individuals. A key challenge is accurately capturing the spatial features that influence choice, as many of these features operate on a micro-scale that is difficult to measure. Research proposes many features to control for, such as density at the origin, destination, or along the route, and these measurements vary significantly in terms of their reported impact on trips (Saelens, Sallis & Frank, 2003).

This approach has been identified in various works. Haugen et al. (2012) extract two cross-sections from a database of geo-located residences and workplaces, and compute euclidean distances between them and other amenities (both from home and workplaces), in order to

understand the variation through time. In this work, relevant places are informed in the original data, but no detailed information on trips is present. Searcy (2018) uses a travel survey from students in different universities targeted only at distances and mode choice. Li (2022) uses big data on grocery store visits, but needs to join the sociodemographic data from census tracts on trips. Birkenfeld et al. (2023) use official OD travel data and also infer missing sociodemographic characteristics from the census tracts (testing a multilevel model to compare, and finally check the validity of the disaggregated approach). They ultimately aggregate to the household level which, given its scale, should also be considered as a disaggregate analysis of this kind.

In summary, disaggregate analysis of trips is the conceptual ideal if the data is available and reasonably detailed. A balance between the volume and detail of the trips registered should ensure variation and reliability of the disaggregate approach. Figures 6 and 7 illustrate the level of disaggregation of the EDM2018 through their categorical and continuous features.

Disaggregation level of the EDM2018

To illustrate disaggregated analysis, the EDM2018 is explored, highlighting trips below a threshold of 15 minutes of duration. In Figures 12 and 13, the total frequency of trips in the survey is shown (elevated for representing all trips) categorized by the variables included, highlighting those trips lower than the 15 minute threshold. The description will focus on imbalanced categories around or beyond the 60/40 threshold of distribution.

- ➔ Gender (Male or Female): Survey shows quite an even distribution of both classes, both in number of trips and proximity trips.
- ➔ Foreign: Describes whether the respondent has Spanish nationality or not. The sample is rather imbalanced, and this is particularly unexpected taking into account the actual percentage of foreign residents in the area of study. In any case, the proportion of proximity trips does not seem to exhibit unbalanced patterns.
- ➔ PRR: Describes whether the respondent has Reduced Mobility. The amount of positive respondents is low, but it is an expected behavior, as PMR respondents will most likely be a minority. Proximity patterns do exhibit quite an unbalanced behavior, as 65% of PMR trips are below 15 minutes.
- ➔ TravelCard: The kind of travel card held by respondents, simplified to a Yes/No response. Holding a travel card is commonly regarded either as an indicator of frequent Transit Ridership, or as an attitude open to it. In the EDM2018 sample, the number of card holders is significant. Interestingly, 64% of respondents without a Travel Card perform trips below 15 minutes.

- ➔ HasVehicle: Whether respondents' households own a vehicle or not. Ownership can be seen either as an indicator of frequent driving, or an attitude open to driving when convenient. Trips below 15 minutes show similar proportions that those above.
- ➔ HasLicense: The kind of driving permit of the respondent, simplified to show a yes/no status. Holding a driving license is a prerequisite for driving in Spain from age 18 for most vehicles, but it can be associated with openness to driving. Car trips for personal reasons, will likely imply that the user holds a driving license. Respondents without a license perform 59% of their trips below 15 minutes.
- ➔ Frequency: Qualitative variable depicting the weekly frequency of the trip. A rather ambiguous class labeled "Sometimes" is the most prevalent, and it will be assumed that it means a low frequency trip. No imbalance pattern in proximity prevalence is shown in this feature.
- ➔ DayOfWeek: The day of the week for the trip, only containing Monday to Thursday. This field can be considered trivial all being weekdays. No imbalance is shown by these categories proximity-wise.
- ➔ EducationLevel: Educational level of the respondent. It has been simplified to show only general classes of education, leaving Secondary school disaggregated, in order to distinguish individuals aiming only for compulsory education or not. Not having completed educational status (commonly associated with either highly older adults or children below common primary education completion age), or having completed primary education stages show 75/25 and 61/39 patterns of proximity trips. This may suggest that below-secondary education children account for a broad share of 15-minute trips.
- ➔ Activity: Labour status of the respondent, with classes aggregated for being negligible, such as "Works and Studies", or different kinds of unemployed people. This category shows interesting patterns. Caretakers perform up to 67% of trips below 15 minutes, while students show a 62/38 proportion. Unemployed and Retired people show less imbalance patterns of 59/41 and 57/43. Finally, workers show a lean towards above 15 minute trips with a 43/57 proportion.
- ➔ NoPrivate: The main reason not to choose a private vehicle. In no case proximity trips seem to show a higher prevalence. However, reasons not pooled in the "other" category are biased by scarcity.
- ➔ NoPublic: Attitudinal variable for the reason not to choose public transportation. This feature is better informed, and a particular response "Is very Close" exhibits an expected outperformance of 15-minute trips (84/16). However, the "Prefer Active Modes" result is counterintuitive, showing a 37/63 proportion leaning towards above 15 minute trips.
- ➔ TripPurpose: General purpose of the trip. Ambiguous classes have been pooled in an "Other" class. Interestingly, "Sport/Stroll" category shows a higher proportion of above 15-minute trips (39/61), and Work trips show an even higher imbalance (30/70). Care and Leisure trips exhibit a higher proportion of 15 minute trips (61/39 in both cases), even higher in Shopping trips (70/30).
- ➔ TransportMode: Main transportation mode of the trip. It has been simplified to show only general classes by ownership and policy implications. Bus and Train modes show imbalance towards non-proximity trips (32/68 and 10/90 respectively), while Walking shows an expected higher proximity prevalence (65/35).

- ➔ Age: The age of the respondent. Inspecting the distribution of this column by 10-years bins, it can be seen that children 0-10 years perform 76% of trips within 15-minute ranges, a proportion that is smoothed in the 10-20 years old range up to 61/38. Younger adults aged 20-30 years old exhibit an opposite proportion of 39/61, to stabilize in the following bins and go back to higher proportions of proximity trips in later stages (56/53 and 67/32 for 70-80 and 80-90 bins, respectively.
- ➔ HouseholdSize: exhibits quite an even proportion of 15-minute-and-beyond trips in all values up to 5 members. The number of households beyond that size is rare and little informed.
- ➔ TripsHousehold: Depicts the number of declared trips per household. It is interesting to note that only the highest bins, up to 10-15 trips, does show a 61/38 proportion of proximity trips, which might indicate that the surplus of trips is actually achieved in proximity ranges.
- ➔ TripSpeed is derived from distance and timestamp values of the survey. Up to 5 km/h, trips below 15-minutes account for 61% of trips, decreasing as speed increases.
- ➔ StartTime and EndTime are the timestamp values of the survey. They only exhibit imbalance towards non-proximity trips during the night hours.

Number of Trips by categories

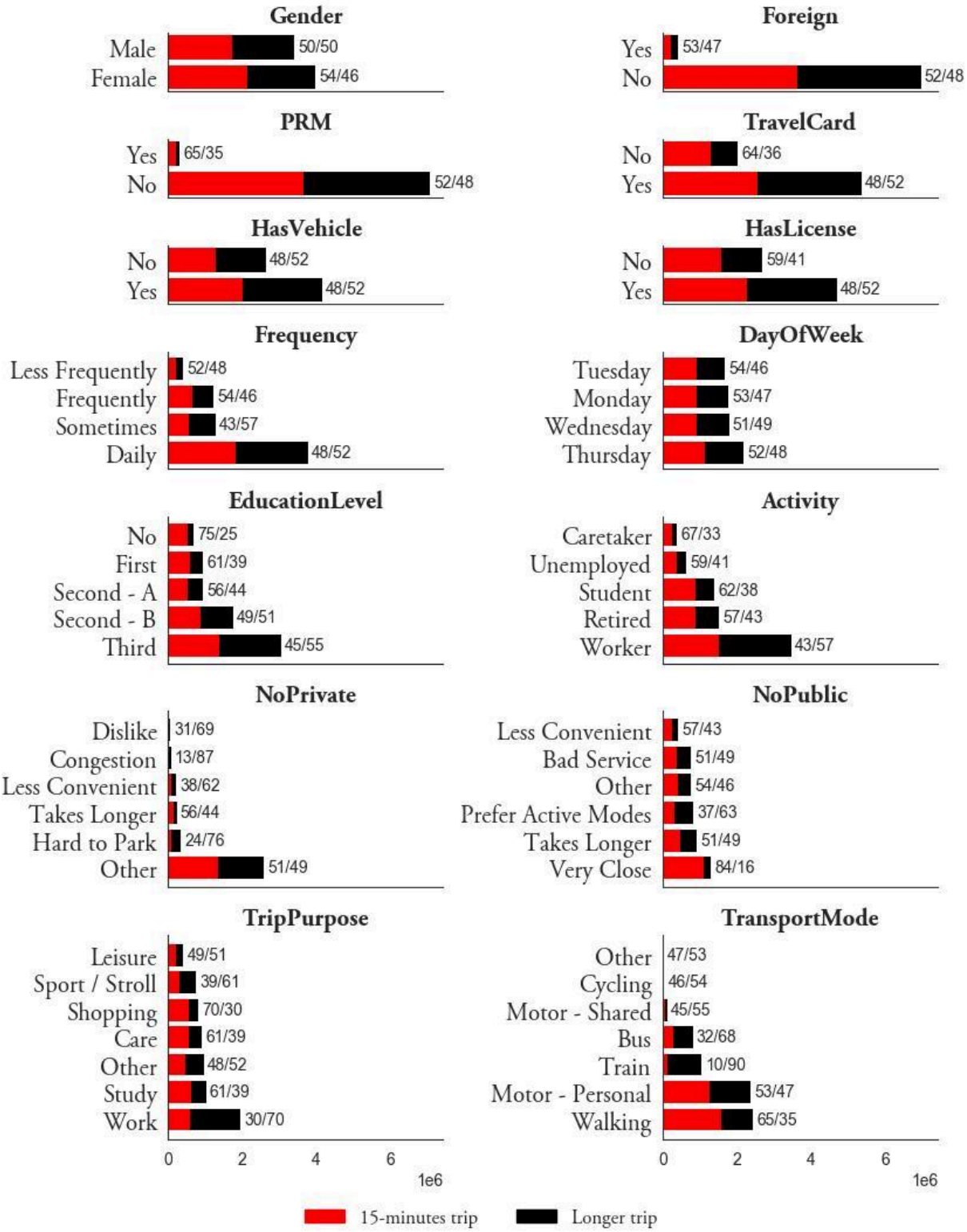


Figure 6: (previous page) Number of Trips by Categories

Number of trips and proportion of up-to 15 minutes trips (in red). Proportions are plotted after each bar, the first number representing the percentage of trips beyond 15 minutes, the second representing trips below. Filters will be built for sparsely populated classes: Foreign, PMR users, "Less Frequently" trips, as well as "Other", "Cycling" and "Shared" modes will be disconsidered. Leisure trips are also very rare in this sample.

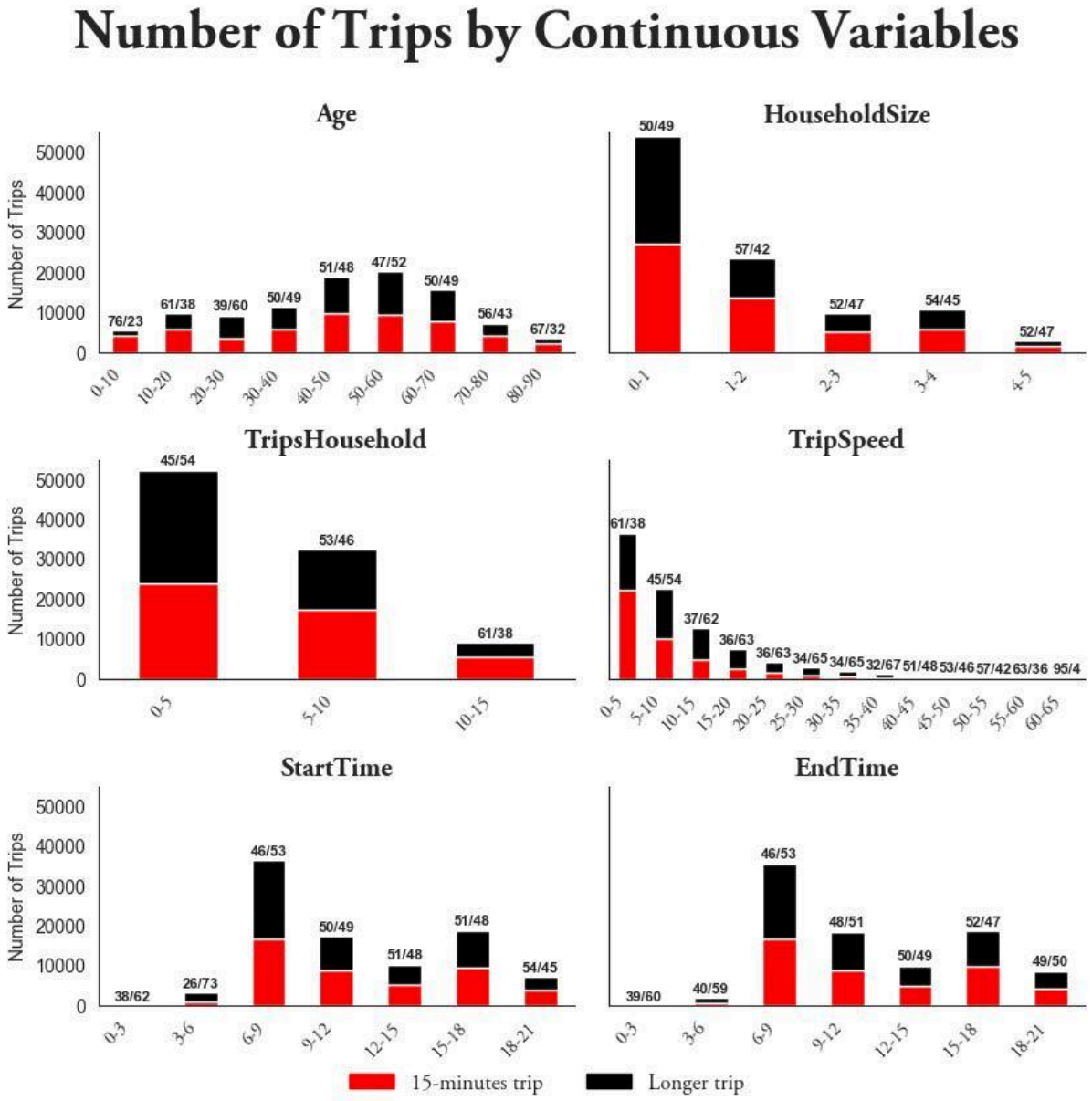


Figure 7 (previous page): Number of Trips by Continuous Variables
Number of trips and proportion of up-to 15 minutes trips (in red), for continuous variables. Proportions are plotted after each bar, the first number representing the percentage of trips beyond 15 minutes, the second representing percentage of trips below .The age and household size are, according to the EDM2018 handbook, two design variables for the survey and Transport analysis Zones. In the case of speed, distance, etc, values are calculated from the origin and destination given by each respondent.

3.2.3 Aggregate Analysis

Aggregate analysis is a similar approach to disaggregate analysis, but statistics are performed at aggregate geographic levels, assuming they are robust enough to establish a place-based relationship. All outcome metrics, and associated features, are aggregated at a certain set of spatial features or, in some cases, different scales are used in a hierarchical way.

This method is widely used due to the ease of data availability, even though it has its limitations. One major issue is the ecological fallacy, where aggregation assumes that individuals are equally affected within geographic boundaries. Additionally, simplifying data for computation, such as in four-step transportation models where zones are represented as centroids, can mask the nuanced characteristics of areas. Despite these limitations, aggregate analysis has been popular in research due to scale coherency to address policy impacts, such as zonal regulations or urban design typologies, across larger areas (Handy, 2002; Aldred, 2019).

In studies concerning proximity, aggregate analysis introduces complexities when considering the scale and spatial units of analysis. There are concerns over the Modifiable Area Unit Problem (MAUP), where arbitrary boundaries influence results. Researchers often try to delineate homogeneous areas or normalize space using grids, though this can reduce the number of observations. When analyzing travel, the “spillover” of behavior across boundaries complicates aggregate studies, making spatial representation and contiguity challenging. To mitigate these biases, some studies use geographic weights in their statistical models to account for spatial dependencies. However, the process of aggregating built environment metrics, especially if calculated from area centroids, risks oversimplifying spatial data, making it less informative for understanding local dynamics.

In this review, multiple works use aggregate analysis. Broad aggregations have been found in Bartzokas-Tsiompras & Bakogiannis (2022) and Elldér (2024) (using data available at the city

level, and Functional Urban Areas), while smaller scales are chosen in Marquet (2015), Calafiore et al. (2022), Poorthuis & Zook (2023), or Knap et al. (2023) who use ready-to-use information available at a neighborhood level. In Abbiasov et al. (2022) or Yu & Higgins (2024), although finer grain mobility data is available, it is also aggregated into census tracts and neighborhoods so as to be able to associate it to other variables available at said levels.

In general, the takeaway from this approach is that, as a rule of thumb, data availability will be a major constraint to the selection of scale, smaller scales or meaningful boundaries (such as neighborhoods) will be preferred (to establish a robust association between boundaries and the individuals within them), and some way of accounting for the spatial arbitrariness of statistical boundaries is desirable, as it is reviewed in section 3.2.6 dealing with spatial analysis.

Aggregation levels at Madrid Metro Area and variable distribution

To exemplify aggregate analysis and show a glimpse of their most repeated caveats on multi-scalar aggregation, a basic measure of density can be explored in the dataset, and aggregate it into different levels, so as to explore changes in distribution. A simple density metric is performed (population/urban area) using the actual urban area to control for the varying size of the boundaries, specifically at census tract, transportation zone, district, municipality levels. The distribution is then normalized using the Standard Deviation of the Log-transformed data. Figure 8 illustrates the results.

Beyond the obvious differences in the number of observations, it is seen how both the raw and the normalized distributions change greatly, which will critically impact the ways this particular characteristic might impact results of statistical efforts. A certain similarity, however, can be observed at the census and transportation analysis zones, both being more homogeneous in population and amount of urban land. Note that, for the latter, those units that do not contain population at all have been removed (this is the case with many boundaries representing industrial or infrastructure areas such as stations).

Distribution of Density at Different Aggregations

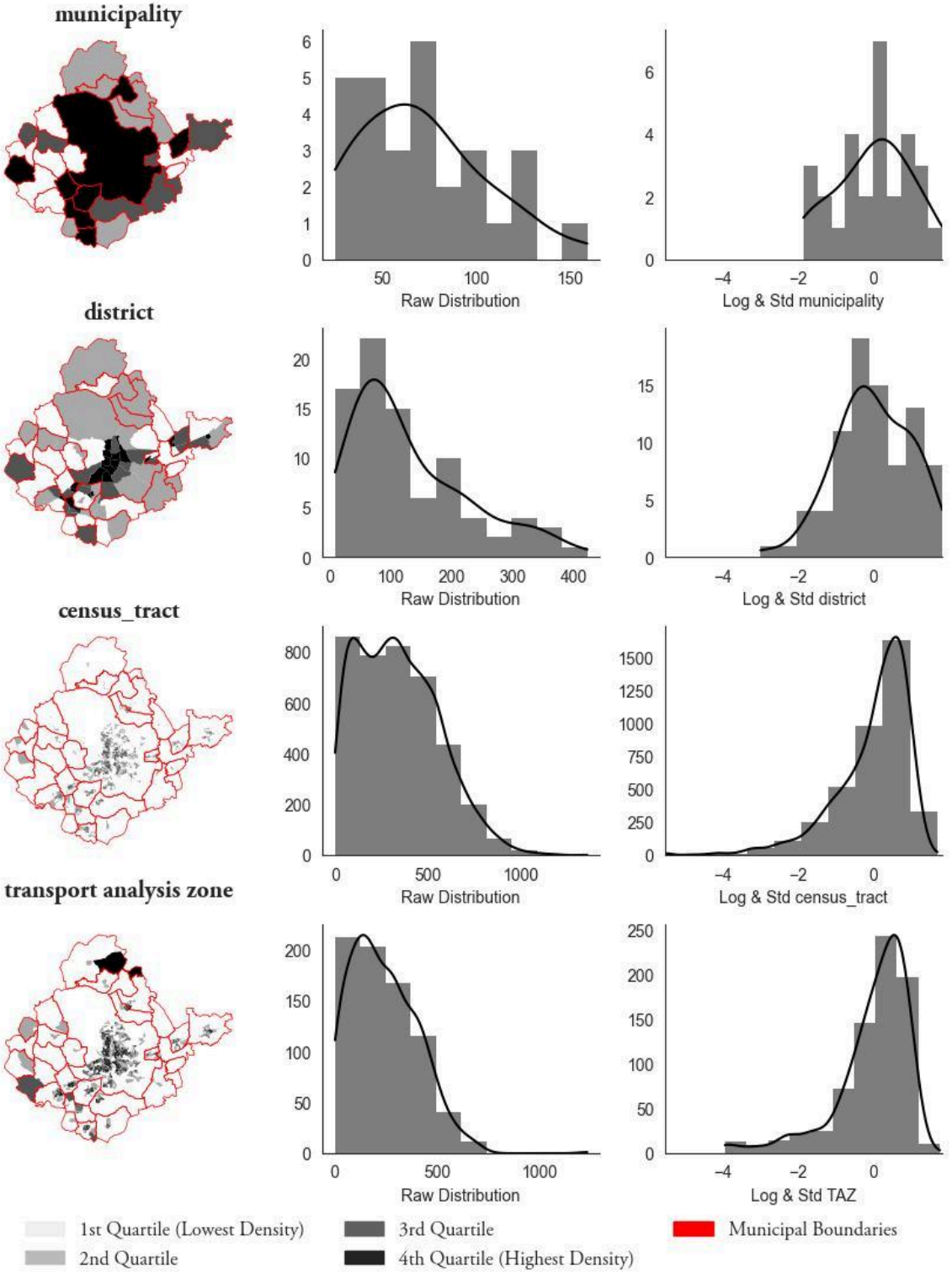


Figure 8 (Previous page): Distribution of Density at Different Aggregations
Distribution of population density (population / area of spatial unit) considering various boundary sets. Maps show 4 shades of grey-to-black depicting the four quartiles for each aggregation level. The raw distribution is a simple histogram (a bar plot of the count of spatial units for each density value on the x axis). The distribution is normalized using a Log and Standard Deviation transformation.

3.2.4 Choice Modeling

Choice modeling is a micro-economic approach to the decision process of individuals on discrete (or categorical) choices, given their own preferences, commonly termed "utility". In transportation research, it was popularized in parallel to the theory of consumer choice (McFadden, 1973). This theory assumes that people make rational decisions, maximizing or optimizing utility. The built environment plays an important role in these models, often influencing decisions as a cost or attractiveness characteristic within utility functions. These models allow testing causality, such as in destination or mode choice, yet often treat built environment features as "unobserved" and assume rational decision-making without fully addressing how and which specific elements influence travel.

According to Handy (1996), choice modeling commonly uses multinomial logit techniques and, though these do not equate the development of choice theory, they have great potential to understand the contribution and complex relationship of different predictors of travel behavior. These models will be further reviewed in the Research Heuristics sections through one of their most common forms: The Random Utility Models.

The main challenge in choice modeling is the complexity of accurately capturing how built environment characteristics, such as density, impact travel decisions. Individuals may perceive these features in different ways, creating a range of utilities or disutilities that are difficult to quantify. For instance, one person may prefer walking through a historic center, while another may find driving more convenient to avoid congestion or for safety reasons. As such, the subjective nature of environmental characteristics can complicate the ability to make generalizable conclusions about their effects on travel decisions.

In the context of proximity, choice modeling becomes more nuanced, as it deals with decisions that individuals make in their local range of action, either in the mode they use to travel, or the mere decision to travel locally. Also, dealing with active modes, complex features such as comfort, safety, aesthetics, trip chaining, or multi-errand trips, among others, influence their choices, posing some challenges to the idea of a fully rational and informed choice from users, which might need reformulations for a local context (Handy, 2002).

The challenge remains in comparing utilities between modes and across users, especially when subjective characteristics are involved (Silva et al., 2023). Although choice modeling is useful for exploring travel outcomes, it often falls short of providing clear mechanisms of effect within utility frameworks. In the review, choice modeling can be seen in the works by Aristizábal et al. (2023), only focusing on pedestrian trips against all other modes, or Yu & Higgins (2024), who explore all available modes. However, none of these references state clear mechanisms of effect, as in utility choice, and simply associate predictors to travel outcome in the same level.

In general, the key ideas to account for when designing a choice modelling approach, are the selection of the alternatives (modal, spatial, or others), their number, and their relationships, along with a clear understanding of the scale and effect of utility of social and built environment features on individuals.

Mode Choice by Distance in the AMM

In this subsection, the prevalence (the percentage) of different transportation modes by region, and the distribution of choice when accounting for the distance traveled for each case is explored. As per the municipal aggregation of percentage of trips per mode, the maps by quartiles show some expected behaviors, while plotting their distribution by distance, differentiating between proximity (less than 15 minutes) trips and beyond, gives some interesting suggestions. Figure 9 illustrates the results.

For instance, Madrid is the least prone municipality to use cars, yet it is true that it is the central business region, it has denser urban tissues (thus impacting the provision of parking space or car speed), and has also the highest provision of alternatives. In fact, bus and train use peaks in the capital municipality, yet it shows other peripheral behavior which could theoretically be inspected for relations with provision, commuting dynamics or other demographic and environmental features. Interestingly, walking for transportation does not seem to peak in Madrid, but rather in the cluster of municipalities to the south, yet also showing high

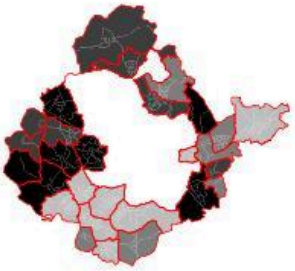
incidence in many of the other municipalities in the area. In any case, mode choice seems elusive and complicated to explain in simple regional terms.

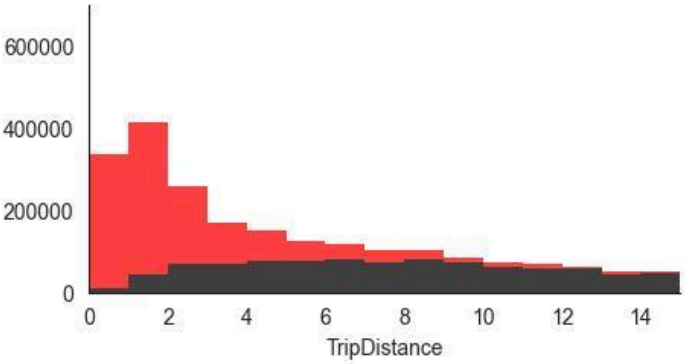
Concerning the distribution by distance, an interesting pattern in the distribution of 15-Minute trips shows how Public Transportation (both bus and train trips, although less in the latter) in the region are way less used for local travel than walking and driving. This might be a hint to think that, in the targeted region, the utility of public transportation is not especially high when it comes to short trips. In this case, it is the comparison of driving and walking which should lead to insights on the role of different features in the trip mode decision.

Figure 9 (Following page): Mode Prevalence by Trip Distance
Mode Prevalence and Trips by Distance. Spatial aggregation to municipality (left) with four quartiles represented from white (lowest) to black (highest); and total number of trips (right) under (red) and over (black) 15-Minutes.

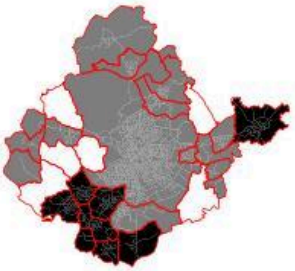
Mode Prevalence and Trips by Distance

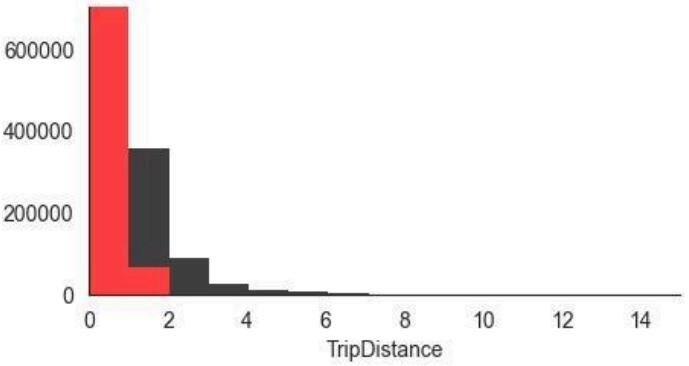
PrivateVehicle



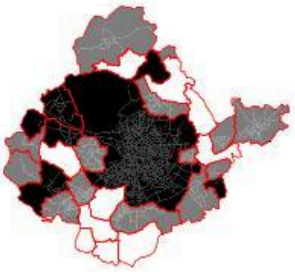


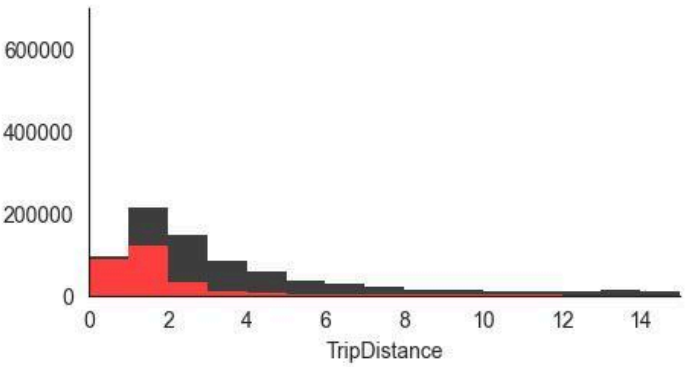
Walking



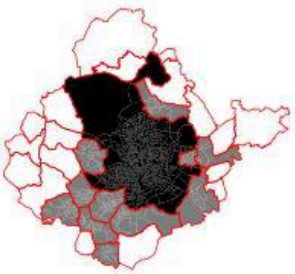


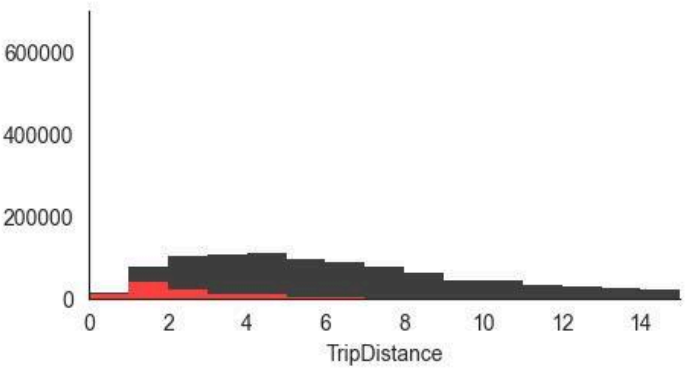
Bus





Train





1st Quartile (Lowest Prevalence)
2nd Quartile
3rd Quartile
4th Quartile (Highest Prevalence)
Municipal Boundaries
15-minutes trip
Longer trip

3.2.5 Activity-based Research

Activity-Based or Activity-Travel research is a kind of research strategy that considers travel as a derived demand for various interrelated activities with spatio-temporal constraints of activity and mobility, the complex interpersonal dynamics in households and social networks, and activity scheduling (coupling activities, temporal or legal restrictions, etc.).

This approach emerged in the 1990s, blending time-geography concepts with the theory of consumer choice. It addresses how different household members coordinate tasks, how time is distributed between activities, and how these dynamics influence travel. Surveys and models are often used to explore how people manage travel in relation to daily activities, providing insights into behaviors like commuting, task chaining, and household decision-making processes (Hagestrand, 1970, McFadden, 1973).

A key strength of activity-based research is its ability to examine travel in the broader context of daily life, shedding light on nuances that other approaches may overlook. For example, commuting might usually be considered a time-optimized activity, but adding school drop-offs, errands, or evening plans introduces additional complexity. The built environment plays a crucial role in facilitating or hindering these behaviors, whether by providing accessible routes or creating barriers to task coordination. While this approach offers valuable detail, it is computationally intensive and often focuses on specific population segments or activities, making it a particular form of disaggregate and/or choice model research. Despite its complexity, activity-based research helps form detailed hypotheses about the interplay between time, space, social roles, and travel behavior (Timmermans, 2009)..

In the context of urban proximity, activity-based research offers valuable qualitative insights, particularly for policy and tailored interventions. Understanding how proximity affects access to services and amenities, residential choice, and daily trips can be framed through this lens. Research could explore how proximity influences trip chaining, travel satisfaction, and the frequency of local trips. However, the high cost (for large samples) and subjectivity of qualitative studies are significant drawbacks when aiming at medium-sized or large samples.

In the reviewed works, Haugen (2011) used a targeted survey to address questions on the respondents' distances to various destinations, valuation of the importance of proximity to these destinations, and satisfaction with the distance. Gil-Solá & Vilhelmson (2012) use an individual-based geocoded database on the importance of geographic proximity and sustainable accessibility, including data on activities and services visited, choice of activity/service location, modal choice, access to modes of transport, environmental values, and experienced time pressure. Birkenfeld et al. (2022) aggregate individual trips of a survey into their households, in order to inspect the complex interactions between members and their travel needs and patterns.

The key lesson from Activity-Based research is understanding urban travel in the contexts of complex time-space and individual-society interactions. Whenever possible, research on travel and the built environment should address these through the tailoring of surveys, predictor selection (and metric construction), or trip data filtering.

Local Lifestyle in the AMM

The ideas by Birkenfeld et al. (2022) on the proportion of Households living a local lifestyle have been explored. From the EDM2018 dataset, a series of categories of households defined by the presence of certain demographic patterns are derived: the presence of Children (aged less than 6 years old); the presence of older children (Aged 6-12, the age of Primary School education in Spain); the presence of youngsters in the age of attending Secondary Education (Aged 13-18); the presence of older students (more than 19 years old); Full-time workers, independent of age and; retirees (in Spain, mostly population aged 65 years old or more). The categories are assigned whenever any individual of the following ordered sequence is found in the household group: Retired, Worker, Ages 13-18, Ages 6-12, Age less than 6.

"Local Lifestyle" has two definitions: Households that perform all their weekly trips under 15 or 30 minutes trips. Most categories have a greater incidence of non-local lifestyle individuals for 15 minute trips, being consistent with Birkenfeld et al. (2023), yet the proportions are notably higher than the aforementioned study. It is households labeled as retirees (28%) and students over 19 years old (23%) that hold the highest share of performing this kind of local trip. When the threshold is set at 30 minute trips, proportions do change significantly. Actually, households labeled as retirees perform only under-30 minute trips in 53% of cases, and Children under 6 go up to 48%. The rest of classes show a rather high proportion of this kind of trips, being the "less local" the students 13-18, hitting a 35% percent of only 30 minute local trip behavior.

Figure 10 illustrates the findings of this exploration.

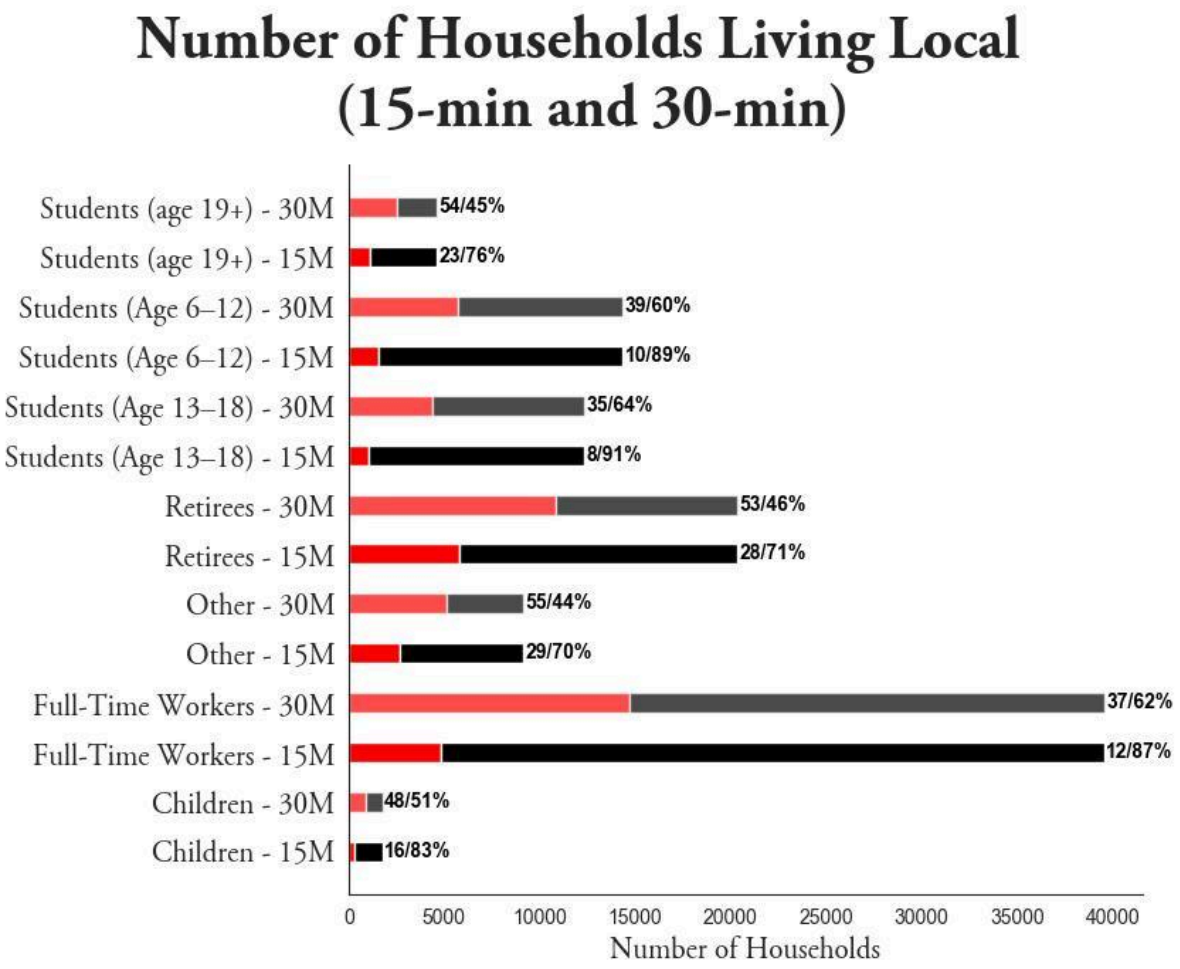


Figure 10: Number of Households Living Local

Number of Households by Household Structure living local (all trips in the Household under 15 or 30-minutes). In red and pink, trips that meet the 15 or 30 minute condition; in black and white, households that do not. Percentages are shown at the end of the horizontal bars. The first number shows the percentage of 15 or 30 minute trips, the second those trips beyond.

3.2.6 Spatial Analysis

Spatial Analysis can be defined as the set of techniques which deal with the first law of Geography: "everything is related to everything, but closer things are more related" (Tobler, 1970). This proposition has led to the development of many approaches to the rather common problems that scientists face when dealing with spatial data, as it is the case of the present review.

At least three important sources of spatial bias are acknowledged in many of the works reviewed: spatial autocorrelation, geographic scale, and modifiable spatial units. For the three sources of bias, a number of techniques can be traced in the literature, but also used as "means to an end" in several works, thus being included in this section on research strategy. In summary, spatial analysis is an approach that targets the study of spatial patterns of phenomena, assuming that their closeness will make them interdependent, and uses them to identify locations of interest, or to further seek other statistical implications (Hong et al., 2013; Duan et al. 2023)..

In the context of travel-built environment, spatial analysis is adopted for understanding how the arrangement of spatial units (like roads, neighborhoods, or amenities) influences travel behavior. Researchers apply these methods to explore spatial interdependencies, helping to resolve issues of bias and providing more accurate representations of how space affects movement and accessibility. Interestingly, measures of spatial patterns (such as autocorrelation), have been used for some time now to detect clusters of outcomes or features, as in Krizek (2003), where these hotspots are directly equated to a notion of local accessibility .

In the present review, these techniques have been mentioned in section 3.2.3, as many of the works reviewed here deal with spatial implications by tailoring their statistical approaches to the use of boundaries. Three particular techniques have been identified: single or bi-variate pattern identification, and spatial lagging. Pattern identification is used to cluster proximity behavior in Calafiore et al. (2022) or Knap et al. (2023), where features are transformed in their spatial clusters before modeling. Spatial lagging or weighting has also been identified in many works, such as Graells - Garrido et al. (2021), Calafiore et al. (2022), Yu & Higgins (2024), Poorthuis & Zook (2023) and Aristizábal et al. (2023), used for "smoothing" the values of spatial

observations, taking into account their proximity or contiguity (in a sense, “borrowing” strength from their neighboring boundaries.

An important lesson of this approach is that spatiality is utterly important when designing a kind of research which will most likely deal with behavior or characteristics that will have strong interactions across boundaries, given that these are preferred in the smallest / more meaningful scales available. Selecting ways of accounting for this "boundary spillover” is desirable. Also, clustering techniques are particularly interesting when taken as a spatial mechanism, as they also capture a sense of proximity between similar portions of space.

3.2.7 Longitudinal, Experimental, Time Series research

A note for the need of longitudinal and experimental studies in empirical approaches to proximity is included, as a limitation pervasively pointed in the reviewed works. Longitudinal and experimental studies are essential for understanding the impact of policies and changes to the built environment on travel behavior. However, longitudinal studies, which track changes over time in the same individuals, and experimental studies, which test interventions on controlled populations, are still rare in the proximity approach.

There are different types of longitudinal studies reviewed in the literature. "Before and after" studies examine specific interventions, such as improvements to walking infrastructure; "movers" studies target populations that have relocated; and “natural experimentation” focuses on “treated” populations (and control groups) (Cao, 2009; Koohsari, 2017; Aldred, 2019). Pure longitudinal studies, which analyze travel behavior over time, are rare due to data discontinuity and the challenges of maintaining consistent data collection. Even when such studies are conducted, conceptual issues arise, such as assuming stability in causal relationships, selecting optimal time intervals, and dealing with self-selection bias.

The complexity of measuring qualitative variables like attitudes over time also adds to the difficulty of conducting effective longitudinal studies (Kitamura, 1997; Naess, 2015; Aldred, 2019). Researchers have attempted to manage this situation through quasi-experimental approaches (conducting cross-sectional research but asking questions about the past), however,

recent research has also pointed to the use of GPS and mobile data to attempt to perform less biased, indirect longitudinal measurement (Handy, 2005; Krizek, 2003; Aldred, 2019)

In the present review, no longitudinal data was collected or used by any of the researchers. However, time series, relying either on aggregated statistical data, or built environment data with robust age attributes, is the most common approach. As an example, Haugen et al. (2012) and Elldér (2024) use the same time-consistent built and social environment data sources to understand changes in travel behavior, provided that they can access a greatly detailed dataset (at the address level), while Kasraian et al. (2019) use a time series of land use / land cover data to model regional evolutions. In Graells-Garrido (2021) a very fine grained GPS time series is available, yet this is perceived as limitation to the preparation of noise-free data, and it is reduced to a "normal-day" average.

While capturing the time dimension is a conceptual ideal, lack of robust individual data, unless having well conducted longitudinal experiments, makes it complicated. Instead, most researchers will need to deal with aggregated time series or, in the rare case of having detailed GPS data, relying on its extraction process. In section 3.6, some more thoughts are given on the availability of these kinds of sources.

Changes in EDM1996 -EDM2018

In the case of the travel dataset used in the present study, longitudinal information is not available. However, for a rough idea of aggregated evolution of its main figures, previous publications are available (yet in no case they have as detailed information as the EDM2018). Many insights have been published by annually presenting a quite detailed analysis of the information. It is pertinent to summarize the longitudinal context of this work.

First, the longitudinal figures presented in the EDM2018 summary report are inspected. The number of trips per person increased from the EDM1996, from 2,09 to 2,44 in the EDM2018, as an indicator of an increased mobility in the MRM, being a stable metric across different sub-regions. Both motorized and non-motorized trips rose during the period, being public transportation the only mode with a decrease in use. Trip duration has increased according to both surveys, from 27 to 29 minutes.

Another interesting insight in the evolution of trip behavior in the region is the decrease in percentage of occupational and non-occupational trips between both surveys (65/35 in the EDM1996 and 43/57 in the EDM2018). However, the great increase in Trip purposes labeled as "Other" makes it complicated to draw conclusions from this figure.

Mode choice between motor vehicles, walking and public transportation shows a clear increase in the 20 years period. Motor trips increase from 28 to 39%, while walking trips move from a 37 to a 34 figure. In this evolution, it is public transportation where the most dramatic decrease occurred, going from 32 to 24%. Also connected with this evolution is the rise in the number of motor vehicles per 1000 inhabitants rising from 300 to 439 in the EDM2018 dataset.

Many insights have been reported around mobility trends in Madrid. According to García-Palomares & Gutierrez-Puebla (2019), these align broadly with other European metropolitan areas, driven by increased income and motorization, demographic shifts, and cultural changes. The city's transport dynamics reflect higher motorized travel due to rising incomes, shifting demographics (fewer children, more working adults), and improved infrastructure. Additionally, Madrid has other relevant specific characteristics: outer zones show higher car use, driven by decentralized urban and employment growth, and suburban lifestyle changes (e.g., low-density housing).

This last reference shows how socioeconomic features shape travel patterns, with income growth expanding mobility and leisure activities, often farther from home. Higher car ownership rates, especially in outer areas, boost private transport usage. Shifts in demographics and employment have increased work-related trips by car, while transit use for shopping and schooling has decreased due to suburban retail expansion and fewer young students (resulting in a higher percentage of college students who tend toward car use).

The geographic expansion of the MRM was supported by new orbital highways (M40, M50), transforming its transport network from radial to radial concentric, enhancing connectivity between suburbs and reducing long-distance traffic within the city center. While car use is growing, public transit has maintained a strong foothold, thanks to extensive investments in the metro and rail networks. These improvements have doubled metro trips and substantially increased rail use from 1996 to 2004. The metro expansion has also enhanced efficiency by reducing trip segments, especially for suburban residents, cutting down on transfers between metro and buses.

3.3 Research Heuristics

How can the statistical relationship between features of urban proximity and travel behavior be established? The statistical modeling question is of utmost importance as it concentrates the assumptions concerning the mechanisms of travel behavior. With time, different “steps” of the early original forecast models in transportation had further statistical evolution which tried to ground their assumptions in more robust theoretical constructs. Acknowledging the

particularities of addressing the influence of the built environment, the evolution of these "steps" became the roots for the general research work described here (Cervero, 2006).

As Banister (2008; 2011) notes, most traditional heuristic approaches in transportation contemplate travel as being a derived demand to realize an opportunity, modeling distance, prices, or even preferences as costs, impedance, or disutilities. The policy implications of these assumptions are critical as they unveil an intention of diminishing cost, increasing speed, expanding infrastructure, which clearly point at mobility and not land-use oriented policy.

Acheampong (2015) published a review of "land-use and transport interaction" (LUTI) models which has an extensive classification and explanation of theoretical constructs (and their commonly associated models) relevant in this review. A number of approaches that are either present in the review of recent works, or have a notable value for a broader investigation of urban proximity, is selected. Coming from different disciplines, these theories (and methods) represent bases for statistical modeling that are not exclusionary, and often are used in mixed approaches.

3.3.1 Gravity Models

Gravity Models are based on the Newtonian idea that interaction between any two entities (in this case, zones or pairs of origin-destination) is proportional to their weight (in this case, the number of activities or generated and attracted trips) and inversely proportional to the friction impeding movement between them (in this case, distance between entities, or more complex forms of impedance, such as cost or time) (Lowry, 1964).

These models have remained popular for macro-scale analysis, particularly in the context of the four-step transportation model, where origins and destinations are represented as nodes and the costs of travel between them as edges in a graph. The strength of the interaction is influenced by the weights assigned to the origin-destination pairs and the chosen form of impedance, which could range from simple euclidean distance to more sophisticated decay functions that model how interaction diminishes with increasing distance (Morris, 1979; Apparicio, et al, 2008; Iacono, Krizek & El-Geneidy, 2010; Acheampong, 2020; Guida & Caglioni, 2020).

Gravity models in the context of urban proximity can take various forms. For example, a two-Step floating catchment area method has been used to assess accessibility by evaluating destination availability within a proximity threshold; and the WalkScore metric is another accessibility-based gravity model that links residents to nearby destinations with an exponential decay function. Gravity models are often seen as a more precise alternative to simpler accessibility measures, because they capture the effect of cost on people's decisions.

One challenge in applying gravity models to urban proximity studies is the friction between network-based approaches and area-based policymaking. Gravity models work well when data on individual nodes (origins and destinations) and edges (travel costs) are detailed enough, but translating these network-like outputs into area-based interventions can be cumbersome. Still, detailed gravity models can help identify specific street segments or buildings for targeted interventions. Additionally, questions arise about whether gravity measures, typically used for macro-scale analysis, apply effectively at micro-scales within urban proximity boundaries.

Concerning urban proximity, many of the reviewed works exemplify the use of accessibility metrics using constructs from gravity models. Knap et al.(2023) use a special case of gravity model called the two-step floating catchment area, which first assesses “destination availability” at supply locations, and then sums up the calculated ratios around each residential (demand) location. In Birkenfeld et al. (2023), the gravity model used is the WalkScore metric, which is an accessibility metric, centered on each resident of an area, with an exponential decay function linking destinations considered relevant. Also, a public transport gravity-based accessibility measure is defined, as the quantity of jobs reachable within the region from a location and weighted by a gaussian-fit decay function derived from census data (Santana-Palacios & El-Geneidy, 2022). Graells-Garrido et al (2021) provides the most detailed example modeling the number of visitors for pairs of origin-destination using a gravity constant of mass (population) per area, and a deterrence function based on the distance between areas.

Yu & Higgins (2024) do acknowledge that gravity-based measures are a better option than cumulative opportunities (which is the common accessibility metric used in the 15-minute city exploration) because they capture the effect of travel time on a person’s travel decisions, but they are considered more difficult to calculate and interpret. In practice, they argue, cumulative opportunities measures tend to be highly correlated with gravity-based measures and, despite

not accounting for the effect of distance decay, are considered an adequate measure of accessibility (Santana-Palacios & El-Geneidy, 2022).

In conclusion, if a "proximity state" exists, in which a particular behavior occurs, do gravity measures apply within these boundaries? If many grocery shops are within reach, will the closest or the "heaviest" be preferred by a particular resident? In this sense, gravity models are more consistently used in macro-scale analysis, in the form of accessibility to the CBD or to employment opportunities (Boarnet, 2011), while micro-scale is addressed differently, for instance as "access to the closest destination", as proposed by Handy (1993), and exemplified in the present review by Li (2022). However, if the weighting of these models takes into account other utilities or features found in destinations or along the route, as in more recent versions of the WalkScore metrics, gravity models can be helpful for research on urban proximity (Hall, 2018).

WalkScore

Walk Score® (referring to the registered name) is an interesting measure of pedestrian accessibility to exemplify gravitational approaches in the urban proximity context. It combines different ways in which a cost or limitation to walking between origins and destinations can be derived. Hall (2018) provides a systematic review of the Walk Score® index, which relies heavily on a gravity-based measure of accessibility, that calculates the shortest distance to a group of preselected destinations (such as grocery stores, parks, schools, and restaurants), and applies a distance decay function that reflects how the likelihood of walking decreases as distance increases. It also incorporates street connectivity and block length as penalties in the decay function. Other features that affect walkability, such as safety, aesthetics, land-use diversity, and recreational walking, are left out of generating the impedance function, mainly for their ambiguity.

3.3.2 Random Utility Models

A Random Utility Maximization Model is a Choice Model which predicts the preferred alternative in a set of choices. Repeated choices by users reveal the different tradeoffs they are willing to make between the attributes of the alternatives. Each individual chooses one

alternative from a number of choice sets. The choice is then modeled as a function of its attributes, under the hypothesis that it will be chosen based on those attributes (an objective component) along with some degree of randomness (a random component), which captures unobserved elements, and can be further modeled after accounting for the known features.

In the context of travel and the built environment, these models are particularly useful because they allow researchers to first model objective constraints, like travel time or cost, and then explore how unobserved features -such as the characteristics of the built environment- affect decision-making. For instance, utility theory is applied to understand how households balance the time and monetary costs of travel against the quality of opportunities accessible through travel (Kockelman, 1998). A key challenge here is how to define and model cost, as travel decisions often involve psychological or behavioral aspects beyond just time or distance. More sophisticated theories, such as expected utility, prospect theory, and regret theory, have been developed to address these complexities, refining the way choices are modeled in transportation (Acheampong, 2015).

In proximity studies, random utility models face challenges in modeling local-related choices, as features beyond cost minimization are even closer to individual “taste” than more utilitarian distant travel (Ewing & Cervero, 2010). Researchers have introduced concepts like "satiation" or "sufficiency" into accessibility metrics, setting a baseline of local supply to model its utility (first seen in Morris, 1978, also found in Yu & Higgins, 2024). In general, these models inspire most empirical research cited here in their adoption of linear or logit models, which are commonly equated to random utility models as they allow the study of unobserved through the study of residuals and errors, intercepts, or the use of latent variables, such as Li (2022), and Birkenfeld et al. (2023).

Random Utility Theory, proximity and Logit modeling in practice

A first exploratory empirical exercise is presented, using the case study. According to utility theory, individuals choose the transportation mode that maximizes their personal utility (or minimizes their disutilities). By translating this idea into models, it is assumed that there is a logical relationship between utility and mode choice: the more accessible the opportunity, for instance, the more chances to walk to it; the higher the income, the more likely to use an expensive mode such as driving. Finally, a certain randomness, or unobserved features, are assumed to be at play, and enforced to enter the model.

Logit and Probit Models have been the most widely used to capture Random Utility Theory, (see, for instance, the review in Ewing & Cervero, 2010). A Logit model is a class of linear model (it assumes that predictors are independent, and can explain the targeted phenomena through a linear function, in this case, of the Logit kind), which can adopt a multivariate form (it can use as many features as needed, as long as they are independent), and a multinomial form (they can model more than two choices as the probability of choosing one option over all others). The target of a Logit model is to estimate the coefficients associated with each variable in the model, which are interpreted by sign and magnitude. The higher the magnitude, the higher the influence. The sign, then, denotes the relationship with the targeted variable.

Given the fact that many of the features that the literature prescribes as potential drivers of modal shift are thought to work in a non-linear form (Galster, 2010), this is acknowledged as the strongest limitation of the linear approach. Also, when selecting the features which are introduced in the model, care needs to be taken not to fall into dependencies among them, which could prevent the models from converging. If this happens, the researcher needs to make a decision to remove highly correlated features, potentially losing valuable information policy-wise. This is also acknowledged to be a great limitation of linear models in this domain.

One of the main contributions of random utility theory is the introduction of the idea that other unobserved (random) features might be influencing either the target variable, or be endogenous to the features contemplated. The thresholds in which each particular household or individual performs their own negotiation on the advantages and tradeoffs of travel and the associated features are then affected by other phenomena which are taken into account in the prediction process. In a linear model, the Intercept represents the baseline utility of using a particular mode when all other variables are set to zero. It provides a reference point for understanding how the other variables influence car use. In practice, this is interpreted as the unobserved features that are missing from the features set.

Referring to the intercept leads to another important caveat on sample balance. The imbalance of classes to be predicted -such as transportation mode-, affects the estimation of the model intercept in Logistic Regression, skewing all the predicted probabilities, and compromising the predictions. Methods such as undersampling or intercept correction are commonly used to avoid this bias (King & Zeng, 2001). Also, studying the residuals of the regression (the differences between predicted and actual values) is a common practice to address the unobserved, random components of utility. Studying their distribution, and looking for other features which correlated to this error in order to introduce them as predictors provides valuable insights on Logistic Regression.

As an example, a Binomial Multivariate Logit Model is fit using a set of variables from the EDM2018 and Catastro to predict the probability of walking over driving. A set of predictors with no inner correlations is selected, the dataset undersampled to have an even representation of both travel modes, filtered all trips to the Shopping purpose, and all individuals to be at driving age, from 18 to 65 years old. Also, the

implementation of a proximity filter in the original data is explored, in order to point at changes that this filtering might exert in a linear model. The selected characteristics are:

- ➔ trip_mode: Value of 1 if a walking trip, 0 otherwise
- ➔ trip_distance: Trip distance in kilometers
- ➔ dem_gender: Value of 1 if Male respondent, 0 otherwise
- ➔ dem_income: Mean household income calculated at the Transport Analysis Zone
- ➔ dem_age: Age of the respondent, in years (filtered between 18 and 65 years of age)
- ➔ dem_education: Ordinal variable representing educational level (from 0 to 5)
- ➔ dem_activity: Value of 1 if respondent is a worker, caretaker, or student, 0 otherwise
- ➔ dem_hou_size: Number of members in the respondent's household
- ➔ acc_shopping: Number of unique shops aggregated

The implementation leverages Maximum Likelihood Estimation (MLE), a statistical method used to estimate the parameters of the model by maximizing the likelihood function, which measures how well the model explains the observed data. In the Binomial Logit Model, MLE identifies the coefficients that maximize the probability of observing the actual choices made in the dataset.

The model yields the coefficients of each predictor as the effect size on the log-odds of the dependent variable, holding all other predictors constant. For instance, if the odds of choosing walking were 2:1, the log-odds are $\ln(2) \approx 0.69$. These coefficients can be interpreted as an increase or a decrease in the probability of walking, for each unit increase of a predictor. It also yields the standard error of each coefficient, with smaller values indicating more precise estimates. The z-scores are calculated as coefficient / standard error, with higher absolute values suggesting stronger evidence against the hypothesis that the coefficient is zero (which would mean that this particular predictor has no effect on the target variable). The p-values represent the probability of observing the coefficient under the null-hypothesis (values below 0.05 indicate statistical significance). Concerning the 95% confidence interval (provided between 0.025 and 0.975), if it does not include zero, it is considered statistically significant.

These results can be interpreted in terms of the characteristics of the predictors as a set of moderate influential characteristics always subordinated to the effect of distance on choosing driving over walking. For each unit increase in trip_distance, the odds of choosing driving over active modes increases by approximately 4.8 points, having a highly significant z-score of 13.89 and a p-value of 0.001. However, the intercept of this model is comparatively quite large (1.1), which means that a baseline preference for driving is not explained by the model's predictors. The only other predictor which could be considered relevant is accessibility, which has a negative effect in choosing driving, and statistical significance, while other predictors are rather weak (such as education, activity), or irrelevant (all other predictors). Figure 17 shows the coefficients magnitude and symbol, and confidence intervals.

The accuracy of the model can also be interpreted, focusing on how well it manages to predict trip modes. Global accuracy means a percentage of trips correctly classified, while Receiver Operation Characteristics (ROC), and Area Under Curve (AUC) means a ratio between true positives (trips correctly predicted as walking trips) and true negatives (trips correctly predicted as non walking trips). This first model yielded 84.9

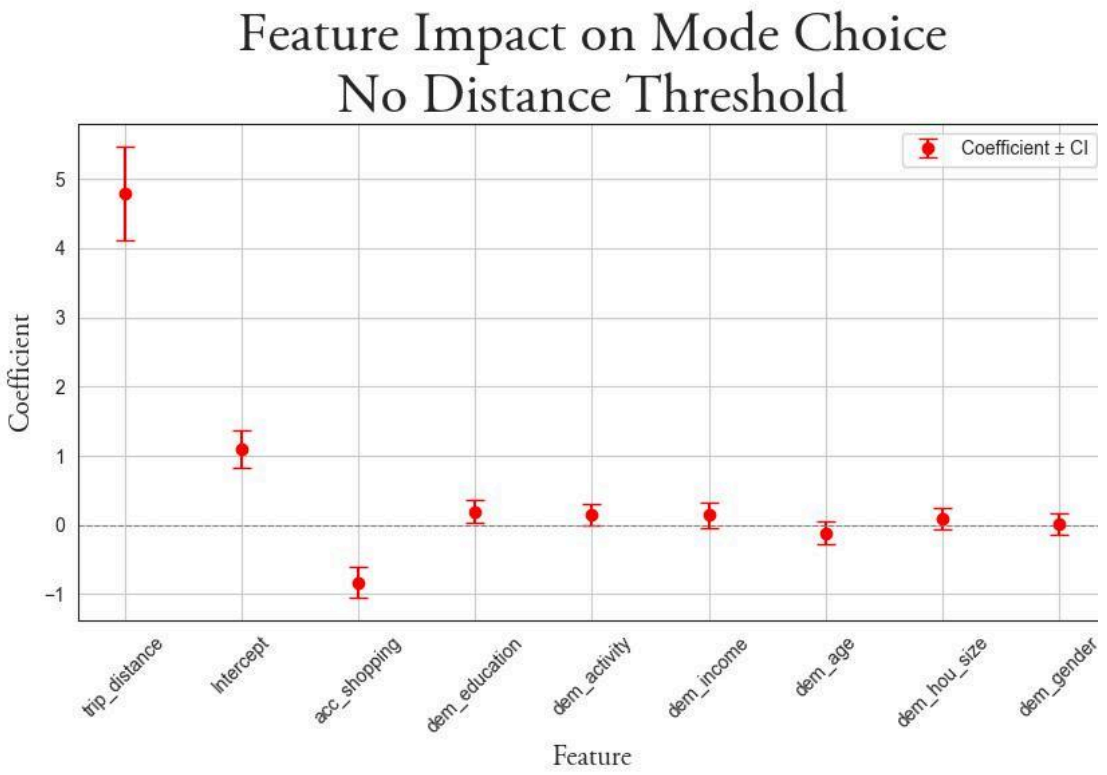
% of accuracy and a 0.93 AUC, meaning that a good overall performance and discriminatory ability has been achieved, keeping in mind that the model is mostly affected by the trip distance values.

The model predictions are repeated filtering the dataset to represent only trips below 1500 meters. The effects on accuracy are significant, with accuracy falling to 0.77% and AUC to 0.85, yet still retaining statistical significance. However, the changes in coefficients are more interesting to inspect. As can be seen in the results, the intercept is drawn close to zero with a p-value of 0.845, suggesting that, in close distances, the baseline difference between the utilities of driving and walking is minimal. Trip distance remains very important, but the difference with the accessibility features is now moderated. Also, all other demographic features become statistically unimportant in this model (p-values well above 0.05). A suggestion that could be made is that the role of demographic and distance is moderated in proximity trips, favouring accessibility as an explanatory variable in this case.

Table 4 displays the results of these two Logit models, numbers in red correspond to the filtered dataset with a 1500 m threshold, while Figure 11 shows the variable importance results..

Table 4:
Results of the experimental Logit Models

	coeff.	std. error	z	P>|z|	[0.025	0.975]
intercept	1.10/-0.02	0.139/0.11	7.896/-0.195	0.000/0.845	0.827/-0.237	1.374/0.194
trip_distance	4.79/1.23	0.345/0.126	13.893/9.822	0.000/0.000	4.122/0.989	5.475/1.482
dem_gender	0.01/0.11	0.077/0.110	0.238/1.059	0.812/0.290	-0.133/-0.099	0.170/0.332
dem_income	0.14/0.17	0.095/0.121	1.525/1.409	0.127/0.159	-0.041/-0.067	0.331/0.408
dem_age	-0.11/-0.16	0.084/0.113	-1.386/-1.416	0.166/0.157	-0.279/-0.381	0.048/0.061
dem_education	0.19/0.21	0.083/0.112	2.299/1.911	0.022/0.056	0.028/-0.005	0.355/0.434
dem_activity	0.14/0.08	0.082/0.110	1.789/0.784	0.074/0.433	-0.014/-0.129	0.307/0.301
dem_hou_size	0.09/-0.04	0.075/0.104	1.197/-0.435	0.231/0.663	-0.057/-0.248	0.238/0.158
acc_shopping	-0.82/-0.86	0.111/0.140	-7.445/-6.170	0.000/0.000	-1.046/-1.142	-0.610/-0.591


Feature Impact on Mode Choice
No Distance Threshold
Coefficient ± CI
Coefficient
5
4
3
2
1
0
−1
trip_distance
Intercept
acc_shopping
dem_education
dem_activity
dem_income
dem_age
dem_hou_size
dem_gender
Feature

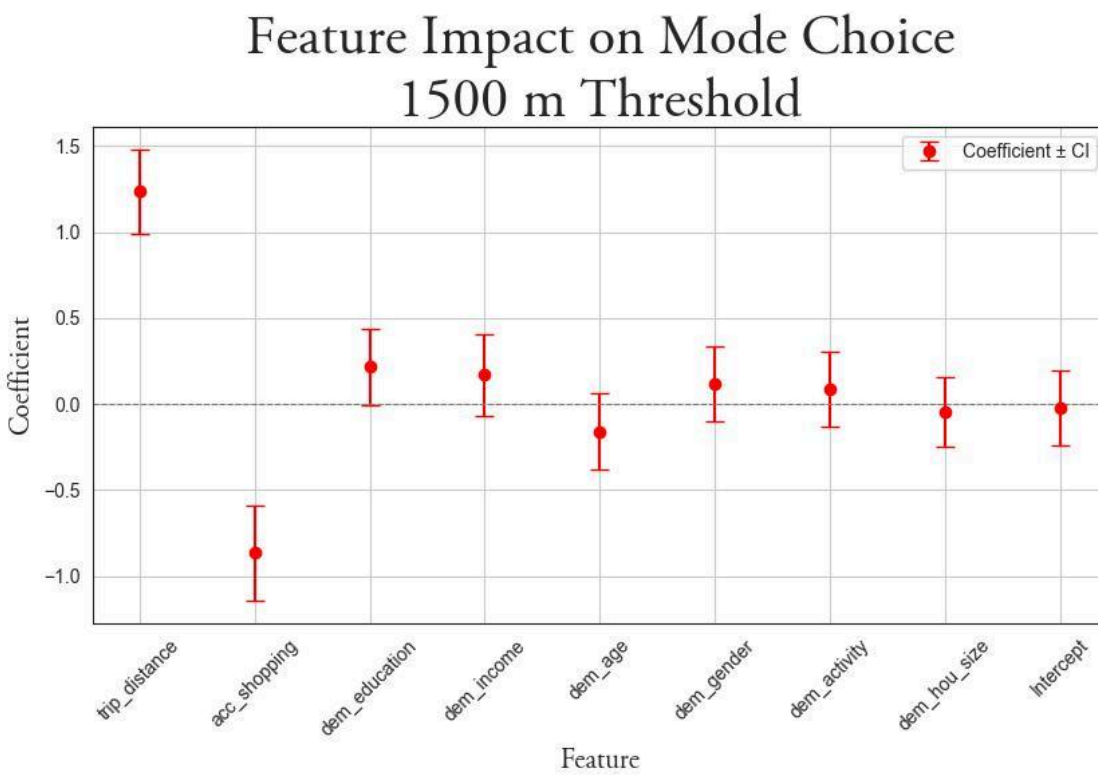

Feature Impact on Mode Choice
1500 m Threshold
Coefficient ± CI
Coefficient
1.5
1.0
0.5
0.0
−0.5
−1.0
trip_distance
acc_shopping
dem_education
dem_income
dem_age
dem_gender
dem_activity
dem_hou_size
Intercept
Feature

Figure 11 (previous page): Variable Importance in Logit Models

Feature impact in both exploratory Logit models. On top, the model that considers distance as a feature and, on the bottom, the model with a threshold of 1500 meters

3.3.3 Theory of planned behavior - Habit Formation

Two prominent psychological theories linked to transportation are the Theory of Planned Behavior (TPB) and Habit Formation (HF). TPB states that intentions (e. g. choosing one transportation mode above other) are the motivational features that influence actual behavior (actually choosing that mode). This way, a "gap" between intentions and actual behavior can be inspected and considered a "latent" potential of travel behavior shift. HF thinks of travel behavior as an automatic and socially reproduced behavior, with little or no rational process, only changing when personal circumstances experience a significant shift.

According to TPB, behavior is driven by intentions, influenced by attitudes, subjective norms, and perceived behavioral control. For example, a person intends to walk believing it is beneficial (attitude), feels social pressure to drive (subjective norm), or prefers driving for a sense of control (perceived behavioral control). TPB explores the "intention-behavior gap": if intentions do not become behavior, latent potential for change exists. HF explains travel behavior as automatic and socially reinforced, often requiring little conscious decision-making. However, the habit discontinuity hypothesis suggests that significant life changes -such as residential relocation, household formation, or new transportation opportunities- can disrupt habitual behaviors and lead to more deliberate choices. This presents opportunities for intervention, as key shifts in personal circumstances can encourage the adoption of new transportation modes or behaviors.

In the context of urban proximity, these theories provide insight into how residential preferences and life-stage characteristics influence travel behavior. From a policy perspective, these theories can aid the effectiveness of urban interventions by recognizing key life events and social dynamics, so that policymakers can better "market" urban improvements and exploit latent changes in travel behavior.

Attitudinal Attributes in the EDM2018

In this work, a number of variables are considered "Attitudinal". The first, and most obvious group of this kind of information is the response to the question "Why didn't you drive?" and "Why didn't you ride?". This information is highly valuable as it gives direct qualitative insight on mode choice. However, it approaches the question in a way which poses a conflict when empirically studying this particular outcome. If for instance, someone responds to the first question, then it is already known that his or her choice was not driving and, if the response was "I rather walk", then mode is already revealed. This led to the decision of not including these variables in the final models but, for the sake of exploration, its information is inspected here.

Some interesting behaviors are revealed when uncovering those trips shorter than 15 minutes in this attitudinal part of the EDM2018. Not many interesting responses were given to the question "Why didn't you drive?", which is greatly unbalanced towards the answer "Other". However, an interesting imbalance towards walking is noted in the answer "Takes longer". The responses to the question "Why didn't you ride?" are more informative. In the "Takes longer" response, way more respondents chose to walk over transit, as well as in the case of "Destination is very close" response, which logically shows great prevalence of walking in 15 minute thresholds.

Although not entirely attitudinal information, variables describing vehicle ownership, and holding a transit card or a driving license were implemented from the EDM2018 data. In a way, these characteristics might inform a positive attitude towards a certain mode. Although many respondents might report these characteristics with an orientation towards "need", not having a vehicle, driving license or a transit card can be seen as a negative attitude towards these modes. Figure 12 illustrates the results.

Number of Trips by Mode and Attitude

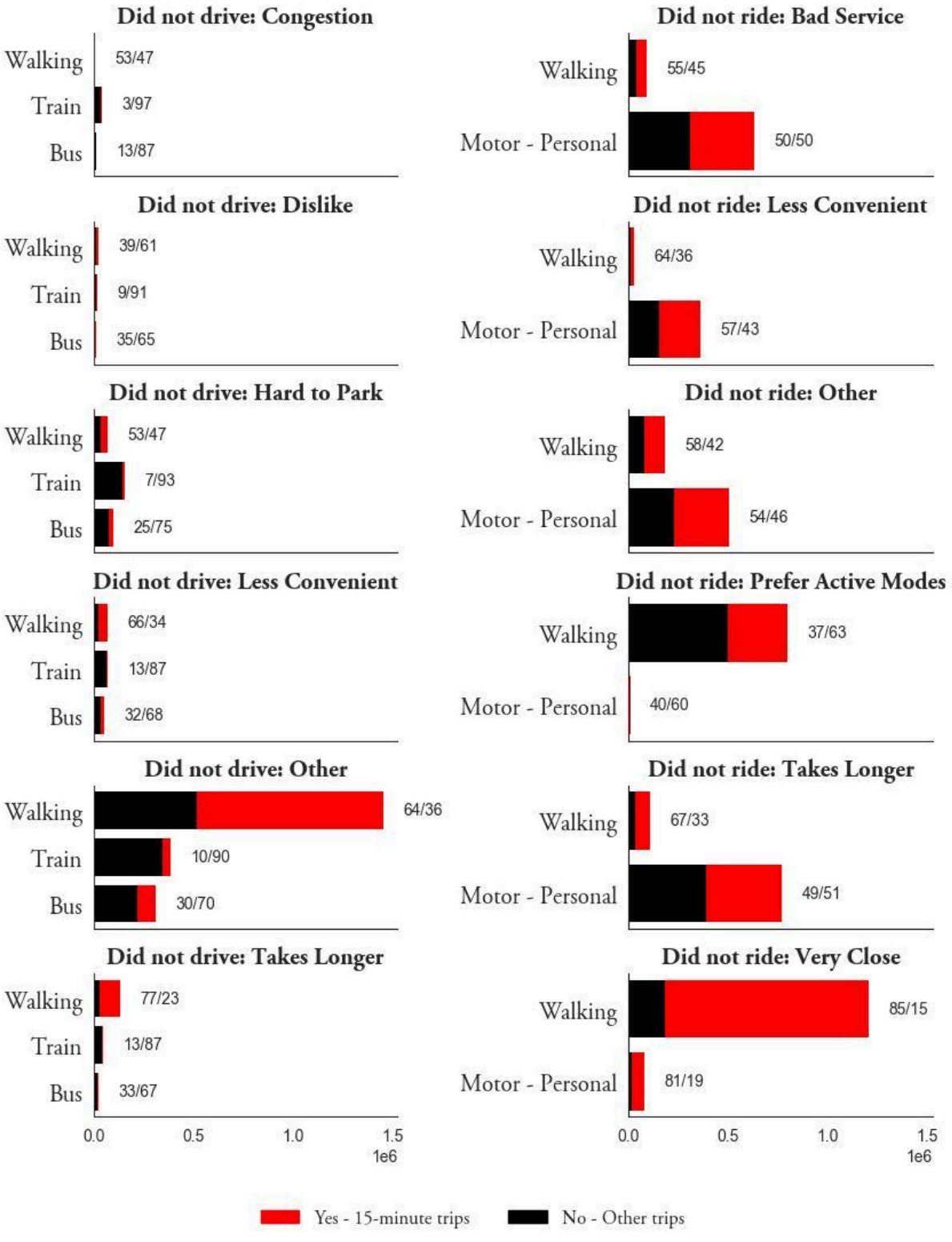


Figure 12 (previous page): Number of Trips by Mode and Attitude

Number of Trips by Mode and Attitude. Number of trips under 15 minutes (in red) and above (in black), for each response in the attitudinal features contained in the EDM2018, by mode. Percentages shown at the end of each bar.

3.3.4 Time-Geography Paradigm

The Time-geography paradigm authored by Hagerstrand (1970) and Chapin (1974), posits that the spatial interaction of individuals occurs within a framework of spatio-temporal constraints, which necessitates trading their time for space. This way, a notion of a time budget is assigned to individuals, and compared with the impact of activities willing to be performed.

The Time-geography paradigm classifies time constraints into three categories: capability constraints, which relate to a person's ability to make a trip (physical, psychological, socioeconomic, or legal); coupling constraints, which refer to activities that need to occur at specific times and locations; and authority constraints, where certain activities are compulsory and tied to specific places and times.

In the context of travel and the built environment, this paradigm helps frame how accessibility is influenced by both physical and time-geographical phenomena. Accessibility is often viewed not just as the spatial relationship between locations but also as a function of mobility resources, which are unevenly distributed across populations. As a result, individual perceptions of proximity and mobility vary, leading to subjective accessibility needs. Time-geography has been frequently coupled with activity-based research, where the constraints of time and space are crucial for understanding travel behavior, especially in intra-household dynamics or other specific groups. These constraints are often integrated into survey design or data filters to ensure a more accurate understanding of travel possibilities in statistical models.

In urban proximity studies, the Time-geography paradigm highlights how the selection of where to live, and how to move, sets the framework for everyday activity decisions, constrained by time, household dynamics, and multiple scales of action. In the review, it can be traced in Haugen (2011) and Gil-Sola & Vilhelmson (2022), who understand the choice of proximity trips as situated in a time-space context in which distances between residence and preferred activity locations, and space-transcending mobility resources play influential roles.

In general, a takeaway from this approach is that seeking for predictors or data filters that capture the complex interplay between time, purpose, and individual-societal characteristics should be addressed.

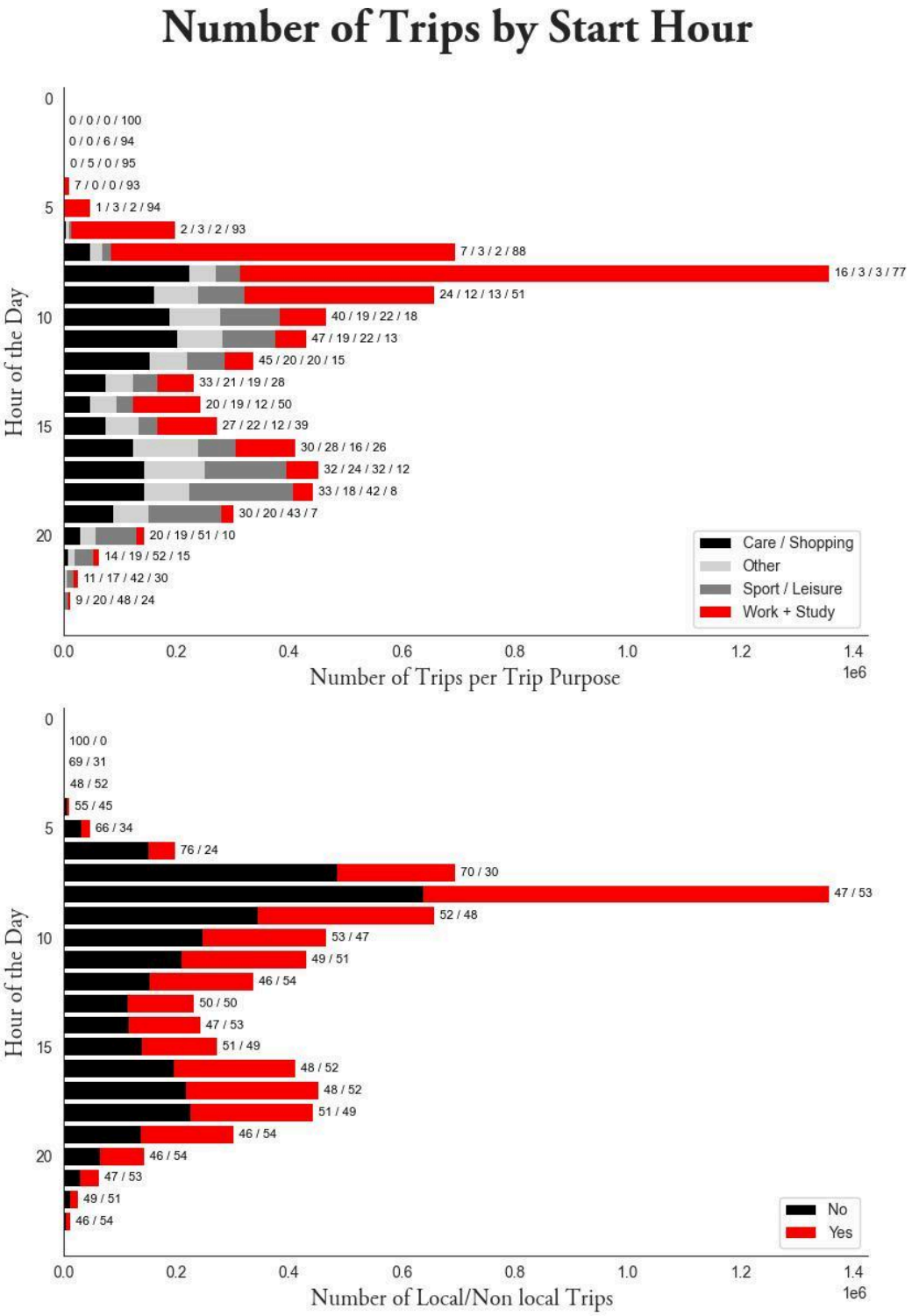
Trips by Hour of the Day in the EDM2018

Concerning the distribution of trips along the hours of the day, the EDM2018 does not show a particular pattern in the proportion of local versus non local trips (defined in this section as 15-minute trips from home). Only between midnight and around 8AM these two classes seem to be strongly imbalanced towards non-local trips. However, looking into the trip purposes in that segment of the data, it is understood that those trips are mostly work trips.

In this sense, a proximity pattern is not seen in the trips by hour data. However, the purpose pattern is reasonable from a time-geography standpoint: Work and School trips peak in the morning before 9 AM; Care and Shopping trips peak around noon and early evening and; Sport and Leisure trips only peak during the evening onwards. Figure 13 illustrates the results of this exploration.

Figure 13 (Following page): Number of Trips by Start Hour

Number of Trips by Start Hour. On top, bars are colored according to travel mode and, on the bottom, bars are colored to show trips above and below 15-minutes of duration. Percentages are shown at the end of each bar, displaying the number in the same order as the color categories.


Number of Trips by Start Hour
Hour of the Day
0
5
10
15
20
0 / 0 / 0 / 100
0 / 0 / 6 / 94
0 / 5 / 0 / 95
7 / 0 / 0 / 93
1 / 3 / 2 / 94
2 / 3 / 2 / 93
7 / 3 / 2 / 88
16 / 3 / 3 / 77
24 / 12 / 13 / 51
40 / 19 / 22 / 18
47 / 19 / 22 / 13
45 / 20 / 20 / 15
33 / 21 / 19 / 28
20 / 19 / 12 / 50
27 / 22 / 12 / 39
30 / 28 / 16 / 26
32 / 24 / 32 / 12
33 / 18 / 42 / 8
30 / 20 / 43 / 7
20 / 19 / 51 / 10
14 / 19 / 52 / 15
11 / 17 / 42 / 30
9 / 20 / 48 / 24
Care / Shopping
Other
Sport / Leisure
Work + Study
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1e6
Number of Trips per Trip Purpose
Hour of the Day
0
5
10
15
20
100 / 0
69 / 31
48 / 52
55 / 45
66 / 34
76 / 24
70 / 30
47 / 53
52 / 48
53 / 47
49 / 51
46 / 54
50 / 50
47 / 53
51 / 49
48 / 52
48 / 52
51 / 49
46 / 54
46 / 54
47 / 53
49 / 51
46 / 54
No
Yes
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1e6
Number of Local/Non local Trips

3.3.5 Complexity theory and General Systems theory

According to Batty (2009), cities can be seen as the quintessential example of complexity. The author notes how, when General Systems Theory popularized in the mid-20th century, cities were regarded as great examples of this approach motto: the whole is greater than the sum of the parts. Cities illustrate the many themes treated: bottom-up spontaneous organization, emergent morphology from simple spatial decision, temporal order at global levels from volatile, seemingly random change at the level of individual decision-making, evolution and progress through co-evolution, competition, and endless variety.

These theories view cities as adaptive systems with multiple interacting components in constant disequilibrium. As dynamic systems, their structure, morphology, and behavior emerge from simple local decisions and evolve over time. These theories are relevant in transportation and built environment studies, where complex behaviors and interactions between land use and mobility create emergent patterns . Three key approaches in transportation research are closely tied to these theories: complex network analysis, agent-based modeling (ABM), and monte-carlo simulations (Acheampong, 2015; Porta et al., 2004; 2006; Guidotti et al., 2016; Marshall et al., 2018; Ding, 2019; Chen, 2012; Bastarianto, 2023).

In the context of proximity, these theories help explain emergent behaviors of active travelers and dynamic relationships between land use and transportation systems. No reviewed papers explicitly mention complexity theory, but tools such as network centrality metrics and ABM have been used to model pedestrian flow. Insights from complex network studies, like the “multiplicator effect” of centrality (spaces with high pedestrian flow tend to attract even more flow) and "conservation of angularity" (pedestrians follow topological and angular rules), have contributed to understanding how configurations shape movement (McCormack, 2021; Sevstuk, 2021; Jabbari, 2023; Lakmali et al., 2024).

Complex Network Analysis

Graph theory has been extensively applied to study complex networks, including urban systems, focusing on two areas: centrality measurements -quantitative importance to nodes or edges based on topological or interactional assumptions-, and community detection -identification of substructures that emerge in a graph when nodes or edges are progressively removed. Additionally, structural properties such as efficiency or average shortest path lengths are measured to understand overall network characteristics.

Centrality in graph theory is rooted in social network analysis, which originated in the 1950s. Early research by Leavitt (1951) and Bavelas (1951) focused on social group interactions represented as graphs, leading to the development of various centrality metrics. Freeman (1977, 1979) further expanded on these ideas, highlighting the multiple possible definitions of centrality and their relevance in research contexts. For urban studies, three centrality metrics are particularly important. Degree centrality (or simply degree) counts the number of edges connected to a node. Closeness centrality measures the average shortest path from a node to all other nodes. Betweenness centrality quantifies how often a node acts as a bridge along the shortest path between two other nodes. These metrics are often classified into radial (e.g., closeness) and medial (e.g., betweenness) categories. This measure was built regionally for this study and is illustrated in Figure 14.

Another critical area of graph theory research is community detection. This process identifies subgraphs whose nodes are more closely connected to each other than to the rest of the graph. Initially introduced by Girvan and Newman (2002), community detection remains an unsolved problem, but it is vital for analyzing complex datasets that need to be disaggregated into meaningful parts.

Graph theory's application to urban systems intersects with transportation geography, Space Syntax theory, and complex network science. Transportation geography views human transport systems through a spatial lens, where networks intuitively represent infrastructure like roads and transit systems. Space Syntax, developed in the 1970s, uses graph theory to analyze human spaces and their social implications. It emphasizes the minimal unit of space needed to analyze configurations, proposing metrics like depth, integration, and choice to study spatial hierarchies and movement possibilities.

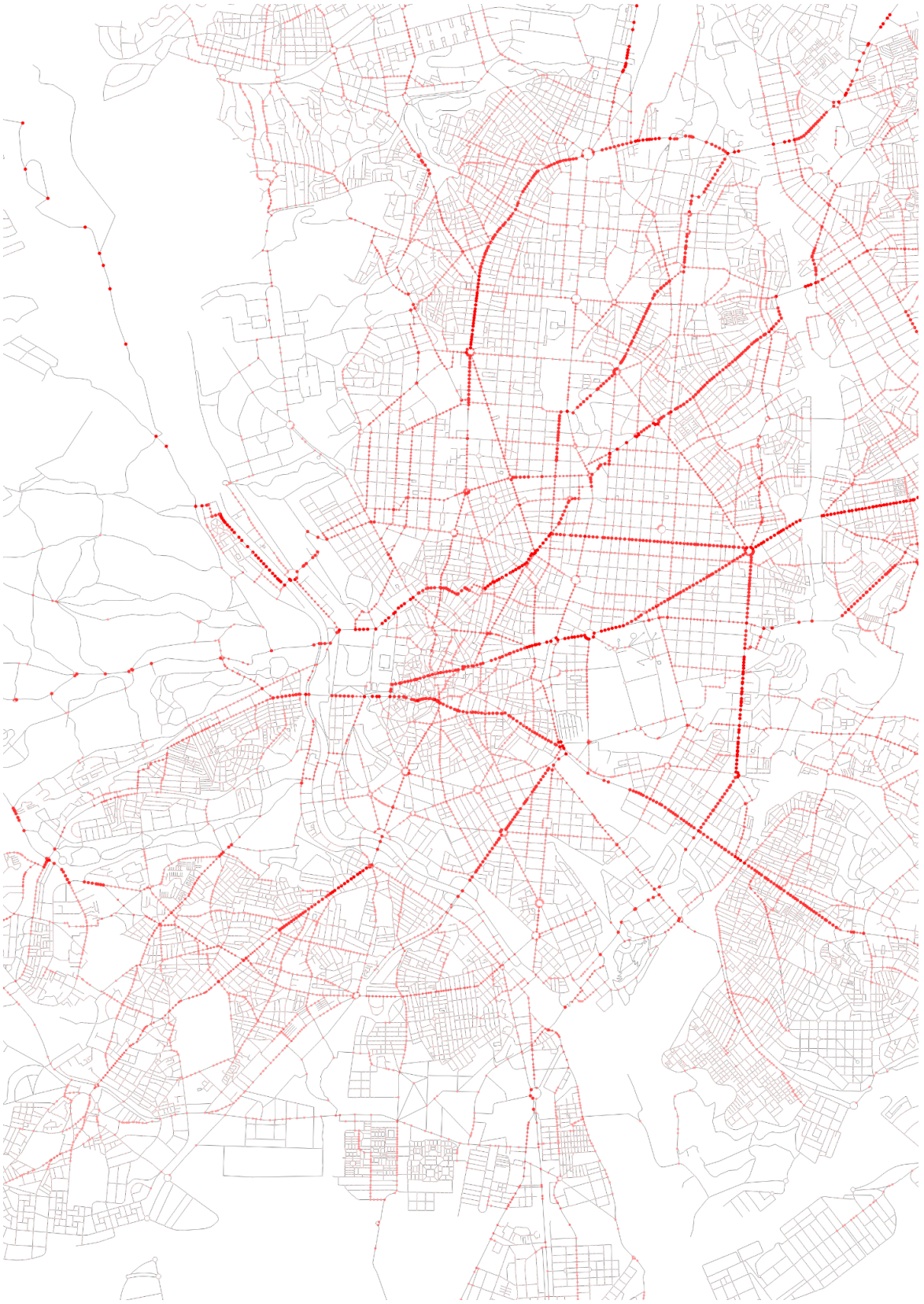
In the context of urban networks, the study of flow is a key research area. Origin-destination matrices, used in traffic assignment models like the four-step model, assign observed movement quantities to graph edges representing transport zones. Centrality metrics such as betweenness have proven highly predictive for understanding traffic flow, accessibility, and infrastructure vulnerabilities.

Space Syntax theory also examines the structural configuration of urban spaces. Early research by Hillier and Hanson (1984) introduced the idea of a "social logic" in human space design, which could be studied using graph analysis. Space Syntax metrics, such as depth and integration, measure how spaces connect and interact within a network, influencing pedestrian movement, traffic flow, and the distribution of land uses.

In recent years, urban network research has increasingly converged across disciplines, leading to more integrated approaches that combine graph theory with urban planning, transportation, and spatial analysis. This interdisciplinary trend has resulted in new insights into the dynamics of urban systems, especially in terms of traffic congestion, infrastructure management, and the broader relationship between urban form and human behavior.

Figure 14 (following page): Detail of Betweenness Centrality Results

Detail of betweenness centrality measured on the nodes of the RCL network.



3.3.6 Statistical Modeling

The most commonly used models in transportation research, particularly for decision-making related to travel and the built environment, are based on utility theory and use linear or logistic regression, modeling choices between modes, routes, or destinations. Linear regression models, particularly Ordinary Least Squares (OLS), and logistic regression models (or logit models) dominate the field for their simplicity and interpretability (Ewing & Cervero, 2010).

Linear regression is often used when analyzing continuous travel outcomes, and Logit models are more common for classification problems. While the assumption of linearity may seem simplistic for such complex phenomena, it provides ease of interpretation. Other approaches like Structural Equation Models (SEM) and Machine Learning (ML), while better suited for the complexity of travel behavior, are not yet widely adopted in research. SEM allows for the incorporation of latent variables and can handle complex causal relationships (Cao, 2009; Golob, 2003). On the other hand, ML models offer flexibility by learning patterns from data without predefined assumptions, but they suffer from overfitting and interpretability issues (Koushik, 2020; van Cranenburgh, 2022; Mukherjee & Kadali, 2022; Gao et al., 2023).

In the broader context of empirical studies of proximity, simpler regression models remain prevalent in the literature (Saelens et al., 2003; Lee & Moudon, 2004; 2006; Boarnet, 2011). Regarding the recent review, for example, OLS is used in several studies to analyze travel outcomes (Haugen, 2011; Haugen et al., 2012; Abbiasov et al., 2022; Calafiore et al., 2022; Aristizábal et al., 2023; Poorthuis & Zook, 2023 and Elldér, 2024), while logistic regression is applied to predict binary, multinomial, or categorical choices (Birkenfeld et al., 2023; Li, 2022; Yu & Higgins, 2024) . Other techniques, such as Moran's I (Knap et al., 2023 and Calafiore et al., 2022), spatial filtering (Calafiore et al., 2022; Graells - Garrido et al., 2021; Aristizábal et al., 2023; Poorthuis & Zook, 2023; Yu & Higgins, 2024), and descriptive statistics (ANOVA, Chi-square tests), are used to account for spatial patterns or test hypotheses about proximity effects (Bartzokas-Tsiompras & Bakogiannis, 2022; Haugen et al., 2012; Kasraian et al., 2019; Gil-Solá & Vilhelmson, 2022; Birkenfeld et al., 2023; Marquet & Miralles-Guasch, 2015). In some cases, more specialized models like beta regression (used for binary responses) and

fractional polynomial regression have been explored, but they are less common (Searcy et al., 2018; Kasraian et al., 2019).

A general comment that can be made is that no consensus can be seen in the review. In general, simpler models are preferred as long as they are tractable enough to yield knowledge about the topic, regression or classification models should be selected by suitability for the nature of the outcome variable, and it is preferred if different features in the models can be inspected for some kind of importance or weight, and direction. This review did not yield sophisticated approaches such as SEM or ML, which can be perceived as a research gap.

Table 5 summarizes the statistics used in the reviewed works.

Table 5:
Statistics used in the reviewed works

Reference	Statistics
Haugen, 2011	OLS
Haugen et al., 2012	Descriptive Statistics and OLS
Marquet & Miralles-Guasch, 2015	Chi - square
Searcy et al., 2018	Fractional Polynomial Regression
Kasraian et al., 2019	Generalised Estimating Equations, Descriptive Statistics
Graells - Garrido et al., 2021	Negative Binomial GWR
Bartzokas-Tsiompras & Bakogiannis, 2022	ANOVA
Li, 2022	Logistic Regression
Gil-Solá & Vilhelmson, 2022	Descriptive Statistics
Abbiasov et al., 2022	Cumulative Distribution Function; OLS
Calafiore et al., 2022	Local Moran's I, GWR - OLS
Knap et al., 2023	Bivariate Moran's I
Birkenfeld et al., 2023	Binary Logistic Regression , Descriptive Statistics
Poorthuis & Zook, 2023	OLS and Spatial Lag
Aristizábal et al., 2023	OLS and Spatial Lag
Yu & Higgins, 2024	Spatially Filtered Beta Regression
Elldér, 2024	OLS, Random Effects, and Fixed Effects

3.4 Outcome variables

In general research of travel and the built environment, the most popular approach is the treatment of social and built environment variables as predictors of travel outcomes. Dependent variables include trip frequencies (rates of trip making in a period, also called trip generation rates), trip lengths (either in distance or time costs), mode choices or modal splits (percentage of trips), cumulative person (or vehicle) miles (or hours) traveled (PMT, VMT, and VHT), and trip capture (a newer variable attempting to measure trips that are somehow prevented, but have a potential to change) (Ewing & Cervero, 2001; 2010; Boarnet, 2011).

Other research domains focus on further outcomes of modal shift, such as physical activity (under the hypothesis that shifting to active transportation leads to health improvement), or transport-related energy consumption (under the hypothesis that shifting to active or public transportation decreases energy consumption per capita). Behavioral questions are more commonly used as statistical controls or independent variables, but some authors do go as far as to use them as dependent variables to be predicted by built environment features (Crane, 2000).

Regardless of the way it is quantified, relationships among travel and the built environment that can be informative to policy are sought. Metrics such as elasticity, or sensitivity analysis are popular (measures of how sensitive a variable is to changes in another), and can inform about how much of a targeted outcome can be achieved by how much increase in a feature treated from policy. These kinds of metrics are preferred over regression or variation coefficients, which require expertise to be read, and also allow for meta-research (Ewing & Cervero, 2001; 2010; Stevens, 2017; with relevant caveats on their usage in Boarnet, 2011).

Though not outcome metrics in a strict sense, another relevant tendency is the grouping of variables in factors or principal components (which are common methods of dimensionality reduction), so as to understand combined impacts of explanatory variable sets. These have been introduced in the work of Cervero and Kockelman (1997) or Lee and Moudon (2006). Some

contemporary approaches through ML also endeavor to extract variable importance from models such as Random Forest Classifiers (Hagenauer, 2017). In this section, the different outcomes expected in empirical research for urban proximity will be described. Table 6 shows the outcome variables targeted in the different works reviewed.

Table 6:
Outcome variables used in the reviewed literature

Reference	Outcome Variables
Haugen, 2011	Residential Location Satisfaction
Haugen et al., 2012	PMT
Marquet & Miralles-Guasch, 2015	% Proximity Trips
Searcy et al., 2018	% Modes
Kasraian et al., 2019	% Change to Urbanised Land
Graells - Garrido et al., 2021	Trip Count
Bartzokas-Tsiompras & Bakogiannis, 2022	Walkability
Li, 2022	Probability of visiting the closest grocery store
Gil-Solá & Vilhelmson, 2022	Grocery shopping and Leisure Activities
Abbiasov et al., 2022	15-minute usage
Calafiore et al., 2022	Proximal Environments
Knap et al., 2023	Proximal Environments
Birkenfeld et al., 2023	Proximity Households
Poorthuis & Zook, 2023	Captive Demand
Aristizábal et al., 2023	% Pedestrian Trips
Yu & Higgins, 2024	% Modes
Elldér, 2024	Proximal Environments (3 types)

3.4.1 Trip Length

In the present research context, trip length is a group of possible outcomes of transportation models which encompasses continuous variables of length (time, distance, etc.), or cumulative variables, such as VMT (Vehicle Miles Traveled), PMT (Person Miles Traveled) or VHT (Vehicle Hours Traveled). The first case addresses either the disaggregate characteristic of travel diaries or surveys, or mean values for aggregated data. The second is aggregated over a user, a vehicle, or a period of time. In all cases, the outcome attempts to capture the dimension of cost in travel.

In this field of study, trip length metrics are used to test hypotheses, particularly the idea that certain development patterns reduce overall trip distances. In utility theory and activity-based research, trip length is essential for understanding household time budgets and the thresholds for making travel decisions (Kockelman, 1999; Boarnet and Crane, 2001). However, data on trip length may sometimes need to be derived from other variables, such as GPS timestamps or declared trip durations, which can introduce subjectivity or error in the analysis. Some studies bridge this gap by comparing perceived and actual distances to understand features that influence travel perceptions. In other works, excess travel, as a measure of the difference between observed and “optimal” travel distances, is operationally defined to inform latent improvements in travel efficiency (Hamilton, 1982; Fan et al., 2010)

According to the literature, trip length is primarily influenced by the built environment, with socioeconomic characteristics playing a secondary role. Other research suggests that trip lengths behave more like cardinal variables, meaning that people operate with certain thresholds in mind when deciding whether to make a trip (Kockelman, 1999; Ewing & Cervero, 2001; 2010).

This notion of distance thresholds becomes particularly relevant in proximity studies, where researchers are interested in identifying the "affordable" distances for different groups and understanding how trip lengths vary depending on access to local services. In proximity studies, trip lengths help identify thresholds that can inform modal shifts, particularly for non-commuting trips. In the reviewed studies, trip length is not just a measure but also a tool for understanding how individuals make travel choices.

In the review, targeting trip lengths is exemplified by Haugen et al. (2012), who survey this particular metric for everyday non-work trips, comparing it with trends in accessibility to services and facilities as a way of understanding different "affordable" distances for different social groups; Searcy et. al (2018), who seek to empirically establish "proximity thresholds" for observed mode choice against distance, or the work by Marquet (2015), who predicts "proximity trips", or trips that comply with a distance definition, using distance as a control.

Flowers of Proximity

Flowers of proximity are a graphic resource for participatory planning used to crowd-source the time thresholds which different social segments are willing to travel in order to achieve different goals. It consists of radar-like plots in which different segments of users display their preferences for proximity. The approach was developed by Solá & Vilhelmson (2018), and has been consistently applied in many real-world scenarios of proximity planning implementation (Büttner et al., 2022; Baquero & Lamíquiz, 2024; Baquero et al., 2024). The graphical result of applying this idea to the EDM2018 dataset is shown in Figure 21.

The maximum average (average of the quantile 0.75), mean and minimum average (average of the quantile 0.25) distances derived from the EDM2018 data are plotted, filtering for Trip Purpose, age buckets and occupational status of the individuals. For the selected dataset, each "petal" has a double bar, being the red-hued those trips made walking, and the black-grey hued all other modes (aggregated to facilitate the visualization at this plot size). This aggregation is derived from the scale of the plot and the focus on walking behavior. The exploration yields differential behaviors regarding walking trips, which tend to be logically shorter than most other modes (though bicycles or e-scooters could be similar). It is the differences across age and activity segments which catch the attention, especially keeping in mind empirical approaches to proximity.

In none of the segments the highest quartiles of walking trips go above 1500 meters of distance and, in the majority of cases, they stay below 1000 meters. Mean values mostly fall between 1000 and 1500 meters, with some exceptions and, in the case of the lower quartiles, the vast majority of walking trips are made below 500 meters. Regarding the rest of transportation modes, it can be seen how the upper quartiles are almost without exception around 1500 meters, the mean values commonly fall around 1200 meters (with some sound exceptions), and the lower quartiles are usually in the range of 500-700 meters (again with some sound exceptions). An interpretation is that walking trips are commonly below other modes by 500-700 meters. Focusing on segments, a finer picture is obtained:

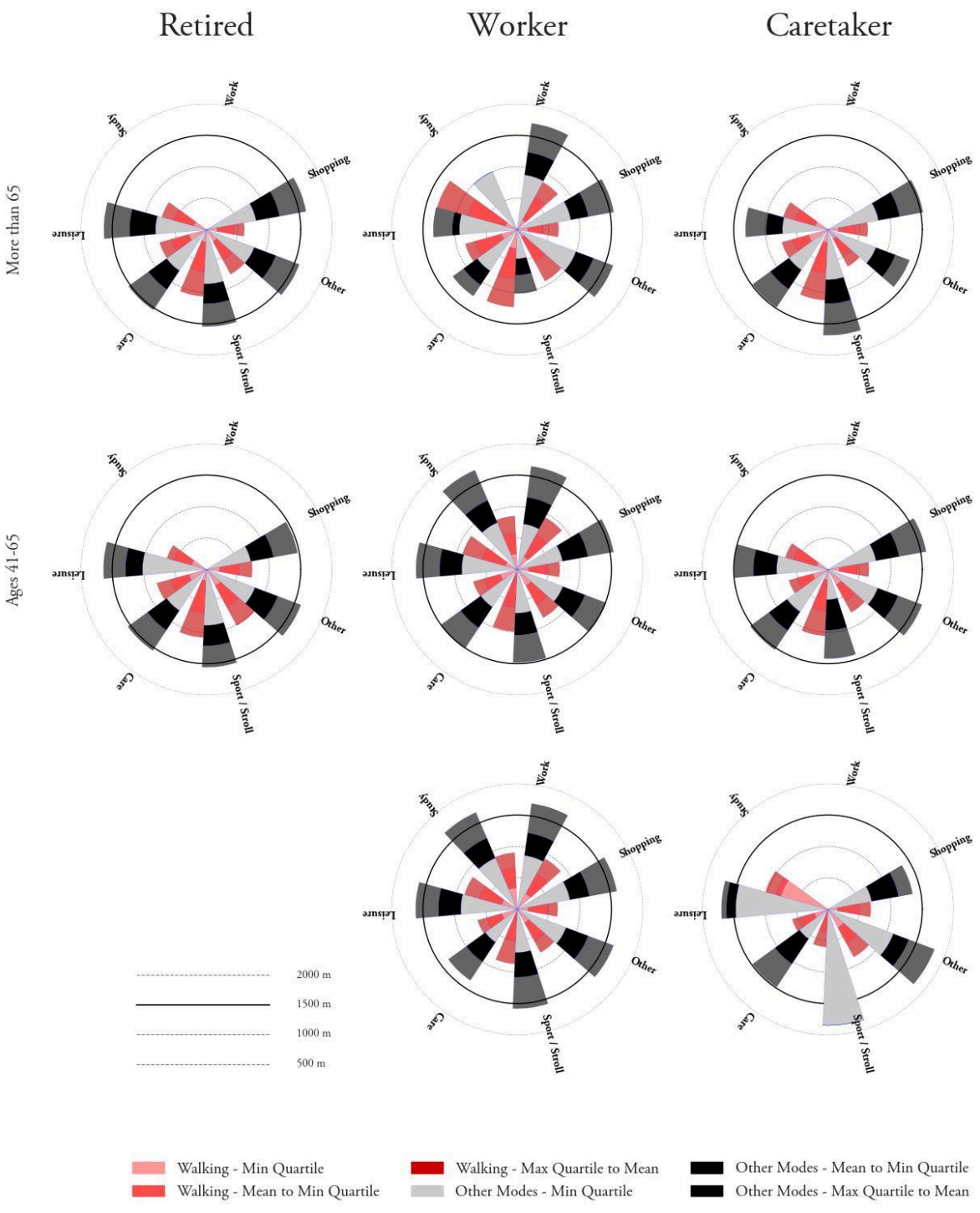
- ➔ Retirees have a similar behavior in other modes, across all purposes, with a lower quartile of 700 meter, a mean value around 1200, and a stable maximum around 1500 meters. Their walking behavior is less

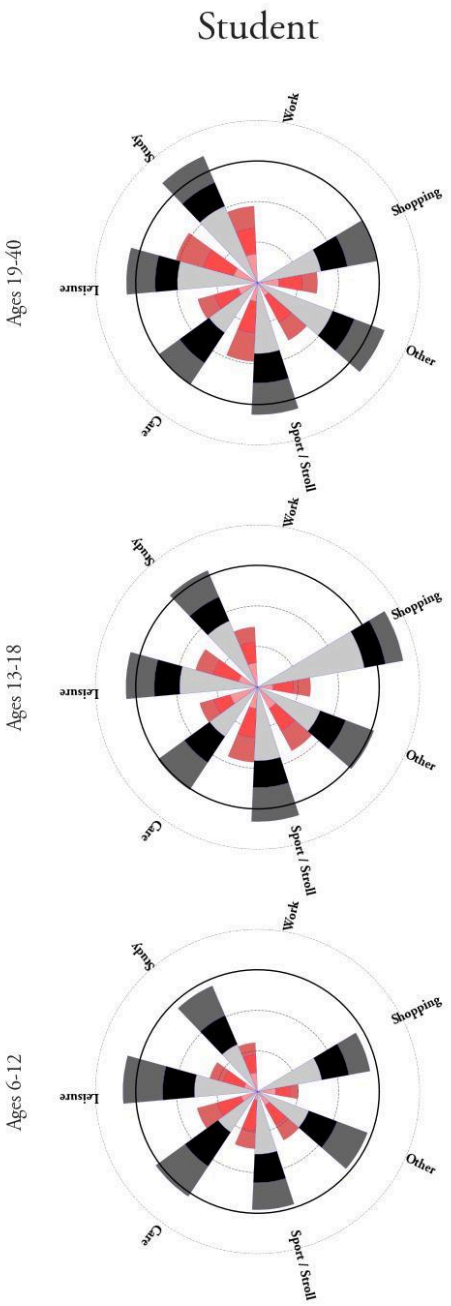
stable, with Sport / Stroll trips stretching up 1000 meters and at an average of 700, this being the longest kind of trip, and Shopping trips with a maximum just above 500 meters and a mean of 400.

- ➔ Workers show a similar behavior in the ranges from 19 to 65 years of age, with all trips in other modes having their maximum around 1500 meters, and their mean values around 1200. Walking behavior of these cohorts is also quite constant, with an exception in Care and Shopping activities, which show a higher quartile of 700 meters and mean values of 500 meters, being all other purposes in the range of 700 meters of mean and a higher quartile of around 1000 meters. Regarding other modes, Work, Shopping and Other purposes stands as the largest maximum, over 1500 m, with mean values around 1200 m. In fact, age cohorts from 19 to 65 years of age exhibit the more distant Other modes pattern of the series.
- ➔ Caretakers exhibit similar behavior in other modes than workers, yet their walking behavior differs in the sense that all purposes, except for Sport / Stroll, show quite a shorter distance behavior roughly around 700 m maximum and 500 minimum. This might highlight that Care activities, when achieved locally, are somehow more proximal than in other purposes. Also, trips in other modes are the shortest in the series, also suggesting that caretakers are the least mobile group.
- ➔ Students somehow exhibit a behavior similar to workers in the cohort 19-40, with distant trips in other modes exceeding 1500 m, and reasonably long walking trips for Leisure, Sport and Study, but also a noticeable short trip behavior for Care, Shopping and Other purposes. This cohort might mostly be formed by university students or other kinds of tertiary education, which somehow value shopping in short distances, and perform less Care activities. Lower student age cohorts, probably secondary education students and less, exhibit an interesting decreasing distance in walking trips. Ages 13-18 rarely exceed 700 m in mean values, and never exceed 1000 m in the upper quartiles. The trend is consistent in the cohort 6-12, which exhibits even shorter walking trips, with mean values falling roughly below 500 m.

Figure 15 (Following two pages): Flowers of Proximity

Flowers of proximity for age buckets and activity status. Each sector is sized according to the distance (in meters) associated to each combination of age, activity status, and purpose. Red tones depict walking mode, while gray tones depict all other modes. Each sector displays three color tones: lighter tones mark the first quartile (25%), medium tones mark the mean, and darker tones mark the upper quartile (75%). The outer circle represents the 1500 meters threshold. All trips have been filtered to have a maximum of 2000 meters of total distance, so as to be able to visualize pedestrian trips together with other modes, without scaling issues.


Retired
Worker
Caretaker
More than 65
Ages 41-65
Work
Shopping
Other
Sport / Stroll
Care
Leisure
Study
2000 m
1500 m
1000 m
500 m
Walking - Min Quartile
Walking - Mean to Min Quartile
Walking - Max Quartile to Mean
Other Modes - Min Quartile
Other Modes - Mean to Min Quartile
Other Modes - Max Quartile to Mean


Student
Ages 19-40
Ages 13-18
Ages 6-12
Work
Shopping
Other
Sport / Stroll
Care
Leisure
Study

3.4.2 Trip Frequency

Trip Frequency refers to the number of times a particular trip is taken (commonly grouped by trip purpose), either for a particular individual or household (generated trips) or a particular destination (attracted trips). It is expressed using a time frame, such as a daily or a weekly basis. Also, individual trips might refer to vehicle frequency, which can be transformed into individual trips through occupancy rates. In the general literature, trip frequency is commonly considered to primarily be a function of socioeconomic characteristics, and secondarily a function of the built environment, in which distance to destination seems to be the most relevant feature. In traditional models, trip frequency is associated with amounts of land use which generate or attract trips, and are later weighted by distance in a gravitational fashion (Ewing & Cervero 2001; 2010).

Trip frequency serves as both an input and output in transportation modeling, particularly in the generation step of the four-step model. In this model, land uses are assigned a number of expected trips based on area units. Trip frequency can also be measured as the total number of trips within or between areas, providing a way to analyze aggregate travel behavior. Disaggregated travel diaries, on the other hand, frequently ask about trip frequency over a specific time span (e.g., weekly). Recent research has revealed an emergent pattern where the number of visitors to a location decreases according to the inverse square of the product of visit frequency and travel distance, reinforcing the importance of spatial clustering and decay (Schläpfer et al., 2021).

Concerning proximity, trip frequency is addressed as the frequency of "proximity filtered" trips (those that meet imposed definitions of proximity) or simply the frequency of active or public transport trips (Marquet, 2015; Abbiasov et al., 2022). Though frequency has been mostly studied in large scale, motorized travel, some works do adapt the "trip generation" rationale beyond this mode Graells-Garrido et al. (2021). For instance, some works such as Currans & Clifton (2015) or Carpio-Pinedo et al. (2021) suggest that adjusting aggregated frequencies to inferred modal split by density alone performs comparably to more complex models and outperforms traditional vehicular rate predictions.

Frequency is quite an interesting way of transforming amounts of land use in theoretical trips triggered, making it suitable for gravity models, or accessibility metrics, popular for proximity studies. Also, in forecast models, frequency by mode is assigned to network edges by route assumptions, transforming into predicted traffic volume. In micro-simulation studies focusing on pedestrians, frequency can be of use when predicting footfall, which has a major impact on street use and vitality.

Trip Rates and Proximity in the AAM

This subsection focuses on trip frequency derived from land use quantities, as proposed in ITE (2021), and tests the adjustment proposed in Currans & Clifton (2015). From the Trip Generation Manual, some caveats are identified. First, trip generation rates are not always associated with area, as in some land use classes, it might be more relevant to understand the capacity of users. Car-associated categories (gas stations, car-washes, logistic infrastructures) are expressed as the number of vehicles that can be fitted in the; or educational and health land use classes, which use the number of students or beds. Some of the land use classes in the ITE handbook are labeled as inconsistent for having too small samples for empirical soundness. Also, this generation manual is defined in the US context, which should not be overseen for Madrid's context.

To consider the use of these rates in the case study context, the idea is to have a comparison scale across land uses which a priori do not trigger the same amount of travel per area unit. Also, as the available data source for this purpose across the region are land use tax records, no dataset exists on numbers of students, or hospital beds, for the whole region. The focus is kept on those associated with total floor area. Many of the land use categories are not easily linked with proximity, especially those associated with car maintenance and supply, or those drive-through / drive-in typologies which are scarce in the region of Madrid. Also, some of the classes proposed by the ITE are simply not easily derived from the tax records of the Spanish cadastre. Moreover, the trip purposes in the EDM2018 survey are also vague in the destination land use they match.

After filtering for area-related rates, potentially weak samples, proximity related classes, and robust possibilities of association with cadastral information, a series of classes which might be associated with the available information are identified. Using area-related metrics leaves out all study categories, and proximity-related classes, in this context, only should consider destinations from residences, leaving trips generation at trip origins out (different rates assumed for housing typologies are also left out). Also, some ambiguous classes such as casinos and lottery stalls (which have high trip generation rates), Nursing Homes and Assisted Living (which are ambiguous in the sense that they might be considered as trip origins), or Religious Venues, not explicitly addressed in the EDM2018.

Table 7: Trip Generation Rates derived from the EDM2018

Trips					Area	Rates					
Purpose	Car	Car 15M	Walk	Walk 15M	sqrmt	Walk 15M	Walk	Car 15M	Car	Description	ITE Rates
Care	281246	281247	270816	204107	4099029	0,05	0,066	0,069	0,106	Assisted Living	0,005
										Clinic	0,035
										Daycare Center	0,12
										Hospital	0,01
										Nursing Home	0,006
Leisure	52541	52541	155876	105582	3681601	0,029	0,042	0,014	0,027	Arena	0,005
										Bread / Donut / Bagel Shop without Drive-Through Window	0,301
										Coffee/Donut Shop without Drive-Through Window	0,391
										Drinking Place	0,122
										Fast Casual Restaurant	0,152
										Fast Food Restaurant without Drive-Through Window	0,305
										High-Turnover (Sit-Down) Restaurant	0,105
										Library	0,088
										Movie Theater	0,066
										Multi-Purpose Recreational Facility	0,039
										Multiplex Movie Theater	0,053
										Museum	0,002
										Quality Restaurant	0,084
										Recreational Community Center	0,025
Shopping	151337	151338	478938	369965	19706936	0,019	0,024	0,008	0,011	Apparel Store	0,044
										Department Store	0,021
										Discount Supermarket	0,09
										Shopping Center	0,041
										Supermarket	0,099
										Variety Store	0,074
										Wholesale Market	0,019
Sport / Stroll	66474	66474	591554	200134	14843895	0,013	0,04	0,004	0,006	Athletic Club	0,068
										Health/Fitness Club	0,037
Study	178700	178700	433226	352210	14514866	0,024	0,03	0,012	0,018	Elementary School	0,015
										High School	0,01
										Middle School / Junior High School	0,013

3.4.3 Modal Split

Modal Split is another outcome of four-step models, and it refers to the prevalence or the proportions of different transportation modes. It is commonly expressed as a prevalence (or percentage) of trips for each available transportation mode, becoming a classification problem between available alternatives. In this context, it has been extensively modeled through the utility maximization approach, especially examining automobile versus transit splits. However, the inclusion of active modes (walking, cycling) in these models adds complexity, as they are often considered intrazonal and thus less influenced by traditional utility features like cost or distance. Active travel introduces challenges, as utility and disutility can be harder to define operationally (Cervero, 2006).

When multiple modes are considered, care must be taken, as assumptions about latent demand (the idea that a trip made in one mode displaces another) may not hold equally for all modes. Mode shift, or the potential for users to switch between modes, can be particularly difficult to model given the complex interplay between the built environment, socioeconomics, and user preferences (Handy, 2002). According to the literature, modal choices are influenced by both built environment and socioeconomic characteristics, though socioeconomic characteristics likely play a more significant role (Ewing & Cervero, 2001; 2010). Utility theory can help disentangle this complexity by identifying critical constraints (e.g., lack of available public transport, parking availability, or highway tolls) before addressing more nuanced utility influences. Another key question is whether all modes should be included in a single model or treated separately, as they respond to different features in varying ways.

Concerning proximity, modal split is critical to understand possibilities of modal-shift. Research has consistently associated the decision whether to drive or ride transit with the cost of reaching destinations using each mode (Stead & Marshall, 2001; Handy, 2002). For active modes, most models of mode choice suffer from a degree of misspecification. Cervero (2006) proposes some enhancements such as simulations (enhancing the modeling of active travel), tour-based models (accounting for stages that involve walking or cycling), auto ownership models (to capture the tendency of auto trip degeneration), pre-mode choice models (that estimate walk and bike trips

before taking the main mode choice), intrazonal estimates (estimating the actual possibilities of travel inside zones), respecified mode-choice models using built environment variables (at the same level of more traditional cost variables), or congestion feedback loops for models (which, after forecasting auto-travel, work the hypothesis that over-congestion could cause the flow towards other modes).

In the present review, the mode choice is addressed in different ways. While Searcy et al. (2018) simplify the problem to a question of distance and choice, and Marquet (2015) or Aristizábal et al. (2023) focus solely in pedestrian share, other approaches like Yu & Higgins (2024) do target all modes, but establish a definition of proximity by filtering only non-work everyday trips under 15 min (calculated for each mode) for essential needs. This last approach is consistent with the proposal in Silva et al. (2023), of using all modes in order to understand the potential for modal shift in "proximal environments".

Proximity Mode Split

In the case study subsection of section 2.3.4, the seemingly large influence of distance in mode choice was introduced. Walking is the preferred mode when performing short trips, yet certain spatial heterogeneity was present, which should be further explored filtering for trip purposes, as the review has shown how different trip behavior in proximity will also be strongly affected by their fundamental nature and the location kind of their destination. In Figure 17, the percentage of travel mode for trips below 15 minutes is represented for municipalities, filtered for trip purpose and mode, and colored using four classes that represent quartiles.

A first suggestion can be drawn from the maps: on one hand, in proximity behavior, the MRM shows a highly prevalent walking behavior, followed by car prevalence, with significantly lower rates. Train and Bus trips, on the other hand, show really lower prevalence for this kind of travel. Both motor and walking trips show heterogeneity in their spatial distribution. Regarding driving, a weak pattern can be sensed in Care, Shopping, and Study trips towards the north-west side of the MRM, where most low-density urban fabric concentrates. Work trips show a clearer monocentric picture that has been aforementioned somewhere. Regarding walking behavior, patterns become more confusing in their distribution, weakly mirroring driving behavior.

A number of further exploratory controls were performed in the dataset, in order to understand if very obvious patterns arise from a simple filtering of the data. Controls such as distance threshold and purpose were extended to allegedly important characteristics such as age, purpose, density or building age. This further control filtering, however, leads to very unbalanced and small samples, which poses some methodological obstacles for modeling purposes. In figure 16, we illustrate the key takeaway in the filter

exploration: given the available data, controls for statistical modeling should be kept simple so as to keep a reasonable amount of variation in the mode choice data. Also, even keeping controls simple, some control combinations will still be rather biased towards walking mode.

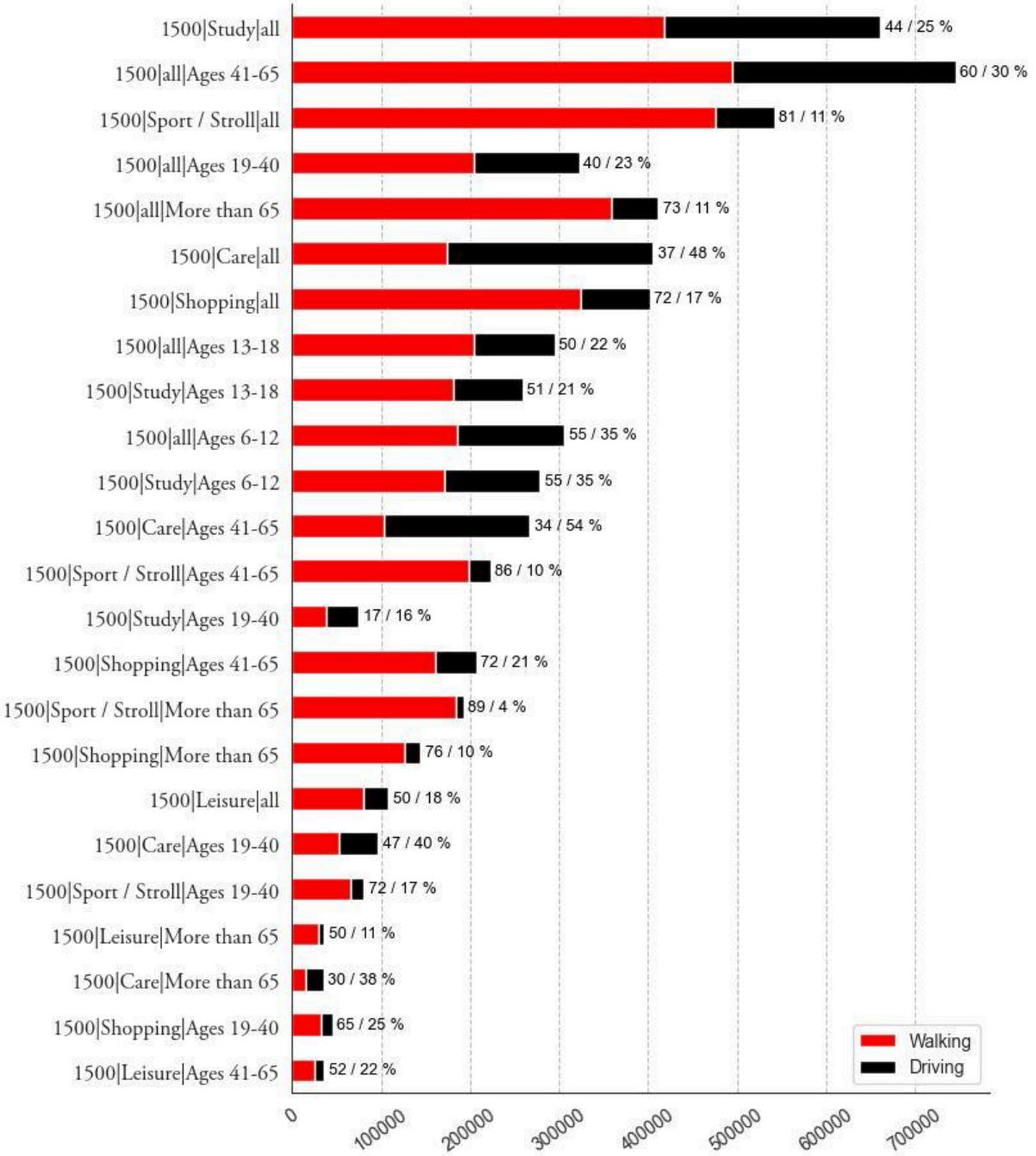
Figure 16 (Following page): Mode Share using different controls

Percentage of trips by mode, purpose and municipality.

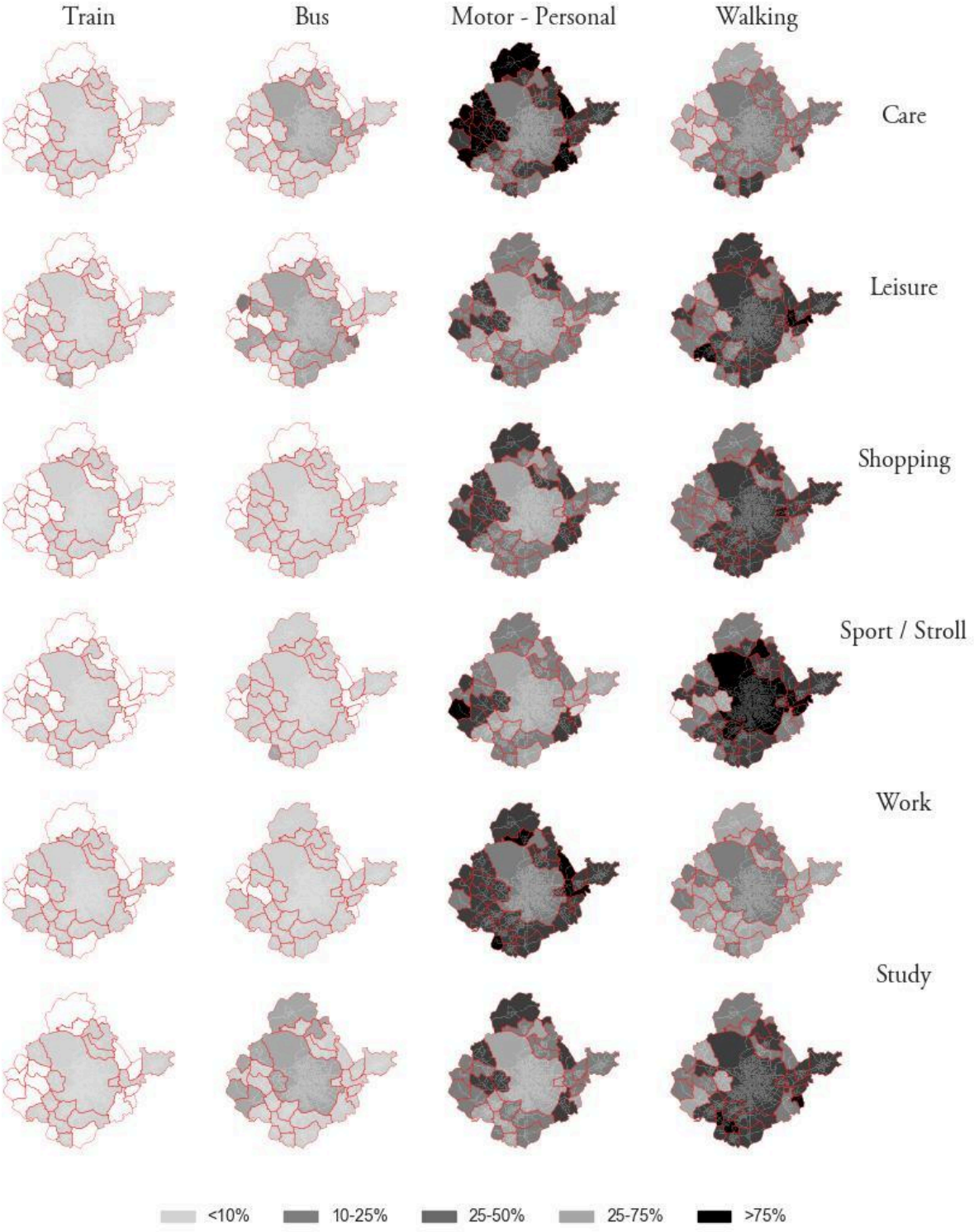
Figure 17 (Following page): % Mode Choice for 15M trips

Percentage of trips by mode, purpose and municipality. Maps are colored by quartiles, being the lightest gray the lower quartile, and the black for the highest quartile.

Mode Share using different controls



% Mode Choice for 15M Trips



3.4.4 Other Outcome Metrics

Less frequently used variables show how creative this line of research can be when exploring different questions, given data availability constraints. Route Selection is an underexplored metric in four-step models but has gained attention in agent-based and complex network approaches. Different methods explore how travelers choose routes beyond shortest distance, factoring in preferences and real-world constraints like congestion or street-level characteristics.

Behavioral and Attitudinal Outcomes, such as residential self-selection, are also targeted for understanding how the built environment influences travel choices. For instance, car ownership is often used as a proxy for attitudes toward urban mobility. It has been linked to both built environment features and travel behavior, offering insight into the relationship between accessibility and reliance on personal vehicles (Crane, 2000; Cao et al., 2009; Acheampong, 2015).

In public health, Body Mass Index (BMI) is commonly used to assess the impact of active travel. Studies show a correlation between increased walkability and lower BMI, highlighting the health benefits of urban designs that promote walking and cycling. GHG Emissions are a key metric for evaluating the environmental impact of transportation. Denser, more walkable areas typically produce fewer emissions from vehicles, making this an essential outcome for sustainable mobility research.

Concerning urban proximity, the route selection outcome is not found in the present review. In a broader search, some works can be mentioned, such as Salazar-Miranda (2021), who studied deviations from shortest pedestrian routes, and positively associated them to visually enclosed streets, with less complex facades, and better access to parks, sidewalks and businesses, are the most desirable streets; or Angel (2024), who used a Machine Learning approach to associate street-level characteristics to pedestrian traffic, and suggest that some features such as land-use mix, have low significance at street level, and areas with low walkability can also show very high walking volume and vice versa.

Behavior / Attitude as study outcomes is exemplified in the review by Haugen (2011) specifically addressing the proximity satisfaction (as a state of accessibility) in a qualitative

survey, and Gil-Solá & Vilhelmson (2022), who also survey socioeconomic, attitudinal, and motivational features to then regress them against objective demographics and built environment characteristics. In these cases, the approach is more observational, not going as far as to attempt to predict attitudinal characteristics, as proposed in Crane (2000) and Cao et al. (2009).

BMI / physical activity - is a common outcome in public health - related studies. For instance, it is shown in the work by Frank (2006), that a 5% increase in walkability is associated with a 0.23-point reduction in body mass index; in the review by Berghauser-Pont (2021) that increased density is associated with lower BMI, or the review by Grasser et al. (2013), who point at a strong association of BMI with walking for transport.

Van Acker et al (2016) formulate a question on a potential two-way relationship between car ownership and travel behavior. In Cao (2009), the reviewed works around the issue of Residential Self-Selection suggest that population density and transit-based job accessibility at home have an association with car ownership. Also, unexpectedly, Javaid (2020) reports no clear evidence on car-ownership and provision of infrastructure. In the study by Calafiore et al. (2022), a strong negative correlation was found between the services accessible in a short walk and car ownership.

GHG emissions are an indirect way of measuring one of the effects of transport and, according to the review by Gao (2023), it has been a hot topic since 2015-2018. Recent research reports that residents living in communities with a higher density emit fewer GHG emissions from both cooling and heating and transport (Berghauser-Pont, 2021).

In general, if the “translation” of the targeted outcomes is helpful to communicate results to the public and policy-makes, the approach can be a very useful way of framing quantitative results of empirical efforts in broader discussions.

3.5 Associated Features

In the context of this work, beyond geographical nearness, proximity means that an actual kind of interaction is realized. According to the review of recent works, accessibility seems to be the preferred metric for mapping a state of proximity to be tested against other outcome metrics, assuming that it is a viable way of quantifying possibilities of interaction. However, accessibility is often mixed with notions of diversity or density and, in many cases, mixed with the notion of proximity.

The literature reviewed has introduced a broader portfolio of nuances of the built environment which has proven informative to policy and impactful on outcome travel metrics, out of which accessibility has a prominent place. However, the lack of an epistemological consensus makes it still complicated to both understand which features to include, and how they can be measured or operationalized for research.

This section refers to the literature around the "D's" approach, being the most referenced framework, and describes the motivations and operationalizations of different features of the built environment (and demography) that have been traditionally used in the study of travel and the built environment. This way, the section connects the recent empirical approaches to urban proximity with the broader legacy of associated features in this scope of research.

3.5.1 Destination Accessibility

In the context of transportation studies and geography, accessibility is a well established concept to capture relational phenomena, mostly attributed to the seminal work of Hansen (1959), a land value forecast model that defined "accessibility of an area as an index representing the closeness of the area to all other activities in a region".

Accessibility can be measured as either an outcome (actual travel behavior) or a process (theoretical potential), and it can be objective (based on data) or perceived (based on individual

experiences). Additionally, it can be relative (comparing two points) or integral (connecting a point to all others in a network). Key elements in constructing accessibility metrics include impedance (the "cost" of travel, such as time or distance), the perceived availability of opportunities, and attractiveness variables like job opportunities or transit frequency (Guida & Caglioni, 2020).

Accessibility measures have been operationalized in three primary ways: contour measures (defining catchment areas by calculating the number of available opportunities within a certain distance or time), gravity-based measures (weighting opportunities by distance decay functions and travel cost) and utility-based measures (capturing accessibility based on individual choices and preferences, considering features beyond mere travel cost) (Weber & Kwan, 2002; Acheampong, 2015; Vale et al., 2016; Silva et al., 2023).

In relation to the built environment, accessibility is tied to three main dimensions: Destination Accessibility, which measures access to regional centers like jobs or the CBD (Handy, 1992; Ewing & Cervero, 2001; 2010; Krizek, 2003; Chen et al., 2008; Clifton et al 2008; Boarnet 2011; Stevens, 2017); Distance to transit, capturing proximity to public transport (Ewing & Cervero, 2001; 2010; Chen, 2008; Stevens, 2017); and local service provision, often operationalized through walkability indices that measure access to nearby facilities, this last approach being the most tightly connected to proximity studies (Logan,2022; Papadopoulos, 2023; Megahed, 2024).

In an early reflection on the concept, Handy (1992) described local accessibility as being primarily determined by nearby activity, mostly oriented to convenience goods, located in small neighborhood centers; Krizek (2003) introduced the concept of neighborhood accessibility, stating it provides local attractive, multimodal options for a variety of travel purposes; Saelens & Handy (2008) find accessibility (as proximity to non residential destinations), as the most powerful predictor of local travel; Iacono, Krizek & El-Geneidy (2010) explored problems related to the development of accessibility measures for non-motorized modes, which primarily arise around data quality, zonal structure and adequacy of models and travel networks for calculation; Vale et al. (2016) or Bolten & Caspi (2021) revealed the fragmentation of active accessibility research in theoretical and measurement terms, scale of analysis, the focus on origins and not on destinations and, to a lesser extent, on routes, as well as the scarce use of multicollinearity tests.

In the research by Logan (2023) and Megahed (2022), it has been reviewed how proximity studies consistently use accessibility metrics to measure compliance with the 15-minute city concept. Researchers often debate the most appropriate metrics, such as cumulative opportunity measures versus user-tailored approaches that consider individual behavior. Challenges in urban proximity research include varying definitions of accessibility thresholds, differences in data quality, and the need for more nuanced models that account for active travel modes and individual experiences. In Table 8, a summary of the approaches in this review is shown, revealing a diverse range of operational definitions of accessibility, and a clear trend in recent years of the use of "cumulative opportunities" or number of different opportunities accessible at a certain cost threshold, often justified by data availability constraints, and being perceived as a very similar metric to other, more nuanced metric approaches.

Table 8:
Accessibility approaches in the reviewed proximity literature

Reference	Accessibility Approach
Haugen, 2011	Outcome Perceived Accessibility in all modes to work, everyday activities, and relatives: ➔ Proximity preferences ➔ Distance satisfaction ➔ Residential satisfaction ➔ Self-reported distance
Haugen et al., 2012	Accessibility in all modes to amenities: distance and diversity of the amenity supply, and their evolution in time.
Kasraian et al., 2019	Transport accessibility measured by distance to transport nodes and travel times on transport networks.
Graells - Garrido et al., 2021	Walking accessibility: Isochrone to everyday amenities.
Bartzokas-Tsiompras & Bakogiannis, 2022	Metropolitan walkability index using seven walking performance indicators of Population-weighted average ratios of accessible destinations within 15 min (network-based accessibility) to nearby destinations within 1 km Euclidean distance (proximity). Aggregated to FUAs through an outranking multicriteria approach for selecting the optimum solution from a list of options based on a set of multiple criteria.

Li, 2022	Visit to the nearest grocery store, compared to the euclidean distance to the "almost nearest" POI within 15-minutes walking
Gil-Solá & Vilhelmson, 2022	Two measures of proximity: geographical distance to a regularly visited activity and whether the nearest alternative for performing the activity was chosen
Abbiasov et al., 2022	15-minute usage is the proportion of trips originating in each neighborhood that were aimed explicitly towards essential amenities within a 15-minute walk from the population-weighted centroid. An index between 0 and 100 is calculated as the average of percentile ranks of each area and category, weighted by the national average trip share per category.
Calafiore et al., 2022	Delineation of areas that approximate 20-minute neighborhoods based on accessibility to key services. A score is obtained to capture the extent to which people can meet their everyday needs with a 10-minute walk.
Knap et al., 2023	Gravity-based 2SFCA accessibility measures that take into account the age of the residents in the area The demand for a service is calculated using the distance decay functions and the fraction of the population per age group. The supply of the destination type is calculated using the distance decay function specific to each destination type. Results are normalized and aggregated based on the frequency of trips to each destination type, derived from the trip distributions calculated based on travel patterns. It uses 10, 15 and infinite time thresholds.
Birkenfeld et al., 2023	Two measures of local and regional accessibility, the ease of reaching destinations, around each household (WalkScore gravity measure), and a public transport gravity-based accessibility measure, defined as the quantity of jobs reachable within the region's from a location and weighted by a gaussian-fit decay function derived from commuting flows
Poorthuis & Zook, 2023	Overall accessibility to daily needs in each postcode, by calculating the number of amenities within a 5-km radius around postal code centroids.
Aristizábal et al., 2023	Calculates the population-weighted pedestrian travel time from TAZs to economic poles.
Yu & Higgins, 2024	A two-step process was used. The first step was to calculate access intensity using the equation from Hansen (1959). The second step was to use the calculated travel time matrices to

determine sufficient access. Accessibility was aggregated at the census dissemination level.

The authors include three outcome accessibility metrics:

- ➔ A Basic-15-min metric is the share of population reaching at least seven of the eight most basic everyday needs within 1 km. from home
- ➔ A Full-15-min metric as the share of the population reaching 16 of the 17 categories of social urban functions within 1 km. from home
- ➔ A Optimal-15-min metric as the share of population reaching 16 of the 17 categories of social urban functions within 1 km. from home, and 150 social urban functions.

Elldér, 2024

Cumulative Opportunities Accessibility in the AMM

These metrics are defined as cumulative opportunities to bundles of land use classes representing trip purposes in the EDM2018 . The number of unique properties of a class are calculated, not accounting for size. The idea is to capture a sense of multiplicity of options. This number can be high for some classes such as retail, while other facilities like hospitals hold low values, and a great number of zero values. For some classes it is exaggerated to say that an area accessible to more registers will attract more trips. The complete list of land use classes accounted for is described in section 4.3.2.

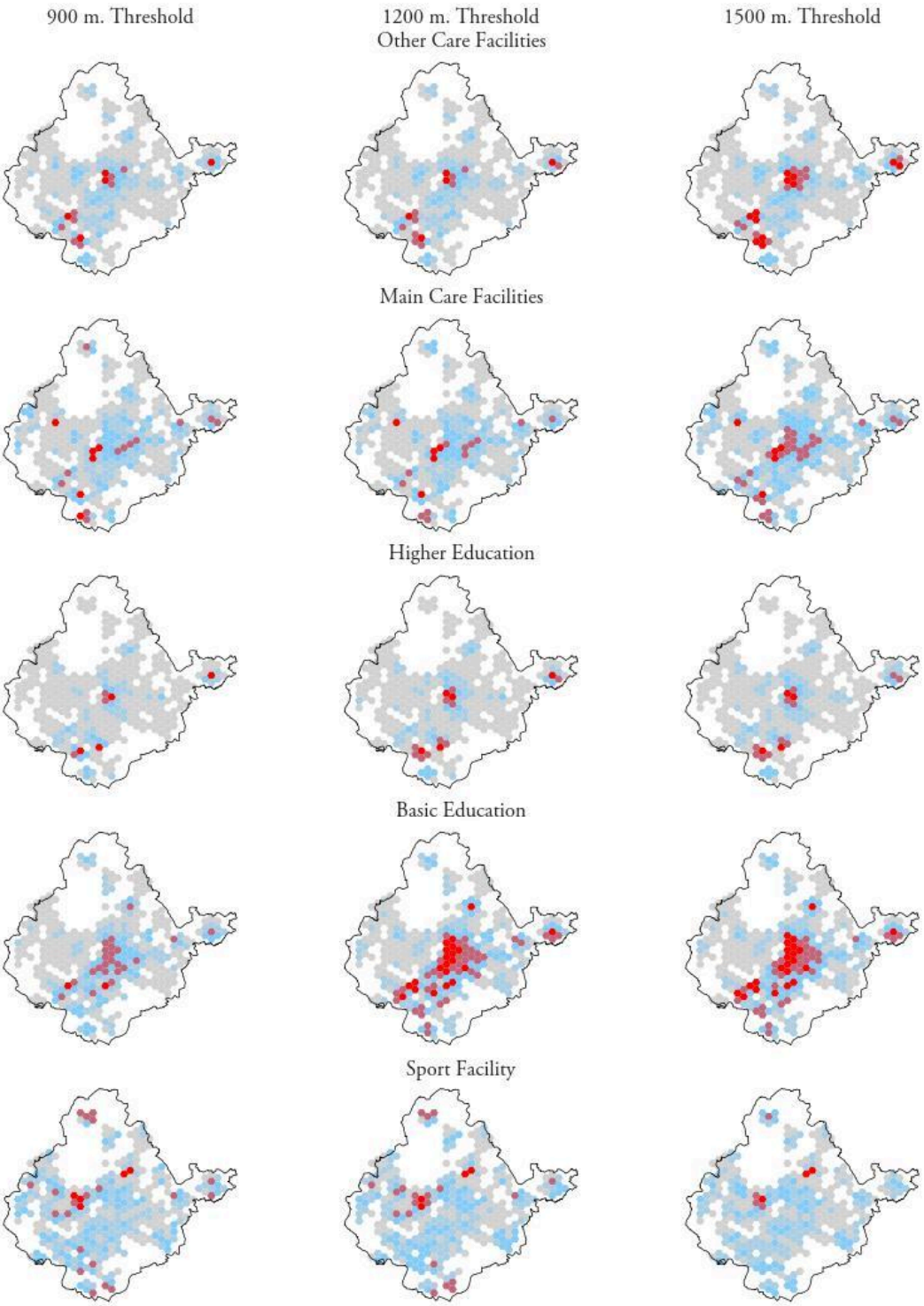
Green Space Accessibility in the AMM

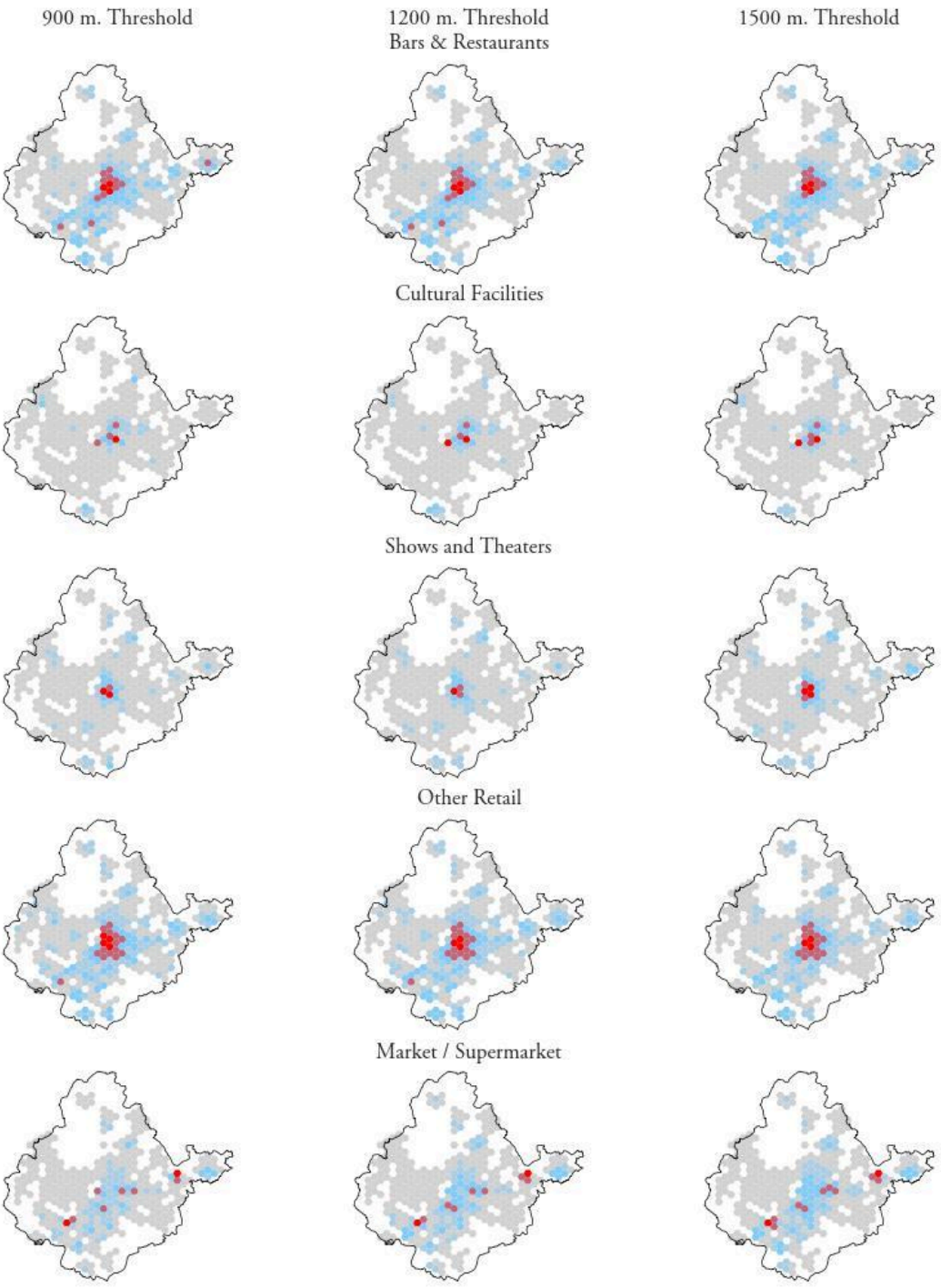
Green areas derived from OSM have been inspected and filtered for relevance, so as to form three groups by size and"‘nature" in the sense that they can be functioning in a more local or metropolitan manner. This classification is then justified by the knowledge of the area. The variable is also calculated as a cumulative opportunities metric, only counting the unique IDs of the parks reachable from each node of the network.

Public Transportation Accessibility in the AMM

The supply of public transportation, according to the literature, is of utmost importance in utility assumptions for choosing to ride or not. This feature is calculated as the number of unique lines reachable from each node, yet it is acknowledged that it could be possible to improve this indicator by adding other nuances of frequency and activity reached by transportation.

Accessibility Features




900 m. Threshold
1200 m. Threshold
Bars & Restaurants
1500 m. Threshold
Cultural Facilities
Shows and Theaters
Other Retail
Market / Supermarket

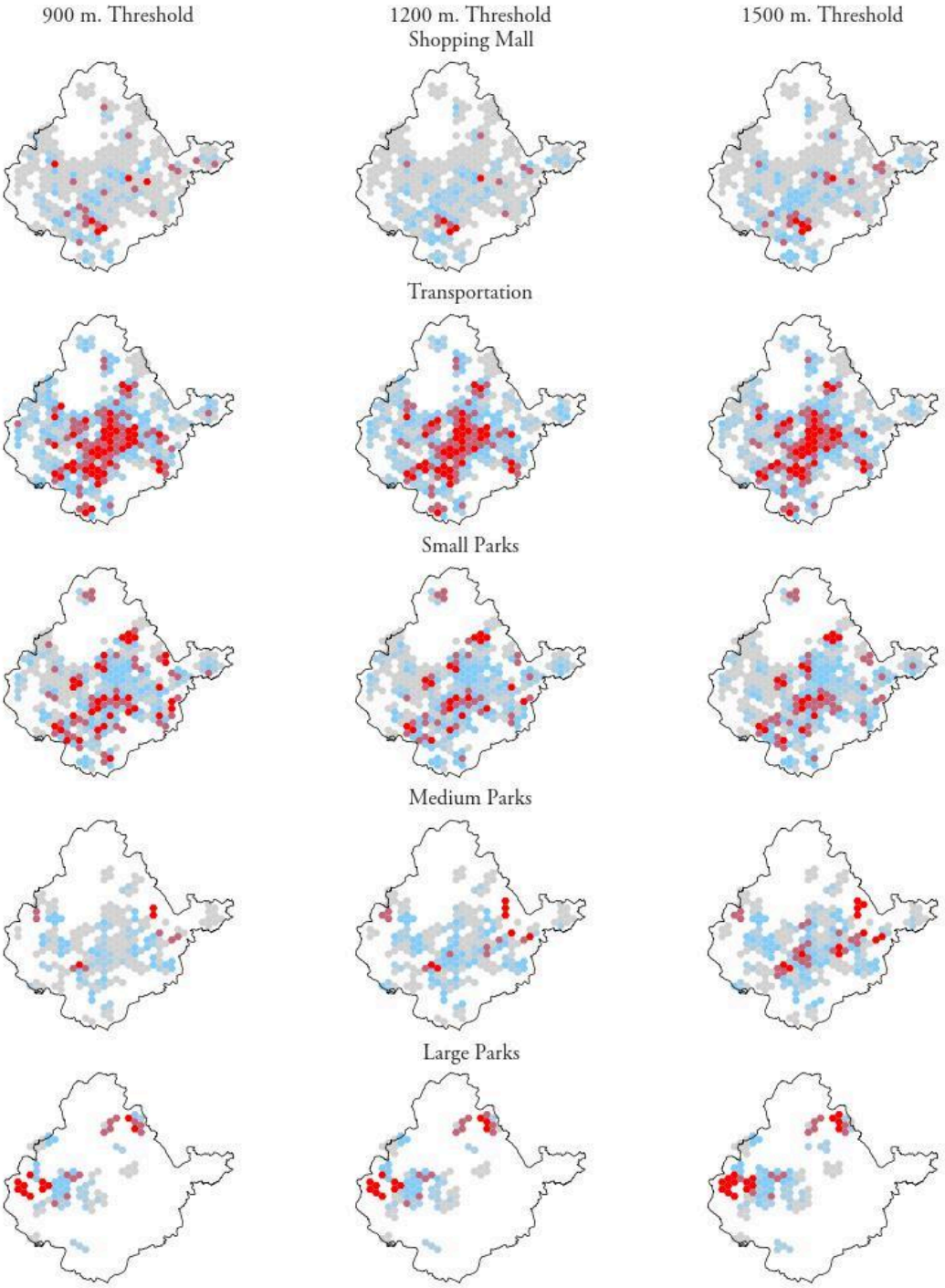

900 m. Threshold
1200 m. Threshold
Shopping Mall
1500 m. Threshold
Transportation
Small Parks
Medium Parks
Large Parks

Figure 18 (Previous pages): Accessibility Features

Maps are colored in three categories using Natural Breaks in the corresponding series, red being the highest value and grey being the lowest value. Only values built with the 900, 1200 and 1500 meters are shown.

3.5.2 Density

Density is the relative measurement of a quantity (in this field of study, commonly population or amounts of land use) within a spatial constraint (usually a boundary, or a grid-like aggregation). Coming from the field of physics, it was one of the earliest measures to be used in urban studies as "a defining characteristic of urbanity, and regional structures" (Wirth, 1938; Clark, 1951). The contemporary links of urban sprawl to transportation inefficiency, sparked debate on how density influences mobility and energy consumption.

In travel and built environment research, density is often used in conjunction with other variables like diversity and accessibility. Its application ranges across domains, including public infrastructure, economic productivity, environmental sustainability, social interaction, and health outcomes. Various types of density measures exist, such as population, building density, and economic activity, and these are applied within diverse spatial scales and aggregation methods to suit research objectives (Berghauser-Pont, 2021).

However, density alone is not a sufficient predictor of travel behavior. Researchers argue that density works in tandem with other features like land use diversity and transit accessibility to influence travel choices. High density areas may reduce car ownership and encourage walking or public transit use, but only if other supportive conditions are in place, such as good urban design or proximity to amenities. Some studies even find mixed evidence, with higher density leading to more car trips under certain configurations or demographic conditions. (Cervero, 1991; Ewing 1995; Handy, 1996; Crane, 2000; Boarnet and Crane, 2001; Ewing & Cervero , 2001; 2010; Stevens, 2017; Handy, 2017).

For proximity studies, density is closely associated with active behavior. Early works established a link between higher density and reduced vehicle trips, while later studies showed that design features like small blocks and urban aesthetics are equally critical (Levinson & Wynn, 1963; Pushkarev & Zupan, 1976; Newman & Kenworthy, 1989; Hess et al., 1999; Moudon et al.,

1997; Moudon & Hess, 2000). Other works further confirmed that density promotes walking, but only when considered alongside other features like land use diversity and walkability (Ewing & Cervero, 2001; 2010; Krizek, 2003; Leck, 2006; Grasser et al.; 2013).

In the scope for urban proximity studies, the literature has yielded a number of relevant thoughts on the use of the density metric. The focus is kept on those inputs that revolve around active modes, and modal shift towards active modes, to find how density has been consistently associated with walking and cycling behavior, yet also unveiled a great number of questions to answer, concerning the mechanisms at work. The operationalization of density, in the review, is either an available indicator of relevant threshold (that particularly point at urban-rural transitions), or a metric of "experienced density", consistent with accessibility studies (De la Roca & Puga, 2017). At least in one case, it is produced only taking into account the amenities used in them. Also, an interesting example of using Floor Area Ratio (FAR) as a regulatory aspect of density was found. In general, its empirical relevance is either assumed a priori, or acknowledged through results, but in all cases is nuanced by other dimensions of it. This way, as seen in the general review, density is treated as a necessary, but not sufficient condition for proximal environments, and not particularly in the "direction" of the variable (higher density means more proximity behavior), but in the "nature" of the territory that can be drawn from it, in a threshold-way. In Table 9, a summary of the use of a density approach in the review is presented.

Table 9:
Approaches to Density in the empirical works on urban proximity reviewed

Reference	Density Approach
Haugen et al., 2012	Three density classes (rough regional differences) and an additional "experienced density" within the same thresholds used. Uses density to control the model, and assumes the non-linearity between distance to services and density.
Marquet & Miralles-Guasch, 2015	Continuous available metric of density to regress the number of proximity trips within neighborhoods, as a predictor. Suggests that density acts both as a precondition and a

	facilitator of proximity; however, in highly homogeneous environments it cannot provide the sole explanation
Graells - Garrido et al., 2021	Index of touristic attractiveness (defined as log-transformed visitation density from mobile phone data. It acts as a parameter in their simulation model.
Bartzokas-Tsiompras & Bakogiannis, 2022	Population density levels (based on tertiles of the OECD metropolitan statistics data at FUA level)
Li, 2022	Readily-available population density for the chosen aggregation as one of its controls.
Gil-Solá & Vilhelmson, 2022	To capture the influence of urban density, authors use only amenities and distinguish four types of areas (ranging from areas of low amenity density in the urban fringe to areas of high amenity density in the city centres), measuring them within 1 km. euclidean around respondents of survey. They use this cardinal variable as a predictor in their model, which is comparable to cumulative opportunities metrics.
Abbiasov et al., 2022	FAR by regulation longitudinally, finding how less restricted areas tend to do better in attracting clusters of business.
Poorthuis & Zook, 2023	Uses a Standardized density-based urbanization variable to determine the degree of urbanization in each postcode within the country. The scale has 5 classes, with 1 being the most urban (>2500 addresses per km2) and 5 being the least urban (<500 addresses per km2).
Elldér, 2024	Produces a population per hectare metric to study the revealed proximal environments. Also accounts for the share of population living in low-density areas.

Experienced Density in the AMM

A metric of absolute reachable quantities through a street network has been selected in this work, inspired by the reviews from Duranton & Puga (2020), or Berghauser-Pont (2021). Both residents and housing units are used, as the intention is to capture the nuance of areas in Madrid which are more "unstable" in population, such as university students, "seasonal workers", or tourists, which might be affected by different dynamics. Also, the total floor and parcel area is calculated, capturing a sense of built density.

Land Use Proportions in the AMM

The total built reachable area is complemented by the proportion of uses that have been involved in this study so far. Some more classes are even added, as categories associated with work dynamics, such as offices or industrial sites, are also included in this set of indicators. Percentages have been inspected and are reasonable.

Unbuilt Proportion in the AMM

This feature could also be considered a sort of Design feature, as the presence of vacant land affects the urban scene. It is calculated as the proportion of vacant land over total urban land according to the cadastral data, meaning that it also represents scattered urban voids, where no activity takes place.

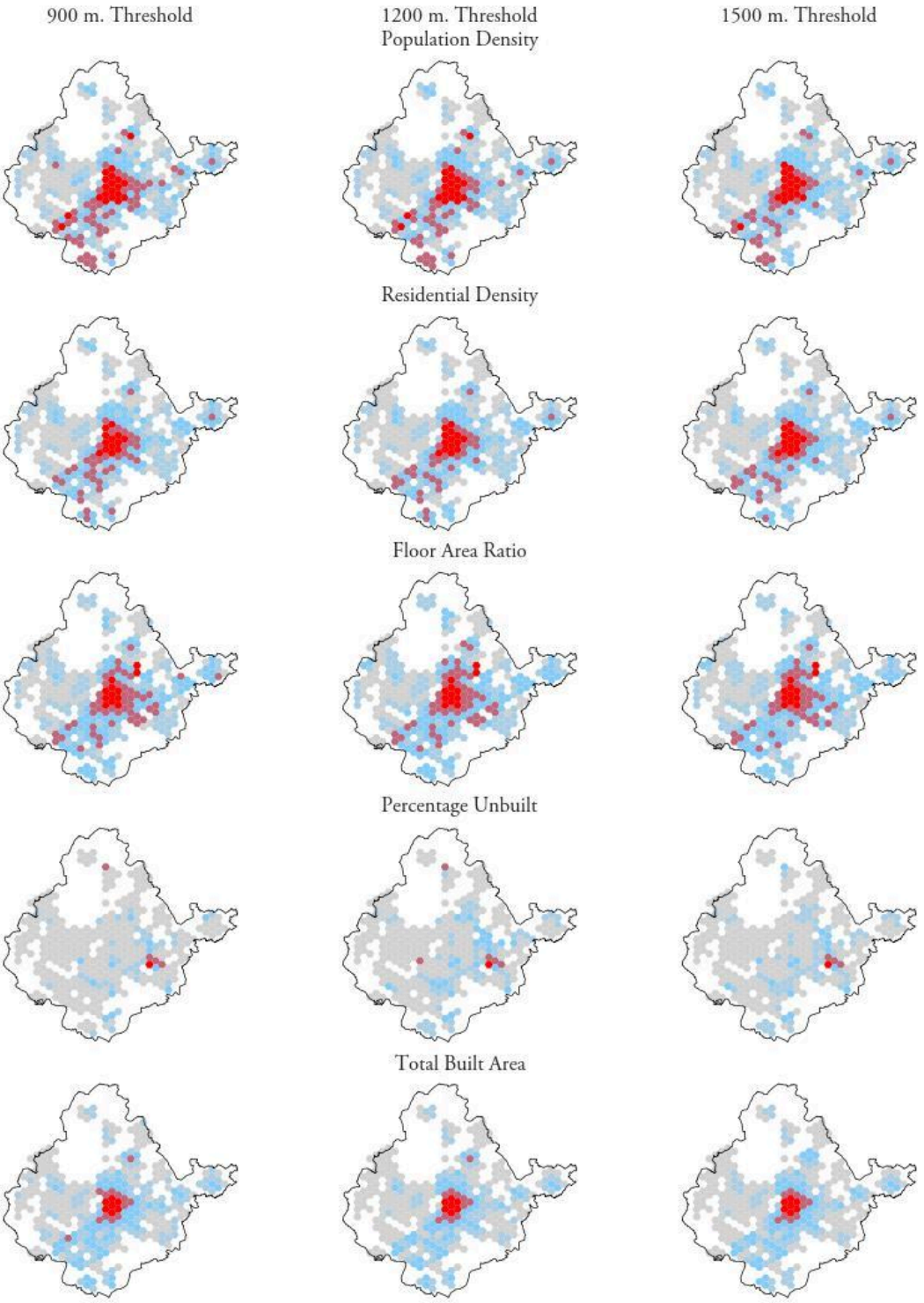
Experienced FAR in the AMM

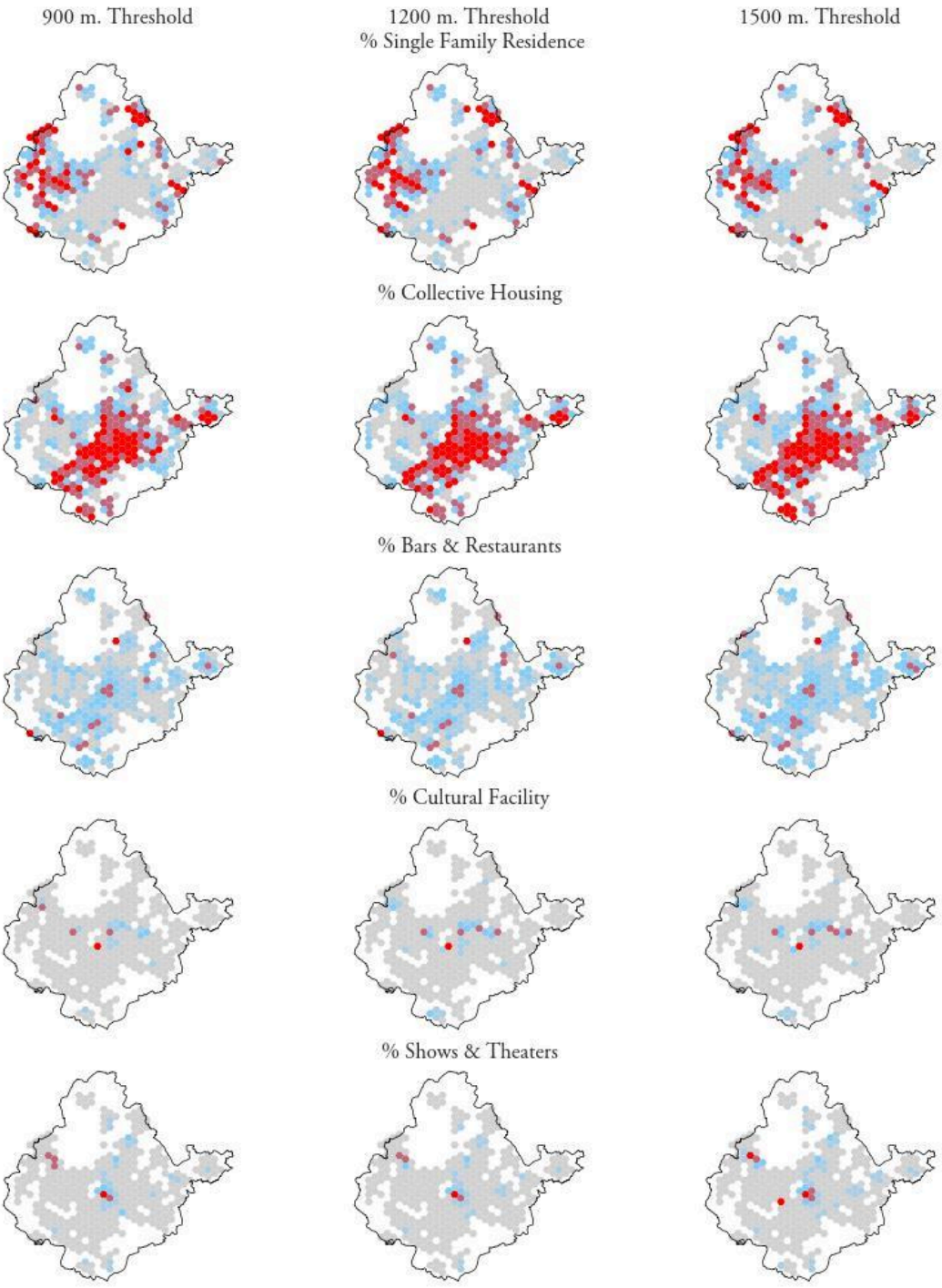
Along with the experienced density measurement, Floor Area Ratio is calculated in an attempt to capture a volumetric sense of the urban scene. However, this idea might be better calculated at the route level, as a design proportion of height and width, which is not easy to achieve with the data available for this work.

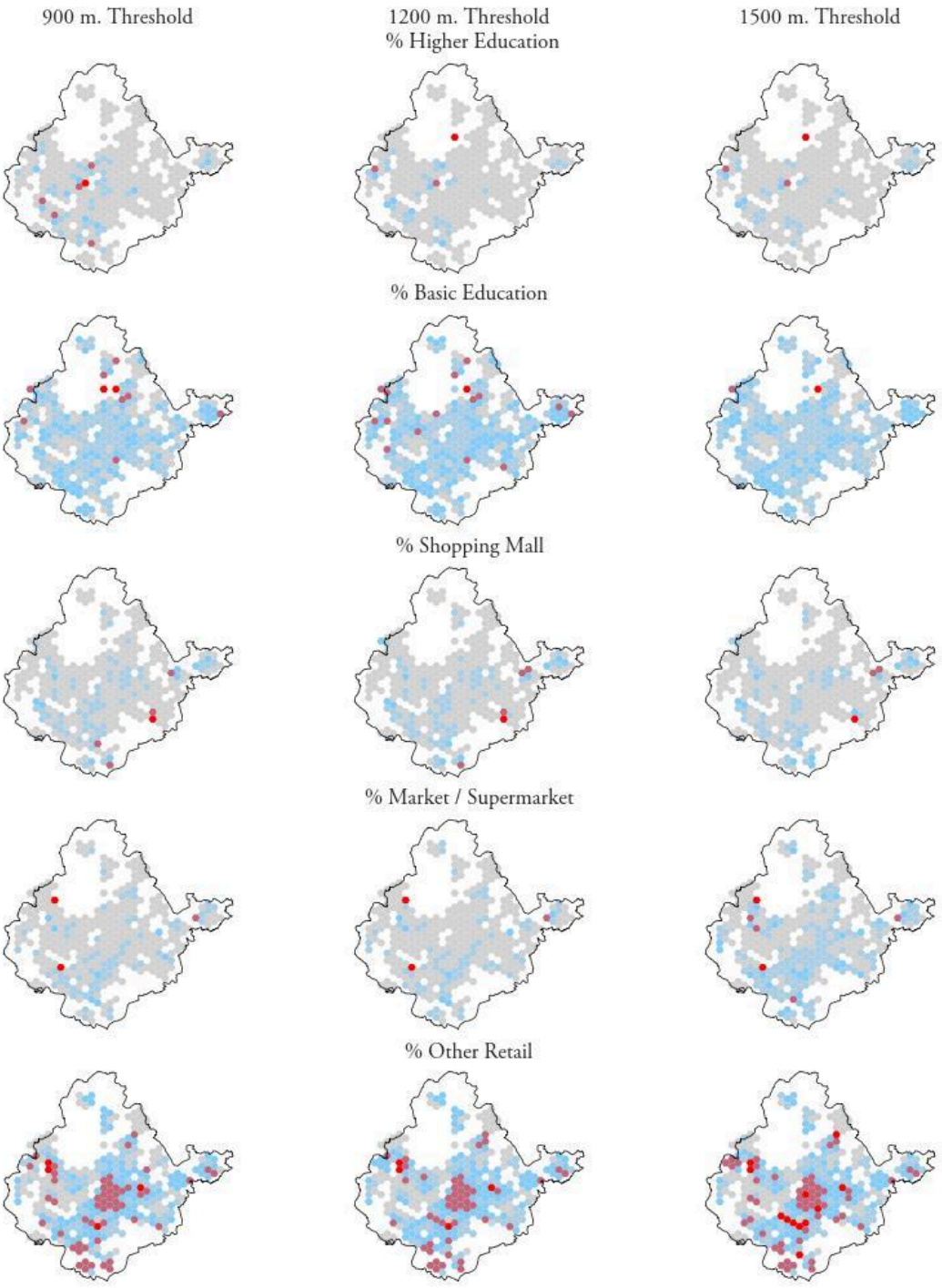
Figure 19 (Following pages): Density Features

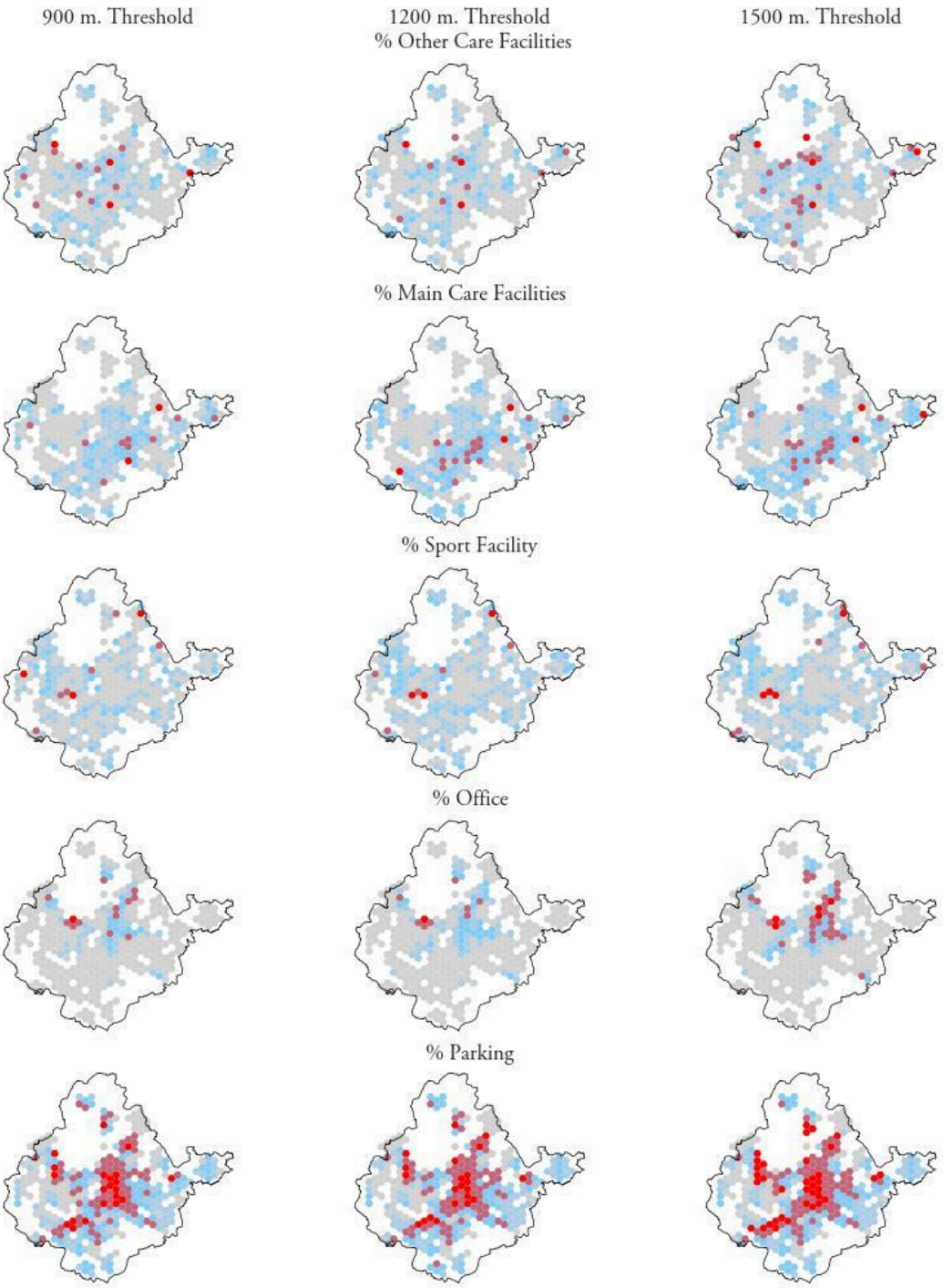
Maps are colored in three categories using Natural Breaks in the corresponding series, red being the highest value and grey being the lowest value. Only values built with the 900, 1200 and 1500 meters are shown.

Density Features

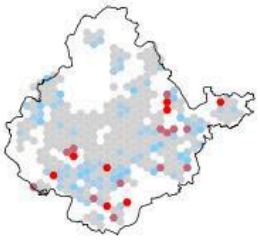



900 m. Threshold
1200 m. Threshold
% Single Family Residence
1500 m. Threshold
% Collective Housing
% Bars & Restaurants
% Cultural Facility
% Shows & Theaters

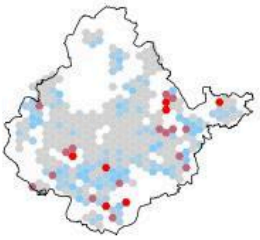

900 m. Threshold
1200 m. Threshold
% Higher Education
1500 m. Threshold
% Basic Education
% Shopping Mall
% Market / Supermarket
% Other Retail


900 m. Threshold
1200 m. Threshold
% Other Care Facilities
1500 m. Threshold
% Main Care Facilities
% Sport Facility
% Office
% Parking

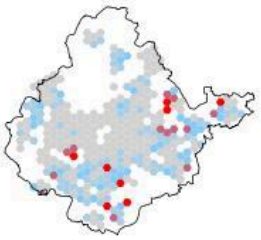
900 m. Threshold

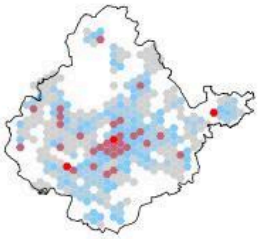


1200 m. Threshold
% Industrial

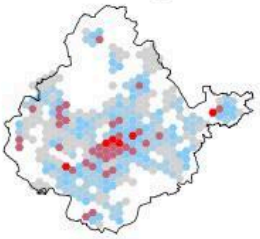


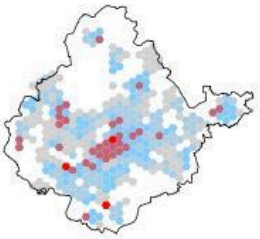
1500 m. Threshold





% Storage





3.5.3 Diversity

In the scope of this work, Diversity points to the ideas posed by Jacobs (1961) in "The Life and Death of Great American Cities", though its evolution in this thread of literature is, for the sake of redundancy, quite diverse. The original concept in Jacob's work deals with how urban vitality depends on diversity of primary uses (which bring people to specific places and therefore act as "people attractors", such as offices, residences, some shops and many -but not all- places of education, recreation and entertainment); and secondary uses or those enterprises and services which grow in response to primary uses, to serve people attracted by primary uses.

In the context of travel and the built environment, diversity, often referred to as land use mix, has become a key feature influencing travel behavior. The concept has been adapted using metrics from landscape ecology (biodiversity) and econometrics (social and economic activity diversity). Several metrics capture land use mix, including simple proportions, balance indices, entropy measures, and landscape ecology metrics like the Shannon Diversity Index and Simpson Diversity Index, which quantify how land uses are distributed within a spatial area (Clifton et al., 2008; Song, Merlin & Rodríguez, 2013; Lowry & Lowry, 2014; Raman, 2019).

Researchers have linked land use mix to increased walking and public transit use, while others have found no significant correlation between mixed-use environments and reduced car trips. Evidence has been found that walking is influenced by land use mix as much as by local density, and jobs-housing balance was more strongly related to walking than general land use mix. The literature reveals mixed results regarding diversity's impact on travel behavior, with land use mix often showing a stronger association with walking and transit use than with driving reduction. More recent reviews suggest that diversity's effectiveness is enhanced when it complements other predictors, such as density and accessibility (Frank and Pivo, 1994; Crane and Crepeau, 1998; Stead & Marshall, 2001; Ewing & Cervero, 2001; 2010; Krizek, 2003; Saelens, Sallis & Frank, 2003; Leck, 2006; Lee and Moudon, 2006; Salens & Handy, 2008; Stevens, 2017; Vale at al., 2016; Javaid, 2020).

For urban proximity studies, land use mix is considered a critical precondition for encouraging active travel and fostering neighborhood vitality, especially when spatial and functional complementarity is achieved. According to these reviews concerning relevant dimensions of urban proximity, land use mix is a relevant feature when it accounts for spatial and functional complementarity, and thus, it has been proposed to become a particular case of accessibility metrics, which could be quite consistent with an approach regarding proximity. Consistent association with walking behavior does support this idea, and an interesting issue arises when controlling for behavioral features such as self selection. In this review, not many works do account for diversity explicitly. Only two works use a dedicated diversity metric in their models, and another two accounts for the diversity of accessible classes of land use. The works that use diversity as a feature in the review are listed in Table 10.

Table 10:
Diversity Approach in the Reviewed Literature

Reference	Diversity Approach
Haugen et al., 2012	One of their goals is to address whether changes in the diversity of accessible amenities in time is due to redistribution of amenities or population. Diversity is captured as the number of different amenities present within reach.
Graells - Garrido et al., 2021	Uses an Shannon Entropy Index per inhabitant (excluding transportation as a destination) to use in their Gravity Model
Aristizábal et a., 2023	Uses Service diversity as a criterion to delineate economic poles which are then tested for accessibility to predict pedestrian trips. It is unclear how this metric is calculated.
Elldér, 2024	Uses jobs-to-houses and old-houses ratio as control variables for the study.

Walkable Trips in the AMM

For capturing diversity in the proposed study area, the concept of the Walkable Trips found in Carpio et al (2021) is leveraged. Essentially, walkable trips are a metric which counts how many trips can be triggered at a certain point in the street network, taking into account the number of origins and destinations of various kinds reachable at a certain distance threshold, and using walking regional trip rates to convert the reachable land use area into "attracted" trips, measured against the origins.

This metric is a combination of reachable land use (intensity) and satiation (balance between origins and destination), and has the advantage of being capable of changing thresholds, and being expressed in total trips, which is an absolute population measure. However, some limitations exist in the method, which uses theoretical regional frequencies (which were derived in section 4.4.2) that can greatly change over space, and assumes that all interactions "within reach" of a particular node, in fact affect that particular node.

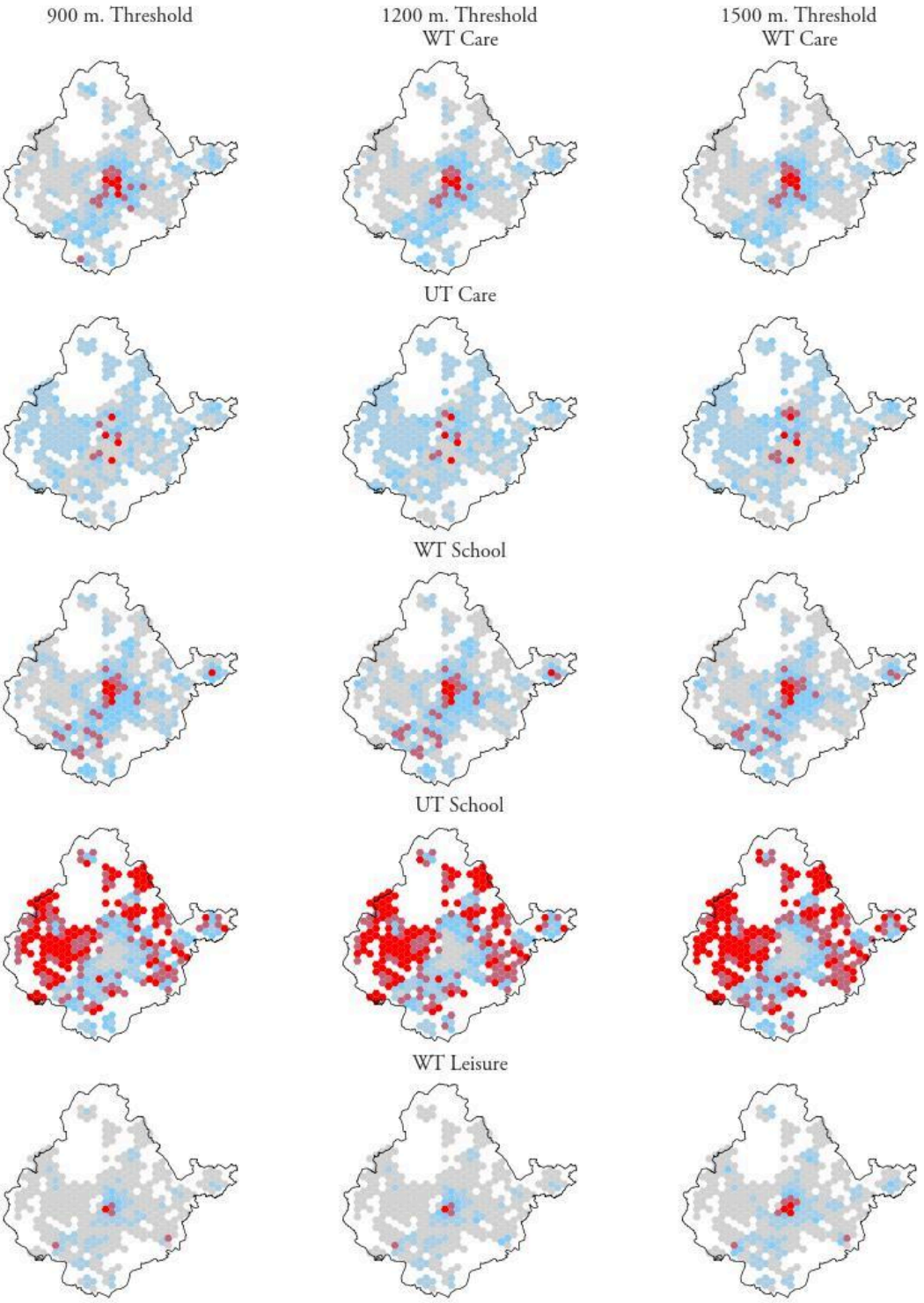
The outcome of the Walkable Trips procedure is twofold: Along with the Walkable Trips (WT), the unmatched trips (UT) are calculated, also expressed in trips and with signs representing whether the unmatched trips are due to an excess of origins or destinations. Although highly general, this metric captures a ranking within the regional scope chosen, so it could change significantly when choosing different universes. In this sense, the generalization of land use categories to associate the metrics to the Trip Purpose categories of the EDM2018 is also a downside of this procedure, and should be expanded in the future.

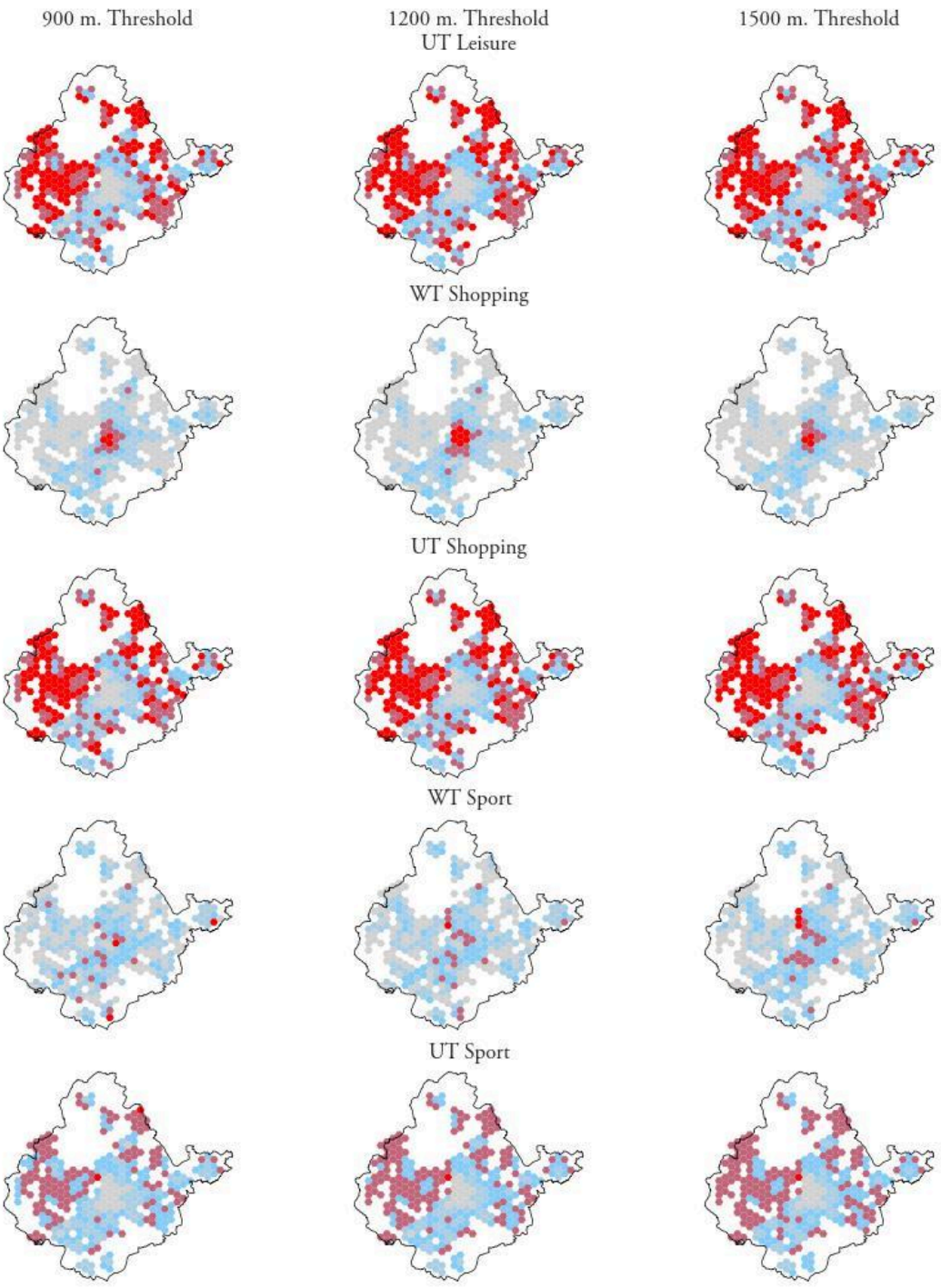
The metric has been calculated for bundles of land use which have been utilized for the calculation of the rates shown in 4.4.2, which are consistent with the trip motivations of the EDM2018.

Figure 20 (Following pages): Diversity Features

Maps are colored in three categories using Natural Breaks in the corresponding series, red being the highest value and grey being the lowest value. Only values built with the 900, 1200 and 1500 meters are shown. WT refers to the Walkable Trips, while UT refers to the Unmatched Trips

Diversity Features




900 m. Threshold
1200 m. Threshold
UT Leisure
1500 m. Threshold
WT Shopping
UT Shopping
WT Sport
UT Sport

3.5.4 Design

In this review, the term design has two meanings: On one hand, it points to the meso-scale configuration of street patterns as a spatial constraint to movement. On the other hand, it deals with the architectural materiality of space as a quality that encourages or prevents behavior (in the literature, these have been classified in many ways, such as categories of infrastructure-level qualities, pedestrian amenities, or experiential elements). It is complicated to trace a firm origin of design as an associated feature to travel, as both urban and transportation planning disciplines have somewhat prescribed design parameters as solutions to their particular and shared problems.

Concerning travel and the built environment, design features affect both freedom of movement and urban vitality, contributing to travel choices. At the street pattern level, metrics such as Intersection Density, Connectivity Index, and Block Size are used to evaluate how easily individuals can traverse an area. These features impact both pedestrian behavior and transit use, though the relationship is not always straightforward. For instance, while grid-like patterns may facilitate pedestrian movement, they can also encourage car travel by offering more direct routes (Ewing, 1996; Montgomery, 1998; Boarnet & Crane, 2001; Stead & Marshall, 2001; Krizek, 2003; Crane, 2000; Porta et al., 2004; 2006; Ewing & Handy, 2009; Ewing & Cervero, 2010; Boarnet, 2011).

On the architectural scale, design includes elements like sidewalk continuity, pedestrian crossings, street trees, and building setbacks, which contribute to the aesthetics and safety of an environment, influencing travel experience (Forsyth, 2015; Koohsari, 2015; Vale et al., 2016). These micro-level features, often bundled into indices like the WalkScore, are essential for promoting walkability and reducing car dependence. However, capturing their individual contributions to travel behavior remains a challenge, as these features tend to work better collectively in models (Cervero & Kockelman, 1997; Ewing & Cervero, 2001; 2010; Handy, 2002; Krizek 2003; Ewing & Handy, 2009; Stevens, 2017; Javaid, 2020). Overall, design plays a critical but complex role in influencing travel behavior, especially for active modes. While composite indices seem relevant in empirical approaches, more nuanced measures and greater testing are needed to fully understand design's impact on mobility.

In this review, the only reference to these "design indices" is made in Birkenfeld et al. (2023), who uses the WalkScore metric to address accessibility as one of the independent variables in their model. The authors found quite significant explanatory power in this metric for the odds of living a more "local lifestyle", using it as a cardinal variable, classified in four categories ranging from "car-dependent" to "walker's paradise".

Mean Building Age

Using the reachable threshold aggregation logic, the mean building age is derived, weighted by the total built area for each building. This predictor, although not strictly a design feature, is commonly related to the kind of urban tissue that can be expected in terms of spatial and land use layout. Expectedly, unplanned, historical tissues will exhibit a higher density of intersections and a more organic pattern of occupation. Conversely, more contemporary tissues will exhibit regular grid patterns of varying size

Mean Block Size

Mean Block Size is calculated as the mean length of street segments between intersections. This feature is closely related to the previous characteristic, and it is related to a perception of proximity either as a simple cognitive metric "say, this destination is two blocks away", or as a metric capturing how often a pedestrian encounters intersections that allow changing paths along the way.

Multiple Centrality Assessment: Degree, Betweenness and Straightness

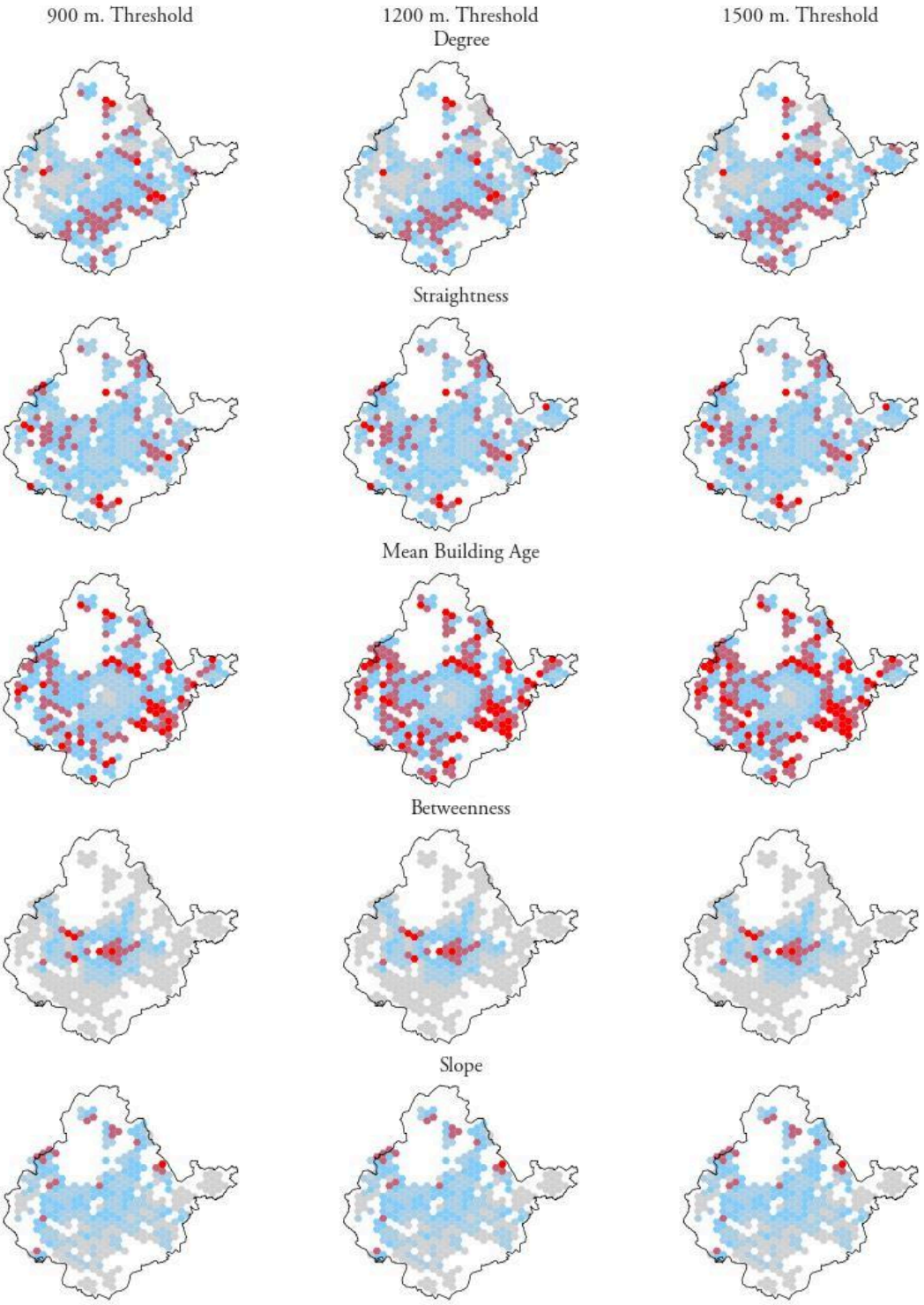
The approach described earlier to derive indices of network configuration has been adopted. Degree is the mean degree of reachable nodes from each node, and it serves as a way of capturing the amount of intersections in which a user can actually change directions or paths. Betweenness is calculated as the proportion of all shortest paths that pass through a particular node. Straightness is the ratio between all short paths from a particular node, and its straight line counterpart. These indices are to be taken carefully as they do not acknowledge the distribution of land use, but rather a configurational dimension.

Slope

The average slope of street segments at reachable distances from each node in the network has been calculated. This feature is related to a physical barrier to active modes. As with previous ones, this attribute does not take into account actual routes that travelers might take alternatively, as slope affects edges locally.

Figure 21 (Following pages): Design Features

Design Features



3.5.5 Demographics

The last category of features associated with travel and the built environment is not, per se, a built environment class, but rather the set of demographic features which help characterize the users whose travel behavior is being inspected, or the kind of trips that are being performed. This way, if disaggregate (and detailed) data is available, or activity based research is conducted, demographics will act as statistical controls in samples. Otherwise, they will be built over the same boundaries as the input data, and either act as controls or predictors, depending on the research strategy.

Early studies of travel and the built environment emphasized the strong influence of demographic characteristics on travel prediction. They found that built environment characteristics are often secondary to socioeconomic variables like income, age, household structure, and employment status. For instance, income constraints travel options, while age and household structure determine time-use patterns and modal preferences (Hanson, 1982; Salomon & Ben-Akiva, 1983; Handy, 1992; Kitamura et al., 1997; Cervero and Kockelman, 1997; Kockelman, 1997; Boarnet & Crane, 2001; Weber and Kwan, 2002; Ewing & Cervero, 2001; 2010; Cao, 2009; Boarnet, 2011)

Modern studies also highlight the importance of lifestyle and behavioral features, such as attitudes and self-selection, as they significantly impact travel decisions beyond what the built environment can explain. Evidence has been found that personal circumstances and lifestyle transitions (such as changes in family composition or employment status) lead to shifts in travel behavior. Some works summarize demographic variables in three aspects: income and price, socio-demographic taste features (e.g., gender and age), and built environment features (Lanzini, 2017; Van Acker, Phil Goodwin and Witlox, 2016; Cao, 2009; Gao, 2023).

Concerning proximity, demographic characteristics become important when considering user-tailored approaches. Income, age, and household dynamics determine who benefits from proximity policies and who might face challenges. In proximity studies, features such as age and income often serve as controls to differentiate user behavior, revealing how certain groups (e.g., older adults or low-income individuals) experience urban environments differently. For instance,

recent works have found that younger men are more likely to engage in active travel modes like biking, while the impact of income and education remains ambiguous (Acheampong, 2015).

In terms of socioeconomic characteristics, the greatest concern to this work is the idea of the user-tailored approach to a notion of urban proximity. In this sense, accounting for income constraints, perception, activity in the household, or individual ability, will be the main target of the approach. Saelens, Sallis & Frank (2003) found that sociodemographic features are way more important in models for active modes; Salens & Handy (2008) call for different modeling of different types of walking and specific segments of the population, all in order to explore the question of whether the built environment has similar effects by race/ethnicity, socio-economic status, age, or ability, also stressing the need for more longitudinal and experimental

In the recent review of empirical approaches to urban proximity, sociodemographic features are mostly used as controls, and rarely as predictors. Income-related features seem to be the most popular, captured in one way or another (for data constraints), followed by Age. Household Structure and Attitudinal - Behavioral variables, are important for Activity-Travel approaches, and other relevant variables such as car-ownership or commuting condition, are present. It is interesting to note that, given the identified approach of "proximity compliance", demographics are also used as statistical characteristics to differentiate within revealed environments, and in many cases, as a proxy to reveal inequity. Some relevant features, such as disability or gender, are less targeted. A summary of the features identified in the reviewed papers is presented in Table 11.

Table 11:
Demographic Features Approach in the Reviewed Literature

Reference	Demographics Approach
Haugen, 2011	Individuals aged 20-64; Gender; Age; Tenure; Considering Moving
Haugen et al., 2012	Individuals aged 6–84
Marquet & Miralles-Guasch, 2015	Income
Searcy et al., 2018	University Students
Graells - Garrido et al., 2021	Human Development Index (HDI); Age; Gender, Nationality

Bartzokas-Tsiompras & Bakogiannis, 2022	Income
Li, 2022	Ethnicity; Poverty; Educational Level; Commuters
Gil-Solá & Vilhelmson, 2022	Gender; Age; Nationality; Disability; Education; Household structure; Tenure; Commuter; Car Use; Environmental Awareness; Proximity Preference; Time-Pressured; Multi-Errands
Abbiasov et al., 2022	Income
Calafiore et al., 2022	Age; Ethnicity; Car-Ownership; Poverty; Disability; Education
Knap et al., 2023	Age
Birkenfeld et al., 2023	Income; Car-Ownership; Household Size; Age; Occupation; Household Composition
Poorthuis & Zook, 2023	Nationality - Ethnicity; Age; Poverty
Aristizábal et al., 2023	Education; Poverty; Age; Own Vehicle; Driving License
Yu & Higgins, 2024	(Composite) Income; Occupation; Nationality; Poverty (Housing Affordability)

Concerning trip purposes, a number of global classifications need to be attended to better frame the concept of urban proximity. First, transportation research commonly classifies trips broadly as mandatory or non mandatory; those of maintenance, discretionary, and subsistence nature; or those under time constraints or not. No consensus exists on the classification or the purposes targeted, apart from the loose idea that they are "everyday" dynamics. In Knap et al. (2023) and Megahed (2024), a summary and comparison of the commonly targeted destinations is presented. Probably the only actual intersection among these are those subsistence trips concerning shopping of basic goods, followed by notions of care (accompanying to school or other medical affairs), and other amenities. Work trips can also be seen in some works which target proximity commuting, though this idea is elusive and most probably quite place-based, or even person-based if movements have been made towards the workplace. In Table 12, a summary of the categories used to conceptualize the purpose of accessible or proximity trips, in the same language used by each of the author(s), is presented.

Table 12
Destination - Purpose Approach in the Reviewed Literature

Reference	Destination / Purpose Approach
Haugen, 2011	Work; Children; Services; Leisure; Social
Haugen et al., 2012	Work; Service; Leisure; Social; Education
Searcy et al., 2018	Higher Education
Kasraian et al., 2019	Transport Nodes; Transport Network; Existing Urban Areas
Graells - Garrido et al., 2021	➔ Barcelona Residents; Regional Commuters; Regional Tourists; National Tourists; Foreign Tourists ➔ Education; Entertainment; Finance, Food; Government; Health; Professional Services; Recreational Areas; Religion Venues; Retail; Public Transport
Bartzokas-Tsiompras & Bakogiannis, 2022	Schools, Food markets; Other People (proxy for opportunities), Recreation Facilities; Restaurants/Bars; Health Care; Green Areas
Li, 2022	Grocery Stores
Gil-Solá & Vilhelmson, 2022	Leisure; Grocery Store
Abbiasov et al., 2022	Restaurant; School; Park; Health Care; Drugstores; Arts and Cultural Institutions, Grocery Stores, Services, Religious Organizations
Calafiore et al., 2022	Public and privately owned businesses, Education, Leisure, Green Space
Knap et al., 2023	Jobs, Commerce; Bars & Restaurants; Education; Food; Recreation; Parks; Entertainment; Healthcare; Sports
Birkenfeld et al., 2023	Jobs; Amenities
Poorthuis & Zook, 2023	Supermarkets; Grocery Stores; Cafes
Aristizábal et al., 2023	Commerce; Jobs; Public Space; Public Transport
Yu & Higgins, 2024	Food; Commercial; Health; Recreation; Education
Elldér, 2024	Care; Education; Provision; Entertainment

Mean Age

Mean Age of the population at reachable distances is calculated in order to capture a sense of the population one can encounter in different regions of the case study area. This feature might not be related to proximity behavior, but it can capture a certain (yet limited) "generational" difference in the areas to study.

Household Structure

Household structures are represented in the environmental features as a metric of mean household size (the number of members in the household). Again, this feature might apply more to the individual trip than as a collective effect, but it is included in order to understand if these population structural metrics show relevance at all.

Net Income

In a sense, as with the two previous features, net income applies in a household scale, rather than in a collective area way. However, and leaving aside the fact that the information is not available for the EDM2018 respondents, this metric is calculated to capture a characteristic of zonal income, assuming that some collective effect can be detected in the study.

Figure 22 (Following pages): Demographic Features.

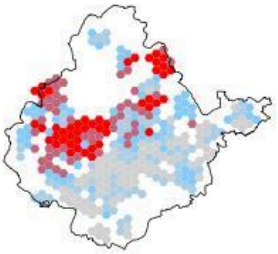
Maps are colored in three categories using Natural Breaks in the corresponding series, red being the highest value and grey being the lowest value. Only values built with the 900, 1200 and 1500 meters are shown.

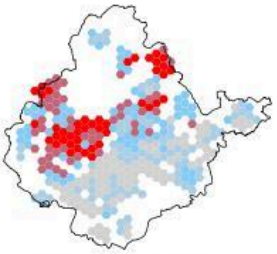
Demographic Features

900 m. Threshold

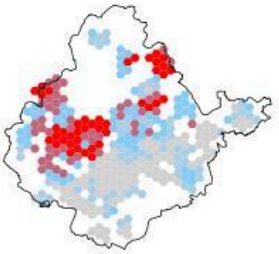
1200 m. Threshold

Net Household Income

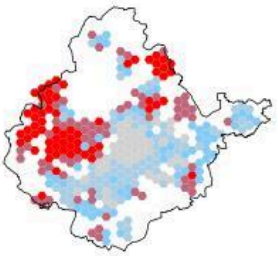


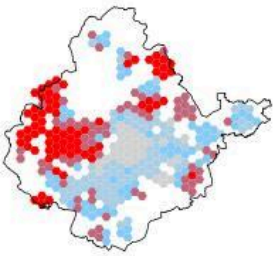


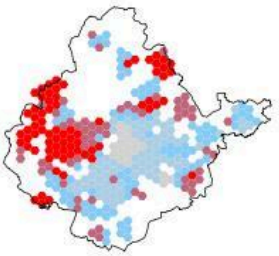
1500 m. Threshold



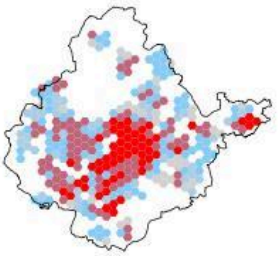
Mean Household Size

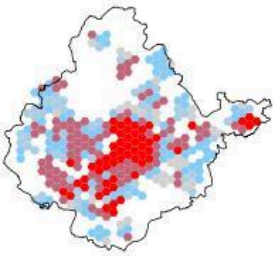


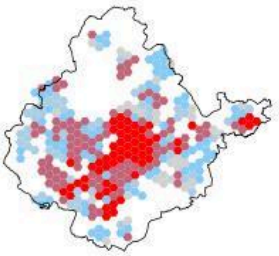




Mean Age







3.6 Data

What kind of observations are more suitable for an empirical approach to travel and Urban Proximity? As Handy (1996), Crane (2000), Stead & Marshall (2001), or Boarnet & Crane (2001) noticed, the form, quality, and reliability of the data used determine most decisions addressed in the previous chapters. Even when study designs are well grounded, it remains unclear how sensitive individual results are to specific modeling approaches or the nature of the data. This lack of transparency can be attributed to the absence of systematic analytical frameworks. Alternative behavioral and statistical assumptions, and the type and geographical aggregation of the data, greatly impact reported results. (Boarnet & Crane, 2001).

Availability is discussed in almost all the queried reviews in this study, and "proxies" are pervasively invoked in the literature when defining research. In this section, issues concerning sources and aggregation are reviewed. The aggregation issue is of great importance, because it impacts the metrics used in a critical manner, even though it is commonly an external condition of data availability.

Certain reviewed works (e.g., Crane, 2000) argue that, when attempting meta-analysis in this line of research, methodological concerns are too important to be performed with incomparable data. Brownstone (2008) suggested that only works that use disaggregate travel data, correct for residential self-selection, are based on areas larger than a metro area; and have a rich set of individual (or household) sociodemographic control variables, are worthy of meta-comparison.

Despite this theoretical "best practices", data is not that easily found in reality. Yabe et al. (2024) have published a rather extensive reflection on the need for open and detailed datasets on mobility, which could be AI-generated from other sources apart from expensive surveys (commonly referred to as synthetic populations), yet still have biases at the many decisions to be taken for generation, thus raising the need for consensus on definition and processing.

3.6.1 Data Sources

For outcome variables reviewed, data is commonly collected from surveys and mobile data (often aggregated for privacy reasons, in grids or polygons). For built environment and sociodemographic features, area data (spatial data of polygon type, with associated values), land use data (building, parcel, or place of interest with use class and square meterage), and network data, (commonly road or street centerline), are the most common data sources.

Concerning proximity, Krizek (2003) suggested that the reliability of the models, for the concept of local accessibility, is extremely affected by the precision of specific methods for measuring features. The author suggests that bottom-up, micro scale approaches are the only theoretically consistent way to go, yet this, of course, implies that fine-grain data is available, reliable, and spatially consistent. For general active modes research, both data on travel behavior (with sufficient detail) and associated features data is important. A variety of sources such as property tax records, building permit records, aerial photos, and street and sidewalk inventories, have also been tested to research active modes, with gaps identified in aesthetics and design (Handy 2002).

Availability of data conditions the approach taken. In the review, a representation of different approaches according to data sources has been found. The most common is the travel survey, as seen in Haugen et al. (2012), Marquet & Miralles-Guasch (2015), Searcy et al. (2018), Poorthuis & Zook (2023), Aristizábal et al. (2023), Yu & Higgins (2024) and Elldér (2024), and the ad-hoc travel survey, as seen in Haugen (2011), and Birkenfeld et al. (2023). Travel surveys are the most detailed data source, having categorical labels describing modes, trip length, or purpose, as well as origin and destination (as boundaries or grid-cells). Qualitative information, such as attitudes or satisfaction is usually missing, so ad-hoc surveys complete this information.

The second most frequently used data source is mobile data. This source offers real records of devices which, upon connecting to antennas, can be triangulated, geolocated, and timestamped at origin and destination. This source is represented in Knap et al. (2023), Li (2022), Graells - Garrido et al. (2021), Gil-Solá & Vilhelmson (2022), and Abbiasov et al. (2022). The advantage

of this data lies in its indirect nature (no respondent bias is expected), and the large sample size (falling into a fair consideration of a *big data* source). The downside is the lack of detailed information on the user and trip. While trip mode can be inferred through metrics such as speed and trajectory of the data (Jiang et al, 2016), user profile is commonly not informed due to privacy terms. To overcome this barrier, mobile data is aggregated into boundaries or cells, with size dependent on the privacy limits imposed by the providers or regulations.

The third relevant data source in the reviewed works is the information used to build objective accessibility metrics. These metrics need -at least- data on Places Of Interest which can be interchangeably used as Origins or Destinations, like residences, places of work, and other services, amenities and facilities. If metrics consider interaction separation as euclidean distance, POIS will suffice to perform the calculation, but the preferred contemporary approach does consider that interaction takes place through the network of paths that can be traversed. Reviewed works show a vast range of approaches which also connect to data availability.

Other relevant data sources in the review are area data, or information aggregated to statistical boundaries, such as population counts or variables like income, tenure, and so on. These datasets are increasingly available, and their usage throughout the sampled works is consistent, yet again reveals some limitations of micro-scale and time-series availability. A particular kind of POIs data, the General Transit Feed Specification or GTSF, are the standard for the modeling of all the components of Transportation systems, yet commonly focus on rail and road levels.

Finally, data reliability is a must in robust studies. A reflection should be made on how different data sources impact the reliability of metrics and their representativeness of the targeted phenomena. Open Crowd-Sourced data like OpenStreetMap, for instance, are increasingly being used to model situations involving POIs or movement networks, yet their completeness and reliability simply can not be traced. Other proprietary data, even claiming quality and completeness, can show the same issue. Official data, on the other hand, usually has better reliability, but data operations can be inconsistent (and even biased, in the worst case scenario). Some tradeoff exists between the availability, the price, and the reliability. If limitations can not be easily overcome, at least caveats and disclaimers should be made on the quality of the data used, especially when -concerning urban proximity-, micro-scale data is likely to be used.

Table 13 shows a summary of the data sources used in the reviewed works.

Table 13:
Types of Data Sources used in the reviewed literature

Reference	Data
Haugen, 2011	Ad-Hoc Travel Survey
Haugen et al., 2012	Travel Survey
Marquet & Miralles-Guasch, 2015	Travel Survey, Area Statistics
Searcy et al., 2018	Travel Survey
Kasraian et al., 2019	Land Use Data
Graells - Garrido et al., 2021	Mobile phone data
Bartzokas-Tsiompras & Bakogiannis, 2022	Area Statistics
Li, 2022	Mobile phone data
Gil-Solá & Vilhelmson, 2022	Mobile phone data
Abbiasov et al., 2022	Mobile phone data
Calafiore et al., 2022	POIS, Population
Knap et al., 2023	Mobile phone data
Birkenfeld et al., 2023	Travel Survey
Poorthuis & Zook, 2023	Travel Survey
Aristizábal et al., 2023	Travel Survey
Yu & Higgins, 2024	Travel Survey
Elldér, 2024	Travel Survey

3.6.2 Data Aggregation

Data aggregation (and disaggregation) is the process of re-scaling data to fit different geographic entities. Also, it deals with the fact that travel behavior, having an origin and a destination, implies that boundaries of aggregation will be easily overflowed, and decisions are needed on the way that data is spatially matched to trip data. If the research strategy focuses purely on individual, household, or single trip characteristics, then no aggregation should be needed but, as seen in previous chapters, measuring their relationship with the built environment needs a firm decision on the scale and -implicitly- the mechanisms of influence.

Dealing with individual trips, the most common method of aggregation is to measure land use around respondents. The scale for measuring and aggregating built environment (or other) features often approximates a walkable neighborhood, an approximately quarter-mile area or a census block group or TAZ. Some reviews reflect how few studies have experimented with varying the scale of geography, thus explicitly (and transparently) inspecting effects on models (e.g., Boarnet & Sarmiento, 1998; Handy, 1993; Handy, 2002; Boarnet, 2011). As mentioned for Simulation designs, disaggregation can also be performed when data sources do not share the same aggregation scale, yet the uncertainty implications should be noted.

Since early works on active modes and local accessibility research, the literature yields no consensus on the most adequate way of measuring (and thus, associating) different features related to behavior. For instance, Frank (1994) found that measuring urban form at both trip ends provides greater ability to predict travel choices than looking at trip ends separately, while Lee and Moudon (2006) proposed that the most relevant features to take into account are the nature of origin and destination of trips (as a proxy for purpose); the area characteristics around the origin and destination and; the characteristics of the route connecting the origin and destination. Apparicio, et al (2008) revealed the critical relevance of attempting to use the smallest grain possible when designing accessibility metrics, even more important than the metrics selected. In Lee & Moudon (2006), two aggregations were used for accessibility metrics (both euclidean and network buffering), yielding significantly different results.

Little consensus is present in this issue, and this poses quite a dilemma to the field of study, as the different aggregations will impact metrics significantly, falling into the Modifiable Area Unit Problem. In a recent study by Gehrke and Wang (2020), an experiment is performed over Portland's travel survey data across multiple scales and spatial extents, identifying scale-related issues which can alter interpretations of neighborhood effects on walking and biking. The authors conclude that scale choice significantly impacts study findings, recommending sliding scales, origin-focused measures, and smaller extents for land use metrics.

In another work by Duan et al. (2023), the D's framework is tested for MAUP and using Optimal Parameter-based Geographical Detector (OPGD) model, which identifies a 900m-sided hexagonal grid as the optimal spatial unit, which more effectively captures spatial relationships with travel behavior. The study finds that features like distance to the city center and commercial density are globally significant, while local features such as road network density and proximity to medical facilities vary spatially in their impact on demand.

In this work, the combination of the selected datasets poses a well known problem of differential aggregation levels. If, on one hand, disaggregated trip data is available, with many linked individual characteristics, the environmental features which can be associated to them can only be measured at the TAZ. This aggregation will be performed starting from the individual dwelling units in the study area. By calculating the reachable subgraphs in the RCL network, for each node, the cadastral POIs are associated to their reachable area (in varying thresholds). Later on, data is finally aggregated to the TAZ using local population as a weight.

Limitations of this approach are evident. One, the actual reachable built environment of each respondent is masked, as its precise location is unknown. This will also result in a lesser variation of environmental features with respect to individual ones. Also, the quality of the RCL dataset to capture the actual reachable area at varying thresholds needs to be assumed sufficient. On the other hand, the advantages are also clear. Thresholds of proximity can be controlled by using this reachable graph approach, and aggregate in a sound manner to the TAZs. Also, this approach smooths the TAZ boundaries effect, which is useful for a local residential accessibility-based approach, having only to account for the origin zones.

3.7 Empirical Analysis of Proximity

Before arriving at the Methodology chapter and the experiment Results, it is convenient to discuss the general findings of the review of travel and the built environment, when read through the lens of urban proximity. What is already known? What should we explore further?

Most works reviewed explicitly point at geographic accessibility as the most suitable approach to decision support of urban proximity policy. Probably, this is due to the fact that accessibility metrics allow to aim at the many components of the problem, that could be reached from policy: supply (for instance, facilities or services) and demand (for instance, households) sides of the land use component, the means of interaction (streets, transportation systems, etc), and the rules of movement (for instance, for different user profiles with different needs or abilities).

The flexibility of accessibility metrics allow, as seen through the work, to consider other characteristics of the built environment such as land use-mix or density, as well as design constraints to the means and thresholds of interaction. All works acknowledge that approaches to urban proximity through accessibility need to meet different nuances of individuals, trip motivation, and transportation mode, which in turn imply different ranges of action considered "local" enough. The flower of proximity as an array of thresholds, movement rules, different users and trip motivations quite well expresses that it is needed to prepare empirical approaches to control for a whole array of possibilities.

Even though it seems the proximity approach is not exclusive to active modes, the majority of works point at them as the principal target, which leads to a particular case of transportation approach, in the intersection of the materiality of places, the social rules of interaction, and the perception and capacity of individuals. As seen in the review, active modes have been studied from many points of view which have yielded insights on rules, limitations, and conditions of movement, also specifically conceptualized from the accessibility point of view, along with many other features.

Walking and biking are the most targeted modes, but also public transportation, from the point of view of the beginning of trip chains, needs to be addressed. Additionally, automobiles can be treated as a mode to be tested for reduction and modal balance, or considered in rural scenarios. In summary, the reviewed empirical studies should point at the methods and findings on the local active side of mobility, and -at least- account for population segments and purposes.

The kind of trips which are being targeted is also of great importance when considering urban proximity empirically. The epistemological review is also not exclusive to, but commonly points at the kind of everyday trips that originate from residences in order to meet basic needs. This point will lead to focus primarily on non-work travel, either for consumption, leisure, learning, care or transportation (to other modes), as the most common necessities which the literature deals with in most planning models reviewed. In this sense, urban proximity deals with highly frequent trips which originate from residences, and do not represent special or punctual situations, but represent the daily "rhythm" of cities. However, many of the reviewed works do point at other "outlier" trips (from an urban proximity point of view), as gaps in the field: trips from work environments, rural or suburban areas, or unique destinations not falling into common categories of "everyday behavior", remain challenging to this approach.

Compulsory trips or origins such as work-related trips should not be simply excluded, but they introduce a logic which seems to fall outside the scope of most realistic policies and research. Work trips, and also many kinds of educational or care trips, are commonly treated differently in the literature for being an unavoidable need for traveling outside ranges of proximity.

The question on centering on residential environments is not a trivial one, as if some unavoidable travel destinations are not under the user's control, the possibility of selecting a residential area under certain preferences (and possibilities) can imply that proximity behavior is more a matter of attitude than it is conditioned by the built environment. In this particular research vector, the question leads to thinking that some segments of the population will actually seek these proximity characteristics. In this sense, attitudinal or behavioral features available will also be core for an appropriate approach, as this "residential self-selection" poses a dilemma of endogeneity of travel behavior and built environment (or in other words, the fact that humans choose their residence based on their travel behavior, and not the other way around).

Most of the planning context and scientific research reviewed implicitly assumes that a prescribed urban model and a measured state of proximity, respectively, triggers desired effects on individuals and, within the scope of this work, in their mobility behavior. In the case of planning context, proximity is both a certain arrangement of quantities of urban functions, and a threshold-like logic by which they interact. Empirically exploring these configuration proposals implies that the notion of interaction and threshold should be present both in the mechanisms theorized, the observed data, and the methodologies for quantifying features and relationships.

As a boolean state, proximity should be a state which can be measured and labeled in urban areas, to then test hypotheses of travel reduction and modal shift within (and outside) these areas. Planning has historically treated these concepts with a loose idea of neighborhood as a cut-out shape in the urban fabric, but the recent exploration of the concept also points at a bottom-up social notion, which should also center empirical approaches. This particular idea of research strategy was also reviewed in the previous sections, as it does show many relevant precedents.

3.8 Summary of the Case Study exploration

Throughout the text, the different sections have been used to explore some of the assertions and methods found in the review, focusing on highlighting local travel behavior through simple thresholds, and finding some relevant characteristics for the purpose of this work. This section summarizes relevant characteristics of the MRM in terms of local travel, so as to account for them in the proposed methodology.

The data exploration showed “proximity evenness” in many characteristics, yet some imbalance was found in others. Also, the small incidence or the nature of some categorical classes is worth mentioning so as to avoid certain predictive approaches which could lead to strong bias. General travel patterns in the MRM have received attention from academics using the different editions of the travel survey (EDM1996 -EDM2018). A general overview points at patterns comparable

to other large European urban areas, in which improved infrastructure, shifting demographics, and income increase has resulted in increased mobility patterns in the last thirty years.

These patterns can be noted in a higher rate of daily trips per person (2,09 to 2,44), which also tend to take longer (27 to 29 minutes), an increased share of driving trips (from 28 to 39%, mostly at the expense of public transportation, going from 32 to 24%), and a slight decrease in walking trips (from a 37 to a 34 figure). A decrease in percentage of occupational and non-occupational trips between both surveys (65/35 in the EDM1996 and 43/57 in the EDM2018) can also be noted, as well as a rise in the number of motor vehicles per 1000 inhabitants rising from 300 to 439 in the EDM2018 dataset.

Although general travel shows increased distant mobility, the present exploration shows uneven distributions looking into 15-Minute trips within a number of variables. In the sociodemographic aspect, educational level shows high proximity behavior in levels associated with children and youngsters. Concerning activity, caretakers and students show high prevalence of proximity trips, while unemployed and retired people show a slightly less prevalence. In the other extreme, workers show a significant lean towards trips way above 15 minute trips.

Closely related to educational level is age, which shows a distribution where children between 0 and 10 years perform 76% of trips within 15-minute ranges, moderating to 61 between 10 and 20 years of age. Younger adults (20-30 years old) proximity trips drop to a share of 39%, which stabilizes in the following bins and goes back to higher proportions in later stages of life (53% and 67% for 70-80 and 80-90 bins, respectively). Both variables point at age thresholds and lifecycle events as very relevant for an urban proximity approach in the data.

In this regard, the lifecycle is closely associated with household structures, which has been inspected for a full prevalence of 15 or 30 minute trips. Unsurprisingly, most categories have a greater incidence of non-local lifestyle individuals for 15 minute trips, yet households labeled as retirees (28%) and students over 19 years old (23%) hold the highest share of mostly performing 15-minute trips. When the threshold is set at 30 minutes, proportions change greatly and are rather even across groups, suggesting a sort of upper limit for local trips. Retirees perform only under-30 minute trips in 53% of cases, and Children under 6 go up to 48%. The rest of classes show a rather high proportion of this kind of trips, being the less “local” the students 13-18, hitting a 35% percent of only 30 minute local trip behavior.

Regarding the trip characteristics, trip purposes yield interesting behaviors. The "Sport/Stroll" category shows a surprisingly higher proportion of above 15-minute trips (39/61), which could be associated. In this sense, it could both be thought that certain kinds of leisure are of a more metropolitan than local nature, or that strolling is an activity which will commonly take longer, or in which time is not a relevant parameter at all. On the other hand, Care and Leisure trips exhibit a higher proportion of 15 minute trips (61/39 in both cases), which is even higher in Shopping trips (70/30). This way, Care, Leisure and Shopping trips are expected to have a more local behavior according to the EDM2018.

Transportation mode also shows an interesting pattern. Bus and Train modes show great imbalance towards non-proximity trips (32/68 and 10/90 respectively), while Walking shows an expected higher proximity prevalence (65/35). This suggestion of a lesser use of public transportation for proximity should be accounted for in an empirical study, as these trips will be less represented in local thresholds, leaving more "room" for walking and driving trips. The number of declared trips per household also shows that more "mobile" households (up to 10-15 weekly trips), does show a 61% proportion of proximity trips, which might indicate that the surplus of trips is actually achieved in proximity ranges.

Transportation mode prevalence by region shows an expected behavior in the city of Madrid, as the least prone to use cars and the most prevalent in public transportation (it is the central business region, has denser tissues, and the highest provision of alternatives). Interestingly, walking for transportation does not seem to peak in Madrid, but rather in the cluster of municipalities to the south. The exploration of mode distribution by distance confirmed the idea that, when it comes to local behavior walking or driving are the most prevalent choices.

Concerning trip distance, the flower of proximity was used to inspect walking trips against other modes, in terms of mean and quartile distribution by individual activity and age. A general comment is that modes other than walking exhibit quite comparable and distant behavior, with an upper limit of around 1500 meters (with some exceptions in working, leisure, and Sport / Stroll trips). The most mobile age and activity cohorts are workers of any age, and students above 19 years of age and, in other modes than walking, caretakers, followed by retirees, exhibit the least mobile behavior.

Concerning walking trips, students below 18 years of age exhibit a decreasing mean trip distance for most trips, falling below 500 meters for the cohort of 6-13. Also, caretakers, when taking

most walking trips, exhibit distances around 700 m. In general, it could be said that walking trips for all cohorts are around 500 to 700 m shorter than other modes, for all purposes and adult social profiles.

Another exploration of these trip characteristics involved an exploratory predictive Logit model, which yielded an expected insight on the high relevance of trip distance in mode choice, which obliterates most demographic variables, and is only followed by accessibility characteristics. When filtering trips distances in the model to not exceed an exploratory threshold of 1500 meters as indicated by the exploration of flowers of proximity, the effect of distance is moderated in comparison to accessibility, but also leads demographic features to non-relevance.

Some variables inspected in the EDM2018 have been found to be less informative or reliable in this proximity exploration. For instance, extremely even categoric variables found in the EDM2018 include Gender, Vehicle Ownership or HouseholdSize. In these variables, a significant lean towards local trips has not been found, and their relationship with urban proximity shall need a closer look. Small incidence was found in labels such as Foreign, Reduced Mobility Person (RMP), and Leisure trips in the EDM2018 sample. The first could be a bias in the survey response, while the two latter exhibit a reasonable minority behavior. RMPs perform a great share of local trips, however, their particular conditions makes it less useful in a regional study. Leisure trips could be less informed due to its Monday-to-Thursday nature. This way, this particular trip purpose might need a closer look or survey to be correctly inspected.

Ambiguous or potentially biased variables include categorical frequency and most attitudinal variables. Concerning the categorical description of Frequency, the “Sometimes” label is the most prevalent, and the different responses do not show great imbalance towards the proximity filter. Attitudinal variables have a number of bias implications. For example, holding a travel card or a driving license seems to be related with a lesser prevalence of proximity trips. However, this has age implications and could be related to the fact that way less proximity trips are performed by public transportation.

NoPrivate and NoPublic variables are categories which hold quite interesting information, as they are an explicit response on the reason not to ride or drive. The particular response “Is very Close” exhibits an expected outperformance of 15-minute trips (84/16). However, the “Prefer Active Modes” result is counterintuitive, showing a 37/63 proportion leaning towards above 15 minute trips. In any case, this variable will surely lead to great bias for approaches such as mode

choice or travel distance prediction, as simply being informed indicates the mode that was not chosen and, in some values (some responses to the survey such as “Prefer Active Modes”), directly indicate which mode is preferred. These variables should be treated as a different (and probably more descriptive) kind of data.

Finally, some information has been considered as rather trivial for the study purpose. DayOfWeek and StartHour/EndHour do not show significant imbalance proximity-wise (except for the night period in which the majority of trips are work trips)

4.Methodology: Feature Selection Approach

In the previous sections, it has been reviewed how recent policies fostering sustainable mobility target urban proximity as one of the strategies for a modal shift towards low carbon modes. Urban proximity, as a characteristic of the built environment, can be studied from the lens of a sub-thread of research on travel behavior and the built environment. This line of literature is a broad and very complex body of research which uses different methods to associate urban features such as density or land use mix with observed travel behavior, so as to address their relative influence on the latter. Building on previous knowledge, this work addresses the importance of a diverse set of features on local travel modal choice between walking and driving, according to the EDM2018 of the MRM, and a large portfolio of built environment characteristics.

The work proposes a set of ML models controlling for relevant thresholds in both socioeconomic and built environment characteristics of the trips, which are inspected for accuracy, feature importance, and model complexity. This chapter presents a brief review of machine learning methods in context, summarizes the data exploration and transformation, and adds the complete specification of the proposed research strategy.

> *All models are wrong, but some of them are useful.*
> Box (1976)
>
> *When a statistical model is fit to data to draw quantitative conclusions:*
> *The conclusions are about the model's mechanism, and not about nature's mechanism; It follows that, if the model is a poor emulation of nature, the conclusions may be wrong.*
>
> Breiner (2001)

4.2 The Machine Learning Approach

A closer look at the alternative approach that has steadily gained attention in the past decades is given. Artificial Intelligence (AI) is a sub-field of computer science which attempts to solve tasks which are rather easy for humans to achieve, but complicated for computers. It is a generic concept which comprises multiple tasks such as planning, object recognition, language functions (understanding, speaking, translating) or performing creative tasks. ML is a discipline within the field of AI which, through algorithms, attempts to equate fuzzy logic, adapt and evolve through experiments, giving computers the ability to identify patterns in datasets, and elaborate descriptions, diagnoses, prescriptions, or predictions (Alpaydin, 2010).

This section focuses on the use of ML for predictive purposes. ML techniques are capable of building a probability for an event to happen, using tendencies, groups and exceptions to predict future trends. The prediction is only an estimation, whose precision greatly depends on the quality and stability of the input data and the targeted phenomena, needing continuous management and optimization.

In this predictive context, the idea of a machine "learning" is based on a loss function, which is a method to evaluate how well a particular algorithm performs in modeling the input data. If predictions deviate a lot from the expected result, this loss function will result in a higher value. Iteratively, and by using some optimization process, the loss function "learns" to reduce the error. Commonly, a controlled sample of the original data (the test data) is kept out of the learning process, so that the final shape of the prediction function can be applied to it, in order to check whether predictions are accurate or not (called the train-test technique).

In the following subsections, a justification of the use of ML to model the relationship between travel and the built environment is given, being such a complex problem in which causal directions are not clearly defined, causal mechanisms are not clear, and feature importance seems to be elusive in measuring, very diverse in reported associations in the literature, and strongly endogenous.

4.2.3 ML in Travel and the Built Environment

The recent rise of ML approaches to the study of travel and the built environment was noted in the bibliometric study by Gao et al., (2023). In different problems such as trip generation, route selection, activity-based research, or choice modeling, the algorithmic approach has proven suggestive and suitable. Moreover, in local and active travel, some interesting examples are already being published, even though none exactly matched the previous chapter literature selection criteria (the empirical approach to urban proximity). The bibliometric analysis by Maisonobe et al. (2022) unveiled the rise of research in transportation using machine learning and its use in all four steps of predictive processes, triggered by the large amounts of data being collected on the matter. In most applications, social and built environment features are used as predictors of the different outcomes of travel.

For instance, in trip generation, Mukherjee & Kadali (2022) review how ML approaches can be useful in the absence of reference data and emergent data collection from non-traditional sources such as GPS, street imagery, social media, or atmospheric composition. Regarding route selection, Mammeri et al (2019) focuses on ABM approaches and, particularly in reinforcement learning, noting that, in this step, lack of benchmarking data and the computational limitations of working with networks remain largely unsolved.

Another trend in which machine learning has been perceived as a relevant improvement is activity-travel research. In the review by Koushik & Nezamuddin (2020), all four steps of traditional models are reviewed from the activity-travel point of view, and point at models such as random forest as a pervasive trend (yet a certain lack of comparison with other classifiers), a worrying focus on accuracy, obscuring other characteristics of the models, a frequent bias of unbalanced datasets, and better accuracy reported by studies using GPS trajectories over surveys.

Concerning mode choice, reviews and discussion papers such as Hagenauer & Helbich (2017), Zhao et al. (2020) or García-García (2022) have been found, who agree on the search for explicable yet accurate models such as random forest (RF), which seems to be the preferred model, as variable importance is still quite an unnegotiable aspect of the decision-making process targeted by this line of research, and RF are models that balance explicability and accuracy well. van Cranenburgh, et al. (2022), published an extensive discussion on the

differences and similarities of traditional and machine learning approaches to travel behavior in the specific context of choice modeling. In this work, it is shown how researchers justify the use of machine learning in this domain mainly for four reasons: The loose data structure assumption,the improved accuracy, large data handling, and alternative data handling.

Concerning loose data shape assumptions, ML models can help with problems of theory-driven choice models to specify optimal models, and the adverse effects caused by model misspecification. In traditional choice models, researchers assume a structure to the problem through functional forms and feature selections, based on hypotheses on their influence. Then, in an often subjective process, decisions are made for a final model which, in case of actually being a poor description of the modeled phenomena, might lead to incorrect conclusions.

ML models are often more accurate than traditional models in this domain (Lee et al., 2018). While accuracy is not usually the main target of this domain (feature relationships are), better model fits are desirable if a particular underlying process is assumed. Also, for simulation exercises (see a detailed overview of these approaches in the previous chapter), accuracy is a very valuable characteristic because it means that the actual phenomena are being well captured by models, being reliable for scenario building and information.

ML approaches perform comparatively well in large data scenarios, and can work with alternative types of data such as text and image data. In the present scope, this last consideration is rather trivial, as data beyond labels or quantities -which do not differ greatly from more traditional approaches- were not used. However, as data on travel behavior and other associated characteristics increases, the ability of maintaining consistency and efficiency when available data increases is interesting.

Some drawbacks of this approach have also been pointed out. In general, the still shy adoption of ML in transportation modeling has been attributed to the idea that ML models are overfitting often, thus reporting more accuracy but not adding knowledge to the field. Also, the tradeoff between accuracy and explainability affects the adoption of these techniques in an analytical-empirical context such as the study of travel behavior (van Cranenburgh, et al., 2022).

4.2.4 Random Forests in Mode Choice

RF has gained traction in transportation research, and particularly in mode choice modeling. Its ability to handle high-dimensional datasets, account for complex interactions, and produce interpretable feature importance metrics makes it a powerful tool for analyzing travel behavior. Researchers have demonstrated the efficacy of RF in capturing nonlinear relationships between mode choice determinants and improving predictive accuracy compared to traditional discrete choice models (Cheng et al., 2019, Zhao et al., 2020). Unlike parametric models such as Linear, Logit or Probit models, that require explicit assumptions about variable distributions and interactions, RF automatically detects patterns from data, making it suitable for heterogeneous urban mobility contexts.

RF has been applied to assess individual and household travel behavior, integrating socio-demographic attributes, built environment characteristics, and trip-related features. Zhao et al. (2020) highlighted that while ML models can function without incorporating the attributes of non-chosen alternatives, omitting this information may introduce bias in mode choice analysis. Their findings reinforce the importance of including modal competition when training machine learning models for travel behavior prediction. In this sense, the methodology proposed here must face a certain bias in not having included features which might be more directly related to other modes than walking.

RF is well suited for identifying and analyzing complex nonlinear relationships in travel behavior. Partial dependence plots, as suggested by Zhao et al. (2020), can reveal causal relationships if the machine-learning model is accurate and domain knowledge supports the causal structure. This feature makes RF particularly valuable in exploring the impact of travel cost, accessibility, and built environment features on mode choice.

As noted before, mode choice analysis traditionally relies on multinomial logit or nested logit models. However, these approaches often struggle with complex interdependencies among explanatory variables and require strong theoretical assumptions. RF addresses these limitations by employing an ensemble of decision trees that iteratively split data based on optimal thresholds of predictor variables, thereby accommodating nonlinear relationships and feature interactions. Studies have shown that RF achieves superior accuracy compared to traditional

models, particularly in datasets with high heterogeneity. Cheng et al. (2019) and Zhao et al. (2020) reported that RF models performed better in predicting walking and biking trips, whereas car mode prediction suffered due to class imbalance.

Key specifications of RF in mode choice studies include data treatment, hyperparameter tuning, and feature selection and importance ranking. Regarding data treatment, RF imputation capabilities ensure robustness against incomplete or imperfect datasets, which are common in transportation surveys, and it also accommodates categorical and continuous variables without requiring transformation, making it suitable for mode choice datasets with diverse feature types.

Hyperparameter tuning in RF involves optimizing parameters such as the number of trees (n_estimators), maximum tree depth (max_depth), and the number of features considered at each split (max_features) to improve predictive performance. Techniques like grid search and random search are commonly used to identify the best parameter combination. Proper tuning helps balance bias and variance, enhancing model accuracy and generalizability

RF provides ranked importance scores for variables, revealing the most influential determinants of mode selection (e.g., travel cost, trip duration, income, vehicle ownership). Regarding specific results of previous works on feature importance, some of the relevant findings that are related to the present work are summarized. Zhao et al. (2020) use Gini Impurity Feature Importance over a set of predictors, and found an expected greater importance of cost features such as Distance and Travel Time, attitudinal features such as the preferred mode, transit accessibility, income, or vehicle ownership. Through the same methods, Cheng et al. (2019) found a greater importance of Travel Time, but this time followed by Land Entropy, Road Density, Distance to Transit, and three specific Trip Purposes (School, Shopping, and Recreation)

4.3 Experiment Design

To situate the selected approach in the wider legacy of the study of travel and the built environment reviewed, it can be classified as a choice model of disaggregate travel behavior, combined with aggregate built environment data and a wide portfolio of demographic variables, including some attitudinal information (highly valued in the literature) (Handy, 1996; Crane, 2000; Stead & Marshall, 2001; Boarnet & Crane, 2001; Cao, 2009; Boarnet, 2011). Operationally, it will deal with many combinations of arrays of data controls (in this work, distance and purpose), which yield diverse data subsets with potential heterogeneity in causal mechanisms, complexity in feature relationships and, in general, high sensitivity to the controls used. Heuristically, it will leverage RF capacity to manage non-linearities and still yield readable and accurate results in many data scenarios. This section describes and justifies each component of the proposed research strategy.

4.3.1 Data Sources

In this section, the characteristics, caveats and limitations, as well as the initial transformation process followed for each of the data sources used is presented. It is relevant to the document to present the sources beforehand, as data constraints will be critical for the following design. After the descriptions, the general data storage and relational schema is shown and detailed. The complete code can be found in the online repository:

https://github.com/manubenitomoreno/pw_sources

In which the folders /data and /notebooks contain the complete dataset creation, modeling, and all figures and maps generated for this thesis.

The data sources are gathered and processed to a database which is divided into a “sources” and a “network” schema. The first schema, “sources”, is fed by the different sources data pipelines, depending on the nature of their spatial component: pois or Points of Interest; aois or Areas of

Interest; road_segments for the original network edges; boundaries_geo for the boundaries; boundaries_data for statistical data associated to boundaries such as municipalities or census tracts and; other_data for the trip data from travel survey, and other useful tables such as derived trips rates or other indices calculated outside the main environment.

The network schema is created through combinations of the sources data (the pois, aois, and road_segments tables), so that the network is already created taking into account the position of relevant Points and Areas of Interest (both nodes and edges tables as the fundamental elements of the network), along with a relations table which stores the one-to-one relationship between aois, pois, and nodes in the network.

Another two tables are created a-posteriori to complete the network schema, one containing the ego-graphs (the isochrones) for each node in the network or, in other words, a vector of all reachable nodes within a defined distance through the edges, and a table which contains all those reachable nodes with a value of the precise distance from the origin node, using the shortest path. As the present work unfolds, it will be clarified how these elements suffice for all the calculations and aggregations performed which will feed the targeted travel dataset.

The complete data sources treatment is performed using Python and PostgreSQL, two general-purpose open source technologies. Each source's treatment is written in a separate module, which is then run by some orchestrator modules, which eventually upload the information into the databases, which are the best solution for faster and more transparent debugging and iteration on the values of features calculated. Also, the elements of the network are pre calculated using Python: the nearest pois and aois to the nodes (the relations table); the ego graphs (the set of nodes reachable from one particular node, at different distances), and the length table, which contains the one-to-one distance value of all shortest paths in the network.

In the next subsections, the data sources used throughout the work are presented, detailing their nature and the opportunities and limitations they pose to a study of travel in relation to the social and built environment. Also, Figure 4 shows a general schema of the data treatment.

Cadastral Data

For land use data exploration, Cadastral data is mainly (though not exclusively) used. Cadastral data is available online from the Spanish Cadastral Direction (Dirección General de Catastro, 2017; henceforth DGC). Its

datasets include a full description of built surfaces and land uses registered at the parcel-level, and the official address assigned to each item. This dataset contains many different variables to capture the physical reality (floor area, construction date, maintenance, etc.) and land use (for detailed descriptions, see official documentation).

This source depicts properties in different aggregate manners, namely parcel, property, building, and part (of different uses within a property). The latter was used to derive particular land uses from a combination of the different labels which reference land use and architectural typologies, as it is the most suitable way of separating very specific uses which might co-exist in the same buildings and properties. For instance, a large educational institution can have primary and secondary education buildings, maintenance, sports areas, or even residential use. A large sample of the targeted proximity activities has been carefully inspected, and come to conclusions on the activities which can be fairly inferred, and those which can't.

As a general comment, DGC data is commonly more detailed whenever a particular tax condition applies to properties. This way, most retail and office activity is not well differentiated and needs to be bundled into a general category, but other uses such as bars and restaurants do show quite a detailed and updated representativeness. Concerning facilities, Health and education uses are fairly trustworthy, while other public buildings are also pooled without further distinction. Regarding residential uses, a fair distinction can be made between single family residence and collective housing, yet a further classification of typologies has proven to be ambiguous without an exhaustive review of this rather large dataset. For the case study area, information such as the total built up area (both above and below ground), the construction / renovation years, or the presence of undeveloped land is extracted.

Another important point about this source is the availability of spatial data to geolocate the tax properties identified. Following the INSPIRE directive, the DGC does offer spatial features to represent its records, out of which addresses points (conveniently merged with their corresponding properties), and land polygons, (which represent the areas where urban or rural planning applies) have been used to derive the extent of urban developed areas. These last spatial features have been slightly modified in some ambiguous cases in which urban tissue is in some regulatory state that does not account for urban legal conditions, yet it is clearly part of the fabric.

OpenStreetMap

Another data source used for some land use and design metrics throughout this work is OpenStreetMap (henceforth, OSM), the most popular crowdsourced set of spatial data, from which additional land data which is not reported by DGC has been derived, namely green areas and pedestrian areas (Mooney & Minghini, 2017). A first caveat with this source is its nature of an open project in which users themselves map and draw features, which makes it rather dubious if using it without further inspection. Another relevant issue regarding this open nature is the overlay and inconsistent format of many polygons, upon detailed inspection. The treatment of this source has involved the detailed correction of major missing elements, checking their validity for each

municipality. OSM has also been used to enhance the street networks used for the present work. Footbridges, footpaths, and other pedestrian exclusive street segments have been derived from OSM data and used to improve the original street network dataset, as it is described in the following section.

Public Transportation Data

The Consorcio Regional de Transportes de Madrid (Regional Transportation Consortium Madrid. Henceforth, CRTM) is the regional authority for multi-modal operation harmonization, planning, and research. This institution is also responsible for the publication of the travel data described below but, in this work, the spatial data representation of the public transportation infrastructure has also been used. These data layers are served by mode and operator (for instance, bus data is divided between Madrid city, Regional lines, and Urban Lines of the rest of municipalities in the Region), and hold relevant information concerning lines, features such as reduced mobility adaptation or covered bus stops.

For each mode/operator, a bundle of layers is offered, namely lines (line features depicting transport lines itineraries), stops (points depicting bus stop positions) elements (for more complex stations, features such as the different access points) and stations, which are a single-point simplified representation of each stop or station). For the sake of simplicity, this last layer has been used, and its "lines" attributes, to derive accessibility metrics to all unique lines from residential units in the Region.

Sociodemographic and economic data

For socioeconomic data exploration, the Spanish Household Income Atlas (Atlas de Renta de los Hogares Españoles) has been used, an open dataset maintained by the Spanish Statistics Institute (Instituto Nacional de Estadística. Henceforth, INE), which holds data for socio-demographic and socio-economic variables at the Census Tract level (Sección Censal). These census delimitations are built for statistical and polling purposes, and attempt to delineate homogeneous groups of around 1000 to 2000 people. However, as they are drawn in a spatially and administrative "nested" fashion, those municipalities which are smaller than that will be represented by a census tract. This is, nevertheless, not the case in the study area. Another caveat on the delimited tracts is the fact that many of them will contain a portion of the urban fabric, but then stretch towards the countryside to reach the municipal boundary. In this sense, the geometry of the tracts needs to be handled with care, as their absolute area can have a great bias.

Regarding the data itself, only the registered population is counted in this statistical operation, so care should be taken when understanding certain metrics of population presence. In this sense, only locally accountable economic activity impacts metrics such as income or unemployment. In the treatment of the data, population metrics have been merged to residential units identified in DGC, so as to be able to perform geographic re-aggregations of data. This means that there is a limitation in assuming that all dwelling units in the area are in fact inhabited by a registered resident, leaving empty houses, unregistered population (think students or temporary workers), or other uses such as tourists, out of the picture. The lack of data in this sense can impact

the intended demographic characterization, this being especially true in areas with high concentrations of "floating" population. However, within the scope of planning decision making and information in urban proximity, it is the housing stock that matters, as population dynamics are less targeted by physical intervention.

The Household Travel Survey in the Region of Madrid

Travel data is obtained from the Household Travel Survey 2018 (Encuesta Domiciliaria de Movilidad. Henceforth, EDM2018), published by the CRTM, which reports individual trips with their different stages, information on the individual travelers, and their household. This travel survey is the last dataset of its kind published in the region and, though it some dynamics might have changed (due, for instance, to events like COVID-19 pandemics or the expansion of some alternative travel modes, such as bicycles or car sharing), the rest of the data considered will be made consistent (e.g. filtering Cadastral information up to 2018).

The survey is quite detailed, and contains information about the origin and destination Transportation Analysis Zone (Henceforth, TAZs), delineated for the operation, as well as fine grain variables of motivation, mode, car ownership, or attitudes for choosing one mode or another.

The TAZs, in this data source, comprise 1259 features which have been filtered down to 737 zones within the selected study area. They have, according to the operation's methodological documents, been delineated according to criteria of homogeneity in urban, sociodemographic, and transportation accessibility terms. The operation targeted a total of 13009 households and 34653 people, on one hand, and additional 50412 individuals, on a second step. A final number of 75208 individuals responded to the survey, following an even selection of gender and age segments in the sample.

The fact that the survey uses an even sample of the complete targeted population means that, virtually, the trips published represent -through an expansion coefficient- the complete universe of population. Using this coefficient as the "count weight" of each trip equates the total trips of a particular set to expect between two zones. The survey is of a declared nature, meaning that it is the respondents who list the number of trips and purposes they perform on an average weekday. However, certain variables such as the trip distance and duration have been calculated from the origin and destinations declared, making them more robust than those values that respondents might estimate.

Road Network

Finally, these sources have been blended with the MRM Street Map, a road-center line (Henceforth, RCL) network geometry that includes the official names, validated and enhanced to sufficiently represent all possible pedestrian routes. Built on a RCL dataset depicting only one central axis for each street segment, any nuance differentiating "sidewalks" (such as tree shading, lighting and pavement quality or design) needs to be cautiously left out of the picture. However, the metropolitan-scale approach makes this simplification pertinent.

The primal graph approach has been selected for network modeling. This approach uses undirected planar graph edges to represent the street network (streets axes as edges, junctions and dead-ends as nodes). The network edges are built from the RCL map, with corrections to include pedestrian connections like tunnels, pathways and footbridges. Beyond intersections or street segment ends, segments are interpolated to have potential intermediate nodes every 50 meters, so as to represent those POIs which are located along a network line, and keep those that do have relevant land use points nearby. A great number of nodes is added to the original dataset, but representativeness is greatly improved.

Other characteristics such as dangles (or cul-de-sac patterns), the number of edges that arrive to each node (the degree of the nodes), and the slope of the segments, are calculated during the processing of the network data, facilitating the composition of some of the metrics described here. Finally, the network is topologically validated following best practices of ensuring edge coincidence at nodes, and the removal of loops and disconnected elements.

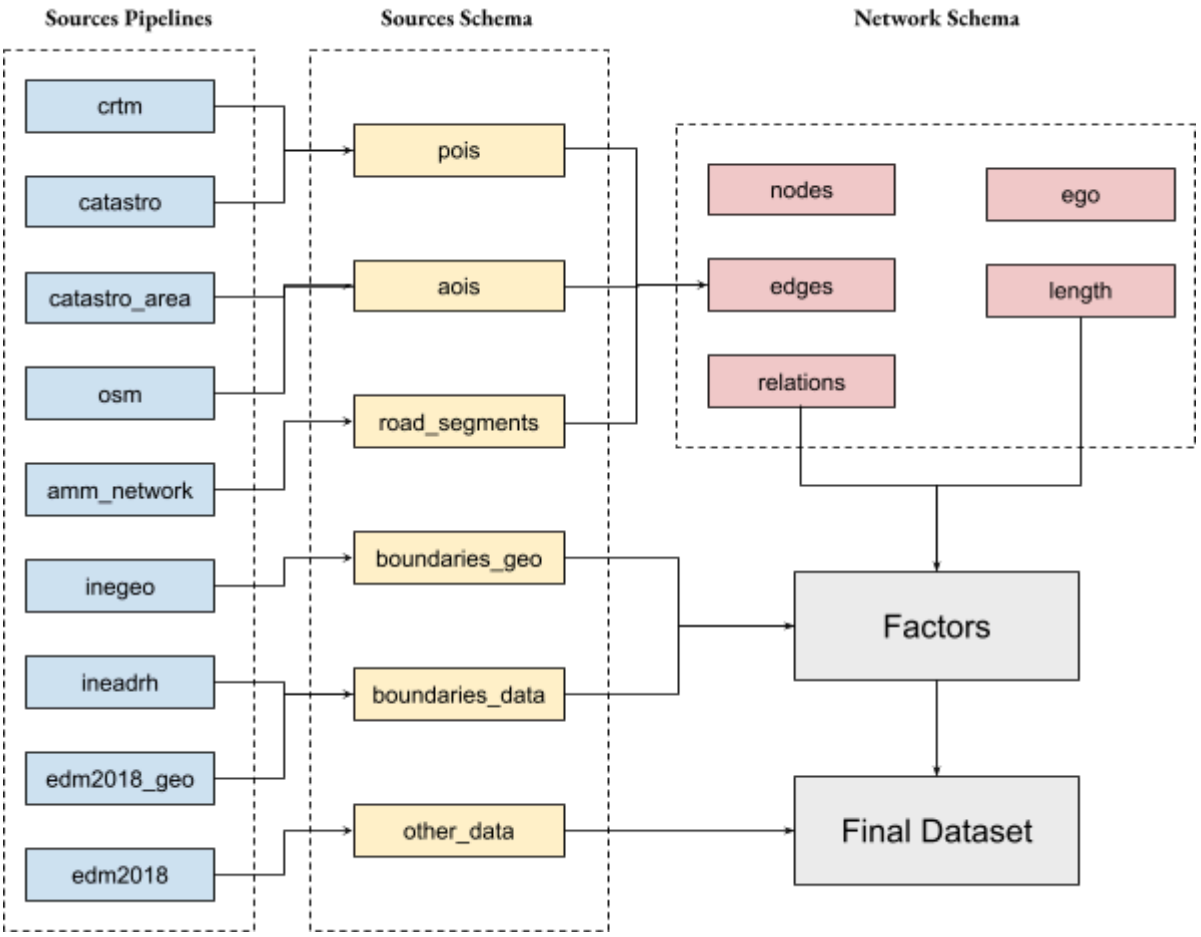


Figure 23: General Schema for Data Treatment
The general schema for data treatment. The different sources are treated independently (as independent Sources Pipelines) for gathering and processing purposes, as they are generally very different in nature. They become homogenized and uploaded into a database schema named Sources, where they are both called for the Network construction, the feature generation, and the final consolidation of the target dataset.

4.3.2 Data Constraints and Measurement Strategy

As aforementioned, data for the analysis were primarily sourced from the Spanish authority of property tax records (Catastro) and the EDM2018 dataset covering daily trips in the MRM. The dataset was copied into four versions, filtering distance ranges in 300-meter intervals (from 600 to 1,500 meters), keeping only home-based, non-work purposes. Each trip was labeled with boolean values for walking (1) and other modes (0), and the different social, trip characteristics, and attitudinal variables were properly encoded for modeling purposes (converting values into independent booleans columns for each unique category).

In this survey, all trips performed by each household member during a normal weekday are “declared” by respondents, with purpose and precise origins and destinations, along with starting and end times, which serve to calculate an objective travel distance, but a subjective travel time. For privacy issues, locations are obscured into carefully defined TAZs. To account for representativeness, the dataset includes a weighting or expansion factor, referred to as the "elevator." This scalar extrapolates the surveyed trips to the broader population, based on a detailed transportation gravity model, and a demographic segmentation developed by the CRTM. The "elevator" reflects the total number of trips for a given category and location, enabling the aggregation of trip behaviors by social segments or geographic zones.

A thorough exploration of the data has been performed in the illustrative subsections shown in most sections of this text. A simple rule of 15 minute trips was inspected for all variables available in the survey, leading to some decisions for not including particular variables or classes, as well as some caveats for dataset imbalance. For instance, information on nationality, reduced mobility conditions, qualitative frequency, day of week, attitudinal or trip_purpose variables with an ambiguous response of “Other”, households above 5 members, or trips performed

between 9 PM and 6 AM, were disconsidered. Also, the significant imbalance between a majority of walking trips in proximity and all other nodes in most of the resulting datasets after controlling for distance or purpose, was revealed.

The built environment, and some additional sociodemographic features were derived from Catastro and INE. Tax records in Spain (Catastro) provide a very detailed description of each individual property and its composition in terms of land use, area, and other architectural details. Even though it can have biases when compared to reality, it is considered ground truth at a legal level. The INE offers detailed information aggregated to the Census Tract boundaries, statistical small areas which house populations around 1000-2000 inhabitants, such as income, household size, or age cohorts. The combination of these two provides a basic “synthetic population” stratum, crucial for building the portfolio of associated features in this study. As mentioned earlier, information about transportation infrastructure and the street transportation network was also gathered from the CRTM open data portal, with the latter being thoroughly modified to accommodate a more realistic pedestrian movement representation, using third sources such as Open Street Map, which contained data on footbridges or other non-vehicular pathways. This last source also served as a reference for building the data on green areas, which was not available in the Catastro database.

Measuring the built environment and social features not directly associated with trips in the EDM2018 dataset has been achieved through an isochrone strategy that replicates many contemporary metrics of accessibility. As these metrics need to be joined together with the trip dataset through the TAZs, weighted average values for each housing unit contained in the tax property records have been calculated, using the varying thresholds of reachable land use or transportation infrastructure data, from each individual node of the network containing housing units. This way, all metrics adopt the form of a basic reach accessibility metric, and smooth the influence of well known sources of spatial bias such as the Modifiable Area Unit Problem.

In summary, the measurement strategy considers all metrics calculated at the housing unit level, from which the particular isochrones for each distance threshold are calculated, becoming the geographic extent for each calculation. As the estimated "synthetic population” has been calculated at the building level (housing units sharing a geolocated address), all metrics have been averaged, weighting by population, and grouping the data by the ID of the TAZ where

each address is contained. The following formula expresses this measurement strategy in a generalized way:

$$M_{TAZ} = \frac{\sum_{i \in H} P_i \cdot f(R_i)}{\sum_{i \in H} P_i}$$

where:

- ➔ MTAZ is the final metric computed for the aggregation zone.
- ➔ H is the set of housing units within the aggregation zone.
- ➔ Pi represents the population associated with housing unit *i*
- ➔ Ri is the set of reachable nodes from housing unit *i*
- ➔ i within the threshold distance.
- ➔ f(R)i) is an arbitrary function to compute the metric based on the information contained in the reachable nodes.

4.3.3 Predictors

As seen, this study examines features across several thematic domains: density, diversity, accessibility, design, and demographics, following the popular framework proposed in Cervero & Kockelman (1997). Some decades after its inception, the "D's" framework has been criticized for having become an endless search for nuances which has created a very disparate literature, allegedly diverging from its original intent of policy making information (Handy, 2018). To account for this issue, metrics which have strong ties with the operationalization of accessibility were selected, considered a highly informative approach in this domain. To find these ties, each built environment dimension in the associated literature has been further reviewed:

- ➔ Density Metrics: These include floor area ratio, population density, built-up area proportions, and land use percentages. Metrics were designed to address recommendations in the literature by representing volumetric characteristics, housing stock intensity, and experienced density (calculated over reachable areas). Density is probably the most used feature in this legacy of research, yet not necessarily for its influential power, but rather for its ease of calculation, and for being acknowledged as bringing along many other characteristics that might trigger the expected local behavior covered here (Handy, 2017). Elsewhere, density has been used to distinguish regional classes of urban fabric (such as

rural vs urban fabric), account for varying intensity of resident or floating population, measure indices of formal spatial volumetric configurations, or describe policy areas (Berghauser-Pont, 2020). In this approach, the so-called experienced density measurement of isochrones centered in residences has been selected, which is close to intensity measures of accessibility (Duranton & Puga, 2020)

- ➔ Diversity Metrics: Spatial co-presence and balance measures were used, using the walkable trips methodology described in Carpio-Pinedo et al. (2021). These metrics quantify the spatial complementarity of residences and land uses within certain thresholds. Initially, this family of metrics borrowed concepts from landscape ecology, but steadily gravitated towards finer metrics that explicitly account for spatial complementarity and interaction, as many operational proposals of land use mix have been criticized for having symmetry issues, or being too sensitive to varying spatial boundaries (Zhuo et al., 2022). The metrics selected leverage the accessibility concept to build a notion of theoretical sufficiency and complementarity at walkable distances, and also yield notions of imbalance, which could be associated with latent demand.
- ➔ Design Metrics: Street network characteristics such as slope, block length, straightness index, intersection degree, and mean building age were included. These measures capture elements of the urban form that influence the effective reachability of destinations, particularly for different demographic groups. Inspiration has been drawn from reviews such as Forsyth (2015), Ewing & Handy (2009), or thoughts on the influence of street layout such as Sevtsuk (2021). While the analysis would benefit from more material design metrics, data limitations at the regional scale precluded their inclusion. Design issues are widely acknowledged to influence walking behavior, but the micro-scale they imply is not easily nor objectively captured, and is a common frontier in the majority of reviewed works. In the present case, street layout and physical characteristics which have been associated with configurational restrictions to reachability and accessibility are selected.
- ➔ Destination Accessibility Metrics: Specific accessibility was measured as a complementary nuance to the previous, counting cumulative opportunities, (the number of unique assets of a particular type within a specified distance), echoing the recent trends sparked by the 15-Minute City concepts. Metrics also include accessibility to green spaces and unique transit options. While some biases regarding the “count of different properties” exist, the combination of land use percentages and absolute density ensures a nuanced representation

of accessibility (see the aforementioned reviews by Logan et al., 2022; Papadopoulos, 2023 and Megahed, 2024).

➔ Demographic and Behavioral Variables: These include household structure (e.g., presence of children, retirees, students), income levels, and other sociodemographic indices derived from census and survey data. These variables were expected to significantly influence mode choice, as suggested by the literature. Variables not present in the travel dataset were calculated as area metrics in the TAZs, by first associating income, household size, or age cohorts to each residential unit in the area, and then performing average metrics for reachable units at the different thresholds. A part of the attitudinal variables present in the EDM2018 (asking respondents to state why they didn't choose a particular mode) is left out of the study for being a too rigged approach to prediction. For instance, if a respondent did submit an answer to the question "Why didn't you drive?" and the answer is "I rather walk", the feature importance would most probably lean towards these features in an undesired way. However, other indicators such as holding a driving license, a transit card, or having a car, were retained. Most ideas for including these variables were drawn from Van Acker et al. (2016); Lanzini (2017) and Javaid (2020).

From the variables that were initially built, some were discarded for having extremely high correlations, or only represented very slight theoretical differences from other predictors already in the portfolio. All variables were also normalized so as not to impact in RF feature importance measurement (see next section). In Table 14, all variables used in the study with their description are detailed.

Table 14: Final columns considered in the dataset

ID Labels		
id_taz	label	Transportation Analysis Zone
id_municipality	label	Municipality Code
Outcome Variables		
trip_mode	categorical	Walking / Driving / Other
elevator*	numeric	Representativeness of the trip (number of persons)
Trip Characteristics		
trip_purpose	categorical	Trip Purpose. Used as Control
trip_distance	numeric	Trip Distance, in meters. Used as Control

dem_gender	categorical / dummy	Male / Female
dem_cohort	categorical	Age Cohort.
dem_education	ordinal	Educational Level
dem_hou_size	numeric	Household Size of respondent
dem_activity	categorical / dummy	Activity (Worker, Caretaker, Student, Retiree)
dem_hou_structure	categorical / dummy	Students, Retiree, Children
Demographics		
dem_income	numeric	Mean Annual Household Income
dem_household_size	numeric	Mean Annual Household Size
dem_mean_age	numeric	Mean Annual Population Age
Destination Accessibility		
acc_care_other	numeric	Number of unique other entities of care
acc_care_public	numeric	Number of unique main entities of care (hospital, etc)
acc_school_superior	numeric	Number of unique superior educational institutions.
acc_school_basic	numeric	Number of unique basic educational institutions.
acc_leisure_bar	numeric	Number of unique bars, restaurants or venues alike.
acc_leisure_cultural	numeric	Number of unique cultural institutions.
acc_leisure_shows	numeric	Number of unique theaters, cinemas or venues alike.
acc_shopping_mall	numeric	Number of unique shopping malls.
acc_shopping_market	numeric	Number of unique markets or supermarkets.
acc_shopping_alone	numeric	Number of unique retail units not in other categories.
acc_sport_other	numeric	Number of unique sports venues.
acc_transportation	numeric	Number of unique transportation lines.
acc_parks_S	numeric	Number of unique green areas less than 2 hectares of area
acc_parks_M	numeric	Number of unique green areas between 2 and 20 hectares of area
acc_parks_L	numeric	Number of unique green areas over 20 hectares of area
Density		
dens_hou_total	numeric	Number of unique housing properties
den_far_ag	numeric	Total built area above ground, over ground built area
den_built_total	numeric	Total built area.
den_perc_unbuilt	numeric	Percentage of unbuilt ground area.
den_perc_housing_sfr	numeric	Percentage of area of single family residence.
den_perc_care_other	numeric	Percentage of area other entities of care
den_perc_care_public	numeric	Percentage of area main entities of care (hospital, etc)
den_perc_school_superior	numeric	Percentage of area superior educational institutions
den_perc_school_basic	numeric	Percentage of area basic educational institutions.
den_perc_leisure_bar	numeric	Percentage of area bars, restaurants or venues alike.
den_perc_leisure_cultural	numeric	Percentage of area cultural institutions.

den_perc_leisure_shows	numeric	Percentage of area theaters, cinemas or venues alike.
den_perc_shopping_mall	numeric	Percentage of area shopping malls.
den_perc_shopping_market	numeric	Percentage of area markets or supermarkets.
den_perc_shopping_alone	numeric	Percentage of area retail units not in other categories.
den_perc_sport_other	numeric	Percentage of area sports venues.
den_perc_office	numeric	Percentage of area offices
den_perc_industrial	numeric	Percentage of area industrial usage
den_perc_storage	numeric	Percentage of area storage space
den_perc_parking	numeric	Percentage of area built up parkings
Diversity		
div_wt_care	numeric	Number of walkable trips care purposes
div_ut_care	numeric	Number of unpaired trips care purposes
div_wt_school	numeric	Number of walkable trips study purposes
div_ut_school	numeric	Number of unpaired trips study purposes
div_wt_leisure	numeric	Number of walkable trips leisure purposes
div_ut_leisure	numeric	Number of unpaired trips leisure purposes
div_wt_shopping	numeric	Number of walkable trips shopping purposes
div_ut_shopping	numeric	Number of unpaired trips shopping purposes
div_wt_sport	numeric	Number of walkable trips sport purposes
div_ut_sport	numeric	Number of unpaired trips sport purposes
Design		
des_mean_degree	numeric	Mean degree of reachable nodes
des_straightness	numeric	Straightness index of nearest node
des_block_length	numeric	Mean block length of reachable street segments
des_culdesac	numeric	Percentage of length in culdesac, over total reachable street length
des_slope	numeric	Mean weighted slope of reachable street segments
des_betweenness	numeric	Mean betweenness centrality of reachable nodes
des_mean_age	categorical / dummy	Mean building age of reachable buildings

*Though not being an outcome metric per se, this feature is mainly present as a multiplier for mode share

4.3.4 Feature Selection process

Being an accuracy-driven approach, RFs have two important design considerations: feature selection and overfitting. On one hand, it is necessary to select the features (in this case, simple column data) which are as little noisy as possible, in order to achieve a good generalization (which will make the models maintain accuracy when presented new data). In this sense, multicollinearity or irrelevant predictors should be accounted for and reduced. In ML, this is

commonly addressed by studying the Feature Importance as a quantity of "impact" in accuracy of each individual predictor. In RF, an interesting method of Permutation Feature Importance exists, which tests the change in models accuracy when randomly shuffling each feature, allowing to answer the question: is this feature better than randomness? This way, those data columns which are either redundant, or a demonstrable source of noise, will be dropped.

On the other hand, overfitting is the situation where a model has learned a particular dataset so much that it does predict with high accuracy only because it knows the shape of the data very well. Thus, when reading new data and attempting to predict new observations, it might not be able to capture actual relationships between the data and the target. This issue is a particular concern to the present approach, as it particularly affects small samples (having two combined control variables will considerably reduce the number of observations in each model). Moreover, the expectation is that walking behavior will most likely be the norm in proximity distances, so artificial "balancing" of the data (also called undersampling) will be desirable, even further reducing the size of each of the samples used to fit the models.

The data constraints in the experiment also add particularities that impact the research strategy decisions. A broad set of different ways of measuring significant features of the social and built environment have been built which, along with the disaggregate data in the EDM2018 travel dataset, conform a starting material in which two conditions arise: First, it will most likely be a quite complex dataset of highly collinear variables and; second, many of them might be available or not in other case studies, depending on the local data availability scenario. This way, addressing the importance of variables for model specification will be thorny, and quite subjective if done manually. Arguably, inspecting the predictive power of different combinations of data can help understanding what information is more relevant to focus on when informing local practice.

Keeping these constraints in mind, the proposed feature selection workflow is detailed. To address what features of the social and built environment better predict "proximity choice", a "survival game" is proposed, a process of extracting the importance of combinations of these features, for each of the proposed combinations of trips distance thresholds and purposes. The process is summarized as follows:

➔ First, each dataset is prepared with the particular controls and an undersampling method is performed to balance the sample.

- ➔ Second, a series of relevant combinations of features is defined to start with (which come from domain knowledge and use PCA for merging variables into meaningful indices).
- ➔ Third, a first iterative process of eliminating highly correlated variables is run.
- ➔ Fourth, an iterative process of model fitting and permutation feature importance evaluation is run, eliminating those features that appear to be no better than randomness.
- ➔ Fifth, if a resulting model is achieved, two indicators of overfitting are run, namely (train - test comparison of performance, and cross data validation)
- ➔ Sixth, results are reported and compared for the most accurate models achieved, which have been reduced to only a significant subset of predictors and pass overfitting tests.

The first step is the preparation of each dataset in terms of row filtering. Table 15 shows the final combined controls in the exercise. Further controls were considered in a preliminary version, including age, household structure, density, income, and building age. These were ultimately not considered, as the resulting "set of datasets" had rather small filtered samples, and consisted in too many diverse situations in terms of mode choice, socio-demographic distribution, and urban configurations. With this decision, information quantity is favoured over specificness.

Table 15: Model Controls

Distance (m)	600, 900, 1200, 1500
Trip Purpose	Study, Sport /Stroll, Shopping, Care, Leisure, Study

The use of short distance thresholds reflects the idea of setting a varying boolean state of proximity. It helps reduce the complexity that other notions of cost such as time or expense imply. As different purposes are being used in this work for predicting walking behavior against all other modes (which will most likely show higher average distances), an array of distances is chosen, starting at a short value of 600, –which is significant regarding mean minimum walking distance in the EDM2018 trip dataset, going up to 1500 meters in 300 m steps, which is also a sound maximum distance for walking trips in the data. The main idea of this control is that, hypothetically, if other modes rather than walking are chosen for trips within this range, there could be identifiable reasons for it, assuming -for simplification- that walking could be universally preferred over other modes.

Trip Purpose control filters the everyday non-work travel behavior targeted in the reviewed literature. It mainly affects the location of the destinations and should show great variation in mode choice. As age will not be controlled for (see the limitations in sample size explored in

section 3.4.3), some distinction in the data will be lost (such as trips to primary schools or universities, or different activities of care). Moreover, some of the purposes have some confounding implications in the data. Stroll / Sport purposes are not further disaggregated in the data sources, and Leisure Trips are not classified for the kind of leisure they represent, and have been identified as complex when captured from a utilitarian perspective, as travel time is less of a constraint in these cases.

To evaluate the relative importance of contributing features, the second step of the workflow involves the definition of relevant combinations of the predictors. Acknowledging the fact that multicollinearity will be present in some models, and the data used in this work might not always be available in other case studies, a series of different schema tests is proposed. To build the schemas, a targeted PCA is performed that "merges" groups of variables in a theoretically sound way. This way, the variation of accuracy and feature importance in different theoretical scenarios is accounted for. For instance, it might be less preferable not to potentially lose valuable information, or not have much information available. The chosen schemas tested in each model include:

- ➔ Models that incorporate all related features: These models will surely be affected by multicollinearity, thus variable importance might be less reliable or confusing. However, incorporating a broad portfolio of nuances of the built environment could theoretically lead to more precise models.
- ➔ Thematic grouping of indicators, such as density, destination accessibility, design, and diversity metrics. Much of the multicollinearity can be expected across these groups. For instance, transportation accessibility, in the region of Madrid, is highly related to density, while average block length has a strong relationship with average building age. If these thematic groups are merged into linear combinations, multicollinearity is significantly reduced, and variable importance can be pointed at them.
- ➔ Aggregated variables that retain trip purpose associated variables. This schema approach is similar to the previous one, yet single variables directly associated to trip purpose are maintained single (they do not become part of principal components). For instance, in the Shopping purpose, features of density, diversity, accessibility, and so on, are merged, but those particular variables such as Floor Area Ratio of Retail Units or Accessibility to Shop Units are left out of the combination.

- ➔ Using only thematic variables for each of the D's. These schemas implicate using only one of the D's at a time in the input data. The main reason for testing these feature aggregation is to avoid the likely multicollinearity that emerges between many variables of the built environment, but also to address to which extent walking behavior can be predicted in data scarcity scenarios in which all nuances of the built environment can't be quantified.
- ➔ Using all metrics, and all combined metrics, both sociodemographic and built environment-themed variables. Multicollinearity is highly expected in these models, as intertwined associations of social conditions and urban tissue will operate in a prolific way.

In Table 16, the grouping strategy is made explicit. Groups of variables have been bundled together considering recommendations and insights found in the literature. Table 17 shows the variables associated with each trip's purpose in the corresponding "purpose schemas". In some cases, trip purposes might not be evenly associated with the built environment metrics, such as in Leisure (think it can range from going to a park to visiting a museum or a restaurant) or Sport / Stroll (which can be a run in the park, a visit to the gym, or simply walking for the sake of it. Table 18 summarizes the strategy and naming for each schema.

Table 16: PCA grouping strategy

Grouped Feature	Original Features
acc_general	acc_care_other, acc_care_public, acc_school_superior, acc_school_basic, acc_leisure_bar, acc_leisure_cultural, acc_leisure_shows, acc_shopping_mall, acc_shopping_market acc_shopping_alone, acc_sport_other
acc_green_areas	acc_parks_S, acc_parks_M, acc_parks_L
den_urban_form	den_far_ag, den_built_total
den_land_use_walkable	den_perc_housing_ch, den_perc_care_other, den_perc_care_public, den_perc_school_superior, den_perc_school_basic, den_perc_leisure_bar, den_perc_leisure_cultural, den_perc_leisure_shows, den_perc_shopping_mall, den_perc_shopping_market, den_perc_shopping_alone, den_perc_sport_other, den_perc_office
den_less_walkable	den_perc_industrial, den_perc_storage, den_perc_parking
div_walkable	div_wt_care, div_wt_school, div_wt_leisure, div_wt_shopping, div_wt_sport
div_unpaired	div_ut_care, div_ut_school, div_ut_leisure, div_ut_shopping, div_ut_sport
dem_attitude	dem_att_license, dem_att_vehicle, dem_att_card
dem_social	dem_education, dem_hou_size, dem_activity_retired, dem_activity_student, dem_activity_unemployed, dem_activity_worker, dem_hou_structure_children, dem_hou_structure_other, dem_hou_structure_retiree, dem_hou_structure_students_age13_18, dem_hou_structure_students_age6_12, dem_hou_structure_worker

For each schema, PCA was implemented using Python's scikit-learn package with the *n_components* parameter set to one (in other words, selecting the first PC, which accounts for most variance in the data. PCA is a common statistical technique used for dimensionality reduction, similar to other approaches such as Factor Analysis, broadly used in the domain (see, for instance, the use of dimensionality reduction in the seminal work of Cervero & Kockelman, 1997, or the many works reviewed in Cao, 2009). It iteratively transforms a dataset with many correlated variables into a smaller set of uncorrelated variables (the orthogonal principal components), while retaining as much of the variability in the data as possible, ensuring each principal component provides unique information about the targeted dataset.

Table 17: Features associated to trip purposes

Trip Purpose	Features
Shopping	acc_shopping_mall, acc_shopping_market, acc_shopping_alone, den_perc_shopping_mall, den_perc_shopping_market, den_perc_shopping_alone, div_wt_shopping, div_ut_shopping
Study	acc_school_superior, acc_school_basic, den_perc_school_superior, den_perc_school_basic, div_wt_school, div_ut_school
Leisure	acc_leisure_bar, acc_leisure_cultural, acc_leisure_shows, den_perc_leisure_bar, den_perc_leisure_cultural, den_perc_leisure_shows, div_wt_leisure, div_ut_leisure
Sport / Stroll	acc_sport_other, acc_parks_S, acc_parks_M, acc_parks_L, den_perc_sport_other
Care	acc_care_other, acc_care_public, den_perc_care_other, den_perc_care_public, div_wt_care, div_ut_care

Table 18: Final schemas

Schema	Definition
all_features_all	All features, including demographic and built environment
combined_features_all	Combined (grouped) demographic and built environment
all_features_be	All built environment features
combined_features_be	Combined (grouped) built environment features
purpose_combined_features_be	Combined (grouped) purpose built environment features
only_purpose_features_be	Only purpose built environment features
only_density	Only density built environment features
only_diversity	Only diversity built environment features
only_accessibility	Only accessibility built environment features
only_design	Only design built environment features

The next step is to iteratively evaluate the pairwise correlations among all variables, discarding the variable from each highly correlated pair (> 0.9) that is less correlated with the target variable. If this approach was to be performed manually, it would be likely that variables that make it to the final model were based on expert-based decisions. For instance, if choosing access to shops over access to parks for a model of shopping trips was preferred, the former would likely be chosen. However, it was decided to keep the process transparent in terms of feature selection, as the aim is to achieve the highest possible accuracy (without bias). Also, it is interesting to test if those variables that remain in each model have actual domain soundness.

The fourth process in the workflow is an iterative process of RF model fitting and variable selection. When fitting a RF model, key parameters to account for include:

- ➔ The number of decision trees in the forest ensemble (more trees generally improve performance but increase computation time and risk of overfitting)
- ➔ The maximum depth of each tree (the maximum number of splits that each decision tree can make)
- ➔ The minimum number of samples required to split a node (in this case the minimum quantity of rows that remain after a split)
- ➔ The minimum number of samples required at a leaf node (the final fragment of the data left after the last split, which makes the classification decision)
- ➔ The number of features considered for each split (decision trees choose the best feature to split the data at each step, and it can be limited how many are considered at each split).

The models are fitted using a non-exhaustive grid search (testing different combinations of the former parameters in order to inform final specifications of the models): it covered two values for the number of trees in the random forest (50 and 100 trees); values for limited versus maximum tree depth (10 splits or no limitation); and allowing deeper trees by setting the size of the minimum sample which can be split and the minimum size of leaves to a value of 2 (which allows for fully developed trees, but also increases the risk of overfitting), or more controlled value of 10 minimum sample and leave size.

For each iteration, the Permutation Feature Importance is run, discarding the features with negative importance or, in other words, features which do not seem to add more predicting power than randomness. Permutation Feature Importance measures how much each feature contributes to a model's predictions by randomly shuffling its values and observing the

performance drop. If shuffling significantly decreases accuracy (or increases error), it's important. Conversely, if a model improves accuracy, the feature can be considered no better than randomness, and it is given a negative importance value. This process is performed until no negative features are found. This decision is motivated by the rather small size of the samples after controlling.

The final models obtained are also tested for two indicators of over-fitting: First, if a sensible difference exists between accuracy of the train and test data in each model, this may be an indicator of overfitting. Second, a cross validation technique is used to understand how well is the generalization of the model. Cross-validation consists of testing the trained model against random subsets of the training data. If the accuracy of the different subsets is very diverse (inspected using mean and standard deviation of accuracy at each test), then overfitting is most likely happening. Those models that pass these tests will be finally highlighted.

For each of the resulting models, accuracy, permutation feature importance, confusion matrices, removed features, and errors in case of non convergence (not meeting the minimum sample size, or ending with no valid features) are stored as a data table. Models were forced to either have a minimum value of 50000 in the total "elevator" sum (as a proxy to the size of the population they represent), and have a minimum of two features remaining in the final model, if the iteration reaches that point. Throughout the process, the Python's implementation contained in the sci-kit learn library has been used.

4.3.5 Limitations of this approach

Some limitations to this approach need to be considered. First, the domain of study acknowledges difficulties in measuring the built environment, as it remains inherently ambiguous. As discussed in the research methods section, an aggregate version of measuring the built environment based on the area surrounding respondents' residences has been used. This choice limits the present scope and it does not capture built environment influences at other destinations, such as workplaces, which remain challenging to quantify and integrate into planning efforts.

Regarding measurement, aggregation to zones presents conceptual dilemmas. Some researchers suggest that aggregation could be conducted along travel routes rather than zones (Lee & Moudon, 2006). Other authors point to the fact that researchers should question if these "surroundings" captured are appropriate to understand a mechanism of affecting residents (Galster, 2018). However, the data limitations required to rely on zone-based aggregation. Whether built environment characteristics measured in aggregation have a direct causal effect on travel behavior remains uncertain, and in this study, they must be interpreted as proxies rather than clear determinants.

In addressing built environment characteristics, "accessibility versions" of the "D's" dimensions have been used to account for notions of distance interaction, which have been noted to be relevant in active travel studies (Handy, 2020; Handy, 2018). However, a limitation is acknowledged in another important constraint to walking: urban design. Researchers argue that these micro-design elements are difficult to measure systematically, but very relevant in studying individual utilities to walking, making them a frontier challenge in this domain (Ewing & Cervero, 2011; Gao et al., 2023). This study does not explicitly incorporate fine-grained influences of design, which remain an issue to be dealt with in future works.

In a more general way, the concept of utility and disutility is not straightforward in this exercise. Particularly for walking and urban design features, establishing linear relationships among features and their perceived utility is complex. Therefore, this approach remains exploratory rather than prescriptive, as was a key motivation behind adopting a ML approach rather than a traditional econometric model (Cheng et al., 2019).

Focusing exclusively on walking also means that other transportation modes are obscured. The intricate relationships between different travel modes and their competitive or complementary effects are not accounted for, and this is noted by some of the researchers in the review (Silva, 2023). However, given that most proximity-based trips are conducted on foot, it is assumed that choosing alternative modes would have clear, identifiable reasons, which are attempted to be captured through the purpose controls defined in the study design, and the wide portfolio of metrics used.

Potential biases such as residential self-selection or the impact of varying spatial quantification parameters in measuring the built environment is not explicitly addressed. Nevertheless, the model benefits from a detailed demographic dataset and a sufficiently large range of distance

thresholds, both of which contribute to refining the understanding of proximity-based travel behavior, as shown in the predictors section (Cao, 2009). More broadly, causality between the built environment and travel behavior has not been definitively established (Naess et al., 2018; Stevens, 2017). Thus, it is acknowledged that these relationships are complex and can even be bidirectional.

Multicollinearity remains one of the most significant challenges in ensuring well-specified models in this domain. While the variable selection process is strict, some limitations persist. More granular metrics are more likely to exhibit collinearity, leading to their exclusion from final models, sometimes in favor of variables that may not be as intuitive or directly related to trip purposes (see, for instance, the conclusions in Cervero and Kockelmann, 1997). To mitigate this, multiple feature schemas have been tested to better assess feature significance.

Multicollinearity also affects feature selection through permutation importance. In a RF model, if two variables (A and B) are highly correlated, and the model treats them interchangeably, another variable (C) may be selected instead. This situation is mitigated by systematically dropping redundant variables and ensuring that the selected features contribute meaningful predictive power, as discussed earlier.

Regarding the methodological approach, it is reiterated that using ML prioritizes accuracy, potentially at the expense of heuristic power (van Cranemburgh, 2021). While ML models excel at handling complexity and large datasets, they lack the interpretability of traditional econometric models. The results should therefore be viewed in the context of predictive performance rather than direct causal inference, as noted in works like Hagenauer (2017).

Similarly, although feature importance approaches have been reported (Rasouli & Timmermans, 2014; Ermagoun et al., 2015; Chang et al., 2019), results are still disparate and have not been meta-reviewed for specific importance or features selected. This might be in part due to the fact that, being an accuracy oriented approach, RF results on each particular dataset can yield very different feature importances, if measurement strategies and available information differs.

5. Results and Discussion

5.2 Model Accuracy

Two of the most common approaches to inspect performance in ML classification are Accuracy and Confusion Matrices, and they have been used to address the experiment results. In this context, accuracy is defined as the proportion of correctly classified instances over the total number of instances. A higher accuracy value indicates better model performance, but it is essential to complement this metric with its parameters (commonly displayed as confusion matrices) to understand classification errors. Mathematically, it is expressed as:

$$Accuracy = \frac{TP + TN}{TP + TN + FP + FN}$$

where:

- ➔ TP (True Positives): The number of correctly predicted positive cases.
- ➔ TN (True Negatives): The number of correctly predicted negative cases.
- ➔ FP (False Positives): The number of negative cases incorrectly classified as positive.
- ➔ FN (False Negatives): The number of positive cases incorrectly classified as negative.

High accuracy, under this formulation, only expresses overall ability to correctly classify a trip as walking or not. Thus, the composition of its parameters needs to be inspected, as models could predict walking trips well, but non-walking trips incorrectly. The previous undersampling to balance classes before modeling, partly helps overcome this issue.

From the sole point of view of accuracy, the most accurate model identified is the Shopping model at a 600-meter distance, achieving the highest accuracy (0.752). The second and third most accurate models are also observed at short distances (Shopping 900-m and Sport/Stroll

600m, with accuracies of 0.724 and 0.712, respectively), also suggesting strong predictive power. Out of the five highest accuracy models, four of them were of Shopping purpose. A step below, the pooled "all" category is found (0.694 accuracy for the 1200-m model); the best Care model (1200-m with an accuracy of 0.691) and; the best Study model (attained at 900-m and a global accuracy of 0.68). Way below these purposes, it is the best performing Leisure purpose model, at a global accuracy of 0.628, and a 1200-m threshold.

Regarding the schemas used, across all tested configurations, demographic-driven models tended to achieve higher accuracy than those using only built environment features. When considering only built environment features, the most accurate models are purpose-driven schemas at 600m (Shopping and Sport/Stroll trips); design-focused schemas, especially those incorporating network centrality measures such as betweenness and straightness and density-based schemas, showing competitive accuracy levels.

Confusion matrices provided another view of model performance by breaking down the correct and incorrect predictions. In the dataset, all models exhibit high TP, suggesting they effectively differentiate walking trips, but also many models exhibit rather high proportions of FN, showing that some models underestimate non-walking trips. This behavior suggests that either the selected features are only well suited to predict walking (and in most cases, probably overfitted), but generally show problems to predict other modes; or that the pooled "other modes" category should be considered in more detail and disaggregation, as it is not as easy to generalize by these models or, in a third stance, that the controls could be actually explaining most of the variation in mode choice.

Table 19 shows the complete selected results, highlighting those models that have at least TN percentage higher than 30% which, though it is not a great performance, can be seen as a tendency towards a better generalization. When seen from this perspective, it is interesting to note that best models only keep "All", "Care" and "Study" models, which suggests that it is only through larger samples (as in the "All" models) or in these specific purposes where a relevant influence of features beyond distance and purpose can be detected.

Table 19: Results

Trip Dist.	Trip Purpose	Schema	Table Size	Sample Size	Acc.	TN (%)	FN (%)	TP (%)	FP (%)
600	Shopping	combined_features_dem	3501	253705	0,752	12	88	98	2
900	Shopping	only_design	4301	308649	0,724	16	84	95	5
600	Sport / Stroll	only_purpose_features_be	3331	245514	0,712	6	94	97	3
600	Shopping	only_design	3501	253705	0,698	10	90	98	2
1200	All	all_features_dem	21228	1560109	0,694	33	67	87	13
1200	Care	all_features_dem	3571	255187	0,691	57	43	82	18
1200	Care	all_features_all	3571	255187	0,691	58	42	77	23
600	All	combined_features_all	13481	1001820	0,689	17	83	95	5
1500	All	only_density	23560	1722129	0,686	37	63	83	17
600	All	combined_features_be	13481	1001820	0,684	16	84	95	5
900	Study	all_features_all	5580	436009	0,682	30	70	88	12
600	All	only_accessibility	13481	1001820	0,679	13	87	92	8
900	Care	all_features_dem	2964	213306	0,674	48	52	86	14
900	Study	all_features_be	5580	436009	0,672	29	71	87	13
1200	Shopping	only_purpose_features_be	4738	338083	0,671	18	82	91	9
600	Study	only_purpose_features_be	3917	305460	0,67	19	81	92	8
600	Care	pr_combined_features_be	2022	145993	0,669	33	67	85	15
600	Study	only_design	3917	305460	0,667	18	82	91	9
1500	Sport / Stroll	combined_features_all	5914	420745	0,656	16	84	94	6
600	Care	combined_features_be	2022	145993	0,644	32	68	86	14

900	Care	all_features_be	2964	213306	0,642	44	56	78	22
1200	Leisure	combined_features_all	1095	80451	0,628	19	81	88	12
1500	Sport / Stroll	only_design	5914	420745	0,621	14	86	94	6
1500	Sport / Stroll	only_density	5914	420745	0,606	13	87	93	7

5.2 Permutation Feature Importance

Permutation Feature Importance helped identify the most influential predictors in the models. As in accuracy patterns, demographics show greater influence on most models. Household size and Income were important across models, followed by some age cohorts (younger and older populations) and activity status. Vehicle ownership or driving license were also important in some models. Regarding built environment features, Building age consistently ranks as one of the most important across schemas, along with street network characteristics. Other emergent features are less frequent, such as some accessibility metrics, unbuilt area, and those associated with urban sprawl, such as single family residences.

Shopping Trips show interesting patterns. The best model is a combination of Gender, Income, and Household size. The next three models are achieved only by means of built environment features, pointing at design features (they all originated from Only Design schemas) with similar importance. Building Age and features of the "configurational" kind such as centralities seem to be the most important. Also, some less important Density metrics arise, such as Percentage Unbuilt or Shopping Mall.

Best models in the "All Purposes" category are similar in accuracy and show expected features combinations. The best model used an Only Demographic schema and pointed at "Has vehicle", "Household Size" , "Income", and a more confusing feature of Household Structure ("Students aged 6 to 12"). Another two models kept "Building Age" obliterating all other features, while the remaining two are first, a combination of characteristic density features

("Population Density", "Percentage Unbuilt", and "Percentage Single Family Residence") and, second, a model exclusively retaining Accessibility to Transit.

Care trips attain the best performance when "Has a vehicle" is present. Also "Has driving license" ranked important in the best three models. Other less informative, yet important features were "Unemployed", "Household Size", "Education" or "Income". These models yielded confusing features in their three best Built Environment Only models. While the general Combination of Accessibilities and Building Age emerged as very important, other confusing features such as Accessibility to Leisure Bar emerged.

Study models were, once again, more demographic oriented. However, in this case, the best model also maintains other more informative Built Environment metrics, such as Accessibility to Transit, Small Parks, and Population Density. Level of education and Age Cohorts arise as very important in these models. The best three models only using Built Environment include a very confusing model including Accessibility to Medium Parks, Leisure Diversity, or Percentage of Shopping Mall; another more reasonable model with features capturing Accessibility to different kinds of School Facilities; and another parsimonious model using only Betweenness and Building Age.

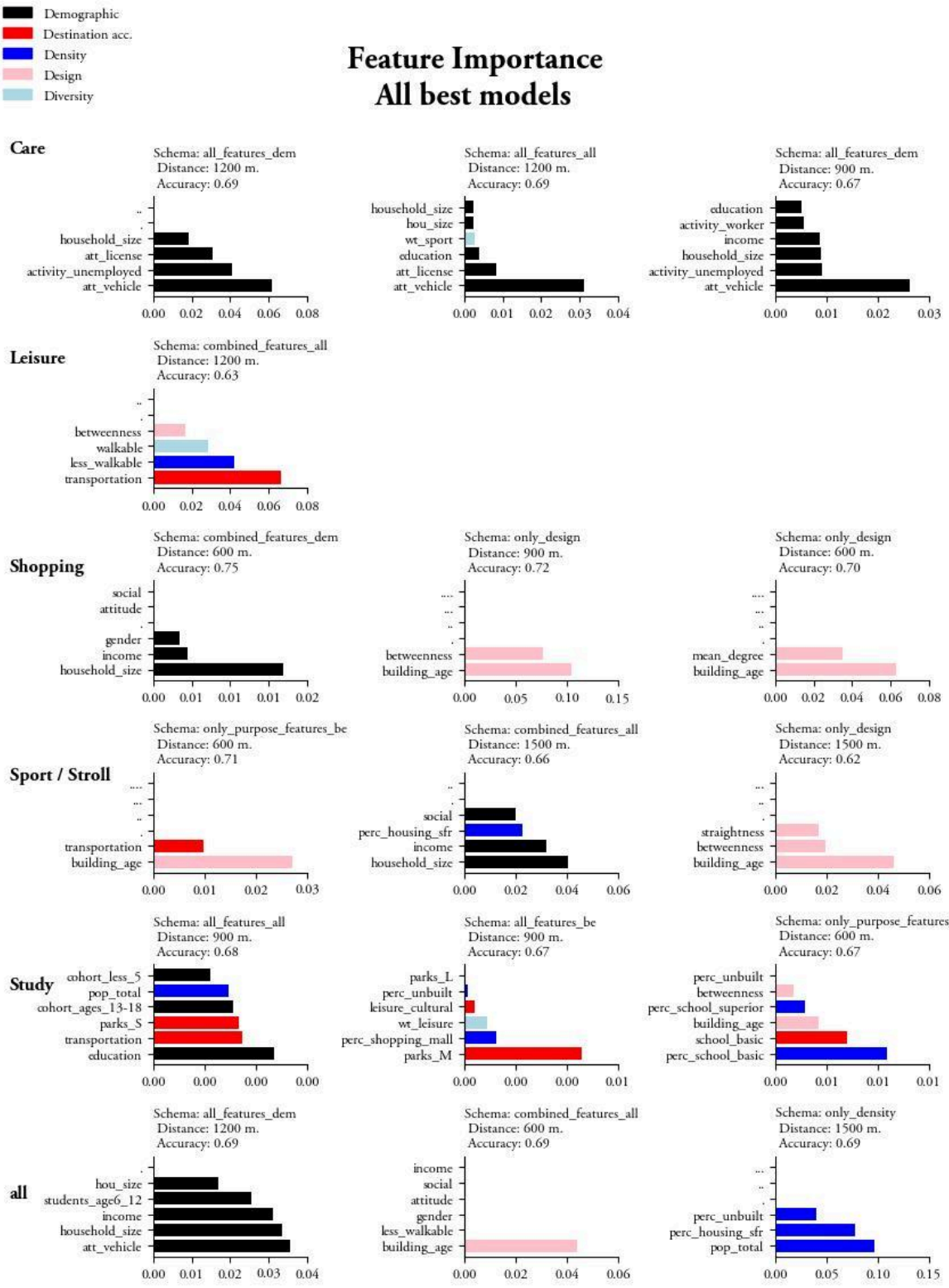
Leisure models had a comparatively low accuracy, only managing to obtain one model, composed of Accessibility to Transit, and Density / Diversity of groups of less and more walkable land uses, respectively. Also, Betweeness played a less important role in this purpose. Features in Sport / Stroll trips also yield somewhat confusing models. The best model is a combination of of Building Age and Transportation, and the second best is composed mostly by combined Demographic features, such as Household Size and Income and, notably below in accuracy, models combining either Building Age with Centrality measures (Betweenness and Straightness), and Population Density with Percentage Single Family Residence, respectively. Figures 23 and 24 show the feature importance results.

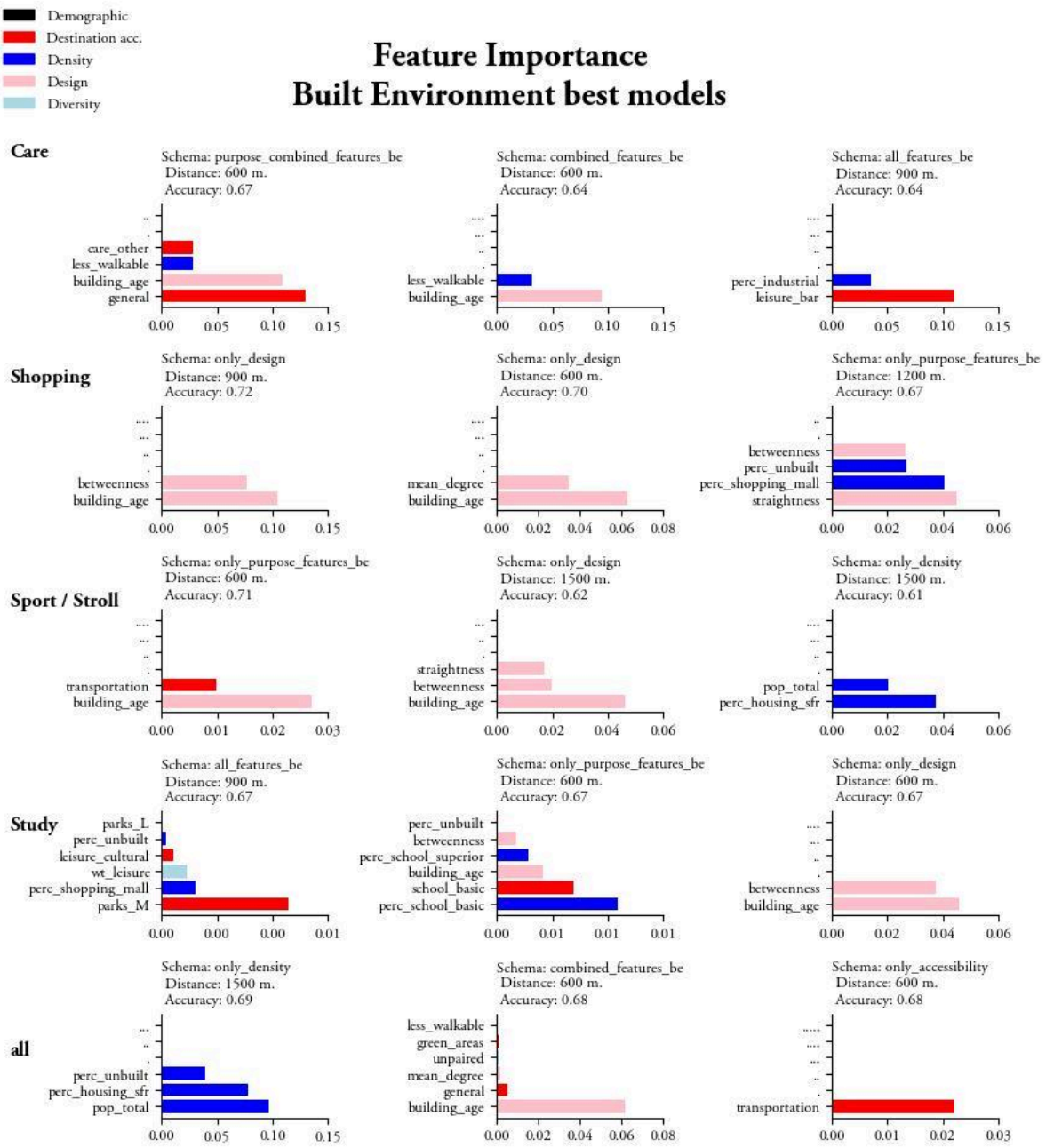
When considering only those models with TN higher than 30%, a slightly more readable set of feature importance results is observed. "All", "Study" and "Care" models generalize better and still consistently point at demographics and accessibility to rele-vant facilities, together with features that point at the presence of less walkable environments.

Figure 23 (Following pages): Most Accurate Models' Feature Importance

Figure 24 (Following pages): Most Accurate Built Environment Models' Feature Importance

- ➔ The color legend indicates the kind of feature used, considering the "D's" approach.
- ➔ Each row shows the most accurate model for each purpose.
- ➔ Each plot shows the starting schema used in the mode, the distance filter, and the accuracy obtained.
- ➔ Permutation Feature Importance is plotted for all the remaining features of the final model. The scale of this importance is trivial and not comparable across models, yet it is consistent within each of them.


Demographic
Destination acc.
Density
Design
Diversity
Feature Importance
All best models
Care
Schema: all_features_dem
Distance: 1200 m.
Accuracy: 0.69
household_size
att_license
activity_unemployed
att_vehicle
Schema: all_features_all
Distance: 1200 m.
Accuracy: 0.69
household_size
hou_size
wt_sport
education
att_license
att_vehicle
Schema: all_features_dem
Distance: 900 m.
Accuracy: 0.67
education
activity_worker
income
household_size
activity_unemployed
att_vehicle
Leisure
Schema: combined_features_all
Distance: 1200 m.
Accuracy: 0.63
betweenness
walkable
less_walkable
transportation
Shopping
Schema: combined_features_dem
Distance: 600 m.
Accuracy: 0.75
social
attitude
gender
income
household_size
Schema: only_design
Distance: 900 m.
Accuracy: 0.72
betweenness
building_age
Schema: only_design
Distance: 600 m.
Accuracy: 0.70
mean_degree
building_age
Sport / Stroll
Schema: only_purpose_features_be
Distance: 600 m.
Accuracy: 0.71
transportation
building_age
Schema: combined_features_all
Distance: 1500 m.
Accuracy: 0.66
social
perc_housing_sfr
income
household_size
Schema: only_design
Distance: 1500 m.
Accuracy: 0.62
straightness
betweenness
building_age
Study
Schema: all_features_all
Distance: 900 m.
Accuracy: 0.68
cohort_less_5
pop_total
cohort_ages_13-18
parks_S
transportation
education
Schema: all_features_be
Distance: 900 m.
Accuracy: 0.67
parks_L
perc_unbuilt
leisure_cultural
wt_leisure
perc_shopping_mall
parks_M
Schema: only_purpose_features_be
Distance: 600 m.
Accuracy: 0.67
perc_unbuilt
betweenness
perc_school_superior
building_age
school_basic
perc_school_basic
all
Schema: all_features_dem
Distance: 1200 m.
Accuracy: 0.69
hou_size
students_age6_12
income
household_size
att_vehicle
Schema: combined_features_all
Distance: 600 m.
Accuracy: 0.69
income
social
attitude
gender
less_walkable
building_age
Schema: only_density
Distance: 1500 m.
Accuracy: 0.69
perc_unbuilt
perc_housing_sfr
pop_total


Demographic
Destination acc.
Density
Design
Diversity
Feature Importance
Built Environment best models
Care
Schema: purpose_combined_features_be
Distance: 600 m.
Accuracy: 0.67
care_other
less_walkable
building_age
general
Schema: combined_features_be
Distance: 600 m.
Accuracy: 0.64
less_walkable
building_age
Schema: all_features_be
Distance: 900 m.
Accuracy: 0.64
perc_industrial
leisure_bar
Shopping
Schema: only_design
Distance: 900 m.
Accuracy: 0.72
betweenness
building_age
Schema: only_design
Distance: 600 m.
Accuracy: 0.70
mean_degree
building_age
Schema: only_purpose_features_be
Distance: 1200 m.
Accuracy: 0.67
betweenness
perc_unbuilt
perc_shopping_mall
straightness
Sport / Stroll
Schema: only_purpose_features_be
Distance: 600 m.
Accuracy: 0.71
transportation
building_age
Schema: only_design
Distance: 1500 m.
Accuracy: 0.62
straightness
betweenness
building_age
Schema: only_density
Distance: 1500 m.
Accuracy: 0.61
pop_total
perc_housing_sfr
Study
Schema: all_features_be
Distance: 900 m.
Accuracy: 0.67
parks_L
perc_unbuilt
leisure_cultural
wt_leisure
perc_shopping_mall
parks_M
Schema: only_purpose_features_be
Distance: 600 m.
Accuracy: 0.67
perc_unbuilt
betweenness
perc_school_superior
building_age
school_basic
perc_school_basic
Schema: only_design
Distance: 600 m.
Accuracy: 0.67
betweenness
building_age
all
Schema: only_density
Distance: 1500 m.
Accuracy: 0.69
perc_unbuilt
perc_housing_sfr
pop_total
Schema: combined_features_be
Distance: 600 m.
Accuracy: 0.68
less_walkable
green_areas
unpaired
mean_degree
general
building_age
Schema: only_accessibility
Distance: 600 m.
Accuracy: 0.68
transportation

5.3 Discussion: Relevant Patterns and Metrics

Regarding the distance threshold approach

Distance thresholds significantly affect model performance across different purposes. This idea aligns with the high importance and granularity of distance in local mode choice (Silva et al., 2023; Büttner et al., 2024). Shorter distances (600m–900m) yielded higher predictive accuracy on average. However these thresholds reduce the "other modes" class considerably and, after undersampling, models in shorter distances receive a bias that should not be overseen, and can be locally very significant (for instance, in places where other modes are especially less used).

In future works, more sophisticated ways of resampling models, particularly those oversampling minority classes, should be tested, probably taking into account the original modes in the oversampled class. Also, another way of reducing the imbalance class could be focusing directly on those areas where non-walking behavior in proximity is significant and, while potentially losing data, obtaining more "naturally" balanced samples.

An implication of distance thresholds is that they constrain the spatial window in which the built environment is measured "around respondents" (in this case, using isochrones). This approach is supported by many reviewed works, from early works such as Handy (1996; 2002), reviews such as Ewing & Cervero (2001; 2010), to more contemporary works such as Duranton & Puga (2020), and the trend of accessibility measurement in the 15-Minute City (Logan et al., 2022; Papadopoulos, 2023; Megahed, 2024). The sensitivity of metrics to this aggregation approach, as recommended in works like Vale et al. (2016) or Bolten & Caspi (2021), was not considered. Future steps could include more pedestrian oriented aggregations such as routes, or specifically addressing how model performance varies with distance thresholds more specifically.

Regarding trip purpose controls

Purpose controls are a fair approach to user needs, but some categories seem to have bias induced by the lack of further controls such as age, household structure, or income, which are gaining more detailed attention in the literature (Gao et al., 2023) (for instance, study or care

trips have strong age and household implications that were not taken into account). Other models can be biased by limitations of the survey used, such as the Sport / Stroll, the Leisure and the Care categories, which could also take advantage of further demographic filtering, but also from the selection of destinations considered. This can be the cause for most of the best models of Care and Leisure being paired with the highest miss classifications (concerning TP and TN),

Best models were for Shopping purpose and, besides one single model for Sport/Stroll, the second best were in the pooled "All Purposes" category. Being more predictable, in this context, may mean that they are easier to generalize. It is interesting that, for Shopping and All Purposes, quite different feature definitions were achieved, suggesting that similar predictions can be obtained from demographic, built environment, and both kinds of features, yet pointing at demographic features as slightly more important. This could mean that: approaches are interchangeable (could lead to a deeper reflection about the endogeneity of travel and residential location seen in Cao, 2009 or Stevens, 2017) or; they have similar importance when making choice predictions (with a slightly more relevant role of demographics), being consistent with ideas expressed in Ewing & Cervero (2001; 2010), or Aston (2021).

Regarding the schemas and features used in the models

Models using built environment schemas exhibit higher FN rates compared to those incorporating demographics, reinforcing the idea that built environment alone does not fully explain mode choice decisions. Schemas having demographic definition were the most accurate, followed by purpose-driven, and those design-centered. In general, schemas using more disaggregate variables (such as those using all variables), ended up having some extraneous predictors, maybe due to the inflexible feature selection. In this sense, future steps could involve relaxing the correlation threshold, allowing experts entering the loop of feature selection, or using more sophisticated grouping techniques.

In models including demographics in their final feature sets, the most important predictors align with established findings in proximity research: Household size and income are strong determinants (Haugen, 2011; Marquet, 2015; Gil-Solá & Vilhelmson, 2022). Some age cohorts and activity status emerged in the final models -particularly younger and older populations-, consistent with their importance in recent research (Gao et al., 2023). Features such as vehicle ownership or driving license were very important in some models, pointing at the dilemma of endogeneity and residential self-selection described in the literature (Cao, 2009; Stevens, 2017).

These features, however, can be very informative as a target variable, or controlled for in future works. In general, it can be said that features revolving around ideas from activity travel research , theories like habit formation, have a relevant role in studying proximity behavior (Acheampong, 2015; Javaid, 2020).

Regarding the built environment features, Building Age and network centrality such as Degree, Straightness or Betweenness emerged in many models. This result is interesting and has a double reading: On one hand, these features "mask" many other predictors of the built environment, which could be consistent with findings of configurational theories such as Space Syntax or Complex Networks (Sevtsuk, 2021). On the other hand, the interplay between configuration and period might be pointing at a more complex condition of metropolitan structure that could be a proxy for walkability, and it is comparable to the results in Elldér (2024). In this sense, though the results are consistent, it remains a future task to inspect further nuances of both regional and local configurational arrangements. As expressed in Handy (2002), the importance is not on the feature itself (in this case, configuration or regional arrangement), but what it brings along with it.

Accessibility, Density, and Diversity metrics yielded more confusing results. Combination of Accessibilities and Accessibility to Transit were important in some highly accurate models, but in other models (and probably highly correlated to some alternative and more informative metric) confusing features emerged, with little or no reasonable connection to the modeled purpose. Regarding density, some accurate models were obtained which pointed to features preventing walkability, such as combinations of Percentage Single Family Residence or Percentage Undeveloped Land. In this case, it is disappointing that more elaborate indices such as the Walkable Trips did not make it into almost any models.

Less "unsupervised" feature selection processes, and a more nuanced study through previous control, unveil these features' implications in walking behavior. A more targeted use of conditions of accessibility or density could be carried out. For instance, they could be used for filtering urban configuration with no pedestrian accessibility before modeling, differentiating more complex "neighborhood types" such as urban sprawl or classes of residential neighborhood, through these features, as in early approaches such as Handy (2002) or Krizek (2003), or improving "compliance metrics" such as Carpio-Pinedo (2021), prior to predictive modeling.

6. Conclusion

6.1 Selected Research Gaps

A comment on some selected relevant research gaps identified in the review is given. The field of travel and the built environment has made significant strides toward creating empirical frameworks that allow for more accessible and comparable studies through meta-reviews. This approach offers researchers numerous heuristic frameworks to navigate the complexities of the field. While these empirical endeavors are often challenging and sometimes produce unexpected results, there is broad agreement on the combined effects of access, density, mix, and design on travel behavior.

Expanding empirical findings in this area is inherently valuable for advancing knowledge. However, recent work suggests a need for broader investigation into qualitative aspects, as the field has historically focused on improving models and data without fully incorporating the complex socio-spatial dimensions of its subjects. The concept of urban proximity in planning research is clear and impactful, but it remains defined in various ways, still needing epistemological debate. This debate generally acknowledges that proximity is a multifaceted phenomenon influencing individuals in diverse ways. In view of this work, the "proximity-centered accessibility" approach is the most theoretically grounded, combining concepts and quantitative methods in a flexible, informative, and transparent manner.

This research direction connects closely with the broader travel and built environment literature, adding a specific focus on accessibility measurement. Advances in tools such as isochrone analysis and policy initiatives like the 15-minute city, have spurred researchers to calculate and explore differences in local environments. While quantifying the built environment remains central, features like behavior, life stage, attitudes, and gender are often treated as separate from built environment analysis. The experimental findings reveal a lack of

integration of these qualitative and social dimensions in supposedly objective measurements of the built environment.

This oversight limits a crucial part of the debate. Concepts like utility, the role of human activity within time-geography constraints, and the causal flow between society, the built environment, and travel behavior should more deeply influence urban proximity studies. The proximity-centered accessibility framework is valuable because it emphasizes all modes and outcomes -placing walking in context with other modes, which recent policies often overlook- and advocates for flexible, customizable thresholds of time and space.

The review also reveals that route selection as an outcome related to proximity is underexplored, despite extensive literature on pedestrian behavior. Connecting this with proximity-focused research, especially in terms of associating urban features with behavior, would enrich the current knowledge. This has been touched upon in notable works, though they were not mentioned in the papers reviewed on urban proximity in the present work.

In terms of travel behavior, the review highlights several clear gaps in the general literature. Accessibility quantification is the dominant method for modeling proximity. However, expanding accessibility metrics beyond simple local provision to include concepts like “minimum or optimal access,” “intensity-oriented access,” and “spatial complementarity”, should be explored more consistently Recent research suggests that accessibility, as a measurement rather than a built environment feature, could integrate well with a broad portfolio of metrics. For example, density measured around a respondent's residence can serve as a form of net accessibility. In terms of density and land use mix, accessibility has been operationalized effectively in proximity studies, with consistent examples emerging from the review.

Design and demographic features, however, are less frequently incorporated into accessibility metrics for proximity studies. Including these would require not only meaningfully selecting origins and destinations but also identifying clear barriers to accessible regions. This remains a frontier for research, demanding much further exploration to refine these approaches. In this case, a matter yet to be explored is the social profiling of proximity preference, as in the broadly acknowledged self-selection problem in the wider literature.

6.2 Conclusions on the experiment

This study performed a complete feature selection workflow on a very diverse set of predictors, attempting to understand if general regularities emerge from their asso-ciation with walking behavior. Results ended up yielding mixed suggestions in terms of heuristic power to study urban proximity. In a broad sense, ML approaches seem to struggle generalizing the problem of local travel mode choice, biasing results towards pedestrian travel, and only achieving balanced results in either large samples or in Care and Study models. However, approaching feature selection only with performance in mind, results in a loss of explanatory power, as the features (and their importance) yielded by models still need further expert interpretation to possibly inform policy.

Many models reveal a high -although rather biased- predictive power using little information on street configurations and broad building period, which is an advantage for models that only need to simulate this local behavior, or studies which focus on particular configurations of urban form revealed by clustering or other kinds of spatial analysis, which could help revealing "states of proximity" in which walking behavior could need to be modeled differently. Also, models only using demographic variables can be an interesting approach, as this in-formation is broadly available, helping to address endogeneity problems such as the "residential self-selection problem".

Overall, an exploration like the one presented here, yielded an interesting set of predictors across all models, which could be further refined and used in more do-main-driven models such as Logit or Probit models, or less explicable ML models (which are commonly more accurate). Future research should explore hybrid modeling approaches combining econometric and machine learning techniques to en-hance both interpretability and predictive power. If some of the ambiguities found in this work are sorted out, ML models could not only detect important features, but also discriminate between those that have linear or non-linear relationships with choice, or those that are "better together", further improving the specification of Linear or Logit models which, in view of this work, seems to be the more informative approach still.

The downsides were that too many models ended up having a disappointing behavior in predicting other modes; being formed by features which become misleading or counterintuitive;

some attitudinal and sociodemographic predictors seem to point out social patterns which are not directly interpretable (or endogenous to travel mode choice), and need further research. The first issue could be mitigated by further implementation of variable selection which takes into account domain driven recommendations. The second could use a prior investigation of social patterns in the targeted geography, and could be adjusted to apply further control to experiments on local mode choice.

The issue with the poor classification of other modes could be addressed by adding new mode alternatives to the models, and addressing sample balance in a more sophisticated "mode-conscious" way. Also, extremely short threshold distances might be diminishing samples very much, to a point in which comparing walking and other modes becomes trivial, so distance should be kept at the maximum ranges of observed walking trips (in this case, the 1500 meter threshold), in order to fully be able to compare modes when seeking to inform "modal shifts".

Implications need to be taken with care, in view of the results. While models have been proven very sensitive to the effects of proximity thresholds and purpose, the sets of features suggested are sometimes misleading, and models struggle generalizing the choice to walk against other modes. Some of the less biased modes point at urban configuration proxies, demographic features, and known characteristics of less walkable environments. Also, Care and Study show the best overall performances, suggesting that these activities and the most implied population segments seem an interesting vector to further inspect combined effects of the social and built environment as a tool for policy information.

7. Policy Implications and Future Steps

To conclude, a general comment on policy relevance is that, beyond yielding reasonable accuracies, the Random Forest approach described here is still a limited way of attempting to disentangle the influence of features of the built environment in local walking behavior. As Box (1976) says, "all models are wrong, but some are useful" and, in the case presented here, it seems that some models do not seem wrong, but their usefulness -for planners- is still limited.

In general (avoiding for now the discussion on maintaining the focus on accuracy or explainability) better accuracy with less overfitting could be useful for agnostic simulation strategies in which the target is to obtain accurate pedestrian flow prediction. However, not being able to generalize the importance of the associated factors (and, particularly, those that can be influenced "by policy design"), hinders the ability of potential simulation efforts in terms of scenario building (not knowing how parameters influence travel behavior would obscure the study of the simulation of their impact).

Results are also lacking spatial information, which obscures a critical need not only for knowing "what to do" but also "where to intervene" in planning practice. This issue could be addressed by using alternative feature importance strategies such as SHapley Additive exPlanations or SHAP values, which yield individual metrics for observations that could potentially be located and studied in terms of spatial patterns. Regarding spatial patterns, another interesting idea could be to spatially cluster (for instance, using unsupervised ML workflows such as DBScan, or Local Indicators of Spatial Autocorrelation) those features that seem relevant across models, and perform more controlled comparisons. In any case, helping planners or local experts into the discussion on the effects of these features on proximity is an appealing future step.

The ability of RF models to converge in many different data scenarios is interesting for a global informative exploration of these datasets. In the reviewed works on the study of urban proximity, a call for accounting for "arrays" of distances, abilities, or needs across users is encouraged, and other statistical approaches, such as linear or logit models (derived from translations of utility theory, among others), would involve a costier process of individual model fitting. However, when it comes to comparison across models, the proposed methodology yields incomparable results (feature importances can not be compared across different models). In this sense, a more controlled feature selection could be helpful for a further iteration in which, after a robust selection, the complete matrix of models could be fit with more "readable" models of the linear or logit kind, yielding readable metrics such as elasticities, more readable model errors, or allowing for the study of "unexplained" variation through intercepts, latent variables, or random utility models.

Finally, some critical questions on endogeneity, such as the residential self-selection or the local vs regional accessibility questions, were not addressed by this method. The former, however, could be addressed by using some of the discarded "attitudinal" variables in the EDM2018

(which held answers such as “I rather walk” or “I rather drive”, which could be further targeted instead of mode choice, to then inspect the similarities and differences. The case of regional vs local accessibility could be further explored by using information about “competing” modes, such as daily distances covered by car from a particular TAZ, which could help explain certain local mode choice behavior, linking for instance daily local trips with daily longer commute (such as intermediate “drop-offs” or errands run on the way to work). Also, a controlled filtering of relevant regional areas could be an interesting approach.

This study has shown that some models of active travel behavior in proximity can achieve high accuracy with minimal input data. In general, this is good news if, again, only an agnostic simulation is intended by planning needs. Many of the features that yielded high importance, such as demographic and network data are broadly available and, generally, more commonly available than detailed travel data, as in our case study. This way, if the replicability of this experiment outside the MRM was addressed, this methodology could be transferred to other regions.

Beyond their “feature importance” applications, the models shown here can be leveraged empirically through network analysis. For example, theoretical paths between an origin-destination pair, enriched with synthetic population data at the building level, could serve as valuable inputs for simulation modeling. Controlled and weighted by distance, these synthetic representations provide the "unseen" data that well-trained models can use for effective simulation studies.

The role of distance in these models requires further investigation. The thresholds employed in this study function as spatial measures akin to isochrones, but testing alternative aggregation methods remains essential to determine their effectiveness. A deeper exploration of route choice behavior and pedestrian accessibility could provide valuable insights, potentially linking the proposed approach to utility theory and expanding its application across different spatial scales, including network "fields" or routes.

On a more granular level, refining model filtering and controlling mechanisms -particularly for demographic attributes- could improve performance and heuristic capacity. Incorporating qualitative information from specific population segments, these models could strengthen connections with fields such as activity-travel research, gender studies, or spatial justice. To do

so, again, it would need to overcome challenges in dataset balancing, probably leveraging oversampling approaches rather than undersampling.

A more nuanced methodological approach should reconsider variables discarded during feature selection. Unexpected predictor variables can sometimes introduce interpretability challenges, such as when accessibility to an unexpected land use emerges as a proxy for other land uses in models focused on particular purposes. In this sense, planning experts could be able to manually validate the elimination of variables step by step. Another idea could be to simply simplify the number of "D's" used at each run of the process, as some works referenced here suggest.

Future research should also explore alternative model structures, testing different schema configurations and decision tree setups to assess their impact on accuracy. Understanding these structures could enhance both heuristic power and interpretability, making the models more actionable for policymakers. Moreover, beyond accuracy measures, analyzing model errors and confusion matrices in a more continuous way -particularly their spatial patterns- could be highly informative. Clustering errors, a common approach in spatial modeling, could also reveal useful insights in machine learning applications, helping to refine future models.

Ultimately, this research highlights the future potential approaches to better understand urban travel behavior. Methodological refinements, along with a closer examination of model interpretability, will be crucial for advancing both theoretical and practical applications in this domain.

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Annex I: Detailed Review Sections

This Annex contains the extended version of the literature review for each section in which deeper reflections or longer summaries were collected, during the writing of this thesis.

2.1.2 Contemporary approaches dealing with proximity

The Spanish Urban Agenda on urban proximity

The urban model chosen to organize the necessary growth of cities is very relevant, both in relation to the strategic objectives already analyzed and, of course, in relation to the aspiration to promote proximity and sustainable mobility. Growth models based on sprawling and expansive urban development increase travel distances, which contributes to greater car dependency, significant consumption of space and energy, and notable environmental impacts. In this context, addressing the challenge of mobility requires a paradigm shift in urban planning, promoting compact cities with mixed land uses and abandoning such sprawling growth models. This paradigm also aligns with the pursuit of territorial and urban proximity models. Proximity to activities, services, amenities, workplaces, and leisure areas generally allows for a more efficient approach to one of the major current challenges of urbanism: managing mobility and urban transportation services, which in turn impacts environmental quality. Seeking this territorial model, characterized from an urban perspective by compact urbanization with diverse uses and a reasonable size, is a priority objective with multiple cross-cutting effects. This is irrespective of the recognized virtues, in terms of opportunities, of metropolitan areas and large cities.

Lines of Action

- ➔ Promote a mixed-use urban model that reduces travel distances within the city.
- ➔ Promote urban connectivity and universal accessibility, with proximity patterns between residence and work, to limit mobility demands.
- ➔ Establish in planning instruments a balanced distribution of urban space for motorized and non-motorized mobility, in accordance with the sustainable development policies of cities.
- ➔ Prioritize, as much as possible, the city for pedestrians by encouraging continuous, safe, and responsible routes and fostering a healthier and more active lifestyle.
- ➔ Promote the efficiency and quality of the most economical and accessible modes of transportation for all age groups: public transport, bicycles, and walking.
- ➔ Implement urban development models that incorporate public transport plans.

Strategic Objective 5: Mobility & Transport

- ➔ Promote metropolitan or supra-municipal public transport chains and encourage their intermodality.
- ➔ Develop pedestrian and cycling networks, including new urban developments, ensuring safe non-motorized travel in a friendly environment. Develop coexistence regulations for cyclists and pedestrians.
- ➔ Adopt measures to encourage the creation of transport plans to work in the main economic activity centers of the urban area to rationalize commuting to work centers, as well as teleworking strategies.
- ➔ Establish logistic distribution platforms in each neighborhood and manage the distribution of goods in urban areas, maximizing consolidation/deconsolidation centers and avoiding low-load distribution by vans and trucks.

Related Descriptive Data

The relationships of this strategic objective with the SDGs and the goals of the 2030 Agenda for Sustainable Development and other international projects can be summarized as follows:

- ➔ d.01 Population variation: The percentage variation of the population, using multiple time spans and age buckets, when possible.
- ➔ d.06 Population density in urban land: Number of inhabitants per unit of urban developed land
- ➔ d.07 Discontinuous urban land: According to the Spanish Land Use classification (which is also consistent with the CORINE Land Cover database, percentage of urban land occupied by this land cover class (sparsely populated or low density settlements)
- ➔ d.08 Housing density: Housing units per spatial unit of urban developed land.
- ➔ d.09 Urban compactness: Refers to the volume of built area per spatial unit of urban developed land. It is similar to Floor Area Ratio index, but takes into account the complete urban area, including public space and roads, but discounts undeveloped areas such as land plots.
- ➔ d.10 Residential compactness: Refers to the same compactness index in d.09, but only accounts for residential area in the numerator.
- ➔ d.11 Urban complexity: The Shannon-Wiener index applied to NACE Codes of urban economic and public activities.
- ➔ d.st01 Activity/ Residence balance. Proportion of economic activity area over number of inhabitants.
- ➔ d.17 Surface area of transport infrastructure: Percentage of land dedicated to transport infrastructure such as roads, railway, ports, and so on.
- ➔ d.18 Motorization index: Number of registered vehicles per inhabitant.
- ➔ d.19 Density of bus lines and rail modes: Number of unique lines through a particular area.
- ➔ d.20 Accessibility to public transport services: Proportion of residents living in a
- ➔ d.21 Provision of cycling paths
- ➔ d.22 Aging population
- ➔ d.39 Urban agenda, strategic planning, and Smart cities

2.1.3 The 15-minute city

Pozoukidou (2021) or Lamíquiz et al. (2022) argue that, even though the concept is not a radical new idea (proximity has been around the discussion for a while), it brings forward the concept of local accessibility in the center of city resource allocation and governance, and is a valid approach to proximity-centred planning in line with its legacy.

Khavarian-Garmsir (2023) sets the 15-minute city concept as a direct offspring of the neighborhood planning trend along the past century, pointing at the use of city-wide accessibility concepts, and the inclusion of digitalization as a lever to a more flexible and ubiquitous use of urban space as the main innovations, but mostly inheriting the attitudes of the former movements.

Megahed (2024) presents an interesting connection between SDGs and the 15-minute concept:

- ➔ Goal 3: Good Health and Well-being by reducing long commutes, promoting physical activity, and improving air quality.
- ➔ Goal 8: Decent Work and Economic Growth by creating mixed-use urban spaces that support local economies.
- ➔ Goal 10: Reduced Inequality through making services accessible within short distances.
- ➔ Goal 11: Sustainable Cities and Communities making cities inclusive, safe, resilient, and sustainable, aligning with the accessibility of the 15-minute concept.
- ➔ Goal 13: Climate Action with emphasis on reducing car dependency, promoting walking, biking, and efficient public transportation.

Bertaud (2022) or Marquet (2024) exemplify the academical and political backlash that urban proximity policies provoke, the first exemplifying a reasonable academic doubt aimed at the 15-minute city as a viable strategy in car oriented developments; the second addressing the frontal post-truth opposition that 15-minute policies have faced from a sector of society.

Papas et al., (2023) and Büttner et al. (2024) review recent policy inspired by the 15-minute city concept. The first reviews 8 cities in 3 countries, and finds gaps for bottom-up approaches for proximity policies, the definition of indicators for progress accountability, and the need for cost-effective measures for such an ambitious horizon. The latter is a wider review of practices worldwide (though again particularly focusing on Europe, which finds a broad acceptance of proximity-centred accessibility measures which mainly result in re-distribution of services and reallocation of street space, yet somehow still leaving behind the social, governance, and logistic aspects of urban proximity.

2.2.1 Epistemological debate

Marquet (2015a) is an extensive reflection on the socio-spatial implications of proximity from the perspective of an observable phenomenon of daily, short-range active mobility. For the author, understanding proximity can't be disassociated from the triad of individuals, society and space and can be traced in observed travel behavior.

Gil-Solá (2019) attempts to set a definition of proximity surveying planning professionals in Sweden. Results yield three levels of understanding: proximity can be seen as individuals and/or groups' perception of an accessible part of the city or the loose notion of neighborhood, yet the authors find how top-down urban planning view is still the mainstream definition: proximity is a planning strategy to increase land-use mix where an improvement margin, increasingly conscious of conditions for accessible and inclusive design (also reviewed in Ramírez et al., 2022).

Silva et. al. (2023) combine review methods along with focus groups of German and Portuguese planners, exploring concepts and thresholds considered in a proximity accessibility approach for a more cohesive research and policy. The authors stress the need for a convergent definition for the lower, shorter, and nearer thresholds of mobility and reveals a lack of consistent terminology, yet a consistent use of thresholds and user tailored metric approach (termed proximity-centered), in a flower-like array of combinations in terms of travel time and distance, users and motivations (Gil-Solá, 2019; Buttner, 2022; Baquero, 2024; Lamiquiz, 2024).

In Silva et al. (2023), a clear trend in accessibility-related literature is revealed in the past decades (and exacerbating since the COVID-19 pandemic in 2020), in which an explicit subset of active-modes and proximity approaches (in which proximity is an implicit condition of these modes' constraints) can be observed. The aforementioned work by Büttner et al. (2024), is also an epistemological input using a survey targeted to local practitioners in 94 cities, and a deep dive into 6 European cases, yielding a similar conclusion on the adoption of active accessibility measures as the main derivative of proximity policies.

2.2.2 Compliance metrics

Carpio-Pinedo et al. (2021) put forward a novel method to reframe, measure and map land use mix as "walkable trips" for proximity policies, based on functional and spatial complementarity. Using pre-defined regional trip frequencies, the authors build a metric of possibility of actual proximity interactions within certain walkable distances in the pedestrian network. The authors argue that, this way, spatial patterns of complementarity and imbalance can be reasonably mapped out in the urban fabric.

Logan et al. (2022) stress the importance of selecting the origins and destinations included in proximity operationalization, and the metric aggregation in quantifying proximity, raising concerns about the loss of information when averaging accessibility ranges and pairs of amenities-population, recommending the use of user-specific metrics in both senses.

Papadopoulos (2023) finds how most works define origins around aggregated residences in statistical boundaries, and their thresholds as the user-defined scale of analysis. The authors also find destinations commonly grouped in broad categories aligned with the 15-minute (or other) approaches, with some underrepresented groups such as workplaces or unique facilities or services (falling out of broad classifications).

Megahed (2024) reviews how most works are focused on everyday local accessibility yet, depending on the approach, they can be combined with other features into complex indexes (out of which age, income, density, street design and conditions are the most prominent in this local scale focus), aggregated to either origins or destinations (or both), nuanced with different movement rules which yield different catchment areas, and represented using different network aggregations (nodes or edges)

3.2.1 Simulation studies

Concerning Travel and the Built Environment

In the context of travel and the built environment, this approach is not particularly suitable for hypothesis testing (Crane, 2000), yet it does help understanding complex impacts of some built environment features, such as street patterns, which have been widely used in micro-studies of active modes (particularly of

walking), (Handy, 2002; Leck, 2006), travel constraints for testing modal alternatives (Boarnet, 2011), or approaches under Complexity and General Systems Theory, in which individual "synthetic" agents are used to simulate movement through transportation networks (Acheampong, 2015).

A highly cited example of a simulation framework is UrbanSim, detailed in Waddell (2002). This framework is not a single model, but a system that orchestrates six interrelated models, which intends to serve as a tool for planners to test scenarios of policy and development. It encompasses models of Accessibility, Economic and Demographic Transitions, Households and Employment (Mobility and Location), Real Estate Development, and Land Price. Each of the models has its own specifications (according to appropriate modeling techniques for each field), and represents one particular behavior for an "agent" with its own specifications which generate inputs for all of the models. This way, by making different assumptions on possible (planned or unplanned) events, the impacts on the whole system and other components can be inspected. Another two examples will be inspected and compared in the Case Studies section.

Concerning Urban Proximity

Simulation has been consistently used in measuring impacts of policy and intervention for motorized and train modes (Acheampong, 2015). However, walking and cycling has been less targeted on urban scales. In the UrbanSim example, the particular model that addresses accessibility in the system, includes two different scales of accessibility (regional and local), which intend to account for different effects of a heavier, long-distance reach (mainly pointing at employment), and an active, local operationalization, accounting for neighborhood dynamics. In recent versions, it already includes modeling for active modes.

Walking behavior, and particularly route choice, has also been addressed through simulation at the "architectural" scale (such as in evacuation or crowd control simulations), and the street network scale. An interesting thread of literature, in this sense, is the appraisal of network effects in pedestrian navigation of urban space, with structural approaches such as Space Syntax theory, which has studied the influence of the spatial enclosure and configuration in simulations of pedestrian navigation, stressing the relevance of the topologies of spaces, beyond distance (Hillier, 1996; Turner, 2007; Porta et al., 2009).

Simulations of local active behavior (or access to public transport), specifically considering the state of art in movement constraints, could help characterize more realistic proximity catchment areas for accessibility analysis beyond pure distance (Vale et al., 2016); understand the role of route choice (which was particularly put forward in Lee & Moudon, 2006) to include micro-scale features into the analysis; and simulate the effects of urban interventions to promote active travel (Aldred, 2019).

Simulation studies, moreover, are quite an open and flexible way of exploring research themes. In the proposed review, for example, Poorthuis & Zook (2023) focus on the 30-minute territory concept (the regional version of the 15-minute city) and use it to model the time viability of substituting automobile trips

above 10 km. with public transportation, attempting to achieve a 30-minute constraint in rural areas. They first analyze car-mode share and its relation to travel time across the urban-rural continuum, to then build their hypothetical scenario of car replacement by public transportation, by simulating both kinds of trips between postal code population-weighted centroids in the Netherlands, through an open-source routing engine. They finally use both mode travel times to analyze how a local accessibility metric fails to explain increased travel times in this hypothetical non-car scenario.

Examples of Simulators involving travel and the built environment

The UrbanSim framework is growth-oriented, and proposes a series of 8 models of varying scale, which react to user specified events (modifications in the input parameters of the different modules, affecting the complete system). It relies on Random Utility Models (introduced later on) in a disaggregate fashion (grid cells of 150 x 150 m.), accounting for two external general models (a macroeconomic and a transportation one), which affect all cells and react to another six small scale models, which affect each cells in terms of social, employment, residential, and land-use dynamics. Users can input scenarios which affect cells in terms of land-use and transportation constraints, and inspect the outcomes of the six models (Waddell, 2002).

The Comprehensive Econometric Micro-simulator for Daily Activity-travel Patterns (CEMDAP) is a micro-simulation implementation of an activity-travel modeling system. It accepts inputs of land-use, sociodemographic, activity system, and transportation level-of-service, and outputs the complete daily activity-travel patterns for individuals (Bhat, 2004). Each individual (worker and non-worker) is assigned a travel pattern as an ordered sequence of stops (places to achieve an activity) and tours (the order in which stops are arranged), and then a trip is scheduled and allocated given the time constraints. Finally, the trip is spatially assigned to possible destinations (stops), according to the final duration of scheduled trips.

Other example of comprehensive simulation is STELARS, and agent-based urban model, that adopts a hybrid of continuous and discrete time simulation technique, which considers that agents (households), become active in the event of relocating to a new residence, which in turn affects (and is affected by), three modeled levels of choice (long, mid, and short term decisions) (Khalil et al., 2024).

General schemas of these simulators are shown in Figures 25-27.

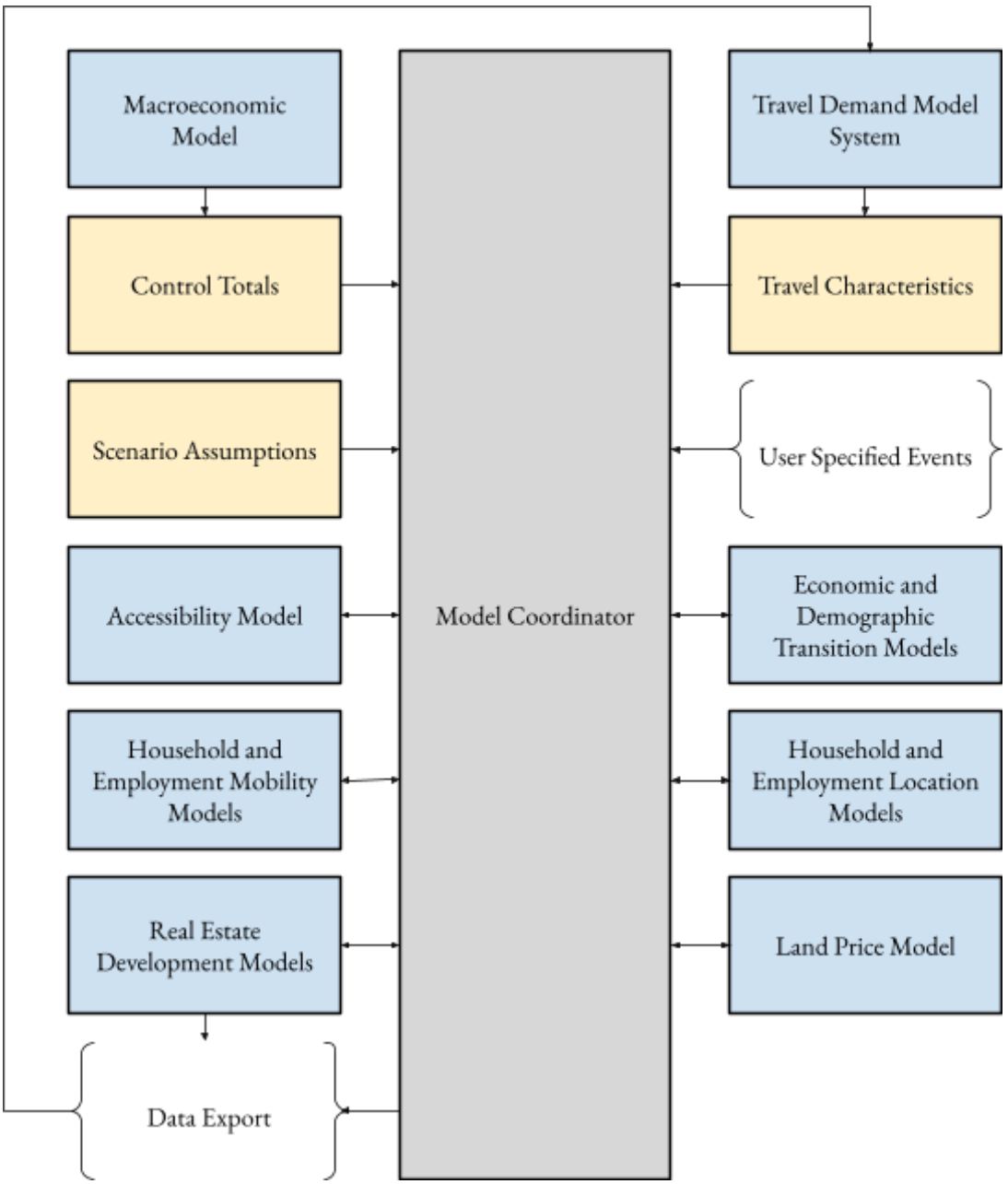

Figure 25: UrbanSim Simulator Schema

The UrbanSim Framework: A model coordinator orchestrates the Macroeconomic constraints and the changes in location and characteristics of jobs, households, and residential / land-use change and value dynamics, first creating, moving or evaporating new units, then assigning them modeled characteristics, and addressing the impact in travel behavior.

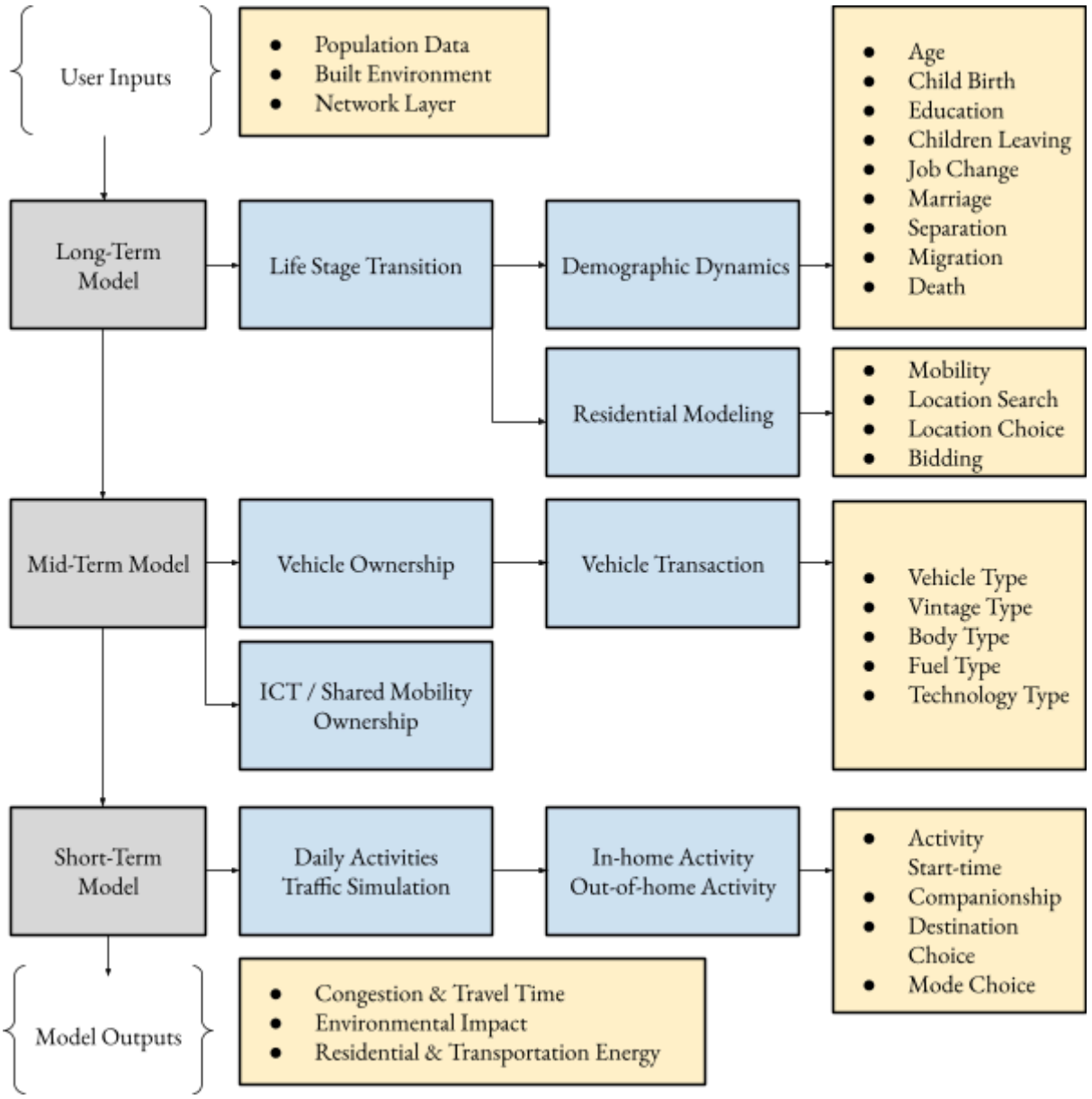

Figure 26: STELARS Simulator Schema

The STELARS Framework relies on three model levels, concerning long, mid or short term decisions that affect travel behavior

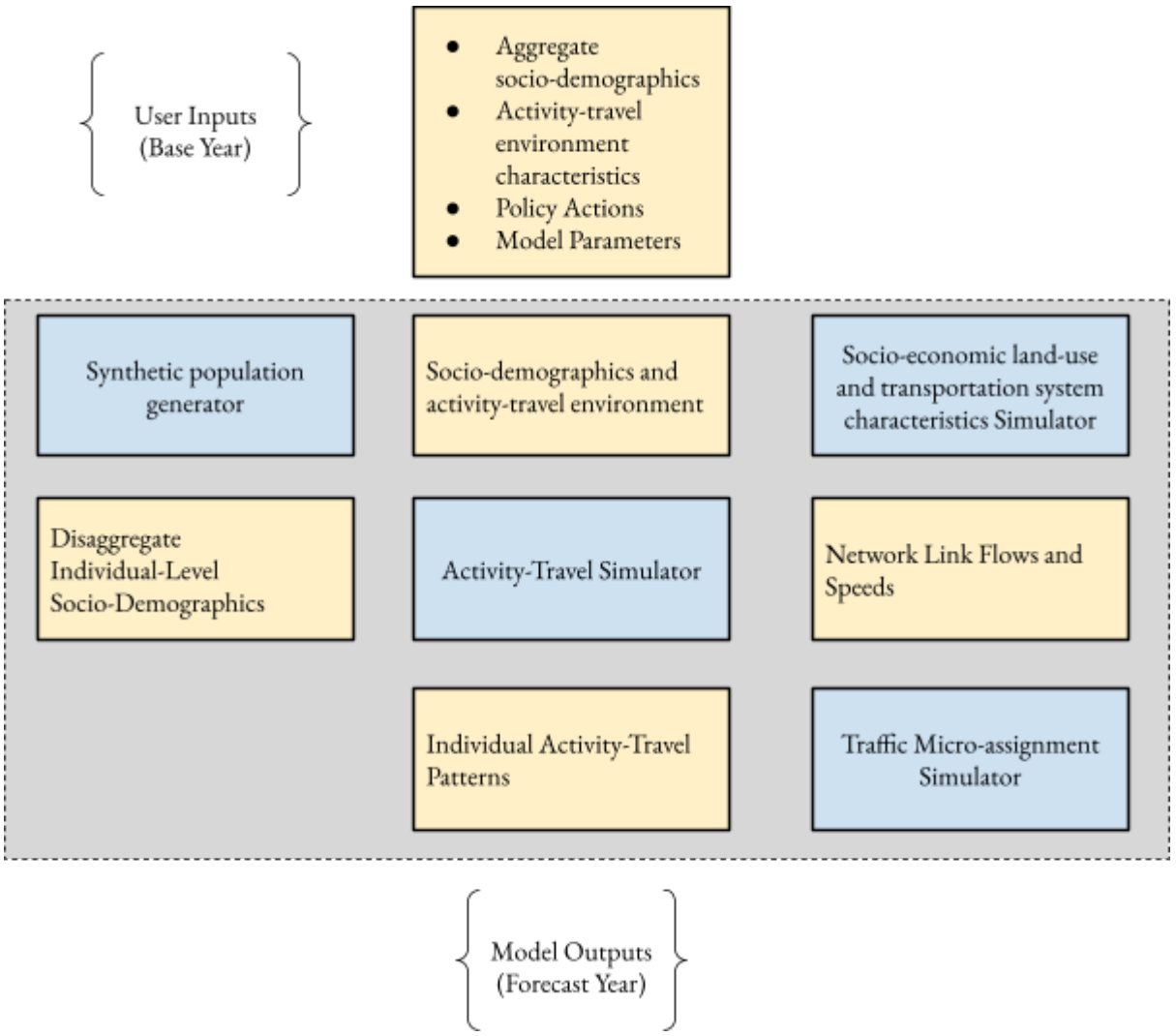

Figure 11: CEMDAP Simulator Schema

The CEMDAP Framework consists of a structure of stops and tours, which together constitute the travel pattern of an individual. They sequentially model working, shopping, and other activities, assigning a duration constraint, which is then assigned to the network in order to inspect the impact of this particular travel pattern.

3.2.2 Disaggregate Analysis

Concerning Travel and the Built Environment

In the present scope of study, if the data is detailed enough, and built environment, route, behavior or attitude, and socio-economic characteristics of the traveler are well informed, this is commonly the preferred approach in research, as it can help isolate different predictors and individual situations, and alleviate the effect of ecological fallacy, or the incorrect assumption that a particular spatial extent accurately represents the mechanisms of effect on individuals (Handy, 2002; Stead & Marshall, 2001; Krizek, 2003; Ewing & Cervero, 2010).

Concerning detail, disaggregate analysis faces a common problem in statistical analysis, which is the tension between generalization and particularization: The level of detail which can be accessed by researchers, tends to be inversely proportional to sample sizes. If particular aspects of travel dynamics are to be inspected, and are not informed by official statistical sources, then ad-hoc surveys need to be conducted, raising the cost of the operations and diminishing samples. If larger survey operations can be conducted, then some critical aspects of the trips or the respondents can be missing.

Recently, disaggregated trip data coming from GPS sources such as mobile phones offer unseen volumes of data but, complying with privacy laws, can lack critical information on purpose or transportation mode. Regarding privacy, unless surveys are conducted by researchers, detail on origin and destination of trips are also commonly missing, posing a big obstacle for the small-scale research scope of urban proximity (Aldred, 2019).

Concerning Urban Proximity

The disaggregate approach has been consistently used in walking, cycling and public transportation modes, trying to gain insights to inform policy. Concerning the walking mode, the greatest challenge mentioned in the literature refers to the spatial matching of characteristics affecting trips, as mechanisms affecting route choice (or, in general, pedestrian choice) might affect at very detailed scales, and are commonly related to design features, which are sometimes too micro to be captured (Cervero & Kockelmann, 1997; Handy, 2002; Lee & Moudon, 2006).

Making a decision on which individual features to control for, and which environmental features to measure (for instance, measuring density at the origin, the destination, or along the route) critically impacts the data associated with individual trips. The common practice is to measure these characteristics around the respondent residence, though thresholds and ways of measuring these areas of influence are not consensual, and rather arbitrary (Lee and Moudon, 2006). The routes taken, as aforementioned, are commonly not informed and need to be inferred through shortest path or as-the-crow-flies assumptions.

Trip chaining (different stages of a trip), and Tours (the whole journey from residence, activities, and back) are also relevant issues in disaggregate analysis, as trips commonly include an active phase (even if it is a very short stage), which is broadly overseen in the literature (beyond access to public transportation), but can be crucial to fully understand accessibility (for instance, for less able users, having a complete accessible path can be decisive on whether to make a trip or not), and to address multi-purpose trips.

Concerning trip motivation, the review shows how non-work, daily activities are the most targeted by urban proximity works. For disaggregate analysis, the labeling of this information is crucial, as the lack of it leads to inferring trip motivations, introducing a degree of uncertainty in analysis. The distinction between walking and cycling for transport and leisure is usually overlooked both in travel surveys and mobile or GPS data, leading to confusion about these kinds of trips. This is important for outcomes of sustainable mobility that intersect with (mental and physical) health strategies (Grasser et al. 2013), and studies that use time constraints to investigate individual trips. The underlying idea is that, in active modes research, travel is sometimes the actual activity pursued by individuals, which leads to many questions to traditional transportation research design and the notion of the cost of travel (Saelens, Sallis & Frank, 2003).

This approach has been identified in various works. Haugen et al. (2012) extract two cross-sections from a database of geo-located residences and workplaces, and compute euclidean distances between them and other amenities (both from home and workplaces), in order to understand the variation through time. In this work, relevant places are informed in the original data, but no detailed information on trips is present. Searcy (2018) uses a travel survey from students in different universities targeted only at distances and mode choice. Li (2022) uses big data on grocery store visits, but needs to join the sociodemographic data from census tracts on trips. Birkenfeld et al. (2023) use official OD travel data and also infer missing sociodemographic characteristics from the census tracts (testing a multilevel model to compare, and finally check the validity of the disaggregated approach). They ultimately aggregate to the household level which, given its scale, should also be considered as a disaggregate analysis of this kind.

3.2.3 Aggregate Analysis

Concerning Travel and the Built Environment

This is **the most prolific approach**, probably due to data availability (Handy, 2002; Aldred, 2019). However, all works include caveats as **aggregation masks results** through the assumption that individuals are equally affected by a phenomenon within a boundary (referred to as the "ecological fallacy"). Commonly, aggregate analysis is also **chosen for simplification**, as highly disaggregated data in transportation models can complicate computation stages. In the four-step models, Transportation Analysis Zones (or TAZs), are simplified as points (centroids or other relevant points), masking characteristics of the zones, which are considered to be "internal" to these points. As Cervero (2006) states, most models in transportation were never meant to be used for research on local characteristics, so **alternatives should still be explored**.

It has been consistently used in past research of travel behavior hypotheses. In general, the two more frequently mentioned **caveats** deal with **the influence of areas on individual behavior**, and the closely related topic of the **scale of analysis**. The way in which a certain area influences individuals needs to be motivated by hypothesis about the mechanism of influence, and the literature either points as **selecting the smallest aggregation available or** a level **derived from expertise or information** needs.

Reviews warn about the bias introduced by spatial units of analysis (such as the Modifiable Area Unit Problem*),* as arbitrary boundaries severely influence statistical distributions. Research either commonly tries to **delineate areas with a sense of homogeneity** or normalization, or attempts to **divide space in equal areas** (such as grids); and general statistical robustness, **testing areas for outliers and comparability**, although this might reduce observations. Aggregate Analysis is also popular for **policy investigation**, as zonal regulations (for instance, speed or transportation fee policies) more often occur within administrative boundaries and; when investigating delineated urban typologies (such as Transit Oriented Design or New Urbanist designs).

Concerning Urban Proximity

For urban proximity studies, aggregate analysis leads to **questions on the scope of influence of closed boundaries**, as in travel research, the targeted behavior "overflows" more often than not, and issues of

contiguity and spatial representation introduce bias. In the review, it is shown that most studies do utilize versions of statistical methods that control for spatial contiguity by means of geographic weights.

Regarding accessibility, and other built environment metrics, the drawback of this approach is how aggregation masks metrics of the built environment. In the best case scenario, metrics are calculated at residences or detailed trip level, and then aggregated by weighting of trip frequency or population. In the worst case scenario, they are calculated from centroids of areas, which greatly simplify the detail of the built environment in them (specially if they are large enough).

In the review, broad aggregations such as functional regions have been found: Bartzokas-Tsiompras & Bakogiannis (2022) use already aggregated data at the city level (produced by the OECD), and further aggregate it into Functional Urban Areas). Elldér (2024) uses a similar input to Haugen (2012), yet models route choice with a more detailed network approach before aggregating data to the city level. Smaller aggregations are either expert or already data-provisioned geographies, which tend to look for the most detailed available. Marquet (2015) uses Barcelona's Neighborhood level, which already has ready-to-use information, building travel data from a travel survey aggregated at customized TAZs.

Data-enriched boundary sets are common. Calafiore et al. (2022) use population weighted code-points as metric basis and aggregate into a neighborhood-like level. Aristizábal et al. (2023) use TAZs which have associated O-D trip data, yet also aggregate accessibility metrics from a lower, residence-based representation. Poorthuis & Zook (2023) and Knap et al. (2023) use neighborhood scale weighted centroids, and associate it with other variables ready for that particular level. In Abbiasov et al. (2022), they infer trip details from the origin and destination zones and the distance / travel time and aggregate travel data into neighborhood levels, calculate access from centroids, and use the ready sociodemographic information for this spatial scale. A similar case is Yu & Higgins (2024), who aggregate data into the census data level.

3.2.4 Choice Modeling

Concerning Travel and the Built Environment

Many theories of associating choices to utility exist, including utility maximization or optimization applied to consumer theory. In transportation, this approach derives from the popularization of the implementation of utility theory in the different steps of the four-step models. It attempts to predict the probability of

individuals/households choosing destinations, transportation modes, or routes based on the relative utility of alternatives, assuming rational decision-making.

This approach has a stronger theoretical basis in testing causality, including destination choice, combinations of choices, or frequency, and modeling the built environment implicitly as costs/attractiveness in utility functions, at the same level of socio-economic characteristics. This way, the built environment becomes a utility or a disutility in different assumptions made by researchers, but it is commonly introduced in the "unobserved features". According to the review in Handy (1996), choice modeling commonly uses multinomial logit techniques and, though these do not equate the development of choice theory, they have great potential to understand the contribution and complex relationship of different predictors of travel behavior.

The most obvious drawback of choice modeling is that, beyond a cost to be minimized (in time, distance, or money), or taste controls, the way in which the built environment affects the decision to travel, the mode to take, and so on, has not yet been addressed sufficiently. Using, for instance, the example of density, the complexity lies in the fact that, what one individual or groups of individuals can perceive as a utility -for instance, walking and not driving through an historical center so as to avoid the complexity of doing so-, others can have an opposite view -for instance, driving through a historical center to avoid agglomeration, or having a perception of less safety-. The fact is, that if the utility of density was to be addressed, difficulties in making clear statements about hypothetical mechanisms of effect arise.

Concerning Urban Proximity

Choice modeling around urban proximity should be primarily oriented at the decisions that residents prefer to make in their local scope. Active modes have been acknowledged as probably needing a particular reformulation of the theory, as derived-demand theories are too narrow to capture the quality of the travel experience. Perceptions of safety, comfort, aesthetics, and so on, may also be important components of utility (Handy, 2002). Also, local destinations should be treated under the hypothesis that closeness (or being within a proximity range) is a main driver of destination choice.

As mentioned earlier, the main problem faced by these models is that comparing the utilities and disutilities of different transportation alternatives (modes, routes, destinations...) might be straightforward when they simply account for time or distance (or price) cost, but when other subjective ideas are to be captured (such as stroll quality, multi-errand possibilities, or taste preferences), the quantification and comparison between modes tends to become arbitrary and complex.

Choice modeling is quite relevant for a modal-shift oriented policy paradigm, and accessibility metrics have been consistently used throughout this research line, as they are thought to be flexible enough to capture all relevant dimensions of choice. Its complexity lies within the nuances of user-segmentation of the perceived

convenience of different transportation alternatives, not only focusing on one, but on all modes, as proposed in Silva et al. (2023). In the review, choice modeling can be seen in the works by Aristizábal et al. (2023) or Yu & Higgins (2024). While Aristizábal et al. (2023) focus solely on the pedestrian, Yu & Higgins (2024) use walking, cycling, public transit, and driving in order to understand how increases of low-carbon modes impact car use. However, none of these references state clear mechanisms of effect, as in utility choice, and simply associate predictors to travel outcome in the same level.

3.2.5 Activity-based Research

Concerning Travel and the Built Environment

This approach to transportation research rose around the 1990s as a **behaviorally-oriented** research proposal for integrating aspects of the **time-geography** paradigm and **human activity system** analysis (Hagestrand, 1970), with the **economic theory of consumer choice** (McFadden, 1973).

In a way, it can be seen as a **more detailed form of choice modeling**, but its goals go beyond choice into **more qualitative angles** that take into account **group negotiations** within human groups (and especially households), **time allocation** in tasks (considering limited time budgets), **task scheduling** (considering limited activity timetables), and interdependence (for instance, of members who can't drive to those who can, or other kind of accompanying) commonly by direct surveying and further modeling (Timmermans, 2009).

Moreover, activity-based research tends to deepen the understanding of travel in the context of the activity being realized. For instance, one can easily understand that commuting is a kind of travel which will normally tend to time optimization in the morning but, what other nuances could be explored if the commute includes a school drop-off, an evening activity, or some errands within? What would be the role of negotiation within a household in the distribution of these tasks? Moreover, what is the role of the built environment facilitating or preventing this behavior?

It is acknowledged -in some of the reviews included in this work- that activity-based research **tends to focus on very particular population segments or activities**, as the multiplicity of **possible combinations** to address this complexity might turn research inviable, computationally. This way, activity-based research can

also be seen as a very particular way of doing disaggregate research, only holding in mind more detailed hypotheses on the complexity of their time-space, social, and intra-household context.

Concerning Urban Proximity

In a broader sense, urban proximity studies can seize the qualitative insights gained by this kind of research to **address local policy and tailored interventions with specific collectives**. For active travel in short ranges, qualitative studies will expectedly be interwoven with bottom-up place and neighborhood definitions and, for travel behavior in general, connected to the aforementioned idea of residential satisfaction and self-selection. The main drawback of this approach is that, for large samples, qualitative studies are more expensive and subjective for research, yet some middle ground needs to be found with recent popular approaches through indirect data (such as mobile data), which commonly has privacy issues concerning qualities of individuals.

As per travel behavior in proximity, understanding the valuation of access to services and amenities in a "virtually time/distance inexpensive manner", could be framed within activity based research. The way in which this **proximity affects residential choice, satisfaction, daily trips of subsistence or recreation, trip chaining and tours originating in residence, and other behavioral aspects**, could use the many methods stemming from activity based research.

In the reviewed works, Haugen (2011) used a targeted survey to address questions on the respondents' distances to various destinations, valuation of the importance of proximity to these destinations, and satisfaction with the distance. Gil-Solá & Vilhelmson (2012) use an individual-based geocoded database on the importance of geographic proximity and sustainable accessibility, including data on activities and services visited, choice of activity/service location, modal choice, access to modes of transport, environmental values, and experienced time pressure. Birkenfeld et al. (2022) aggregate individual trips of a survey into their households, in order to inspect the complex interactions between members and their travel needs and patterns.

3.2.6 Spatial Analysis

Concerning Travel and the Built Environment

Spatial Autocorrelation refers to the degree to which a set of spatial data objects are similar to nearby features (given an explicit definition of nearness), either because they are affected by a third factor, or because they simply group naturally in space. This has statistical implications for research. When it is present, statistical techniques that assume independent observations may yield biased or inefficient results, as a third location factor violates the assumption of independence of the observations, leading to unreliable results. Commonly, spatial autocorrelation is controlled using spatial regression models, which incorporate location, or spatial autocorrelation metrics on residuals that point at misspecification. Scale and the Modifiable Unit problems deal with the implicit assumption of statistical areas being the limits of the influence of phenomena on the travel that originates in, is attracted to, or happens within them. This problem is commonly addressed by multi-scale analysis or scale optimization (Hong et al., 2013; Duan et al. 2023).

Though many reviewed works account for spatial dilemmas, a purely spatial analysis would target a spatial outcome, or the inspection of clustering in space as the aim of study. This is the least represented research strategy in the general review of Travel and the Built Environment. It is usually a kind of study that uses spatial statistics to identify regions in which a certain behavior concentrates in a significant manner. In Krizek (2003), an interesting methodology for addressing local accessibility hotspots is presented. Using a grid-like aggregation, and measuring a series of built environment factors around each cell (using a 1/4 mile radius), it explores the sensibility of the patterns identified, both spatially and statistically.

Concerning Urban Proximity

Three spatial analysis techniques have been identified in the review of recent empirical approaches: pattern identification, spatial lagging, and a bivariate identification of spatial clusters. Metrics of pattern identification are being used to cluster proximity behavior along with other factors, to establish statistical associations, as exemplified in Calafiore et al. (2022) or Knap et al. (2023). The work by Knap et al. (2023), particularly, uses a bivariate Local Moran approach, which is the testing for coincidence in spatial autocorrelation variables. Spatial lagging or weighting has also been identified in several of the reviewed works, such as Graells - Garrido et al. (2021), Calafiore et al. (2022), Yu & Higgins (2024), Poorthuis & Zook (2023) and Aristizábal et al. (2023). Spatial lagging is commonly used for smoothing the values of spatial observations, taking into account their proximity or contiguity. This approach is common ground in the use

of spatial data, however, it is prone to significant biases, as the definition of proximity directly impacts the distribution of the smoothed variables.

3.2.7 Longitudinal, Experimental studies, and Time Series

Concerning Travel and the Built Environment

Testing policy impact is extremely valuable. However, it is complicated when only cross-sectional information is available, meaning that changes in behavior can not be attributed to changes in the context, whether it is of the political or the built environment kind. Also, and even less present in the literature, experimental studies which test actions or changes on a controlled population, are rare. In Cao (2009), a number of longitudinal studies are reviewed and show at least three tendencies: "before and after" intervention studies, commonly targeting a controlled group (for instance, a certain school population before and after walking infrastructure is improved); "movers" studies, or targeting an observed population which has changed residential location; and pure longitudinal studies in which a robust time series on travel and other variables are available (this being also quite rare, for data operations are sometimes discontinued).

Longitudinal designs are also limited for conceptual reasons: the required assumption of stability of the causal processes over time; the difficulty in achieving optimal time spacing of measurements; self-selection into participation groups (survey participants sharing characteristics); and the added time and expense of data collection. Studies are also hampered by not measuring qualitative features (such as attitudes) across time, and by not including feedback loops from the built environment to attitudes. Though longitudinal studies are a conceptual ideal, causality can't get rid of the dilemmas of complexity. (Naess, 2015; Aldred, 2019).

Recent reviews such as Koohsari (2017) or Aldred (2019), suggest the use of natural experimental research designs borrowed from health science. Though this approach -targeting groups which are "treated" by an urban intervention- seems appealing, there are difficulties in objectively measuring qualitative outcomes, defining the extents of interventions and their effects, and controlling for other confounders.

Concerning Urban Proximity

Longitudinal studies are positive for one main reason: testing policies effectiveness. A seminal work by Kitamura (1997), studied the before and after the implementation of the rapid transit system in San Francisco (BART). In the quasi-experimental proposal by Handy (2005), a survey is conducted including "past" questions. Also, the residential self-selection question has been addressed by surveying current home location versus previous ones (Krizek, 2003). In general, reliable data obtained from two points in time remains a challenge (Krizek, 2003), and probably the most promising source is mobile data (Aldred, 2019).

In the review, Haugen et al. (2012) and Elldér (2024) use the same time-consistent data sources to understand changes in travel behavior, while Kasraian et al. (2019) use a time series of land use data to model the regional evolution of the Netherlands. In Graells-Garrido (2021) a very fine grained time series is available, yet it is considered a certain limitation, as it is reduced to a "normal-day". They exemplify how longitudinal studies can only be proposed with data consistency and, design-wise, they can afford the use of percentage variations.

Haugen et al. (2012) used consistent datasets of 1995 and 2005 to disentangle the evolution of the Swedish territory in terms of accessibility, either by influence of the redistribution of services, or the redistribution of the population. Using a regression model estimated for 1995 on the 2005 data is an interesting research design for applying the service structure and conditions of one year into the other, thereby only changing the population distribution, and yielding an estimate of a reasonable "pure" population redistribution effect. Elldér (2024) and Kasraian (2019) are examples of research based on reliable and fine-grained datasets with time attributes, allowing to map the evolution of distances between residences and workplaces.

3.3.1 Gravity Models

Concerning Travel and the Built Environment

Gravity models are still the most popular approach to macro-scale interaction in quantitative geography. These models popularized with the formulation of the four-step model and are still a common approach to transportation modeling. They use graph representations of all possible origins and destinations as nodes (labeled with their associated weights), and their relationships as edges (labeled with the cost of traversing the

edge), usually in the form of an origin-destination matrix (Morris, 1979; Apparicio, et al, 2008; Iacono, Krizek & El-Geneidy, 2010; Acheampong, 2020).

These models use weights to connect pairs of origin-destination (quantities of land-use, residents or trip frequencies). Interaction is quantified by defining units and "decay" functions. The simplest case could be an euclidean as-the-crow-flies line, measured in metric distance, used as the denominator of the gravity function. But, as theoretical nuances are added, this case can be more sophisticated, for instance, if it is assumed that two points interact through specific paths in a graph representation (the shortest path, or other justified form); or if it is assumed that the interaction "decays" with distance, for instance, in an exponential, gaussian or logistic way (Guida & Caglioni, 2020).

Concerning Urban Proximity

In Knap et al.(2023), a special case of gravity model called the two-step floating catchment area is used, which first assesses "destination availability" at the supply locations as the ratio of destinations to their surrounding origin within a proximity threshold, and then sums up the calculated ratios around each residential (demand) location. In Birkenfeld et al. (2023), the gravity model used is the WalkScore metric, which is an accessibility metric, centered on each resident of an area, with an exponential decay function linking destinations considered relevant to proximity. Also, a public transport gravity-based accessibility measure is defined, as the quantity of jobs reachable within the region's from a location and weighted by a gaussian-fit decay function derived from census data (Santana-Palacios & El-Geneidy, 2022).

In the review, Graells-Garrido et al (2021) is the most detailed example of a gravity model. It models the number of visitors at the destination area from the origin area using a gravity constant, is a measure of mass (population) per area, and a deterrence function based on the distance between areas. They find that "a common and well-behaved way" to estimate the parameters of this model is by adjusting a Generalized Linear Model (GLM), with a Negative Binomial (NB) distribution for count data. The GLM is fitted by maximizing the log-likelihood function.

Yu & Higgins (2024) do acknowledge that gravity-based measures are a better option than cumulative opportunities (which is the common accessibility metric used in the 15-minute city exploration) because they capture the effect of travel time on a person's travel decisions, but they are considered more difficult to calculate and interpret. In practice, they argue, cumulative opportunities measures tend to be highly correlated with gravity-based measures and, despite not accounting for the effect of distance decay, are considered an adequate measure of accessibility (Santana-Palacios & El-Geneidy, 2022).

Accessibility metrics themselves can adopt the form of gravity measures, whenever their conception assumes both the weighting of origins and destinations, and costs between them. This class of accessibility metrics are also designated attraction-accessibility or potential metrics (Vale et al., 2016). However, a few questions arise

on the validity of gravity-model for proximity studies. Concerning policy-making, there is a friction between graph models and area-based policy making. A challenge is being able to delineate discrete areas for intervention when appraisal comes in a network-like format (as results of statistical modeling will be associated either to nodes and/or edges). However, if nodes and edges of the graph are detailed enough, they become a great approach for identification of street segments or specific buildings that could be prone to intervention. What origins and destinations are involved, (and what is their weight) and what are the means of interaction (the edges in the graph, their cost weights, and their decay functions), is a question that will be detailed in the section dedicated to accessibility, yet it can be advanced that these will vary greatly when considering different modes, and particularly active modes.

Finally, if a "proximity state" exists, in which a particular behavior occurs, do gravity measures apply within these boundaries? Say, if many grocery shops are within reach, will the closest or the "heaviest" be preferred by a particular resident? In this sense, gravity models are more consistently used in macro-scale analysis, in the form of accessibility to the CBD or to employment opportunities (Boarnet, 2011), while micro-scale is addressed differently, for instance as "access to the closest destination", as proposed by Handy (1993), and exemplified in the present review by Li (2022).

3.3.2 Random Utility Models

Concerning Travel and the Built Environment

Random Utility Models are based on choices of a user between attributes of the alternatives (in this case, transportation modes, distances, or even routes), which can be observed, and other features which can not be observed. In these models, choices are predicted as a function of the allegedly most objective "cost" attributes of the alternatives (time, distance, etc.), and a random component which, after the first fitting of the utility function, is normally regressed against other unobserved features, which can be variations in the knowledge, perceptions, taste, preferences, and socio-economic characteristics of decision-makers or, concerning the present scope of study, the influence of characteristics of the built environment.

The main advantage of this heuristic is that the most objective choice constraints can be modeled first (for instance, if the cost of a transportation alternative is out of reach for a particular income), and other unobserved variations can be associated later, after the cost variables are controlled for.

A great example of application of Utility Theory can be found in Kockelman (1998). The author proposed a Utility Theory consistent way of modeling household behavior; first, assumed that access times for general activity types are endogenous, and households tend to optimize quality of activity over time cost, as long as the marginal value of travel time plus the monetary cost of travel remains below the marginal value of increased opportunities brought about by traveling farther. The challenge, however, is that the quality of an activity is latent or unobserved, and the distance and time required to access activities is dependent on the household location and the mode chosen. The author segments destinations by a measure of quality, defined as the number of opportunities at different travel times for the four types of trips.

The thorny question in these models is then the notion of cost, as time or distance constraints are only a rough simplification. For instance, further iterations of this theory have included more complex behavioral and psychological aspects such as the expected utility theory (the user prefers to minimize uncertainty), the prospect theory (the user prefers to minimize loss in choice), and the regret theory (in which the payoff of all transport alternatives are modeled simultaneously) (Acheampong, 2015).

Concerning Urban Proximity

Concerning urban proximity studies, in the review, they are represented by works which use multinomial logit and nested logit probability formulations with accessibility metrics, such as Li (2022), and Birkenfeld et al. (2023). By implementing these models, researchers imply that people will select the most accessible locations to their needs to minimize travel costs, all things being equal. The thorny questions for modeling Random Utility Models are that, beyond accessibility and personal taste, other features of influence can be at work (not particularly in the "minimization" way) and, again, whether in proximity thresholds, these "minimization" assumptions still apply (Ewing & Cervero, 2010)

Random Utility Models have been consistently used in activity-based research, and as a way of formulating more theoretically-sound metrics of accessibility, attempting to "maximize" utility (Acheampong, 2015), or by introducing the concept of "satiation" (Morris, 1978), a concept that it is perceived equivalent to the approach by Yu & Higgins (2024), in which a notion of "sufficiency" and "intensity" is modeled in the accessibility metrics. For policy making, it is important to focus on those features that can be actually intervened (such as accessibility, but also density or land-use mix), and also to understand other taste or preference features, so as to tailor policies to targeted groups.

3.3.3 Theory of planned behavior - Habit Formation

Concerning Travel and the Built Environment

The Time-geography paradigm classifies constraints for an individual to interact in three main groups: **Capability constraints** are the individual's ability to perform a trip (physical, psychological, socioeconomic, or legal), the **coupling of activities** that can be realized (running on a schedule that imposes time restrictions of length and coincidence), or **authority issues** (some activities need to be compulsory done in a specific place at a specific time).

Accessibility has been revealed as a quite relevant metric to the general review, and a common way of implementing ideas stemming from the Time-geography paradigm. Geographical aspects of accessibility include **both physical spatial relationships** between places and **mobility**, as well as the **time-geographical constraints**. Mobility requires resources that are unevenly distributed across sub-groups, and influence their distance-bridging ability. Also, the perception of proximity may also vary across groups. Thus, individual-level accessibility needs and/or wishes should be understood as subjective and relative to individual preferences must be accounted for.

Activity-Based research is also often coupled with the Time-Geography paradigm. The three constraints mentioned are usually either general survey design lines to account for, or filters for available data to be inspected. When concerning intra-household research -or other specific groups-, the constraints become very relevant to understanding the actual travel possibilities that can be expected in statistical approaches.

Concerning Urban Proximity

Concerning proximity, the Time-geography paradigm can be traced in Haugen (2011) and Gil-Sola & Vilhelmson (2022), who **understand the choice of proximity trips as situated in a time-space context in which distances between residence and preferred activity locations, and space-transcending mobility resources play influential roles**.

Haugen (2011) applies this approach to **residential location choice**. To the author, residential location defines the prerequisites for everyday destination choices, in the context of household dynamics, evolving with time, having a multi-scale and multi-purpose logic, and constrained by capability, coupling and authority issues. Gil-Sola & Vilhelmson (2022) inspect constraints influencing the considerations of

households as to perform activities -nearby or at a distance- considering **three strategies**: **high-speed mobility, spatial proximity, and virtual mobility**. From a time-geographical perspective, individuals implement these strategies separately or in combination to maintain and extend their opportunities to act in time and space. The choice of one or a combination of these strategies is situated between the place of residence and preferred activities, and the individual's command of space-transcending mobility resources.

3.3.5 Complexity theory and General Systems theory

Concerning Travel and the Built Environment

Reviewed in Acheampong (2015), Complexity Theory and General Systems Theory seem to have gained recognition in urban and regional planning and modeling. They mostly deal with **cities as complex adaptive systems** with several **interacting components** that manifest **perpetual disequilibrium**. Three approaches have been identified as most connected with the present scope of study: **complex network analysis, agent based travel research, and Monte-Carlo simulations**.

Complex **network analysis** is used to understand the web of interactions within transportation systems, extracting properties such as **connectivity, centrality, and resilience**. It focuses on emergent properties of networks that help identify **structures and significant elements** within them. A paradigmatic set of works in this sense are the studies by Porta et al. (2004; 2006), who build graphs from street networks (either by using intersections or street segments as nodes, which they call the primal or dual approach), and a number of centrality (structural) properties, which show differences between planned and unplanned cities, and connections with the emergence of retail activity and movement flow.

Recent studies point at other methods for unveiling network complexity such as **community detection** (an approach which attempts to differentiate connected subsets of networks) (Guidotti et al. (2016). Marshall et al. (2018), highlights the **non-trivial** task of associating **weights** and **properties** to graph-like representations. Ding (2019), summarizes research directions using complex network approaches as: importance identification, centrality assessment and density estimation approaches; research on **coevolution** of network growth and land-use change; and challenges such as modeling overlaid transport networks.

Agent-based models (ABMs) simulate interactions of **agents** with **defined behavioral response**, and allow examination of **emergent phenomena** that arise **from simple rules** governing their interaction. By incorporating behaviors, preferences, modes or route scenarios, ABMs provide hints on how policies or infrastructural changes impact transportation systems. Despite its consistent use in research -particularly in simulation-, ABM faces validation problems: "even if its output matches reality, it's not always clear if this is because of careful tuning of those parameters, or because the model succeeds in capturing realistic system dynamics". (Chen, 2012; Bastarianto, 2023).

Monte-Carlo simulations involve using random **sampling** and statistical modeling to understand the impact of risk and uncertainty in prediction and optimization problems. In transportation, they simulate scenarios of demand and network performance under varying conditions. They allow planners to assess the probability of different outcomes, the **robustness** of systems **under uncertainty**, and develop strategies to mitigate risks. Monte-Carlo simulations are particularly useful for stress-testing transportation networks against extreme events and ensuring that urban infrastructure can withstand and adapt to unforeseen disruptions.

Concerning Urban Proximity

These propositions allow **path-dependent** and **emergent behavioral** studies of **active travelers**, and the feedback relationship between land-use and transportation (such as foci of activity which suddenly attract pedestrians, and the activity attracted by pedestrian flow). No papers in the present review explicitly mention complexity theory. However, some tools could be connected to its scope. Emergent properties of proximity behavior -and, particularly, active travel behavior-, or emergent properties of the built environment in which it takes place, could be inspected for association.

In the case of complex networks, the association of structural centrality metrics and other techniques such as community detection, have been consistently used to predict pedestrian flow, especially through the aforementioned Multiple Centrality Assessment or Space Syntax inputs (McCormack, 2021; Sevstuk, 2021; Jabbari, 2023). These inputs include the multiplicator effect of configurational centrality -the idea that spaces which already have naturally flow attract even more flow and activity; the conservation of angularity -humans follow topological and angular rules to navigate space, above distance; or the role of the betweenness centrality metric (the proportion of shortest paths in a network that cross a particular edge or node) concentrating flow. The idea is that configuration, movement, and activity form a complex causality set, but the former is the preceding phenomenon.

In the case of ABM and Monte-Carlo simulations, active modes are represented by so-called "artificial pedestrians". In a recent review by Lakmali et al. (2024), directions given are similar to general trends in the literature, such as the need for more universal validation and calibration, the use of efficient computational frameworks and contemporary data-centric techniques such as Machine Learning; and some specific ones which connect with previously reviewed theories on this field, such as the investigation of the influence of

human-centric urban design on pedestrians, the incorporation of behavioral and cognitive theories and cross-disciplinary studies, or the use of GPS and VR-collected data sources, among others.

3.4.1 Trip Length

Concerning Travel and the Built Environment

Distance traveled are widespread metrics in the travel and the built environment literature (specifically connecting the hypothesis that New Urbanist development could reduce trips' distance globally). The work by Newman and Kenworthy (1989, 1998), associated mean density of cities to total traveled distance, as a proxy to fuel consumption. In both Utility Theory and Activity-based research, these metrics are important to control for logical thresholds of households' time budgets (Kockelman, 1999; Boarnet and Crane, 2001).

This variable might come in a way which is not exactly the target of study, so it needs to be translated (for example, GPS data can have a timestamp logic from which to derive total trip time, but the distance is unknown; or travel data has a declared trip time, but distance is unknown). In other cases, it will be a perceived (declared) quantity, so caution is advised when deriving conclusions with it. Some studies compare perceived and objective distances as a way of capturing the influences of different features in perception.

Another metric found in the literature is excess travel, originally coined by Hamilton (1982). It compares a theoretical metric of minimum travel required, accounting for land use distribution of residence and other land use categories, such as work places and, more recently, non work travel (Fan et al., 2010). This metric assumes a state of efficiency or balance among pairs of land use, and then compares it to the observed situation, in order to identify locations, purposes, or population segments which have unbalanced travel dynamics, which can be seen as a latent situation prone to some mode or distance shift.

According to Ewing & Cervero (2001; 2010), trip lengths are primarily a function of the built environment and secondarily of socioeconomic characteristics. According to the work presented by Kockelman (1999), trip lengths are more of a cardinal than a continuous variable, meaning that a notion of thresholds might be at work when making a decision of actually performing a trip.

Concerning Urban Proximity

Concerning the scope of this thesis, most works already assume a threshold to be targeted for modal shift which will likely happen within non commuting trips, possibly not affecting them much. It might be interesting to study global trip distance reductions as an indicator of modal shift only if the means available do not permit to actually study modal split trends. However, the empirical use of distance thresholds is quite relevant for proximity studies, particularly to position destinations and users into definitions of proximity.

In the review, targeting trip lengths is exemplified by two works: Haugen et al. (2012), who survey this particular metric for everyday non-work trips, comparing it with trends in accessibility to services and facilities in Sweden. The outcome of distance is treated as a way of understanding different "affordable" distances for different social groups. Searcy et. al (2018) seek to empirically establish "proximity thresholds" for mode choice, deriving them from the continuous distribution of declared distance in a travel survey. Another connection with the notion of thresholds is the work by Marquet (2015), who predicts "proximity trips", or trips that comply with a definition. This way, even though the target is to measure frequency, a certain distance threshold is imposed on the original trip length variable, turning it into a binary feature.

3.4.2 Trip Frequency

Concerning Travel and the Built Environment

Trip frequency is an outcome (and an input in the generation step) variable in transportation four-step models. The way in which trip generation and attraction is modeled into the four-step model is to assign a **number of expected trips** (in a fixed period of time) to different land uses, **per unit of area**. For instance, the Institute of Transportation Engineering (ITE) of the US maintains a statistical relation of **trip rates** per land class, widely adopted in that country for development modeling (ITE, 2021). It can also be used globally, **as a count of trips between areas**, or within a boundary, and it is a common way of serving aggregated datasets. In disaggregated diaries, frequency can be a survey question referring to a week, or other relevant time span. According to the meta-reviews by Ewing & Cervero (2001, 2010), trip frequencies appear to be **primarily** a function of **socioeconomic** characteristics and **secondarily** a function of **form.** A more recent insight in Schläpfer et al. (2021), is the finding of a consistent emergent pattern using worldwide data:

"the number of visitors to any location decreases as the inverse square of the product of their visiting frequency and travel distance". This suggests frequencies exhibit spatial clustering and decay behavior, consistent with gravity, accessibility, and complex emergent behavior approaches.

Concerning Urban Proximity

Concerning proximity, trip frequency can be adjusted to proximity trips, as a proxy for modal-shift policy information. If, instead, the focus is on active modes, **specific frequencies** could be derived from observations of destination **footfall**, for instance. The approach in this review is that -after assuming a filter of observed trips through a definition of proximity- predicting the number of trips through simulation or regression. This prediction can adopt many forms, such as the percentage of active trips in a period of time, as seen in Marquet & Miralles-Guasch (2014, 2015), simply the number of trips that fall into the defined time threshold, as in Abbiasov et al. (2022) (who transform their results into elasticities), or total number of trips, given a global simulation, as in Graells-Garrido et al. (2021).

Beyond the particular review of empirical works, works like Currans & Clifton (2015) can be mentioned, who propose inferring modal split from the ITE rates (adapting vehicular rates to active and public transportation modes) by using built environment, policy and trip end characteristics. They use three methods of adjustment: a parsimonious expected modal split by density buckets (derived from regional trip survey datasets), and two sets of binary logistic regression models using combinations of variables such as residential, activity, intersections density, distances to CBD, and policy characterizations. They conclude that simply adjusting by density, works better than the ITE rates. Carpio-Pinedo et al. (2021), use trip frequency rates to build an accessibility metric that captures complementarity and imbalance of land use in proximity.

Frequency is quite an interesting way of **transforming amounts of land use in theoretical trips triggered**, making it suitable for **gravity models**, or **accessibility metrics,** popular for proximity studies. Also, in forecast models, frequency by mode is assigned to network edges by route assumptions, transforming into **predicted traffic volume**. In micro-simulation studies focusing on pedestrians, frequency can be of use when predicting footfall, which has a major impact on street use and vitality.

3.4.3 Modal Split

Concerning Travel and the Built Environment

Modal Split is the most targeted outcome through **utility theory**. However, most models have been designed for regional scale and automobile - transit splits, considering active modes as intrazonal dynamics (Cervero, 2006). The utility maximization approach makes sense when dealing with long trips and their alternatives. But, **in the case of active travel, utility and disutility are more elusive concepts** to define. Whenever research includes all modes in the equation, caution should be taken with irrelevant alternative bias (Handy, 2002). Researchers think that different alternatives are connected by **latent demand**, in the sense that, whenever a trip is made in one mode, this trip "evaporated" from another. This potential for mode shift raises questions when it is acknowledged that not all factors or utilities can be applied across modes. Also, it means that some endogeneity exists between choices (Ewing & Cervero, 2001; 2010).

According to Ewing & Cervero (2001; 2010) **mode choices depend on both the built environment and socioeconomic characteristics (though probably more on socioeconomics)**. This means that quite a complex set of factors will influence the decision, making it very difficult to disentangle their relative importance. As aforementioned, utility theory can be quite helpful here. If a number of **critical factors** can be pointed out (for instance, if no subway is reasonably available, it will not be possible to use that mode; if no parking space is available, it will not make likely to drive; if a highway fare is beyond the budget of a user, it will most likely not be possible to take it; and so on), **then more elusive nuances of utility can be tested** for importance or influence **in a second iteration**. The **question** remains, however, if the models should be specificated to account for all modes, or be particularized for each.

Concerning Urban Proximity

Concerning proximity, modal split is critical to understand possibilities of modal-shift. Through accessibility metrics, research has consistently associated the decision whether to drive or ride transit with the cost of reaching destinations and the level of service (fares, time, and distance, but also the availability of parking space or the levels of congestion), and the accessibility of public transportation itself (not only in distance but also in the whole out-of-vehicle time, waiting, and transferring) (Stead & Marshall, 2001; Handy, 2002). These topics have been hot topics in the debate over better (and commonly, faster) automobile level of service, transit coverage, or other nuances such as experience or reliability (Banister, 2008).

For active modes, **most models** of mode choice **suffer from a degree of misspecification**. Cervero (2006) proposes some enhancements such as **simulations** like the aforementioned UrbanSim (to explore how other complex factors can affect travel), **tour-based models** (which account for the complete trip chain, including all stages that might involve walking or cycling), **auto ownership models** (to tune-up the aforementioned trip generation through frequency and capture the tendency of auto trip degeneration), **pre-mode choice models** (that estimate walk and bike trips before taking the main mode choice), **intrazonal estimates** (estimating the actual possibilities of travel inside zones), **respecified mode-choice models using built environment variables** (at the same level of more traditional cost variables), or **congestion feedback loops** for models (which, after forecasting auto-travel, work the hypothesis that over-congestion could cause the flow towards other modes).

Data availability constraints arise when targeting active modes. When available travel data express the modes of transportation, it is usually the longest trip mode which is labeled for complete trip chains, so a limitation on the tour-based or the pre-mode choice exists in the sense that these **trip stages are obscured by data**. Also, though **indices** of walkability (or other complex approaches to built environment suitability for active modes) **bear some relationship with choice** (Ewing & Cervero, 2001; 2010), their influence is **sometimes too micro** to be transparently accounted for (Cervero & Kockelmann, 1997).

In the present review, the problem of Mode Choice is addressed in different degrees of complexity. While Searcy et al. (2018) simplify the problem to a question of distance and choice, and Marquet (2015) or Aristizábal et al. (2023) focus solely in pedestrian share (the first accounting for the percentage of proximity trips and the second for purely pedestrian trips); other approaches like Yu & Higgins (2024) do target all modes, but acknowledge a definition of proximity by filtering only non-work everyday trips under 15 min (calculated for each mode) for essential needs. This last approach is consistent with the proposal in Silva et al. (2023), which proposes to use all modes in order to understand the potential for modal shift in “proximal environments”.

3.4.4 Other Outcome Metrics

Concerning Travel and the Built Environment

Three outcome metrics of the four-step procedure have been identified as popular targets in this work. A fourth step, however, is largely missing from both the general and particular reviews: Route Selection. In four-step models, after a frequency per mode is obtained between two areas or pairs of origins and destinations, a route is assigned to this frequency to capture the expected "volume" in segments of the infrastructure. This route is modeled through the shortest path assumption, or the minimization of the cost associated with each edge of the network. This "cost", as in other parts of the review, can be a distance or time cost, but it can also model events like congestion or level of service.

It is the already reviewed ABM and Complex Network approaches which have explored further in the line of route selection, by investigating the possible rules that affect navigation in space, beyond metric (or time) shortest path constraints. Even though these are very particular threads of the literature, more emphasis should be put on them if urban proximity studies need to acknowledge user-tailored metrics, and more realistic catchment areas. Another interesting approach to travel outcomes can be related to behaviors and attitudes towards mobility. These more social, qualitative outcomes are relevant to policy so as to strategize implementation, and relevant to research mainly to address the question of the endogeneity of travel attitudes to residential zones (the problem of self-selection).

Crane (2000) and Cao et al. (2009) summarized a number of ways to express the idea of residential self-selection statistically, ranging from qualitative approaches like direct questioning for residential satisfaction or dissonant opinions or travel behavior, to more sophisticated statistics such as joint choice models. Even though these are normally used to control statistical models using other predictors, behavioral outcomes can become the main target of research, especially in activity-based research. Closely related to behavioral questions of self-selection, the outcome of Car-Ownership has been largely explored by researchers, as an attitudinal proxy towards less car-dependent urban environments.

Other metrics can be related to trip outcomes, in a way of "translating" their effects,, as seen in the Trip Frequency chapter. BMI, for instance, is an alleged outcome of active transportation which can capture the importance of walking or cycling for transportation in public health promotion. GHG Emissions, as a proxy to understand whether modal splits which rely less on automobile travel achieve the targets of sustainable

mobility. Real Estate prices or revenue, associated with pedestrian flow, are also an interesting metric which has gained some attention in recent years.

Finally, the "spatial" outcome, or targeting a significant region "automatic" delineation, given a series of associated hypotheses of definition, can also be noted here. Though they are not per se an empirical approach, spatial techniques such as regionalization (differentiating groups of spatial regions through some statistical method) or the analysis of spatial patterns (testing the non-random distribution of values in spatial features) can also be outcomes of works concerning these reviews.

Concerning Urban Proximity

Concerning urban proximity, the route selection outcome of transportation models is not found in the present review, though widening the scope of search, some interesting works on the matter have been found: Salazar-Miranda (2021) studied deviations from shortest pedestrian routes, and associated these to network-level metrics, using computer vision techniques, concluding that visually enclosed streets, with less complex facades, and better access to parks, sidewalks and businesses, are the most desirable streets. Angel (2024) used a Machine Learning approach to -similarly- associate 20 street-level characteristics to pedestrian traffic data, and suggest that importance attributed to them vary across different time definitions, some characteristics such as land-use mix, have low significance at street level, and areas with low walkability can also show very high walking volume and vice versa.

Behavior / Attitude as study outcomes is exemplified in the review by Haugen (2011) specifically addressing the proximity satisfaction (as a state of accessibility) in a qualitative survey. Gil-Solá & Vilhelmson (2022) also survey socioeconomic, attitudinal, and motivational features to then regress them against objective demographics and built environment characteristics. In these cases, the approach is more observational, not going as far as to attempt to predict attitudinal characteristics, as proposed in Crane (2000) and Cao et al. (2009).

BMI / physical activity - is a common outcome in public health - related studies. For instance, it is shown in the work by Frank (2006), that a 5% increase in walkability is associated with a 0.23-point reduction in body mass index; in the review by Berghauser-Pont (2021) that increased density is associated with lower BMI, or the review by Grasser et al. (2013), who point at a strong association of BMI with walking for transport.

Car ownership is quite an interesting variable that lies in the intersection of attitudinal, behavioral, and age and/or income constrained parameters. Van Acker et al (2016) formulate a question on a potential two-way relationship between car ownership and travel behavior (does car ownership affect travel choices and does travel behavior affect car ownership?) In Cao (2009), the reviewed works around the issue of Residential Self-Selection suggest that population density and transit-based job accessibility at home have an association with car ownership. Also, unexpectedly, Javaid (2020) reports no clear evidence on car-ownership and

provision of infrastructure. In the review, the study by Calafiore et al. (2022) a rather strong negative correlation was found between the services accessible in a short walk and car ownership.

GHG emissions are an indirect way of measuring one of the effects of transport and, according to the review by Gao (2023), it has been a hot topic since 2015-2018. Some earlier reviews noted that emissions were positively associated with increases in walkability (Frank, 2006), and they might be especially important when measuring work-related travel (Boarnet, 2011). Recent research reports that residents living in communities with a higher density emit fewer GHG emissions from both cooling and heating and transport (especially passenger vehicle, while results for truck-related emissions are inconclusive (Berghauser-Pont, 2021).

3.5.1 Destination Accessibility

Concerning Travel and the Built Environment

Reviews in transportation reveal the accessibility concept was early adopted in quantitative studies: it was a core operation in the trip distribution of the four-step model (Ortúzar y Willumsen, 2011); used to measure distance to transit in utility models (Vickerman, 1972; Hanson, 1987), and used to address policy information, evaluation, and simulation (Vickerman, 1974; Morris, 1978).

The recent review by Guida & Caglioni (2020) reveals an annual percentage growth of 7.5% in related publications since Hansen's work, with a growing interest in accessibility as a planning tool, revolving around land use and transport, individual perceptions, and socioeconomic context, all playing a role in recent research. Advances since then include nuancing metrics by needs and abilities, the transport system considered, and advances in readability. Accessibility can be formulated in multiple ways:

- ➔ Either outcome (actual transportation behavior) or process phenomena (theoretical access potential)
- ➔ Either objective (in an indirect and theoretical way) or perceived (declared data) accessibility.
- ➔ Either relative (the degree of connection between two points, or the effort involved in it) or integral (the degree of interconnection between a point and all others, or a measure of total travel).

Early reviews recommended feasible and simple metrics, and revealed some dilemmas in using accessibility modeling for trip generation and modal choice, as it could both be seen as an outcome or a predictor in the parameters estimation. Parameters in the metric construction of accessibility are:

- ➔ An impedance to reflect the cost of travel (the ease of traversing space via a given system, and the rules of using a system). It can be metric, time, transportation expenditure, and so on. No consensus exists, although it can impact catchment areas greatly (Vale et al., 2016). Epistemological works on proximity advocate for the use of metric impedance, as average user speed (if using time) makes too bold assumptions on constant speed, ability, and commonly overlooks topography (Weber & Kwan, 2002; Silva et al., 2023).
- ➔ The set of opportunities to account for. For example, transit stops or economic activities.
- ➔ Attractiveness variables to reflect availability of opportunities at destinations to satisfy particular needs. For instance, the trip frequency in four-step models, number of jobs, or transit frequency.

It is acknowledged that potential indicators of accessibility are as numerous as the combinations of these parameters. In an operational sense, accessibility approaches have been summarized as follows:

- ➔ Contour measures (cumulative opportunity, or isochrones measures), define catchment areas (ego-graphs around nodes) by drawing travel contours around a node in a movement network, and measure the number of opportunities within the boundary (number, square meterage, etc).
- ➔ Gravity-based measures (or potential accessibility measures, based in the aforementioned work by Hansen), which define catchment areas by measuring travel impediment on a continuous scale, applying a factor or decay function (commonly power, gaussian, or logistic) to each opportunity reached, which is also weighted by the size of the opportunity in question.
- ➔ Utility-based measures (based in the aforementioned Utility Theory), which interpret accessibility as the outcome of a set of travelers' choices, and measure the accessibility from each individual to the potential destination, as the sum of the utility that each opportunity represents, being able to intrinsically introduce utilities beyond movement cost. These are encouraged in reviews such as Acheampong (2015), as they can be tailored to individuals' time and activity constraints.

Concerning travel and the built environment research, accessibility is present at least in three of the "D's" dimensions:

- ➔ Destination Accessibility: Capturing a regional structural condition, accessibility has been consistently used in the investigation of urban sprawl (Clifton et al 2008). It is acknowledged as a detached (yet complementary) condition to local accessibility (Handy, 1992), having a greater impact in commuting and broad-scale travel (Ewing & Cervero, 2001; 2010). It has been proved to have impacts in traveled distances, auto ownership and use (Chen et al., 2008; Stevens, 2017), residential self-selection (Krizek, 2003) and, in terms of modal balance, in local mobility choices (Boarnet 2011). Commonly, it is operationally defined as total accessibility to jobs by car or transit, or distance to the CBD.
- ➔ Distance to Transit: It is conceived as the cost to reach the nearest public transit stop, commonly separated by modes, and often weighted by its level of service, or the regional accessibility it can provide. It has been related to the particular choice of public transit, and is usually measured as an

average of the shortest street routes from the residences or workplaces in an area to the nearest rail station or bus stop. Alternatively, it may be measured as transit route density, distance between transit stops, or the number of stations per unit area (Ewing & Cervero, 2001; 2010). It is also linked to the regional issue, as transit-based and job accessibility at home also had a moderate association with car ownership and mode share (Chen, 2008; Stevens, 2017).

- ➔ The local provision of services and facilities: Strongly connected to the review, and it has been either Walkability Index, (measuring and weighting the provision of local services through a gravity index), or using a contour measure to address the number of facilities around particular residents which, as aforementioned, is the most literal and popular approach to operationalize the 15-minute premises (Logan,2022 ; Papadopoulos, 2023; Megahed, 2024).

Concerning Urban Proximity

Accessibility metrics are transversal to most studies in the present review. These review local and active accessibility, pointing at the user-tailoring of metrics, and particularities of walking, as research gaps.

- ➔ Handy (1992) described local accessibility as being primarily determined by nearby activity, mostly oriented to convenience goods, located in small neighborhood centers. The author distinguished it from regional accessibility in terms of distance, but also on relevant destinations.
- ➔ Krizek (2003) introduced the concept of neighborhood accessibility, stating it provides local attractive, multimodal options for a variety of travel purposes. The author measures it in a continuous, grid-like, spatial threshold and contiguity manner, operationalizing metrics of density, diversity and design within neighborhoods, but with a bottom up strategy using a disaggregated grid.
- ➔ Saelens & Handy (2008) review environmental features associated with walking and find accessibility (as proximity to non residential destinations), as the most powerful predictor. They find recreational walking and accessibility are very equivocal in the reviewed works.
- ➔ Iacono, Krizek & El-Geneidy (2010) explored problems related to the development of accessibility measures for non-motorized modes, which primarily arise around data quality, zonal structure and adequacy of models and travel networks for calculation. Authors propose measures sensitive to spatial scale and more behavioral realism. Using gravity measures on a tailored network to capture walking, cycling, and transit accessibility, the authors found a limitation on shortest-path assumptions, and improvement gaps in the inclusion of a temporal and individual component.
- ➔ Vale et al. (2016) revealed the fragmentation of active accessibility research in theoretical and measurement terms (associated to data limitations, but also theoretical flails), scale of analysis (little works test sensitivity in this aspect, critical in spatial threshold selection, or other geographical biases such as edge effects), the focus on origins and not on destinations and, to a lesser extent, on routes (as frameworks such as Lee and Moudon, 2003 propose), as well as the scarce use of multicollinearity tests (when merging different built environment dimensions into walkability or accessibility scores).
- ➔ Bolten & Caspi (2021) propose a personalized pedestrian network analysis accessibility framework for embedding and retrieving pedestrian experiences. Authors discuss traditional methods for studying neighborhood accessibility of residents to amenities with aggregation error effects and biases as they ignore the travel network, assuming pedestrians mobilize only init, or aggregating neighborhoods or blocks into points of origin. They propose pedestrian mobility profiles where an individual (or a subpopulation) is represented as a vector of cost parameters determining composite internal costs of

travel through particular environments. The profiles are used as a parametric expression of features and weights that impact route choice through pedestrian paths. Also, the study of "the last 50 meters" as a proxy to micro scale design features and complete travel chains is still seen as a research gap.

Accessibility in proximity studies needs a more detailed view. It has been mentioned how their use has been the cornerstone of compliance measurement in the 15-minute proposals, with a number of conclusions.

- ➔ Logan (2023) acknowledge the same critical points in accessibility metrics for the 15-minute city (the scale and amenities included, and the user-tailored approach), and extend the recommendations: measuring the percentage of residents within isochrones should not be the sole measure of a city's accessibility, and using amenity statistics is misleading. Also, statistical threshold-based measures (in the sense of "how accessible is 90% of the population in an area") or measures of the kind "minimum distance to" or "maximum distance to" have several critical limitations for x-minute statistics.
- ➔ Megahed (2022) reviews different approaches in measurements of the X-minute city, and found the POI catchment area approach (cumulative residents around opportunities) as the most popular, although not recommended in Logan (2023). Less popular approaches are Grid-based approach/Origin Destination (cumulative or weighted opportunities around residents), Building Catchment Area (reach from different POIS), or other mixed approaches, and a minority of works using graph representations and indicator/index-based methods.

Though generally using aggregated isochrone-cumulative opportunities from residences, metrics are built with greatly varying thresholds, means of interaction, and sets of opportunities. Works that do not follow this approach use accessibility as an outcome of observed or surveyed behavior, without assumptions on thresholds. Works that do calculate theoretical states of accessibility (to regress it against other outcomes, or differentiate it through predictors) mostly take a set of "everyday" destinations which, although similar, differ in their particular definition, yielding incomparable results. Means of interaction differ in the use of decay functions, euclidean metrics, and network-based approaches. Some works take the challenge of translating a "compliance" approach by building metrics on the concept of "satiation", using "optimal" or "sufficient" states of access to necessary urban functions, and an "intensity" measure of access above these optimal states.

3.5.2 Density

Concerning Travel and the Built Environment

Concerning the present scope of study, it was the work by Newman & Kensworthy (1989) which triggered the contemporary debate around density and its influence in energy consumption. The authors studied mean densities in a sample of American cities and compared transportation energy use, arguing that the sprawling tendency in the US was the main cause of congestion and inefficiency. These claims sparked a public debate over the validity of both of the ideas (density driving mobility issues) and their measurement.

The review by Berghauser-Pont (2021) reveals how grounded the idea of density is in contemporary planning for sustainability, and how its measurement evolved towards a more solid basis, becoming the main parameter in zoning strategies and a pervasive feature in research on morphology travel and mobility. According to this review, transport was the most frequent domain to use as a predictor (35% of 229 papers; 49% of consumption, emissions and health effects are accounted for).

Along with transportation, it is noteworthy that density is pervasively used in other domains, such as public infrastructure (provision and efficiency of public services), economics (around scale and agglomeration economies, innovation and efficiency), environmental impact (noise, energy demand and efficiency, and pollution), social impact (social interaction) and health effects (mental and physical).

Types of measures of density depend on the quantity in the numerator, and the spatial area in the denominator. Concerning the quantity being measured, a simple classification can be made as follows:

- ➔ Metrics concerning population, such as population or household, as a “fixed” amount living in an area. To a lesser extent, working population density is also addressed, as a “floating” population that exerts an influence on the occupation of an area, during the day.
- ➔ Metrics concerning morphological aspects of density. Floor Space Index (or floor area ratio in the North American context) (FAR, FSI), which accounts for the total built floor space; Building Density or Total Building Units count; or Urban Cover Density (ground space index - GSI).
- ➔ Categorical Metrics, such as urban, suburban and rural classifications based on density.
- ➔ Economic Density or number and/or quantity of functions or activities, labeled by land-use types.
- ➔ Other metrics accounting for perception, or capturing phenomena such as urban sprawl.

Concerning the denominator, measures of density also show a diverse range of options, both accounting for the scale and method to define the units. Concerning scale, decisions on research strategy and targets (but also on availability issues) are made to draw the size of aggregation areas. Researchers tend to seek for homogeneous areas but sometimes information goals or availability lead datasets to uneven situations.

Concerning **shape**, definition methods are crucial if tending to homogeneity, but also if directing research to a particular mechanism of influence (perceived neighborhoods, or ecological regions). If evenness is a value, arbitrary administrative boundaries are discouraged by research, in favor of grid-like or catchment-area aggregations. This last approach, called "experienced density" elsewhere (De la Roca & Puga, 2017), is analogous to accessibility metrics of the isochrone type, and opposed to "naive density", which uses arbitrary sets of boundaries.

All documents reviewed treat density as a critical feature. Also, it is treated as a multifactorial characteristic: along with density, other features such as diversity and accessibility are expected. However, density is treated as an independent condition of intensity which is necessary, but not sufficient, to trigger desired effects on travel behavior. Moreover, the review by Berghauser-Pont (2021) underlines the idea that density has a threshold behavior: if certain thresholds are not attained, local travel will not be likely to happen and, if exceeded, negative effects on urban well-being can be expected. Selected papers have been reviewed to understand the way in which density is treated in the domain of urban proximity:

- ➔ Handy (1996) reflects on how many initial studies focus on density and automobile travel, but overseeing what goes along with density. The impact of density per se may be limited to whatever disutility attaches to auto ownership at high densities due to traffic congestion and limited parking and speeds. This way a number of difficult-to-measure variables are acknowledged to end up masked by density (Cervero, 1991; Ewing 1995).
- ➔ Crane (2000) and Boarnet and Crane (2001) found mixed evidence supporting these initial limitations: some studies suggest that higher density is associated with fewer car ownership and trips, smaller VMT per household and lower car trip rates; but other studies report that, in certain configurations or demographic characteristics and attitudes, closer shopping destinations relate with more shopping trips by car. This way, density is proven as a feature that needs further explanation by behavioral or more detailed demographic or built environment features.
- ➔ Ewing & Cervero (2001; 2010) suggested that preoccupation with residential density may be misguided, as it could be greatly impacted by co-variables such as regional structure and transit provision, when looking into automobile and transit modes. Their meta-reviews suggest that -controlling additional features-, transit use varies primarily with local densities, secondarily with the degree of land use mixing and, in third place, with walking conditions, shorter distances to transit, and parking provision. The relatively weak relationships found between density and travel likely indicate that density is an intermediate variable that is often expressed by the other predictors.
- ➔ Stevens (2017) reviewed conclusive yet small impact results for density associated with less driving, advancing how the mechanism might be lower speeds in dense environments.
- ➔ Handy (2017) suggests that researchers use density more because data is readily available, but do not deepen into its influence in travel behavior. The influence is indisputable, yet not determining.

Concerning Urban Proximity

In a broader scope for urban proximity studies, the literature has yielded a number of relevant thoughts on the use of the density metric. The focus is kept on those inputs that revolve around active modes, and modal shift towards active modes, to find how density has been consistently associated with walking and cycling behavior, yet also unveiled a great number of questions to answer, concerning the mechanisms at work.

Seminal studies such as Levinson & Wynn (1963), Pushkarev and Zupan (1976) or Newman and Kenworthy (1989) advanced the relationship between neighborhood density, lower vehicle trip frequency, and higher prevalence of transit use. However, later iterations such as Hess et al. (1999) or Moudon et al. (1997), demonstrated how pedestrian activity varies for similar density but areas with different design. Moudon & Hess (2000) identified several clusters of relatively high-density residential environments, all with nearby retail, among which many were found not to stimulate pedestrians for they lacked qualities such as good urban design and/ or small block sizes.

Krizek (2003), in the review on neighborhood accessibility, pointed to a similar issue as the aforementioned multi-factorial behavior: Density calculations separate population from employment measures, but it is the synergistic relationship between the two that affects travel, captured by diversity or accessibility metrics, which does promote pedestrian travel; also, a distinction between gross (total land area) and net (excluding open and undeveloped areas) density is pervasive in the literature. Though most research uses net density because it represents how efficiently land is used, net density is preferred as roadways, parking lots, and undeveloped areas affect the quality of pedestrian environments. More recent reviews such as Grasser et al. (2013), still confirm how density is greatly associated with prevalence of walking trips, as long as walkability measures are taken into account.

Ewing & Cervero (2001; 2010) also reviewed how walking varies as much with the degree of land use mixing as with local densities. Also, as with VMT, job density is less strongly related to walking than is population density. Concerning transit use, it is sometimes said that mass transit needs mass, however, according to these reviews, this is not supported by the low elasticities of transit use with respect to population and job densities.

In the review by Leck (2006), residential and employment density, when controlling for residential self-selection, was found strongly correlated with outcomes targeted by urban proximity, namely shorter trips, an increased general prevalence of walking, and an increased prevalence of commuting by transit.

In the reviewed works, density is almost always addressed some way or another, either as a control variable or as a predictor. The parallelism between the idea of “experienced distance” and the isochrone accessibility approach is particularly interesting, as their equivalence could be of use in urban proximity approaches. This way, then, many works are using a “version of density as an accessibility metric”. Also, the fact that “net density” can affect active modes in a more significant way, should be an issue to account for, so the way in which density is measured is also of great importance in this section. In Table 9, a summary of the use of a density approach in the review is presented.

The operationalization of density, in the review, is either an available indicator of relevant threshold (that particularly point at urban-rural transitions), or a metric of "experienced density", consistent with accessibility studies. At least in one case, it is produced only taking into account the amenities used in them. Also, an interesting example of using FAR as a regulatory aspect of density was found. In general, its empirical relevance is either assumed a priori, or acknowledged through results, but in all cases is nuanced by other dimensions of it. This way, as seen in the general review, density is treated as a necessary, but not sufficient condition for proximal environments, and not particularly in the "direction" of the variable (higher density means more proximity behavior), but in the "nature" of the territory that can be drawn from it, in a threshold-way.

3.5.3 Diversity

Concerning Travel and the Built Environment

For Jacobs, there is a certain notion of the multiplying effects in small-scale interaction of a more diverse set of primary and secondary uses. The literature reviewed mostly borrowed metrics from landscape ecology (capturing species interactions with increased biodiversity) and econometrics (dealing with the variety of social groups associated with the attraction of economic activities). Interaction allegedly brings beneficial effects, such as a tighter sense of community or the concept of natural surveillance.

The literature found is not as prolific, yet diversity is pervasively mentioned. It is also addressed as variety or land use-mix. The recent taxonomy proposed by Raman (2019), points at policy-oriented land-use mix as a facilitator of integration and urban vitality and stronger neighborhood character, shorter commuting and walkability, suitability for small investments and economic blend of compatible land uses, or safety, among others. Zhuo (2022), published a deep dive in the concept as a policy tool (and natural phenomenon), with a rather weak theoretical framework, and a still unclear influencing mechanism.

Song, Merlin & Rodríguez (2013) presented a review on metric approaches, with two groups: Metrics based upon land use distribution as a whole (named integral measures, which work better for small geographies such as neighborhoods), and those that make use of subdivisions (which the authors call "districts" or

divisional measures) to look at finer land use distributions. These metrics are presented briefly, along with landscape ecology metrics, which are left out of the former review, but quite used in the scope of this work:

Integral Measures: Used to capture distributions of land use within an area with a single readable number:

- ➔ Percent/Proportion: measures jobs/residential proportion, or other binary relation of interest.
- ➔ Balance Index, Entropy Index, and Herfindahl-Hirschman Index: different approaches to the measurement of the degree to which two (in the case of the balance index) or more (for the rest of metrics) different types of land use exist in balance within an area, allowing adjustment factors of theoretical proportions which can be considered balanced (typically the metropolitan proportion).

Divisional Measures: Metrics sensitive to the shape and size of activity spatial patterns within an area, so the definition of the area itself greatly impacts results. The usage of grids or isochrones of varying scales is explicitly underlined, so as to explicitly address spatial sensitivity:

- ➔ Atkinson Index is a metric of evenness of a particular land use type.
- ➔ Clustering Indexes or "pattern recognition" metrics, labeling spatial units according to their concentration or dispersion.
- ➔ Dissimilarity Index, or the degree to which the distribution of land uses within districts is similar to the area as a whole.
- ➔ Exposure Index, or the degree of potential contact or possibility of interaction, more suitable for absolute interaction effects.
- ➔ Gini Index, or the evenness of distribution of two different land use types across districts, suitable for relative distribution, and somewhat more difficult to calculate.

Landscape ecology measures: Such as the Shannon Diversity Index, the Simpson's Index, or the Interspersion Index, left out of the review by Song and Merlin (2013), but reviewed in Clifton et al. (2008).

- ➔ Shannon Diversity Index: Or the Shannon–Wiener index, is an entropy approach for species diversity, using the number of species living in a habitat (richness) and their relative abundance (evenness). It has been used to address land-use mix either using square meterage or trip frequencies.
- ➔ Simpson's Diversity Index: Takes into account the number of species in an area, as well as the relative abundance of each species. The main difference is that it takes a value that ranges between 0 and 1.
- ➔ Interspersion Index - Juxtaposition Index: Measures not only number of species, but also the relative position of their habitat patches. Originally conceived for habitat fragmentation, it takes into account the length of border between patches (Lowry & Lowry, 2014).

Summarizing, important parameters to account for diversity metrics selection are: the number of classes to be compared; the symmetry they might present (or the question of whether interchangeable proportions of different uses would yield similar values), their sensitivity to scale (widely neglected in the literature), their computation cost, and their usefulness for absolute or relative measurement. In general, though an

acknowledgement of the initial thoughts of Jacobs on the importance of land use mix, qualitative ideas are left out of the question. For the author, diversity of urban settings did mean more than co-presence (and explicitly mentioning proximity) of classes of land-use: the layering at the edge of streets, from sidewalk to buildings, the diversity of building ages (which can trigger a social and income diversity), the diversity of social settings and contexts, and the diversity of uses over the course of a day.

Concerning Urban Proximity

In general, most of the reviewed metrics are present in the meta-reviews, but the most popular metrics are entropy measures such as Dissimilarity, or ecologic measures like Shannon / Simpson indices. However, much of the works compiled in the meta reviews use simple proportions of particular land uses, or manual labeling of mixed areas, which seem to work similarly in explaining certain behaviors as their more sophisticated counterparts. A summary of relevant findings for proximity follows:

- ➔ Frank and Pivo (1994) associate an entropy index to transit usage and walking, and find it to increase as density and land-use mix increase, whereas single occupant vehicle usage declines. The findings from this research suggest that measuring urban form at both trip ends provides a greater ability to predict travel choices than looking at trip ends separately.
- ➔ Crane and Crepeau (1998) found little role for land use mixture in explaining travel behavior. Mixed use settings, labeled by manual inspection, were not found to be significantly correlated with fewer car trips or lower car mode splits.
- ➔ Stead & Marshall (2001) relate the diversity of activity with settlement size (bigger settlements can accommodate more specialized market segments). Their review section around diversity focuses on job-residential ratio, finding some evidence that suggests it is not as important as density, has no particular influence on trip frequency, but it is somehow important in walking and cycling prevalence.
- ➔ In Ewing & Cervero (2001; 2010), land-use mix is reviewed from a perspective of micro-accessibility from residents to different activities or services. Transit use seems to vary primarily with local densities and secondarily with the degree of land use mixing. Land use mix makes it possible to efficiently link transit trips with errands on the way to and from transit stops. Walking varies as much with the degree of land use mixing as with local densities. Also of interest is the fact that jobs-housing balance has a stronger relationship to walking than the more commonly used land use mix (entropy) variable.
- ➔ Krizek (2003) suggests that land-use mix needs to answer a two-sided question: the extent to which the land uses complement one another from a functional and a spatial standpoint. The different strategies include inspection and labeling of mixed-neighborhoods (including the use of accessibility metrics for this particular labeling), the focus on employment percentages, and entropy or dissimilarity indices of diversity. The former are not considered a good indicator of functional nor spatial complementarity, and the latter only measures spatial difference, but not complementarity.
- ➔ Saelens, Sallis & Frank (2003) propose an alternative definition of Proximity as a predictor, considering straight-line distances between land uses and calculating two variables: density and land use mix and; also accounting for a third variable of connectivity as access (in terms of design or the absence of barriers).
- ➔ In the meta-analysis by Leck (2006) it is shown how controlling for self-selection suggests that land use

mix is significantly and inversely related to VMT, automobile prevalence, and positively linked with transit or slow mode commuting.

- ➔ Lee and Moudon, (2006) propose distance measures to routine daily destinations as simple and effective alternatives to complicated composite measures of land use mix. The authors found a small number of variables that remained significantly associated with walking, built as specific destination land uses, measured as their distances from homes (consistently significant in both airline and network models).
- ➔ Salens & Handy (2008) found mixed land use in proximity consistently associated with walking, only behind proximity to potential destinations, and at the same level of importance as density. A particularly interesting finding regarding walking to school, is that results on land use mix were rather equivocal.
- ➔ In Stevens (2017) updated meta-analysis, land use mix increases controlling for self selection were found to make people actually drive more, whenever they already live in a car-oriented neighborhood. While not controlling for self selection yields the expected (negative) direction, this issue implies that if people were to be placed into the type of neighborhood that matches their preferences for transportation, adding additional land uses to that neighborhood would tend to increase VMT.
- ➔ In Vale at al. (2016), land-use mix is considered a pre-condition to trigger the effects of active accessibility, meaning that, without a diversity of places to go, accessibility by walking or cycling is useless.
- ➔ Javaid (2020) review concludes that features such as job or population density and land-use diversity tends to show very low or moderate correlation values with mode shift related outcomes and VMT, but significant importance with walking behavior, when controlled for demographic and perception characteristics.

According to these reviews concerning relevant dimensions of urban proximity, land use mix is a relevant feature when it accounts for spatial and functional complementarity, and thus, it has been proposed to become a particular case of accessibility metrics, which could be quite consistent with an approach regarding proximity. Consistent association with walking behavior does support this idea, and an interesting issue arises when controlling for behavioral features such as self selection. In this review, not many works do account for diversity explicitly. Only two works use a dedicated diversity metric in their models, and another two accounts for the diversity of accessible classes of land use. These are listed in Table 10.

3.5.4 Design

Concerning Travel and the Built Environment

This review deals with design that triggers specific travel behavior, (supporting active modes or preventing driving), but also brings urban vitality, closely related to proximity; which has been addressed by many authors since the postmodern critical wave detailed in chapter 3.1., such as Montgomery (1998). Design features are difficult to capture and test for influence. Boarnet & Crane (2001) reviewed how the problem is complex and poorly addressed by research. To the authors, the latter issue could be addressed by systematically isolating what is separable from urban design, what is properly addressed at individual level, and identifying hypotheses to use. The difficulty is that endogeneity and co-dependence is common with this realm of measures, complicating isolation (Ewing & Cervero, 2010), and quantification.

In the meso-scale of street patterns, measures deal with "freedom of movement" or "ease of traversing space" or, in other words, connectivity. In the architectural scale, research focuses on level of service (width of lanes or sidewalks, or time spent at intersections), the aesthetics of places (the visual attractiveness of a place), and the presence of amenities which facilitate active travel (lighting, benches, universal access features, and so on). These features, since early works, have been considered as too micro to measure consistently, having data availability obstacles, and aggregation-mechanisms dilemmas. For both scales, the common way to go is to bundle characteristics together to form indices of mode-orientation or friendliness, either by labeling neighborhood types manually or deriving composite indices (Krizek, 2003).

The test of design features as predictors has also thwarted efforts to become part of empirical research. For instance, Crane (2000) proposed linking design to price and cost variables as a systematic framework for empirical interpretation. To the author, the greatest challenge is to make this explicit linkage in an utility paradigm (translate design into a number that captures utility). Design features are averaged into indices, as their individual relevance is more elusive than their aggregate effect. Ewing (1996) summarized the general problem: Urban design characteristics may appear insignificant when tested individually, but significant when combined into "pedestrian friendliness" measures. Conversely, design characteristics may appear significant when tested alone, but insignificant when combined. In the literature, it is mostly accepted that design features' influence is a collective one (Ewing & Cervero, 2001; 2010; Ewing & Handy, 2009).

To capture and model street patterns, categorical labeling or quantitative measurements have been tested (Stead & Marshall, 2001), not reporting straightforward results. While many report no relationship between transit use and network design "after controlling for density or service frequency", others suggest that grid-like patterns can be more transit friendly as they allow greater penetration by transit and pedestrians, but also promote more direct routes for automobiles. Pattern type may not influence travel behavior per se, but network form can affect other features like coverage of transit routes (Ewing, 1996) or directness to public transport (Marshall, 2001b), becoming closely related to accessibility. Beyond reach, other ideas of efficiency are related to the street pattern, such as comparisons between grid and dendritic patterns (Boarnet, 2011): Grid-like street patterns are thought to function more efficiently than dendritic ones because increased route choices make real-time route choice possible, prevent traffic from channeling into arterial roads, and allow uninterrupted flow (Crane 1996). Some recurrent metrics of street network patterns have been found:

- ➔ Intersection Degree or 4-way Intersection Index: Captures to which extent a network allows freedom of choice. Degree is a graph attribute of the number of edges (road segments) that end in a node (an intersection), averaged for a network sub-section. Measuring the proportion of nodes which have four edges, only considers those that allow movement in all directions.
- ➔ Connectivity or Straightness Index: Computes the difference between the shortest path between two nodes in a network with the euclidean as-the-crow-flies distance between the same nodes. It captures the efficiency of movement through a network to reach a particular destination.
- ➔ Block Size: Computes the average length of edges in a network, which is commonly associated with shorter trips, but also with a higher number of intersections (and thus, options for movement). It also connects with Jacobs (1961) conditions for urban vitality.
- ➔ Intersection Density: As in block size, it computes the node-to-edge ratio in a section of a network.
- ➔ Dendritic Pattern: Originally conceived to capture the particular pattern in car-oriented sprawl neighborhoods, it is measured as the proportion of cul-de-sac streets in a network.

In terms of street configuration, the aforementioned approaches from Space Syntax or the Multiple Centrality Assessment are absent in this review. However, there are some equivalences in the presented predictors, and interesting mentions which connect with accessibility characteristics. Concerning equivalences, three of the metrics proposed in Porta et al. (2004; 2006) are present in the review, only in the latter they are presented as structural (and unweighted) configurational conditions of the networks: First, Closeness Centrality is equivalent to the Isochrone Accessibility approach, only accounting for the number of nodes reachable, without weighting them by any class of "opportunities". Second, the Straightness Centrality metric is presented in many of the works reviewed here. Third, the Degree Centrality, has already been presented as the number of edges arriving at intersections. The two metrics which are left out, but could theoretically have interesting local implications are the already mentioned Betweenness Centrality, and the Delta or Information Centrality metric, which is a popular measure of "criticality" of elements in a network.

Concerning other direct mentions, in Forsyth (2015), Koohsari (2015) and Vale et al. (2016), all dealing with active and local accessibility or walkability, the configurational theories of Space Syntax are mentioned as

"design" impedances for accessibility catchment areas computation. These ideas work in the intersection of pattern measurement and movement impedance for accessibility metrics, and are referred to as "topological distance", "dual graph approaches" or, in the terms proposed by Space Syntaxs, "axial maps". A summary of these metrics is presented, which can be of interest for general research of features affecting travel behavior.

- ➔ Degree Centrality: From the MCA approach and general Graph Theory, the Degree of a node is defined as the number of edges touching it. A caveat in street networks is that most nodes will have a maximum degree of four (a simple intersection), as most networks of this kind are planar graphs.
- ➔ Closeness Centrality: From the MCA approach, closeness centrality is defined as the average shortest distance to all reachable nodes from a particular node. If a threshold is defined, the metric is weighted by the number of reachable nodes.
- ➔ Betweenness Centrality: From the MCA approach, it is defined as the proportion of shortest paths that cross a particular node or edge, accounting for all possible shortest paths.
- ➔ Information or Delta Centrality: Given a measure of network efficiency as the average shortest path length, it is the degree to which it varies if a particular node or edge is removed from the graph.
- ➔ Integration: Given a dual representation of space, it measures the amount of street-to-street transitions needed from a street segment, to reach all other street segments in the network, using shortest paths.
- ➔ Choice: Represents the number of intersections that need to be crossed to reach a street. It is computed for each road segment by iteratively splitting a value starting in the unit by the number of other connecting segments, until all segments are reached.
- ➔ *Depth:* Given a dual representation of space, it explains the linear distance from the center point of each street segment to the center points of all the other segments.

The architectural materiality related to travel behavior is even more elusive, an "unmeasurable" quality of space -as Alexander (1979), Lynch (1960) or Appleyard (1964) would call it-. Urban Design impacts on travel seldom prove significant when measured individually, but it is definitely unclear that this is not a product of poor measurement and operationalization in statistics. At this micro-scale and level of ambiguity of concepts and mechanisms of influence, design is considered the furthest frontier in this line of research (Ewing & Cervero, 2001; 2010; Ewing & Handy, 2009). Particularly elusive are aesthetics characteristics (Handy, 2002), which drive to subjectivity of perception and cultural constructs. The classifications proposed by Krizek (2003) and Javaid (2020), have been used here to present and update the metrics that are commonly used to research the influence of material design in travel behavior. Concerning infrastructure level features, and with a focus on pedestrian amenities, the following have been identified:

- ➔ Segregated infrastructure: existence of segregated infrastructure for active modes of transportation, which induce safer or more pleasant travel.
- ➔ Traffic Calming infrastructure: actions such as widening sidewalks, traffic calming measures such as narrowing the width of streets at crossings, adding speed bumps, altering road alignments, adding traffic circles, or installing pavement treatments (Salens & Handy, 2008).
- ➔ Sidewalk Provision: the share of block faces with sidewalks and their width, which facilitates pedestrian movement. A great extension is the quality and maintenance of the sidewalks.

- ➔ Sidewalk Continuity: the perception of psychological and physical safety (e.g. segregation of faster modes), the efficiency of movement (shorter trips by easier intersections or crossings), and the ease of movement for multiple user abilities.
- ➔ Pedestrian crossings: the ease and effectiveness of crossing traffic lanes by pedestrians, either in number (or density), or time taken to cross.

Other relevant class of features are experiential elements, which are more opaque characteristics that have been associated with travel experience:

- ➔ Traffic Presence: Fast-moving vehicles, wide turning radii, right-of-way, or average speed limit or traffic volume is measured to assert the influence of the presence and intensity of vehicles in other modes
- ➔ Mean Building Age: Also a proxy for building orientation and network type, it captures predominant architectural style and a condition of design philosophy and evolution.
- ➔ Street width: both a network-level metric and experiential feature, as it might imply higher volume of traffic, if the network is auto oriented, and a less pleasant or effective crossing.
- ➔ Street Setback: understanding if a certain private-public outdoor interface exists, associated with an extra space for outdoor activities, which can in turn attract more passer-by traffic.
- ➔ Active Ground Floor: grounding Jacobs' idea of vitality, (also reported as inactive ground) captures pedestrians' attraction to lively paths, in which trip chaining and natural surveillance can happen.
- ➔ Presence of Parking: level of service for automobiles, it also affects active modes through a decrease in freedom of movement and a worsening of urban scenery.
- ➔ *Street Trees:* Urban Greenery is mentioned in several of the reviews. Whether it is a mere aesthetic or climatic comfort measure, it is included as an area or path index.
- ➔ Other Amenities: Other features ranging from covered transit stops, to benches or fountains.
- ➔ Other Design Characteristics: in Ewing & Handy (2009), other features are presented dealing with the perception, such as composition or perceptions of vitality.
- ➔ Other Physical Attributes: lighting, slope, or even climate, have been used in the literature, also linking with network conditions and, for active modes, as impedances for accessibility.

Another way of describing design qualities affecting travel, is to derive composite indices of mode-oriented appropriateness. These capture collective effects of design features, or the interactive effect involving land-use and transportation. They vary in underlying variables and their combination, through arbitrary weighting of or statistical estimation of weights based on associations among variables, using Principal Components Analysis (PCA) or Factor Analysis (see, for instance, Cervero & Kockelman, 1997). Composite Index impacts on travel bear some relationship to mode choices yet require much more empirical testing and replication of results (Ewing & Cervero, 2001; 2010).

Concerning Urban Proximity

Concerning active modes, studies highlight design considerations (Krizek, 2003). For instance, Cervero and Kockelman (1997) uncovered a design dimension representing overall walking quality. Other early examples in specific planning initiatives such as The Pedestrian Environment Factor (1000 Friends of Oregon, 1993), a score derived from four different components: the ease of street crossings, sidewalk continuity, topography, and fineness of the street grid for local streets; or a similar approach in the city of Sacramento, which derived an index of pedestrian and bicycle friendliness based on a rating of sidewalks, land use mix, setbacks, transit stops, and bicycle facilities, relying on a modified Delphi process.

WalkScore is one of the most consistent approaches to index composition (Forsyth. 2015). It is based on distance, destinations, and connectivity, using 9 destination types, with a penalty for big blocks and low intersection density. It acknowledges not only destinations, but also compactness and connectivity. These indices are derived from definitions of Walkability such as the one given in (Forsyth, 2015): "Traversable environments, with short distances for utility walking, perceived and actual safety, physically-enticing with dedicated pedestrian facilities, pleasant architecture and views, and attractive services."

Lastly, the labeling of Neighborhood Type has been proposed as an holistic classification concerning the orientation of design in terms of transport planning or dynamics (for instance, TOD, auto or pedestrian friendly). It is a way of nesting many difficult to measure variables and, if done carefully, it holds a significant amount of explanatory power, yet it is difficult to generalize and, in many urban tissues, it will be complicated to draw a consistent boundary between types. A number of interesting findings have been made in the general literature, in many cases dealing with this particular sub-thread of proximity.

- ➔ Boarnet and Crane (2001) claim that the only land-use strategy that reduces vehicle-miles traveled by car is traffic calming by design, and other associations lack theoretical foundation.
- ➔ Ewing & Cervero (2001; 2010) conclude that, above density or diversity, VMT and walking prevalence have a strong association with intersection density and street connectivity. Interestingly, intersection density is a more significant variable than street connectivity. This seems right, as walkability may be limited even if connectivity is excellent when blocks are long.
- ➔ Leck (2006) points at studies that suggest that traditional grid circulation patterns reduce VMT. Sidewalk and cycling path ratios influence mode choice to some degree (to some authors) or in a fairly weak manner (to others). Overall, this meta-analysis found the linkage between sidewalk ratio and transit ridership or active commuting to be insignificant. However, the effect of grid percent coverage on the probability of commuting by automobile, was found surprisingly high.
- ➔ Ewing & Handy (2009) presented a model for rating the quality of urban scenery, using video recordings and a well designed sample of respondents, rating different qualities. It illustrates significant features used in the post-modern narratives: Imageability (number of people; proportion of historic buildings; number of courtyards, plazas and parks; presence of outdoor dining; buildings with non-rectangular silhouettes; noise level rating; major landscape features; and buildings with identifiers); Enclosure (proportion of street wall on the same side of the street; idem opposite side of the street;

proportion of sky across; number of long sight lines; and proportion of sky ahead), Human Scale (number of long sight lines; number of all street furniture and other street items; proportion of first floor with windows; building height on the same side; number of small planters), Transparency (proportion first floor with windows; proportion active uses; proportion street wall on the same side) and Complexity (number of people, number of buildings, number of dominant building colors, number of accent colors, presence of outdoor dining, and public art).

- ➔ Stevens (2017) finds a significant correlation between intersection and street density with VMT, comparing areas with high levels of connectivity (such as grid street network) with areas with low connectivity (such as dead-end streets and cul-de-sacs). The author suggests that, as connectivity increases so too do the feasibility and convenience of walking and other non driving forms of transportation, although this does not seem to induce large reductions in driving.
- ➔ Javaid (2020) finds street-design and accessibility measures highly correlated with lower car use, while features such as job or population density and land-use diversity tend to show very low correlation. Transit choice correlates with street design and accessibility (street connectivity and 4-way intersections), while pedestrian share improves most with intersection density.

In this review, the only reference to these "design indices" is made in Birkenfeld et al. (2023), who uses the WalkScore metric to address accessibility as one of the independent variables in their model. The authors found quite significant explanatory power in this metric for the odds of living a more "local lifestyle", using it as a cardinal variable, classified in four categories ranging from "car-dependent" to "walker's paradise".

3.5.5 Demographics

Concerning Travel and the Built Environment

In this chapter, not only individual features are further inspected but, closely related, insights on trip purposes -also a common control in models- is presented. Sociodemographic features can affect travel behavior through a number of mechanisms, according to reviewed theories in chapter 4.4: Distances or others costs will apply differently depending on user profiles, utility will be perceived differently, time constraints and activities and social habits will be closely related to individual and social group characteristics, and so on. Trip purpose can be seen as both a control for trip data, if available, also connected with accessibility destinations, as the hypothesis of accessibility triggering local travel is strongly affected by them.

Hanson (1982), Salomon & Ben-Akiva (1983) and Kitamura et al. (1994) are the most referenced early works in the present scope which dive into the demographic question, and underpin the inescapable influence of sociodemographic features in travel prediction. Preceding approaches had already introduced these features: four-step models using surveys aggregated to traffic analysis zones (TAZ) defined based on socio-economic, demographic, and land-use characteristics (Ortúzar & Willumsen, 2011). In Random Utility Theory, choices between alternatives are predicted as a function of attributes of the alternatives, subject to probabilistic variations in knowledge, perceptions, taste, preferences, and socio-economic characteristics of decision makers, later allowing to introduce other characteristics in a second step. The review search yielded reviews on the psychological and behavioral determinants of travel (Lanzini, 2017), the importance of lifestyle (Van Acker, Phil Goodwin and Witlox, 2016), and the self-selection issue (Cao, 2009) as relevant demographic concepts beyond basic characteristics. Also, as reviewed in Gao (2023), the focus on young individuals and older adults is a rising topic also connected with proximity:

- ➔ Morris (1978), proposed methods of stratifying the population for accessibility analysis, to account for income, socio-economic status, number of cars owned, etc., which vary systematically, and are independent from accessibility. These are likely to affect trip generation as some groups are more "mobile".
- ➔ Hanson (1987) found that, for most dimensions of travel, built environment variables were way less important than socioeconomics and, for recreation and social trips, had no impact at all.
- ➔ Handy (1992), comparing developments with “local accessibility” or “regional accessibility” (or both), also ensured socio-economic characteristics were consistent across the sample.
- ➔ Kitamura et al. (1997) used socio-economic descriptors (along with transit access), and is one of the first studies to incorporate attitudes, lifestyle choices and perceptions. The features were also used to normalize areas of study and test travel behavior. It found that attitudes and lifestyle were way more important than built environment characteristics.
- ➔ Cervero and Kockelman (1997) and Kockelman (1997) show how, even though land use variables have significant effects in some models, elasticities are smaller than sociodemographics.
- ➔ In Boarnet & Crane (2001), the estimation strategies proposed have three classes of independent variables which are then related through different hypotheses: First, the price of travel and income level of the individual as a basic constraint. Second, socio-demographic “taste” variables, known to influence travel (gender, education, age and number of persons in the households), these being different to budget constraints. And third measures of the built environment.
- ➔ Weber and Kwan (2002) also detected the need to separate the influences of location and travel behavior of individuals, as well as relating travel behavior to socio-economic characteristics. Authors warn about relying on aggregate data for individual behavior, and debate over the methods and questions to account for individual characteristics, such as multilevel modeling.
- ➔ Ewing & Cervero (2001; 2010) suspect that the contribution of the built environment is relatively small compared to contributions of socio-demographic and unmeasured variables.
- ➔ Focusing on self-selection, Cao (2009) defines the issue as the tendency of people to choose locations based on their travel abilities, needs and preferences and results from two sources: attitudes and sociodemographic traits. Most studies have employed multivariate analysis and accounted for the sorting effect of socio-demographic characteristics, but a need for more attitudinal variables still persists

- ➔ Among other features, Boarnet (2011) reviewed demographic variables were being typically treated as controls at the time of publication: number and ages of children, gender, employment status and ages of adult household members, number of cars per licensed driver in the household (or other measures of vehicle availability), income, education level, race and ethnicity, and immigration status of the household or household members.

Two suggestions are particularly interesting: Among these variables, vehicle availability is often considered endogenous to the travel behavior decision, and so may be modeled separately; Some studies include measures of attitudes as additional controls beyond sociodemographic characteristics, but there is some debate as to whether attitudes may be endogenous to travel behavior if, for example, persons adjust attitudes toward travel based on the options available or the choices they habitually make.

- ➔ Acheampong (2015) reviewed current Land Use and Transport Interaction models as having three main components: land use, transportation, and socio-demographic. Concerning this last one, researchers understand they are critical, but largely ignore them in meta-analyses, as the overall evidence base is weak. Some of the most consistent findings so far point at pervasive differences: Car use differs between socio-demographic segments, gender, employment status, household characteristics, and income.
- ➔ Van Acker, Phil Goodwin and Witlox, (2016) propose, instead of focusing on objective sociodemographics, a psychographic lifestyle approach that analyzes subjective characteristics such as personality traits and related motives, norms, and values as a lifestyle as a personality style. Two findings call the attention: certain lifestyles, a set of personal preferences, and the options open for each individual, have a clear influence on modal choice, which also changes over time as these influential features evolve; A large body of work relates transitions in family composition (changes in employment or marital status, children, age, and death of family members) to changes in travel behavior, suggesting certain life milestones lead to volatility in travel behavior.
- ➔ Javaid (2020) reviewed individual and social-level features affecting mode choice, which are mostly treated narratively and not systematically. Individual level is mostly assessed through Behavioral and Cognitive features (mostly through the Theory of Planned Behavior and the Habit Formation Theory) such as intention, attitudes, beliefs, awareness, moral, and other personality relevant traits; a. Social level features focus on social norms, (also in the context of the theory of planned behavior, and seen as the behavior considered normal by society), but new approaches are emerging, such as social signaling and social identity perspective (transportation choice as a sort of personal and social statement of values and aspirations, or identity), or social practices (complex symbolic interplays between individuals and social groups).

It seems clear that sociodemographic characteristics are in fact more important than the built environment characteristics or, put it in an utility-theory perspective, they are crucial for the "cost" or "price" function, before testing for other random components, which will come later, in the form of built environment variables. This way, these features are commonly used either as controls to the targeted datasets or the areas of study, or as the main variables for utility testing. Also, the emergence of other, more complex attitudinal and behavioral variables are present, but considered less easy to operationalize than sociodemographic data

derived from surveys or statistical information. The most relevant features found in this review have been divided into categories that seem to share similar mechanisms on travel behavior:

- ➔ Age: Age can affect travel behavior through many relevant mechanisms of effect. The first, and most obvious, is the impact of age in individual ability (for instance, both in active travel or automobile licensing. Lifestyle features, as reviewed by Van Acker (2016), are both affected by the continuous evolution of personal circumstances, and the generational aspects that affect habits and attitudes towards travel behavior. Life events also play an important role in habit formation and change, which are crucial to targeted policy. This feature can be used in a discrete (labeling age groups) or continuous manner, both as an influential feature or a control variable. Older adults, children and youngsters are a particularly relevant group to the present scope, as proximity-related studies are naturally attached to their common dynamics of non-work, residential centered travel.
- ➔ Household Structure: Closely related to the age characteristic is the household structure and the complex co-dependence relationships, which are relevant when studying travel behavior under the paradigms such as Time-Geography, Activity-Based research, or focuses on Lifestyle or residential Self Selection. This feature can be expressed as household size (or mean size in an area), or more finely categorized into meaningful labels that help understand travel dynamics, such as one-member households, families with children, students, retirees, and so on.
- ➔ Income, Employment Status, Tenure: Income (again, of respondent or area-based) is quite a relevant feature as much of the research reviewed here is linked with utility theory under the hypothesis of utility maximization. If it is assumed that users will attempt to minimize costs, then the initial budget of users is a natural constraint. Also, other more complex sociological implications such as status and social signaling, both in residential choice (or lack of opportunity) and transportation mode, are relevant features to account for. Closely related to income is employment status, which has also been seen in a number of the studies reviewed and, as a relevant proxy to spending capacity, car ownership (or number of cars per household) is usually addressed if the data is available.
- ➔ Gender and Ethnicity: Features linked to perception, cultural constructs, and other social dynamics, are quite relevant for understanding travel behavior, either under the Utility Theory if taste features are involved, or more complex disparities that can be relevant for research.
- ➔ Disabilities: Disability, and other closely related concerns such as Universal Access or Inclusive Design are a common goal in policies promoting low carbon mobility. They can impact travel heavily in many aspects, especially concerning complete trip chains in which critical access points can prevent users from even taking the trip in certain modes. This concept has been identified as a gap in the literature around proximity (Ramirez, 2022), both concerning data availability and specific research.
- ➔ Trip Purpose: A final category of demographic features is the Trip Purpose issue. This feature is obviously also a trip characteristic (or a travel outcome), which is commonly used as a control in general studies of travel behavior. However, and given the fact that it is closely related to user profiles, it is included in this section. Trip Purpose will mainly affect the destination of each trip, although depending on the labeling available in data, it will be easier to spatially match it with a destination or not. However, if a theoretical metric (for instance, an accessibility metric) is being built, categories of destination can be bundled into classes according to purposes. This last issue can be thorny for some categories. If, for example, a university trip to a particular zone is given, not many destination candidates will be available to choose but, if a label of “Leisure” is given to a trip, many more kinds of destinations can be observed.

Concerning Urban Proximity

In terms of socioeconomic characteristics, the greatest concern to this work is the idea of the user-tailored approach to a notion of urban proximity. In this sense, accounting for income constraints, perception, activity in the household, or individual ability, will be the main target of the approach. A summary of findings in the specific literature is presented, which basically points at the specific greater importance of socioeconomic traits than built environment characteristics, as in the general review:

- ➔ Concerning active modes, Saelens, Sallis & Frank (2003) found that the inclusion of neighborhood variables significantly adds to the regression models for walking/cycling beyond sociodemographic variables, but only with small magnitude increments. This means that sociodemographic features are way more important in models for these particular modes.
- ➔ Studying walking behavior, Salens & Handy (2008) call for different modeling of different types of walking and specific segments of the population, all in order to explore the question of whether the built environment has similar effects by race/ethnicity, socio-economic status, age, or ability. Also stressed the need for more longitudinal and experimental (before and after intervention) studies, that examine change in behavior before and after a change in the built environment, and studies that examine changes in behavior before and after a move from one environment to another.
- ➔ In Acheampong (2015), an interesting example is given on active modes. For biking, there is evidence that being young and a man increases the likelihood of bicycling, and an ambiguous evidence for the impact of higher income and education level on bicycle usage.

In the recent review of empirical approaches to urban proximity, sociodemographic features are mostly used as controls, and rarely as predictors. Income-related features seem to be the most popular, captured in one way or another (for data constraints), followed by Age. Household Structure and Attitudinal - Behavioral variables, are important for Activity-Travel approaches, and other relevant variables such as car-ownership or commuting condition, are present. It is interesting to note that, given the identified approach of "proximity compliance", demographics are also used as statistical characteristics to differentiate within revealed environments, and in many cases, as a proxy to reveal inequity. Some relevant features, such as disability or gender, are less targeted. A summary of the features identified in the reviewed papers is presented in Table 11.

Concerning trip purposes, a number of global classifications need to be attended to better frame the concept of urban proximity. First, transportation research commonly classifies trips broadly as mandatory or non mandatory; those of maintenance, discretionary, and subsistence nature; or those under time constraints or not. No consensus exists on the classification or the purposes targeted, apart from the loose idea that they are "everyday" dynamics.

In Knap et al. (2023) and Megahed (2024), a summary and comparison of the commonly targeted destinations is presented. Probably the only actual intersection among these are those subsistence trips concerning shopping of basic goods, followed by notions of care (accompanying to school or other medical affairs), and other amenities. Work trips can also be seen in some works which target proximity commuting,

though this idea is elusive and most probably quite place-based, or even person-based if movements have been made towards the workplace. In Table 12, a summary of the categories used to conceptualize the purpose of accessible or proximity trips, in the same language used by each of the author(s), is presented.

3.3.6 Statistical Modeling

Concerning Travel and the Built Environment

In view of the diverse theoretical models and the level of micro-simulation commonly needed for active accessibility modeling, the present approach is situated into utility theory decision-making, though nuanced with uncertainty of individual, social, and environmental nature. Utility theory, being a matter of choice between alternatives, is commonly operationalized using logistic regression models, although the diverse outcome variables targeted do not always make these models suitable, and other approaches are taken. In the meta-review by Ewing & Cervero (2010), it can be seen how simple Linear Models or more advanced Logistic Regression (as well as Probit Models, which are similar), are the most popular approaches to the matter. Even when using simple linear models, variables are usually transformed into their logarithmic scale, to account for non-linear behavior.

Linear regression is useful where travel variables are continuous. Although assuming a simple linear relationship in such a complex research thread might seem optimistic, it can help the readability of the model, making it useful for the present research goals. Simple models such as OLS (Ordinary Least Squares) are consistently used in the literature. Out of the 62 studies inspected in Ewing & Cervero (2010), roughly 50% of them use Linear Regression models. Logistic regression or Probit Models (models using sigmoid functions), are particular generalized linear models which are suitable for modeling probability of boolean choices (such as travel modes). In the meta-review by Ewing & Cervero (2010), around 25% of the reviewed works use these kinds of models.

Many authors suggest that complex models are more suitable for such a complex research topic. SEM has been pointed out as the conceptual ideal for merging utility theory with other psychological or time-geography paradigms (Cao, 2009), and the rise of ML approaches (Gao et al., 2023) has been consistently noted in choice modeling (van Cranenburgh, 2022) and trip generation models (Mukherjee & Kadali, 2022), route selection (Angel, 2024), and even activity-travel research (Koushik, 2020). However, their adoption is still somewhat shy in practical cases, as they are more difficult to operationalize.

In the case of SEM, unobserved or latent variables can be introduced as a linear combination of observed features (which makes it interesting for the complexity of this scope of research), but the modeler is required to construct a model in terms of a system of unidirectional effects of one variable on another, which can also be seen as a disadvantage (Golob, 2003). In ML Models, the fact that the problem is learned from the data makes directional effects not so important, but models can be difficult to explain (diminishing the heuristic validity), and are prone to overfitting issues (specifying the models so much for the available data that predictions with new data can be subject to bias).

Concerning Urban Proximity

In a broad scope on urban proximity, a number of relevant suggestions on statistical models are found in the literature. Saelens et al. (2003) found that, even with a lack of consistency across statistical approaches to active modes and local travel behavior, strong correlations are pervasive for density, land use mix, and some design metrics such as connectivity or directness. In order to integrate utility theory and social approaches, Lee & Moudon (2004, 2006) introduced a socio-ecological framework of characterization of origins, destinations, and route selection as predictors for walking behavior. Boarnet (2011) advanced that, concerning residential self-selection coincident with a model of travel behavior, the use of a rich set of sociodemographic variables can reduce the associated bias, if direct behavioral measurement is not possible.

In the reviewed works, Ordinary Least Squares (the common technique for estimating coefficients of linear regression equations) is used to regress travel outcomes against predictors in seven of the selected papers (Haugen, 2011; Haugen et al., 2012; Abbiasov et al., 2022; Calafiore et al., 2022; Aristizábal et al., 2023; Poorthuis & Zook, 2023 and Elldér, 2024). Logistic Regression in the binary form (probability is measured between 0 and 1) is used in Birkenfeld et al., 2023 and Li (2022), whereas Yu & Higgins (2024) use Beta Regression, another model suitable for binary responses. Moran's I, a metric of spatial cluster classification, is used in Knap et al., 2023 and Calafiore et al., 2022 and, in general, spatial filtering or weighting (in short, accounting for values of nearby observations when introducing each observation into regression models), is used in many of the works, such as Calafiore et al. (2022); Graells - Garrido et al. (2021); Aristizábal et al. (2023); Poorthuis & Zook (2023) and Yu & Higgins (2024).

Finally, a number of papers simply use descriptive statistics to inspect proximity filters or simple hypothesis tests within observation samples or surveys, such as Bartzokas-Tsiompras & Bakogiannis (2022), who use ANOVA tests; Haugen et al. (2012), Kasraian et al. (2019), Gil-Solá & Vilhelmson (2022), and Birkenfeld et al. (2023), who use first-moment descriptive statistics, or Marquet & Miralles-Guasch (2015), who use Chi-square tests. Also, less used approaches include Fractional Polynomial Regression (Searcy et al., 2018) and Generalised Estimating Equations (Kasraian et al., 2019).

A general comment that can be made is that no consensus can be seen in the review. In general, simpler models are preferred as long as they are tractable enough to yield knowledge about the topic, regression or

classification models should be selected by suitability for the nature of the outcome variable, and it is preferred if different features in the models can be inspected for some kind of importance or weight, and direction. This review did not yield sophisticated approaches such as SEM or ML, which can be perceived as a research gap.

4.2.1 Machine Learning Overview

The two most general classes of ML approaches, concerning the nature of their target, are classification and regression models. Classification attempts to label observations given a finite number of input classes, while regression attempts to give observations a continuous value, given the range of an input target variable. Regarding problem design, a common classification is Unsupervised Learning, Supervised Learning, Reinforcement Learning, and Deep Learning. Supervised Learning is based on the use of a "training dataset". Given an outcome variable, the predictive system is fitted (trained) until it is capable of predicting this variable or, in other words, minimizing the loss function. This work focuses on the most comparable approach to traditional heuristics in the field of urban proximity: Supervised learning.

Supervised Learning is based on a "training" process in which the questions to ask take the form of features (equivalent to "variables" in statistics), and the answers take the form of "labels", defined by the user. It minimizes the error between the automatically labeled observations and the human input. As in traditional statistics, it seeks a balance between generalization and accuracy. There is a need for a balance between accounting for particularities and general behavior. This is a central concept in ML, and it is referred to as bias-variance balance or "overfitting vs underfitting". The idea is that if it is possible to predict beyond the sample used to learn from the problem, then the problem has been well learned.

In Supervised Learning, the two most common techniques to assess generalization are test-train and cross-validation methods. The former extracts a portion of the data which will not be used for training, but used afterwards as if the trained model received "new" data. This way, the error of the prediction is calculated when new data enters the model. However, the way in which the data is split can influence the error measurement, so cross validation is performed, a process of

splitting this train-test subset in different ways, in order to understand the sensitivity of errors. More information about models is obtained through approaches such as Precision-Recall, Sensitivity, Confusion Analysis, or the many ways of approaching the error in a model. Confusion Analysis is broadly used in classification problems as a way to compare the proportion of negative and positive true and false predictions, and it is quite interesting for binary problems (such as, is this a walking trip or not?). It visualizes how well the predictions perform looking independently at true and false values.

Balance is another important concept to note. If, for instance, the need is to classify data in two classes which are present in the train data in the proportion of 1/99, the model will most likely predict the majority class with a very high precision, which in turn is an effect of an unbalanced train dataset. In this case, more nuanced evaluation metrics, and more balanced datasets are the common approach for a more suitable model. Sub-sampling (such as random subsampling or using Tomek-Links) is commonly the way to go when unbalanced situations exist, although other proposals of over-sampling (such as SMOTE) or feature weighting (like the LASSO Regression) have been proposed elsewhere.

Hyperparameter optimization is another particularity of ML approaches. In data models, the parameters are variables which are estimated during the training process, such as the coefficients of linear or logistic regressions. Hyperparameters, on the contrary, are defined by the researcher and can be seen as the configuration of the training process. Finding the best values for the best possible model is called hyperparameter optimization. It searches three basic elements: Possible states of solutions for the search, a set of actions which allow to generate new states from the previously generated states, and a target function which allows to define the "quality" of each state. It is a costly process that involves running the model iteratively, and it can be done in an ordered "grid-like" search, or a more random approach.

Finally, a note on explainability is given, the common term to refer to techniques which help extract information from the predictions to which ML algorithms arrive. It is a conceptual opposition to the idea of a "black box", and is behind efforts to improve and research new ways in which the balance between accuracy (or relevance, or precision, etc.) and interpretation is attained. An interesting approach to a classification problem is permutation feature importance. It evaluates the importance of individual features in the prediction by randomly shuffling its values while keeping the other features unchanged, thereby breaking its relationship with the

target variable. The performance of the model is then re-evaluated, and the change in performance quantifies the importance. This method provides a comparable heuristic to coefficients in data models, without being tied to the specific internals of the model.

4.2.2 Data Statistics vs Machine Learning

When using quantitative approaches in science, a tradeoff between theory, data availability and mathematical modeling is made for the sake of heuristics and, in all fields of science, this improvement needs to be continuous and critical. When choosing to use the emergent machine learning approach, its particular philosophy should not be overlooked. In Breiman (2001), a thorough discussion is brought about the "two cultures" of modeling to reach conclusions from data: The traditional one that assumes that the data are generated by stochastic data models, and the emergent use of algorithmic models which treat the data mechanisms as unknown. According to this author, when a natural observable phenomenon **y** is considered as a result of the influence of a feature **x**, data modeling will attempt to impose a way in which both y and x are mathematically related, while machine learning assumes that the nature of this relationship is unknown and opaque.

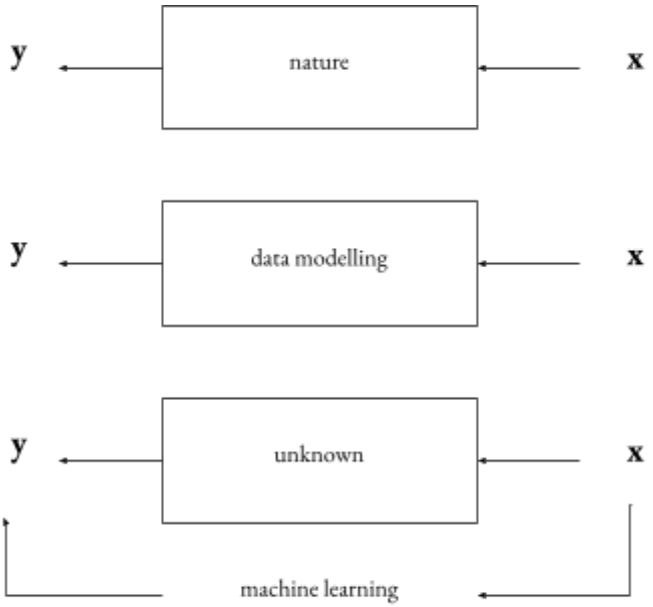

Figure 28 (Previous page): Machine Learning vs Data Models (from Breiman, 2001)

In the first approach, the "data modeling approach", outcome variables are treated as being a known function of the predictor variables, along with random variables or noise which represent unobserved or unknown mechanisms at work. Models are then tested for goodness of fit and residuals examination. In the second approach, the "algorithmic modeling approach", considers the relation between outcome variables and predictors as a "black box" which is inherently impossible to be "tamed" by theory, so the functions that relate the former need to be iteratively formulated and refined, in order to minimize errors in prediction, yet learning them "from scratch", this is, without strong assumptions on the shape of these functions.

To Breiman (2001), the use of data models leads to conclusions about the model's mechanism, but not necessarily about nature's mechanism. The greatest barrier for traditional statisticians is that, as data becomes more complex, models become more difficult to tame in a simple and clear picture of nature's actual mechanisms. To this author, the dilemma between data models and machine learning poses three questions: First, the fact that multiple specifications of data models can be well fitted to a certain problem, but strongly depending on the selection of covariates (say, eliminating less important ones) and observations (say, trimming those extraneous or outlying observations), needs close attention. ML models can potentially learn

from the relative importance of covariates, or the influence of outliers, and reduce their influence without a hard intervention from the modeler.

Second, an heuristic dilemma between simplicity and accuracy arises when statistics attempt to be informative and precise at the same time. In this sense, data models have been long preferred for being straightforward in legibility, over machine learning models which are, in the majority of cases, virtually inaccessible black boxes. A good prediction could be satisfactory if accuracy was the main goal but, if the goal is learning from the nature of a particular phenomenon, then a less accurate, but more interpretable approach might be preferred.

Finally -and closely related to the first dilemma-, the presence of a high multidimensionality (a high number of predictors) has been traditionally avoided in data models. Simplifying input variables through techniques such as factor analysis or principal component analysis, or any other technique to reduce dimensionality, is considered a good practice in traditional statistics. In ML, however, most algorithms are actually benefited by the presence of many dimensions, as the probability of correctly "separating" or "recognizing patterns", increases with the number of -relevant- dimensions.