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UNLOCKING THE 15-MINUTE CITY:

Diagnosing Infrastructural Lock-Ins

BEATRIZ VERSIANI PONCE LOPES

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MASTER IN SPATIAL PLANNING AND URBAN PROJECT

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Dedicated to my parents

“There is a sense of enchantment and triumph in being simple.

It doesn't take much to be much.”

Lina Bo Bardi

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ABSTRACT

The 15-Minute City (15MC) concept promotes urban redesign based on proximity, accessibility, and quality of life. However, its implementation is often constrained by infrastructural lock-ins: rigid, path-dependent configurations of the urban form inherited from car-centric planning. This research focuses on measuring these lock-ins that hinder transitions toward walking mobility, using two distinct case studies: the Administrative Region of Plano Piloto in Brasília (Brazil) and the municipality of Porto (Portugal), both selected for their centrality within larger metropolitan contexts.

Using a curated set of spatial accessibility and walkability indicators defined by the author based on a literature review, the study applies GIS to locate those infrastructural lock-ins on the case studies. Two main objectives guide the research: (1) to identify and categorise key infrastructural lock-ins of car dependency; and (2) to spatially analyse constraints on 15MC implementation.

The findings show that Porto and Plano Piloto are each constrained by distinct dominant lock-ins, shaped by divergent planning legacies. In Porto, the territory offers a sufficient mix of destinations and adequate street activity, but pedestrian path connectivity remains the primary obstacle to walkability; while in Plano Piloto, the absence of land-use mix itself – concentrated in non-aedificandi zones and single-use sectors separating inhabited neighbourhoods – is the most severe and spatially extensive lock-in. These distinct profiles indicate that constraints on 15MC implementation are not uniform: in Porto, intervention would need to target street network granularity outside the historic core, whereas in Plano Piloto, it would require reconnecting isolated mixed-use neighbourhoods rather than reconfiguring land use directly. However, infrastructural lock-ins alone are necessary but not sufficient to explain car dependency in either case, indicating that institutional and behavioural lock-ins also require further investigation to support 15MC implementation.

This study contributes a replicable GIS-based indicator framework for the comparative assessment of macro-scale infrastructural lock-ins, advancing empirical understanding of the structural barriers to proximity-based urbanism across contrasting urban contexts.

KEYWORDS: Proximity planning; 15-minute city; car dependency; proximity-centred accessibility; sustainable mobility; urban form.

RESUMO

O conceito de Cidade de 15 Minutos (15MC) propõe a reconfiguração urbana com base em proximidade, acessibilidade e qualidade de vida. No entanto, sua implementação é frequentemente condicionada por bloqueios “lock-ins” infraestruturais: configurações rígidas e dependentes da trajetória da forma urbana herdadas do planejamento centrado no automóvel. Esta investigação concentra-se na medição desses bloqueios que dificultam a transição para a mobilidade a pé, a partir de dois estudos de caso distintos: a Região Administrativa do Plano Piloto em Brasília (Brasil) e o município do Porto (Portugal), ambos selecionados por sua centralidade em contextos metropolitanos mais amplos.

Com base em um conjunto de indicadores de acessibilidade espacial e caminhabilidade definidos pela autora a partir de uma revisão de literatura, o estudo aplica SIG para localizar esses bloqueios infraestruturais nos estudos de caso. Dois objetivos principais norteiam a pesquisa: (1) identificar e categorizar os principais bloqueios infraestruturais de dependência do automóvel; e (2) analisar espacialmente os condicionantes à implementação da Cidade de 15 Minutos.

Os resultados mostram que o Plano Piloto e o Porto são cada um condicionados por lock-ins dominantes distintos, moldados por diferentes legados de planejamento. No Porto, o território oferece uma mistura suficiente de destinos e atividade de rua adequada, mas a conectividade da malha de percursos pedonais permanece como o principal obstáculo à caminhabilidade; já no Plano Piloto, a ausência de diversidade do uso do solo em si – concentrada em zonas non-aedificandi e setores monofuncionais que separam os bairros habitados – é o lock-in mais severo e espacialmente mais extenso. Esses perfis distintos indicam que as barreiras à implementação da 15MC não são uniformes: no Porto, a intervenção precisaria visar a granularidade da malha viária fora do centro histórico, enquanto no Plano Piloto seria necessário reconectar bairros de uso misto isolados, em vez de reconfigurar diretamente o uso do solo. Entretanto, os lock-ins infraestruturais isoladamente são necessários, mas não suficientes para explicar a dependência do automóvel em ambos os casos, indicando que os lock-ins institucionais e comportamentais também requerem investigação adicional para apoiar a implementação da Cidade de 15 Minutos.

Este estudo contribui com um modelo de referência de indicadores baseado em SIG e replicável para a avaliação comparativa de lock-ins infraestruturais em macroescala, ampliando a compreensão empírica das barreiras estruturais ao urbanismo de proximidade em contextos urbanos contrastantes.

PALAVRAS-CHAVE: cinco palavras-chave separadas por vírgula.

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ACRONYMS AND ABBREVIATIONS

GIS	Geographical Information System
15MC	15-Minute City
CO2	Carbon dioxide
CO2-eq	Carbon dioxide equivalent (CO2 + other GHGs converted to the same warming potential)
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
CBD	Central Business District
IPEN	International Physical Activity and the Environment Network
PDAD-A	District-Level Expanded Household Sample Survey (Federal District)
IPEDF	Institute of Research and Statistics of Federal District
CODEPLAN	Company of Planning of Federal District
INE	Instituto Nacional de Estatística (Portugal) / Statistics Portugal
OECD	Organisation for Economic Co-operation and Development
PDM	Municipal Master Plan (of Porto)
CMP	Porto City Council
RA(s)	Administrative Region(s)
RA-I	Administrative Region of Plano Piloto
IBGE	Instituto Brasileiro de Geografia e Estatística / Brazilian Institute of Geography and Statistics
SEDUH	Secretariat for Urban Development and Housing of Federal District
AMP	Metropolitan Area of Porto
AMB	Metropolitan Area of Brasília
DF	Federal District (of Brazil)
UNESCO	United Nations Educational, Scientific and Cultural Organization
OD-Matrix	Origin-Destination Matrix
OSM	OpenStreetMap
BGRI	Base Reference Geographical Information (from INE/Statistics Portugal)
POI(s)	Point(s) Of Interest

1
INTRODUCTION

1.1 BACKGROUND AND MOTIVATION

Although the urban environment covers a small fraction of planet Earth's surface, it accounts for a large proportion of global energy consumption and gas emissions, with the transport sector representing one of the largest and fastest-growing contributors. In 2019, transport accounted for approximately 15% of greenhouse gas emissions caused by human activity, around 8.7 billion tonnes of CO2-eq (IPCC, 2022). Within the sector, road transport remains by far the most dominant source: global road transport emissions reached just over 6 billion tonnes of CO2 in 2024, with passenger cars and vans alone responsible for more than 60% of this total, considerably more than trucks (roughly one-third) or buses and two/three-wheelers (7%) (IEA, 2025). As urban populations continue to expand, the way cities are planned and organised has become increasingly important for achieving climate mitigation, public health, and sustainability goals.

Throughout history, urban mobility has evolved alongside technological innovation, moving through distinct periods of urban form: the Walking-Horsecar era (1800-1890), the Electric Streetcar era (1890-1920), the Recreational Auto era (1920-1945) and the Freeway era (1945-) (Muller, 2004). While each technological transition expanded opportunities for movement, the rise of mass car ownership transformed the structure of cities. Over the course of the 20th century, urban development increasingly prioritised the automobile, encouraging lower-density expansion, greater separation of land uses, longer travel distances, and street networks designed primarily to maximise vehicular flow. Therefore, the private car evolved from one transport option among many into the organising principle of urban development worldwide.

Despite these transformations, walking remains the universal foundation of human mobility, since every journey – regardless of the transport mode used – begins and ends on foot (Sim, 2019). This observation highlights an important distinction between mobility and accessibility. While advances in transport technology have increased people's ability to travel longer distances, they have often reduced the proximity between everyday destinations, making access increasingly dependent on motorised transport.

Today, this legacy presents one of the greatest challenges for cities seeking to transition towards more sustainable and resilient forms of urban development. The dominance of the private automobile is not simply a matter of individual travel preference, but rather the cumulative outcome of decades of planning decisions that have embedded car dependence into the urban structure. As a result, in many urban contexts, driving has become less a matter of choice than of necessity.

It is against this scenario that proximity-based planning paradigms have regained prominence in both academic research and urban policy, most notably through the concept of the "15-Minute City" (Moreno et al., 2021). Grounded in the principles of chrono-urbanism - the notion that the quality of urban life depends not only on where activities are located, but on how much time is needed to reach them - the 15-Minute City proposes that residents should be able to meet their essential daily needs, organised around the social functions of living, working, supplying, caring, learning and enjoying, within a short walk or bicycle ride from home. The model has been presented as a way of simultaneously advancing climate mitigation goals, improving wellbeing, and strengthening local economies and social ties at a smaller scale.

However, cities inherit decades – sometimes centuries – of accumulated spatial and institutional decisions that continue to shape patterns of accessibility and mobility. Even where local governments seek to implement proximity-based planning principles, the inherited urban structure – including dispersed, low-density settlements, segregated land uses, and road networks designed for high-speed motorised traffic - can act as a persistent barrier to change, irrespective of the planning ambitions expressed on paper. These inherited characteristics function as persistent barriers to urban transformation. In this dissertation, they are conceptualised as lock-ins: self-reinforcing features of the built environment that hinder the transition from automobile-dependent urban systems towards more accessible, sustainable, and resilient cities.

According to Seto et al. (2016), "carbon lock-in" is a path-dependent process that results in the inertia of technologies, institutions, and behaviours, both individually and interactively, thereby limiting the rate of systemic transformations like climate change mitigation. Therefore, lock-ins refer to path dependencies that obstruct the transition from one socio-technological regime to another.

Three types of path dependencies can be distinguished (Seto et al., 2016): infrastructural/technological, institutional, and behavioural. The first involves technologies and infrastructure that indirectly or directly emit CO2 and shape the energy supply. The second is associated with governance, institutions, and decision-making processes that control energy production and its consumption, thereby shaping both supply and demand. The third and last type is related to behaviours, habits, and norms that drive demand for energy-related goods and services.

Seto et al. (2016) argue that these three levels of lock-in are not independent of one another: they reinforce each other across multiple scales, such that infrastructural decisions can entrench particular institutional arrangements and behavioural norms, while institutional and behavioural factors can, in turn, justify and sustain further infrastructural investment in the dominant, car-oriented regime.

This dissertation focuses specifically on the infrastructural dimension of lock-in. Conceptually, infrastructure occupies a distinctive position within this framework: the built environment is characterised by exceptionally long lifespans and high replacement costs. Once built, urban form tends to persist for generations, continuing to shape mobility choices long after the institutional or political conditions that produced it have changed. Infrastructural lock-ins are therefore not static obstacles but active, self-reinforcing processes: as discussed in Chapter 2, the literature documents multiple feedback loops in which, for instance, low-density, single-use development increases reliance on the private car, which in turn justifies further road and parking provision, which further disperses activities and reduces the viability of walking, cycling and public transport. Practically, this dimension of lock-can be measured by spatial analysis: because infrastructural lock-ins are, by definition, entrenched in the physical configuration of the city, they can be identified, located and measured through the urban form characteristics of a given territory, making the infrastructural dimension particularly well suited to the GIS-based approach adopted in this dissertation.

Diagnosing infrastructural lock-ins in a city-scale, however, requires more than the conceptual identifying the barriers that sustain car dependency: it requires an operational framework capable of locating where these barriers are most pronounced within the urban fabric in a way that is both replicable and comparable across different urban contexts. In this dissertation, that role is executed through the concepts of accessibility and walkability. Accessibility - understood as the ease with which residents can reach the destinations and opportunities that meet their daily needs, resulting from the combined effect of mobility and proximity (Silva, 2017; 2020) - and walkability - understood as a quality of place (Bradshaw, 1993), the degree to which the built environment supports walking as a viable mode of everyday travel - together provide a set of spatial measures that correspond to the infrastructural lock-ins identified in the literature. Low Land-use Mix, Long Distances to Essential Destinations, Low Urban Density, and Low Street Connectivity for Alternative Transport, for example, are not only recurrent solo drivers of car dependency, but are also measured through established and validated indicators in the literature. This convergence between the two bodies of literature forms the analytical foundation of the present study. By applying a Geographic Information Systems (GIS)-based framework, this dissertation identifies the areas where infrastructural lock-ins to car dependency are most severe, as well as those that already exhibit the spatial conditions associated with the 15-Minute City model.

This framework is applied comparatively to two case studies that, while broadly comparable in terms of resident population and functional role within their respective greater cities, represent contrasting planning traditions and urban morphologies: the Municipality of Porto (Portugal), shaped by centuries of organic city-building, and the Administrative Region of Plano Piloto (Brasília, Brazil), the product of a Brazilian modernist masterplan conceived in the late 1950s. Comparing two contrasting contexts makes it possible to examine not only where infrastructural lock-ins are located within each city, but also how their nature, severity and policy implications vary according to the planning tradition that shaped their urban form. In turn, this comparison provides insights into the extent to which the 15-Minute City model can be transferred across different urban contexts.

Building on this background, the following section sets out the specific objectives pursued in this dissertation and outlines, in general terms, the methodological approach adopted to achieve them.

1.2 Objectives and Methodology

The primary objective of this research is to evaluate the infrastructural lock-ins that sustain the stability of the automobile regime across different urban contexts, and how breaking these lock-ins can promote the development of 15-Minute Cities. This general aim is pursued through two more specific objectives. First, building on the systematic literature review presented in Chapter 2, the dissertation seeks to identify and categorise the infrastructural lock-ins most consistently associated with car dependency, and, drawing on the accessibility and walkability literature reviewed in Chapter 3, to establish which of these lock-ins can be operationalised through spatial indicators measurable at a city-wide scale. Second, it aims to apply this reduced set of indicators, through a replicable GIS-based methodology, to the case studies of the Municipality of Porto and the Administrative Region of Plano Piloto, producing a comparable, grid-based classification of infrastructural lock-ins across both territories. The resulting spatial patterns are then interpreted in light of the contrasting planning traditions of the two case studies, and their implications for the feasibility and design of strategies to unlock car dependency.

To this end, a quantitative approach is employed, relying on GIS-based spatial analysis. Spatial indicators are calculated to operationalise infrastructural lock-ins, enabling the identification of physical and systemic features of the built environment that reinforce automobile dependence.

1.3 Structure of the Dissertation

The dissertation is structured into six chapters. Following this introduction, Chapter 2 - titled "How Infrastructure Locks in Car Dependency" - provides a literature review on the concept of infrastructural lock-ins. It aims to understand what lock-ins are, how they emerge and persist within the urban environment, and their interrelationships. Chapter 3, "Accessibility and Walkability to Unlock Car Dependency," continues the literature review by examining the conceptual foundations of accessibility and walkability. It aims to define these terms, explore how they have been operationalised in previous studies, and demonstrate how their measurement can be used to identify and potentially break up existing lock-ins. Chapter 4 presents the methodology employed for the analysis of Infrastructural Lock-Ins, including the spatial indicators and GIS techniques used. Chapter 5 reports the results of this analysis. Finally, Chapter 6 concludes the dissertation by synthesising the findings, discussing their implications for 15-Minute City planning, and suggesting directions for future research.

1.4 Contribution to the Sustainable Development Goals (SDGs)

The scope of this dissertation is aligned with several United Nations Sustainable Development Goals (SDGs). Most directly, it engages with SDG 11 (Sustainable Cities and Communities), which calls for inclusive, safe, resilient and sustainable cities and transport systems for all. By diagnosing where infrastructural lock-ins constrain non-motorised mobility, this research provides an evidence base for prioritising urban interventions that expand access to sustainable transport rather than reinforcing car dependency.

Secondly, given that road transport is among the largest sources of greenhouse gas emissions, the study's focus on unlocking car dependency also contributes to SDG 13 (Climate Action). By spatially identifying the built-environment conditions that sustain automobile dependence, the analysis raises awareness to mitigation strategies directed at urban form and infrastructure, supporting efforts to combat climate change and its impacts.

Because walkability and proximity-centred accessibility are closely linked to physical activity, the dissertation further relates to SDG 3 (Good Health and Well-being): environments that support walking mobility tend to reduce exposure to motorised traffic, lowering the risk of injuries from road traffic accidents, while encouraging more physically active communities.

The study also speaks to SDG 10 (Reduced Inequalities), since infrastructural lock-ins – which entrench car dependency – tend to place people without access to private vehicles at a disadvantage, limiting their access to jobs, services and opportunities.

Finally, the work aligns with SDG 9 (Industry, Innovation and Infrastructure), through the development of a replicable, GIS-based methodology for assessing urban infrastructure across different planning traditions, enhancing scientific research (Target 9.5). This also contributes to the broader aim of building infrastructure that is reliable and resilient, supporting economic development and human well-being with equitable access for all (Target 9.1).

1.5 Relationship with the UNLOCK15 Project

This master's thesis builds on the UNLOCK15 research project, in which the author was involved as a research assistant (from February 2025 to July 2025) and subsequently as a junior researcher (from September 2025 to July 2026). The UNLOCK15 project is a research-oriented initiative funded under the Driving Urban Transitions (DUT) 2023 Call, aimed at empowering citizens and local authorities to transition toward the 15-Minute City model by overcoming barriers to sustainable mobility through participatory methods, institutional learning, and local narratives.

As a research assistant, the author was responsible for the literature review on infrastructural lock-ins, which forms the basis of Chapter 2 of this thesis. This review followed all steps guided by the PRISMA method, including article search by queries, identification of relevant records, article screening, content analysis of included papers (full-text review), and categorisation with framework development. Although assistance was received – specifically with the full-text review of 21 articles out of a total of 101 analysed papers, as well as with the contribution of those 21 papers to the summary table, categorization, and framework development – the entire analysis and construction of this dissertation were carried out independently.

As a junior researcher, the author was responsible for the GIS-based spatial analysis conducted for the following urban areas: the neighbourhood of Carvalhido (Porto, Portugal), the Meidling and Ottakring districts (Vienna, Austria), the Almere Buiten district (Almere, the Netherlands), the city centre of Sète (France), and the city of Augsburg (Germany). Although assistance was received with some of the calculations themselves for certain neighbourhoods within the project, the methodology for these calculations was also developed solely by the author (under the guidance of Professor Dr. Cecília Silva). The case studies presented in this thesis are exclusive to it, and the author is entirely responsible for the results reported in this dissertation.

2
HOW INFRASTRUCTURE LOCKS IN CAR DEPENDENCY

Aiming to contribute to the understanding of infrastructural lock-ins that maintain the stability of the automobile regime - and how these barriers can be unlocked to promote the development of 15-Minute Cities - the primary objective of this literature review is to identify and categorise the infrastructural lock-ins that affect sustainable mobility in urban areas, examining how they emerge and persist within the urban environment and how they interrelate.

2.1 RESEARCH METHOD

A systematic literature review was used as the research method. This approach identifies, evaluates, and synthesizes all relevant studies on a specific question using a transparent protocol. The Preferred Reporting Items for Systematic Reviews and Meta-analyses (PRISMA) is used as a guideline to ensure transparency.

As presented in Figure 2.1, this review was conducted in five main steps. The first four steps followed the PRISMA method, while the final step consisted of the synthesis and expected outcomes of the review: (1) articles search by queries; (2) identification of relevant records; (3) articles screening; (4) content analysis of included papers; and finally (5) categorization and framework development.

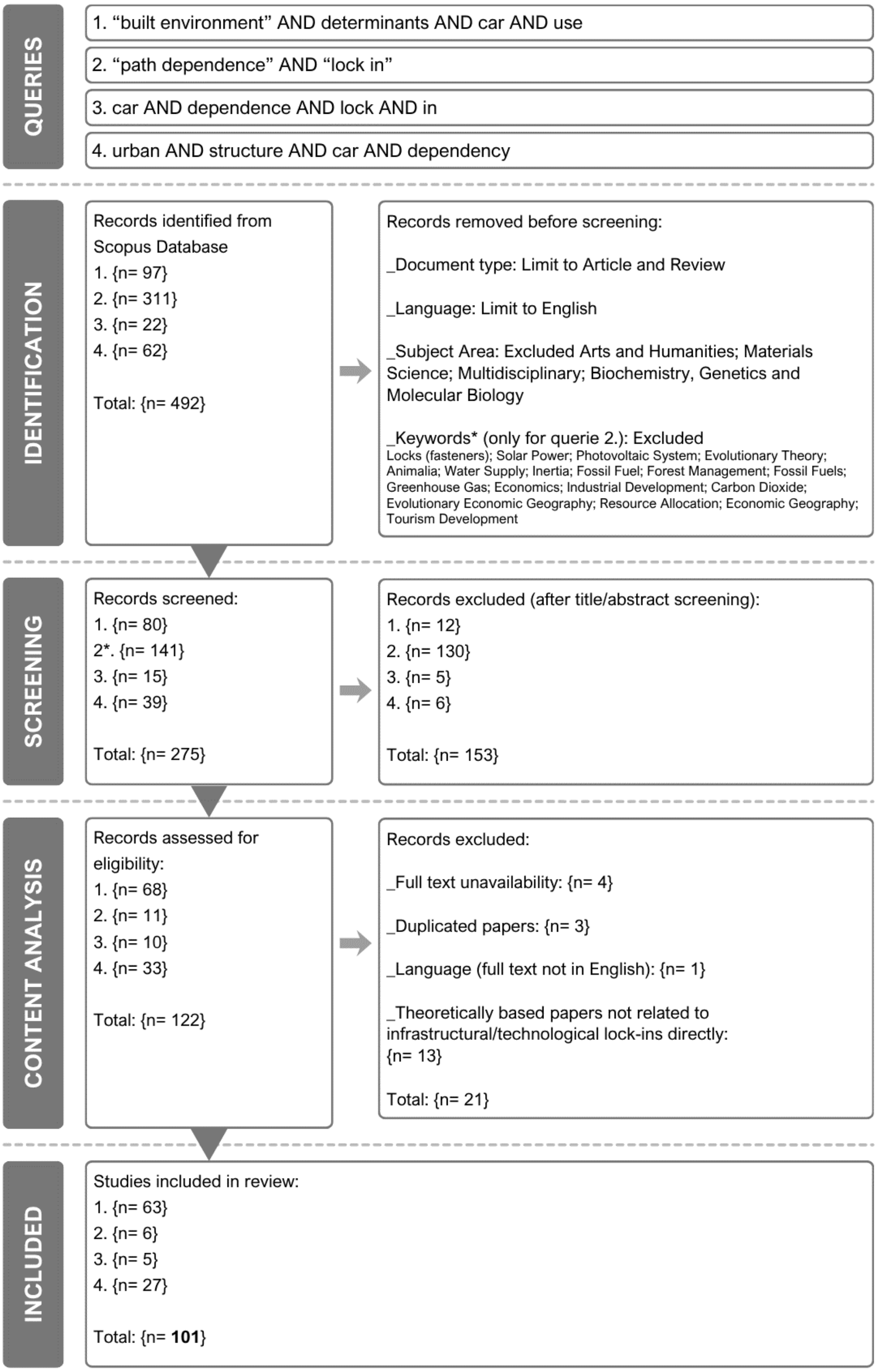


Fig. 2.1 – PRISMA Flow diagram

2.1.1 Articles search by queries

In the first stage, four sets of keywords “queries” were used separately in the Scopus database. The first query, *“built environment” AND determinants AND car AND use*, had 97 identified records. The second one, *“path dependence” AND “lock in”*, had the largest number of records, 311, which can be explained by its intentional lack of specificity – to identify more papers that explicitly addressed path dependence. The third set of keywords, *car AND dependence AND lock AND in*, had 22 identified records, and the last query, *urban AND structure AND car AND dependency*, had 62 records, resulting in a total of 492 identified records.

2.1.2 Identification of relevant records

Three main filters were applied to each query in Scopus: Document type (Limited to Article and Review), Language (Limited to English), and Subject area (Excluded Arts and Humanities; Materials Science; Multidisciplinary; Biochemistry, Genetics and Molecular Biology).

An additional filter of Keywords was applied to the second query, *“path dependence” “lock in”*, given its large number of identified records: Excluded Locks (fasteners); Solar Power; Photovoltaic System; Evolutionary Theory; Animalia; Water Supply; Inertia; Fossil Fuel; Forest Management; Fossil Fuels; Greenhouse Gas; Economics; Industrial Development; Carbon Dioxide; Evolutionary Economic Geography; Resource Allocation; Economic Geography; Tourism Development.

2.1.3 Articles screening

After applying the filters, 275 papers were selected for screening. In this phase, each document had its title checked for consistency and alignment with the research theme. When a title was not clear about its theme, its abstract was checked. After this title and abstract screening, 153 documents were excluded from the previously selected ones (275), resulting in 122 records to be assessed for eligibility.

2.1.4 Content analysis of included papers

Of the 122 eligible records for review, 21 were excluded. Four full texts could not be retrieved, three papers were duplicated (appeared in more than 1 query), and one article was not in the right language (despite its record indicating English). The remaining 13 exclusions were made after its full text review, which determined that their theoretical base was not directly related to infrastructural/technological lock-ins - the excluded studies included work on path dependence unrelated to transport, health and wellness, institutional lock-ins, and behavioural lock-ins.

Therefore, a total of 101 papers were included in the final review. For each, a full-text reading was conducted, and a pre-developed summary table was completed to synthesize all relevant findings, focusing primarily on evidence of infrastructural and technological lock-ins.

2.1.5 Categorisation and framework development

Following the main objective of identifying and further categorising infrastructural lock-ins, a summary table was developed to support a structured data extraction process and to synthesise the information collected from the literature while ensuring the inclusion of all relevant records. As shown in Table 2.1, the table organised the extracted information into key dimensions related to the lock-ins themselves, including: Name of Lock-In (developed and refined during analysis), Original name of lock-in (according to the authors), Description of Lock-In (what it is and how it contributed to car dependency), and Effect/Relationship with other lock-ins; as shown in Table 2.1. In addition, contextual information was recorded, such as the case study or intervention examined (if applicable), and standard reference data (including author, year, methodology, main findings, keywords, and the source query).

The review of the 101 included studies revealed a lack of consistent terminology for the identified lock-ins. While some, such as “Urban Sprawl,” had well-established labels, many others were described inconsistently or lacked a specific designation. To ensure clarity and consistency throughout this review, a standardized terminology was developed based on the most frequent usage in the literature and a conceptual synthesis of the underlying concepts.

Table 2.1 - Summary table of Infrastructural Lock-Ins literature review (extracted)

Lock-Ins			
Name of Lock-In	**Name of Lock-In (according to the authors)**	**Name of Lock-In (according to the authors)**	**Effect/Relationship with other lock-ins**
Long distance to work	Destination accessibility; Distance to CBD	Destination accessibility is usually represented as distance to CBD (Central Business District) and accessibility to the job. The longer the distance from the neighbourhood to CBD, the more likely the residents are to drive to work.	
Low urban density	Low population and building density (Low Density)	Lower-density areas cause the dispersion of origins and destinations. "Low population and building density result in greater levels of car use" "Lower population densities make it more challenging to effectively organize public transport networks"	*Interdependency* with Low land-use mix and Urban Sprawl; Causes Long distance to essential destinations

2.2 IDENTIFICATION AND EVALUATION OF CONNECTIONS

The content analysis of included papers identified 31 lock-ins (standardized terminologies) and their interconnections, which were recorded in the summary table previously mentioned. These lock-ins were then organized into three core typologies — Spatial Organization, Transport Infrastructure and Street Design, and Transport Technology and Services — and further subdivided into six sub-typologies as shown in Figure 2.2.

Appendix A.1 showcases these identified lock-ins, including their number of mentions in the literature and the corresponding list of references for each. Because the lock-ins reflect standardized terminologies, the number of mentions is commonly greater than the number of references for some lock-ins – this occurs when a single author employs multiple distinct terms that were consolidated under the same terminology in this research.

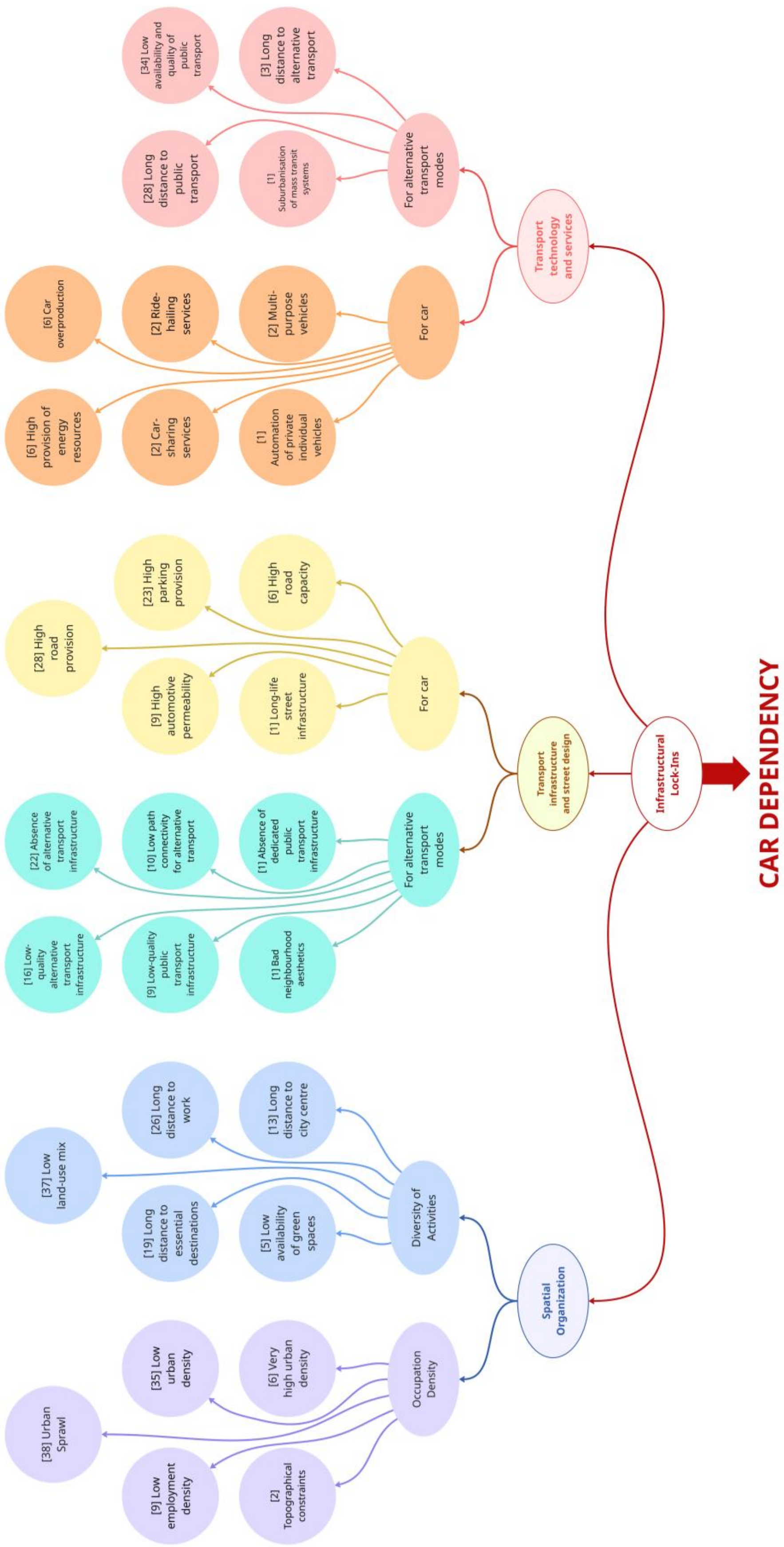


Fig. 2.2 – Infrastructural Lock-Ins framework

2.2.1 Spatial Organization

The first typology, Spatial Organization, is subdivided into two sub-typologies**: Occupation Density** and **Diversity of Activities**. The lock-ins within those categories, described in Table 2.2, refer to the (low) density, (low) accessibility, and (poor) diversity of an urban space's land use.

Table 2.2 - Spatial Organization Lock-Ins

Sub-Typology	Lock-In	Description	Number of mentions
Occupation Density	**Urban sprawl**	The growth, the expansion of the city's outskirts/fringes/periurban areas.	38
	Low urban density	An insufficient number of residents in an urban area.	35
	Low employment density	An insufficient number of jobs in an urban area.	9
	Very high urban density	An excessive number of residents/of people in an urban area.	6
	Topographical constraints	Areas with mountainous, steep, rugged terrains.	2
Diversity of Activities	**Low land-use mix**	The lack - or an insufficient number of - different services such as residential, commercial, and institutional in an urban area.	37
	Long distance to work	The physical distance to reach the workplace and/or a longer time to reach that workplace.	26
	Long distance to essential destinations	The physical distance to shops, pharmacies, services, schools, and/or a longer time to reach those destinations.	19
	Long distance to city centre	The physical distance to a city's centre and/or a longer time to reach that city centre.	13
	Low availability of green spaces	The lack - or an insufficient number - of green spaces such as squares and parks.	5

Table 2.2 presents an overview of the first 10 lock-ins, detailing their sub-typology, name, description, and frequency of mention in the reviewed studies. Unsurprisingly, the three most frequently cited lock-ins were **Urban sprawl**, **Low land-use mix**, and **Low urban density**. As can be seen from Figure 4, these most mentioned lock-ins are also the ones with the greatest number of interconnections. Furthermore, as shown in Figure 2.3, these three form a core vicious cycle within the framework, demonstrating strong mutual reinforcement.

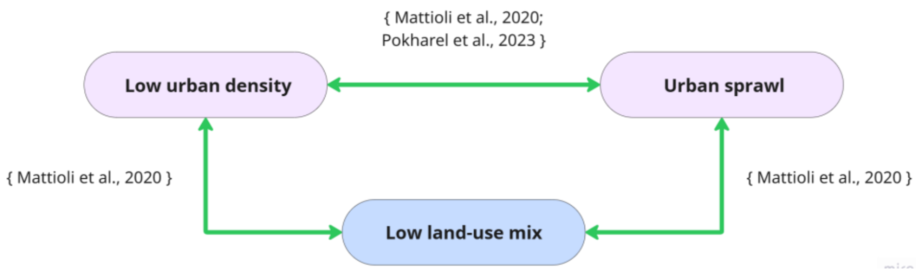


Fig. 2.3 – Core vicious cycle of infrastructural lock-ins

The relationship between urban density and urban sprawl is widely recognized as reciprocal, as Pokharel et al. (2023) state, a reduction in urban density leads to an increase in urban sprawl, and vice versa. This definition is similar to that found in Mattioli et al. (2020), who define urban sprawl as the spatial diffusion of residences and activities, marked by low-density and car-dependent settlement patterns.

Urban sprawl is also described as the practice of ever-expanding suburban fringe development, which entrenches and exacerbates car-dependency (Haarstad et al., 2022). It operates through a self-reinforcing cycle "chicken-and-egg" paradox: its connections with other lock-ins create a chained system of causal relationships, such that even a single unidirectional increasing link ultimately leads to a lock-in that the literature identifies as mutually reinforcing with **Urban sprawl**. For example, **Urban sprawl** is reported to increase **Low employment density** and **Long distance to city centre**, both of which are mutually reinforced with **Low urban density** – a lock-in that, in turn, is mutually reinforced with **Urban sprawl**.

Low employment density is characterised by a low concentration or number of jobs within an area (Saeidizand et al., 2025; Miranda-Moreno et al., 2011; Diab et al., 2020; Iseki et al., 2018), indicated by a low ratio of jobs to residents (Schwanen et al., 2004) and associated with limited employment resources (Liu et al., 2025). This lock-in is often discussed in relation to **Urban sprawl** characteristics (Barter, 2004).

The lock-in **Long distance to city centre** refers to the physical distance from home to the city centre (Xianyu, 2022; Ioannou, 2019; Jarboui and Bouzouina, 2025; Yang and Zhou, 2020; Zhao and Zhang, 2018; Zhao and Li, 2021) and/or a longer time to reach it (Milakis et al., 2017; Ton et al., 2019). Longer distances increase the likelihood of car ownership (Xianyu, 2022; Zhao and Zhang, 2018; Zhao and Li, 2021) and driving (Milakis et al., 2017) to the city centre, while decreasing the odds of active transport (Xie and Liao, 2025; Ton et al., 2019) and public transit use due to its dispersion in the outskirts (Nikolaou and Dimitriou, 2024; Zhao and Zhang, 2018).

Low urban density, one of the most frequently reported characteristics of car-dependent urban form in the literature (35 mentions) (De Angelis et al., 2021; Haarstad et al., 2022; Kent, 2025; Rahman, 2023), encompasses low population density (Diab et al., 2020; Jarboui and Bouzouina, 2025; Mattioli et al., 2020; Xiao and Wei, 2024), low building density (Mattioli et al., 2020; Xiao and Wei, 2024), and a low concentration of activities within a given area (Diab et al., 2020; Millard-Ball and Kapshikar, 2024), leading to greater spatial separation between origins and destinations (Mattioli et al., 2020; Feng et al., 2017).

The low availability of diverse activities – represented by **Low land-use mix** (opposite of High land-use mix/entropy) – discourages pedestrian activity and other active modes (Miranda-Moreno et al., 2011; Ton et al., 2019). This happens because a lack of land-use diversity (residential, commercial, services, etc.) increases the distance to everyday destinations and therefore the need for long motorized trips. This reduction in accessibility entrenches car dependency: monofunctional urban areas are found to have greater levels of car use (Mattioli et al., 2020; Xianyu, 2022), and in contrast, land-use mix is associated with reduced odds of car use (O'Driscoll et al., 2025; Soltani et al., 2018; Eldeeb et al., 2021; Dam et al., 2022; Marquet, 2020; Braver et al., 2020; He et al., 2022), reduced odds of car ownership (De Gruyter et al., 2025; Soltani, 2017), and greater active transport activity (Miranda-Moreno et al., 2011; Yu et al., 2019; Kandt, 2018; Dam et al., 2022; Ramezani et al., 2021; Hawa et al., 2021; Mehzabin Tuli et al., 2021).

Although it may seem counterintuitive, this review identified **Very high urban density** as a distinct lock-in. Naturally, all six records mentioning this lock-in are based on case studies in countries marked by their higher density (compared to Europe), specifically in China, India, Turkey, and Brazil. However, **Very high urban density** is not simply the opposite of **Low**

urban density: it refers to an excessive number of people per unit area that can overwhelm the infrastructure. Shkera and Patankar (2024) point out that in areas with higher block density in Mumbai (India), traffic congestion may occur, ironically leading to sustained car use due to trip chaining or perceived convenience. For Kandt (2018), who also based his work in Mumbai but compared it to São Paulo (Brazil) and Istanbul (Turkey), “hyper-dense neighborhoods” may counter the potential ease of walking, suggesting that there might be levels of density that are counter-productive, depending on the capacity of the transport network. Ahmad and Creutzig (2019) also associate the most urbanized and dense areas with the highest commuting emissions due to high car ownership in India.

Topographical constraints refer to contexts where mountainous or rugged terrain makes the use of alternative transport modes less feasible, and where infrastructure is insufficient to overcome this natural barrier. As Liu et al. (2025) found in Guiyang (China), men are more likely to choose car travel as the slope increases, and cars become essential for managing complex trip chains in suburban and rural areas with rugged terrain and underdeveloped pedestrian infrastructure.

A surprising finding of this review was the limited discussion of green spaces as a lock-in, with only five records identifying what was called **Low availability of green spaces**. Regardless, green space is known as an important part of “infrastructure provision” (Milakis et al., 2017) and is significantly correlated with active mode use (Milakis et al., 2017; Ton et al., 2019; Xiao and Wei, 2024). Its presence makes active transport more attractive (ten Dam et al., 2022), and conversely, its absence discourages walking and cycling.

Most lock-ins on Occupation Density and Diversity of Activities exhibit strong interconnections of mutual reinforcement or direct causal influence. For instance, an urban area with **Low employment density** will naturally diminish accessibility by increasing the **(Long) distance to work**. According to Schwanen et al. (2004), “Commute distance for driving to and from work tends to decrease as the number of jobs per hectare rises”, which also works the other way around. In locations with limited employment, such as remote/suburban areas, people choose employment farther away from their residences, prioritizing access to more resources over commuting distance (Liu et al., 2025).

Long distance to work refers to the commuting distance from home to workplace (Xianyu, 2022; Wiersma et al., 2017; Ramezani et al., 2021; Schwanen et al., 2004; Ma et al., 2017; Millard-Ball et al., 2022); Zhao and Zhang, 2018; Sarangi and Manoj, 2020); Ahmad and Creutzig, 2019; Soltani, 2017; Sharma and Jain, 2025; Feng et al., 2017; Liu et al., 2025) or to the CBD (Xianyu, 2022; Wang et al., 2024; De Gruyter et al., 2024; Rahman, 2023; Shkera and Patankar, 2024; Yin et al., 2018; He et al., 2022; Hawa et al., 2021). Longer distances increase the likelihood of car ownership (De Gruyter et al., 2024; Yin et al., 2018; Soltani, 2017) and driving to work (Xianyu, 2022; Vale, 2013; Zhao e Zhang, 2018; Sarangi and Manoj, 2020; He et al., 2022; Liu et al., 2025), while decreasing the odds of using public transit (Rahman, 2023; Liu et al., 2025; Ma et al., 2017; Diab et al., 2020; Sharma and Jain, 2025) and active transport (Wiersma et al., 2017; Rahman, 2023; Vale, 2013; Millard-Ball et al., 2022; Zhao e Zhang, 2018).

2.2.2 Transport Infrastructure and Street Design

Transport Infrastructure and Street Design is also divided into two sub-typologies based on their designated user, **For Alternative Transport Modes** and **For Car**, as described in Table 2.3. The latter encompasses infrastructure designed for all non-automotive options. This typology refers to the physical design and distribution of infrastructure that determines how streets and transport networks are used.

Table 2.3 - Transport Infrastructure and Street Design Lock-Ins

Sub-Typology	Lock-In	Description	Number of mentions
Transport Infrastructure and Street Design ***For Alternative Transport Modes***	**Absence of active/soft transport infrastructure**	The lack of infrastructure dedicated to active modes - such as bicycle lanes and sidewalks.	22

*Transport Infrastructure and Street Design **For Alternative Transport Modes***	**Low-quality active/soft transport infrastructure**	The lack of quality - such as small width and inadequate pavements - in active transport infrastructure - such as bicycle lanes, sidewalks, pedestrian-oriented street lights.	16
	Low path connectivity for active/soft transport	The lack of path continuity for modes such as walking and cycling, related to an insufficient number of street intersections and/or longer average street lengths within an urban area. It can also result from physical barriers, such as railways.	10
	Low-quality public transport infrastructure	The lack of quality - such as inadequate maintenance of vehicles, poor hygiene conditions of vehicles and bad location of bus stops - in active transport infrastructure - such as bicycle lanes, sidewalks, pedestrian-oriented street lights.	9
	Absence of dedicated public transport infrastructure	The lack of infrastructure dedicated to public transport - such as bus corridors and rails.	1
	Bad neighbourhood aesthetics	The bad quality of architectural design of residential, civic buildings and/or street furniture in the environment.	1
*Transport Infrastructure and Street Design **For Car***	**High road provision**	Improvements, widening of the road transportation system, such as overpasses, freeways and arterials that target more space for car use.	28
	High parking provision	The excessive number of car parking in an urban area.	23
	High automotive permeability	Refers to a high level of path continuity for cars, characterised by the absence of physical interruptions - such as dead ends - and operational interruptions - e.g. traffic signal prioritisation for cars. It describes the excessive number of areas and routes accessible to motor vehicles within an urban area	9
	High road capacity	The dedicated space to motorised transport - buses and cars - in a street, the urban design that favours motorised transport.	6

Lock-ins within Transport Infrastructure and Street Design are widely seen as the primary obstacle to adopting sustainable transport. The logic is simple: without the necessary infrastructure, there is no viable alternative to the car, and if there is too much infrastructure for the car, there is no space for infrastructure for alternative modes. These lock-ins are fundamentally about the provision and quality of that infrastructure.

Absence of active/soft transport infrastructure refers to limited or missing active mobility infrastructure, including low density or continuity of sidewalks and bicycle lanes or paths (Eldeeb et al., 2021; Hidayati et al., 2019; Ton et al., 2019; Piras et al., 2021; Majumdar et al., 2021), absence of cycling facilities such as parking or bikesharing stations (Ton et al., 2019; Piras et al., 2021; Moura et al., 2023), and lack of separated or pedestrian-oriented design features (Sharma and Jain, 2025; Shkera and Patankar, 2024; Strauss et al., 2014; Younes and Baiocchi, 2023).

Low-quality active/soft transport infrastructures are inadequate walking and cycling conditions (Milakis et al., 2017), poor design and maintenance of active transport facilities (Pokharel et al., 2023), limited physical integration (Barter, 2004), insufficient lighting (Khademi et al., 2024), lack of weather protection (Drapeau et al., 2024), and unsafe intersection design (Strauss et al., 2014).

Low path connectivity for active/soft transport results from an insufficient number of street intersections (Liu et al., 2025; Yin et al., 2018) and/or longer average street lengths (Miranda-Moreno et al., 2011) within an urban area, discouraging pedestrian activity. It can also result from physical barriers, such as railways (Wang et al., 2024) and **High automotive permeability** features such as cul-de-sacs (Avenarius, 2012; Millard-Ball and Kapshikar, 2024). Furthermore, street connectivity is interdependent with **Low urban density**, since limited demand makes it difficult to provide frequent transit service to low-density neighbourhoods with culs-de-sac and other disconnected street patterns, as argued by Millard-Ball and Kapshikar (2024).

Low-quality public transport infrastructure comprises inadequate or weak transit availability (Sharma and Jain 2025; Younes and Baiocchi, 2023), facilities perceived as not very good (Webb et al., 2017), unsafe or unreliable (Sharma and Jain 2025; Majumdar et al., 2021), overcrowded or unhygienic (Sharma and Jain 2025), lacking comfort (Majumdar et al., 2021), with barriers to easy transfers (Barter, 2004) and poorly located stops (Strauss et al., 2014).

Absence of dedicated public transport infrastructure is defined by the lack of exclusive, separate pathways or lanes for public transport, commonly described in terms of shared use with other traffic, leading to slower service and reduced efficiency (Haarstad et al., 2022).

Bad neighbourhood aesthetics comprises the absence or poor quality of architectural design in urban buildings and street furniture. Evidence suggests that more attractive neighbourhood aesthetics are positively associated with cycling (Milakis et al., 2017).

High road capacity is defined as the dedicated space for motorised transport within a street's section/design. This lock-in should be distinguished from **High road provision**. Although both are categorized under the "For Car" user and share the Transport Infrastructure and Street Design typology, they operate at different scales:

- **High road capacity** refers to the design of the street itself;
- **High road provision** involves systemic improvements to the road network, such as constructing overpasses, freeways, and arterials.

While the key difference between the two lock-ins is scale, they are also part of a feedback loop. As Pokharel et al. (2023) state, road construction/widening (**High road provision**) increases **High road capacity**, allowing for the accommodation of more cars than before. However, this increased capacity indirectly fuels demand for more road provision by causing induced congestion, creating a vicious cycle.

Parking is a good example of an infrastructure that ‘locks-in’ a car-dependent lifestyle (Hrelja and Rye, 2023), identified here as **High parking provision** and mentioned by 23 articles. Garber et al. (2025) argue that abundant parking encourages more driving by making active transportation unappealing or impractical. This effect is clarified by Pérez et al. (2025), who note that pedestrians walk in the road to avoid stationary cars, leading to a less safe and more stressful pedestrian experience. Garber et al. (2025) also state that off-street parking requirements promote low-density development, causing key destinations to become more spread out than they would be without excessive parking supply. This indicates that **High parking provision** affects spatial organization by increasing **Low urban density** and **Urban sprawl**. Furthermore, the presence of parking directly promotes automobile use (Pokharel et al., 2023; Wang, Hu and Jiang, 2021; Millard-Ball et al., 2022) and ownership (De Gruyter et al., 2025; Zhao and Li, 2021; Soltani, 2017).

High automotive permeability, commonly termed car accessibility (Milakis et al., 2017; Kandt, 2018; Lehmann, 2013), refers to a high level of path continuity for cars, characterised by the absence of physical interruptions and high provision of car infrastructure: it is increased by **High road provision**, **High parking provision** and **High road capacity**. This also creates a self-reinforcing cycle with **Low path connectivity for active/soft transport**. As Yin et al. (2018) demonstrate, "lower intersection density […] can increase the odds of purchasing a car," thereby enhancing car permeability. Conversely, Ioannou (2019) observes that even dense central areas can become "car-dominated with narrow pedestrian spaces and safety issues [...] making walking and cycling difficult," further illustrating how automotive permeability compromises alternative modes' permeability.

Naturally, **High automotive permeability** creates a reinforcing cycle with **Low path connectivity for active/soft transport**, since Yin et al. (2018) state "lower intersection density in workplace neighborhood […] can increase the odds of purchasing a car for households without cars" (Yin et al., 2018), increasing car permeability, and Ioannou (2019) states that "Central areas, despite being denser, are car-dominated with narrow pedestrian spaces and safety issues due to illegal parking, making walking and cycling difficult".

Long-life street infrastructure is a component of entrenched technological systems, characterised by its extended lifetime with a high degree of interrelatedness and interdependence with other infrastructural components (Helmrich et al., 2023) that sustain car dependency.

2.2.3 Transport Technology and Services

The last typology, Transport Technology and Services, is divided into two sub-typologies based on their designated user: **For Alternative Transport Modes** and **For Car**, similar to the second typology previously presented. The lock-ins presented in Table 2.4 refer to the technological innovations and service models that sustain car dependency.

Table 2.4 - Transport Technology and Services Lock-Ins

Sub-Typology	Lock-In	Description	Number of mentions
*Transport Technology and Services **For Car***	**Car overproduction**	The mass production of car manufacturing, and the development of high-tech cars such as electric vehicles.	6
	High provision of energy resources	Refers to the abundant and affordable supply of energy, particularly fossil fuels (e.g. gasoline, diesel).	6
	Car-sharing service	On-demand car rental service, where the customer is the driver, having a flexible pickup and return point based on specific stations.	2
	Ride-hailing service	On-demand service where passengers can request a private ride with a personal driver, usually using a mobile application that intermediates the contact and payment between the person and driver.	2
	Multi-purpose vehicles	The flexibility of the private car, the development of cars that serve different purposes for an individual.	2
	Automation of private individual vehicles	The technology that enables a vehicle to perform driving tasks without continuous human input, ranging from partial automation (with some human input) to full autonomy (when the vehicle drives itself).	1
*Transport Technology and Services **For Alternative Transport Modes***	**Low availability and quality of public transport services**	A condition where the transit system is characterized by infrequent service, limited spatial and temporal coverage, and/or poor connectivity, failing to meet users' needs in terms of comfort and overall efficiency.	34
	Long distance to public transport	Refers to a long distance between a journey's start/end point and the nearest public transport stop, station, or other public transport service.	28
	Long distance to active/soft transport	Refers to a long distance between a journey's start/end point and the nearest infrastructure or services that support alternative mobility options such as bike-sharing stations, cycle paths, pedestrian networks, or others.	3

Sub-Typology	Lock-In	Description	Number of mentions
	Suburbanisation of mass transit systems	Describes the extension of the public transport system into low-density suburban areas.	1

The modernization of the automobile industry represents a major lock-in into car dependency, as demonstrated by Briggs et al. (2015)'s historical analysis of Automotive Modal Lock-in (AML) in the United States. **Car overproduction** is a clear example of this dynamic: in a subsequent review by the same authors, Webb et al. (2018) argue that the mass production (of vehicles) has historically been associated with internal economies of scale, along with reinforcing positive feedback mechanisms, which together established the internal combustion engine automobile as the dominant market technology. This effect continues to happen nowadays, as explained by Kent and Harris (2025), who argue that growing demand drives increased production, and overproduction in turn fuels even greater demand, creating a vicious cycle.

Electric vehicles, often promoted by the automotive industry as a pro-environmental shift, are an increasing problem as well. These vehicles, beyond burdening the future electricity grid, will still contribute to the non-environmental externalities of car dependence (ten Dam et al., 2022), since they congest the roads just as much as vehicles powered by internal combustion (Millard-Ball and Kapshikar, 2024). Furthermore, **Car overproduction** is mutually reinforced by the development of **Multi-purpose vehicles**, which lock in consumers by changing travel practices once acquired; their multipurpose nature and surplus capacity dominate individual mobility choices (Mattioli et al., 2020). The flexibility of the private car fits nicely as a mobile extension of this attachment and expectation (Kent, 2025), providing a perceived superior experience to public transit and active modes, which are often viewed as less flexible.

High provision of energy resources refers to abundant and affordable supply of fossil fuels. Fuel availability creates adaptive expectations that its infrastructure (e.g. gas stations) will be provided (Helmrich et al., 2023), reinforcing car ownership over alternatives. Low fuel prices boost car dependence (Saeidizand et al., 2025) and transit decline (Iseki et al., 2018). The increasing returns of petroleum-based system then create a self-perpetuating cycle of automobility (Marletto, 2011).

Although less problematic than private vehicle ownership, **Car-sharing** and **Ride-hailing services** still compete with more sustainable modes. Diab et al. (2020) find that the presence of Uber systems in Canada within small transit agencies service areas is associated with a decrease in the transit service ridership, meaning that **Ride-hailing services** are increased by **Low availability and quality of public transport services**. Haarstad et al. (2022) also warn that autonomous **Car-sharing services** might increase car dependency without push measures that reduce personal car use and ownership. Following this trend, Emberger and Pfaffenbichler (2020) argue that the **Automation of private individual vehicles** is expected to reduce the use of active and public transportation modes, resulting in a decreased modal share for these options.

The lock-in **Low availability and quality of public transport services**, characterized by limited, infrequent, and insufficient transit, is frequently cited in the literature (34 mentions) as a key barrier to choosing public transport over automobiles. As Wiersma et al. (2017) note, if public transport does not adequately connect key areas, residents may feel compelled to use cars. This lack of supply is mutually reinforcing with **Low land-use mix** and **Low urban density**, since the transport system is influenced by land-use structure and people's travel needs, while changes in transportation supply, in turn, affect residential and work location preferences as well as business site decisions, thereby altering land-use configuration (Okeke et al., 2021).

Furthermore, the low density of public transport stops (such as metro and bus) can discourage pedestrian activity, as found in Canada (Miranda-Moreno et al., 2011). However, competition among sustainable modes also plays a role, given that residing in cities with robust public transit networks has been associated with increased passive mode use, as demonstrated in a Dutch study by ten Dam et al. (2022).

Long distance to active/soft transport – which means the proximity to infrastructure for active and soft modes - is just as if not more important than the existence of this infrastructure for promoting active mobility. Piras et al. (2021) affirm the need for the presence of bike paths within 400m from home to positively affect cycling frequency, finding that individuals in such areas are less likely to be only occasional cyclists. This relationship is supported by Vale et al. (2018) and Millard-Ball et al. (2022): The latter state that a greater walk and bicycle accessibility also increases the propensity to use those modes, and Vale et al. (2018) highlight the low multimodal accessibility of isolated suburban university campuses, where a significant number of students commute by car. This illustrates a systemic relationship where **Urban sprawl** increases **Long distance to active/soft transport**, thereby reinforcing car dependency.

The relationship between distance and the service of transport also appears on public transit, described by the lock-in **Long distance to public transport**. Xianyu (2022) states that a high distance to the nearest transit stop has a slightly positive influence on car ownership, a finding corroborated by Millard-Ball et al. (2022), who note that greater public transport accessibility reduces the propensity to own and drive a car, while increasing the propensity to use public transport. Furthermore, distance to public transit also discourages the use of active modes: as the distance from home to a station increases, travellers are less likely to walk or cycle to it (Park et al., 2014). This pattern extends to bike sharing, with Moura et al. (2023) finding that a higher distance from the workplace to the train station decreases the probability of generating trips with Lisbon’s bike-sharing system.

Finally, while transport provision is essential, its excessive expansion can also be a problem. The lock-in **Suburbanisation of mass transit systems** exemplifies this principle, using improved mobility to increase accessibility in already dispersed, low-proximity urban structures. However, as Barter (2004) demonstrates in the case of Kuala Lumpur (Malaysia), the rapid rail expansion arriving late in the motorisation process – and without complementary transit-oriented development – tends to complement suburbanisation and automobile dependence rather than mitigate them, serving mainly to sustain the viability of the city centre rather than to reshape the dispersed urban structure it was built to serve.

2.2.4 Analysis of infrastructural interdependencies

Figure 2.4 presents the interconnections among the 31 infrastructural and technological lock-ins that contribute to car dependency, visualized through a Causal Loop Diagram (CLD). In this framework, lock-ins are represented as nodes connected by causal links that indicate positive (increasing) or negative (decreasing) influences, as well as potential feedback loops (mutual). The diagram highlights variation in connectivity across nodes: those with a higher number of connections exert a broader indirect influence on car dependence, generating synergies with other lock-ins, while those with few or no links operate more directly and in isolation.

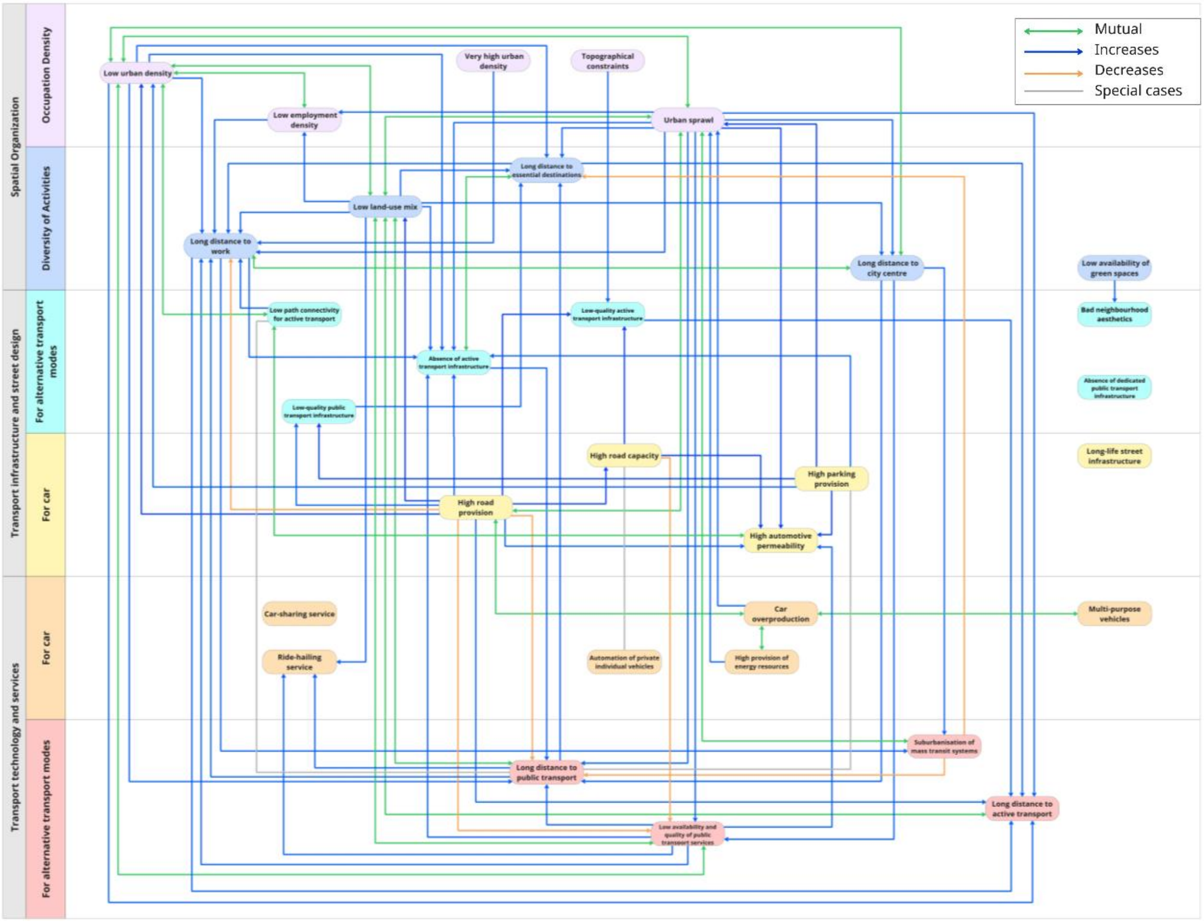


Fig. 2.4 – Infrastructural Lock-Ins connections

A hierarchy was established for the connections within the framework, prioritising mutual reinforcement (increases and it is increased by) as the strongest link. Consequently, in cases where the literature presented mixed interpretations - for instance, one source reporting a unidirectional increase from Lock-in A to Lock-in B, and another reporting mutual reinforcement - the mutual connection was selected for the framework. Similarly, if different studies suggested opposing unidirectional influences (e.g., A increases B in one source, B increases A in another), a mutual relationship was also inferred.

Special cases (Figure 2.5) were also included, namely connections that change to the opposite direction depending on the contextual conditions – such as such as urban density, cultural preferences, or the maturity of transport systems—thereby acknowledging that infrastructural interdependencies are not always fixed and may vary across different spatial settings.

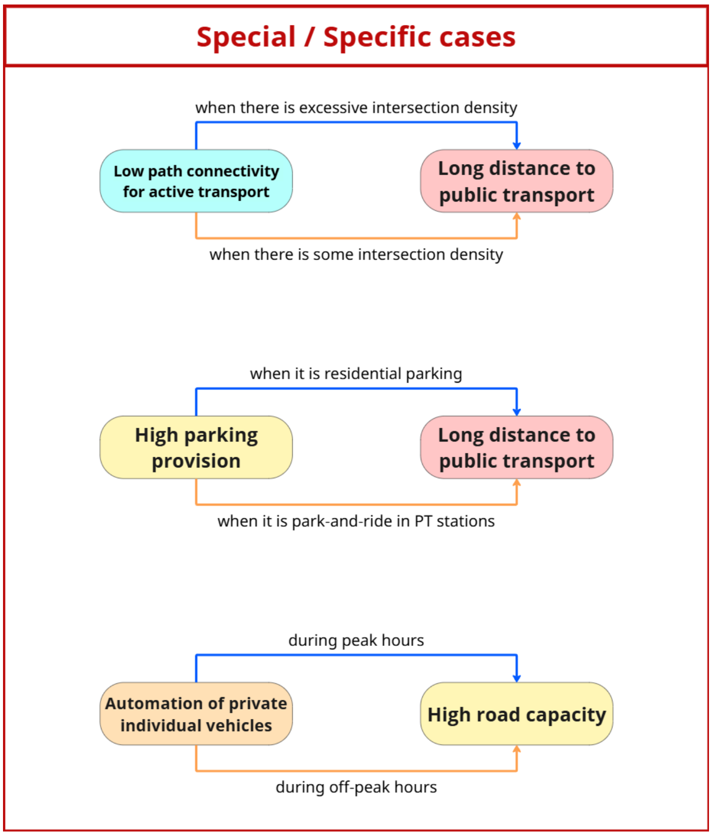


Fig. 2.5 – Special cases of Infrastructural Lock-Ins connections

The infrastructural lock-ins represented in this framework do not operate in isolation: they are also connected to lock-ins from the other two levels — Institutional and Behavioural — which were likewise identified in the literature review of 101 papers and incorporated into the diagram, thereby complementing the overall system of interdependencies.

Although this literature review was conducted primarily through an infrastructural lens, these additional levels consistently emerged in the assessed studies as complements to and interconnections with the infrastructural lock-ins. Therefore, the Institutional and Behavioural lock-ins, along with their reciprocal relationships with Infrastructural Lock-Ins, are addressed in the following chapter.

2.3 Connections with institutional and behavioural lock-ins

As introduced in this chapter, Seto et al. (2016) conceptualize three major types of carbon lock-in: infrastructural/technological, institutional, and behavioural. The authors exemplify numerous interconnections among and within these different levels of carbon lock-in, at multiple scales, with mutual reinforcement between and among the levels. According to them, changes in institutional and behavioural systems can reinforce the increasing returns to scale that drive technological lock-in:

> "For example, the lock-in of gasoline-powered automobiles reflects development, introduction, and marketing by automobile companies that also lobbied for transportation policies and subsidies for relevant highway and energy infrastructures that both created and responded to social and cultural preferences for individual transportation." (Seto et al., 2016)

There is a common causal progression, where institutional lock-ins influence infrastructural ones, which subsequently shape behavioural lock-ins. However, this progression is not deterministic: as illustrated in the Global Lock-Ins framework (Figure 2.6) and further detailed in Chapters 2.3.1 and 2.3.2, the literature also presents exceptions where these influences flow in other directions.

Naturally, this systematic literature review on infrastructural lock-ins found several connections to both institutional and behavioural dimensions.

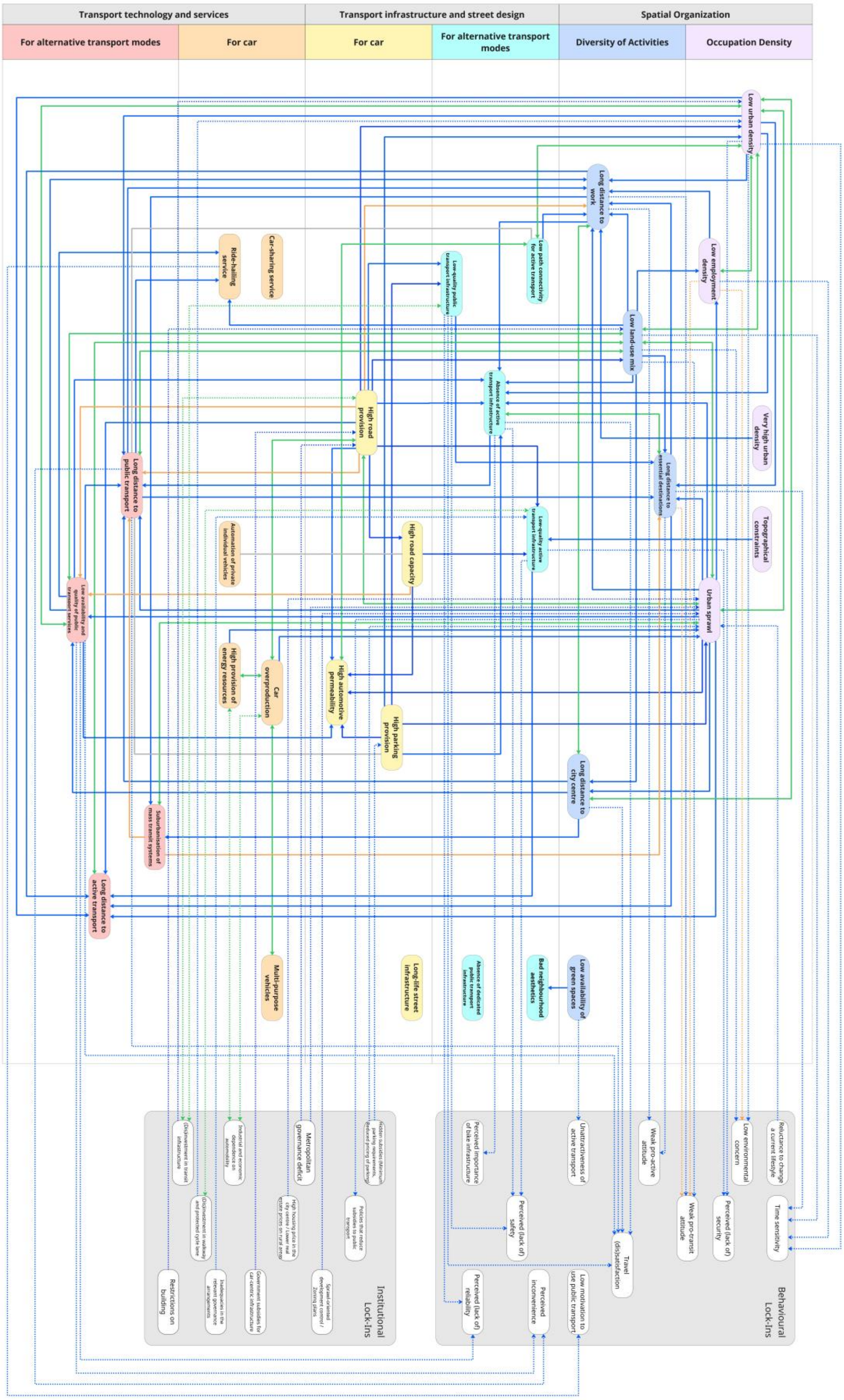


Fig. 2.6 – Global Lock-Ins connections: Infrastructural Lock-Ins and the other levels of lock-ins

2.3.1 Relation with Institutional Lock-Ins

The review documents that most connections between institutional and infrastructural lock-ins are characterised by either unidirectional influence (increasing infrastructural lock-ins) or mutual reinforcement. A single exception to this pattern is identified, as visualized in Figure 2.7.

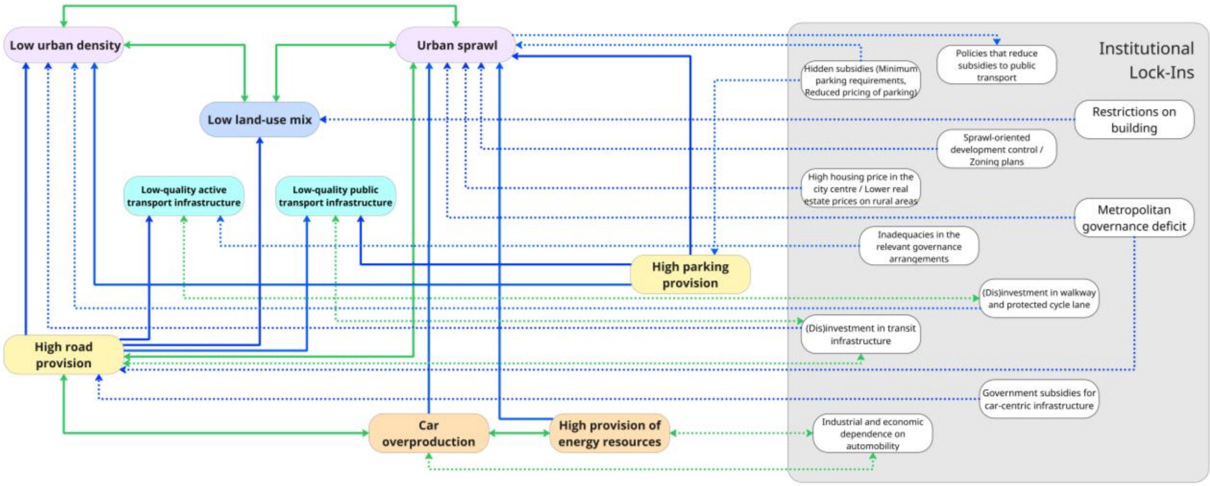


Fig. 2.7 – Interconnections between Infrastructural and Institutional Lock-Ins

Haarstad et al. (2022) identify a "metropolitan governance deficit," defined as an absence of clear and effective institutional arrangements for metropolitan-scale planning and coordination of urban services. They argue that this lock-in partly explains Melbourne's car-dependent practice of ever-expanding suburban fringe development (**Urban sprawl**) and freeway building (**High road provision**).

Other institutional lock-ins worth highlighting are the “(Dis)investment in transit infrastructure” and “(Dis)investment in walkway and protected cycle lane”. Webb et al. (2017) argue that Redirecting transport infrastructure resources causes the deprioritisation of public transport investment and is caused by the redirection of transport infrastructure resources, establishing a mutually reinforcing relationship between **High road provision** and “(Dis)investment in transit infrastructure”.

Pokharel et al. (2023) corroborate with this theory, affirming that "Disinvestment in transit and active mode infrastructure leads to a decrease in the quality of transit and active mode infrastructure, and vice versa,” indicating a mutual reinforcement with **Low-quality public transport infrastructure** and **Low-quality active/soft transport infrastructure**.

The only exception previously mentioned to the pattern of institutional lock-ins influencing infrastructural ones is the connection where Urban sprawl increases "Policies that reduce subsidies to public transport," as suburban car-dependent areas maintain the 'hidden welfare state', supporting sprawl and automobility (Mattioli et al., 2020).

2.3.2 Relation with Behavioural Lock-Ins

The review documents that most connections between behavioural and infrastructural lock-ins are characterised only by unidirectional influence, either **increased** or **decreased by** infrastructural lock-ins. A single exception to this pattern is identified, as visualized in Figure 2.8.

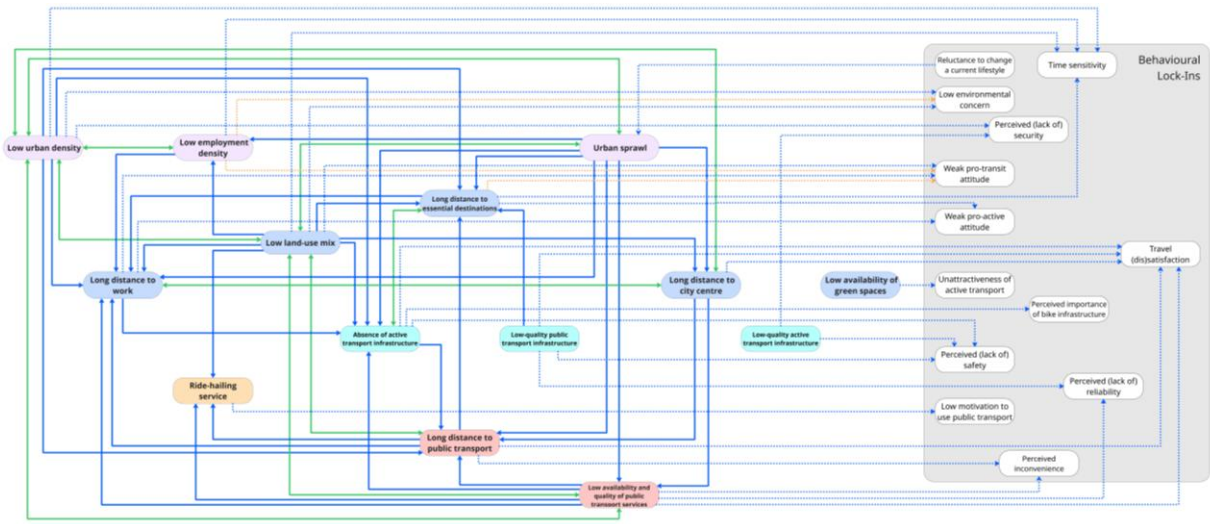


Fig. 2.8 – Interconnections between Infrastructural and Behavioural Lock-Ins

Majumdar et al. (2021) highlight a behavioural lock-in that this review terms "Travel (dis)satisfaction". They relate it to several key infrastructural features of the urban environment, including **Long distance to city centre**, **Absence of active/soft transport infrastructure**, **Low-quality public transport infrastructure**, **Low availability of public transport services**, and **Long distance to public transport**.

Perception is a critical factor influencing travel behaviour: a negative perception of infrastructure or transport services can result in low ridership/mode share for the corresponding system. Among the perception-related behavioural lock-ins, there are: "Perceived (lack of) reliability", "Perceived (lack of) security", "Perceived (lack of) safety", "Perceived importance of bike infrastructure" and "Perceived inconvenience".

Sharma and Jain (2024) attribute Delhi's declining bus ridership to overcrowding, poor hygiene, and perceived issues of reliability and safety, illustrating how **Low-quality public transport infrastructure** increases "Perceived (lack of) safety" and "Perceived (lack of) reliability". This perceived unreliability is also increased by **Low availability and quality of public transport services**, as Huang et al. (2021) note: more complex trips are constrained by the uncertainty and inconvenience associated with public transit, also linking the **Low availability and quality of public transport services** with "Perceived inconvenience".

The absence of moral orientation is captured by behavioural lock-ins such as "Weak pro-transit attitude," "Weak pro-active attitude," "Low motivation to use public transport," and "Low environmental concern." **Long distance to essential destinations** and **Long distance to work** are found to reinforce a "Weak Pro-Active Attitude" (Ramezani et al., 2021). In addition, "Low Motivation to Use Public Transport" is reported to be influenced by the presence of **Ride-hailing services** in highly accessible areas of the city (Marquet, 2020). However, "Low Environmental Concern" and "Weak Pro-Transit Attitude" exhibit mixed effects of being increased or decreased by infrastructural lock-ins. While **Low urban density** and **Low land-use mix** are shown to increase "Low Environmental Concern," **Low employment density** is surprisingly associated with a decrease in this behavioural lock-in (Ramezani et al., 2021). Similarly, **Low urban density**, **Long distance to work**, and **Low land-use mix** are found to increase a "Weak Pro-Transit Attitude," whereas **Low employment density** and **Long distance to essential destinations** are reported to reduce it (Ramezani et al., 2021).

The only exception previously mentioned to the pattern of infrastructural lock-ins influencing behavioural ones is the connection where **Urban sprawl** is increased by "Reluctance to change a current lifestyle". As Kruszyna et al. (2021) explain, this occurs because migrants from rural areas often choose suburban locations to avoid giving up their hard-to-break countryside way of living.

2.4 Chapter synthesis

The framework developed in this chapter identifies and organises 31 infrastructural and technological lock-ins into three interconnected typologies, clarifying the conditions that constitute infrastructural lock-ins, the mechanisms through which they reinforce one another, and their interrelationships with the other lock-in dimensions, following Seto et al.'s (2016) tripartite model of carbon lock-in. The findings demonstrate that infrastructural lock-ins operate as an interconnected system rather than as isolated barriers, meaning that addressing individual lock-ins in isolation is unlikely to produce substantial changes unless their systemic interactions are also considered. The review also highlights the central role of the Spatial Organization lock-ins – namely Urban Sprawl, Low Urban Density and Low Land-use Mix – as highly connected lock-ins that reinforce one another through multiple feedback loops.

Despite the growing body of literature on car dependency and transport transitions, some research gaps remain. First, although numerous studies analyse individual determinants of car dependency, relatively few adopt a systemic perspective that explicitly identifies the interdependencies among infrastructural lock-ins. Second, the literature rarely translates these conceptual relationships into operational frameworks that can support spatial diagnosis and planning practice, providing limited guidance on how these lock-ins can be identified and measured within a real urban context.

These gaps directly motivate the next stage of this research. To identify where infrastructural lock-ins arise and assess their spatial distribution and relative importance, it is necessary to operationalise them through measurable spatial indicators. Consequently, the following chapter reviews the concepts, indicators, and measurement approaches related to accessibility and walkability, providing the methodological foundation required to diagnose infrastructural lock-ins within both case studies.

3
MEASURING ACCESSIBILITY AND WALKABILITY TO REVEAL CAR DEPENDENCY LOCK-INS

Given the central objective of this research – diagnosing infrastructural lock-ins to soft mobility – and the role that accessibility and walkability measures play in identifying them, this chapter provides a conceptual and methodological grounding in both domains. It examines how accessibility and walkability are defined, theorised, and operationalised, with particular attention to the measurement approaches most relevant to detecting the lock-ins that this thesis seeks to address.

3.1 PROXIMITY-CENTRED ACCESSIBILITY

Over the past century, there has been a dramatic expansion of cities and their outskirts, increasing distances to essential destinations and reinforcing patterns of spatial injustice. This uncoordinated growth, also known as urban sprawl, has not only reshaped the urban form but also reconfigured how different services and everyday activities are distributed across the urban space, favouring individuals with access to private motorised transport to the detriment of those without. In this context, accessibility planning based on proximity can play an important role in addressing these challenges by supporting more inclusive and sustainable urban environments and future 15-minute cities.

3.1.1 Concept

Accessibility is defined as the ease of reaching desired activities, resulting from the combined effect of mobility and proximity within the urban environment (Silva, 2020). Accessibility builds on proximity, adding quantity and relevance. Given common misconceptions, accessibility must be clearly distinguished from **transport**, **mobility**, and **proximity**.

According to Silva (2017), **transport** relates to the system that enables mobility (the movement of people or goods), while **mobility** concerns the manner and ease with which this transport system is used to access opportunities dispersed across the territory. **Proximity**, in turn, relates to the physical closeness of destinations and has been defined using a variety of physical distances or travel times (Silva et al, 2023). Figure 3.1 exhibits the relation between the three concepts. Silva (2020) states that mobility has traditionally been managed within the domain of transport planning, while proximity has fallen under the remit of spatial planning. However, this division of responsibilities can reinforce a fragmented approach to urban development, potentially enabling and even incentivising unsustainable travel patterns in cities, as illustrated by the analysis of Melbourne's governance deficit by Haarstad et al. (2022) and discussed in Chapter 2.3.1.

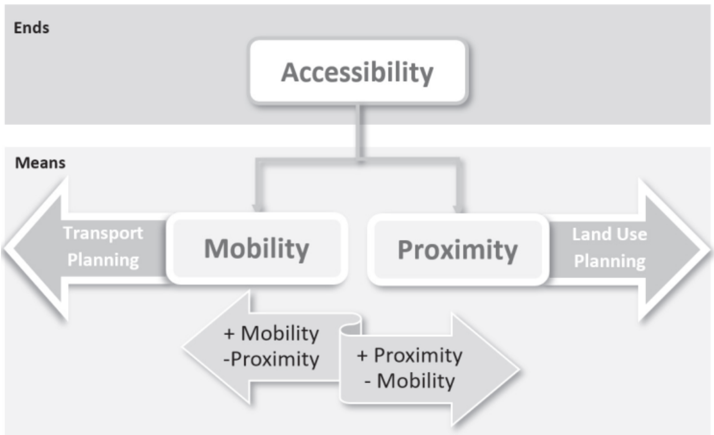


Fig. 3.1 – Accessibility, mobility, and proximity. Retrieved from: Silva (2020).

While mobility is defined by the potential for movement, accessibility relies on the spatial distribution and availability of opportunities. High accessibility might coexist with low levels of mobility if high proximity is provided between origin and desired destination, and vice versa: high levels of accessibility can be achieved with less proximity and higher mobility (Silva, 2020). This situation is illustrated by the lock-in **Suburbanisation of mass transit systems**, as previously discussed in Section 2.2.3.

3.1.2 Indicators

Silva (2020) identifies four challenges in measuring local accessibility: 1) defining the concept of local accessibility, 2) improving spatial detail of accessibility measures, 3) selecting relevant local destinations, and 4) ensuring comparability with regional-scale measures. Regarding destination selection (challenge three), Silva notes that while work is a primary focus at the regional scale, destinations such as shopping, healthcare, recreation, and green areas gain more relevance at the local scale.

In a study involving experts and planning practitioners from Portugal and Germany, Silva et al. (2023) found mixed evidence regarding activities relevant at proximity, defined as those located within an approximately 1,600-meter (20-minute walk) threshold. At the shortest travel times (5 min), playgrounds, parks/green spaces, and food shopping were considered the most relevant. Healthcare, pre-primary, and primary schools were also highlighted, though their perceived relevance varied by context. Most participants (>50%) across all groups considered other activities such as restaurants, post offices, banks, and sports facilities relevant within a 15-minute threshold. Other destinations such as employment, higher education, hospitals, non-food shopping, and cultural facilities were not considered relevant within a 15-minute scope.

3.1.3 Measures

Building on the institutional division between transport and spatial planning described in Chapter 2.2, and recognising accessibility as a concept that integrates these two domains, the application of accessibility measures offers a pathway to bridge this gap. By doing so, it ensures that transport concerns are safeguarded within land-use planning and, conversely, that land-use considerations are safeguarded within transport planning (Silva, 2017).

Despite the wide range of accessibility measures proposed in the literature, Silva (2017) defines four fundamental ones: **distance (or time)** measures, **isochrones**, **cumulative opportunity measures**, and **potential accessibility** measures.

Distance or time measures evaluate accessibility by calculating the distance or travel time between a point of origin and a chosen destination, usually along the most favourable route (Silva, 2017).

Isochrones outline areas reachable within a specific time or distance from a given origin or destination, covering all possible routes within that distance (or time) - for instance, maps may show areas accessible within 5-, 10-, or 15-minutes' walking distance from a transit stop or school.

The **cumulative opportunity** (or contour) measure is an evolution of the basic isochrone. It builds upon the isochrone by quantifying the opportunities available within a defined travel threshold (Silva, 2017). Rather than simply mapping reachable areas, it counts what is inside them - for example, calculating the number of schools within a 10-minute walk or the population residing within 600 meters of a metro station.

The fourth method, **potential accessibility**, introduces distance-decay functions, acknowledging that farther opportunities contribute less to accessibility than those nearby (Silva, 2017). Instead of using a fixed threshold (as in cumulative opportunities), it assigns decreasing weights to distant destinations. While this measure offers a more realistic assessment of accessibility, it requires additional methodological considerations (mathematical and interpretative), as the specific shape of the decay curve must be selected or calibrated for the given context.

3.1.4 Application of measures

The research by Pimentel (2025) examines proximity-centred accessibility in the city of Porto, Portugal, defining relevant local destinations by age group while accounting for differences in mobility constraints: young people and the general population (15-minute walking threshold at an average speed of 1.33 m/s), children 10-minute walking threshold at 1.20 m/s) and older people (10-minute walking threshold at 0.75 m/s). The **isochrone-based measure** was applied using GIS to develop a series of maps organised by amenity type, displaying one isochrone per age group. These maps were complemented by urban density charts to ensure a comparative assessment of accessibility levels across the different population groups. Overall, the author notes that the maps indicate a relatively well-distributed network of activities in Porto, despite the presence of gaps in certain areas, including some with high population density. The analysis further indicates that age groups such as children and young people are better served in central areas, whereas older adults experience greater accessibility in peripheral neighbourhoods, where services are more dispersed.

To construct their 15-minute city index for Bogotá, Guzmán et al. (2024) initially employed a **cumulative opportunity measure**. They counted establishments across six categories - Healthcare, Education, Recreation, Services, and Public Transport - reachable within a 15-minute walk from each city block. Recognizing that raw counts favour categories with more numerous establishments, they normalized the scores to a comparable 0–1 scale. Their analysis revealed that, on average, the city provides high access to restaurants, hairdressers, pharmacies, local shops, and grocery stores. However, high standard deviation numbers indicated a significant imbalance in access to these opportunities. Acknowledging a further limitation of the measure employed – that the indicator assigns equal importance to all establishment types, whereas different population segments might value each type of establishment differently -, to compose their 15-minute city index, the authors developed a final "diversity indicator”, composed by the logarithm of each normalized accessibility indicator multiplied by its weighting of activities from a ranking survey originally developed and applied to Bogotá's residents.

3.2 Walkability

Promoting sustainable mobility - and thus more sustainable cities - requires not only enhancing accessibility through the relocation of activities but also improving infrastructure for public transport, cycling, and walking (Milakis et al., 2017). Ensuring proximity-centred accessibility, combined with enhanced infrastructure and connectivity for alternative transport modes to the car, is therefore fundamental to unlock the potential of sustainable urban models, such as the 15-minute city.

3.2.1 Concept

Different theories exist in the literature regarding the definition of walkability. Traditionally, it has been argued that walkability is a quality of place (Bradshaw, 1993), describing how suitable an area is for walking. According to the same author, walkability has four basic characteristics: a "foot-friendly" physical micro-environment (related to the quality of walking infrastructure and path connectivity for alternative transport), a range of useful and active destinations within walking distance, a natural environment that moderates the extremes of weather (related to climate comfort) and a local culture that is social and diverse (related to the mix of low- and high-income households).

A complementary perspective is offered by Sim (2019), who frames walkability as making walking easier, more efficient, and more enjoyable, recognising that walking is the most fundamental form of mobility — every journey, regardless of the mode of transport chosen, begins and ends on foot.

Beyond these definitions, walkability has been operationalized in different ways depending on the focus of each study: while some studies incorporate accessibility into walkability (Bradshaw, 1993; Ribeiro and Hoffimann, 2018), other studies (Ruiz-Padillo et al, 2022; Fina et al, 2022; Guzman et al, 2024) consider walkability only related to actual distances (proximity) and the quality of walking infrastructure. Guzman et al (2024) split accessibility and walkability in different indexes to develop a new 15-minute city index (Guzman et al, 2024).

3.2.2 Indicators

The reviewed studies reveal a consensus around a core set of walkability indicators – Density, Diversity, different scales of Design and Safety - and considerable variation in the indicators used to operationalise them, reflecting differences in scale, data availability, and methodological approach. At a macro-scale, residential density, land-use mix, intersection density and retail density (floor area ratio or simply regular retail density) are common indicators. On the other hand, when the scale is more proximate - at the neighbourhood level or even at street level - more indicators are used, especially regarding Environmental Design and Traffic Safety. Public Safety indicators are less used and appear to be more relevant in specific contexts (Ruiz-Padillo et al., 2019; D'Orso et al., 2025). Table 3.1 synthesises the full set of indicators identified across the reviewed works, mapping their presence by author.

Much of the current literature on walkability gives particular attention to the development of walkability indexes/scores (Bradshaw, 1993; Adams et al, 2014; Ribeiro and Hoffimann, 2018; Ruiz-Padillo et al, 2022; Guzman et al, 2024) and even GIS plugin-based walkability toolboxes (Fina et al, 2022).

Table 3.1 - Indicators used in walkability indexes and scores, by author.

Indicator	Bradshaw (1993)	Frank et al. (2009)	Adams et al. (2014)	Ribeiro & Hoffimann (2018)	Ruiz-Padillo et al. (2022)	Fina et al. (2022)	Fonseca et al. (2022)	Guzman et al. (2024)	D'Orso et al. (2025)
DENSITY									
Residential density	●	●	●	●		●	●	●	
Commercial density								●	
Institutional density								●	
DIVERSITY OF DESTINATIONS									
Land-use mix / Proximity to diverse amenities		●	●	●		●	●		
Parkland area / green areas density	●					●		●	
Retail floor area ratio / Commercial frontage		●							●
Retail density					●		●		
CONNECTIVITY & NETWORK DESIGN									
Intersection density		●	●	●	●		●	●	●
Block length								●	
Pedestrian radius of activity / Catchment Area						●			●
Road density									●
ACCESSIBILITY TO MOTORISED TRANSPORT									
Access to PT							●	●	
Transit (PT) responsiveness	●								
Proximity to car parking (positive)							●		
Parking places per household (negative)	●								
SIDEWALK DESIGN / INFRASTRUCTURE									
Sidewalk width					●		●	●	●
Sidewalk surface / Pavement quality					●		●	●	●
Sidewalk / Pavement slope					●	●	●	●	●
Obstacles on sidewalk							●	●	●
Street furniture	●						●		●
Trees on sidewalks							●	●	●
Sidewalk provision / presence	●							●	
Ramp presence								●	
Sun/Rain protection									●
COMFORT & ENVIRONMENTAL DESIGN									
Attractiveness / Architectural context					●			●	●
Streetscape enclosure							●		
Streetscape complexity							●		

Streetscape transparency							●		
TRAFFIC SAFETY									
Pedestrian activity / flow							●	●	●
Traffic speed							●	●	●
Traffic lanes / volume / flow							●	●	●
Risk of accidents / Traffic accident records					●			●	
Traffic lights / Control devices								●	●
Crosswalk visibility									●
Congestion levels								●	
Driveways									●
Protection from vehicles									●
Street crossing time								●	
PUBLIC SAFETY / CIVIL SECURITY									
Lighting quality								●	●
Age child walks alone	●								
Crime records								●	
Proximity to police stations								●	
Security (police officers/residents)					●				
Security cameras								●	
Women's safety rating	●								
SOCIAL									
Chances of meeting acquaintances	●								
Neighbourhood places of significance (density)	●								

● *Indicator included in the respective walkability index or score. Empty cells indicate the indicator was not included.*

Bradshaw (1993) advocates for a walkability index structured as a questionnaire, based on ten main indicators:

- Density (persons per acre, up to centre-line of bordering features)
- Parking places off-street per household (unrestricted street access)
- Number of sitting spots on benches per household (include seating in front yards)
- Chances of meeting someone you know while walking
- Age at which a child is allowed to walk alone
- Women's rating of neighbourhood safety
- Responsiveness of transit service
- Number of neighbourhood "places of significance" named by average respondent

- Parkland (measurement)
- Sidewalks

Based on the foundational work of Frank et al. (2009), who originally composed a walkability index from four elements, Adams et al. (2014) computed a walkability index as the sum of standardized scores of net residential density, land use mix, and intersection density. This analysis was conducted within the framework of the International Physical Activity and the Environment Network (IPEN) Adult Study, which aims to understand how the built environment influences physical activity across multiple countries. The index proposed by Adams et al. (2014) does not include retail floor area ratio due to data unavailability across participating countries. The authors describe this adapted version as not the most precise, but one that still captures both proximity and connectivity, which they consider the two main theoretical constructs of walkability.

Following a similar approach, Ribeiro and Hoffimann (2018) develop a neighbourhood walkability index for the Porto Metropolitan Area (Portugal) following the same approach, using the three main variables and excluding the fourth variable (retail floor area ratio) due to data unavailability:

- Residential density (number of households per km2 within each neighbourhood)
- Street connectivity (number of intersections per km2 within 800 m of the centroid of each neighbourhood)
- Entropy index (number of destinations of each type within 400 and 800 m of the neighbourhood centroid)

Ruiz-Padillo et al (2022) propose a questionnaire-based walkability score for the medium-sized Brazilian city of Cachoeira do Sul (Brazil), incorporating eight attributes:

- Safety (Risk of Accidents)
- Security (number of police officers per 1.000 residents)
- Aesthetic quality of the urban environment (Attractiveness)
- Land-use diversity (number of shops and services in the neighbourhood)
- Slope of terrain (Topography)
- Sidewalk width (quality of walking infrastructure)
- Sidewalk surface (quality of walking infrastructure)
- Street connectivity (total number of intersections)

Guzman et al (2024) categorise four non-observable broader factors for their walkability index, with five observable components each:

- Pedestrian infrastructure robustness: Presence of sidewalk (segment), Sidewalk width (segment), Quality of sidewalk pavement (segment), Presence of ramps (segment), Obstacles on sidewalk (segment)
- Road safety: Motorized traffic speed (segment), Motorized traffic flow (segment), Presence of traffic control devices (segment), Traffic accident records (segment), Street cross-time (segment)
- Personal security: Presence of security cameras (segment), Presence of police stations (500 m buffer), Pedestrian flow (zone), Crime records (zone), Quality of lighting (segment)
- Destination access: Commercial density (zone), Institutional density (zone), Residential density (zone), Access to public transport (segment), Park or green areas density (zone)
- Comfort: Presence of trees (segment), Quality of the urban environment (zone), Congestion levels (segment), Sidewalks slope (segment), Block length (segment)

Fina et al (2022) developed a QGIS plugin toolbox that calculates the walkability of urban neighbourhoods for 500 by 500-meter vector grids. Its concept is structured into the so-called three Ds - density, diversity and design (Cervero and Kockelman, 1997), later enhanced by destination accessibility and distance to public transport. However, according to the authors, “destination accessibility” is covered by the “Diversity dimension” through a refined selection and weighting of amenities in the diversity dimension, and “distance to public transport” is not covered by the index since the focus is on neighbourhood-oriented residential walkability. Therefore, three main dimensions and indicators are assessed within this toolbox:

- Residential density (Density dimension)
- Proximity to (diverse) amenities (Diversity dimension)
- Pedestrian radius of activity, share of green and blue infrastructure (Design dimension)

Fonseca et al. (2022) propose a multi-criteria walkability evaluation structured around accessibility, land use, sidewalk facilities, street connectivity, traffic safety, and streetscape design, operationalised through binary and threshold-based measures derived from both GIS data and field audits. D'Orso et al. (2025) complement this perspective with a segment-level scoring system covering three weighted dimensions — practicability, pleasantness, and safety

— applied separately to sidewalks and crosswalks, and incorporating indicators such as pavement slope, pedestrian level of service, architectural context, lighting, and crosswalk visibility.

3.2.3 Measures

The indicators reviewed in the preceding section are not only diverse in their content but also in the way they are measured and aggregated. A first distinction concerns the logic of index construction: some authors assign specific threshold values or ideal parameters to each indicator — establishing explicit benchmarks against which each segment or area is scored — while others rely on relative measures, using the mean or statistical distribution of the observed data to standardise indicator values without presupposing what a desirable level should be, and therefore, composing an index based on weighted scores.

A second distinction concerns the source and nature of data: certain indicators lend themselves to quantitative measurement through Geographic Information Systems (GIS), drawing on spatial datasets to compute densities, distances, and network properties with relative objectivity and reproducibility. Others, however, capture dimensions of the pedestrian environment at a smaller scale — such as pavement condition, architectural quality, or the sense of safety — and are therefore assessed qualitatively, through field audits or surveys conducted with the target group of the study (e.g. residents).

In practice, many frameworks combine both approaches to assess neighbourhood or street scales, pairing GIS-derived structural indicators with empirically observed or perceived ones. Nevertheless, qualitative-based measures are less feasible at larger scales (city, metropolitan or country scales). Therefore, in studies covering big or medium-sized cities (Frank et al., 2009; Adams et al., 2014; Ribeiro and Hoffimann, 2018; Fina et al., 2022), the remote quantification becomes the predominant - if not the sole - viable approach.

Appendix A.2 synthesises the full set of indicators and their respective measurement methods by author. It also incorporates Cerin et al. (2022), which seeks to establish threshold values and optimal ranges from the IPEN Adult Study dataset — shifting from the indicator development and methodological harmonisation that characterised earlier contributions (e.g. Adams et al., 2014) toward policy threshold estimation and the definition of evidence-based planning targets. The walkability indicators assessment in Chapter 5.2 builds upon this body of work.

3.2.4 Application of measures

As previously mentioned in the section 3.2.2. (Walkability Indicators), Ribeiro and Hoffimann (2018) developed and validated a walkability index for the Porto Metropolitan Area by assessing its association with walking for transportation. Their index builds on the foundational work of Frank et al. (2005), which found a positive association between land-use mix, residential density, and intersection density with a higher number of minutes of moderate physical activity per day, and their subsequent work (Frank et al., 2009), which one included four measures (Net residential density, Retail floor area ratio, Intersection density and Land use mix/entropy score) and has also been widely adopted despite data limitation (e.g., Adams et al., 2014).

The final index of Ribeiro and Hoffimann (2018) converts their three components -residential density, intersection density, and an entropy score (land-use mix) - into z-scores and sums them with equal weight. It can be used as a continuous score or categorized into quintiles (Q1: least walkable to Q5: most walkable), following Frank et al. (2009). Their analysis showed that the residents of the most walkable neighborhoods – characterized by a variety of destinations within walking distance, a well-connected street network, and a high density of residences – presented 81% higher odds of walking for transportation (to/from work/school) compared to those living in the least walkable areas. Furthermore, the index revealed a clear radial decay from the urban core (Porto municipality) toward peripheral municipalities like Matosinhos and Vila Nova de Gaia. The authors attribute this pattern to the periphery's lower land-use mix and street connectivity, despite sometimes having higher residential density.

The final index of Ruiz-Padillo et al. (2022) combined eight built environment attributes - connectivity, sidewalk surface quality, sidewalk width, topography, number of shops and services, risk of traffic accidents, attractiveness, and number of police officers - into a weighted walkability score (WS) per neighborhood, derived from mixed logit panel models estimated through a best-worst scaling survey applied to 175 residents. Each attribute received a normalized weight (W_m) reflecting its relative importance as a barrier to walking, combined with field-assessed normalized values collected through GIS data, municipal records, and Google Street View audits. Their analysis showed that connectivity was the strongest barrier to walking (W_m = 0.20), followed by sidewalk surface quality (W_m = 0.16) and topography (W_m = 0.14), while the number of police officers presented the lowest weight (W_m = 0.05), which can be explained by the comparatively low crime rates of the small city. The resulting scores revealed a clear center-periphery gradient, with only the central neighborhoods reaching scores above 0.6, while most peripheral areas scored below 0.4, reflecting the concentration of shops, better sidewalk infrastructure, and more connected street networks in the urban core.

3.3 CHAPTER SYNTHESIS

Building upon the conceptual framework developed in Chapter 2, this chapter examined how accessibility and walkability indicators and measurement approaches can be used to assess infrastructural lock-ins, establishing the conceptual and methodological foundation upon which this dissertation builds. The review showed that accessibility and walkability are complementary concepts: while accessibility focuses on the opportunities that can be reached within a given travel threshold, walkability evaluates how supportive the built environment is for walking.

The literature reveals considerable methodological convergence regarding the main dimensions that influence accessibility and walkability. Residential density, land-use mix, proximity to destinations and street connectivity consistently emerge as the core indicators used across different studies and planning contexts. At the same time, the review demonstrates that additional indicators – such as traffic safety, environmental quality, topography, public transport accessibility, and public space characteristics – become more relevant when analyses are conducted at the neighbourhood or street scale.

Although the accessibility and walkability measures reviewed in this chapter are methodologically mature, most rely on continuous or locally standardised scores (e.g., z-scores, quintiles, weighted sums) that support comparisons within a specific study area but do not provide explicit thresholds for determining whether different locations can be considered "locked-in". Only a few studies attempt to establish evidence-based thresholds, such as Cerin et al. (2022), which proposes threshold values associated with more walkable environments based on the IPEN Adult Study dataset.

Nevertheless, the literature reviewed in this chapter provides methodological guidance and, where available, evidence-based threshold values that support the operationalisation of some of the infrastructural lock-ins identified in Chapter 2. The following Chapter 4 develops a spatial methodology capable of mapping and evaluating infrastructural lock-ins – identified in Chapter

2 – by building upon the quantitative accessibility and walkability approaches reviewed in this Chapter 3, linking the two bodies of knowledge and providing evidence to support planning strategies aligned with the principles of the 15-Minute City.

4
METHODOLOGY EMPLOYED FOR INFRASTRUCTURAL LOCK-INS CALCULATIONS

Identifying infrastructural lock-ins from a city-wide perspective is a selective exercise. It hinges on decisions regarding which destinations matter, how far people should reasonably walk to reach them, and what are the indicators best capture the quality of the pedestrian environment. These decisions shape which lock-ins are prioritised for intervention and which remain unassessed. This chapter aims to elucidate those decisions. It describes the two study areas of Porto (Portugal) and Plano Piloto (Brasília, Brazil), presents the lock-ins assessed, the justification for their selection, and their representative indicators. It further details the assessment framework and its underlying parameters, including the destination criteria and distance thresholds applied.

4.1 CASE STUDIES

The cases of Porto and Plano Piloto (Figure 4.1) were selected as they represent contrasting planning traditions and urban morphologies – one shaped by organic European city-building, the other by mid-20th century modernist planning – while remaining broadly comparable in inhabited extent, resident population, and position as centres of larger urban agglomerations. Despite appearing significantly different when measured by total classified urban area, a substantial portion of Plano Piloto's territory is subject to *non-aedificandi* restrictions, rendering its genuinely inhabited extent. Their resident populations reflect this equivalence: 207,996 in the Plano Piloto (PDAD-A, 2024) and 231,800 (INE, 2021) in Porto. Both areas, the

Municipality of Porto (within the greater city of Porto) and the Plano Piloto Administrative Region (within the city of Brasília), are detailed in the sub-chapters that follow.

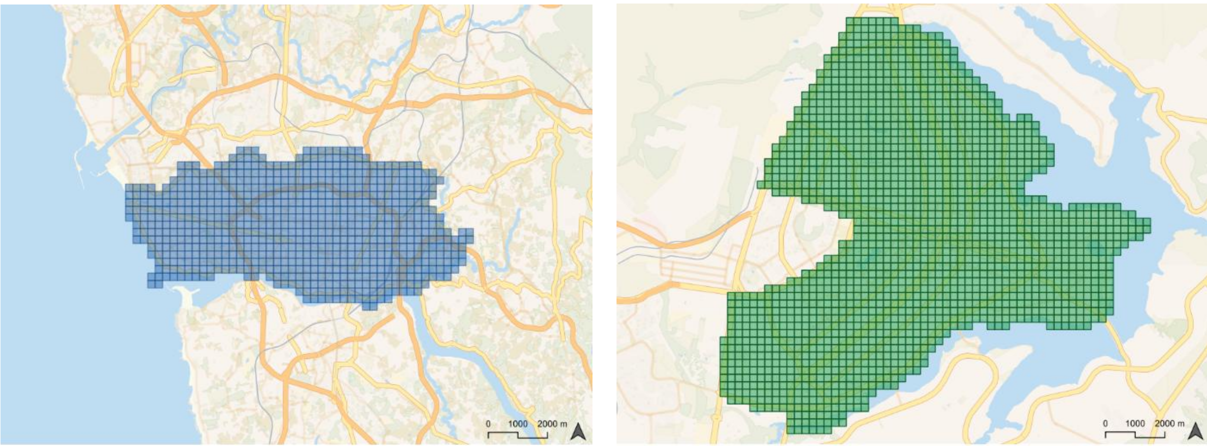


Fig. 4.1 – Porto and Plano Piloto study areas at the same scale with 250x250m grids

4.1.1 Study Area 1: Municipality of Porto (Portugal)

According to the most recent census conducted by Statistics Portugal (INE, 2021), Porto has a population of 231.800 inhabitants, placing it as a medium-sized urban area, as defined by the OECD (2012) Glossary. In territorial terms, the municipality is among the smallest in the country, covering 39.80 km² when the River Douro is excluded (41.42 km² in total). Under the Porto Municipal Master Plan (*Plano Diretor Municipal* – PDM), the whole municipality is formally classified as urban land (CMP, 2021). With a population density of 5,596.33 inhabitants per km² (INE, 2021), Porto ranks as one of the most densely populated municipalities in Portugal.

Figure 4.2 shows the population density of Porto by census tract, categorized into four classes ranging from under 500 to over 2,000 inhabitants per km².

Following the nomenclature of territorial units for city statistics established by Eurostat, the concept of a *greater city* acknowledges that urban centres often stretch far beyond their administrative boundaries (Eurostat, 2017). Under this definition, the Greater City of Porto (Figure 4.3) is composed of five municipalities – Porto, Vila Nova de Gaia, Gondomar, Valongo, and Matosinhos (Eurostat, 2017) – forming a continuous built-up area, even though only one of these municipalities bears the name "Porto." This spatial configuration explains why Porto is frequently described as Portugal's second largest city, despite its municipality ranking only fifth in population terms.

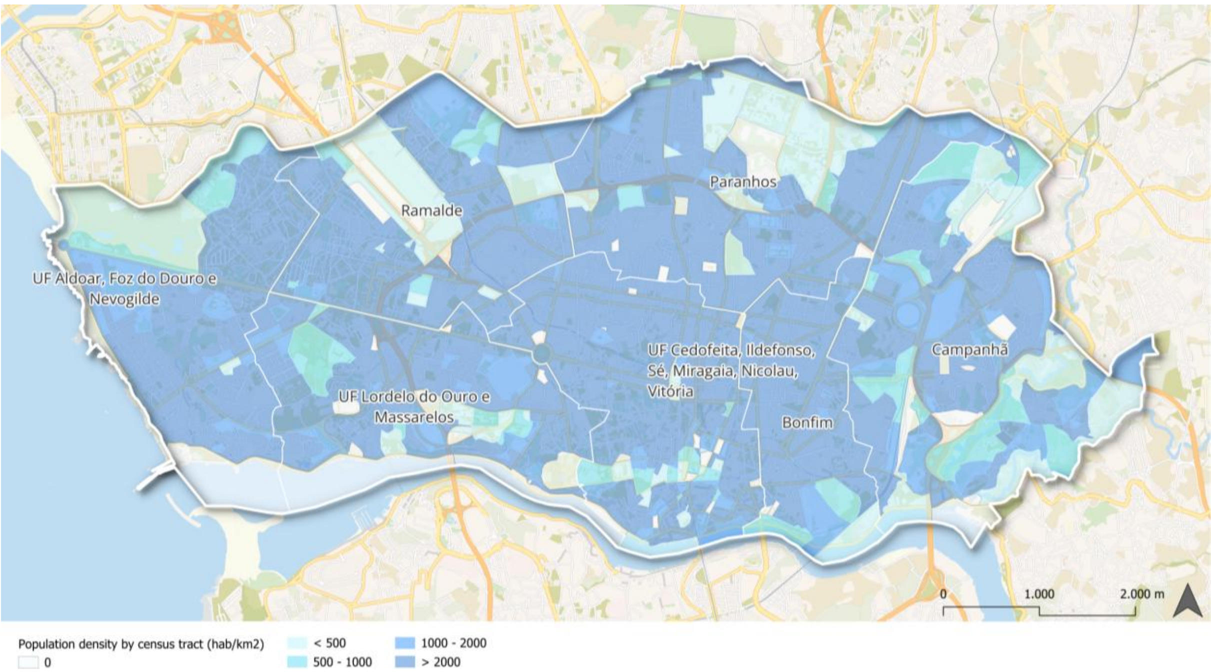


Fig. 4.2 – Population density of Porto

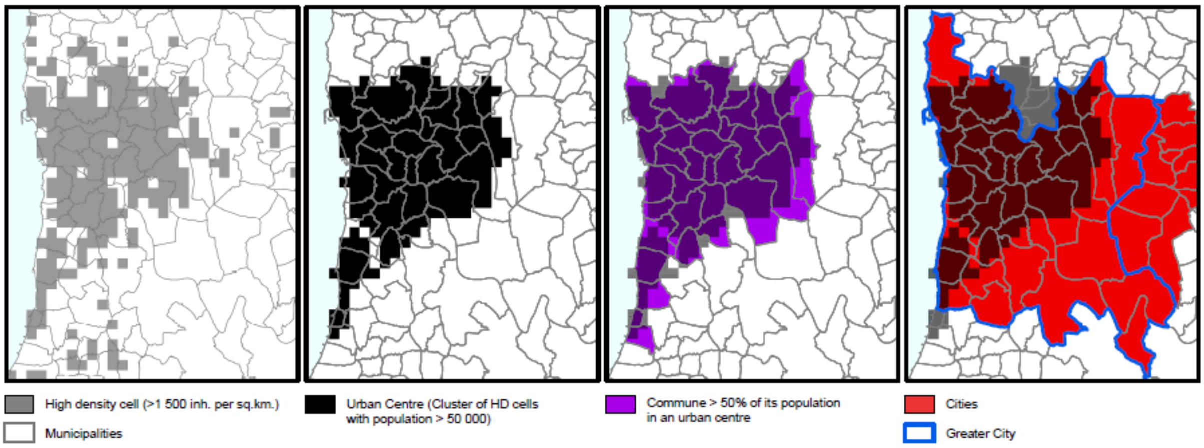


Fig. 4.3 – High density cells, urban centre, City and Greater city (Porto). Note: “Municipalities” in the legend actually refer to Parishes “freguesias”. Retrieved from: Eurostat (2017).

At a broader territorial scale, the Metropolitan Area of Porto (Área Metropolitana do Porto, AMP), depicted in Figure 4.4, covers an area of 2,040 km². According to the same national census (INE, 2021), the AMP is home to 1,736,228 inhabitants, making it the second largest metropolitan area in Portugal by population.

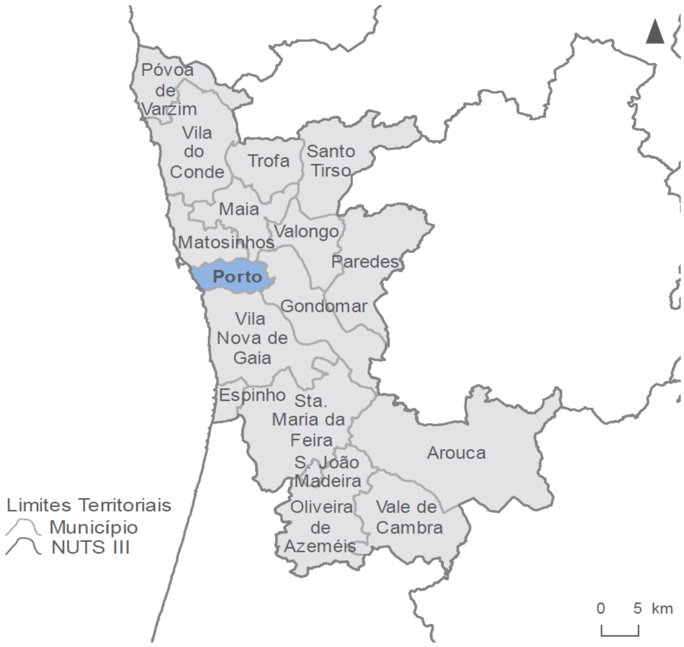


Fig. 4.4 – Metropolitan Area of Porto (AMP). Retrieved from: INE (2018).

Nevertheless, the municipality of Porto remains the functional core of the greater city of Porto – a central hub of regional significance, recognised at the European level when it was designated the European Capital of Culture in 2001.

4.1.2 Study Area 2: Administrative Region of Plano Piloto (Federal District, Brazil)

According to the most recent household survey conducted by the Companhia de Planejamento do Distrito Federal (CODEPLAN, 2024) — the PDAD-Ampliada (Pesquisa Distrital por Amostra de Domicílios Ampliada) —, the Administrative Region of Plano Piloto (RA-I) has an urban population of 207,996 inhabitants. However, according to the most recent national census conducted in 2022 by Brazilian Institute of Geography and Statistics (IBGE), the area comprises 198,697 inhabitants. This value accounts only for the census tracts within RA-I, given that the administrative region's boundaries also encompass the National Park of Brasília and Lake Paranoá, neither of which supports permanent settlement, as illustrated in Figure 4.5. Therefore, in territorial terms, the study area covers 98.24 km² – consistent with the spatial scope adopted by the household survey.

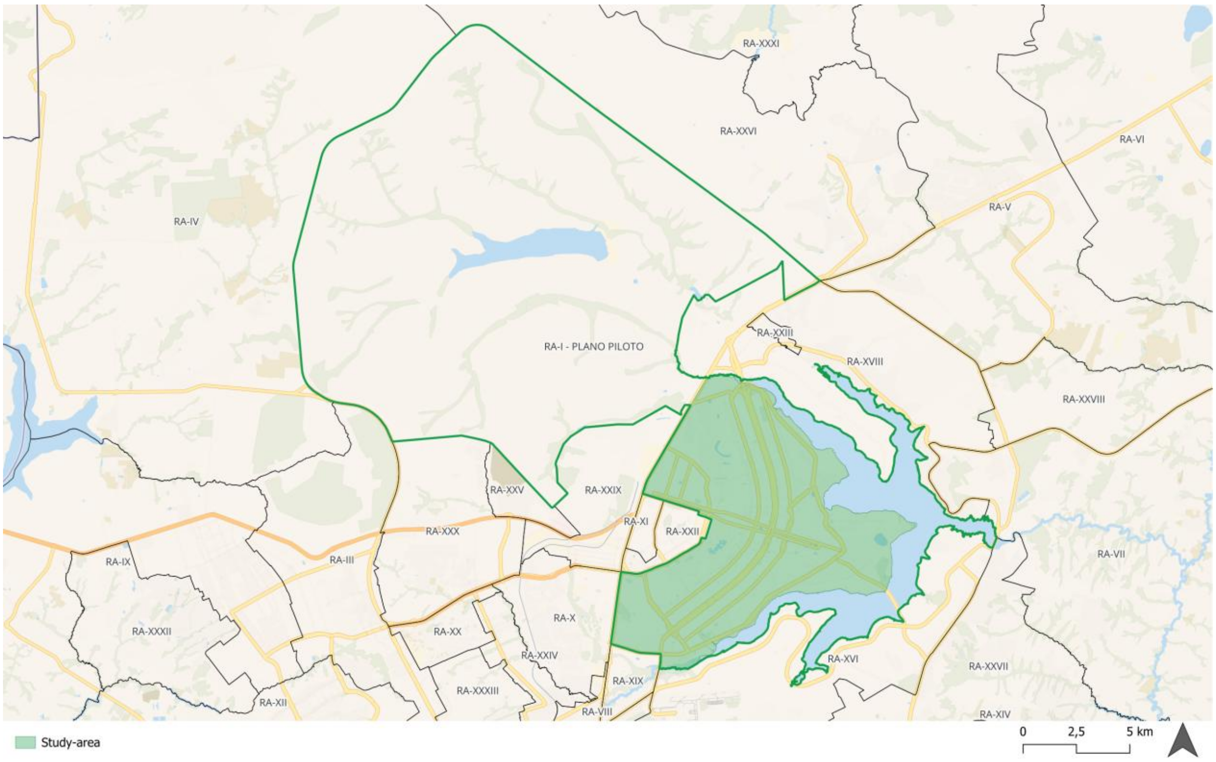


Fig. 4.5 – RA I - Plano Piloto and study area

Regarding population density, the RA-I is classified as low-medium-density, as depicted in Figure 4.6, which shows a density classification map of the administrative region, produced using the Densities dataset also from SEDUH (Secretaria de Desenvolvimento Urbano e Habitação do Distrito Federal) database. More specifically, the neighbourhoods of Asa Sul, Asa Norte, and Vila Planalto present medium density levels (between 1000 and 2000 inhabitants/km²), while the remaining areas of the administrative region are classified as low density (between 500 and 1000 inhabitants/km²).

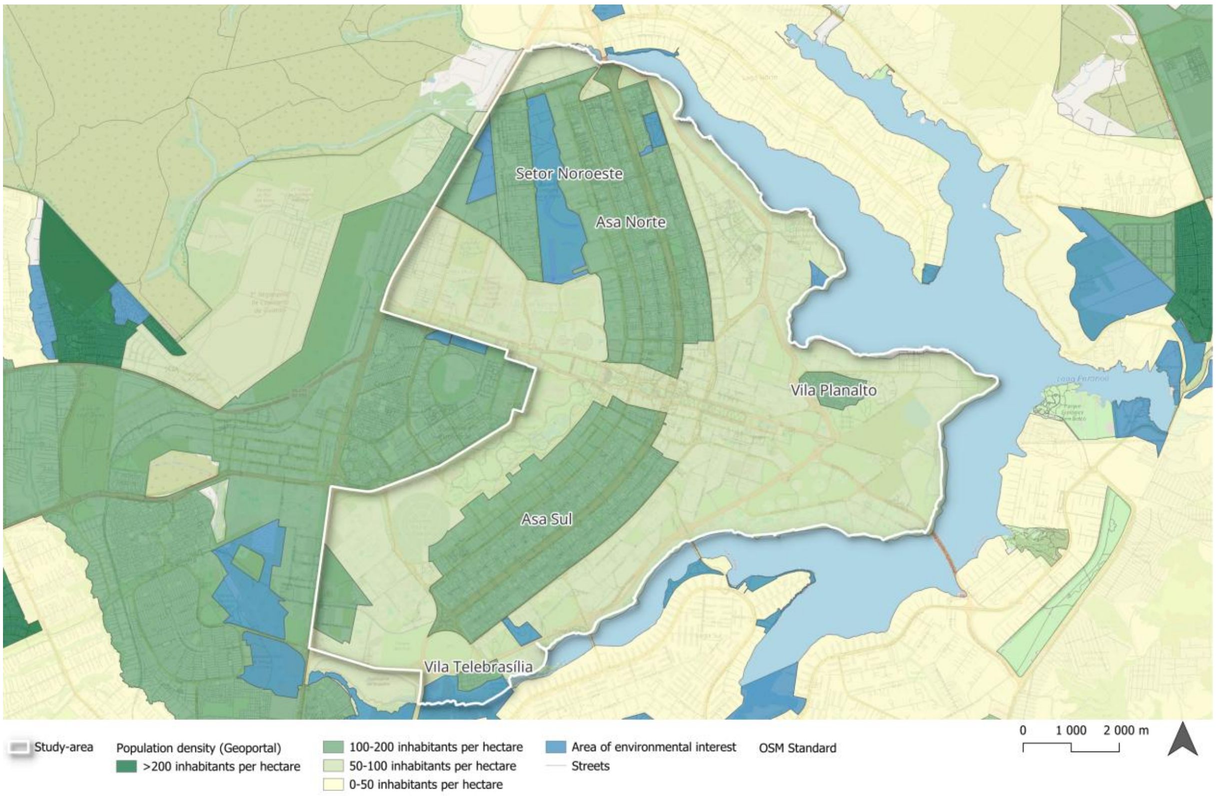


Fig. 4.6 – Population density of Plano Piloto.

Similar to the Municipality of Porto, which represents the core of a broader urban agglomeration, the Administrative Region of Plano Piloto occupies an analogous position within the city of Brasília. Although the Federal District contains no municipalities - being instead divided into 35 Administrative Regions (RAs), as illustrated in Figure 4.7 - the concept of a greater city equally applies in this context: urban centres often stretch far beyond their administrative boundaries (Eurostat, 2017), and Brasília is no exception. The city of Brasília is broadly understood as the urban Federal District as a whole, extending well beyond the Plano Piloto's limits. Within this structure, according to Paviani (2017), the Plano Piloto constitutes the functional core not only of Brasília but of the broader metropolitan area.

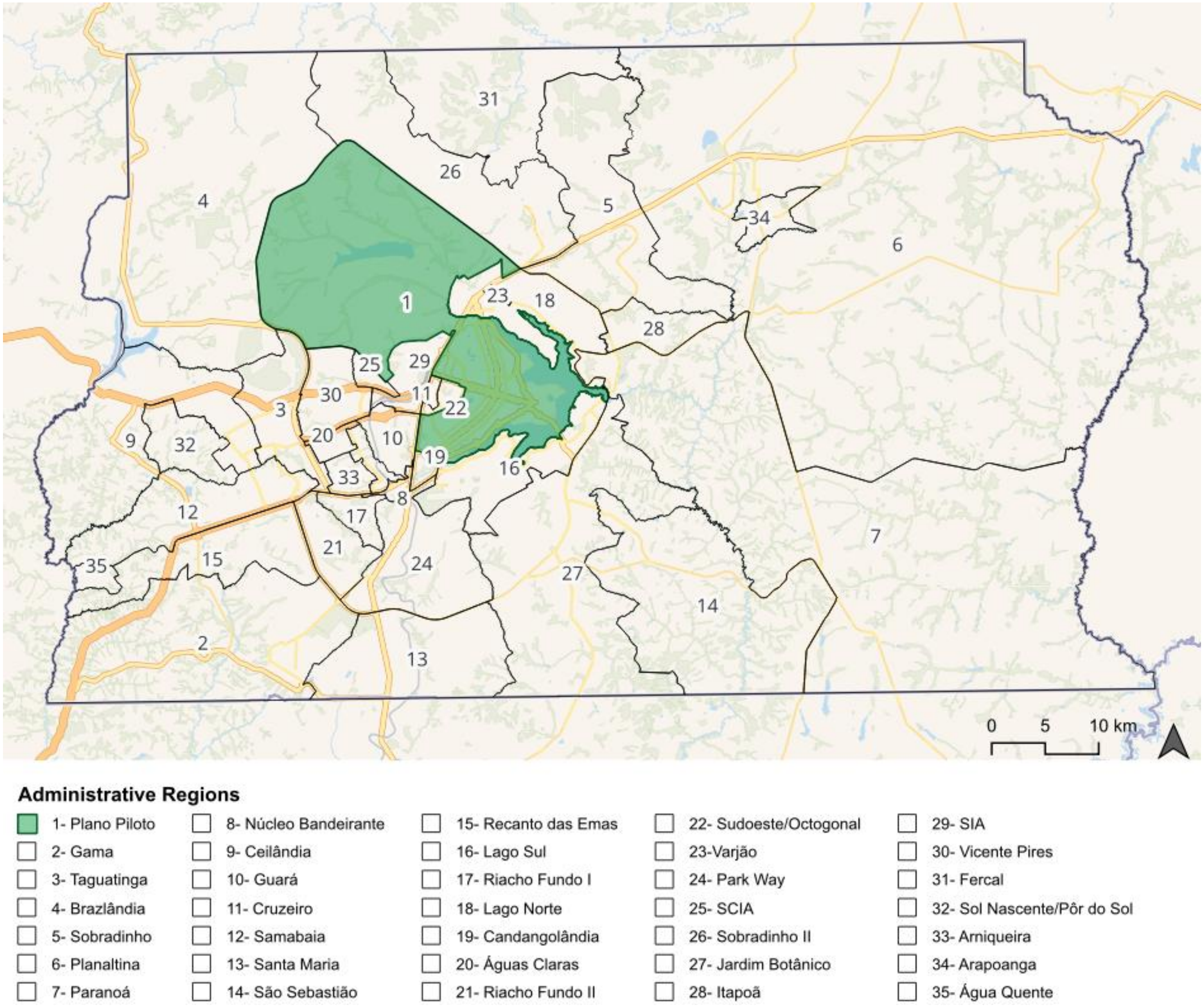


Fig. 4.7 – Administrative Regions of the Federal District.

At a broader territorial scale, the Metropolitan Area of Brasília (AMB), depicted in Figure 4.8, covers an area of 31813.72 km². According to the Federal District Atlas 2020, the AMB is home to 3,548,438 inhabitants, making it the third largest metropolitan area in Brazil by population. The AMB is composed of the Federal District — which accounts for more than half of the metropolitan population — and 13 neighbouring municipalities located in the Brazilian state of Goiás.

Nevertheless, the Plano Piloto remains the functional core of Brasília and a central hub of regional significance. As the seat of Brazil's federal capital, it concentrates the country's main government institutions, cultural landmarks, and administrative functions. Its exceptional architectural and urban planning heritage led UNESCO to designate it a World Heritage Site in 1987, making Brasília one of the few cities in the world to receive this recognition less than 40 years after its founding.

Fig. 4.8 – Metropolitan Area of Brasília (AMB).

4.1.3 Mobility patterns in Porto and Plano Piloto

Despite their distinct urban morphologies and historical trajectories, Porto and the Plano Piloto exhibit mobility patterns consistent with car dependency. Examining these patterns in detail, however, requires a note regarding data comparability: Commuting modal shares were aggregated into comparable categories across both surveys. For Plano Piloto, data are derived from the PDAD-Ampliada 2024 survey published by IPEDF Codeplan (IPEDF, 2024): "Private transport" includes car, ride-hailing/taxi, and motorcycle; "Public transport" refers to bus trips only (metro is an insufficient sample); and "On foot" is presented individually. For Porto, modal split data are available at the municipal level, drawn from the Census 2021 data published by Statistics Portugal (INE, 2021): "Private transport" includes cars drivers, passengers and motorcycles; "Public transport" includes bus, metro, and train; "On foot" and "Bicycle" are presented individually; and "Other" comprises school/company transport and other minor travel modes reported. Figure 4.9 displays the percentage distribution by transport mode in Plano Piloto and Porto.

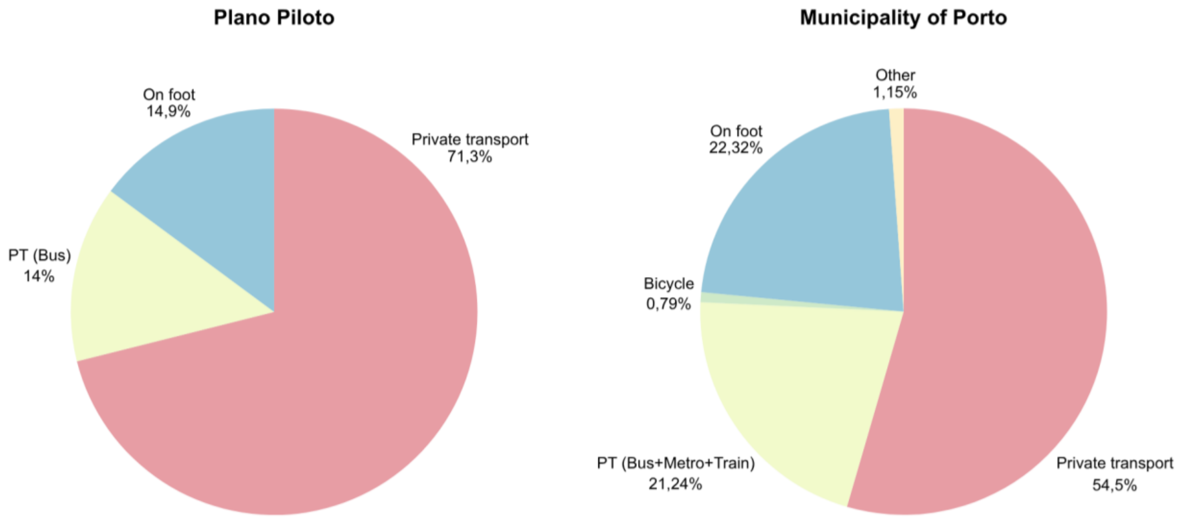


Fig. 4.9 – Distribution of number of trips by main mode of transport in Brasília and Porto. Produced by the author based on IPEDF (2024) and INE (2021).

In both cases, the private automobile emerges as the predominant mode of transport. In Plano Piloto, it accounts for 71.3% of all trips, while in Porto it accounts for 54.50% (Figure 4.9). The second most significant mode is also the same in both contexts, although their respective shares differ substantially: in Plano Piloto, only 14.9% of all trips are made on foot; while in Porto, walking represents 22.32% of all trips.

These aggregate figures nonetheless converge on a common finding: in both contexts, the dominance of private motorised transport supports the hypothesis that certain urban functions and destinations are either insufficiently accessible or inadequately served by sustainable modes, driving residents to rely on the private automobile for a substantial share of their daily movements.

Taken together, the mobility patterns of both Porto and the Plano Piloto reveal conditions consistent with car dependency: despite their distinct urban morphologies and historical trajectories, neither context has achieved the conditions necessary to make sustainable transport modes sufficiently competitive with the private automobile. In Porto, the coexistence of higher walking shares – although still considerably lower than those of the automobile – with automobile dominance points to a pedestrian environment that is only partially supportive of walking. In the Plano Piloto, the low share of both walking and public transport reinforces a picture of more structurally embedded car dependency.

4.2 Key indicators to measure Infrastructural Lock-Ins

The literature review presented in Chapter 2 identified 31 infrastructural lock-ins associated with car dependency. However, operationalizing all of them within the scope of this research was neither feasible nor methodologically appropriate. The selection of the five lock-ins measured in the cases of Porto and the Plano Piloto was therefore guided by six criteria applied conjunctively.

First, each selected lock-in had to demonstrate consistent relevance in the lock-in literature, appearing recurrently across the literature assessed in Chapter 2 as a structural barrier to reducing car dependency.

Second, the indicators that would represent each lock-in also had to hold recognized relevance in the accessibility and walkability literature, ensuring that the measured dimensions affect active mobility and sustainable urban transport outcomes directly.

Third, given that both case studies operate at a macro-scale, remote measurement through GIS was a prerequisite: indicators requiring field audits or fine-grained observational data collection were excluded, as such methods are not scalable to city-level analysis.

Fourth, each selected indicator had to have established measurement parameters, including threshold values and optimal ranges documented in the literature of Chapter 3, so that the operationalisation would rest on validated benchmarks.

Fifth, the spatial data required to calculate the indicators representing each lock-in had to be available through either OpenStreetMap or the official databases of the respective case study administrations: Portal de Dados Abertos da cidade do Porto (managed by Porto City Council, CMP) and Geoportal (managed by the Secretariat for Urban Development and Housing of Federal District, SEDUH-DF). Lock-ins whose operationalisation depended on data sources outside these repositories were excluded on grounds of consistency and replicability.

Sixth, although the walkability and accessibility literature reviewed in Chapter 3 encompasses indicators related to both active mobility and public transport, this research focuses specifically on infrastructural conditions that constrain walking. Lock-ins whose primary effect operates through public transport accessibility, rather than through the built environment's support for active travel, were therefore excluded from the measurement framework.

Together, these criteria ensured that the selected lock-ins are theoretically grounded, practically measurable at the scale of analysis, and quantifiable through reproducible and comparable methods across both case studies. Table 4.1 presents the selected lock-ins alongside their corresponding indicators, as established in the literature.

Table 4.1 - Selected Lock-Ins and their indicators for measurement according to the literature.

Lock-In	Indicator that represents the Lock-In	Frank et al. (2009)	Adams et al. (2014)	Cerin et al. (2022)	Ruiz-Padillo et al. (2022)	Fonseca et al. (2022)
DENSITY						
Low urban density (cited 35 times)	Residential density			≥ around 5700 people per km² = Optimal range		≥ average local density = 1 < average = 0
DIVERSITY OF DESTINATIONS						
Low land-use mix (cited 37 times) / **Long distance to essential destinations** (cited 19 times)	Land-use mix	Single use = 0 Even distribution of floor area across 5 uses (residential, retail, entertainment, office and institutional) = 1	Single use = 0 Equal distribution of residential, retail combined, and civic/institutional land area within the buffer across uses = 1			> 3 uses = 1 ≤ 3 uses = 0
Low land-use mix (cited 37 times)	Retail density				Number of shops and services / Neighbourhood area Low density = ≤ 25 per km² Medium density = 25-85 km² High density = >85 km²	≥ average local density = 1 < average = 0
CONNECTIVITY & NETWORK DESIGN						
Low path connectivity for alternative transport (cited 37 times)	Intersection density			≥ 100 intersections per km² = Optimal range		≥ 3 intersections in a street = 1 < 3 intersections in a street = 0

Finally, to assess how unlocked each grid cell is for walking at the macro-scale — capturing the connectivity, density, and diversity of destinations reachable within a walking distance — the measurement parameters for each indicator were established, based on the optimal ranges documented in the literature (Table 4.1) and adapted where necessary to enable computation through the OD Matrix framework, in Table 4.2. Each indicator is scored on a binary scale — criterion met (1) or criterion not met (0) — to subsequently compose the final Infrastructural Lock-In classification, enabling direct comparability across both study areas. The methodology for the calculation of each indicator is detailed in the sub-chapters that follow.

Table 4.2 - Selected Lock-Ins and their indicators for measurement with final optimal ranges.

Lock-In	Indicator that represents the Lock-In	Values for final classification	Input database	Base literature
DENSITY				
Low urban density	Population density	≥ 5700 people per km² = 1 < 5700 people per km² = 0	Census tract units accessed in January 2026. **Porto**: Small Statistical Areas (BGRI 2021) from Statistics Portugal (INE). **Plano Piloto**: Census Sectors (Setores Censitários 2022) from the Brazilian Institute of Geography and Statistics (IBGE).	Cerin et al. (2022) [Optimal range = ≥ 5700 people per km²]
DIVERSITY OF DESTINATIONS				
Low land-use mix / Long distance to essential destinations	Land-use mix	"W_Acc" = '1_Full_Complete', '2_Almost-Complete', '3_Mostly-Essential' or '4_ Mostly-Functional' = 1 "W_Acc" = '5_Low_Mix' or '6_Nothing' = 0	OpenStreetMap (OSM) database for both areas Points of interest (point): gis_osm_pois_free_1 gis_osm_pois_a_free_1 Network (string): gis_osm_roads_free_1	Ruiz-Padillo et al. (2022) [Number of shops and services / Neighbourhood area Low density = ≤ 25 per km² Medium density = 25-85 km²]

Low land-use mix	Retail density	> 25 shops per km² = 1 ≤ 25 shops per km² = 0	OpenStreetMap (OSM) database for both areas Points of interest (point): gis_osm_pois_free_1 gis_osm_pois_a_free_1 Network (string): gis_osm_roads_free_1	Fonseca et al. (2022) [≥ average local density = 1 < average = 0]
CONNECTIVITY AND NETWORK DESIGN				
Low path connectivity for alternative transport	Intersection density	≥20 intersections accessed in 250m = 1 <20 intersections accessed in 250m = 0	OpenStreetMap (OSM) database for both areas Network (string): gis_osm_roads_free_1	Cerin et al. (2022) [Optimal range = 100 intersections per km²]

4.3 Indicator 1: Population Density

Residential population density is one of the foundational predictors of pedestrian travel and street activity in transportation and urban planning literature. The association is well-established: denser residential environments are associated with higher rates of walking (Miranda-Moreno et al., 2011; Kandt, 2018; Macioszek et al., 2022). The mechanisms underlying this association are multiple. Higher residential density concentrates potential pedestrians, increasing the likelihood that local destinations will have sufficient demand to remain economically viable, which in turn reinforces the availability of walkable destinations. According to Kent (2025), increasing density to decrease travel distances is an example of material structural affordance designed to encourage the use of alternative transport modes: density and destinations enable local living, and a lack of these things across the wider city mean some activities are hard to access. A city defined by lower density urban form is filled with opportunities only accessible by private car.

The threshold adopted for this indicator is 5,700 inhabitants per km², following Cerin et al. (2022). This value corresponds approximately to the lower boundary of what is characterised in the international planning literature as ‘medium-density urban’ development and has been shown in the empirical literature to be associated with meaningfully higher rates of active travel compared with lower-density environments.

To compute origins at the macro-scale, city-level Origin-Destination Matrix, the study area was divided into a regular grid of 250x250m cells, whose centroids were used as origins for the OD Matrix. Population data were derived from census tract units sourced from the institutional databases of each case study: Small Statistical Areas (BGRI 2021) from Statistics Portugal for Porto, and Census Sectors (*Setores Censitários*) from IBGE (2022) for the Plano Piloto, both accessed in January 2026.

A straightforward approach to computing population density for each grid cell would be to divide the number of residents within each 250x250 m cell by the cell area (0,0625 km²). However, this raw cell-level density is subject to distortion: the population is aggregated to census tract in the source data, and its spatial distribution within each census unit is typically assumed to be uniform, however, since the census units do not align with the grid cells, the distribution of population across grid cells may be poorly estimated, particularly in areas where a single census unit spans multiple grid cells with very different land uses (for example, a cell containing a park adjacent to a cell containing a residential block). To address this concern, the normalised density measure was used to average population density across the neighbourhood context of each centroid. This was done by spatially smoothing the population density: for each grid centroid, the mean density of all grid cells intersecting a 500m Euclidean buffer was computed, a radius chosen to represent the immediate neighbourhood context. The resulting mean value was then used as the input for the subsequent binary scoring.

4.3.1 Binary Scoring of Population Density indicator

The binary score for population density (Table 4.3) was assigned by comparing each grid cell's normalised density value against the 5700 people/km² threshold. Grid cells with a normalised density of 5700 people/km² or above received a score of 1; all others received a score of 0.

Table 4.3 - Binary scoring of Population density indicator

Population Density Scoring	Estimated value of population density in grid cell
1	≥ 5700 residents/km²
0	< 5700 residents/km²

4.4 INDICATOR 2: LAND-USE MIX

Among the key infrastructural lock-ins identified in sub-chapter 4.2, two lend themselves to measurement through proximity-based accessibility: **Long Distance to Essential Destinations** and **Low Land-use Mix**. These two lock-ins share a common spatial logic: both are rooted in the relationship between where people are and where they need to go, making proximity-based accessibility a particularly appropriate analytical lens.

The methodology developed to measure these lock-ins is structured into four sequential phases: (i) selecting relevant activities and distance thresholds; (ii) computing the measure Origin-Destination Matrix (OD Matrix); (iii) classifying accessibility by diversity of activities and (iv) binary scoring of Land Mix indicator.

4.4.1 Selecting relevant activities and distance thresholds

The most relevant destinations are defined according to an expert-based ranking of activities by proximity importance. Drawing on Silva et al. (2025), who surveyed urban planning practitioners and accessibility experts to establish reasonable access times for a range of urban activities.

The first six activities considered reasonable to reach within a 10-minute walking threshold by both practitioners and experts - pre-primary schools, playgrounds, food shopping, primary schools, parks/green spaces, and pharmacies - were classified as Essential Points of Interest. The subsequent group, considered reasonable to reach within a 15-minute threshold, comprising general practitioners, post offices, banks, restaurants/cafés, and sports facilities — were classified as Functional Points of Interest. Figure 4.11 presents the selected activities and their respective classifications, based on the graphical representation provided by Silva et al. (2025).

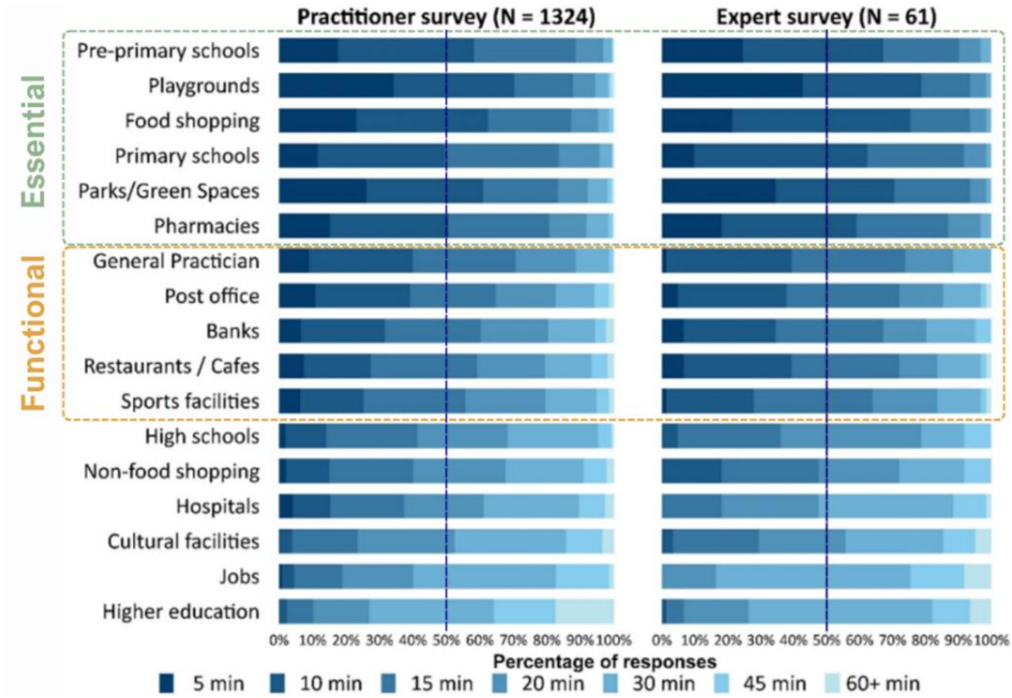


Fig. 4.10 – Reasonable access time to each activity. Retrieved and adapted from Silva et al, (2025).

This classification is further grounded in the theoretical connection between the 15-minute city and Mobility of Care established by Soukhov et al. (2025), building on the concept coined by Sánchez de Madariaga (2013). Soukhov et al. (2025) operationalise care-related mobility through 14 destination types grouped into four categories — dependent-centric (schools, nurseries, parks), grocery-centric (supermarkets, convenience stores), health-centric (pharmacies, clinics, hospitals), and errand-centric (banks, libraries, post offices) — and demonstrate that such trips constitute a significant share of daily travel, are universal across population groups, and occur predominantly at the local scale. The Essential POIs adopted in this study correspond closely to the dependent-centric, grocery-centric, and health-centric dimensions of this framework, while the Functional POIs extend coverage to services aligned with the errand-centric category, together capturing the full spectrum of care-adjacent daily mobility.

It is important to highlight that the presence of green spaces is also considered an essential activity, considering both the literature (Silva et al., 2025) and the original classification of essential activities adopted in this thesis. Accordingly, green spaces were measured within the Proximity to diverse amenities / Land-use mix and Retail density indicators, which represent the lock-ins of **Long distance to essential destinations** and **Low land-use mix**. Furthermore, despite having been primarily discarded according to the criteria explained in Chapter 4.3 - and therefore not selected for formal assessment - the lock-in **Low availability of green spaces** (cited five times in the literature) is nevertheless assessed in this accessibility calculation.

Regarding distance thresholds, this methodology draws on Silva et al. (2023), adopting two pedestrian distance thresholds that correspond to different walking times at an average speed of 1.33 m/s (4.8 km/h), as summarised in Table 4.4.

Table 4.4 - Pedestrian distance thresholds adopted

Threshold	Time	Distance
Essential	10 minutes	800 metres
Functional	15 minutes	1,200 metres

Accordingly, Essential activities (categories 01–06: pre-primary school, playground, food shopping, primary school, park, and pharmacy) are considered accessible when the nearest POI within each category is located within 800 metres of the origin grid cell. Functional activities (categories 07–15) are considered accessible within a 1,200-metre perimeter radius.

4.4.2 Computing the measure Origin-Destination Matrix (OD Matrix)

An Origin-Destination matrix was produced using the QNEAT3 plugin for QGIS to estimate network travel distances between each grid cell centroid and its relevant destinations, with thresholds of 800m for Essential activities and 1,200m for Functional activities, as determined in the preceding sub-chapter. The analysis adopted the shortest-path criterion, ensuring that distances reflect actual routing through the street network rather than straight-line Euclidean approximations. Origins corresponded to the population grid centroids described in sub-chapter 4.2, and both the street network and destination Points of Interest (POIs) were sourced from OpenStreetMap data accessed in January 2026. POIs were filtered to retain only those categories relevant to the activity types defined for this study; green spaces and playgrounds, which were found to be systematically underrepresented in both study areas, were supplemented with additional features to ensure adequate spatial coverage. The resulting POIs were subsequently reclassified into the activity categories defined for this study, as detailed in Appendix A.3.

Two complementary dimensions of accessibility were computed for each activity category:

- Presence (PS) – whether at least one POI of a given category is reachable from a grid cell (0 = absent; 1 = present);
- Quantity (QT) – the total number of POIs of a given category reachable from a grid cell.

Building on the Presence dimension, three composite accessibility scores were then calculated: accessibility to Essential activities in 800m (sum of categories 01–06), accessibility to Functional activities in 1200m (sum of categories 07–11), and a Global accessibility score combining both. These composite scores served as the input for the accessibility classification described in the following sub-chapter 4.4.3.

4.4.3 Classifying accessibility by diversity of activities

The accessibility classification captures the diversity of Essential POIs (0–6 categories) reachable within 800m and Functional POIs (0–5 categories) reachable within 1,200m through the street network, as defined in sub-chapter 4.4.1. Rather than treating raw counts as a continuous measure, presence was grouped into four levels for each activity type – absence (0), low presence (1-3 Essential; 1-2 Functional), high presence (≥4 Essential; ≥3 Functional), and full presence (6 Essential; 5 Functional) – and then combined into six composite classes capturing the joint distribution of Essential and Functional accessibility, as presented in Table 4.5.

Table 4.5 - Accessibility Classification for Land-use Mix indicator

Accessibility Classification	Essential	Functional
1_Complete [Full presence of both Essential (6) and Functional (5) POIs]	6	5
2_Almost-Complete [High presence of both Essential (4–6) and Functional (3–5) POIs]	6	3-4
	4-5	5
	4-5	3-4
3_Mostly-Essential [High Essential presence (4–6) but low Functional presence (1–2)]	6	1-2
	4-5	1-2

4_Mostly-Functional [Low Essential presence (1–3) but high Functional presence (3–5)]	1-3	5
	1-3	3-4
5_Low-Mix [Low presence across both categories, OR total absence of one]	1-3	1-2
	1-6	0
	0	1-5
6_No-Mix [Absence of both Essential and Functional POIs]	0	0

4.4.4 Binary scoring of Land-Use Mix indicator

For the binary variable (depicted in Table 4.6), Grid cells classified in the four highest categories – Complete, Almost-Complete, Mostly-Essential, and Mostly-Functional – were scored 1, indicating a sufficient degree of land-use mix to support walking behaviour, and cells classified as Low-Mix or No-Mix were scored 0. This binary distinction reflects the theoretical position that a meaningful diversity of destinations – not merely the presence of a single category – is necessary to generate the pedestrian trip generation associated with walkable environments (Ewing and Cervero, 2010).

Table 4.6 - Binary scoring of Land Mix indicator

Land Mix Scoring	Accessibility Classification
1	**1_Complete** [Full presence of both Essential (6) and Functional (5) POIs] **2_Almost-Complete** [High presence of both Essential (4–6) and Functional (3–5) POIs] **3_Mostly-Essential** [High Essential presence (4–6) but low Functional presence (1–2)] **4_Mostly-Functional** [Low Essential presence (1–3) but high Functional presence (3–5)]
0	**5_Low-Mix** [Low presence across both categories, OR total absence of one] **6_No-Mix** [Absence of both Essential and Functional POIs]

Critically, the Land Mix indicator also plays a structural role in the final composite classification (see section 4.7): any grid cell with a Land Mix score of 0 is classified as ‘Locked-In’, irrespective of its scores on the other three indicators. This design choice operationalises the theoretical primacy of land-use mix / proximity to different destinations in the literature and ensures that the composite classification does not assign high walkability scores to grid cells that are merely dense or well-connected but lack accessible destinations.

4.5 Indicator 3: Retail Density

Retail density captures the quantity of commercial activities — specifically food shopping, restaurants and cafes, and non-food retail — accessible within walking distance of each grid cell. It functions as a specific sub-dimension of destination accessibility, complementing the Low Land-use Mix lock-in but also serving as a metric of street activity, considering the pedestrian trip-generating capacity of commercial uses.

Commercial activities are singled out for dedicated treatment because they are among the most frequent generators of pedestrian trips in urban environments, alongside residential density: errand-running, dining, and shopping collectively account for a substantial proportion of non-commute walking (Handy et al., 2006; Saelens and Handy, 2008). Beyond their role as trip destinations, active retail frontages have been shown to influence the attractiveness of streets for walking by contributing to perceptions of safety, interest, and liveliness (Gehl, 2010). Accordingly, retail floor area ratio is widely regarded as the most informative indicator of street-level commercial activity and has been adopted in multiple walkability studies (Frank et al., 2009; D'Orso et al., 2025). However, it is equally frequently excluded due to data unavailability (Adams et al., 2014; Ribeiro & Hoffimann, 2018), as is the case in this study. Retail density therefore represents the most suitable available proxy for commercial street activity.

The retail density indicator is constructed by comparing the density of accessible retail activities at the grid cell level – defined as the number of retail POIs reachable within a 15-minute walking radius divided by the corresponding catchment area with the threshold identified in Ruiz-Padillo et al. (2022), who define low density as ≤ 25 retail units per km^2, and medium density as > 25 retail units per km^2.

For each grid cell, the number of reachable food-shopping POIs within 800m and the combined count of restaurant and non-food shopping POIs within 1200m were extracted from the OD matrix computed for the Land-use mix indicator. These counts were converted to density values by dividing by the area of the corresponding circular catchment (πr^2, where $r = 0{,}8$ km or 1,2 km), and the two densities were then aggregated into a single value representing the total number of accessible retail activities per km². Figure 4.11 illustrates this process for retail density analysis originating from a centroid in Porto.

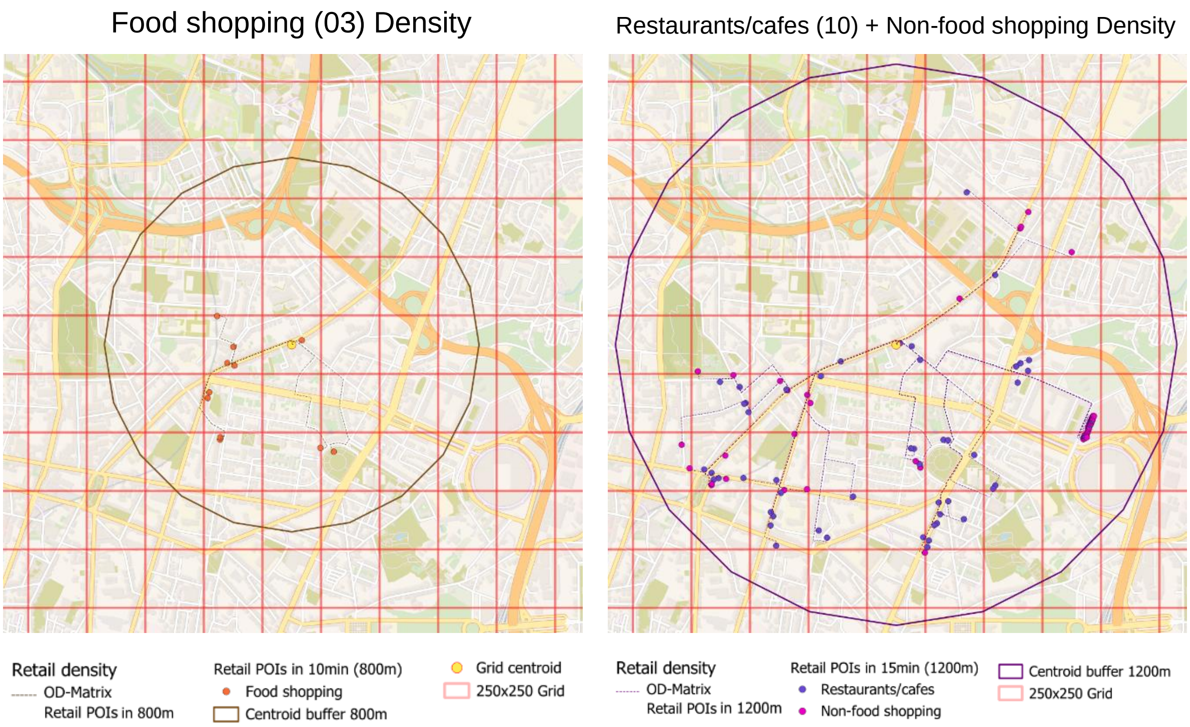


Fig. 4.11 – Example of circular catchments of retail density from a centroid in Porto

4.5.1 Binary scoring of Retail Density indicator

The binary score for Retail density indicator, depicted in Table 4.7, was assigned by comparing each grid cell's retail density value against the 25 retail units/km² threshold. Grid cells with a retail density above 25 retail units per km² received a score of 1; all others received 0.

Table 4.7 - Binary scoring of Retail density indicator

Retail Density Scoring	Estimated value of retail density in grid cell
1	> 25 retail units/km²
0	≤ 25 retail units/km²

4.6 Indicator 4: Intersection Density

Street connectivity is a significant predictor of walking behaviour in the built-environment literature, as the theoretical rationale is straightforward: a well-connected street network minimises travel distances between origins and destinations and maximises route choice, increasing pedestrian's permeability. Low-connectivity environments force pedestrians to travel substantially longer distances, discouraging walking as a practical mode of transport. Intersection density is the most widely used operational measure of street connectivity in the walkability literature. It captures, within a defined catchment area, the number of locations at which three or more street segments intersect, thereby reflecting the frequency of route choice opportunities available to a pedestrian. Figure 4.12 illustrates this process for intersection density analysis originating from a centroid in Porto.

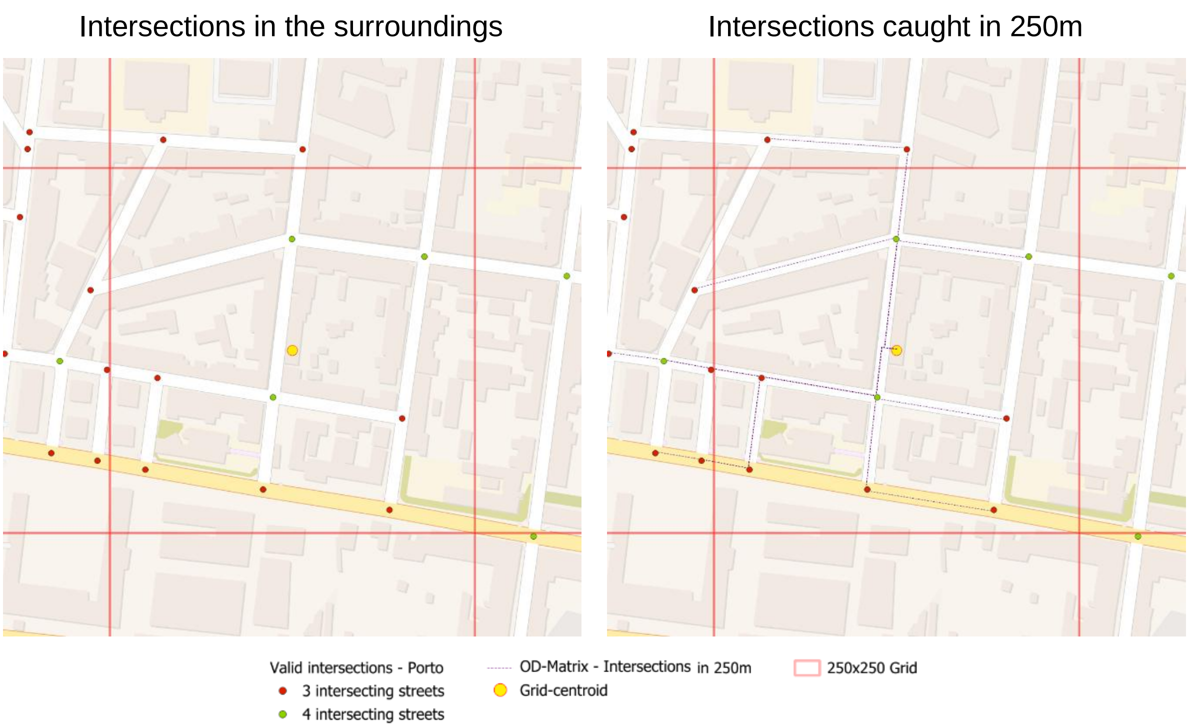


Fig. 4.12 – Example of true intersections

In this study, street connectivity is scored as a binary indicator based on whether each grid centroid has access to at least 20 valid intersections (those with three or more intersecting streets) within a 250 m network distance. This threshold was adopted from Cerin et al. (2022), who associate a density of 100 intersections/km² with higher levels of pedestrian activity. To operationalise this area-based metric within a walkability assessment framework grounded in pedestrian-shed analysis, the density threshold was converted into an equivalent count for a circular catchment area of 250-meter radius. Given that such a circle encompasses roughly 0.196 km², a density of 100 intersections/km² translates to a threshold of approximately 20 intersections within the catchment area – reflecting the premise that, within a short walking radius from any point, a pedestrian should encounter multiple genuine route choices, thereby minimising the distance between origins and destinations.

Regarding the generation of valid intersections, it should be noted that the street network was sourced from OpenStreetMap and originally processed as part of the accessibility analysis conducted prior to this intersection density assessment. For this assessment, the network was further refined:

- In Porto, the "service", "footway", "pedestrian", and "steps" classifications were removed. "Service" had already been excluded from the accessibility calculations, while the other classifications were removed because they generated numerous network errors, including duplicated streets and false intersections.
- In Plano, in addition to the streets already excluded from the accessibility calculations (although a small number of "service" streets were retained), the "footway" and "steps" classifications were also removed, as they similarly generated numerous network errors, duplicated streets, and false intersections. The "pedestrian" classification was retained but heavily filtered, as the relatively small number of such streets made a manual audit feasible. All "_link" classifications were also excluded, as they predominantly represent road ramps and slip roads, which tend to create false intersections within the network.

The ‘service’ category in OSM covers a wide range of access-restricted or semi-private routes, including driveways, parking aisles, and internal estate roads. In the Porto study area, this category is heavily represented and, if retained, would introduce a large number of false nodes into the intersection calculation. The decision to exclude ‘service’ roads was therefore taken on the grounds of functional relevance: these segments do not form part of the pedestrian route network as experienced by most users.

Given the distinctive morphological characteristics of Plano Piloto, additional manual cleaning was also required. Dead-ends and cul-de-sac configurations associated with roundabouts were simplified so that each roundabout was represented by a single node rather than a loop of short segments. This step prevents the misidentification of roundabout exits as independent intersections and avoids the inflation of the intersection density score in areas dominated by this street typology.

The number of intersections reachable within 250 metres of network distance from each origin cell was then derived from the OD Matrix calculation, allowing the identification of grid cells meeting or falling below the 20-intersection threshold.

4.6.1 Binary scoring of Intersection Density indicator

The binary score for intersection density (depicted in Table 4.8) was assigned as follows: grid cells with 20 or more intersections within the 250-meter catchment area received a score of 1, while all remaining cells received a score of 0. This binary field represents the final street connectivity score for each grid cell.

Table 4.8 - Binary scoring of Intersection density indicator

Retail Density Scoring	Intersections caught in 250m by grid cell
1	≥ 20 intersections
0	< 20 intersections

4.7 Aggregation of Infrastructural Lock-Ins

The four binary indicator scores – Land-use mix, Population density, Retail density, and Intersection density – were combined to produce a composite classification for each grid cell. Unlike additive index approaches, which sum the indicator scores to produce a single numerical value, the approach adopts a typological perspective, recognising that different combinations of urban characteristics may produce qualitatively different pedestrian environments. The indicators were aggregated into a simplified five-class classification, guided by two conceptual principles.

The first is the primacy of land-use mix. Any grid cell with a land-use mix score of 0, regardless of its scores on the remaining three indicators, is classified as ‘Locked-In’ (class 5). Without destinations within walking distance, no amount of street connectivity or residential density can generate habitual pedestrian travel, because there are insufficient destinations to generate everyday pedestrian trips. The ‘Locked-In’ label captures the idea that mono-functional / low mixed areas effectively trap their residents in car dependence, even if the street network and population density would, in principle, support walking.

The second principle concerns the joint interpretation of population density and retail density as indicators of the potential for street-level activity. Street activity – meaning the visible presence of people in public space – is both an outcome of walkability and a factor that can reinforce it, as active streets tend to be perceived as safer, more attractive, and more engaging for pedestrians (Jacobs, 1961; Gehl, 2010). Population density contributes by increasing the number of potential pedestrians, while retail density contributes by attracting trips and generating destinations. Accordingly, a grid cell is considered to have ‘street activity’ if at least one of the two density indicators is positive.

Table 4.9 presents the binary scoring system used to classify Macro-scale Infrastructural Lock-Ins, combining the scores for Land-use mix, Population density, Retail density, and Intersection density into five categories ranging from 'Unlocked – Mixed, Active, Connected' to 'Locked-In – Not mixed'.

Table 4.9 - Binary scoring of indicators and Macro-scale Infrastructural Lock-Ins Classification

Infrastructural Lock-Ins Classification	Land mix	Street activity		Connectivity
	Land mix	*Population density*	*Retail density*	*Intersection density*
1_Unlocked – Mixed, Active, Connected	1	1	1	1
	1	1	0	1
	1	0	1	1
2_Mixed, Active, Not Connected	1	1	1	0
	1	1	0	0
	1	0	1	0
3_Mixed, Not Active, Connected	1	0	0	1
4_Mixed, Not Active, Not Connected	1	0	0	0
5_Locked-In – Not mixed	0	1	1	1
	0	1	1	0
	0	1	0	1
	0	0	1	1
	0	1	0	0
	0	0	1	0
	0	0	0	1
	0	0	0	0

Class 1 (Unlocked – Mixed, Active and Connected) represents the highest level of walkability in this typology: land uses are mixed, street activity is generated by density or retail (or both), and connectivity provides frequent route choices. These areas offer the basic infrastructural conditions identified in the literature as conducive to walking behaviour.

Class 2 (Mixed, Active, Not connected) contains areas with a good mix of destinations and urban activity, but with a street network that does not provide frequent junctions within short distances. In these areas, walking is likely to occur but may be less convenient or spontaneous than in Class 1 areas, as pedestrians must travel slightly further to find a crossing opportunity. Planning interventions in these areas would prioritise network permeability improvements.

Class 3 (Mixed, Not active, Connected) contains areas with a mixed land-use base and a well-connected street network, but with neither population density nor retail density above the district-average threshold. These may include transitional areas undergoing development, recently built mixed-use zones that have not yet achieved commercial viability, or areas in which the mix of uses is present but the population is still sparse. The street environment may be physically conducive to walking but lacks the demand-side conditions that generate consistent street activity.

Class 4 (Mixed, Not active, Not Connected) contains areas in which land uses are mixed but neither density nor connectivity meets the threshold. These represent the most challenging planning context among the mixed-use classes.

Class 5 (Locked-In) encompasses all grid cells with a Land-Mix score of 0, representing the absence of a sufficient mix of accessible destinations. As noted above, this class is assigned irrespective of connectivity or density, on the grounds that the absence of different destinations cannot support habitual walking regardless of their other attributes.

5
MACRO-SCALE INFRASTRUCTURAL LOCK-INS RESULTS

This chapter presents the results of the Infrastructural Lock-Ins calculations conducted for the Municipality of Porto (Portugal) and the Administrative Region of Plano Piloto (Brasília, Brazil). Following the methodology established in Chapter 4, the analysis proceeds in two stages: first, each of the four indicators is calculated and scored individually for both case studies; and second, the indicator scores are aggregated to produce the final macro-scale Infrastructural Lock-Ins classification for each city. Throughout the analysis, spatial patterns and differences between the two cases are highlighted, aiming to identify which areas are most restricted by infrastructural barriers to walking and, as a result, most dependent on the private automobile.

5.1 Population Density in Porto and Plano Piloto

Population density is the second metric of potential street activity and the indicator expected to show the greatest divergence between the two case studies, given Plano Piloto's well-documented low-density urban form. The results, however, point towards a more nuanced interpretation.

Figures 5.1 and 5.2 showcase the spatial distribution and binary scoring of Population density indicator in Porto.

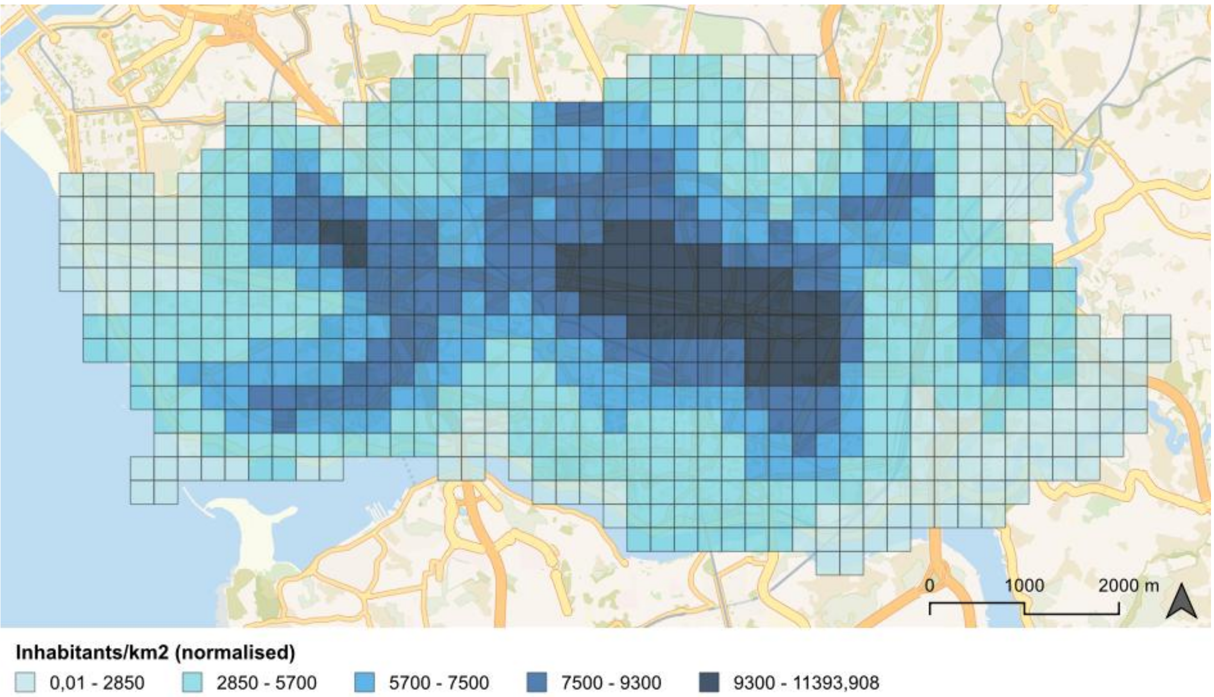


Fig. 5.1 – Spatial distribution of ‘Population density’ indicator in Porto.

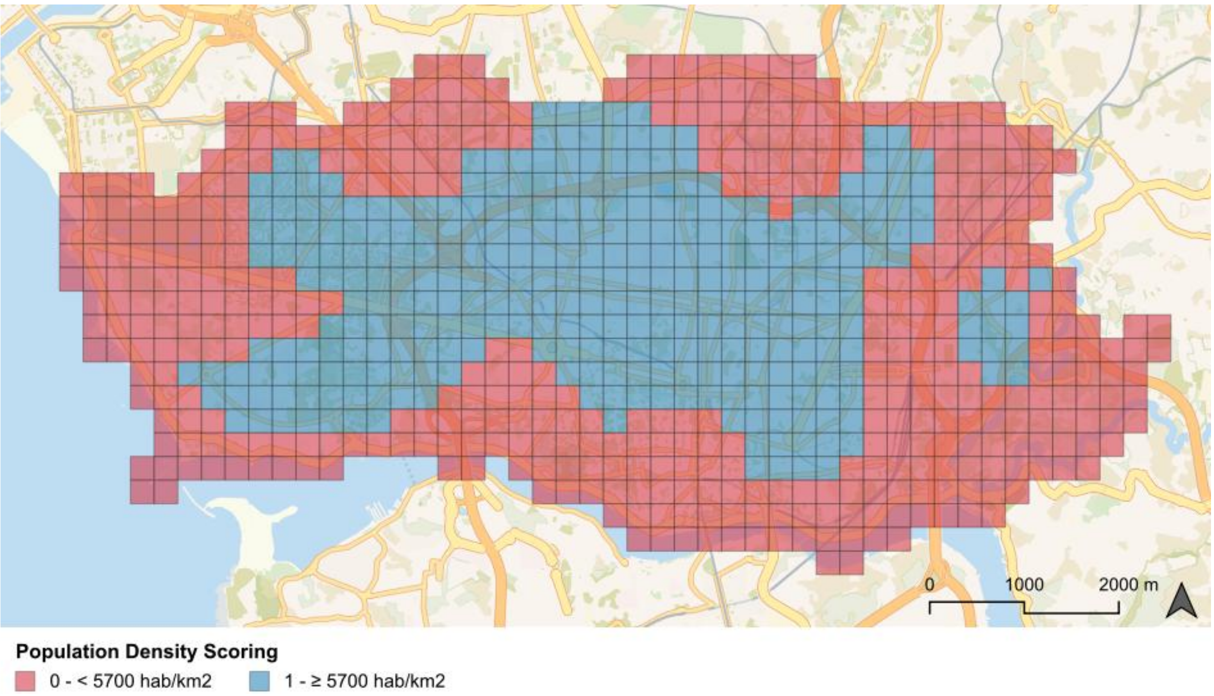


Fig. 5.2 – Scoring of ‘Population density’ indicator in Porto.

Surprisingly, the maximum normalised population density recorded in grid cells across both cities is similar: the most densely populated cells in both Porto and Plano Piloto reach approximately 11,300 inhabitants/km². At the aggregate scale, the contrast remains: 58.8% of grid cells in Porto display population densities below 5,700 inhabitants/km², whereas in Plano Piloto the vast majority of cells remain below this level, and a small number continue to register zero population even after spatial smoothing.

The most densely populated areas of Porto are concentrated in the centre of the municipality, above the city centre. By contrast, several peripheral zones remain sparsely inhabited: Foz, situated towards the west near the coastline; Baixa, located to the south along the riverfront; and the areas adjacent to Parque Oriental da Cidade do Porto, in the east. This pattern of low population density is worsened by single-use zones within the city fabric, including the industrial district of Ramalde to the northwest and the Pólo Universitário da Asprela to the north.

Therefore, most grid cells in Porto receive negative scores on the population density indicator, reflecting the concentration of residents in the central municipality and the correspondingly reduced levels of street activity in surrounding neighbourhoods.

In Plano Piloto, the spatial distribution of the population density indicator (Figure 5.3) reveals that the highest population densities are concentrated in Asa Norte, which achieves the highest values within the study area, followed by parts of Asa Sul and a few cells in the recently developed Noroeste neighbourhood.

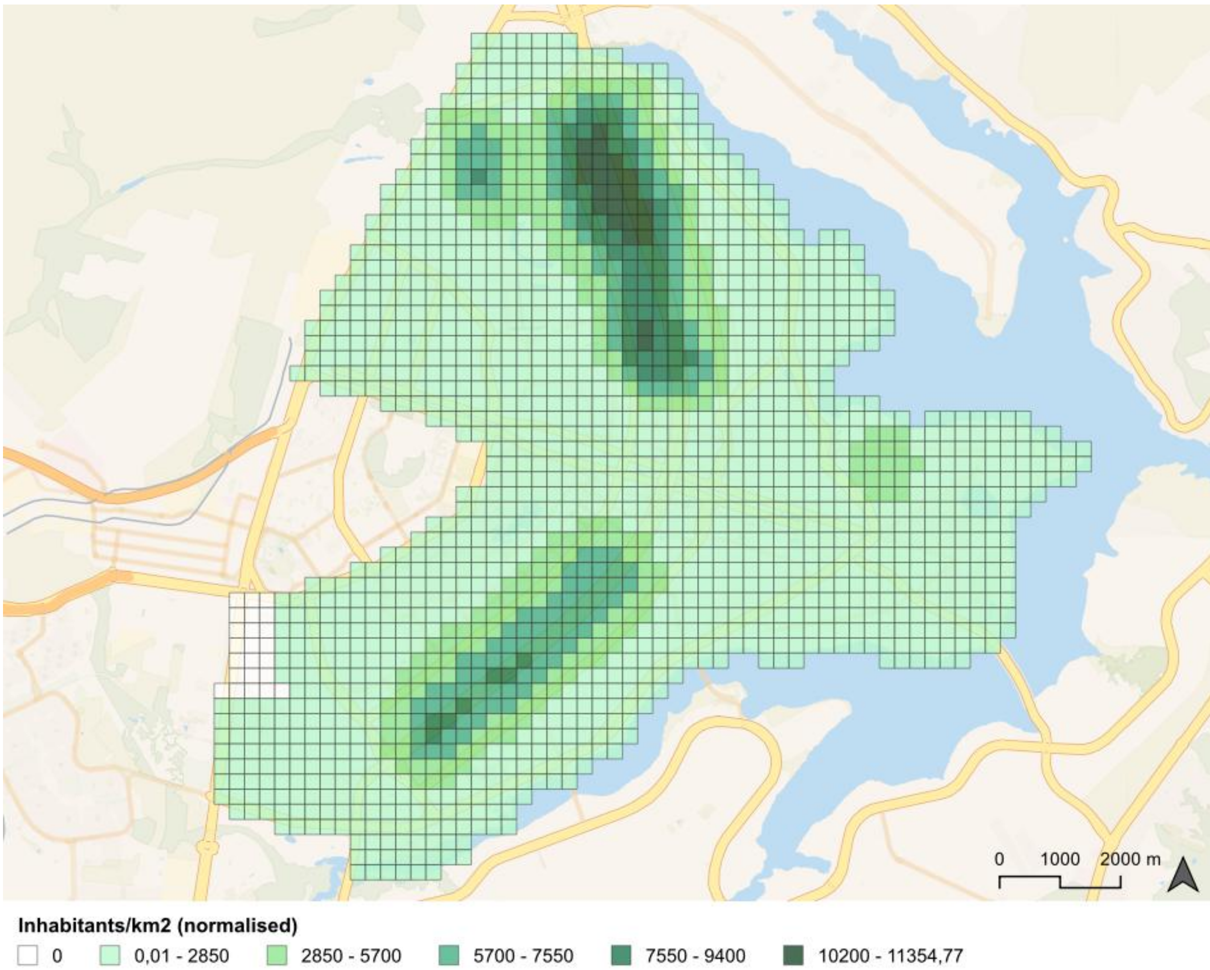


Fig. 5.3 – Spatial distribution of ‘Population density’ indicator in Plano Piloto.

As a result, a substantial share of grid cells in Asa Sul receives negative scores on this indicator (Figure 5.4), despite the neighbourhood’s relative centrality, functional diversity, and Brasília’s generally low retail densities. Asa Norte records the most favourable scores, while Asa Sul exhibits a more heterogeneous density distribution. A likely explanation is the greater extent of single-family detached housing in Asa Sul, which contributes to lower residential densities. Although detached housing is also found in Asa Norte, it represents a smaller proportion of the neighbourhood’s urban fabric.

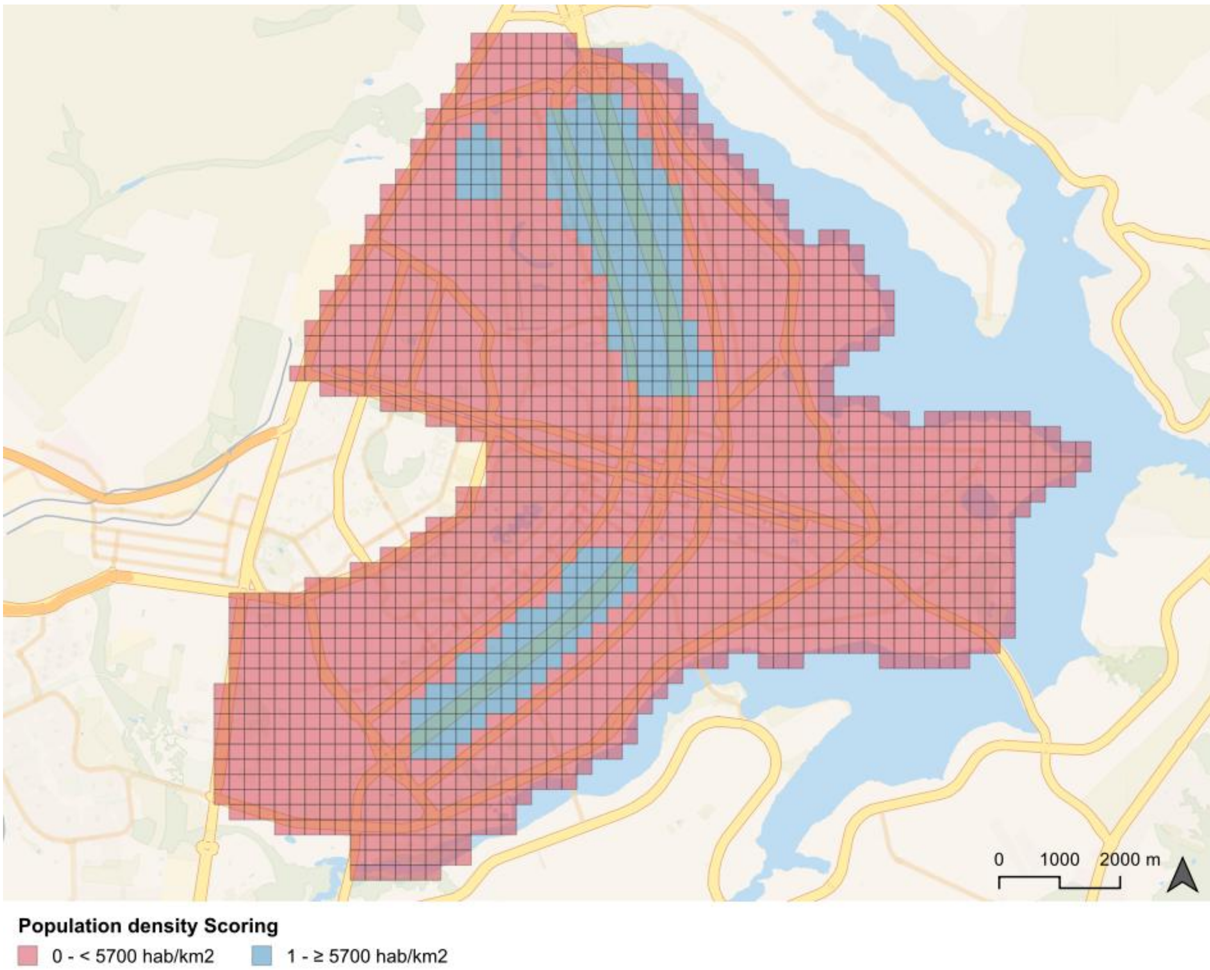


Fig. 5.4 – Scoring of ‘Population density’ indicator in Plano Piloto.

5.2 Land-use mix in Porto and Plano Piloto

5.2.1 Walking Accessibility Classification of Porto and Plano Piloto

At the level of the accessibility classification, the two case studies already reveal different spatial profiles. Porto presents a relatively balanced distribution of accessible activities across its territory (Figure 5.5), whereas Plano Piloto exhibits a more fragmented pattern, with a sharper divide between areas well served by destinations reachable on foot and those that are not, as depicted in Figure 5.6.

In both cities, grid cells achieving the highest accessibility class – those where all Essential and Functional activities are reachable within the respective distance thresholds – are few and spatially concentrated. In Porto, these cells cluster around the city centre, particularly in the vicinity of Aliados Avenue. In Plano Piloto, the highest-scoring cells are confined to the first superblocks of the Asa Norte neighbourhood.

Adopting the threshold of a positive Land-Use Mix score – i.e., classification as Complete, Almost Complete, Mostly Essential, or Mostly Functional – Porto demonstrates considerably greater territorial regularity. The overwhelming majority of the municipality (85.6% of grid cells) achieves this threshold, reflecting the high degree of urban consolidation associated with a compact, historically layered city with 92.66% urban land cover. This spatial regularity translates into a stronger potential for the 15-Minute City model.

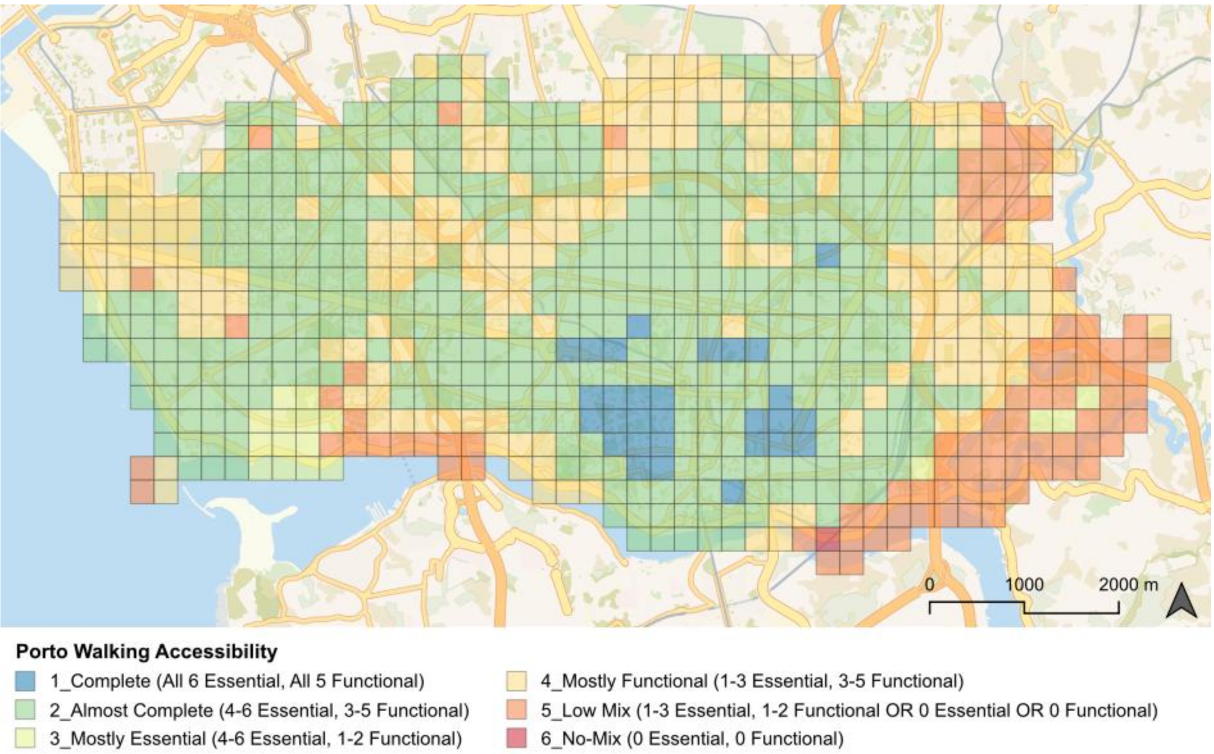


Fig. 5.5 – Walking accessibility of Essential and Functional Activities in Porto.

Plano Piloto has less balance in terms of gradient of activities, presenting a more polarised picture. Roughly 36% of grid cells covering the study area meet the same threshold of good accessibility. This imbalance is partly due to the lower urban land cover of the area (82.16%) and to the extensive presence of *non-aedificandi* land, legally designated as non-buildable and forming a continuous buffer between inhabited neighbourhoods.

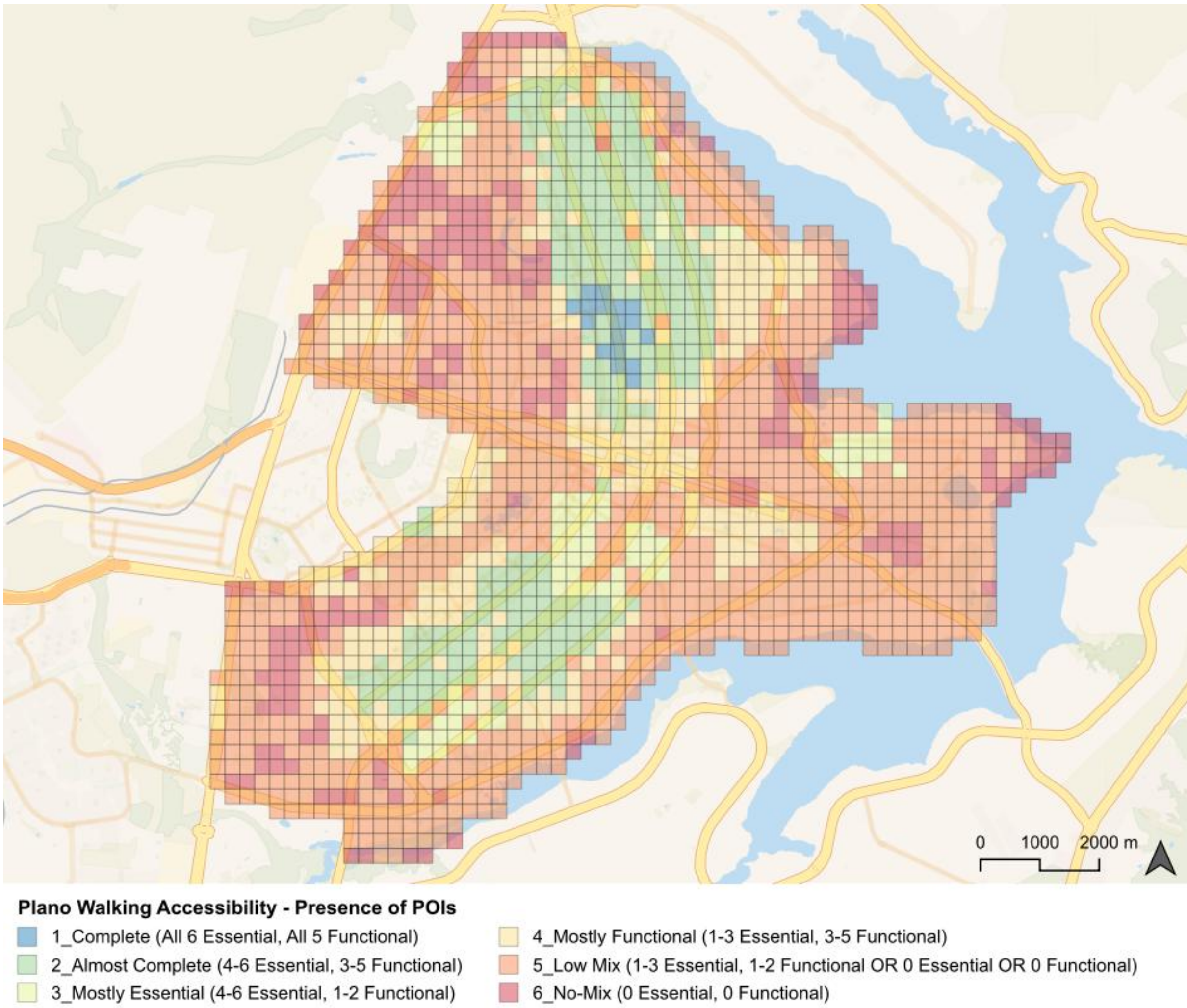


Fig. 5.6 – Walking accessibility of Essential and Functional Activities in Plano Piloto.

However, it is important to note that among the cells covering inhabited areas, the proportion meeting the good accessibility threshold is considerably higher. The areas classified as poorly accessible (64.21% of cells) are predominantly located in *non-aedificandi zones*, in single-use sectors (such as the South Police Sector and the South and North Banking Sectors), around large roundabout interchanges (known locally as '*tesourinhas*'), and in areas occupied by cemeteries and urban parks. Within the inhabited neighbourhoods themselves – especially Asa Norte and Asa Sul – the coverage of Essential and Functional activities is mostly adequate, also pointing to a real potential for reducing car dependence at the neighbourhood scale.

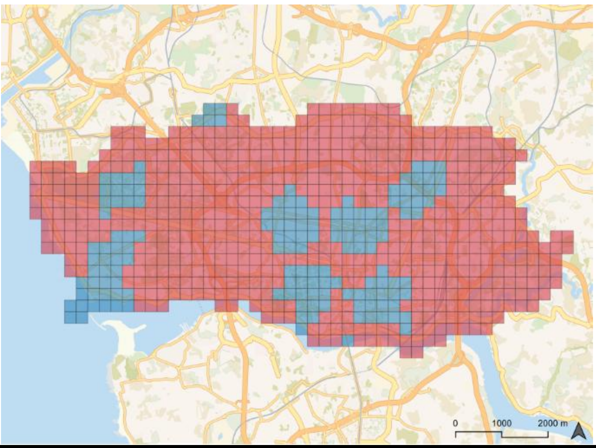
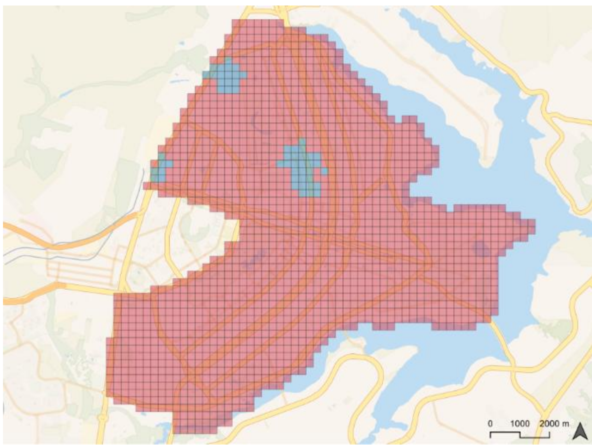
5.2.2 Presence of each activity in Porto and Plano Piloto

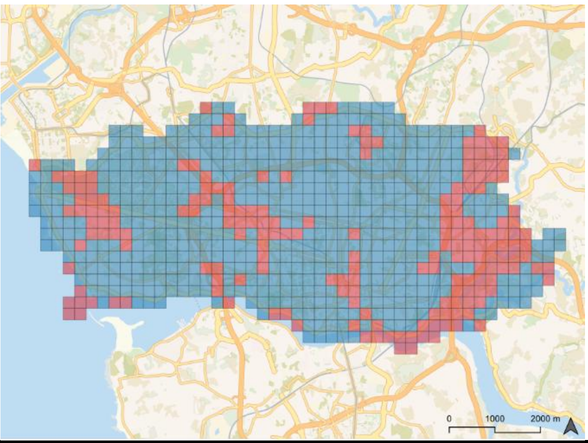
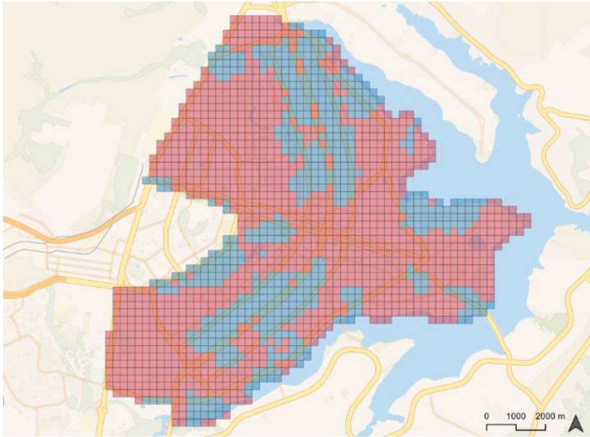
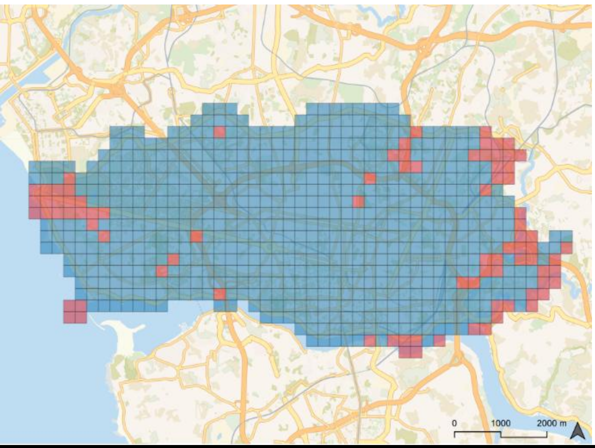
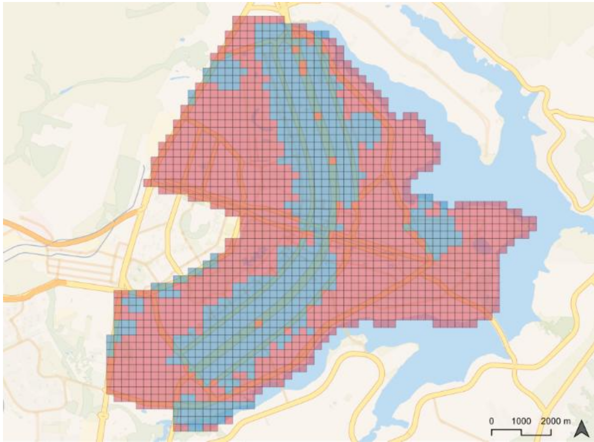
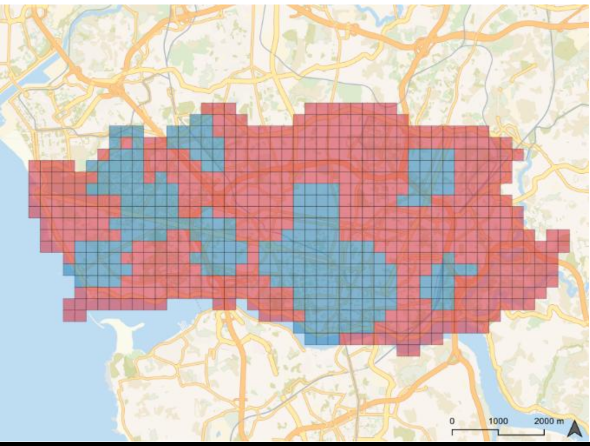
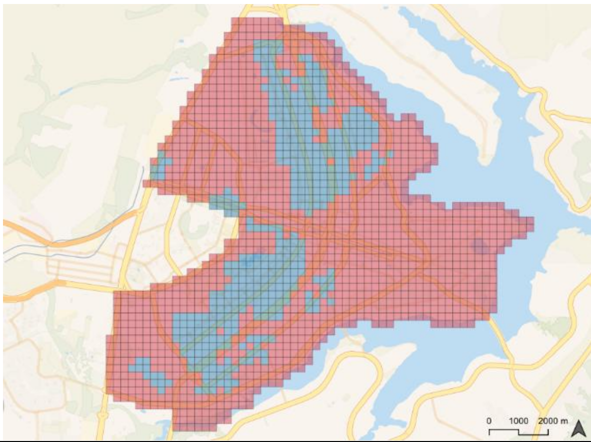
Pre-primary schools and primary schools emerge as the least accessible Essential activities in both case studies, a finding that carries significant implications for car dependency. Given that children typically require longer travel times to reach these destinations — and that many families lack any viable alternative to the private car for school drop-offs — the low walkable accessibility of educational facilities represents a structural lock-in affecting daily mobility patterns across all income groups. This concern is especially intense in Plano Piloto, where the number of grid cells registering the presence of a primary school within 800 metres is extremely low.

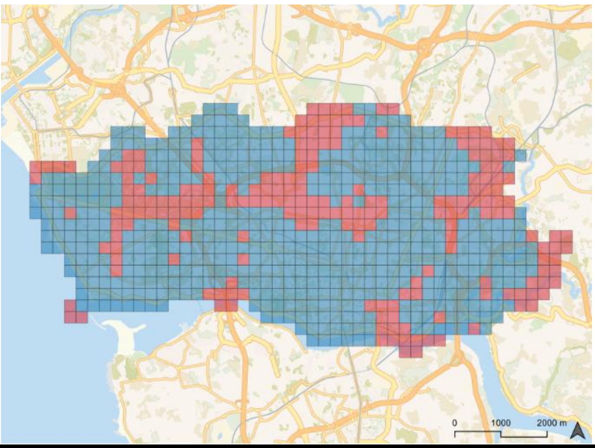
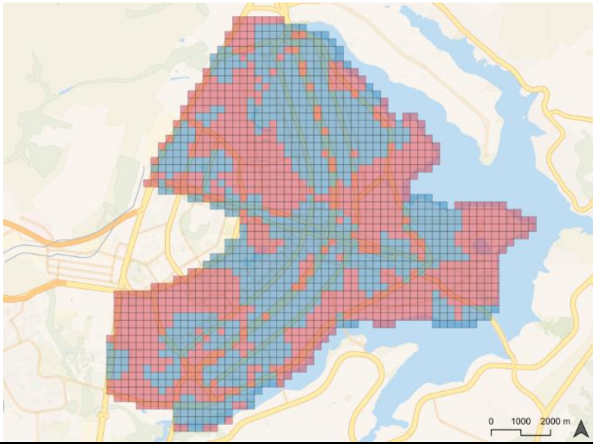
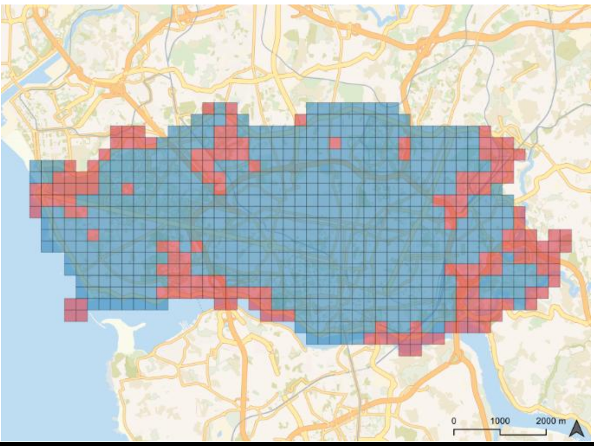
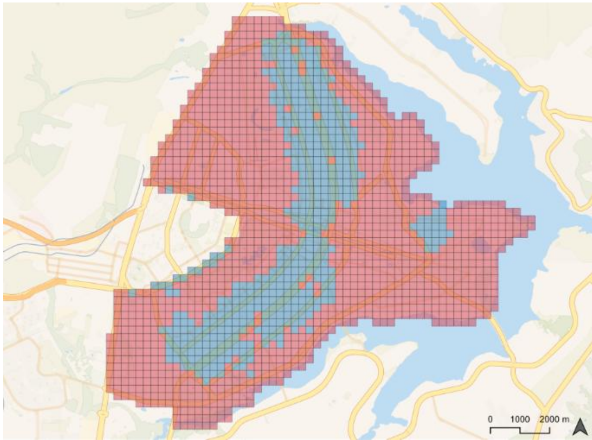
In Porto, more than 50% of grid cells are positively scored for every activity category with the exception of pre-primary and primary schools, indicating broad spatial coverage of most essential urban functions. In Plano Piloto, the only activity for which the majority of grid cells are positively scored is Parks/green spaces. This result is largely explained by the presence of large-scale parks in both the Asa Sul neighbourhood (with Parque da Cidade) and the Asa Norte neighbourhood (which contains the Parque Ecológico Burle Marx) — as well as by the amount of smaller green spaces distributed across the administrative region's neighbourhoods.

Table 5.1 compares the availability of Essential activities within an 800m distance for Porto and Plano Piloto, using red to indicate absence and blue to indicate presence.

Table 5.1 - Essential activities accessible in 800m by case study.

Porto	**Plano Piloto**
Pre-primary schools	
	

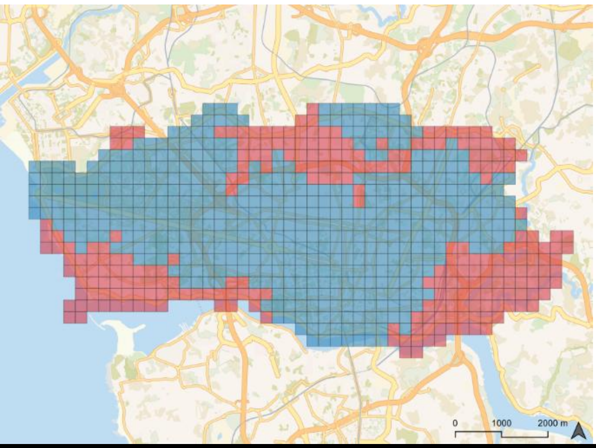
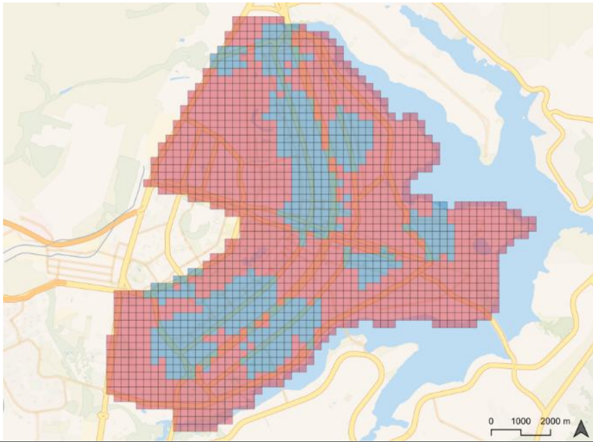
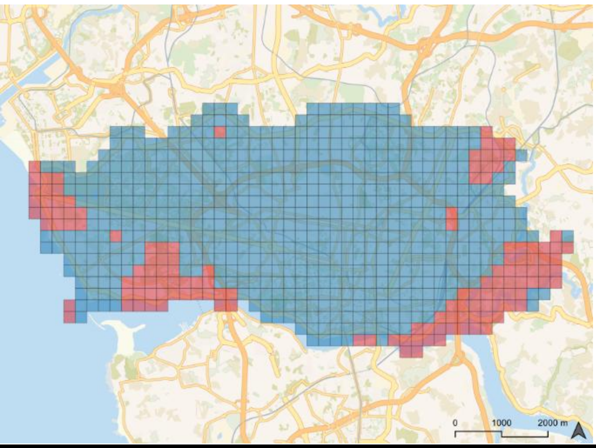
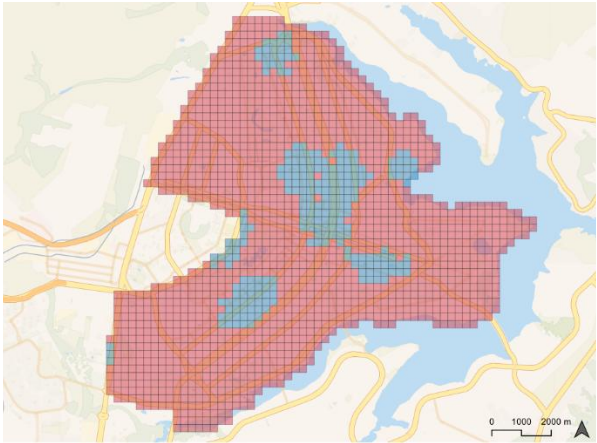
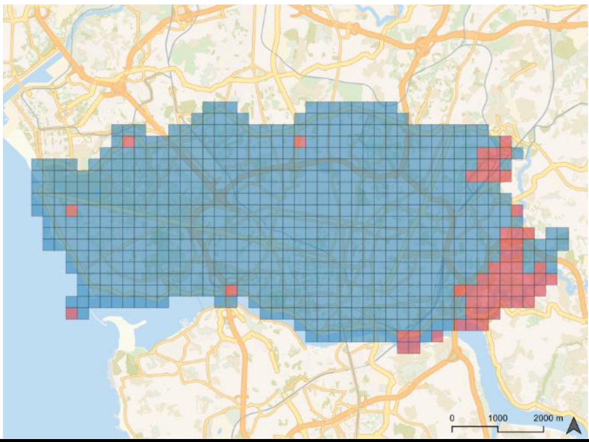
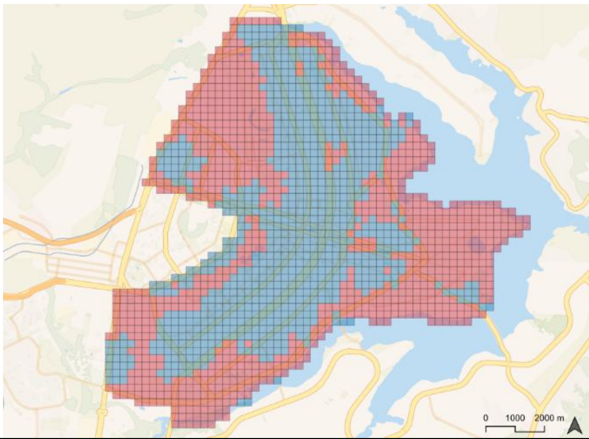
Porto	**Plano Piloto**
Playgrounds	
	
Food shopping	
	
Primary schools	
	

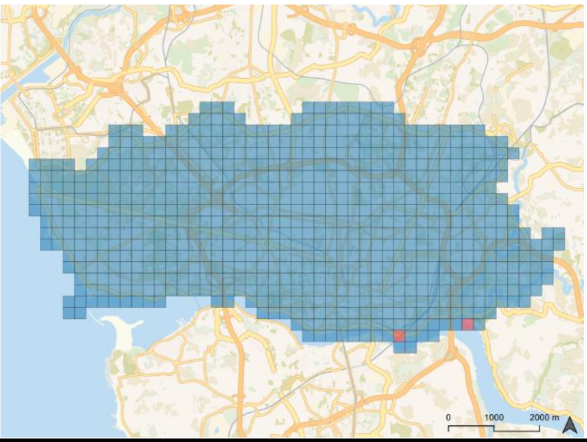
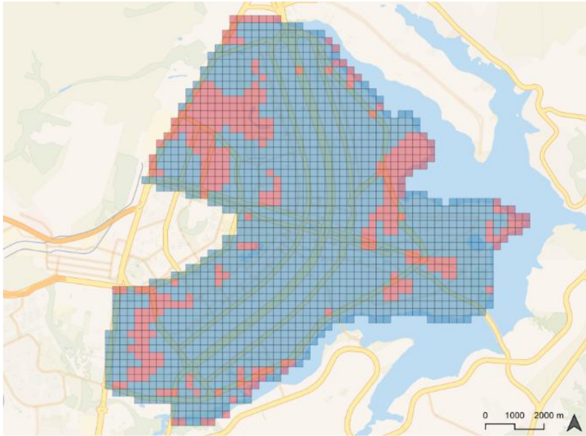
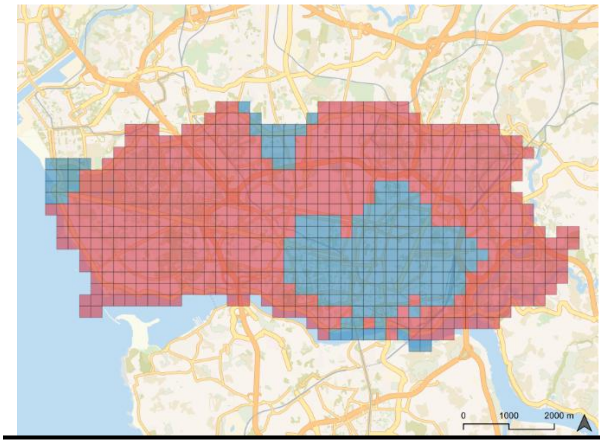
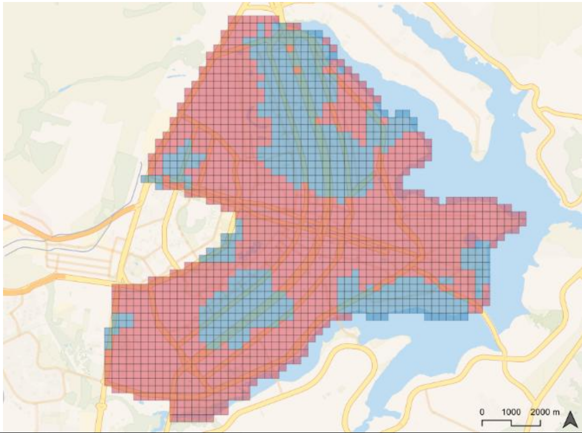
Porto	Plano Piloto
Parks / green spaces	
	
Pharmacies	
	

Among Functional Activities, Porto registers a deficit only in sports facilities, where more than half of grid cells record the absence of this activity within 1,200 metres. General practitioners represent the second weakest category, though the majority of cells are still positively scored. Restaurants and cafés are the most universally accessible activity in both cities: in Porto, only 3 grid cells record an absence, confirming the density of food and beverage provision across the municipality. The greatest divergence between the two cities is observed for post offices: in Porto, post offices are accessible to the vast majority of the urban area, with absences limited to coastal and eastern peripheral zones (closer to the Parque Oriental da Cidade do Porto); in Plano Piloto, access is effectively restricted even in the Asa Norte and Asa Sul neighbourhoods.

Table 5.2 compares the availability of Functional activities within an 1200m distance for Porto and Plano Piloto, using red to indicate absence and blue to indicate presence.

Table 5.2 - Functional Activities accessible in 1200m by case study.

Porto	**Plano Piloto**
General practitioner	
	
Post office	
	
Banks / ATM	
	

Porto	**Plano Piloto**
Restaurants / cafes	
	
Sports facilities	
	

Overall, Porto is very accessible in terms of distance of both essential and functional activities, with weaknesses concentrated in educational and sports facilities. Plano Piloto, by contrast, exhibits a more severe and spatially concentrated accessibility deficit. The "wings" – Asa Norte and Asa Sul – are reasonably well served, though with significant divergence: Asa Norte consistently outperforms Asa Sul across most activity categories. The remaining inhabited neighbourhoods within the administrative region – Noroeste to the north, Setor Militar Urbano to the northwest, Vila Planalto to the east, and Vila Telebrasília to the south – display severe deficits across nearly all activity categories, pointing to a high level of car dependency for any daily journey beyond their immediate surroundings.

5.2.3 Land-use mix scoring in Porto and Plano Piloto

As established in Chapter 4, the grid cells classified in the four highest accessibility categories – Complete, Almost-Complete, Mostly-Essential, and Mostly-Functional – were scored 1 (Mixed); those classified as Low-Mix or Locked-In were scored 0 (Not Mixed).

In Porto, the indicator distribution (depicted in Figure 5.7) reflects the accessibility results described in Section 5.1. The vast majority of grid cells are positively scored, confirming good territorial coverage of mixed land uses across the municipality. The few negatively scored cells are concentrated at the eastern edge of the municipality, in the vicinity of Parque Oriental da Cidade do Porto, and along certain peripheral areas with lower functional diversity.

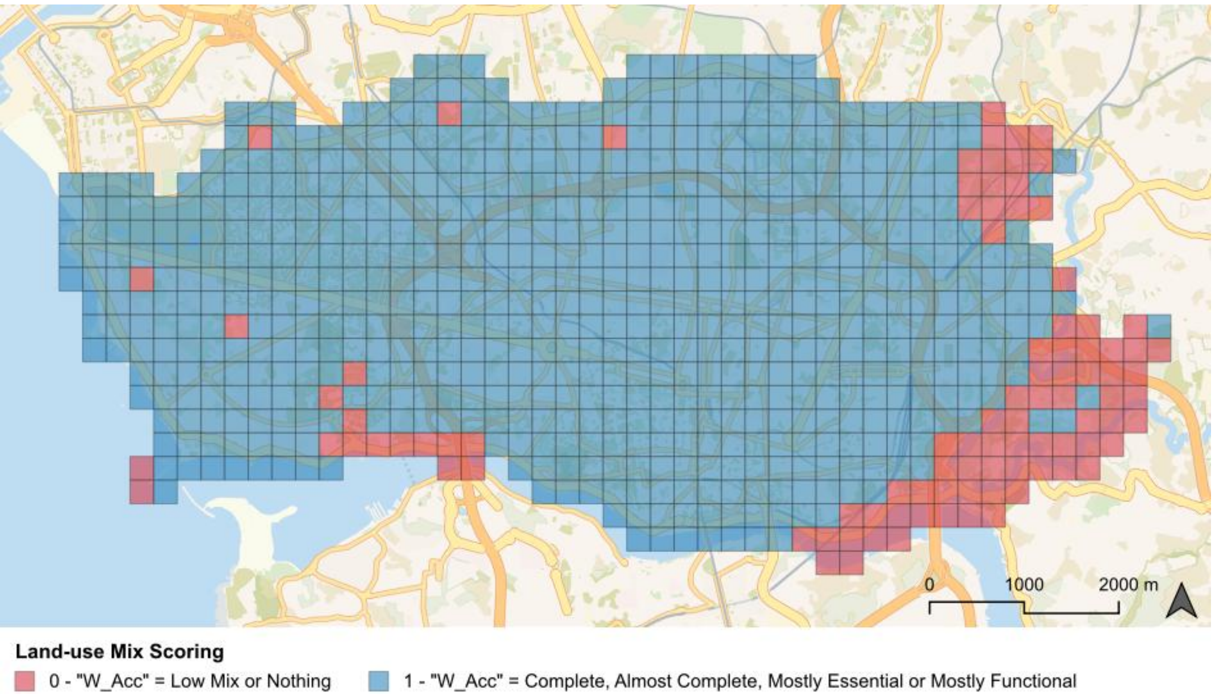


Fig. 5.7 – Scoring of 'Land mix' indicator in Porto.

In Plano Piloto, the inhabited neighbourhoods were also scored mostly positively on this indicator (Figure 5.8), with one notable exception: Vila Telebrasília, where all grid cells received a score of 0. Non-aedificandi zones and single-use sectors remain entirely negatively scored, as expected. Overall, the scoring confirms the premise introduced in Section 5.1: within its inhabited area, Plano Piloto contains a mix of land uses that, despite being unevenly distributed, could support pedestrian mobility.

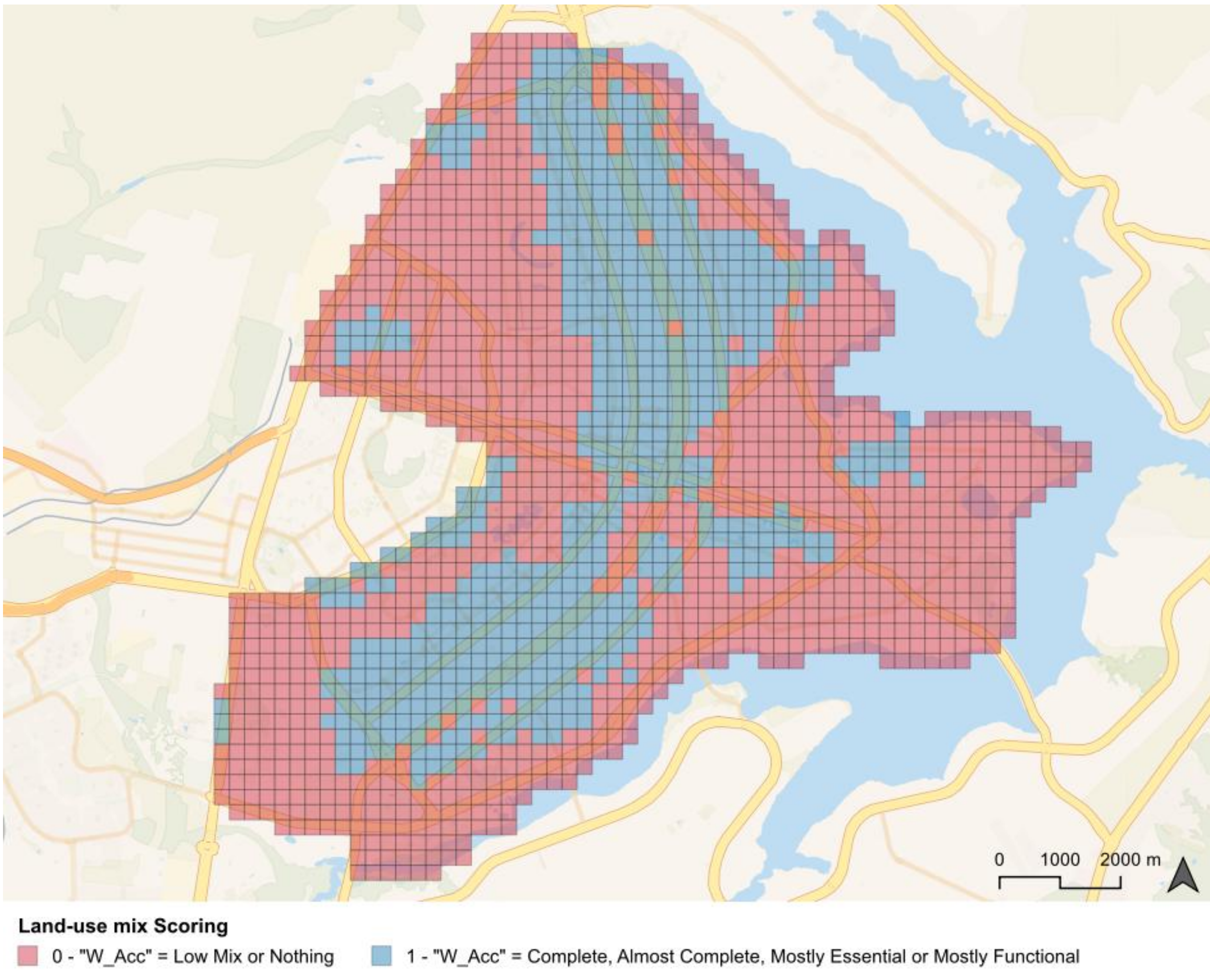


Fig. 5.8 – Scoring of ‘Land mix’ indicator in Plano Piloto.

5.3 Retail Density in Porto and Plano Piloto

The retail density indicator measures the quantity of commercial activities accessible within walking distance of each grid cell. Firstly, as established in subsection 4.5.2, the threshold associated with medium levels of retail density of all food shopping, restaurants/cafes and non-food shopping Points of Interest combined is above 25 retail units/km².

This indicator contributes to the street activity evaluation of both case studies, comparing the density of shops and services within their areas – the number of reachable food-shopping POIs within 800m and the combined count of restaurant and non-food shopping POIs within 1200m divided by the corresponding catchment area – with the threshold identified in the literature.

In Porto, retail activities are concentrated in the city centre (Figure 5.9), as expected, with a clear gradient of densities declining as distance from the city centre increases – except for the area around Hospital São João to the north, and the upper section of Avenida da Boavista to the west, which forms a commercial corridor linking the city centre with the coast.

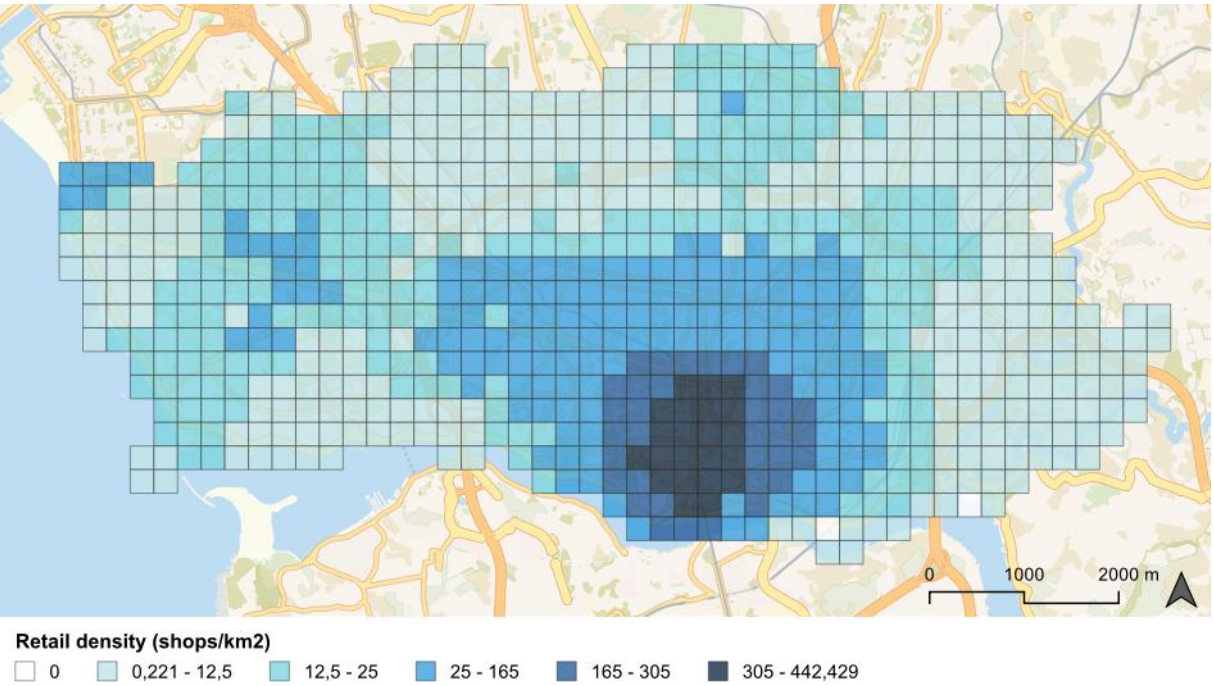


Fig. 5.9 – Spatial distribution of 'Retail density' indicator in Porto

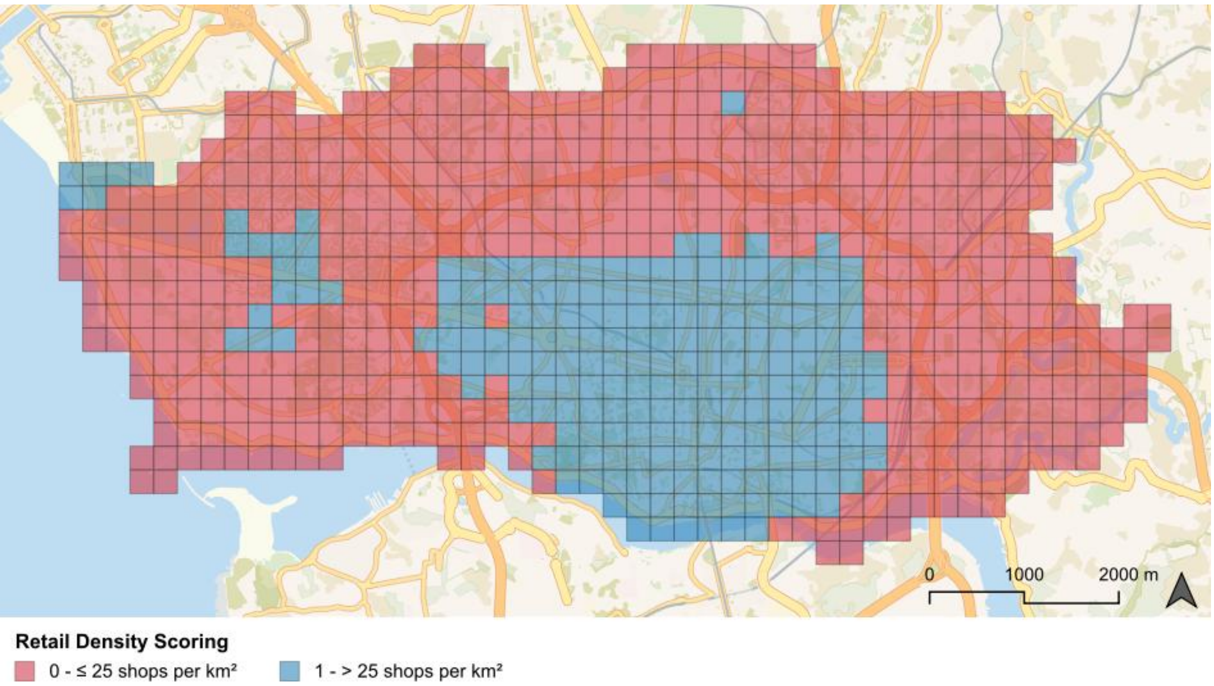


Fig. 5.10 – Scoring of 'Retail density' indicator in Porto

However, most cells in Porto are scored 0, as depicted in Figure 5.10. High retail density is effectively concentrated within the area delimited by the Via de Cintura Interna (VCI) expressway. These scores in Porto also reveal a contrasting pattern in relation to the Population density indicator presented in Section 5.1. Despite its relatively low residential population, Baixa records comparatively high retail density values, partially neutralising the population deficit and revealing a significant distinction between two overlapping urban realities: an inhabited city, characterised by higher population density but lower retail density, and a tourist city, characterised by lower residential density but considerably higher commercial activity.

In Plano Piloto, Asa Norte exhibits higher values of retail density in its spatial distribution (Figure 5.11), followed by Asa Sul. The large number of cells with a complete absence of retail activities (shown in red) highlights the lack of retail activity outside the inhabited neighbourhoods.

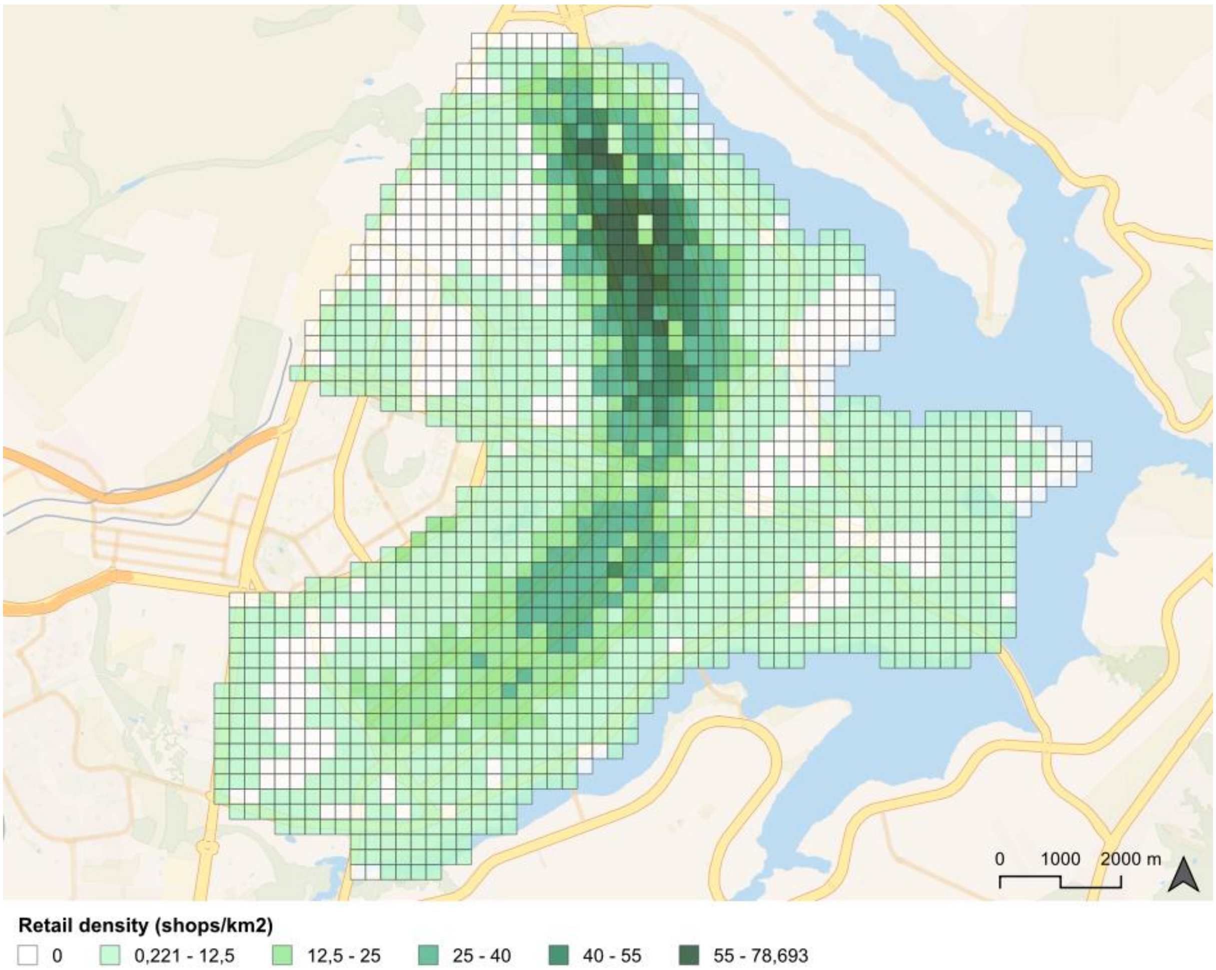


Fig. 5.11 – Spatial distribution of 'Retail density' indicator in Plano Piloto

Most grid cells in Plano Piloto were negatively scored in retail density, as depicted in Figure 5.12. Asa Norte neighbourhood performs best, followed by the first superblocks in Asa Sul. However, most grid cells in the study area do not reach the threshold of above 25 retail units per km², even in populated areas. These values reflect the contrasting zoned commercial structure of Brasília's planned fabric compared to the dense and commercial streetscape of a traditional European city.

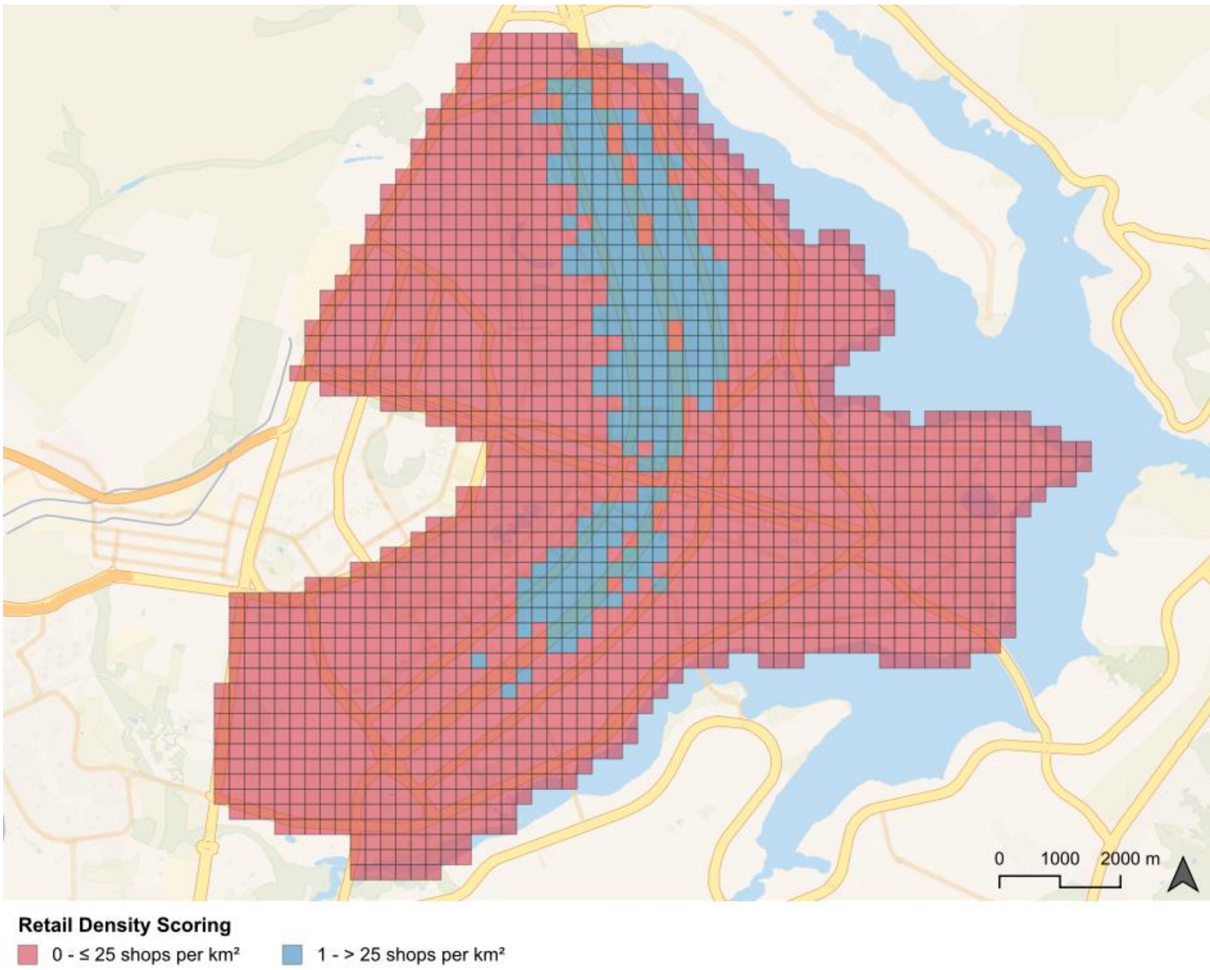


Fig. 5.12 – Scoring of 'Retail density' indicator in Plano Piloto

5.4 Intersection density in Porto and Plano Piloto

Intersection density is the indicator of path connectivity, measuring the number of valid street intersections – those at which three or more segments meet – reachable within 250 metres of network distance from each grid centroid. A positive score requires at least 20 such intersections, equivalent to a density of approximately 100 intersections/km², the threshold associated in the literature with higher pedestrian activity.

This indicator records the lowest scores of the four across both study areas, and the difference between the two cities is more pronounced in Plano Piloto. It is important to acknowledge at the network cleaning procedure described in subsection 4.5.4 – which excluded footway, pedestrian path, and steps classifications to avoid topological errors and false intersections – inevitably leads to an undercount of true pedestrian route options in areas where off-street walking infrastructure forms a meaningful part of the network. This is relevant to both cities, though its impact is more significant in Plano Piloto, where the modernist urban fabric of Asa Norte and Asa Sul deliberately separates the pedestrian domain from the vehicular street network through a system of internal superblock paths.

In Porto, only cells located in areas characterised by the smallest block sizes record 20 or more reachable intersections within 250 metres, as can be seen in Figure 5.13 and Figure 5.14. Even in Baixa, a zone widely regarded as Porto's most pedestrianised, only a handful of cells score positively, reflecting the disparity between perceptions of walkability and the formal metric of street intersection density. The overall distribution reveals that most of Porto's street network, while functionally supportive of walking, does not achieve the granularity of path connectivity associated with the optimal threshold.

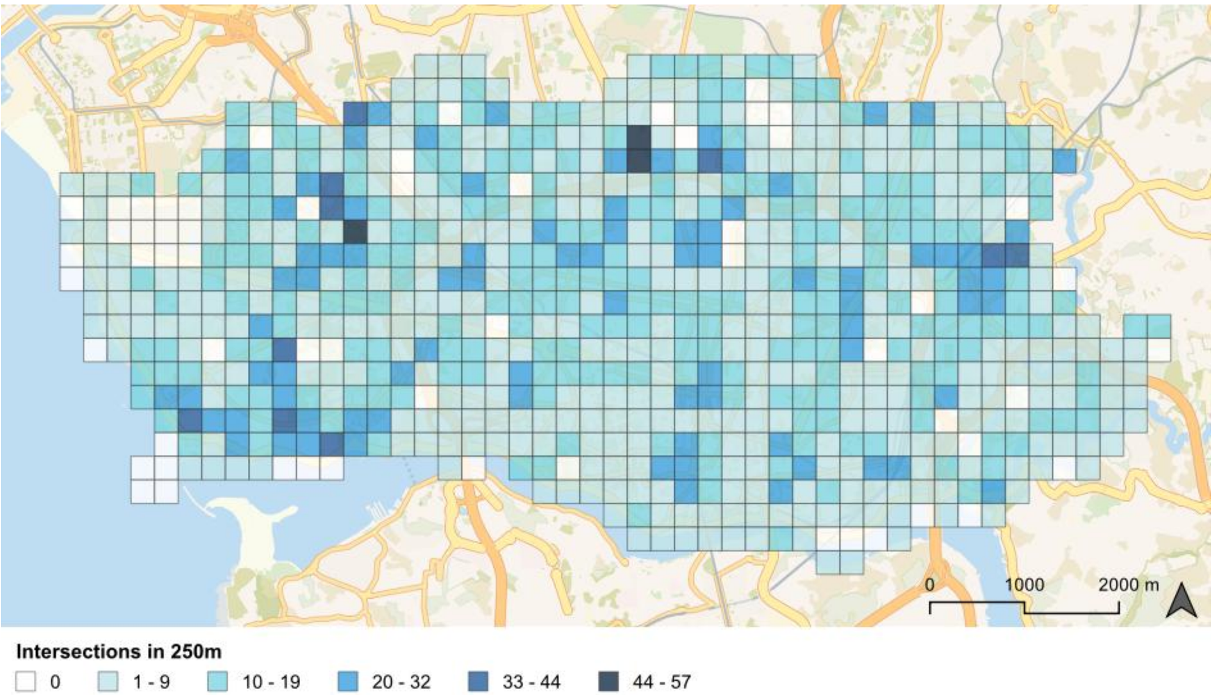


Fig. 5.13 – Spatial distribution of ‘Intersection density’ indicator in Porto

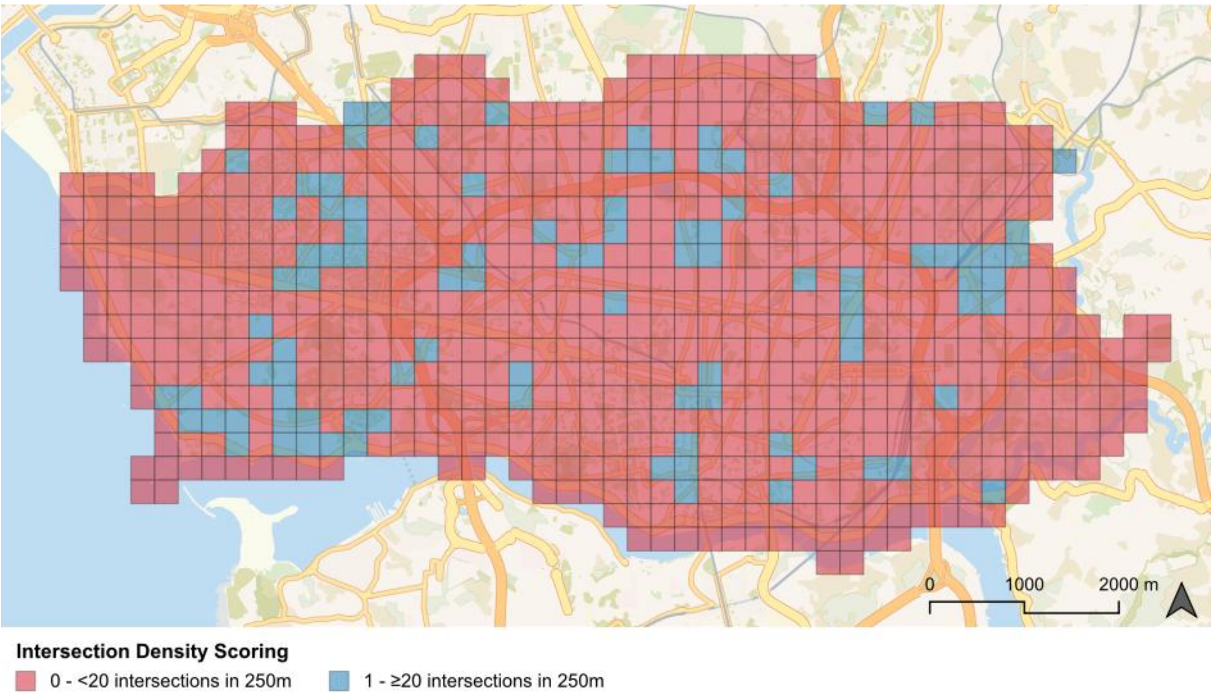


Fig. 5.14 – Scoring of ‘Intersection density’ indicator in Porto

In Plano Piloto, the low intersection density scores are even more pronounced, and must be interpreted considering the city's distinctive morphology. The superblock structure of Asa Norte and Asa Sul is defined by large residential blocks served internally by pedestrian networks that do not connect to the primary street grid at frequent intervals. Therefore, the number of true vehicular intersections reachable within a short walking radius is structurally low across most of the administrative region, as seen in the indicators' spatial distribution depicted in Figure 5.15.

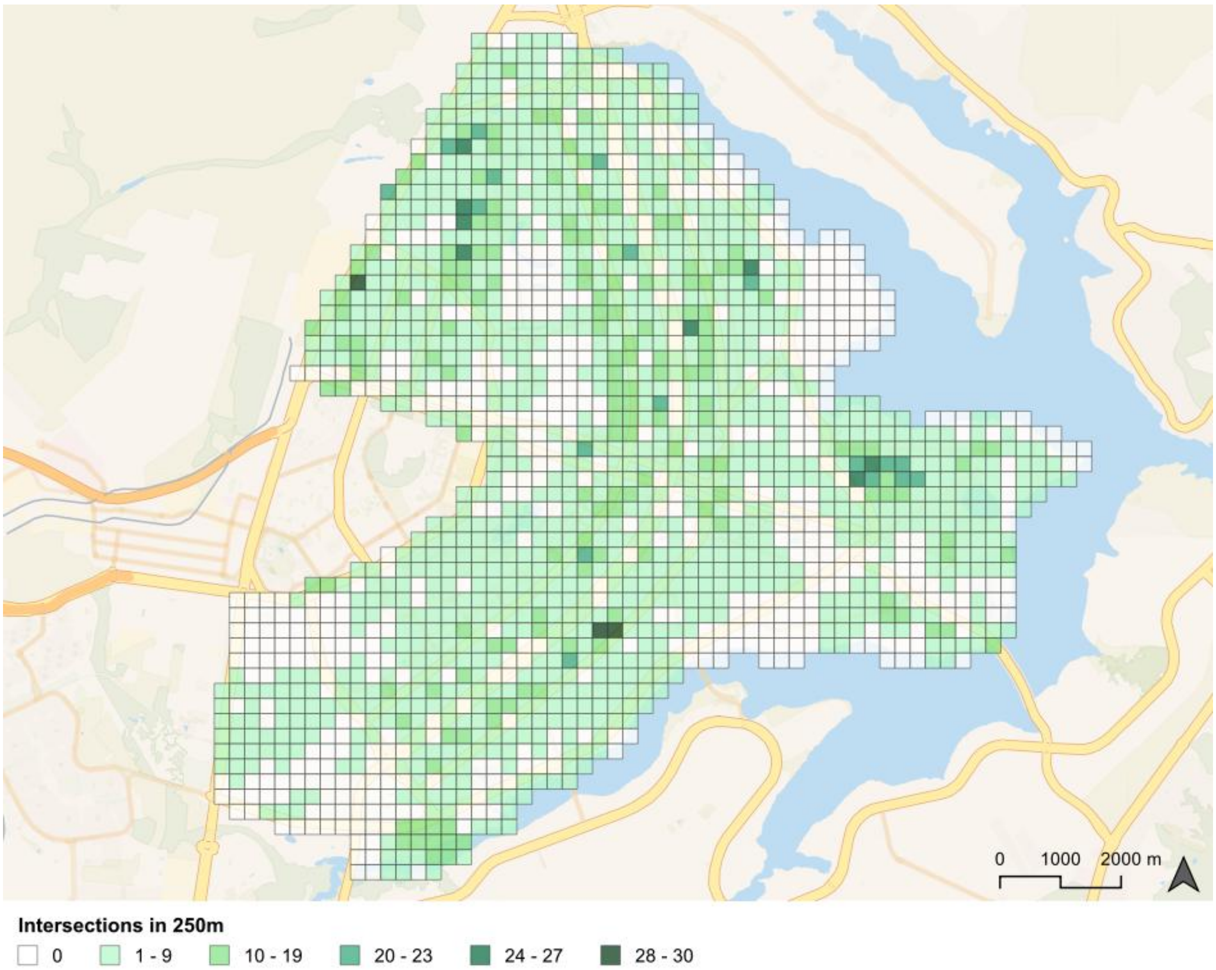


Fig. 5.15 – Spatial distribution of 'Intersection density' indicator in Plano Piloto

Regarding the binary scoring of Intersection density for Plano Piloto, the only neighbourhood where a meaningful concentration of positively scored cells is observed is Vila Planalto. This neighbourhood within the study area exhibits a more traditional urban pattern, developed organically as a workers' settlement and granted heritage protection in 1988.

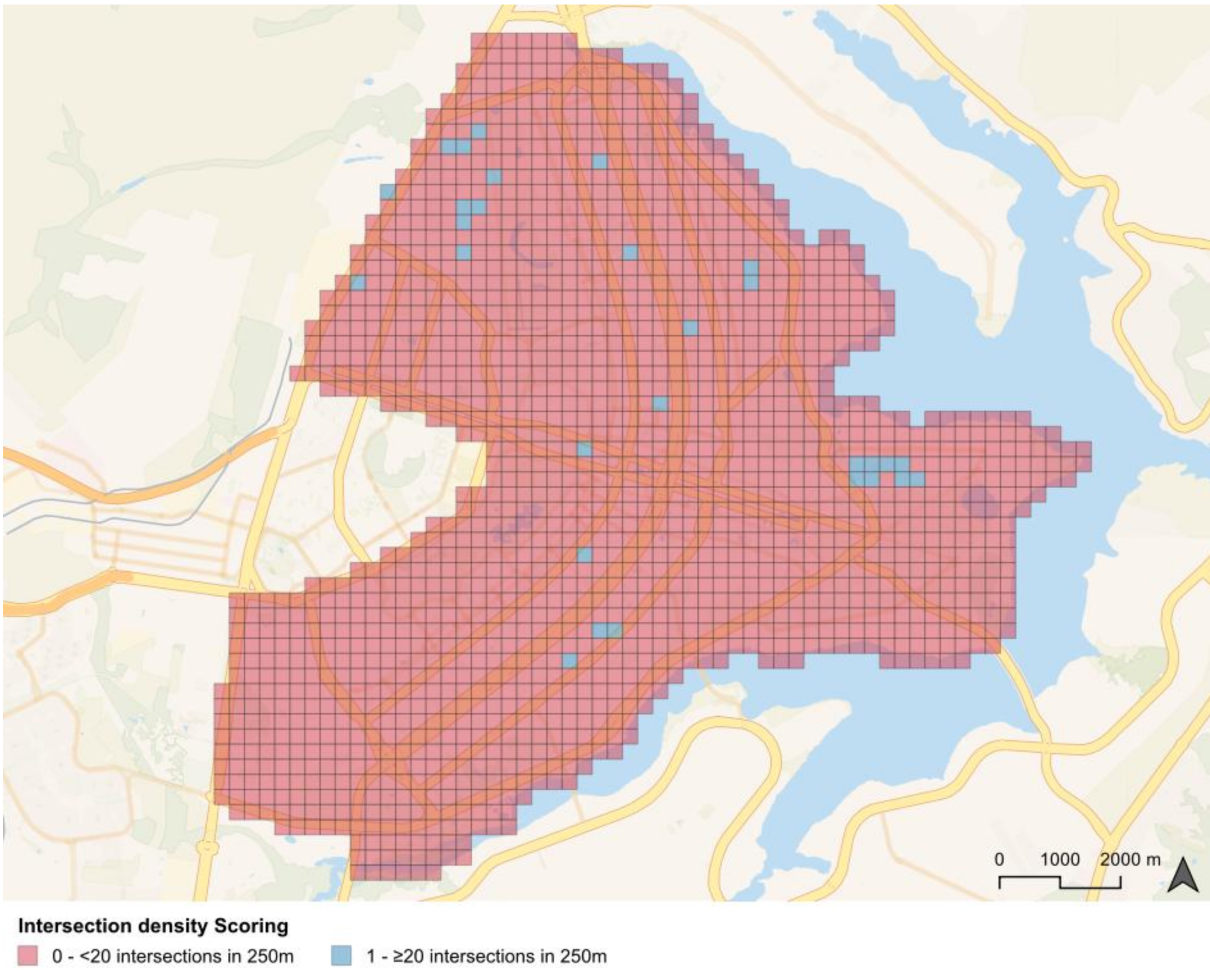
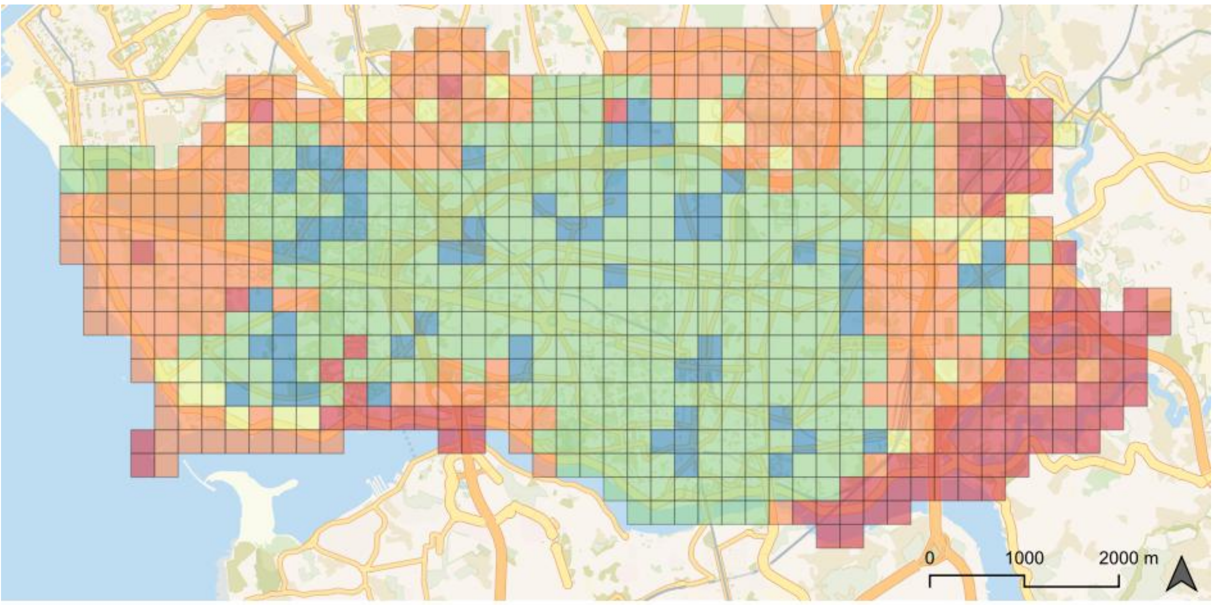


Fig. 5.16 – Scoring of 'Intersection density' indicator in Plano Piloto

5.5 Macro-Scale Infrastructural Lock-Ins Analysis for Porto and Plano Piloto

The four binary indicator scores were aggregated into the five-class classification of macro-scale infrastructural lock-ins. Figures 5.17 and 5.18 illustrate the spatial distribution of these classes across both study areas, while Table 15 presents the percentage of the population covered by each class. The results are summarized in the following text.



Macro Infrastructural Lock-Ins Score - Porto

1_Unlocked - Mixed, active, connected
2_Mixed, active
3_Mixed, connected
4_Mixed
5_Locked-In - Not mixed

Fig. 5.17 – Macro Infrastructural Lock-Ins in Porto

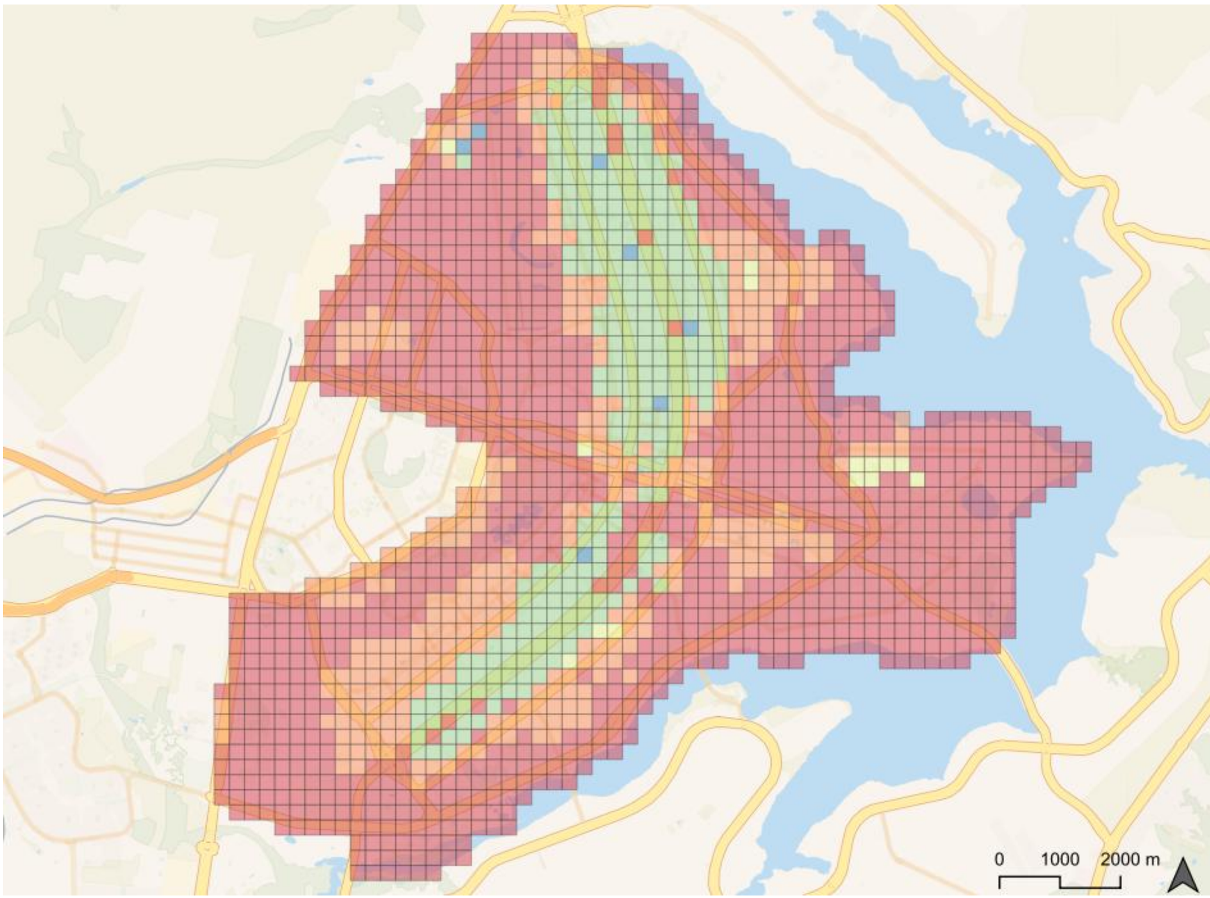


Fig. 5.18 – Macro Infrastructural Lock-Ins in Plano Piloto

Table 5.3 - Percentages of area and population covered by each class in each case study

Macro Infrastructural Lock-Ins Classification	Porto		Plano Piloto	
	Area	*Population*	*Area*	*Population*
1_Unlocked - Mixed, Active, Connected	8,49% (62 cells)	14,02% (32.499,92 inhabitants)	0,41% (7 cells)	1,95% (3.864,41 inhabitants)
2_Mixed, Active, Not Connected	44,79% (327 cells)	63,27% (146.648,52 inhabitants)	15,67% (466 cells)	57,47% (114.186,44 inhabitants)
3_Mixed, Not Active, Connected	3,97% (29 cells)	4,01% (9.289,41 inhabitants)	0,82% (14 cells)	2,38% (4.730,05 inhabitants)
4_Mixed, Not Active, Not Connected	29,73% (217 cells)	14,85% (34.427,17 inhabitants)	18,89% (323 cells)	16,87% (33.520,14 inhabitants)
5_Locked-In – Not Mixed	13,01% (95 cells)	3,85% (8.934,85 inhabitants)	64,31% (1098 cells)	21,33% (42.372,17 inhabitants)

Class 1 – Unlocked (Mixed, Active and Connected)

The class representing the highest potential for activating the 15-Minute City – where land-use mix, street activity, and path connectivity all meet their respective thresholds simultaneously – is scarce in both study areas. This scarcity is a consequence of the consistently low intersection density scores: since the connectivity criterion is almost never met, relatively few cells can satisfy all four conditions jointly. In Porto and Plano Piloto, there is no significant concentration of this class observed.

Class 2 – Mixed and Active (Not connected)

This is the dominant class in Porto – covering most the municipality's area and population – and Plano Piloto – in terms of population. It describes areas that combine a sufficient mix of destinations with adequate levels of street activity — generated either by population density or retail density, or both — but without meeting the intersection density threshold. While the absence of high path connectivity can be seen as a constraint, the prevalence of this class across Porto and Plano Piloto reflects a good foundation for pedestrian mobility. In Plano Piloto, this class is confined primarily to Asa Norte and parts of Asa Sul neighbourhoods, pointing to the same potential for reducing car dependence within the "wings" that was identified in the accessibility analysis.

Class 3 – Mixed and Connected (Not active)

This class represents areas characterised by a mixed land-use structure and adequate path connectivity, but fail to meet the required thresholds for population and/or retail density. It is relatively scarce in both study areas, reflecting the limited occurrence of positive intersection density scores. Although Porto contains a larger proportion of both its area and population within this class than Plano Piloto, a concentration of Mixed and Connected cells can be found in the Vila Planalto neighbourhood on the eastern edge of Plano Piloto.

Class 4 – Mixed (Not active and Not connected)

Only Mixed class covers a substantial share of grid cells in Porto, with particular concentration in peripheral areas and along the western edge of the municipality. The Nevogilde neighbourhood, characterised by large single-family properties and adjacent to Parque da Cidade do Porto, exemplifies this class: it presents adequate land-use diversity in terms of accessible destinations but lacks both the population and commercial density required to generate street activity and the street network granularity required to facilitate pedestrian movement. In Plano Piloto, this class also appears across a considerable range of cells, encompassing the central civic area between Asa Norte and Asa Sul. Despite hosting the main bus terminal and generating significant weekday movement, this central civic area lacks the spatial conditions to sustain habitual pedestrian activity (on evenings and weekends). These areas represent the most challenging planning context among the mixed-use classes.

Class 5 – Locked-In (Not mixed, Not active and Not connected)

The final class, denoting the complete absence of an adequate mix of accessible destinations, encompasses all grid cells with a land-use mix score of 0, irrespective of their scores on the remaining three indicators. This class reflects the most deeply entrenched macro-scale lock-in, given that the absence of diverse walkable destinations cannot be compensated by street connectivity or residential density alone — without somewhere to walk to, neither a well-connected network nor a populated neighbourhood can generate habitual pedestrian travel.

In Porto, Locked-In cells are concentrated along the eastern edge of the municipality, in the zone corresponding to Parque Oriental da Cidade do Porto and its surroundings. This spatial pattern points to a clearly demarcated area of the city where some residents – approximately 3,85% of Porto's population – face structural barriers to accessing daily needs on foot.

In Plano Piloto, however, Locked-In is the single most prevalent classification across the study area, accounting for 64% of grid cells. While most of these cells are located in non-aedificandi zones or single-use sectors – areas that are, by design, excluded from mixed-use occupation – they still cover a substantial part of Plano Piloto's population – a concerning value of approximately 21,33% – indicating that almost ¼ of the RA's population is completely constrained.

6
CONCLUSIONS AND METHODOLOGICAL CONSIDERATIONS

This final chapter synthesises the principal findings of this study, reflects on the methodological decisions that shaped the analysis, and discusses the contributions and limitations of the work. It concludes by outlining directions for future research.

6.1 MAIN FINDINGS

The central objective of this dissertation was to diagnose, at a macro-scale, the infrastructural lock-ins that sustain car dependency in two structurally distinct urban contexts: the Municipality of Porto (Portugal) and the Administrative Region of Plano Piloto (Brasília, Brazil). Drawing on a GIS-based framework grounded in the lock-ins literature, the analysis combined proximity-based accessibility measurement with a four-indicator walkability assessment – land-use mix, retail density, population density, and intersection density – produce a comparative Infrastructural Lock-Ins classification across both study areas.

These findings respond directly to the two guiding objectives of this research. Regarding the first, identifying and categorising infrastructural lock-ins, the five-class classification presented in Chapter 5 isolates, for each case study, which macro-scale infrastructural lock-ins act as the most challenging constraints, and where it concentrates spatially.

Regarding the second – spatially analysing constraints on 15MC implementation – the same classification identifies, cell by cell, where the territorial preconditions for 15-Minute City implementation (a sufficient mix of destinations, adequate street activity, and pedestrian connectivity) are jointly met, partially met, or absent, thereby mapping not only where car dependency is reinforced but where 15MC-oriented interventions would face the fewest versus the most severe structural obstacles. Figure 6.1 illustrates this principle.

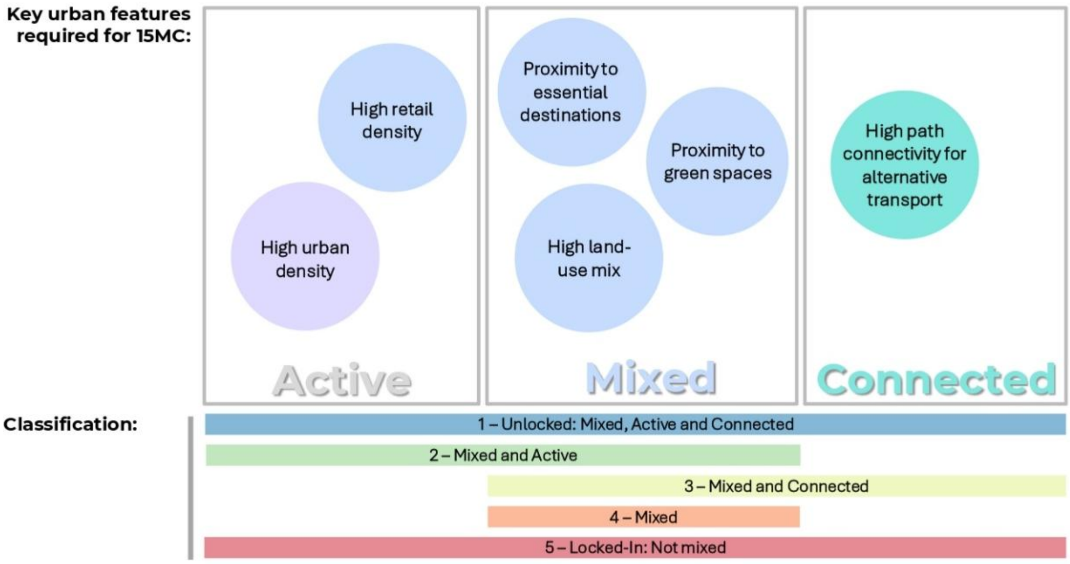


Fig. 6.1 – Key urban features required for 15-MC: absence of Macro-scale Infrastructural Lock-Ins

6.1.1 Porto

Porto emerges from the analysis as a city with strong structural foundations for walking. The proximity-based accessibility calculation – conducted for land-use mix indicator – demonstrate broad territorial coverage of both essential and functional activities across the municipality: approximately 87% of grid cells achieve the threshold of Mixed areas, confirming the spatial coherence of a historically consolidated, compact urban form. Restaurants and cafés are effectively omnipresent; pharmacies, banks, general practitioners, and post offices are accessible to most of the urban area. The principal gaps are concentrated in educational provision – pre-primary and primary schools – which fall below the 50% positive-score threshold, and in sports facilities, whose spatial distribution remains uneven.

Regarding the Infrastructural Lock-Ins classification, Porto is dominated by Mixed, Active and Not Connected areas, which covers most of the municipality's grid cells, indicating that the main lock-in of the study area is the Low Path Connectivity for Alternative Transport. This finding points to a paradox that runs through Porto's pedestrian environment: the city possesses the destination diversity, and, in parts, the street activity/density required to support walking, but its design street network lacks connectivity for pedestrians. The implication is that Porto's pedestrian accessibility is sustained by the richness and proximity of its destinations rather than by the formal granularity of its street network.

Regarding the presence of all lock-ins, represented by Locked-In class cells, are concentrated in the eastern municipality, in the vicinity of Parque Oriental da Cidade do Porto, eastern part of the municipality. This area calls for particular attention: it registers a positive score on the population density indicator, suggesting a relatively high concentration of residents. However, when considered alongside the preceding indicators, this same area proves notably deficient in essential and functional destinations accessibility – a combination that points to a disparity between residential demand and the available supply of urban services, identifying a demarcated zone where residents face structural barriers to accessing daily needs on foot.

However, this relatively limited extent of Locked-In cells should not be read as evidence that Porto's car dependency lock-ins are resolved. The four indicators assessed here do not capture the Institutional (e.g. Hidden subsidies, Industrial and economic dependence on automobility), Behavioural (e.g. Perceived inconvenience, Weak pro-active attitude), or other Infrastructural (e.g. High parking provision, High road capacity) lock-ins identified in Chapter 2. Given that the private automobile accounts for 54,5% of all trips in Porto the favourable macro-scale profile observed here appears necessary, but not sufficient, to explain Porto's car dependency: the conditions the literature identifies as a basis for walking are largely present, yet have not, on their own, translated into lower car reliance.

6.1.2 Plano Piloto

Plano Piloto presents a more fragmented spatial profile. Only 36% of grid cells achieve the threshold of Land-use mix: a number that approaches near-universal coverage when the analytical scope is restricted to the inhabited neighbourhoods of Asa Norte, Asa Sul, Vila Planalto, Setor Noroeste and Setor Militar Urbano, also reflecting the structural reality of the administrative region as a whole, in which non-aedificandi zones and single-use sectors account for the majority of the study area. Asa Norte outperforms Asa Sul across all activity categories in the land-use mix analysis. The most pronounced accessibility deficit in both “wings” concerns educational facilities: primary school coverage is extremely low across the study area by the 800-metre threshold.

Regarding the Infrastructural Lock-Ins classification, in terms of area, Plano Piloto is dominated by the worst class – Locked-In (5) – which encounters all macro-scale infrastructural lock-ins assessed in this analysis, Low Land-use Mix, Long Distance to Essential Destinations, Low Urban Density, and Low Path Connectivity for Alternative Transport. These locked-in zones do not merely represent empty land: they function as physical barriers between inhabited neighbourhoods, making non-motorised travel between residential areas effectively impossible over much of the administrative region. The vast distances of unmixed, undifferentiated space that separate Asa Norte, Asa Sul, Vila Planalto, and the remaining settlements not only reinforce existing car dependency but actively encourage further urban sprawl by inducing residents to seek destinations in adjacent, better-connected administrative regions by car. In this sense, the Locked-In areas of Plano Piloto are not passive voids in the urban fabric but active contributors to the automobile regime that the 15-Minute City seeks to dismantle.

Vila Planalto emerges as the most notable internal exception, being the only neighbourhood in the study area where a meaningful concentration of Mixed and Connected cells is observed, considering its small size. Its traditional street morphology – characterised by short blocks, frequent intersections, and higher mix of uses – produces scores that stand in sharp contrast to the surrounding planned fabric, offering empirical evidence that the spatial conditions conducive to walking are achievable within the administrative region's boundaries, even if they were not the product of its governing planning paradigm. However, this apparent severity of permeability across the study area – measured by intersection density – in Plano Piloto should be read with caution. The residential buildings of Asa Norte and Asa Sul – inserted in the "superblocks" residential areas – are elevated on pilotis, following Lucio Costa's principle of ensuring the "free use of the ground" (Costa, 1957). This design keeps the ground level continuous, publicly accessible, and unprivatised, allowing the space beneath and between buildings to merge with the superblocks' green areas. As a result, pedestrians can move through these open spaces along routes that are not constrained by the street network, making permeability substantially greater than intersection density alone would suggest. The network-cleaning procedure – which excluded footway and steps classifications to avoid false nodes – removes precisely those elements most relevant to superblock permeability, contributing to the near-universal absence of Unlocked – Mixed, Active and Connected cells in Asa Norte and Asa Sul.

6.1.3 Comparing Infrastructural Lock-Ins in Porto and Plano Piloto

Taken together, the results indicate that Plano Piloto is considerably more Locked-in than Porto at the macro infrastructural scale, but for a different reason than might initially be assumed. The contrast is clearly comparable in population terms: the Locked-In class covers 21,33% of Plano Piloto's population against 3,85% of Porto's, and while the area figures seem more extreme (64,31% versus 13,01%), they still point to a structurally different condition. In Plano Piloto, the strongest lock-in is Low Land-Use Mix itself: because this indicator determines the Locked-In classification irrespective of the other three, the extensive non-aedificandi zones, single-use sectors, and large road infrastructure corridors separating Asa Norte, Asa Sul, Vila Planalto and the remaining settlements act as the principal barrier, embedded in and protected by the planning paradigm that earned the city its UNESCO World Heritage status. In Porto, by contrast, the strongest lock-in is Low Path Connectivity for Alternative Transport: across the Mixed-Active class that dominates the municipality, the destinations and street activity needed for walking are present, but the street network does not provide frequent route choices for pedestrians.

These findings only partly align with the modal split data presented in subsection 4.1.3. For Plano Piloto, the modal split is consistent with the spatial assessment: a private transport share of 71.3% of all trips is consistent with a territory where most of the area, and around a quarter of the population, face the most severe form of infrastructural lock-in identified here. For Porto, however, the picture is more contradictory. Despite a high private transport share of 54.5% – still lower than Plano Piloto – Porto's infrastructural profile is considerably more favourable. As discussed in Chapter 5, this mismatch suggests that the macro-scale conditions assessed here, while supportive of the 15-Minute City model in terms of infrastructure, are not on their own sufficient to explain Porto's persistent car dependency.

The implications for unlocking car dependency in both case studies also diverge. In Plano Piloto, addressing Low Land-Use Mix directly – e.g. by reconfiguration of different destinations across predominantly mono-functional zones – is constrained by the heritage protections safeguarding its modernist urban form; a more feasible pathway may lie in improving connections between the existing mixed-use – currently isolated – neighbourhoods through expanded cycling infrastructure or higher-frequency public transport, also considering that land-use mix alone cannot provide across the city's characteristically greater distances. In Porto, addressing Low Path Connectivity would involve targeted improvements to pedestrian network granularity outside the historic core; however, given the disjunction between Porto's infrastructural profile and its modal split, such interventions would likely need to be accompanied by research of the non-infrastructural lock-ins – car-centric policies, fiscal incentives, or travel habits – that fall outside this dissertation's scope.

In terms of 15MC implementation specifically, this comparison indicates that the spatial constraint – infrastructural lock-ins at a macro scale – is qualitatively different in each case: in Plano Piloto, implementation is restricted by an absence of destinations to walk to between neighbourhoods, requiring land-use intervention before connectivity or density improvements can have effect; in Porto, the destinations and density already exist, and the spatial constraint on 15MC implementation is the granularity of the pedestrian network itself.

6.2 METHODOLOGICAL CONTRIBUTIONS AND REFLECTIONS

This dissertation makes a methodological contribution by developing a replicable GIS-based framework for the comparative assessment of macro-scale infrastructural lock-ins, grounded in and the walkability and accessibility literature. The framework operationalises five lock-ins identified in the systematic literature review – Low Land-use Mix, Long Distance to Essential Destinations, Low Urban Density, and Low Path Connectivity for Alternative Transport – through a set of binary indicators that are comparable across cities.

The decision to aggregate the four indicators of Population density, Land-use mix, Retail density and Intersection density in the five-class Macro-Scale Infrastructural Lock-Ins classification, making Land-use mix a priority when compared to the remaining three indicators, reflects a theoretical position with empirical support: without a sufficient range of accessible destinations, street connectivity and residential density cannot generate habitual pedestrian travel. This design choice proved its effectiveness in the Plano Piloto analysis, where the prevalence of Land-use mix scores of 0 in non-inhabited areas prevented an inflation of other indicator scores in zones that, by design, are not meant to support pedestrian activity.

The comparative use of OpenStreetMap data for both case studies was a deliberate choice motivated by the principle of data justice between the two cities: institutional datasets from Porto City Council and SEDUH-DF differ in structure, coverage and completeness, and their combined use would have introduced asymmetries into the analysis that would have been difficult to account for.

However, this choice also includes important limitations. First, the use of OpenStreetMap introduces variation in data quality across study areas. The completeness of the street network and points of interest (POIs) is generally higher in historic centres and major retail corridors than in peripheral or informal areas, while smaller neighbourhood businesses and recently opened or closed establishments may be systematically underrepresented.

Another source of underestimation concerns the representation of pre-primary schools in OpenStreetMap. Because each POI can only be assigned a single category, facilities that provide both pre-primary and primary education are typically classified only as school (reclassified here as primary) rather than also as kindergarten (reclassified here as pre-primary). This is particularly common in Plano Piloto, where most pre-primary schools also provide primary education. Consequently, many grid cells can be incorrectly recorded as having no pre-primary school, resulting in an underestimation of accessibility to this type of educational facility.

Second, the analysis provides a cross-sectional snapshot that does not address micro-scale infrastructural Lock-Ins (e.g. Low-quality alternative transport infrastructure) or capture temporal change in activity distribution and street configuration that also influence walking behaviour. These limitations are inherent to macro-scale, remotely measured assessments and do not undermine the comparative value of the methodology, but they define the scope within which the results should be interpreted.

The binary scoring convention also suppresses the continuous variation underlying each indicator: a centroid with 19 intersections within 250 metres is scored identically to one with none, which may produce spatial discontinuities that are artefacts of the threshold rather than genuine step-changes in the urban environment.

Nevertheless, the limitations and findings discussed throughout this dissertation suggest some directions for further development. Incorporating updated street network and POI datasets – either through location audit or the use of official municipal datasets – would substantially improve the representativeness of the indicators measuring distance to destinations, land-use mix and intersection density. Particularly, a more complete street network would provide a more nuanced representation of pedestrian permeability within the Asa Norte and Asa Sul neighbourhoods in Plano Piloto.

If field audits are feasible, additional indicators – particularly those capturing micro-scale infrastructure – could also be incorporated into the framework using thresholds already established in the literature. These include indicators related to Sidewalk Design, Comfort and Environmental Design, Traffic Safety and Public Safety, presented in Appendix A.2.

Finally, the macro-scale classification developed in this dissertation could also be integrated with the institutional and behavioural dimensions of the lock-in framework presented in Chapter 2, enabling a fuller diagnosis of the conditions under which infrastructural improvements are likely to translate into modal transition.

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APPENDIX

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A.2 Indicators and their parameters used in walkability indexes and scores, by author

Indicator	Bradshaw (1993) [Less score is more walkable]	Frank et al. (2009)	Adams et al. (2014)	Ribeiro & Hoffimann (2018)	Cerin et al. (2022)
DENSITY					
Residential density	≥ 15 persons per acre (≅ 3700 persons/km2) = 1 10-15 = 2 5-10 = 3 < 5 = 4	**Residential units / residential area per block group**	**Number of dwellings / land area within participant' buffers devoted to residential use**	**Ratio of dwellings per neighborhood area**	**≥ around 5700 people per km² = Optimal range**
Commercial density					
Institutional density					
DIVERSITY OF DESTINATIONS					
Land-use mix / Proximity to diverse amenities		**Single use = 0 Even distribution of floor area across the five uses (residential, retail, entertainment, office and institutional) = 1**	**Single use = 0 Equal distribution of the available residential, retail combined, and civic/institutional land area within the buffer across uses = 1**	**Number of destinations of each type (Retail, Recreation, Service, Institutional and Residential) within 400 and 800 m of the neighborhood centroid**	
Parkland area / green areas density	>50 acres/square mile and average residence and <1,500-foot walk = 1 >50 ac/mi2 and average residence and >1,500-foot walk = 2 <50 ac/mi2 and average residence and <1,500-foot walk = 3 <50 ac/mi2 and average residence and >1,500-foot walk = 4				
Retail floor area ratio / Commercial frontage		**Retail building floor area footprint / Retail land floor area footprint**			
Retail density					
CONNECTIVITY & NETWORK DESIGN					
Intersection density		**Number of true intersections (≥3 legs) / land area of the block group (in acres)**	**Ratio of the number of intersections within each participant's buffer / the total buffer area**	**Density of intersections within 400 and 800 m of the neighborhood centroid**	**≥ 100 intersections per km² = Optimal range**
Block length					
Pedestrian radius of activity / Pedestrian Catchment Area					
Road density					
ACCESSIBILITY TO MOTORISED TRANSPORT					
Access to public transport					**≥ 25 public transport stops per km² = Optimal range**
Transit (PT) responsiveness	≤ 10 minutes = 1 10-20 minutes = 2 >20 minutes = 3 No service = 4				
Proximity to car parking (positive)					
Parking places per household (negative)	<1 = 1 1-2 = 2 2-3 = 3 >3 = 4				
SIDEWALK DESIGN / INFRASTRUCTURE					
Sidewalk width					

Sidewalk surface / Pavement quality					
Sidewalk slope / Pavement slope					
Obstacles on sidewalk					
Street furniture	>.75 sitting spots on benches per household = 1 .5 to .75 = 2 .25 to .5 = 3 .25 or fewer = 4				
Trees on sidewalks					
Sidewalk provision / presence	(Single point each) - Not on both sides of 90% of streets - Dips at each driveway - Widths less than 5 feet on residential streets; 8 feet on shopping streets - More than one discontinuity (1" or more) per block				
Ramp presence					
Sun/Rain protection					
COMFORT & ENVIRONMENTAL DESIGN					
Attractiveness / Architectural context					
Streetscape enclosure					
Streetscape complexity					
Streetscape transparency					
TRAFFIC SAFETY					
Pedestrian activity / flow					
Traffic speed					
Traffic lanes / volume / flow					

Risk of accidents / Traffic accident records					
Traffic lights / Control devices					
Crosswalk visibility					
Congestion levels					
Driveways					
Protection from vehicles					
Street crossing time					
PUBLIC SAFETY / CIVIL SECURITY					
Lighting quality					
Age child walks alone	*Age 6 or younger = 1 Ages 7-9 = 2 Ages 10-13 = 3 Age 12 or older = 4*				
Crime records					
Proximity to police stations					
Security (police officers/residents)					
Security cameras					
Women's safety rating	*"I walk alone anywhere anytime" = 1 "I walk alone, but am careful of routes" = 2 "I must walk with someone at night" = 3 "I never walk, except to car visible from entrance" = 4*				
SOCIAL					
Chances of meeting acquaintances	*10 or more per mile = 1 3-10 /mi. = 2 < 3 /mi. = 3 "Are you kidding?!" = 4*				
Neighbourhood places of significance (density)	*≥ 10 = 1 5-10 = 2 3-5 = 3 < 3 = 4*				

Type of source:

GIS *Audit / Survey* Not specified

Indicator	Ruiz-Padillo et al. (2022)	Fina et al. (2022)	Fonseca et al. (2022)	Guzman et al. (2024)	D'Orso et al. (2025)
DENSITY					
Residential density		**Number of residents / 500×500 m grid cell (continuous normalized score)**	**≥ average local density = 1 < average = 0**	**Population density Z value**	
Commercial density				**Commercial establishments density Z value**	
Institutional density				**Institutional establishments density Z value**	
DIVERSITY OF DESTINATIONS					
Land-use mix / Proximity to diverse amenities		**Weighted pedestrian-network accessibility to diverse amenities using distance-decay functions, amenity-category weights, and terrain slope penalties**	**> 3 uses = 1 ≤ 3 uses = 0**		
Parkland area / green areas density		**Green and blue infrastructure areas / grid cell area**		**Park and green areas density Z value**	
Retail floor area ratio / Commercial frontage					*Absence of shops on sidewalk = 0 Presence of shop windows and shops = 1*
Retail density	**Number of shops and services / Neighbourhood area Low density = up to 25 per km² Medium density = 25-85 km² High density = >85 km²**		**≥ average local density = 1 < average = 0**		
CONNECTIVITY & NETWORK DESIGN					
Intersection density	**Number of four-way intersections / total number of intersections - %**		**≥ 3 intersections in a street = 1 < 3 intersections in a street = 0**		**Number of road intersections per 1 km2 area**
Block length				**Average block length, Z value**	
Pedestrian radius of activity / Pedestrian Catchment Area		**Area of 2km pedestrian-network isochrone / Area of an ideal 2 km Euclidean-radius circle from each grid centroid**			**Area of 500m pedestrian-network isochrone / Area of an ideal 500m Euclidean-radius circle from each grid centroid**
Road density					**Total street length per 1 km2 area**
ACCESSIBILITY TO MOTORISED TRANSPORT					
Access to public transport			**Bus stops ≤ 400m = 1 Bus stops > 400m = 0 Train stations ≤ 800m = 1 Train stations > 800m = 0**	**Stops/stations in the segment = 1 No = 0**	
Transit (PT) responsiveness					
Proximity to car parking (positive)			**Car parking ≤ 500m = 1 Car parking > 800m = 0**		
Parking places per household (negative)					
SIDEWALK DESIGN / INFRASTRUCTURE					
Sidewalk width	*Visual perception (Google Street View audit) ideal / good / reasonable / bad / very bad conditions*		*≥ 1.5m = 1 < 1.5m = 0*	**Width ≥ 2.0 m = 1 Width < 2.0 m = 0**	*High pedestrian flows, insufficient sidewalk width or presence of obstacles (LOS = E, F) = 0 Level Of Service (= C, D) = 1 Low pedestrian flows, adequate pavement width or absence of obstacles (LOS = A, B) = 2*

Sidewalk surface / Pavement quality	*Visual perception (Google Street View audit) ideal / good / reasonable / bad / very bad conditions*		*Good = 1 Bad = 0*	**Sidewalk suitable for walking or jogging = 1 Practicable sidewalk but with caution = 0.6 Sidewalk in bad condition = 0.3 No presence of a sidewalk = 0**	*Very degraded pavement = 0 Presence of some potholes or depressions = 1 No potholes or depressions, pavement in good condition = 2*
Sidewalk slope / Pavement slope	**Average of slopes (%) Low slope = <7% High slope = ≥7%**	**Slope is penalty of accessibility: Adjusted Accessibility = Accessibility × Slope Penalty**	**≤ 5% = 1 > 5% = 0**	**Slope < 2% = 1 Slope between 2-3% = 0.5 Slope > %3 = 0**	*≤ 5% = 1 > 5% = 0*
Obstacles on sidewalk			*No = 1 Yes = 0*	**Remaining width due to the presence of bicycle paths ≥ 2.0m = 1 Remaining width < 2.0m = 0**	*High pedestrian flows, insufficient sidewalk width or presence of obstacles (LOS = E, F) = 0 Level Of Service (= C, D) = 1 Low pedestrian flows, adequate pavement width or absence of obstacles (LOS = A, B) = 2*
Street furniture			*Presence of 4 elements = 1 No (<4) = 0*		*Absence of litter bins, benches, and other elements of street furniture = 0 Presence of litter bins, benches, and other elements of street furniture = 1*
Trees on sidewalks			*Yes = 1 No = 0*	**Yes = 1 No = 0**	*Absence of flowerbeds or green areas = 0 Presence of flowerbeds or green areas = 1*
Sidewalk provision / presence				**Presence of sidewalk segments on the city road network Z value**	
Ramp presence				**Presence of ramps /special infrastructure for the vulnerable people = 1 No = 0**	
Sun/Rain protection					*Lack of shelter from the sun or rain = 0 Presence of shelters from sun or rain = 1*
COMFORT & ENVIRONMENTAL DESIGN					
Attractiveness / Architectural context	*Visual perception (Google Street View) ideal / good / reasonable / bad / very bad conditions*			**High socioeconomic strata = 1 Medium SES = 0.5 Low SES = 0**	*Degraded architectural context (presence of graffiti, degraded facades, industrial buildings or abandoned buildings) = 0 Pleasant architectural context = 1*
Streetscape enclosure			*H/W ratios of 1:2 to 1:4 = 1 H/W ratios >1:2 and <1:4 = 0*		
Streetscape complexity			*Variation of 4 elements = 1 No (<4) = 0*		
Streetscape transparency			*≥50% transparency = 1 <50% = 0*		
TRAFFIC SAFETY					
Pedestrian activity / flow			*Pedestrian activity = 1 No pedestrian activity = 0*	**Number of pedestrians (modal split) Z value**	*High pedestrian flows, insufficient sidewalk width or presence of obstacles (LOS = E, F) = 0 Level Of Service (= C, D) = 1 Low pedestrian flows, adequate pavement width or absence of obstacles (LOS = A, B) = 2*
Traffic speed			*≤30 km/h = 1 >30 km/h = 0*	**Average traffic speed (in km/h) Z value**	*High traffic volumes (>1000 vph) or high speeds (>50 km/h) = 0 In other cases = 1 Free flow (<300 vph) and low speeds (<30 km/h) = 2*
Traffic lanes / volume / flow			*≤2 lanes = 1 >2 lanes = 0*	**Vehicular flow (veh/h) Z value**	*High traffic volumes (>1000 vph) or high speeds (>50 km/h) = 0 In other cases = 1 Free flow (<300 vph) and low speeds (<30 km/h) = 2*

Risk of accidents / Traffic accident records	**Number of accidents in the neighborhood in the previous three years**			**Presence of traffic accidents in the segment = 1 Absence = 0**	
Traffic lights / Control devices				**Presence of traffic control devices in the segment = 1 Absence = 0**	*Absence of traffic lights at the crosswalk = 0 Traffic lights at the crosswalk but presence of conflicts between vehicles and pedestrians = 1 Traffic lights that eliminate conflict points between vehicles and pedestrians = 2*
Crosswalk visibility					*No crosswalks or very poor crosswalk visibility = 0 Good crosswalk visibility = 1 Excellent crosswalk visibility = 2*
Congestion levels				**Congestion level by segment (relative to city value)**	
Driveways					*Presence of driveways along the route = 0 Absence of one or more driveways = 1*
Protection from vehicles					*Absence of barriers to protect pedestrians from vehicles = 0 Presence of protection elements = 1*
Street crossing time				**Walking time from sidewalk to sidewalk (in sec) Z value**	
PUBLIC SAFETY / CIVIL SECURITY					
Lighting quality				**Covered area with excellent lighting = 1 Sufficient lighting to see clearly = 0.6 Presence of lighting with deficiencies = 0.3 No public lighting = 0**	*Poor or no lighting = 0 Adequate and efficient street lighting = 1*
Age child walks alone					
Crime records				**Presence of crimes Z value**	
Proximity to police stations				**Presence of stations in the segment = 1 Absence = 0**	
Security (police officers/residents)	**Number of police officers per 1.000 residents**				
Security cameras				**Presence in the segment = 1 Absence = 0**	
Women's safety rating					
SOCIAL					
Chances of meeting acquaintances					
Neighbourhood places of significance (density)					

Type of source:

GIS *Audit / Survey* Not specified

A.3 Reclassification of OpenStreetMap activity categories for land-use mix indicator

OSM Original Classification		New Classification
Porto	**Plano Piloto**	
kindergarten	kindergarten	**preprimaryschool**
playground	playground	**playground**
bakery	bakery	**foodshopping**
butcher	butcher	
convenience	convenience	
greengrocer	greengrocer	
market_place	market_place	
supermarket	supermarket	
school	school	**primaryschool**
park	park	**park**
dog_park	-	
pharmacy	pharmacy	**pharmacy**
clinic	clinic	**generalpractician**
doctors	doctors	
post_box	post_box	**postoffice**
post_office	post_office	
atm	atm	**bank**
bank	bank	
cafe	cafe	**restaurant**
bar	bar	
fast_food	fast_food	
food_court	food_court	
pub	pub	
restaurant	restaurant	

OSM Original Classification		New Classification
Porto	**Plano Piloto**	
sports_centre	sports_centre	**sportsfacility**
swimming_pool	swimming_pool	
beauty_shop	beauty_shop	**nonfoodshopping** (Not classified as Essential or Functional Activity, but further assessed in Retail density calculation)
bicycle_shop	bicycle_shop	
bookshop	bookshop	
chemist	chemist	
clothes	clothes	
computer_shop	computer_shop	
department_store	department_store	
doityourself	doityourself	
florist	florist	
furniture_shop	furniture_shop	
garden_centre	garden_centre	
gift_shop	gift_shop	
hairdresser	hairdresser	
jeweller	jeweller	
kiosk	kiosk	
laundry	laundry	
mall	mall	
mobile_phone_shop	mobile_phone_shop	
optician	optician	
outdoor_shop	-	
shoe_shop	shoe_shop	
sports_shop	sports_shop	
stationery	stationery	
toy_shop	toy_shop	
vending_any	-	
vending_machine	-	