# Exploring Double Energy and Transport Poverty: Case study of Madrid


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# Abstract

This study examines the spatial differentiation of transport vulnerability and energy poverty at the scale of neighborhoods (*barrio*s) of Madrid. The aim of this work is to develop a methodology for assessing transport poverty and identify the most vulnerable areas in Madrid considering the simultaneous impact of transport and energy factors. The research focuses on five aspects of transport vulnerability and conducts mapping and analysis, comparing them with energy poverty.

The findings indicate significant transport poverty in peripheral areas and challenges related to energy and transport affordability in the southern districts (double energy poverty). Simultaneous transport and energy poverty are prevalent in the southern and south-eastern regions. However, no overlap between extremely poor areas with concurrent transport and energy vulnerability was identified.

The recommendations include improving transport networks and implementing social policies to reduce inequality between poor and wealthy neighborhoods, such as reconstruction programs and preferential tariffs.

**Keywords:** Transport poverty · energy poverty · mobility · transport poverty indicators · vulnerability mappig · GIS · geospatial analysis

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# 1 Introduction

In the modern world, the undeniable importance of studying energy poverty becomes evident. A multitude of studies underscore the impact of domestic energy consumption on people's well-being, particularly in the face of an increasingly dire energy crisis. The economic burden predominantly hits the most vulnerable socio-economic groups, worsening their already arduous circumstances.

At the same time, more and more scientists, driven by concerns of equity in mobility and society, are suggesting a new concept called Transport Poverty. This issue is more about people's access to transportation and has some similarities with energy poverty, particularly in terms of social dynamics and geographical considerations.

Simultaneously examining these two challenges can facilitate a more effective identification of households that are either at risk or already residing in substandard living conditions. Rigorous analysis of the spatial distribution of energy and transport poverty holds promise in guiding proper planning, effective management strategies, as well as providing valuable insights for the development of legislative frameworks and policy actions. Double poverty assessment approach holds promise for addressing the complexities of these interrelated issues.

## 1.1 Research focus

The aim of this study is to examine the phenomena of transport and energy poverty in Madrid, exploring its spatial characteristics, then to develop indicators and general classification for transport poverty. Additionally, the study seeks to establish a classification system dedicated to simultaneous manifestations of transport and energy poverty, which would intersect these two problems within a single map.

Given the broad and incompletely understood nature of transport poverty, the research will concentrate on its five key aspects. While previous research and classifications have been conducted regarding personal transportation, the primary focus of that thesis will be on public transportation and the associated challenges of mobility and transport poverty.

Madrid, as a major metropolitan city characterized by a diverse array of transportation modes and a sizable population, has been selected as the case exemplar for this study. This choice allows to evaluate future classification system across a large territory and population.

## 1.2 Aim and Research Questions

This study further develops the existing concept of transport poverty, proposing advancements in terms of practical applications. The primary objectives of this study are twofold: first, to develop a comprehensive methodology for assessing transport poverty; and second, to investigate the occurrence of simultaneous transport and energy poverty in the city of Madrid. The creation of a methodology for mapping and classifying vulnerable areas in the face of transport poverty will aid in project management and policy development. Additionally, to explore the current vulnerable areas in Madrid, a combined classification of transport and energy poverty will be compiled. This innovative approach aims to provide a more comprehensive and nuanced understanding of the population's current issues.

To compile and analyze the resulting classifications, it is necessary to address the following research questions (RQ):

1. What is the significance of energy and transport for contemporary society?
2. How do we define and differentiate transport poverty and energy poverty, and what are their intersections?
3. Can Double Energy Poverty be considered analogous to Double Transport and Energy Poverty?
4. What are the existing indicators of transport poverty and mobility?
5. Which indicators can be utilized for mapping and classifying transport poverty?
6. How can intra-urban disparities in transport poverty be assessed in Madrid?
7. What are the characteristic issues of transport poverty in different zones of Madrid, and what are the underlying reasons for their existence?
8. Are there areas in Madrid where the population experiences simultaneous transport and energy poverty, placing them in the most vulnerable position?
9. What suggestions can be made to enhance the created classifications?
10. How can the obtained data be utilized?

By addressing these research questions, the study aims to deepen our understanding of transport and energy poverty in Madrid and provide valuable insights for urban planning, policy-making, and interventions aimed at improving the well-being of vulnerable populations.

# 2 Contextualisation

This chapter answers RQ1, examines the current situation with global energy consumption and the state of the transportation sector to understand the causes of rising prices and the threats of poverty. Contextualisation study reveals the importance of transport and energy in the context of the research.

## 2.1 Energy and Fuel. Global Energy Crisis

Energy use is a fundamental aspect of our daily lives, powering various sectors such as transportation, communication, and households. However, the majority of our energy still relies on finite fossil fuel resources like coal, oil, and natural gas, which have significant environmental consequences.

In recent years, the demand for energy has continued to rise, even amidst the COVID-19 pandemic. For instance, in 2021, primary energy demand surpassed 2019 levels by 1.3%, despite a substantial decline of 4.5% in 2020 (bp, 2021). While renewable energy sources played a crucial role in the increase of primary energy, fossil fuel consumption remained constant during that period (bp, 2022). Despite a plateau in oil demand and a 0.8% decrease in gas generation due to the Russia-Ukraine war (IEA, 2022a; bp, 2023), fossil fuels are projected to account for 81% of total energy consumption in 2022 and are expected to remain at 78% by 2032 (EIU, 2022). The finite nature of fossils and environmental damage expose their significant pricing vulnerability.

Same time the world faces a global energy crisis, driven by various factors. The COVID-19 pandemic has disrupted global supply chains and caused fluctuations in energy demand. Reduced economic activity during the pandemic resulted in decreased energy consumption, particularly in transportation fuels like gasoline and jet fuel. However, as the world recovers, energy demand is rebounding, placing strain on energy supplies (Ozili and Ozen, 2022).

Geopolitical tensions and conflicts, particularly in oil-producing regions, also contribute to the energy crisis. Disruptions in supply from these regions lead to price spikes and supply shortages, impacting global energy markets (Ozili and Ozen, 2022; bp, 2023; IEA, 2023).

The energy crisis has a direct impact on household expenses. As energy supply becomes more constrained, the prices of oil, natural gas, and other energy sources rise. This results in increased costs for gasoline, heating oil, electricity, and other essential expenses, which can particularly burden low-income households (Taylor, 2021; Guan *et al.*, 2023).

Moreover, rising energy prices affect the cost of goods and services that rely on energy. Transportation costs escalate, leading to higher prices for shipped goods, while energy-intensive industries, such as manufacturing, face increased costs that can be passed on to consumers (Ibáñez, 2022).

Overall, the energy crisis has the potential to impact households and the broader economy significantly. Finding solutions to ensure a stable and affordable supply of energy is essential to mitigate these impacts and ensure a sustainable energy future. And not less – even more important – would be a close attention to the vulnerable social groups, helping them to overcome worldwide disturbances and prevent marginalization of population.

## 2.2 Transport Usage. Impact

The transportation sector has emerged as a significant contributor to global energy consumption, since 2017 outpassing the industrial sector (Selçuk and Köktaş, 2020). Currently, the transportation sector accounts for approximately one-fifth of total carbon emissions globally (EDGAR/JRC., 2022). As a result, share of transport expences is continiously growing and emerging transport and energy poverty.

Analyzing data within the transportation sector is essential but challenging due to the lack of uniform definitions and techniques for comparing transport data globally (OECD, 2013). However, three main factors impact energy consumption in the transportation sector: the price and volatility of energy sources, technological advancements in energy performance, and environmental externalities related to emissions.

Land transportation, particularly road transportation, is the largest consumer of energy within the transportation sector. In developed countries, road transportation alone accounts for 85% of total energy use in the sector (Rodrigue, 2020) and it is responsible for 81% of global CO2 emissions (Figure 1). The level of energy consumption is a bit lower (72%) in EU at 2017 (EEA, 2019). But even while there has been a slight decrease in energy consumption for land transportation in some regions, the overall consumption remains relatively constant.

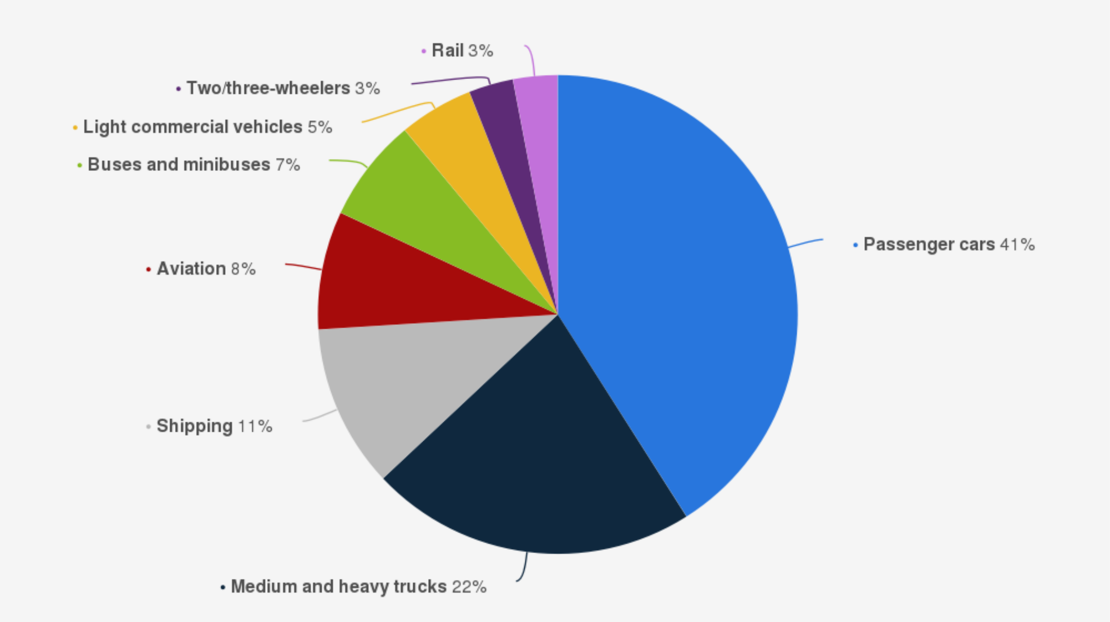


Figure 1. Distribution of carbon dioxide emissions produced by the transportation sector worldwide in 2020, by subsector. Source: (IEA, 2021)

Maritime transportation, which handles 90% of cross-border world trade volume (Rodrigue, 2020), is the most energy-efficient mode of transport, consuming only 7% of all energy used in transportation activities. However, fossil fuels still play a significant role in maritime shipping.

Air transportation consumes 8% of the energy used in transportation activities (Li *et al.*, 2017) and has experienced significant growth in recent decades (Dr. Schlumberger, 2014; OWiD, 2022). High speeds contribute to high energy consumption levels in avia-tion, and fuel accounts for a substantial portion of the industry's expenses.

Also, energy consumption in transportation varies between passenger and freight mobility, relying on different modal configurations. Passenger transportation accounts for approximately 65% of energy consumption in transportation activities, with private cars being the dominant mode (Rodrigue, 2020; IEA, 2022b). Improvements in fuel efficiency have been substantial since the 1970s, but private cars still contribute significantly to energy consumption. Freight transportation accounts for about 35% of energy consumption, with rail transportation dominating this sector (IEA, 2022b).

The energy consumption and environmental impact of the transportation sector emphasize the need for effective policies and infrastructure development to address mobility issues.

# 3 Literature Review

In this chapter various definitions of transportation and energy poverty are provided, highlighting their differences. Due to the absence of indicators for transportation poverty, existing mobility indicators are studied for potential future use.

## 3.1 Poverty Definitions

### 3.1.1 Energy and Fuel Poverty

In the previous chapter, the general energy situation in the world was considered, which is especially unstable in recent years of the pandemic and global conflicts. We also saw the close relationship of economic volatility and price increases with the state of the market for fossil fuels, especially unpredictable in the last few years, and, in addition, looked at how the transport sector affects the economy and energy use – as transportation is one of the main consumers of primary energy around the world.

This chapter is dedicated to the demonstration of impact of the above factors on the population, especially on sensitive social groups. The term “energy poverty” is now widely used to distinguish them.

Energy poverty emerged as a distinct concept in the 1990s, primarily in developed countries, where it was initially known as "fuel poverty". The most sources combine these definitions and count them as the same, naming “Boardman’s 10% of income” principle as starting point for Energy poverty concept development (Taltavull de La Paz et al., 2022).

Generally, energy poverty (EP) usually refers to a situation where individuals or households are unable to afford an adequate access to energy services, such as heating, cooling, lighting, and cooking.

Energy poverty sometimes confused with the fuel poverty and, as we will see, it can be with some assumptions called similar definitions. Fuel poverty was developed earlier, since 1970s (Li et al., 2014), and has a lot in common with definition of energy poverty: the first definition, given by (Boardman, 1991), says that “if a householder needed to spend more than 10% of their income on total household fuel costs to achieve a satisfactory indoor temperature regime then they were classed to be in fuel poverty". UK government (DEFRA, 2001) then established new regulation, introducing standardized temperatures of 21-18 degrees of Celsium in the thresholds. Later in 2011 the "fuel poverty" definition developed at 'low income high cost' (LIHC) measure considering households, where people spend more than median level on fuel costs – so the rest of their income puts them below poverty line (Hills, 2011).

As it could be noticed, the term "fuel poverty" was first used in the United Kingdom in the 1990s to describe households that were unable to afford adequate heating for their homes. The definition of fuel poverty focused on the ability of households to pay for heating and cooling costs and maintain a comfortable temperature in their homes. Over time, the concept of fuel poverty has evolved into a more comprehensive understanding of energy poverty. Although, some experts find definitions of Energy and Fuel poverty overlapping but not mutually inclusive (Figure 2):

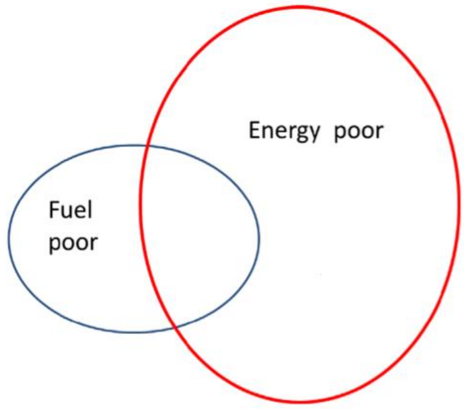


Figure 2. The categories of energy poor and fuel poor. Source: (Li et al., 2014).

Energy poverty is now recognized as a multidimensional issue that encompasses not only the inability to pay for energy services but also inadequate access to modern energy services, such as electricity, commercial energy and clean cooking fuels (IEA, 2002; IEA, 2010). The IEA also developed the Energy Development Index (EDI): a gauge of a nation's advancement in contemporary fuel and contemporary energy amenities.

The concept of "energy poverty" has extended beyond the United Kingdom, finding application in other countries such as the United States and Canada. One of the most recent definitions of energy poverty was given by (Bouzarovski, 2018): "when a household is unable to ensure a sufficient level and quality of domestic energy services for its social and material needs".

The consequences of energy poverty can be severe, including adverse health outcomes, reduced quality of life, and increased social and economic inequality (Castaño-Rosa, Solís-Guzmán and Marrero, 2020; Dong, Dou and Jiang, 2022; Drago and Gatto, 2023). Energy poverty disproportionately affects vulnerable populations, including low-income households, the elderly, and those living in substandard housing (Aristondo and Onaindia, 2018; Heredia et al., 2022).

Efforts to address energy poverty include improving energy efficiency in homes and buildings, providing financial assistance for energy bills, and expanding access to modern energy services. The United Nations' Sustainable Development Goals include a target to ensure access to affordable, reliable, sustainable, and modern energy for all, recognizing the importance of energy access as a key component of global development (United Nations, 2022).

### 3.1.2 Transport Poverty

It is evident that the definition of energy poverty has evolved from a specific issue concerning the lack of heating to the problem of social injustice and common access to energy service, aiming to eliminate social exclusion. Almost same time there was given a start of studies for a problematics of mobility exclusion of society and financial burden it puts on the households.

Since 1990s, several studies dedicated to transport disadvantage problems can be found. For example, (Nutley and Thomas, 1995) have considered the conception of “transport-poor” or “transport-induced deprivation” as “deprivation not necessarily through poverty, but through not having the transport resources to overcome the distance barrier between them and the locations of the various social and economic opportunities which would otherwise be available”. It’s also interesting that they use the term “transport-poor” long before it became commonly used in the literature.

Next references to transport poverty and travel poverty appear in papers like (Wickham and Lohan, 1999; TRaC, 2000), where Whickham concentrates more on the social exclusion and car dependency affecting social classes (and touches the topic of income share spent by households on transport), when TraC complex study more general transport planning questions and also starts to mention such aspects as affordability, accessibility and availability.

Some of the studies did not focus on mobility as the main issue, but considered social exclusion in general – including aspects of transport accessibility, such as (Barry, 1998; Denmark, 1998; Burchardt, Le Grand and Piachaud, 1999): that is reflected in their names, which speak mostly of social exclusion or transport disadvantage.

Thus, the problem of transport mainly was studied from the positions of social exclusion and financial burden, which shows there a strong similarity with energy poverty problems.

In this context, it's remarkable that when the concept of energy poverty developed over time, it even paid an attention to transport costs taken by households as a part of energy expenses. For example, (Sovacool et al., 2012) in their work consider mobility as one of the possible broadenings for energy poverty concept as it was important both from financial and social side. But the most part of studies on mobility or transport poverty and lack of mobility developed separately from energy poverty or fuel poverty.

Starting mostly within UK in 1990-2000, around 2010 that studies have become globalized and applied worldwide (Hine, 2009; Currie et al., 2010; Páez et al., 2010). Numerous case studies conducted in various geographical contexts have shown that inadequate access to efficient transportation services can result in social exclusion, which limits opportunities for development and obstructs progress, ultimately affecting overall well-being. Also, during this period the concept of "double energy poverty" has emerged (Mayer et al., 2014).

Speaking about transport poverty it's important to mention one of the most famous names in the field of transport poverty studies - Karen Lucas, who leads numerous studies concerning transport poverty and includes fundamental analysis of state-of-art and policies in this area (Lucas, 2004; Lucas, 2006; Lucas, 2012; Lucas et al., 2018). In the work (Lucas et al., 2016) their collective examines current tendencies and provides categorization of aspects for transport poverty, which formed the basis for the definition presented later on the website of the European Parliament.

### 3.1.3 Aspects of Transport Poverty

In October 2022 European Parliament released an article generalised the concept of "transport poverty" for the Members and staff of the European Parliament as background material to assist them in their parliamentary work (Kiss, 2022). It stands the definition of transport poverty as "the situations when people do not have access to essential services or work because of a lack of affordable or available transport options. […] In a broader perspective, transport poverty can also refer to individuals or households who do have access to affordable transport options, however, since transport represents an important share of their budget (10 % or more), they are therefore sensitive to increases in transport price”.

Transport poverty can manifest itself in various forms, including a lack of transport availability, poor accessibility, unaffordable prices, time poverty, and inadequate transport conditions.

Mobility poverty, also known as availability poverty, refers to a situation in which a person or household cannot access specific means of transport due to a lack of transportation options. This may occur when individuals do not have access to a private vehicle, or when public transportation options are limited or not available in their area. With the reference on (Moore, 2013), (Lucas et al., 2016) provides the definition of mobility poverty as:

*“A systemic lack of (usually motorised) transport that generates difficulties in moving, often (but not always) connected to a lack of services or infrastructures”.*

Poor accessibility to transport can occur when a person (or household) finds it difficult to access locations where goods and services, such as employment, health, education, or essential shopping, are located. This question was studied, for example, in (DfT, 2014). In particular cases, poor accessibility also creates significant challenges for individuals who require specialized transportation services due to age, disability, or other circumstances (for example, a lack of wheelchair accessibility in public transportation can prevent mobility of individuals with mobility impairments). This can be due to a lack of transportation options or inadequate transportation infrastructure, which can affect not only individuals with disabilities but also others who may face barriers to accessing essential services. Lack of accessibility can lead to social exclusion, as individuals are unable to fully participate in their communities or access opportunities that are available to others.

Unaffordable transport costs or low transport affordability can force individuals or households to spend a large portion of their income on transportation. This can be also applied to those who can’t meet the cost of transport.

(Lucas et al., 2016) provides next definition, based on previous studies of (Estupinan et al., 2007) and others:

*“The lack of individual/household resources to afford transportation options, typically with reference to the car (in developed countries) and/or public transport”.*

Low affordability fully includes definition of transport energy poverty as household’ transport expenses – which would be discussed below.

Time poverty or too much time spent traveling can occur when individuals have limited or unreliable transport options, leading to long travel times and limited time for other activities, such as work or family obligations.

Exposure to transport externalities means inadequate transport conditions when available transport options are unsafe or unreliable.

*“The outcomes of disproportionate exposures to the negative effects of the transport system, such as road traffic casualties and chronic diseases and deaths from traffic related pollution. Often considered within the US literature from an environmental justice perspective”* – how describes that element (Lucas et al., 2016) with links on (Barter, 1999) and chapter “Adverse impacts of transport on rural livelihoods” by (Booth, 2000).

In this manner, if at least one of those conditions is applicable, individuals or households can be identified as "transport poor."

### 3.1.4 Transport Energy Poverty. Double Energy Poverty

As it was mentioned above, over the years, some scientists included transport expenses inside the definition of energy – or fuel  poverty. One of the reasons is that transport consumption of energy (so the expenses of households) takes a great part of total household energy consumption, so it should be considered all together with domestic spends (Robinson and Mattioli, 2020). Another factor is that both transport poverty and energy poverty can be identified in the same households pretty often, as they mostly hit the most vulnerable groups of population. Also it can be noted that ecological transition to more green sources of energy will affect both transport and domestic energy use (Simcock et al., 2021).

After analysing those problems, it also can be said, that the most similarity and – the possibilities to consider two problems together – can be performed with one particular area of transport poverty problem: transport energy poverty. Transport energy poverty is closely linked to domestic energy poverty. Both types of energy poverty are connected with income inequality and have negative impacts on health, education, and economic opportunities. That's why they have the greatest potential to be considered together as double energy poverty.

This topic got its popularity recent years and it was widely studied by (Sanz, 2022). In her study we can find the following definition of transport energy poverty, taken from the work of (Mattioli, 2019):

*"A situation in which a person (or household) spends more than twice the median expenditure relative to income on fuels to meet their motorised mobility needs".*

From the same study, it is worth noting that transport energy poverty should be regarded as a component of transport affordability, which is a part of the broader issue of transport poverty. This way the definition of transport poverty has much broader perspective, than just transport energy poverty,as it gathers the general problem of social mobility and inclusion.

Turning back to the transport energy poverty (TEP), it can be said that TEP is mostly connected with financial burden of transportation. But it's important to notice that from the definition of TEP individuals or households can experience transport energy poverty even when they can cover all the costs within their budget. TEP can occur when transport costs represent a significant portion of their income, making households sensitive to increases in transportation prices.

The high cost of fuel can create a vicious cycle, where households that are already struggling to make ends meet are forced to purchase cheaper, but less efficient fuels, which can further increase their energy bills. Additionally, households that rely on older, less fuel-efficient vehicles may face higher fuel costs, making it difficult for them to maintain their vehicles or upgrade to more efficient models.

Considering this topic, it's necessary to mention that fuel transport needs usually are more fluctuating than domestic energy needs. While households may be able to adjust their energy consumption to some extent by reducing their heating or lighting, transportation needs are typically more inflexible, particularly for those who rely on personal vehicles for commuting or other essential trips.

As a result, when fuel prices rise, transport expenses tend to increase more rapidly than domestic energy expenses. This can have a significant impact on low-income households, who may already be struggling to afford basic transportation needs.

Overall, addressing fuel expenses is an important aspect of addressing both domestic energy poverty and transport energy poverty. This may involve policies and programs to improve energy efficiency, promote the use of renewable energy sources, and support low-income households in accessing affordable and reliable energy services, improving public transportation infrastructure, promoting active transportation options like walking and cycling, and supporting the adoption of electric and other low-emission vehicles. That's why discussing both problems simultaneously – as double energy poverty - has great potential.

Based on abovementioned studies of (Robinson and Mattioli, 2020; Simcock et al., 2021), (Sanz, 2022) defines double energy poverty as "a situation in which a person (or household) is simultaneously in domestic energy poverty and transport energy poverty". This way, such a factors as distance to work, travel time, local accessibility, accessible means and modes of transport and other compositions of Transport poverty problem stay out of scope while considering Double Energy Poverty (RQ3).

### 3.1.5 Double Energy and Transport Poverty

For current moment, studying Transport poverty in correspondence with Energy poverty remained uncovered topic. But exploring only in the field of energy – or double energy – poverty is not sufficient. Mobility problems can have significant impacts on an individual's and households social, economic, and health outcomes, and they affect the most vulnerable social groups together with energy poverty (Simcock et al., 2021).

For households that experience transport poverty but have sufficient incomes for the moment, the rising costs of transportation can lead to the growth of household's direct expenses for it. This can result in a situation where households are forced to allocate a disproportionate amount of their income towards transportation expenses, limiting their ability to invest in other essential needs - such as housing, education, and healthcare. It also can provoke energy poverty as a reaction, if households won't be able to spend their previous share of incomes on the domestic needs, while ensuing mobility.

Moreover, households, that are experiencing transport poverty and, in contrast to the previous example, are already too poor to fully cover transportation costs, may find themselves unable to afford the mobility, necessary to access employment opportunities, healthcare, education, and other essential services. In this situation, for example, if persons cannot afford transportation to work, they may be unable to earn an income – what would limit their ability to afford other essential expenses.

In this way, transport poverty can create a cycle of poverty that is difficult to escape, resulting in a general reduction in income and quality of life and leading to a severe circle of poverty and exclusion. Same way energy poverty can force people to spend less on their mobility, which can lead to the situation of double poverty.

When a household is facing double poverty, they are often forced to allocate a significant portion of income towards meeting their basic needs, leaving them with little disposable income to invest in other essential needs, such as healthcare, education, and housing. Double poverty often sets off a downward cycle, creating limited opportunities for upward mobility, as individuals lack access to transportation mobility, hindering their ability to earn sufficient income to meet regular household expenses.

Double poverty can have significant implications for the health and well-being of households, as well as broader social and economic outcomes. For example, households facing double poverty may experience greater health risks due to exposure to extreme temperatures and limited access to healthcare.

Thus, both energy and transport poverty can exacerbate social inequality by disproportionately affecting marginalized groups such as low-income households, older adults, women, people with disabilities, marginalized groups, and those living in rural or remote areas.

Therefore it is necessary to study transport poverty - that address the multiple dimensions of transportation disadvantage, including mobility poverty, accessibility, affordability, time poverty, and inadequate transport conditions - along with energy poverty to develop comprehensive policies and interventions (RQ2). By doing so, policymakers can promote social inclusion, economic mobility, and quality of life for all individuals and communities.

In addition, it may be useful to conceptualize double poverty as a form of “local living-externalities” burden, reflecting the social, economic, and environmental costs associated with spatial features of household. By framing double poverty in this way, policymakers can more effectively communicate the geographical dependence of addressing this issue and mobilize resources to develop effective solutions to this critical challenge.

## 3.2 Indicators of Transport Poverty

The aim of this chapter is to explore various indicators and classification sets to select the most appropriate ones for assessing and understanding transport poverty in the research context (RQ4). These indicators will contribute to a comprehensive evaluation of the mobility situation and facilitate the development of effective strategies for addressing transport poverty in urban areas.

In terms of indicators, the issue of transport poverty has not been sufficiently explored. There is a lack of well-established indicator sets specifically addressing transport poverty, except for the aspect of transport expenditure. However, a considerable amount of research has focused on studying and identifying indicators related to mobility. Primarily, this thesis considers the indicators developed at the inter-city scale, but there are also indicators created for national and regional levels.

It is important to note that there is no universally accepted system for creating indicators. There is a wide range of indicators available, including indexes as *Composite Accessibility Index (Curtis, 2019) or Sustainable Urban Transport Index (Regmi, 2021)* and sets designed for multidimensional assessment, some of which may be narrowly specialized, —such as those grounded in GPS-derived data (Fillekes *et al.*, 2019) —are extant.

Many of the mobility indicators are associated with the issue of sustainable development and reflect the effectivity of present mobility level in enhancing overal urban sustainability. But even among these classification frameworks, there are variations. Several examples are considered below.

For example, a study (Gillis, Semanjski and Lauwers, 2015) identifies distinct categories of mobility indicators, including Global Environment, Economic Success, Quality of Life, and Mobility System Performance.

The study (Sharifi and Khavarian-Garmsir, 2023) identifies and evaluates indicators not only based on their specific groupings but also in terms of their potential linkages to resilience abilities: Planning, Absorption, Recovery, and Adaptation.

The work "Key Transportation Indicators: Summary of a Workshop 2002" (Council, 2002) examines transportation safety indicators, mobility indicators, and transportation indicators of economic growth. Specifically, in the area of mobility indicators, they assert that "*the most commonly cited measures fall into six major categories: congestion-related measures (such as level of service, volume/capacity, and delay), trip time, amount of travel (vehicle miles traveled, vehicle hours traveled), mode share, transfer time, and transit performance*".

Considering the scope of our research, it is necessary to review existing European studies.

"Urban Mobility Indicators for Walking and Public Transport" (UITP, 2019) presents indicators in a tiered approach. Tier 1 measures establish a broad framework for internationally comparable benchmarking across the four topic areas. Tier 2 measures provide supplementary information to enhance the measurement of these four areas. Tier 3 measures encompass a comprehensive set of 33 factors that enable a deeper understanding of patterns within the core topic areas.

All indicators of that review can be groupped into the following component factors: service demand, connecting destinations, support and encouragement, comfort and safety.

Furthermore, the European Commission has created a set of practical and reliable "Sustainable Urban Mobility indicators" (SUMI) that aid cities in conducting standardized evaluations of their mobility systems and assessing the impact of new mobility practices or policies. These indicators ensure consistency and reliability in measuring improvements over time (Consult, 2017).

These indicators encompass both "core" and "optional" components. Interesting aspect is that among proposed mobility indicators, one can observe indicators related to environmental pollution and quality of life (Indicator 3: Air pollutant emissions, Greenhouse gas emissions, Noise hindrance), as well as indicators dedicated to the development of urban environments within walking distance (Indicator 14: Quality of public spaces).

Also to promote the development of European cities, the CleanCities assessment program was launched (Barbara Stoll and Matteo Giaconi, 2022). A set of five categories (*Space* *for people, Safe roads, Access to climate-friendly mobility, Policies, Clean air*), collecting a total of 11 indicators, was selected. The categories range from urban space, road safety, and public transport to electric vehicle charging infrastructure, as well as policies such as low and zero emission zones and air quality. The performance of cities has been benchmarked against official or widely accepted references, such as the World Health Organization air quality guidelines and the EU's "Vision Zero" for road safety. In cases where such references do not exist, a "best in class" approach has been adopted.

For the purpose of our research, it is necessary to identify the most convenient and indicative indicators capable of reflecting the situation in the domain of transport poverty and vulnerability, primarily in the public transport sector. Among the listed indicators, we have chosen a larger group of indicators called “Sustainable Urban Mobility Indicators” (SUMI), which closely aligns with the issue of transport poverty, and we will also utilize the indicator proposed in the CleanCities program: “Access to public transport”. The selection of indicators will be further discussed in the Methodology chapter (RQ5).

# 4 METHODOLOGY

In this section a methodology is proposed to evaluate transport and energy poverty in the municipality of Madrid, which can also be extrapolated to other European cities with sufficiently detailed data. This comprehensive approach involves selecting indicators and creating maps to assess poverty levels. The chapter begins by presenting the main characteristics of the case study and data sources. Indicators for transport poverty are chosen based on five key aspects, with each aspect represented by a single indicator. Open data sources are utilized, and individual maps are generated for each indicator. These maps are then combined into a unified map that represents transport poverty in Madrid.

Additionally, the methodology incorporates an assessment of energy poverty using an existing classification and the "Habita_RES" project map. By combining the transport and energy poverty maps, a holistic understanding of poverty in relation to transportation and energy is obtained. The methodology's strength lies in its ability to consider multiple indicators and leverage open data sources, enabling researchers and practitioners to assess and compare levels of transport and energy poverty across European cities. The resulting spatial visualization of poverty levels facilitates the identification of areas requiring intervention, supporting targeted efforts to address the complex issue of poverty in the context of transport and energy.

## 4.1 Case Study and Data Sources

The scope of this research is centered on the city of Madrid, a major capital city with a notable public transport system recognized for its outstanding attributes. The system is characterized by its efficiency, speed, safety, cleanliness, and reliability. Even despite the fact that in comparison to other European cities, satisfaction by Madrid's public transport network can’t be considered as the best one (Union, 2016), it still stands out for its affordability (Fiorio, Florio and Perucca, 2011) and, due to the unification of all transportation companies under a single regulatory agency “Regional Consortium of Transportation for Madrid” (CRTM), simplicity of usage. The comprehensive public transport system encompasses various modes of transportation, including the regional train system, known as "Cercanías," efficiently connects Madrid with its surrounding regions, ensuring seamless transportation services for commuters, or the Madrid Metro, which comprises underground lines, as well as an extensive fleet of day and night buses. Additionally, the city benefits from the "Metro Ligero," a modern light rail system.

However, many urban planning decisions are based on existing road systems, which sometimes require transfers or inefficient routes. Nevertheless, a significant factor contributing to the favorable ratings of public transport by users is that the city's transportation network operates under a unified authority, the CRTM (Consorcio Regional de Transportes de Madrid), which facilitates the resolution of significant issues when they arise. Also, complex monthly passes are available for usage on all the public transport in the correspondent city zones.

Nonetheless, it is not possible to distribute equally the benefits among the population. It can be assumed that certain neighborhoods in Madrid will always have lower transport accessibility compared to more affluent areas. Moreover, previous studies have shown that the energy efficiency and vulnerability of households in the city vary significantly depending on factors such as the year of construction, orientation, proximity to "heat islands," household income, heating type, and various other characteristics.

Therefore, Madrid presents an intriguing choice for studying the peculiarities of the distribution of transport and energy poverty within the city, especially on a lower scale. For this thesis, neighborhood (*"barrio"*) scale was chosen as the most appropriate. This is connected first with scale of an existing mapping of Madrid's energy vulnerable zones, and second – this scale is accessible for all the open data which was located in open access. The shape-file with borders of *barrios* and *secciones censales* was obtained from (Madrid, 2019).

For this master's thesis, primary reliance was placed upon open sources of information, including CRTM (CRTM, 2023), INE (INE, 2023), Portal web del Ayuntamiento de Madrid (Madrid, 2023b), OSM (Contributors, 2018), and Comunidad de Madrid (Madrid, 2023a). Additionally, for insights into energy poverty, data from the "Habita_res" project was utilized ((IETcc), 2017). The "Habita_res" analyzes the current state of vulnerable areas in Madrid and proposes intervention criteria to improve health, housing suitability, and energy efficiency. These diverse and reputable sources contribute to the robustness and reliability of the research findings.

## 4.2 Derivation of transport poverty indicators

To determine the indicators suitable for assessment of transport poverty (RQ6), a complex analysis was conducted on the mobility indicators found in terms of their applicability to each of the five aspects of transport poverty. The SUMI set yielded the most share of suitable indicators. Additionally, the CleanCities indicator and self-created indicators were also selected for future work. Next, the indicators were ranked in order of interest for use, taking into account technical and time constraints, as well as potential availability of information (Table 1). The calculation and discussion for indicators' choice will be introduced for each aspect (limiting condition) of transport poverty.

| Limiting condition: | Affordability | Accessibility | Availability (frequency) | Time Spend | Safety |
|---|---|---|---|---|---|
| Indicators ranking: 1) | Share 10% of transport expences of the household [P] | Access to public transport CleanCities [C] | Access to mobility services indicator (provides frequency) [S] | Commuting travel time (Survery) [S] | Road deaths indicator [S] |
| 2) | Affordability of public transport for the poorest group (monthly pass) [S] | Access to mobility services [S] | Availiability of transport (per mode) [P] | Congestion and delays indicator [S] | Security Indicator [S] |
| 3) | Potential poverty (10 trips/week) [P] | Accessibility of PT stops[P] | | | Satisfaction with public transport indicator [S] |
| 4) | | Access for mobility-impaired groups [S] | | | Traffic safety active modes indicator [S] |

Table 1. Ranking of indicators of transport poverty by 5 aspects for Madrid project by their suitability. [P] Personal Proposal, [S] SUMI, [C] CleanCities indicator.

### 4.2.1 Affordability

For the "Affordability" aspect, the indicator "Household expenditure on transportation exceeding 10%" was deemed the most suitable. However, during the process, sufficiently detailed data at the required scale could not be found. Therefore, the next indicator on the list, "Affordability of public transport for the poorest group (monthly pass)," was used instead. This indicator is also favorable as it relates better to potential expenses on public transport, demonstrating its affordability: since this research primarily focuses on issues related to public transportation, the selection of indicators prioritizes aspects relevant to public transport.

The indicator "Affordability of public transport for the poorest group" is part of the SUMI group of indicators. This particular indicator measures the share of the poorest quartile of the population's household budget that is required to purchase public transport passes (unlimited monthly travel or equivalent) in their urban area of residence. The calculation is performed using the following formula:

*Score = (Price monthly PT pass * average household size) / income of the 25% poorest residents of the urban area*

To calculate this indicator, the following information is needed: Monthly PT price, Household size, and Monthly income for the poorest 25% of the population.

However, in the case of Madrid, data on income for the lower quartile of the population was not available in open access. Therefore, in this study, the indicator was modified. Average income data by neighborhood, obtained from the Madrid City Council website, were used and divided in half to approximate the income of the poor population in each neighborhood (for future research, it is recommended to use original indicators based on their respective methodologies whenever possible).

Data on median income by neighborhood (obtained from the Web portal of Madrid City Council (Madrid, 2023b)) were used and then divided in half to approximate the income of the poor population in each neighborhood. The data on average income (in euros) were obtained from Urban Audit (Madrid, 2023c) for 2020 ("Average income indicators by District, Neighborhood and Census Section "), as well as data on average household size ("Demographic indicators according to District, Neighborhood and Census Section "). In this context, a household is considered as a house or an apartment and its occupants are regarded as a unit. The household size considers the number of occupants, averaged per *barrio*.

The data on the price of a monthly public transport ticket were taken from the CRTM website.

Before mapping the Affordability indicator, preparatory work was conducted. The average income data for each *barrio* were recalculated for the conditionally poorest population groups in each *barrio*. The average household income was multiplied by a coefficient of 0.5 to obtain half of the average income, which represents the income of the poorest population.

When calculating the indicator, the cost of a monthly pass in pricing Zone A (for all neighborhoods in Madrid except El Goloso, which is located in Zone B) was multiplied by the average household size. Then, it was determined what percentage of the income of poor households would be spent on public transportation. These calculations were also performed for the data on entire city of Madrid (7.6%) to get average for the whole city (Appendix A).

It should be noted that in this study, when calculating the Affordability indicators, there is a simplification assumption that all residents of the Municipality of Madrid travel only within the city boundaries. Also this study is not considering reduced prices for children, students or other social groups. Therefore, we considered the regular pass prices within zones A1 and A2 for the purpose of this research.

As an alternative option for future studies, it was suggested to use a similar indicator when the monthly pass data was not available. In this case, the indicator would consider the cost of a round-trip commute (to work or school) multiplied by the number of working days. This approach would provide an estimate of transportation expenses for the poor households in terms of their daily commuting needs.

### 4.2.2 Accessibility

For the "Accessibility" aspect, the chosen indicator is one of CleanCities (Barbara Stoll and Matteo Giaconi, 2022), which simply reflects the number of public transportation stops within a given zone. To calculate this indicator, the minimum spatial unit is suggested to be utilized. In this case, it involves determining the number of stops per square kilometer in each neighborhood (*barrio*).

To calculate the "Accessibility" indicator, data on the location of public transport stops and the boundaries of neighborhoods are required. To avoid inaccuracies due to the uneven population distribution in Madrid and the presence of large undeveloped areas in some *barrio*s, it was proposed to calculate the number of stops per square kilometer of developed territory within each *barrio*.

The calculation of the indicator was performed in ArcMap. Data from OpenStreetMap (OSM) (Contributors, 2018) was used to obtain information about the stops. The data on stops were downloaded and imported into ArcMap. Then, in the attribute table, only the necessary data classes were manually selected. Categories such as "bus stop," "railway station," "railway halt," "tram stop," and "bus station" were chosen from the geospatial database. In the OSM classification, metro stations are considered as railway stations.

Next, a vector layer of land use for the year 2018 (CLC18 (CORINE, 2018)) with a resolution of 1:100,000 was added. Only urban development classes were retained, including "1.1.1) Continuous urban fabric," "1.1.2) Discontinuous urban fabric," and "1.2.1) Industrial or commercial zones." The "Intersect" and "Spatial Join" tools were used to combine individual development patches within each *barrio* with the corresponding spatial attribute.

Using the "Add spatial join" tool, the number of stops in each *barrio* for built-up territory was calculated. Then, using the “Field calculator”, the values for the number of stops per square kilometer were calculated.

Alternatively, an additional enhancement could be applied by assigning a "weight" to each stop, representing the number of routes passing through that specific location. However, for the sake of simplicity and time efficiency, it was decided to maintain the original indicator without incorporating the weighting system. The data sources for this indicator included OpenStreetMap (OSM) and the Madrid City Council's records regarding the administrative boundaries of the neighborhoods.

Another indicator that could have been used is the Access to Mobility Services (SUMI) indicator. However, within the scope of this accessibility study, it may be overly complex and, despite its name, is more suitable for investigating availability. Therefore, it will be discussed separately later on.

Considering accessibility for mobility-impaired groups from SUMI seems intriguing. However, calculating this indicator requires data on the number of vehicles, stops, ticket sales points, and facilities specifically equipped for individuals with low mobility. Also, that indicator comparatively less informative than CleanCities one, as it can be applied to the part of all the population only.

Another proposed indicator is the "Accessibility of public transport stops," where Thiessen polygons are constructed around each stop to define its influence area. By examining the average area of these "responsibility" polygons, it would be possible to identify vulnerable areas. Alternatively, this indicator could also be represented by point density, allowing for the adjustment of the "weight" assigned to each stop to account for the number of departures or routes. Additionally, there was a suggestion to investigate the number of stops within walking distance of each household. However, at the neighborhood (*bar-rio*) level, this approach may be inefficient as the size of neighborhoods can exceed the walking distance radius.

### 4.2.3 Availability

For the "Availability" indicator, the Access to Mobility Services indicator was used as it effectively captures not only the geographic accessibility but mostly the frequency of arrivals – this way it determines number of vehicles availiable.

Official description of that SMI indicators is given as: *“Share of population with appropriate access to mobility services (public transport)”*.

In short, to calculate this indicator, data on the locations of stops and average departures during working hours are required (6:00-20:00, Monday-Friday). Next, the zones of walking radius from each stop should be determined. Using the following classification (Table 2), the accessibility of transportation is assessed. For the calculation only straight-line distance is considered, not street walking time.

| | | | **Metro and train** | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | **distance**** | <=833 m (10 minutes walking) | | | >833 m | | |
| | **distance** | **frequency* (departures/ hour)** | >=10 | >=4 and < 10 | < 4 | >=10 | >=4 and < 10 | < 4 |
| **Bus and tram** | <=417 m (5 min walk) | >=10 | Very High access | High access | High access | High access | High access | High access |
| | | >=4 and < 10 | High access | Medium access | Medium access | Medium access | Medium access | Medium access |
| | | < 4 | High access | Medium access | Low access | Low access | Low access | Low access |
| | >417 m | >=10 | High access | Medium access | Low access | No access | No access | No access |
| | | >=4 and < 10 | High access | Medium access | Low access | No access | No access | No access |
| | | < 4 | High access | Medium access | Low access | No access | No access | No access |

Table 2. Typology zones on the basis of service frequences and distance from PT stops. (Consult, 2017).

Additionally, an adjustment is made based on the population of each neighborhood. This adjustment accounts for the fact that even with average accessibility, high population density (more than 100 000 people per neighborhood) may still result in insufficient mobility if the number of transportation vehicles is limited. Ultimately, this process produces a map with the classification of neighborhoods based on their level of availability.

So for calculation of that indicator, dataset needed is: "Location of PT stops, Number of departures per hour, Population size". For greater accuracy and alignment with reality, calculations were conducted considering only the built-up areas to eliminate unpopulated areas of neighborhoods. To achieve this, the built-up zones from the CLC18 data were used, following the same approach as in the Accessibility indicator.

Availability indiicator required extensive work for its calculation. Firstly, data from City Council (Ayuntamiento, 2023c) regarding the number of bus departures for each bus line within the city during March 2023 were collected and processed. Through consolidation, the average number of departures per hour (during working hours) was calculated for each bus line. The data on bus stops and lines were obtained from the official website CRTM (CRTM, 2023) and it was taken with buffer of 833 m (see Accessibility indicator) around Madrid – as some citizens of Madrid would use nearest stop even if it's not inside of the municipality (Figure 3). Additionally, they were compared with OSM data. The data for each bus stop was converted to Excel format. For EMT buses, the VLOOKUP function was used to sequentially add line numbers for each stop, and the number of departures was summed accordingly.

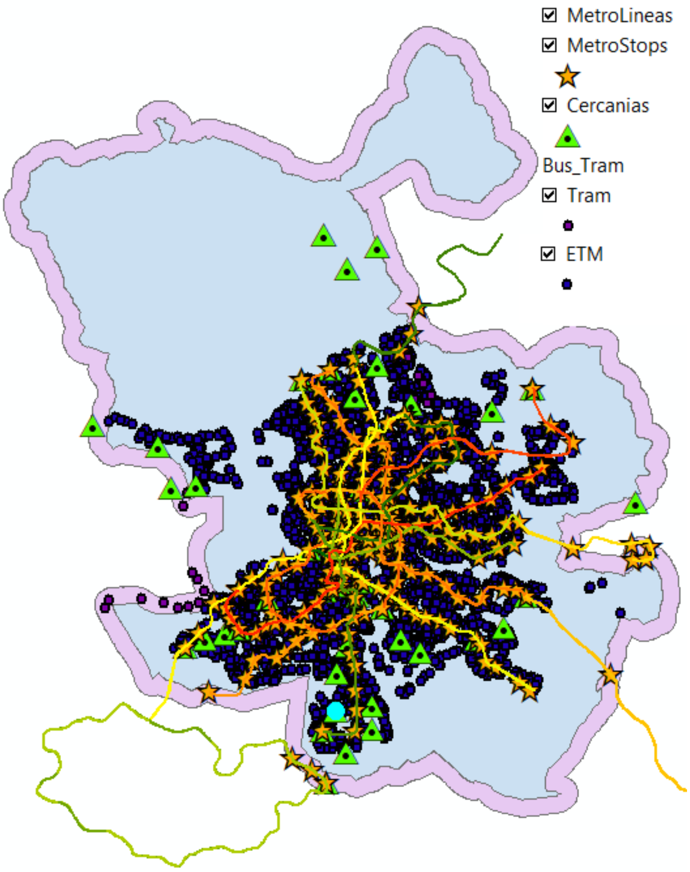


Figure 3. Net of Public transport stops of Madrid (except interurban buses).

Next, the average train intervals for the metro, trams, and suburban trains (Cercanías) were manually calculated, and similarly, the average number of departures per hour was calculated for each station. Schedule data was obtained from the website of Madrid Metro (Metro, 2023) for the metro and trams, and Renfe (oficial railroad provider) (Renfe, 2023) and Moovit maps website (Moovit, 2023) for suburban trains. As a result, the sum of departures per hour was calculated for each stop.

Unfortunately, it was not possible to include the bus stops for intercity buses in the study, which connect some remote areas of Madrid with the city center. The schedule for each of these stops depends on the season and is not necessarily tied to a specific line, as many buses pass through the stops at certain hours. Additionally, the task is complicated by the large number of additional routes that reflect minor differences between them, so creating a departure table for each stop would require extensive and meticulous manual work for individual verification.

Calculation after that point was processed in ArcMap and it directly maps the territory of Madrid for classes of availability. For that reason the detailed description of further work on map and classification process is presented in subchapter "4.3 Mapping process: 4.3.1 Mapping of indicators”.

It was also proposed to calculate the "Availability of transport (per mode)" indicator, which represents the average number of public transport vehicles per population for each neighborhood (*barrio*). To calculate this indicator, it would be necessary to determine the average number of vehicles that cross or are located within the *barrio* during a typical working hour. However, this method is quite labor-intensive and, additionally, has not been tested as it is a self-developed approach. Therefore, it was decided to refrain from using this method.

### 4.2.4 Time Spend

The information about the time spent on commuting is calculated using the "Commuting travel time" indicator SUMI, based just on a survey questions. It describes “Duration of commute to and from work or an educational establishment, using any types of modes”.

For calculation of this indicator, data on time spend in daily travels is required. In case of Madrid, by utilizing the survey results from the CRTM survey 2018 (CRTM, 2018), it was determined how much time residents of different *barrio*s spend on their daily travels.

For the calculation of that indicator, tables of surveys for 2018 “HOGARES (households)”, “VIAJES (trips)” were used.

The file “HOGARES” provides an information about location of households within CTRM classification units. “VIAJES” contains an information about trips of respondents, their households, and describes frequency of such a trips and time/place of trip’s departure and arrival.

For locating the households within *barrio*s, ZT1259 file (EDM2018, 2018) containing the unit boundaries used by CRTM (transport zones) was utilized. These units are almost entirely within the boundaries of neighborhoods of the Municipality of Madrid, but they represent smaller subdivisions that resemble cadastral sections (Figure 4).

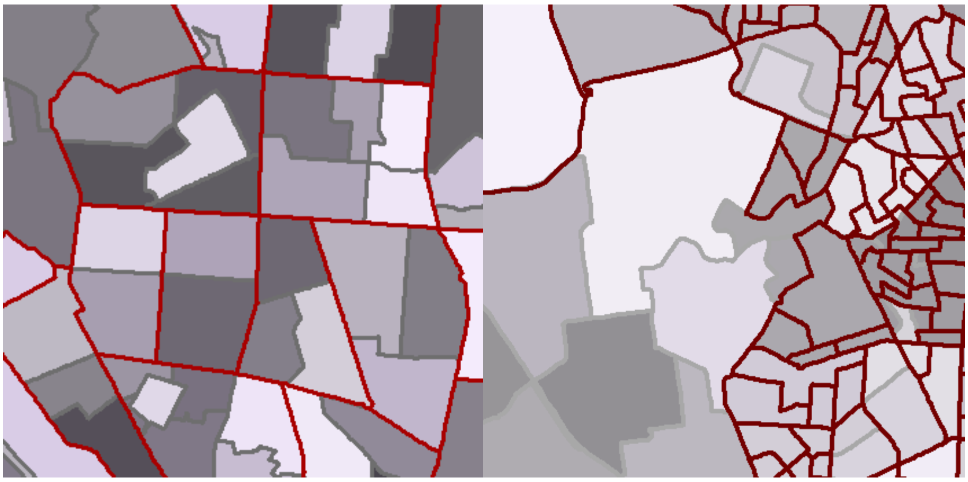

Figure 4. ZT1259 (gray shading) in comparison with neighborhoods (red borders) (left), and with census sections (red borders) (right).

Additionally, the household surveys were conducted specifically for working hours during the workweek, which is highly convenient for the aim of choosing indicator calculation.

The ZT1259 file was cropped to the boundaries of Madrid, and then extensive manual work was performed to add the corresponding *barrio* numbers to each transportation zone. In cases where there was ambiguity, the zone was assigned to the *barrio* if the majority of the zone was located within its boundaries. Since the disputed zones were relatively small in size, the impact of any data inaccuracies resulting from this division was deemed minimal.

Next, a pivot table was created in Excel that contained the numbers of transport zones and their corresponding *barrio*s. Using the VLOOKUP function and table of *barrio*s' and transport zones' numbers, each registered household from the CRTM "Hogares" table was assigned a *barrio* number. Then, in the "Viajes" table, only the trips made by households from Madrid were selected. Each trip was then calculated to determine the time spent on it in minutes from the data on start and end time of each trip, and the average time in minutes was calculated for each *barrio* with the CONSOLIDATION tool (using Mean value).

The median travel time for a single trip is 25 minutes and 48 seconds, while the maximum time recorded is 37 minutes and 5 seconds.

Additionally, for exploration of time taken within each *barrio*, tables of surveys CRTM "INDIVIDUOS (individuals)", and "ETAPAS (parts of trip)" were also used.

“ETAPAS” provides and information about main transport type used for each trip. Then, “INDIVIDUOS” contains information on each respondent.

Using the VLOOKUP function, each registered household from the CRTM “Hogares” table was assigned a *barrio* number in the tables of “ETAPAS” and “HOGARES”. Then, within *barrio*s, quantities of transport mode used for each trip were calculated. That provided an information about structure of transport usage within neighborhoods. Information on individuals was used to explore situation on one of outstanding trips in *barrio* Zofío and define possible data inconsistency.

The indicator "Congestion and delays indicator" is more complex. It reflects the weighted sum of delays over representative road corridors for private and public transport. However, calculating this indicator requires knowing the share of people traveling with different modes of public transport and cars, the number of car and public transport trips during peak hours on the 10 main road corridors, and the difference in travel time between cars and public transport during peak and off-peak hours. Even if we simplify this indicator and apply it only to public transport, it is extremely challenging to find open data on the number of cars serving the main roads during peak hours.

### 4.2.5 Safety

In order to assess safety, it could be considered to use SUMI indicators based on surveys and residents' perception to assess the satisfaction of the population with public transportation. However, for more precise analysis, the "Road deaths" indicator was opted. That indicator also described at SUMI dataset: “*Road deaths by all transport accidents in the urban area on a yearly basis”*. For it’s calculation it is needed to get the data on “Number of deaths within 30 days after the traffic accident as a corollary of the event per annum caused by urban transport” and “Number of inhabitants”.

For this study, the indicator was modified into “Road accidents number”. It mostly connected with the fact that the available data included information on all accidents, not just fatal ones. This approach is particularly relevant when examining intra-city differences, as even a significant number of minor accidents can influence road safety and people's perception of safety. Therefore, all accidents that occurred on Madrid's roads were analysed to determine the percentage of accidents per population in each *barrio*.

To calculate that parameter, the data from City Council of Madrid (Ayuntamiento, 2023a) on road incidents in Madrid for the year 2022 was used. It is represented as a table with list of all traffic accidents on Madrid's roads. Each accident contents the XY coordinates, that allows to put the locations into the ArcMap and calculate the number of accidents, falling in borders of neighborhoods. The details of mapping and processing are described further in subchapter "4.3 Mapping process: 4.3.1 Mapping of indicators".

## 4.3 Mapping process

During the data processing and mapping of indicators, ArcGIS (ArcMap) software and Microsoft Excel were used, projected coordinate system UTM (N30) was choosen as a reference. Each of the indicators selected for the five aspects of transportation poverty was mapped, the *barrio*s of Madrid were classified with representation within built-up territories of urban, commercial and industrial land (taken from CLC18 (CORINE, 2018)) and then the five aspects were combined into a comprehensive map depicting neighborhood vulnerability to transportation poverty.

As a result, by combining the maps of Transportation Poverty and Energy Poverty, a classification of Double Transportation and Energy Poverty was created (Figure 5).

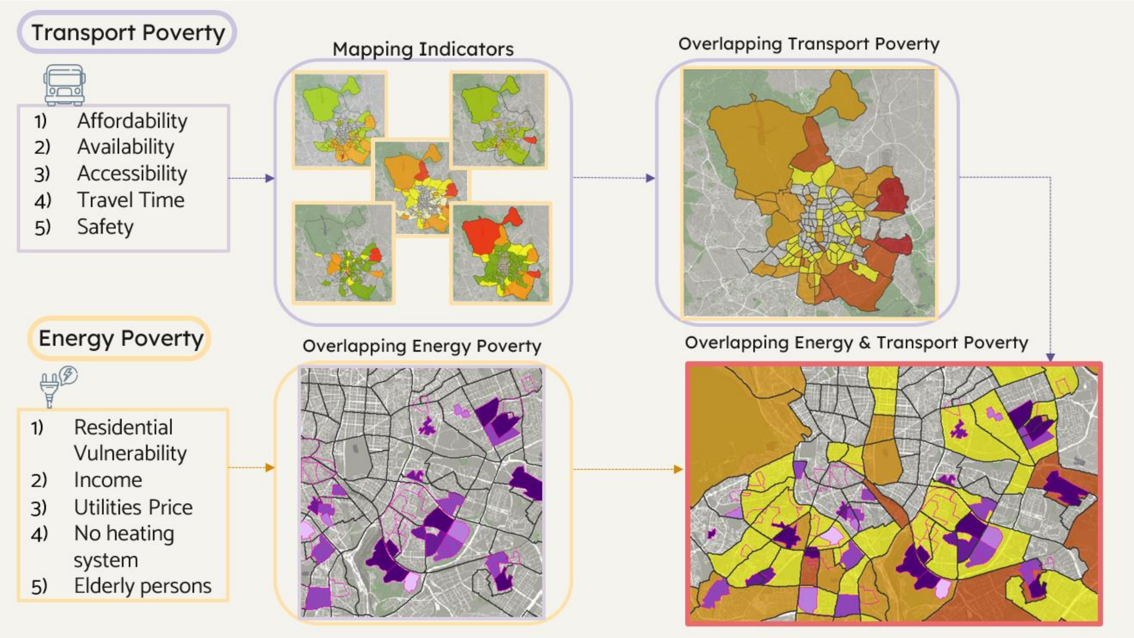


Figure 5. Schematic methodology of processing Double Energy and Transport Poverty map.

### 4.3.1 Mapping of Indicators

During the mapping of the Affordability indicator, preparatory work was conducted. The data from Urban Audit (Madrid, 2023c) for 2020 was calculated in previous subchapter and share for each *barrio* was obtained as a percentage. These calculations were also performed for the entire city of Madrid (7.6%). This value was selected as the threshold for categorizing *barrio*s into those with a better situation than average (Category 1) and those at risk of falling into the vulnerable group due to changes in the economic situation (7.6% - 10%).

The value of 10% expenditure was chosen as the threshold for the existing transport at poverty group, as it is a classic and widely recognized criterion of expenses to be considered as “poor”. The population spending more than 15% is considered to be in severe transportation poverty, as even minor economic changes would not be enough to alleviate their transportation poverty.

To transfer the data from Excel to ArcGIS and associate it with the existing neighborhoods boundaries, a common field was added to the attribute tables of the *barrio* boundary layer and the table containing the calculated percentage values of transportation expenditure. The Excel file was then converted to CSV format and added to the ArcGIS workspace files.

Using the "Join" tool, the information on the "Affordability of public transport for the poorest group" indicator was added to each *barrio*. Subsequently, classification was performed based on the categories described above (Figure 6, Appendix B).

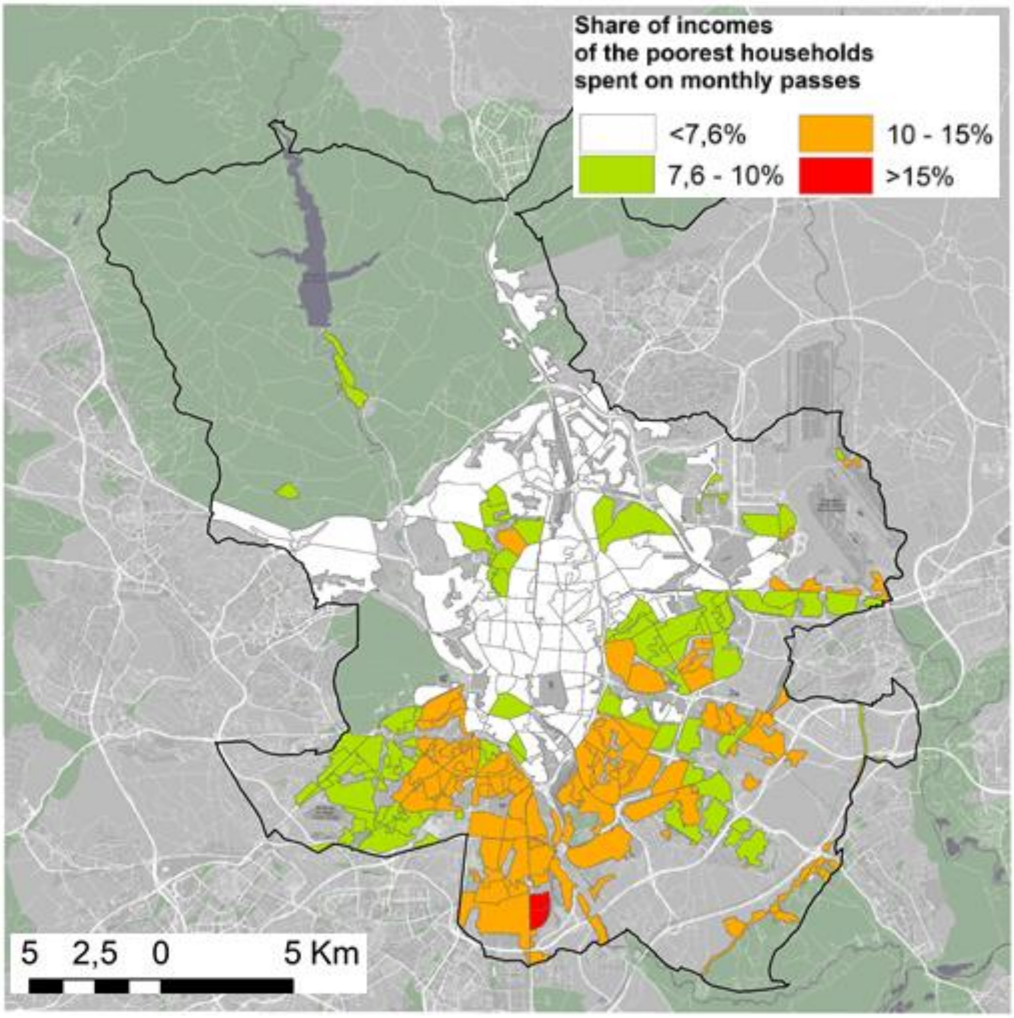


Figure 6. Affordability of public transport for the poorest group in Madrid neighborhoods.

To create the classification for the Safety aspect, data from Ayuntamiento de Madrid on road incidents in Madrid for the year 2022 were used. These data were loaded into ArcMap as points using the "Add XY Coordinate" tool (Figure 7). Then, using the "Add Spatial Join" function, the number of points within or on the boundaries of each *barrio* was calculated. Through the joining operation, the *barrio* boundaries were combined with population data from Urban Audit. The "Calculate Field" tool was used to calculate the ratio of the incident count to the population in each *barrio* (Figure 8, Appendix C).

The median value of the incident rate is 1.33%. Based on this value, it was decided to determine the minimum risk threshold for categorizing *barrio*s into the "relatively safe" group, which represents a low transportation poverty risk. The next category can be considered as "unfavorable" and has a threshold value twice as high as 1.33%. The third category ("unsafe") increases the threshold value almost four times, and the fourth and fifth categories ("highly unsafe") increase proportionally by doubling the previous category. The division into the fourth and fifth groups is necessary for a more detailed analysis of the safety aspect. However, in the further work on the complex classification, the fourth and fifth categories will be combined.

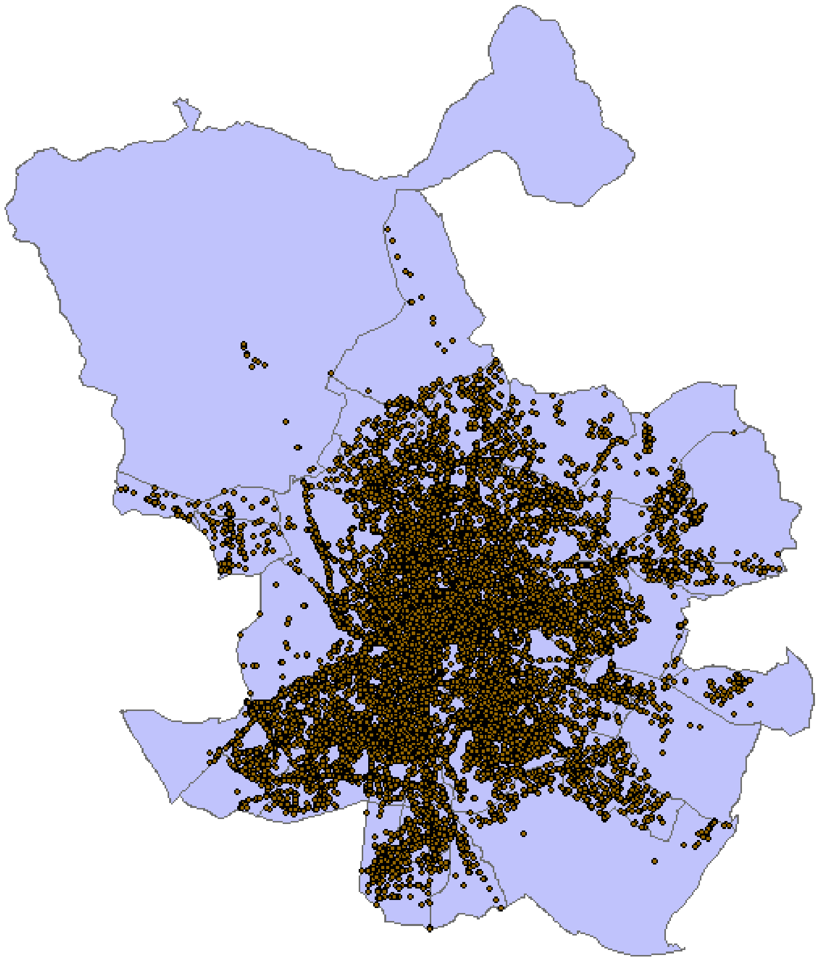

Figure 7. Accidents on the roads in Madrid.

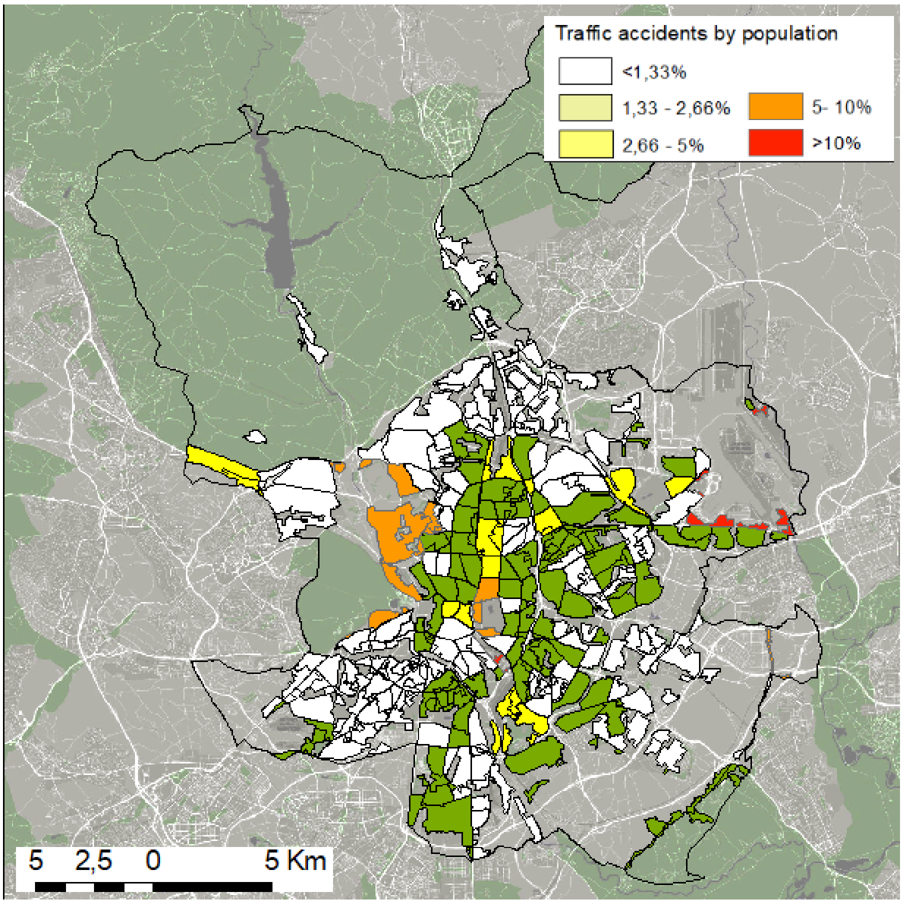


Figure 8. Road Safety rate for each Madrid neighborhood.

Similarly to the previous case, for the creation of the classification of Accessibility the median value of 27 stops/km$^2$ was calculated. In this case, a higher number of stops was considered favorable and indicative of good accessibility (Figure 9). Furthermore, it was decided to examine this indicator in more detail and create four categories to identify negative situations (Figure 10, Appendix D). To simplify the process, the median value was divided into four parts with a step of 7 stops (rounded). In the future, the categories of 8-13 stops and 14-21 stops are planned to be merged into a single category, representing areas with relatively insufficient accessibility for the population. This will allow us to focus on zones with extremely low access to public transport stops.

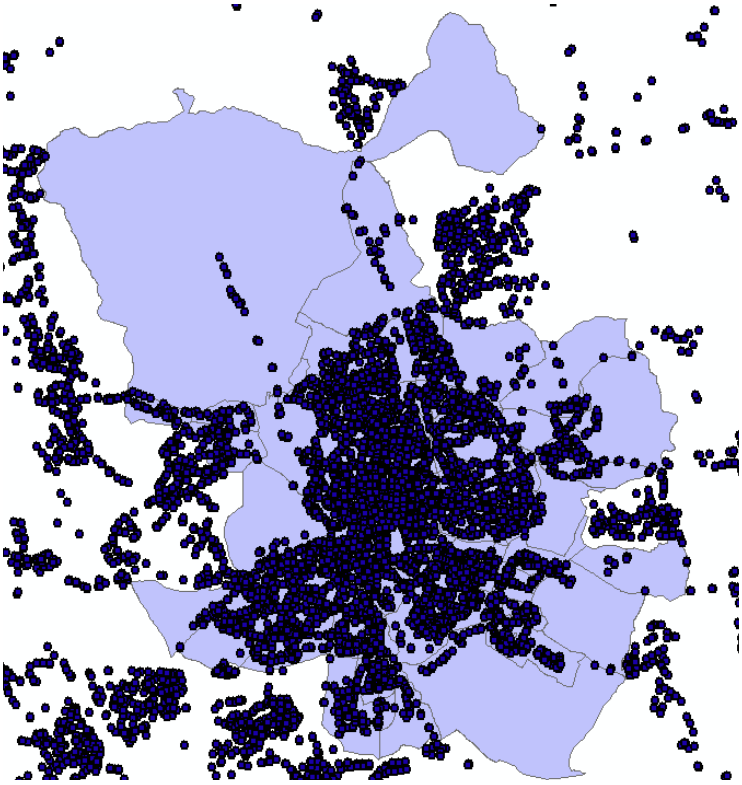

Figure 9. OSM stops data.

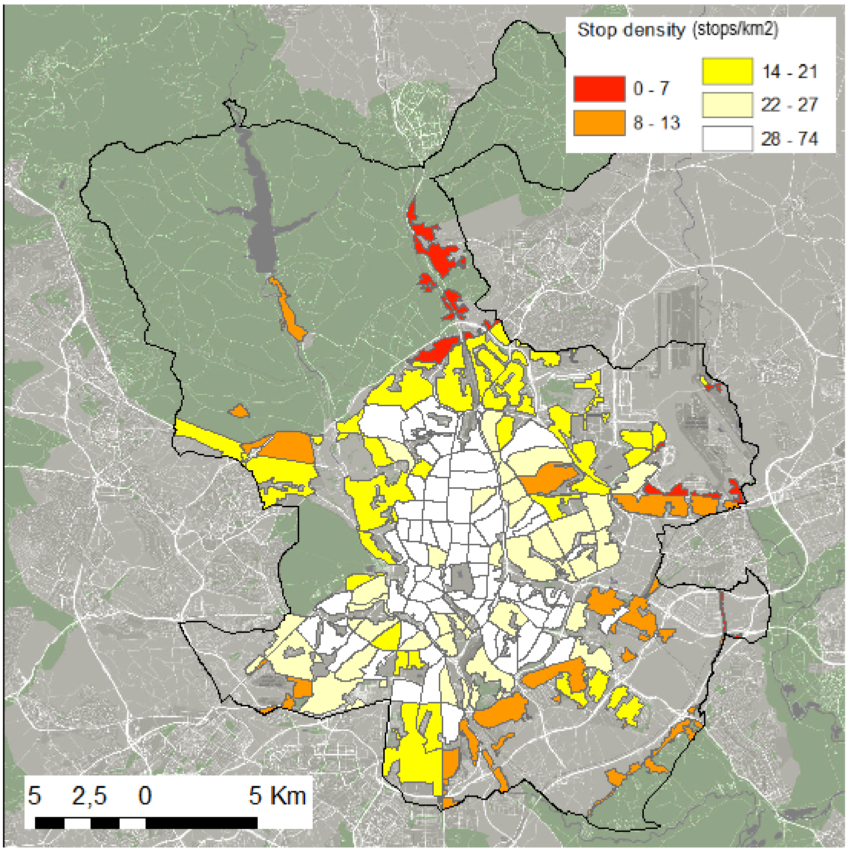


Figure 10. Accessibility map for Madrid neighborhoods.

For mapping the Time spent indicator, the median travel time for a single trip was calculated. It is equal to 25 minutes and 48 seconds, while the maximum time recorded is 37 minutes and 5 seconds. Half of the difference between these values, rounded, determines the lower threshold for the most time-consuming category, which is roundly 31 minutes and 30 seconds. Another threshold is set in the middle of the time range and rounded to 28 minutes and 30 seconds. Therefore, we identify four categories based on travel time (Figure 11, Appendix E).

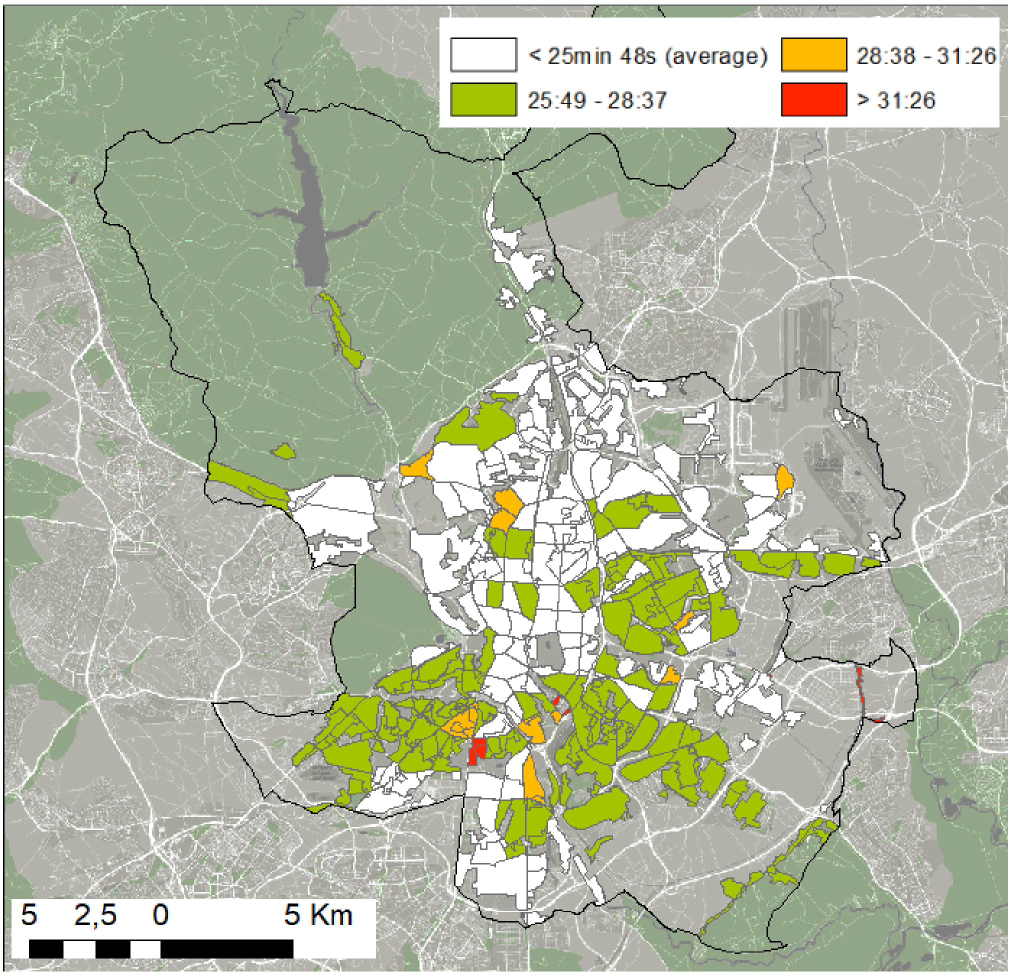


Figure 11. Time spent for everyday travels from each *barrio* in Madrid.

All the tabular data was converted to GIS format and added to their corresponding stops. In the process, unnecessary layers were removed, and then the overall layers for buses+trams and metro+trains were obtained through merging. To combine stops within a 50 m radius (as required by the SUMI indicator), a hexagonal grid was created using "Generate Tessellation" with each hexagon having an area of 6495 $m^2$ (R=50 m). Then, using "Spatial Join," the arrivals of each stop within the hexagon it fell into were summed up. All hexagons with zero value (no stops) were deleted. The remaining hexagons were converted to points using "Feature to Point."

The newly established "stops" were ranked based on their arrival frequency, and a buffer of accessibility was meticulously designed for each stop. The buffer distances were set at 417 meters for buses and trams, while the accessibility range was extended to 833 meters for metro and trains. Employing a sophisticated algorithm, the areas within Madrid's territory were systematically classified into distinct accessibility categories using the tools of intersection, erasing and merging. This process resulted in the creation of visually striking maps delineating the varying degrees of accessibility across the city (Figure 12).

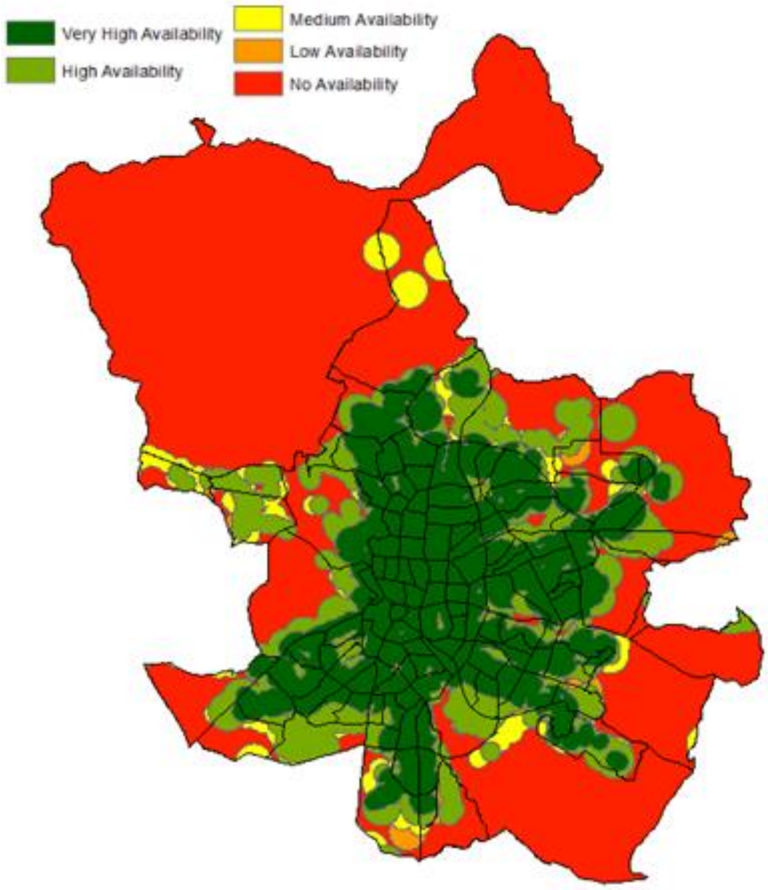


Figure 12. Classification of Madrid area by availability level.

To calculate the mean statistical value for built-up area in each *barrio*, the polygon layer was converted to a raster (cell size of 10m) and passed through the "Zonal Statistics" tool using the "mean" method. After that, built-up territories of each neighborhood were merged in *barrio*s also with rastering and zonal statistic's "mean" calculations for obtaining average value of availability for all the populated area of neighborhood.

The resulting fractional values for each developed territory were reclassified to whole numbers using the "Reclassify" tool, and the raster was converted back to a polygon layer.

According to the methodology for calculating the indicator, an additional adjustment for population size was required. However, since the population in all *barrio*s did not exceed 100,000 people, this step was omitted. As a result, the *barrio*s in Madrid were classified into 5 categories based on the level of availability within built-up zones (Figure 13, Appendix F). To create a classification for transportation poverty, it is suggested to merge the "Very High" and "High" categories in future for overlapping.

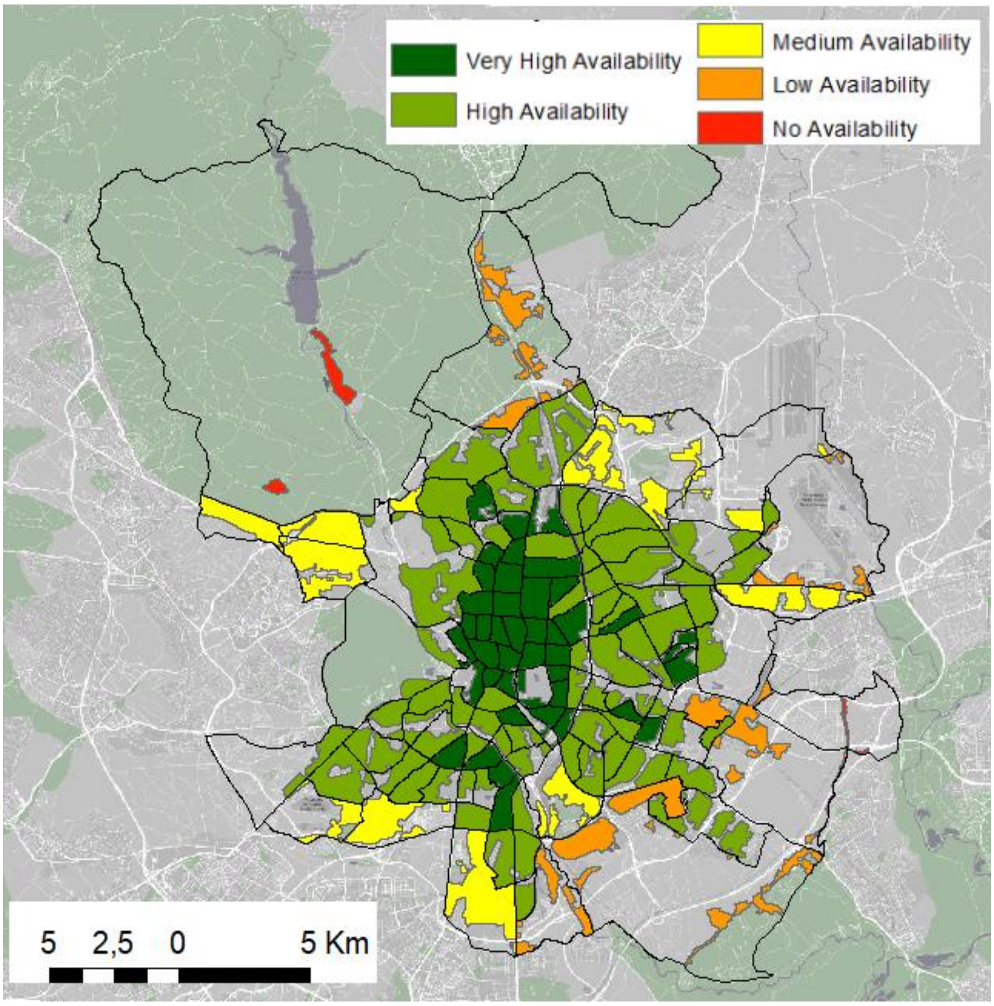


Figure 13. Availability of Madrid neighborhoods.

### 4.3.2 Overlapping Transport Poverty

Before applying the indicators, generalizations were made into four categories: "No risk", "Sensitive to Transport Poverty", "Transport Poverty", and "Severe Transport Poverty." Then, these four categories were summed up, and the average value was calculated to obtain the first comprehensive map of "Madrid Vulnerability to Transport Poverty".

This comprehensive indicator reflects the depth of the impact on neighborhoods facing mobility problems, taking into account risks for areas close to the transport poverty situation. With changes in demographic, economic, or other conditions, households in the sensitive category may transition to an actual problematic situation.

The resulting classification has seven categories. In the case where a territory is not affected by transport poverty in any way (typically having indicators below the average for Madrid), it falls into category 0: "No Transport Poverty". If the value is below 0.5, it is assigned to category 1 or 2. Class 1 means that the territory is characterized by only one or two risk indicators ("Easy-fix TP"). Class 2 indicates the presence of a real existing transport poverty problem in the area ("Mild TP").

Next, a simplified grading system is applied: if the value is below 1, it is assigned to class 3 ("Moderate TP"); if below 1.5, it is assigned to class 4 ("Severe TP"); if below 2, it is assigned to class 5 ("Critical TP"); and if the average value is equal to or greater than 2, it is assigned to class 6. Class 6 is also considered "Critical TP," but it aims to highlight the most severe conditions even within its own group. Areas with values above 2 have more than two indicators of deep transport poverty and two indicators not lower than the average transport poverty. Overall, this class can be omitted, but in this study, it was used solely to simplify the identification of the most disadvantaged areas in Madrid (Figure 14 (left), Appendix G).

However, this method, despite its usefulness when considering risk zones, has a problem. The mathematical characteristics of the calculation require accepting areas as "Moderate" and "Severe" transport poverty, even if actual transport poverty may not be present, but they fall within a risk zone based on three or more indicators. This approach has its advantages as it emphasizes the significance of risks and recognizes a high number of risks as a serious vulnerability in neighborhoods. It is also useful for identifying the most stable areas in the city. However, it can be misleading as it does not accurately reflect the actual presence of transport poverty. Therefore, for the purposes of this research and the identification of the most vulnerable areas in Madrid, an alternative classification approach was chosen.

The purpose of the "Transport Poverty of Madrid" map (Figure 14 (right), Appendix H) is to specifically highlight areas with actual problems. To achieve this, the vulnerability category (risks) was excluded when combining the indicators. Instead, areas that do not currently exhibit transport poverty were assigned a value of 0. The presence of transport poverty was represented by a value of 1, while a critical situation was denoted by a value of 2. As a result, each indicator was categorized into three classes: "No Transport Poverty," "Transport Poverty," and "Severe Transport Poverty." Under this classification, it can be assumed that one severe transport poverty issue carries the same weight as two “regular” transport poverty issues in terms of scoring.

Following the same methodology as before, the indicators were combined and recalculated into a cumulative sum. It was decided to establish 5 classes: "No Transport Poverty," "Low Transport Poverty" for sums less than 2 (representing 1 problematic aspect without severe depth), "Moderate Transport Poverty" for sums less than 4 (indicating 2 severe problems or equivalent). The category of "Severe Transport Poverty" was assigned to neighborhoods with sums of 4-5 points, indicating fewer than 3 severe problems or equivalent. Finally, any sum above 6 points (representing 3 or more severe problems) falls into the category of "Critical Transport Poverty."

This map does not reflect the risks of transport poverty; however, it effectively demonstrates the actual situation and the depth of existing problems.

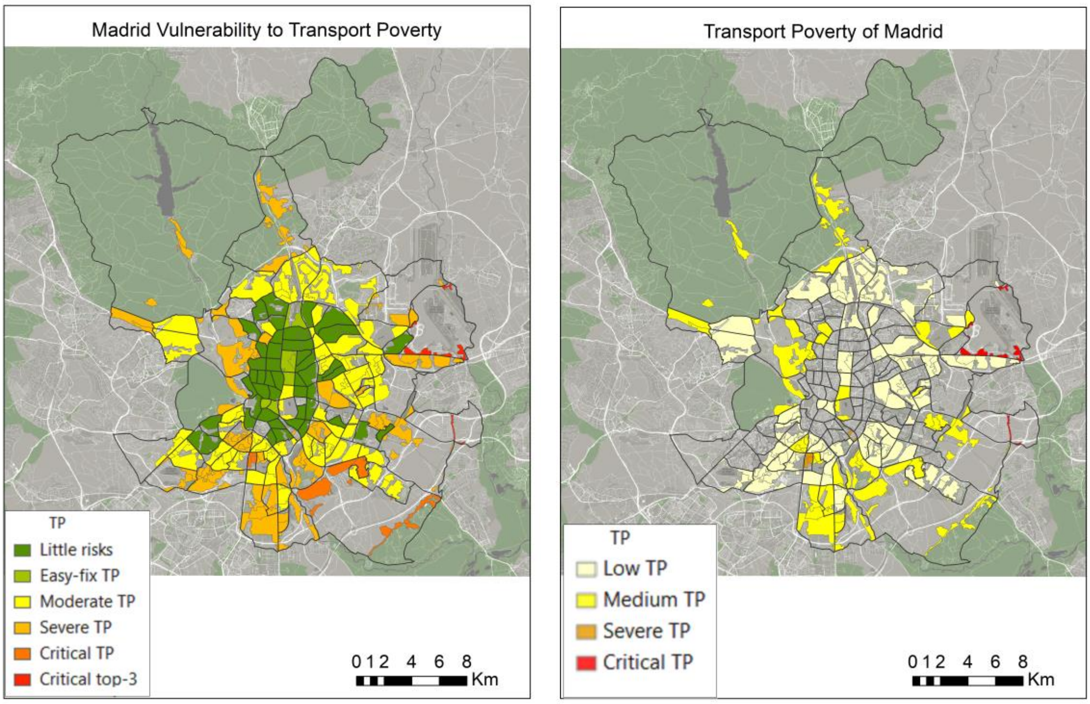


Figure 14. Classification of Madrid area by Transport Poverty risks and problems (left). Classification of Madrid area by Transport Poverty problems (right).

### 4.3.3 Overlapping Transport and Energy Poverty

The final "Double Poverty" map was created by combining the previously obtained "Transport Poverty of Madrid" classification with the analysis from the "Habita_res" project ((IETcc), 2017), specifically focusing on energy-poor areas. Initially, energy inefficient areas of Madrid were identified in conjunction with indicators, assessing residential vulnerability to obtain a list of deprived neighborhoods. Within these areas, indicators such as Income, Utilities costs, Lack of heating system in the house, and the share of elderly persons were assessed. Each indicator was assigned a score of 1 and summarized. A maximum summarized vulnerability score of 4 (or 5 with the possibility of an additional "overlay" score) was considered critical. The resulting map was then overlaid onto the "Transport Poverty of Madrid" classification, to analyse combined vulnerabilities patterns (refer to Appendix I).

# 5 Transport Poverty Analysis

This chapter examines the main trends in the spread of transport poverty in Madrid to answer the Research Question 7. To facilitate visual analysis for the reader, neighborhoods (*barrios*) were classified as a whole (Figure 15, Appendix H).

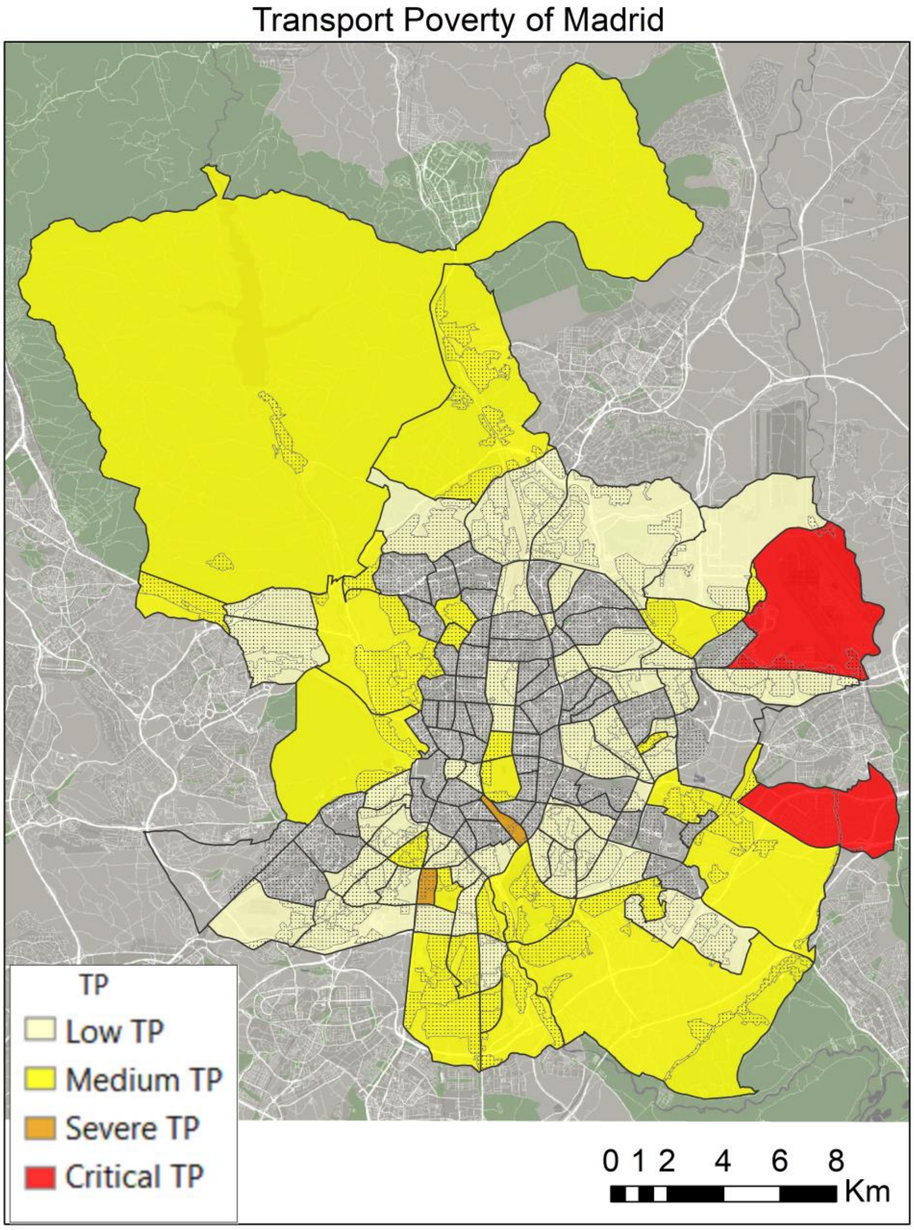


Figure 15. Transport Poverty in Madrid Neighborhoods. Coloring based on neighborhood boundaries, with dot shading based on actual built-up areas.

Upon analyzing the obtained classification, it is apparent that a majority of vulnerable neighborhoods are located farther away from the city center. This pattern can be explained by the higher density of public transportation networks in the central areas, which gradually decreases as one moves towards the outskirts. As a result, the central districts tend to appear out of transport poverty.

However, there are exceptions to this trend, such as the Retiro and Atocha neighborhoods. In Retiro, the issue of safety stands out as a significant concern, potentially affecting its classification to “Medium”. Overall, most indicators within the city center remain relatively “favorable” in terms of transport poverty risk, except for safety considerations, which can be attributed to the higher volume of roads and transportation infrastructure, leading to a relatively higher frequency of accidents. Additionally, the smaller size of neighborhoods in the city center may contribute to a higher accident rate per capita – as it limits the number of population.

The second important factor is travel time. While a detailed analysis would require further investigation, it is worth noting the significant amount of time spent commuting in the Atocha neighborhood. Two initial theories have been proposed to explain this phenomenon.

One possible explanation for this phenomenon is that Atocha serves as a major railway and urban interchange hub. It is likely that individuals who frequently rely on trains to travel to distant destinations choose to reside in the surrounding area. This hypothesis is supported by data from CRTM survey on priority transport mode, which reveals that suburban trains are the most widely utilized mode of transportation (Figure 16).

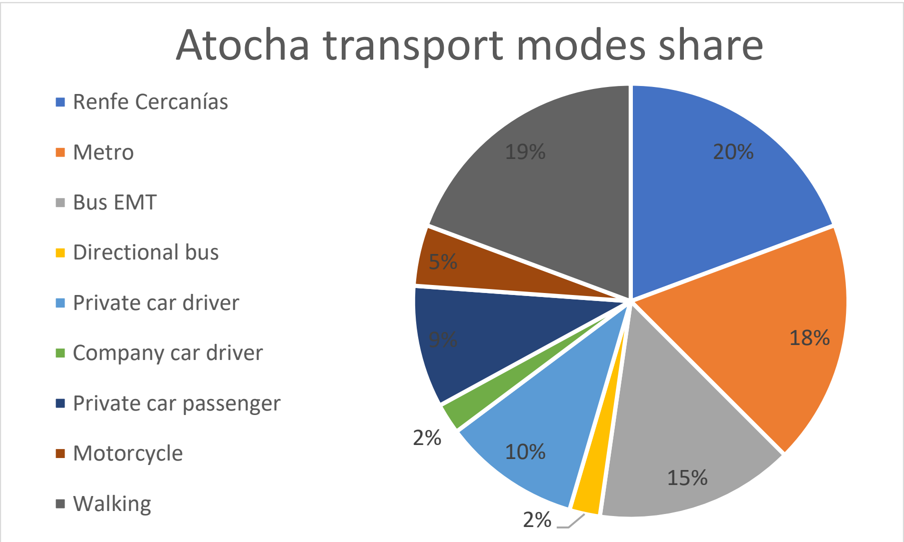


Figure 16. Atocha transport modes share.

Atocha, along with Zofío and several other neighborhoods, could potentially serve as a settlement area for undocumented migrants due to the presence of informal labor gathering points in close proximity (EuropaPress, 2018; Leguina, 2020). The nature of migrants' movements may result in them spending a significant portion of their day attempting to get a job's vehicle that would take them outside the city for undocumented construction or other work purposes. This situation can directly impact respondents' perceptions of the time spent in commuting for their daily routines, potentially influencing the average travel time - even if the proportion of migrants in the population of studied neighborhoods is not particularly high. El Cañaveral also emerges as an additional outlier, which will be discussed in further detail later on.

Safety has a substantial impact on the city center, but the main "high-accident" areas are predominantly found in the eastern and western parts of Madrid. Significantly, many of these areas have low population density, such as Casa de Campo Park and the Barajas Airport district. Furthermore, these neighborhoods are either traversed by or situated along major highways, including Avenida de Portugal, the M-30 ring road, and others.

The affordability of neighborhoods poses a significant issue in the southern part of Madrid. This is a predictable pattern, given that the southern districts generally experience higher levels of poverty compared to the central and northern regions. Among these neighborhoods, San Cristóbal in Villaverde stands out with remarkably low average income per capita (6 916 euros) and per household  (22 430 euros). Moreover, it is characterized by relatively larger household sizes (3 persons/household, 7 place out of 131 *barrio*s) accentuating its position as one of the most economically disadvantaged areas ("Indicadores de renta media según Distrito, *Barrio* y Sección censal", "Indicadores demográficos según Distrito, *Barrio* y Sección censal") (Madrid, 2023c).

As we move away from the city center, the density of bus stops per square kilometer decreases. In the central areas, bus stops are abundant, with almost every street having one. However, in peripheral neighborhoods, the distribution of bus stops tends to be concentrated along major transportation arteries. El Goloso and Barajas emerge as the two most underserved areas in terms of bus stop accessibility, with relatively low numbers compared to other regions. The limited number of bus stops in Barajas can be attributed to the proximity of the airport, while in El Goloso, the presence of a military base restricts the available route options.

The indicators of availability exhibit similarities to indicators of accessibility, as they decline towards the city periphery. However, due to the emphasis on the quantity of buses serving a route and the utilization of pan-European standards instead of Madrid's average, variations in the data exist. For instance, within the Fuencarral del Pardo Park area, the presence of only an interurban bus network with two routes operating along a single road leads to inadequate coverage for such a vast territory. Consequently, while accessibility would be classified as a severe problem, availability would be categorized as a critical issue.

El Cañaveral neighborhood stands out as a district in Madrid that faces significant mobility issues. It is marked by its rapid and ongoing urbanization process, resulting in a largely newly developed area. To explore this particular case, additional research was conducted to examine the recent construction of new stations and the expansion of approximately half of the neighborhood's territory. However, despite these developments, the objective indicators consistently demonstrate a low level of mobility within the area.

As an illustration, in 2023, the majority of the area (73%) lacked available transportation within walking distance (Figure 17 (left)). With only 3.5 stops per square kilometer and a high incidence of road accidents, this could be attributed to the reliance on private vehicles for commuting within the neighborhood (55% from all trips, maximum share of one transport mode from all the *barrio*s). The presence of a higher number of vehicles coupled with limited exit routes from the area contributes to the elevated rate of accidents (Figure 17 (right)). Consequently, the substantial amount of time required for transportation by residents is a direct consequence of these factors.

This rapidly growing neighborhood is already attracting significant attention due to transportation issues and social infrastructure challenges (Aguilera, 2022).

In light of the population increase projected from 12,000 in November 2022 to 50,000, as reported in (As, 2022), it is crucial to prioritize two key measures. Firstly, the construction of a metro or suburban train line is imperative. Secondly, there is a pressing need to enhance the neighborhood's exit corridors and expand the network of bus routes.

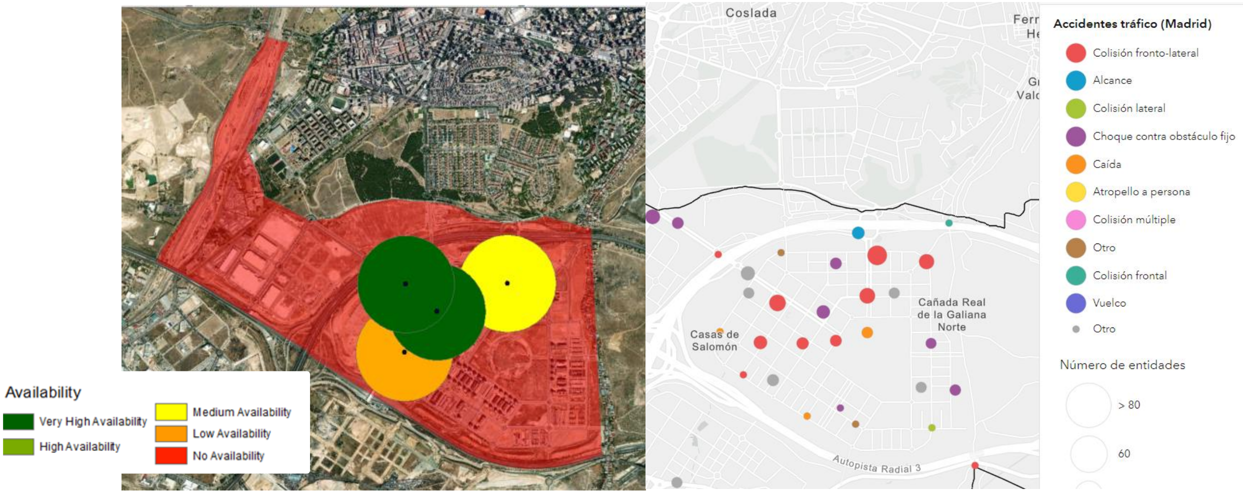


Figure 17. Availability of the developed part of El Canaveral (left) (compiled by the author). Road accidents in the El Canaveral neighborhood in 2022 (right) (Ayuntamiento, 2023b).

# 6 Double Poverty Analysis

The aim of this chapter is to investigate the primary patterns of spatial distribution of energy poverty in Madrid, answering the Research Question 8. It examines the underlying causes and explores the potential correlation with the prevalence of transportation poverty. To enhance clarity, the neighborhoods in Madrid have been shaded entirely based on the indicator of transportation poverty, rather than solely focusing on developed areas. Only critical indicators of energy poverty have been retained. The accompanying map is zoomed in on the areas where the zones of interest intersect (Figure 18, Appendix I).

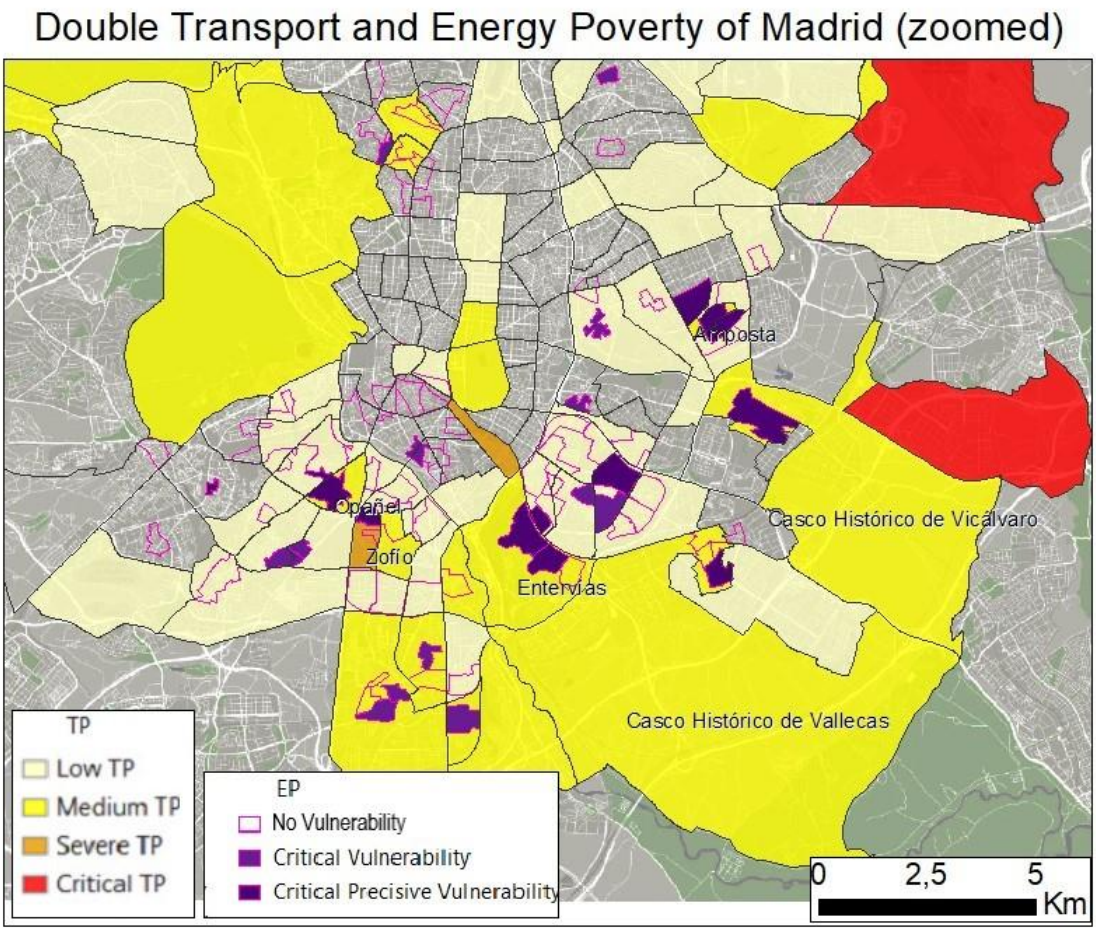


Figure 18. Overlapping of transport and energy poverty in Madrid.

As mentioned in Chapter 4, transportation poverty is primarily prevalent in urban outskirts. Within the central districts of the city, poverty is often attributed to road safety issues.

At the same time, it can be observed that critical issues of energy poverty are primarily prevalent in the "middle zone" between the city center and the outskirts. There is also a noticeable trend towards the southeast direction. This is largely attributed to the timing of housing construction and the resettlement of the most impoverished population. The outskirts have mainly been developed in the past two decades, when energy efficiency laws and new building standards were already in place (Martín-Consuegra Ávila, 2019). Older houses are less adapted, and the wear and tear of structures and elements also play a role. Additionally, the impoverished population lacks the means to afford homes with better conditions among the available options, leading to a cycle of financial and energy poverty. People are forced to spend more on maintaining comfortable living conditions or compromise their health. This issue is particularly acute for elderly individuals who are unable to relocate to more comfortable housing.

Energy poverty and transportation poverty in Madrid, while having some areas of overlap, are only correlated in terms of monetary expenditures, which can be referred to as "Double Energy Poverty." This is due to the fact that the purchase of transportation passes in public transport systems is significantly influenced by fuel prices and the energy efficiency of vehicles.

However, the majority of energy vulnerable areas are situated within low or moderate transportation poverty zones, or even outside of them. Specifically, central and northern neighborhoods, considered relatively "privileged" in terms of transportation vulnerability, exhibit a significant presence of energy vulnerability.

The neighborhoods of Casco Histórico de Vallecas, Casco Histórico de Vicálvaro, Opañel, Amposta, and Entrevías are among the most vulnerable to transportation poverty and exhibit the highest levels of critical energy poverty. Additionally, the neighborhood of Zofío stands out as the sole area experiencing severe transportation poverty while also falling within the critical energy poverty zone (Table 3).

| N of *barrio* | Name | EP rate | TP rate | Affordability | Availability | Access | Travel Time | Safety |
|---|---|---|---|---|---|---|---|---|
| 126 | Zofío | 5 | Severe | 1 | 0 | 1 | 2 | 0 |
| 112 | Opañel | 5 | Medium | 1 | 0 | 1 | 1 | 0 |
| 131 | Entrevías | 5 | Medium | 1 | 0 | 0 | 0 | 1 |
| 191 | Casco Histórico de Vicálvaro | 5 | Medium | 1 | 1 | 1 | 0 | 0 |
| 181 | Casco Histórico de Vallecas | 5 | Medium | 1 | 1 | 1 | 0 | 0 |
| 203 | Amposta | 5 | Medium | 1 | 0 | 0 | 1 | 0 |

Table 3. The most vulnerable neighborhoods to Energy Poverty (EP) and Transport Poverty (TP) simultaneously.

It is noteworthy that all the most vulnerable neighborhoods face affordability challenges. This is a logical correlation, as household income plays a significant role in determining energy poverty.

Regarding the most vulnerable neighborhood in terms of Double Poverty, Zofío, the aspect of travel time emerges as a crucial factor (Figure 19 (left)). Upon examining all recorded journeys, an extreme case was identified with a commute duration of six hours. Excluding this outlier from the calculations slightly improves the situation (unlike Atocha and El Canaveral, for example) and reduces the average travel time for the neighborhood by 42 seconds. This reclassification places Zofío in a lower category based on the travel time indicator and the overall classification of transportation poverty. Consequently, Zofío can be considered alongside the other mentioned neighborhoods.

The accessibility indicator in Zofío does not coincide with availability, highlighting the disparity between these two metrics. The coverage of bus stops within the built-up area of the neighborhood is relatively low (Figure 19 (right)). However, outside the neighborhood, there is a significant number of well-served stops, indicating good transportation options for Zofío's residents based on the availability indicator. Nonetheless, residents will have to travel to neighboring areas, making Zofío dependent on its neighbors and their respective stops.

Due to the absence of major roads within or along the borders of the neighborhood, and a substantial portion of the area remaining undeveloped, the number of traffic accidents is relatively low. It is worth noting that despite the lower population size, there is a sufficient number of residents in Zofío to avoid compromising the per capita indicator.

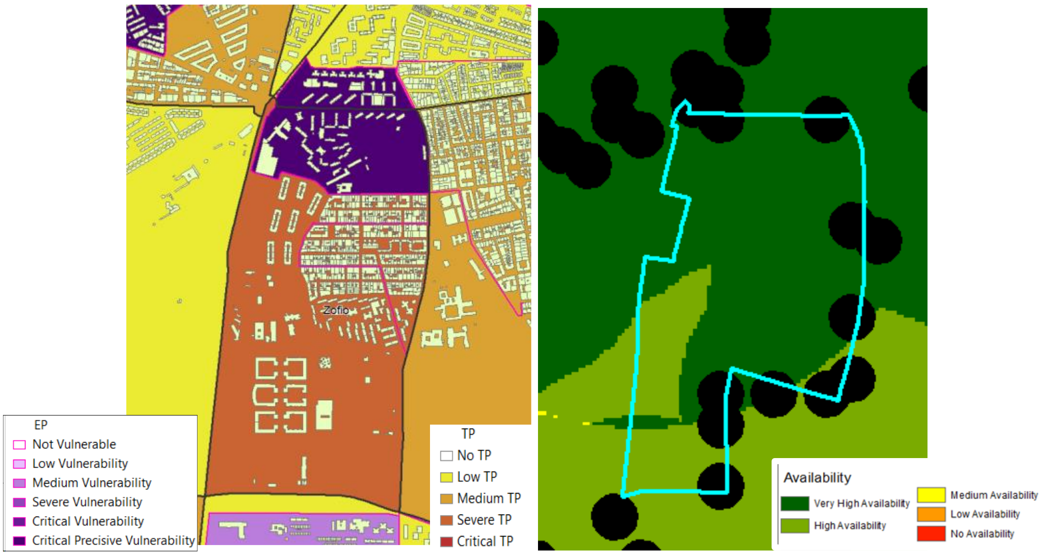


Figure 19. Overlaying the urban development of Zofío on the maps of Transport and Energy Poverty (left). Accessibility of the built-up area of Zofío (blue line represents the boundary of the development, dots indicate public transportation stops) (right).

# 7 Conclusion and future work

Transport and energy problems are crucial aspects of human existence and pose significant hindrances to urban communities' development. This research examines modern understandings of transport, energy, and dual poverty, explores the dimensions of transport poverty, and identifies relevant indicators for each. By adopting this approach, the study integrates diverse indicators into a comprehensive map, highlighting the population's transportation-related issues in the city of Madrid.

Through the spatial analysis conducted, it has been revealed that transport poverty assumes greater significance in peripheral neighborhoods distant from the city center. Nonetheless, due to the higher road network density and lower population density, road safety in the central areas tends to be considerably lower, then at the most outskirts. Furthermore, it has been observed that the issue of economic affordability of transportation is predominantly concentrated in the southern districts characterized by higher levels of poverty. The challenges associated with longer travel times are likely linked either to major transportation hubs facilitating travel to remote areas and beyond the city, or to informal markets catering to migrants (although this latter possibility is less likely, as the percentage of migrants in neighborhoods with longer travel times is not higher and sometimes even lower than in the surrounding areas). These findings warrant further investigation in future studies.

When analyzing the distribution patterns of simultaneous energy and transport poverty, it becomes evident that double poverty is predominantly observed in the south-southeast region of Madrid. This can be attributed to a higher concentration of individuals living in poverty compared to the north and central areas of the capital. However, it is important to note that energy vulnerabilities are not found in the newer areas of Madrid, which are primarily affected by transport poverty. This distinction can be attributed to the implementation of stricter building standards and improved building efficiency in these newer regions. Overall, areas with the highest energy poverty rates are typically characterized by moderate to low levels of transport vulnerability.

In order to mitigate vulnerabilities in disadvantaged neighborhoods, a comprehensive analysis of each specific case is imperative while creation of policies. Aim of the research is to provide the necessary data to identify the most vulnerable areas, as well as justification for decision-making processes (RQ10). However, two primary recommendations can be made. Firstly, there is a need to enhance the transportation infrastructure in the El Cañaveral neighborhood. This could involve the introduction of a metro or train line, along with broader infrastructural improvements and improved exit options. Secondly, social policies should focus on reducing the socioeconomic gap between affluent and impoverished neighborhoods to prevent further segregation and the perpetuation of poverty cycles. Potential support measures may include prioritized building renovation programs, tax incentives, and discounted utility tariffs. To enhance transportation accessibility, discounted fares for the most economically disadvantaged households could be implemented, alongside efforts to generate sufficient job opportunities within impoverished areas, thereby minimizing travel-related challenges and enhancing overall accessibility.

In the future work, it is recommended to undertake a more detailed analysis of the spatial differentiation within Madrid, focusing on smaller units obtained through the intersection of ZT1259 and cadastral sections. This approach will provide a higher level of granularity and accuracy in understanding the distribution patterns of simultaneous energy and transport poverty. Furthermore, it is crucial to examine the correlation between Accessibility and Availability parameters and make any necessary adjustments to the indicator calculation methodology. This will enhance the reliability of the findings and ensure a comprehensive understanding of the factors influencing energy and transport vulnerabilities. Additionally, exploring the precise correlation between Transport Poverty and Energy Poverty and developing a unified classification system specific to the Madrid case will contribute to a more effective policy and planning approach. Such research will provide valuable insights for future strategic interventions aimed at reducing energy and transport poverty in Madrid and potentially other similar urban contexts (RQ9).

Moreover, it is worthy to highlight that this methodology has the potential for application at different levels in various countries. Given the availability of data, the approach can be implemented in multiple cities within developed nations. In situations where data may lack granularity, adaptations can be made to the indicator set. However, the overall methodology for evaluating transport poverty based on its five dimensions remains comprehensible and user-friendly. This suggests its suitability and versatility for implementation in different contexts.

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# Appendix A

**Affordability of Madrid neighborhoods (Share of income for monthly pass expences of poorest households)**

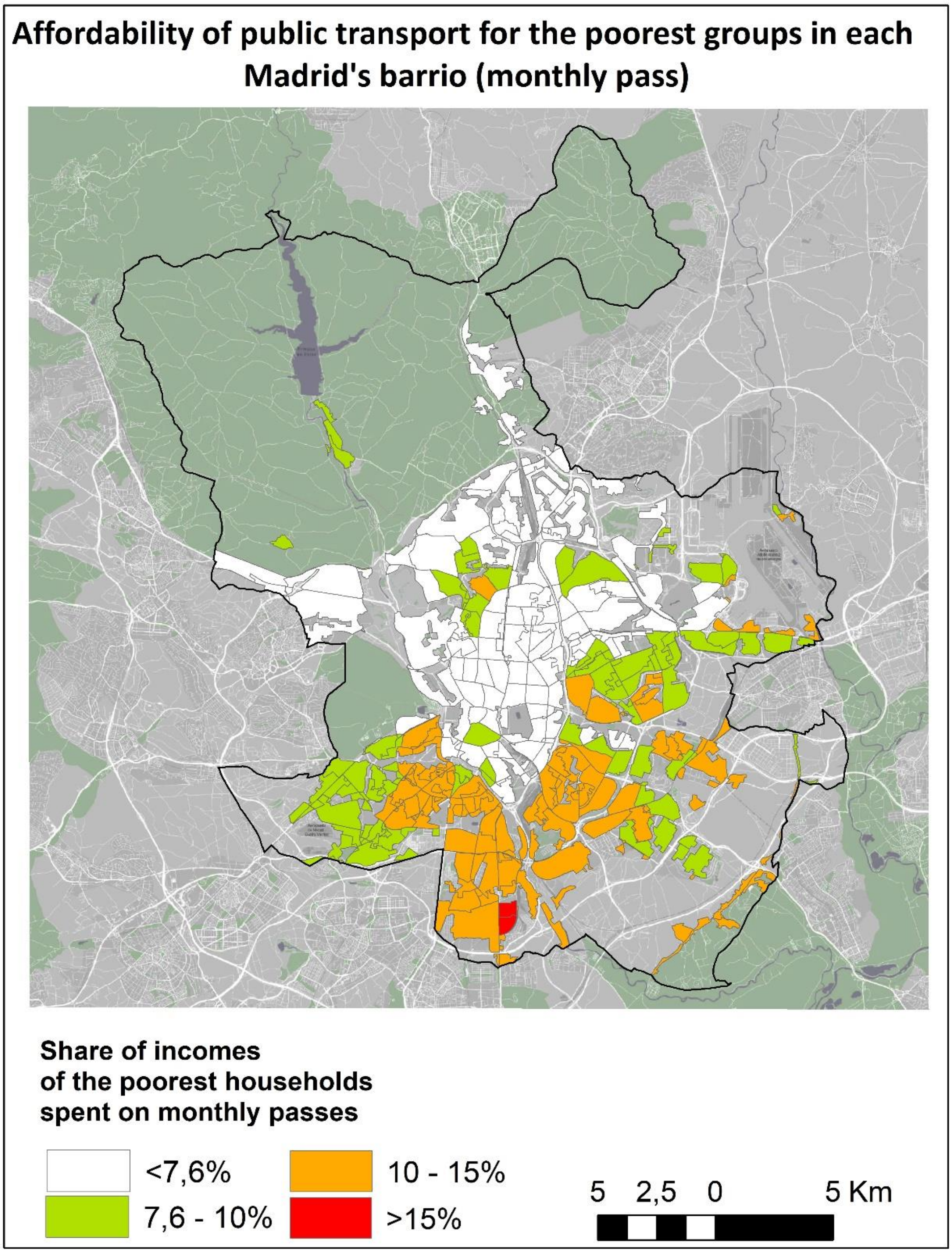
| 2020 Neighborhood Name | Average income per house-hold (euros) | 50% of average income (euros) | Household Size | Pass price (euros) | Share | 2020 Neighborhood Name | Average income per house-hold (euros) | 50% of average income (euros) | Household Size | Pass price (euros) | Share |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | |
| **CITY of Madrid** | **43.003** | **21.502** | **2.49** | 54.6 | 7.6% | | | | | | |
| | | | | | Share | | | | | | |
| 011. Palacio | 39.390 | **19.695** | 1.96 | 54.6 | 6.5% | 111. Comillas | 30.868 | **15.434** | 2.35 | 54.6 | 10.0% |
| 012. Embajadores | 30.825 | **15.412** | 2.01 | 54.6 | 8.5% | 112. Opañel | 30.853 | **15.427** | 2.47 | 54.6 | 10.5% |
| 013. Cortes | 40.008 | **20.004** | 1.89 | 54.6 | 6.2% | 113. San Isidro | 29.019 | **14.510** | 2.54 | 54.6 | 11.5% |
| 014. Justicia | 48.352 | **24.176** | 1.96 | 54.6 | 5.3% | 114. Vista Alegre | 30.153 | **15.076** | 2.60 | 54.6 | 11.3% |
| 015. Universidad | 37.188 | **18.594** | 1.94 | 54.6 | 6.8% | 115. Puerta Bonita | 28.320 | **14.160** | 2.68 | 54.6 | 12.4% |
| 016. Sol | 34.704 | **17.352** | 1.91 | 54.6 | 7.2% | 116. Buenavista | 35.003 | **17.501** | 2.68 | 54.6 | 10.0% |
| 021. Imperial | 46.721 | **23.360** | 2.37 | 54.6 | 6.6% | 117. Abrantes | 30.910 | **15.455** | 2.70 | 54.6 | 11.5% |
| 022. Acacias | 48.967 | **24.483** | 2.36 | 54.6 | 6.3% | 121. Orcasitas | 30.835 | **15.417** | 2.63 | 54.6 | 11.2% |
| 023. Chopera | 36.345 | **18.172** | 2.32 | 54.6 | 8.4% | 122. Orcasur | 28.518 | **14.259** | 2.88 | 54.6 | 13.2% |
| 024. Legazpi | 55.486 | **27.743** | 2.57 | 54.6 | 6.1% | 123. San Fermín | 28.655 | **14.328** | 2.80 | 54.6 | 12.8% |
| 025. Delicias | 45.392 | **22.696** | 2.37 | 54.6 | 6.8% | 124. Almendrales | 29.898 | **14.949** | 2.73 | 54.6 | 11.9% |
| 026. Palos de Moguer | 38.852 | **19.426** | 2.17 | 54.6 | 7.3% | 125. Moscardó | 28.875 | **14.438** | 2.62 | 54.6 | 11.9% |
| 027. Atocha | 47.715 | **23.858** | 2.76 | 54.6 | 7.6% | 126. Zofio | 28.223 | **14.111** | 2.73 | 54.6 | 12.7% |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 031. Pacífico | 46.093 | **23.047** | 2.27 | 54.6 | 6.5% | 127. Pradolongo | 24.874 | **12.437** | 2.83 | 54.6 | 14.9% |
| 032. Adelfas | 50.837 | **25.419** | 2.43 | 54.6 | 6.3% | 131. Entrevías | 25.324 | **12.662** | 2.68 | 54.6 | 13.9% |
| 033. Estrella | 62.973 | **31.486** | 2.70 | 54.6 | 5.6% | 132. San Diego | 23.954 | **11.977** | 2.56 | 54.6 | 14.0% |
| 034. Ibiza | 52.793 | **26.397** | 2.31 | 54.6 | 5.7% | 133. Palomeras Bajas | 32.081 | **16.040** | 2.63 | 54.6 | 10.7% |
| 035. Jerónimos | 71.312 | **35.656** | 2.47 | 54.6 | 4.5% | 134. Palomeras Sureste | 30.247 | **15.123** | 2.63 | 54.6 | 11.4% |
| 036. Niño Jesús | 72.311 | **36.155** | 2.68 | 54.6 | 4.9% | 135. Portazgo | 26.468 | **13.234** | 2.57 | 54.6 | 12.7% |
| 041. Recoletos | 79.782 | **39.891** | 2.33 | 54.6 | 3.8% | 136. Numancia | 27.444 | **13.722** | 2.57 | 54.6 | 12.2% |
| 042. Goya | 55.488 | **27.744** | 2.24 | 54.6 | 5.3% | 141. Pavones | 36.541 | **18.270** | 2.65 | 54.6 | 9.5% |
| 043. Fuente del Berro | 46.114 | **23.057** | 2.26 | 54.6 | 6.4% | 142. Horcajo | 50.026 | **25.013** | 2.92 | 54.6 | 7.6% |
| 044. Guindalera | 51.932 | **25.966** | 2.41 | 54.6 | 6.1% | 143. Marroquina | 43.531 | **21.765** | 2.52 | 54.6 | 7.6% |
| 045. Lista | 56.249 | **28.124** | 2.26 | 54.6 | 5.3% | 144. Media Legua | 38.562 | **19.281** | 2.45 | 54.6 | 8.3% |
| 046. Castellana | 76.960 | **38.480** | 2.42 | 54.6 | 4.1% | 145. Fontarrón | 30.951 | **15.476** | 2.46 | 54.6 | 10.4% |
| 051. El Viso | 83.519 | **41.760** | 2.76 | 54.6 | 4.3% | 146. Vinateros | 32.218 | **16.109** | 2.33 | 54.6 | 9.5% |
| 052. Prosperidad | 48.327 | **24.163** | 2.29 | 54.6 | 6.2% | 151. Ventas | 31.461 | **15.730** | 2.42 | 54.6 | 10.1% |
| 053. Ciudad Jardín | 49.051 | **24.525** | 2.33 | 54.6 | 6.2% | 152. Pueblo Nuevo | 33.329 | **16.665** | 2.54 | 54.6 | 10.0% |
| 054. Hispanoamérica | 70.450 | **35.225** | 2.52 | 54.6 | 4.7% | 153. Quintana | 33.611 | **16.805** | 2.35 | 54.6 | 9.1% |
| 055. Nueva España | 78.336 | **39.168** | 2.70 | 54.6 | 4.5% | 154. Concepción | 38.258 | **19.129** | 2.28 | 54.6 | 7.8% |
| 056. Castilla | 62.012 | **31.006** | 2.55 | 54.6 | 5.4% | 155. San Pascual | 45.513 | **22.756** | 2.41 | 54.6 | 6.9% |
| 061. Bellas Vistas | 34.744 | **17.372** | 2.41 | 54.6 | 9.1% | 156. San Juan Bautista | 62.813 | **31.406** | 2.52 | 54.6 | 5.3% |
| 062. Cuatro Caminos | 48.478 | **24.239** | 2.32 | 54.6 | 6.3% | 157. Colina | 55.524 | **27.762** | 2.46 | 54.6 | 5.8% |
| 063. Castillejos | 49.475 | **24.737** | 2.22 | 54.6 | 5.9% | 158. Atalaya | 73.959 | **36.980** | 2.61 | 54.6 | 4.6% |
| 064. Almenara | 33.159 | **16.579** | 2.37 | 54.6 | 9.4% | 159. Costillares | 70.743 | **35.371** | 2.76 | 54.6 | 5.1% |
| 065. Valdeacederas | 31.244 | **15.622** | 2.41 | 54.6 | 10.1% | 161. Palomas | 83.533 | **41.767** | 3.07 | 54.6 | 4.8% |
| 066. Berruguete | 32.467 | **16.234** | 2.40 | 54.6 | 9.7% | 162. Piovera | 84.205 | **42.103** | 3.01 | 54.6 | 4.7% |
| 071. Gaztambide | 49.435 | **24.717** | 2.19 | 54.6 | 5.8% | 163. Canillas | 43.396 | **21.698** | 2.52 | 54.6 | 7.6% |
| 072. Arapiles | 47.995 | **23.998** | 2.19 | 54.6 | 6.0% | 164. Pinar del Rey | 36.609 | **18.305** | 2.45 | 54.6 | 8.8% |
| 073. Trafalgar | 47.561 | **23.781** | 2.10 | 54.6 | 5.8% | 165. Apóstol Santiago | 40.604 | **20.302** | 2.57 | 54.6 | 8.3% |
| 074. Almagro | 72.371 | **36.185** | 2.38 | 54.6 | 4.3% | 166. Valdefuentes | 59.987 | **29.993** | 2.88 | 54.6 | 6.3% |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 075. Ríos Rosas | 55.426 | **27.713** | 2.25 | 54.6 | 5.3% | 171. Villaverde Alto, C.H. Villa-verde | 27.992 | **13.996** | 2.72 | 54.6 | 12.7% |
| 076. Vallehermoso | 63.246 | **31.623** | 2.41 | 54.6 | 5.0% | 172. San Cristóbal | 22.430 | **11.215** | 3.00 | 54.6 | 17.5% |
| 081. El Pardo | 38.460 | **19.230** | 2.41 | 54.6 | 8.2% | 173. Butarque | 33.059 | **16.530** | 2.82 | 54.6 | 11.2% |
| 082. Fuentelarreina | 88.753 | **44.377** | 2.90 | 54.6 | 4.3% | 174. Los Rosales | 31.264 | **15.632** | 2.80 | 54.6 | 11.7% |
| 083. Peñagrande | 49.757 | **24.879** | 2.60 | 54.6 | 6.9% | 175. Los Ángeles | 30.947 | **15.474** | 2.55 | 54.6 | 10.8% |
| 084. Pilar | 36.799 | **18.399** | 2.37 | 54.6 | 8.4% | 181. Casco Histórico de Vallecas | 27.339 | **13.669** | 2.64 | 54.6 | 12.6% |
| 085. La Paz | 61.451 | **30.725** | 2.67 | 54.6 | 5.7% | 182. Santa Eugenia | 39.914 | **19.957** | 2.72 | 54.6 | 8.9% |
| 086. Valverde | 48.350 | **24.175** | 2.68 | 54.6 | 7.3% | 183. Ensanche de Vallecas | 36.616 | **18.308** | 2.42 | 54.6 | 8.7% |
| 087. Mirasierra | 73.969 | **36.984** | 3.10 | 54.6 | 5.5% | 191. Casco Histórico de Vicálvaro | 27.740 | **13.870** | 2.56 | 54.6 | 12.1% |
| 088. El Goloso | 69.983 | **34.991** | 2.94 | 54.6 | 5.5% | 192. Valdebernardo | 42.891 | **21.446** | 2.88 | 54.6 | 8.8% |
| 091. Casa de Campo | 46.362 | **23.181** | 2.26 | 54.6 | 6.4% | 193. Valderrivas | 44.111 | **22.055** | 2.89 | 54.6 | 8.6% |
| 092. Argüelles | 56.921 | **28.460** | 2.29 | 54.6 | 5.3% | 194. El Cañaveral | 38.310 | **19.155** | 2.33 | 54.6 | 8.0% |
| 093. Ciudad Universitaria | 65.088 | **32.544** | 2.54 | 54.6 | 5.1% | 201. Simancas | 34.579 | **17.289** | 2.46 | 54.6 | 9.3% |
| 094. Valdezarza | 38.630 | **19.315** | 2.41 | 54.6 | 8.2% | 202. Hellín | 26.712 | **13.356** | 2.43 | 54.6 | 11.9% |
| 095. Valdemarín | 89.731 | **44.866** | 3.34 | 54.6 | 4.9% | 203. Amposta | 24.314 | **12.157** | 2.48 | 54.6 | 13.4% |
| 096. El Plantío | 89.731 | **44.866** | 3.18 | 54.6 | 4.6% | 204. Arcos | 32.835 | **16.418** | 2.60 | 54.6 | 10.4% |
| 097. Aravaca | 71.212 | **35.606** | 3.12 | 54.6 | 5.7% | 205. Rosas | 48.314 | **24.157** | 2.83 | 54.6 | 7.7% |
| 101. Los Cármenes | 32.487 | **16.244** | 2.62 | 54.6 | 10.6% | 206. Rejas | 41.606 | **20.803** | 2.51 | 54.6 | 7.9% |
| 102. Puerta del Angel | 30.717 | **15.358** | 2.37 | 54.6 | 10.1% | 207. Canillejas | 34.162 | **17.081** | 2.61 | 54.6 | 10.0% |
| 103. Lucero | 33.514 | **16.757** | 2.51 | 54.6 | 9.8% | 208. Salvador | 57.409 | **28.705** | 2.62 | 54.6 | 6.0% |
| 104. Aluche | 33.351 | **16.675** | 2.46 | 54.6 | 9.7% | 211. Alameda de Osuna | 56.971 | **28.486** | 2.69 | 54.6 | 6.2% |
| 105. Campamento | 34.426 | **17.213** | 2.57 | 54.6 | 9.8% | 212. Aeropuerto | 28.191 | **14.096** | 2.60 | 54.6 | 12.1% |
| 106. Cuatro Vientos | 38.972 | **19.486** | 2.46 | 54.6 | 8.3% | 213. Casco Histórico de Barajas | 31.566 | **15.783** | 2.40 | 54.6 | 10.0% |
| 107. Las Águilas | 32.801 | **16.401** | 2.46 | 54.6 | 9.8% | 214. Timón | 45.064 | **22.532** | 2.67 | 54.6 | 7.8% |
| 111. Comillas | 30.868 | **15.434** | 2.35 | 54.6 | 10.0% | 215. Corralejos | 72.657 | **36.329** | 2.94 | 54.6 | 5.3% |

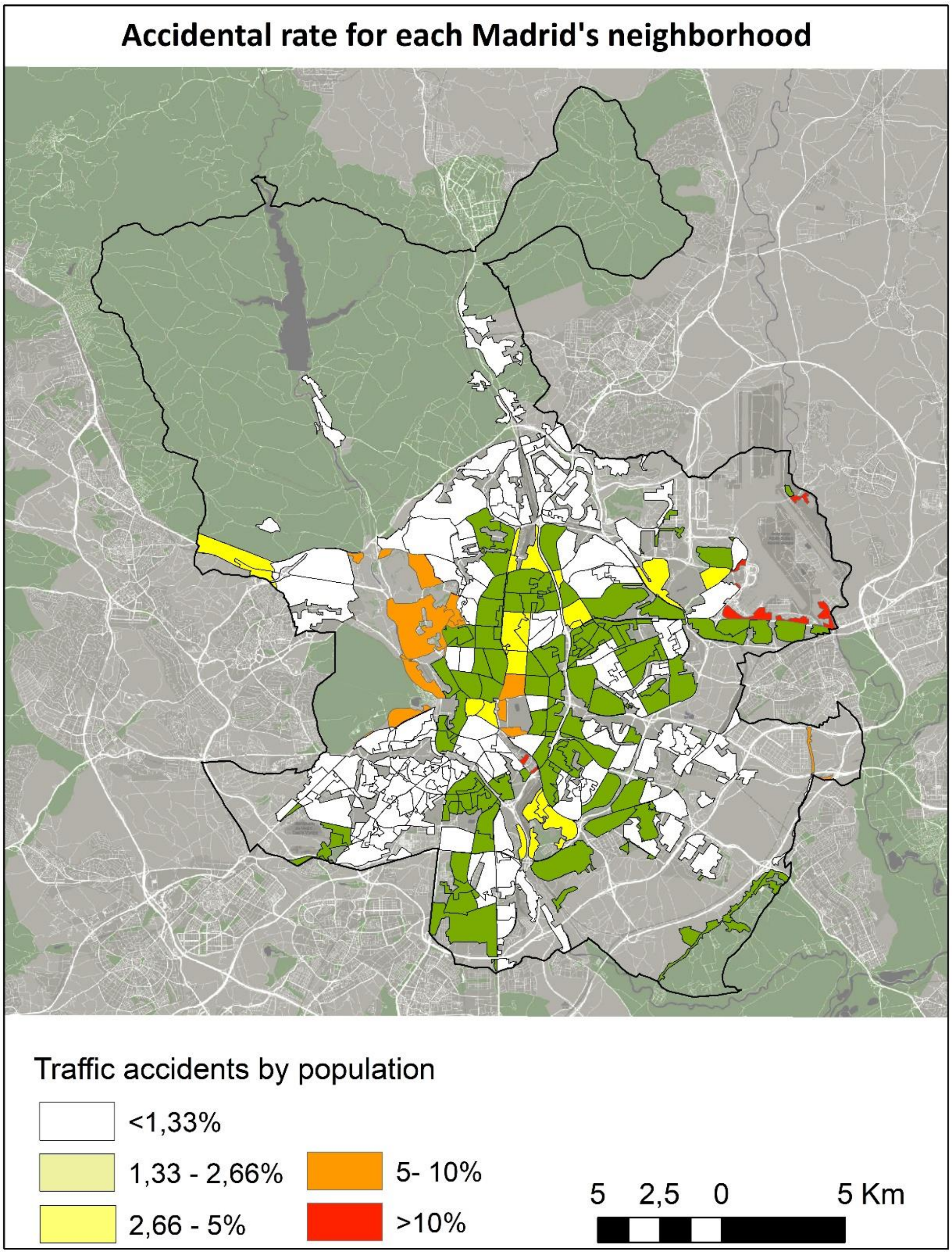
# Appendix B

**Affordability of Madrid neighborhoods**



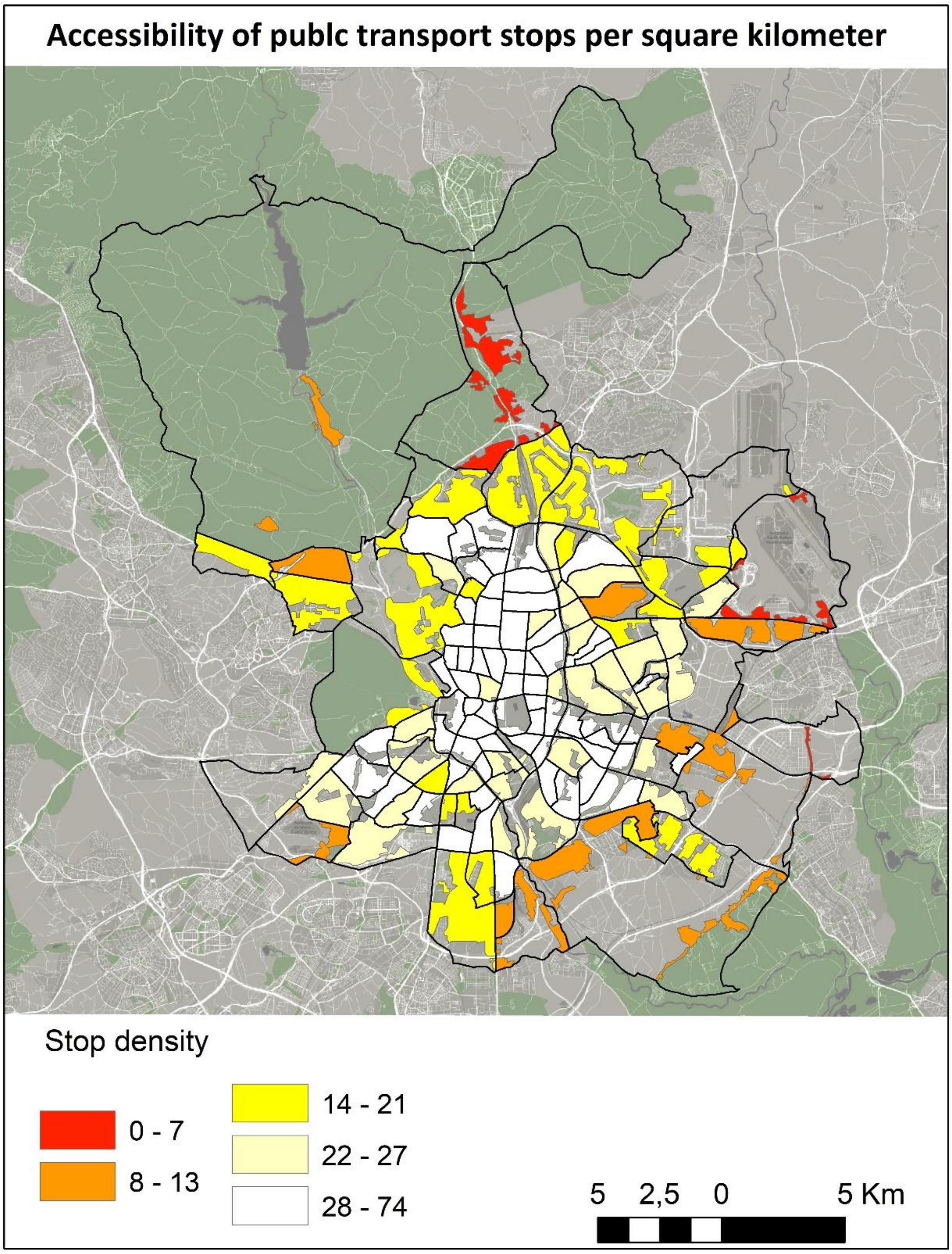
# Appendix C

**Safety of Madrid neighborhoods**



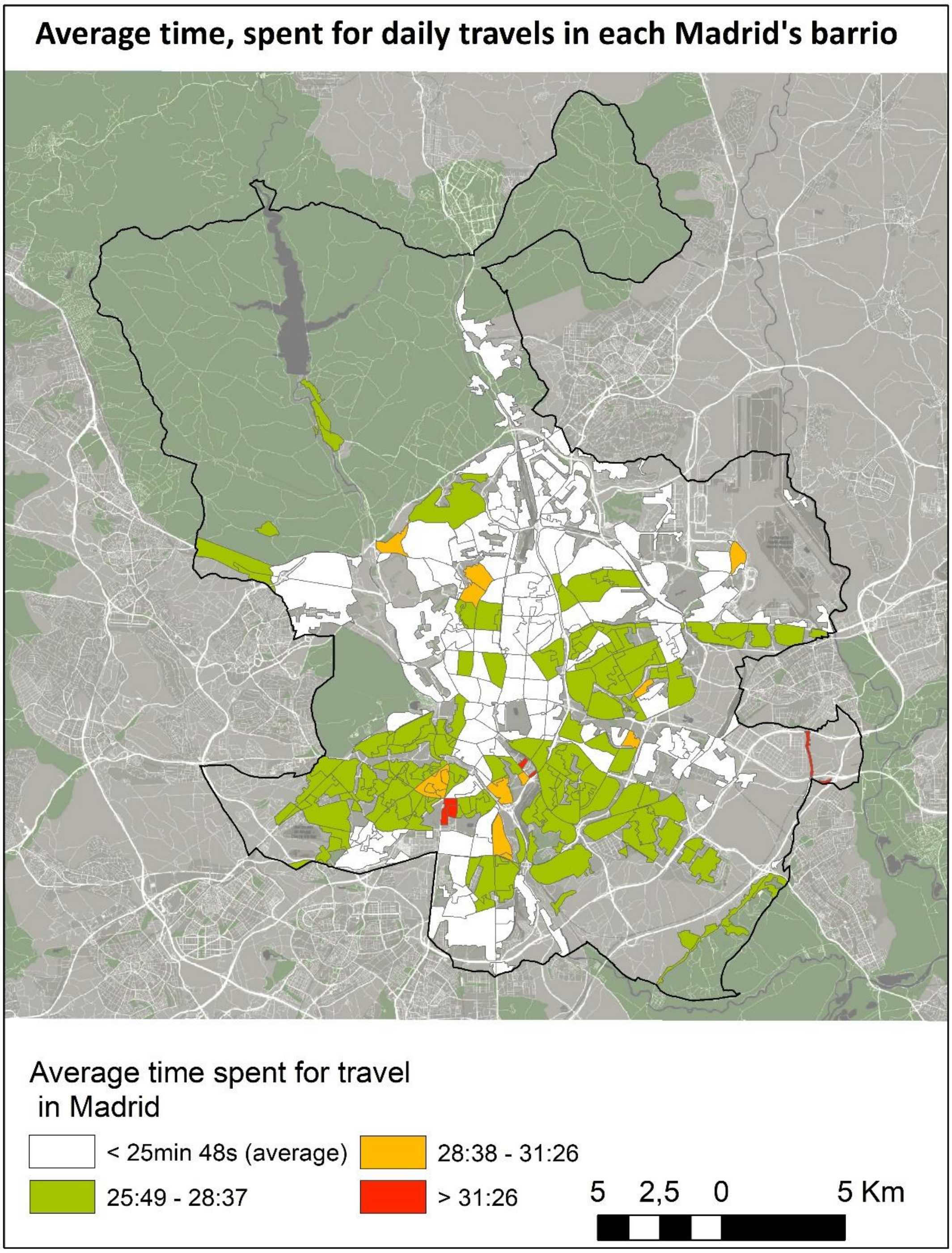
# Appendix D

**Accessibility of Madrid neighborhoods**



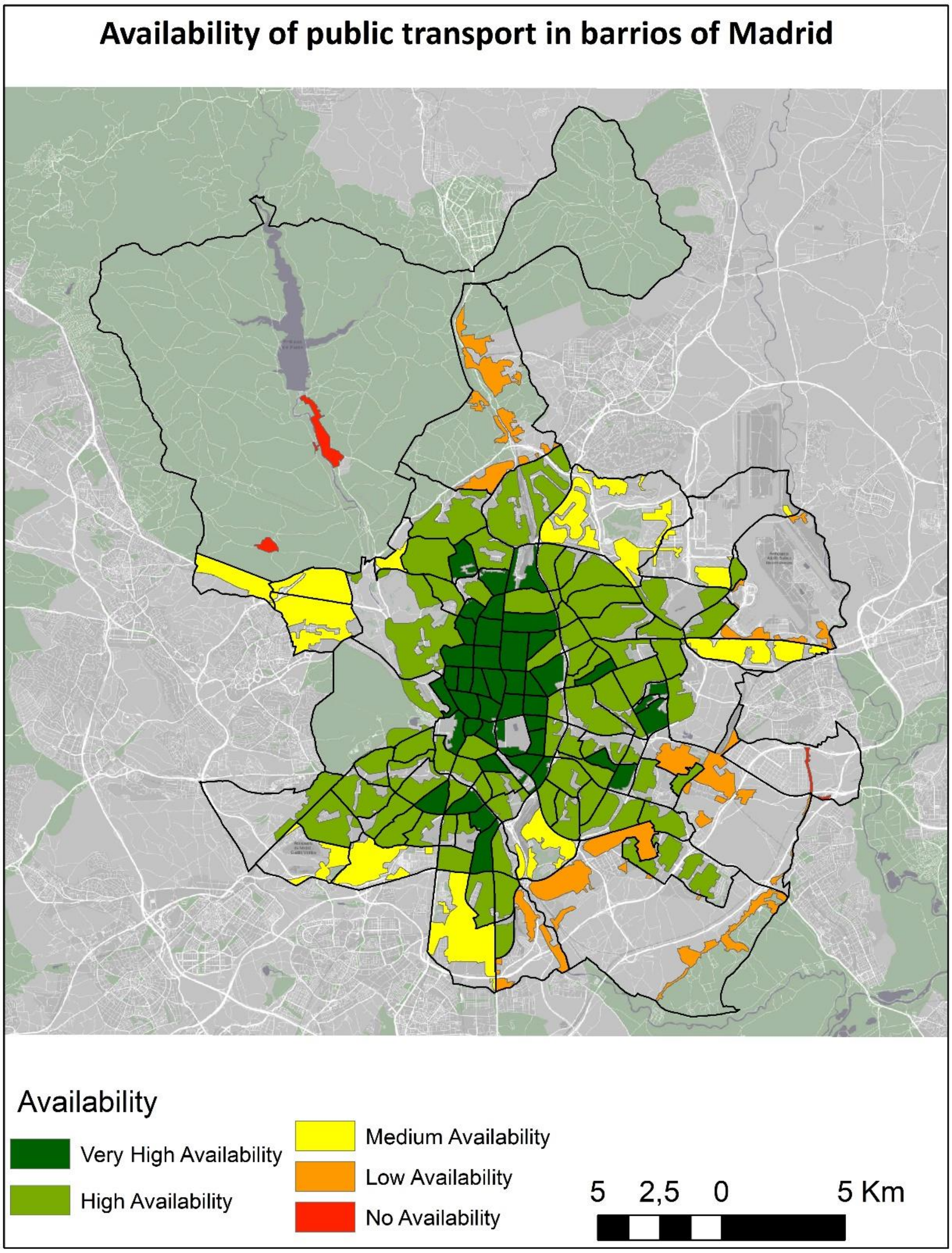
# Appendix E

**Time spent for daily trips in Madrid neighborhoods**



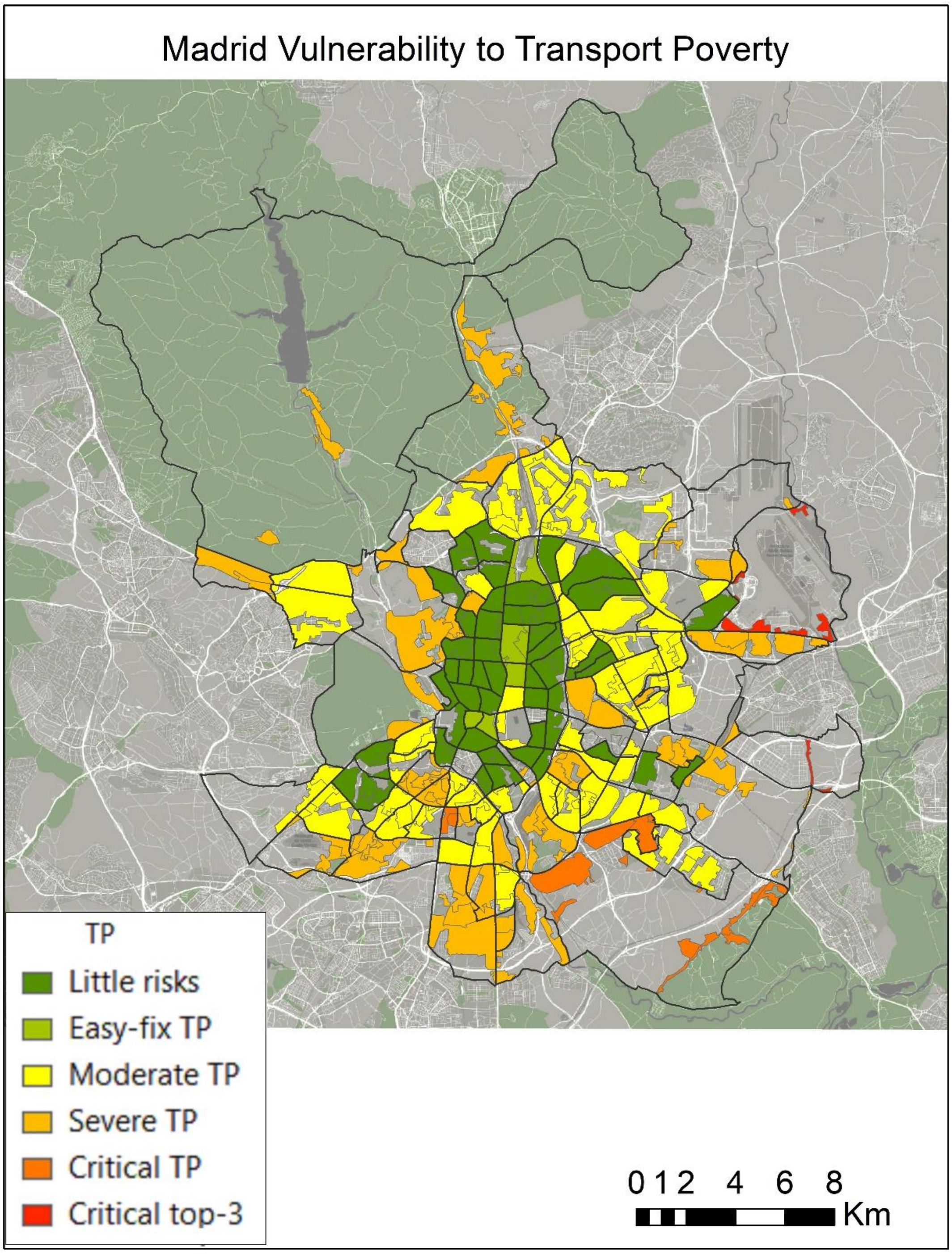
# Appendix F

**Availability of Madrid neighborhoods**



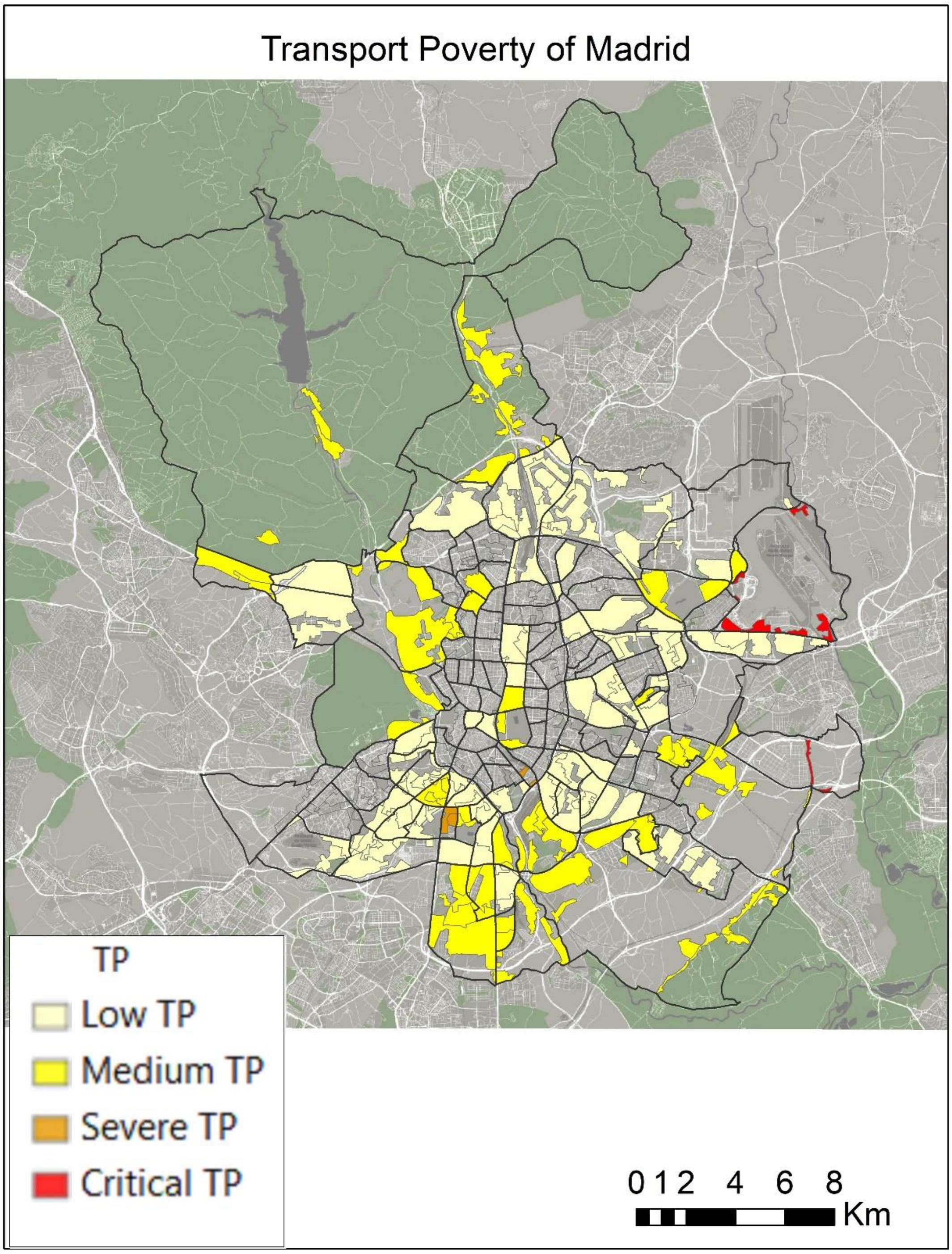
# Appendix G

**Classification of Madrid area by Transport Poverty risks and problems**



# Appendix H

**Classification of Madrid area by Transport Poverty problems**



# Appendix I

**Overlapping of transport and energy poverty in Madrid**