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Identifying Transit Deserts and Directional Dependencies in Vienna's Public Transport Network

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Abstract

Public transport plays a crucial role in people's daily lives by enabling them to participate in various activities and fostering connections with places and individuals. Furthermore, with anthropogenic climate change becoming an increasingly urgent issue, and transport being a major contributor to greenhouse gas emissions in Austria, efficient and widely accessible public transport is essential. To achieve this, an evaluation of the transit network is required to identify problem areas and uncover opportunities for improvement.

The aim of this thesis is to describe the importance and functions of public transport, explore methods to identify transit deserts and develop a new approach to detect transit deserts and directional dependencies in Vienna's public transport network.

To address these objectives, a literature review on accessibility measures was conducted, and the significance of directionality in transport networks was discussed.

Based on this foundation, an empirical analysis was performed. Various methodologies were employed, and a reproducible approach was developed to identify transit deserts and directional dependencies using isochrones (lines connecting points that can be reached in equal travel time from a specific location).

The results, presented in multiple maps, reveal that transit deserts are predominantly located in the outer districts of Vienna. This is not solely due to the proximity to natural barriers but also structural factors within the transit network. Furthermore, the findings demonstrate that directional dependencies can be identified using the proposed methodology, enabling the detection of areas requiring additional transport infrastructure. This is shown by the U2 subway extension, which addresses an identified directional accessibility gap.

These findings show the importance of considering a wide variety of spatial information to adopt a holistic approach and achieve a comprehensive understanding of accessibility and network performance.

Zusammenfassung

Öffentlicher Verkehr spielt eine zentrale Rolle im Leben vieler Menschen, da er die Teilnahme an verschiedenen Aktivitäten ermöglicht und Verbindungen zu anderen Individuen und Orten schafft. Angesichts des fortschreitenden Klimawandels und dem Ziel, den globalen Temperaturanstieg zu begrenzen, müssen zahlreiche Veränderungen in verschiedenen Sektoren erfolgen. In Österreich ist der Verkehrssektor einer der größten Treibhausgasemittenten, weshalb ein leistungsfähiges und von möglichst vielen Menschen genutztes öffentliches Verkehrsnetz von entscheidender Bedeutung ist. Um ein solches Netz zu schaffen, ist eine Analyse des aktuellen Zustands notwendig, damit Problembereiche und mögliche Verbesserungen identifiziert werden können.

Das Ziel dieser Arbeit ist es, die Bedeutung und Funktionen des öffentlichen Verkehrs zu beschreiben, bestehende Methoden zur Identifikation von Transit Deserts (relativ schlecht angebundene Bereiche) zu untersuchen und eine neue Methode zu entwickeln, die sowohl Transit Deserts als auch Richtungsabhängigkeiten in Wiens öffentlichem Verkehrsnetz aufdeckt.

Um diese Ziele zu erreichen, wurde zunächst eine Analyse bestehender Erreichbarkeitsmaße durchgeführt und die Relevanz von Richtungsabhängigkeiten beschrieben. Auf dieser Grundlage wurde ein reproduzierbares Skript entwickelt, welches Transit Deserts und Richtungsabhängigkeiten mit Hilfe von Isochronen identifiziert.

Die Ergebnisse zeigen, dass Transit Deserts vor allem in den äußeren Bezirken zu finden sind. Dies lässt sich nicht nur durch die Nähe zu natürlichen Barrieren wie dem Wienerwald erklären, sondern auch durch strukturelle Merkmale des Verkehrsnetzes. Außerdem belegen die Ergebnisse, dass sich Richtungsabhängigkeiten mit der entwickelten Methode erkennen lassen. So können Bereiche identifiziert werden, die zusätzliche Verkehrsinfrastruktur benötigen. Dies wird anhand des U2-Ausbaus gezeigt, der ein erkanntes Erreichbarkeitsdefizit in eine bestimmte Richtung ausgleichen wird.

Diese Erkenntnisse verdeutlichen die Bedeutung einer ganzheitlichen Herangehensweise, die möglichst vielfältige räumliche Informationen berücksichtigt. So kann ein umfassendes Verständnis der Leistungsfähigkeit und Erreichbarkeit des Verkehrsnetzes dargelegt werden.

Acknowledgements

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1 Introduction

Public transport (PT) enables people to participate in daily activities, connects them with places and other individuals, and ensures inclusive access across society. It is vital for enabling equitable accessibility, including individuals without access to private vehicles, the elderly, and people with disabilities. Ensuring everyone can independently reach workplaces, healthcare, education, or social engagements requires a well-developed and inclusive PT network (Saif, Zefreh, & Torok, 2018, pp. 36–37).

Beyond its role in social inclusion and enhancing quality of life, PT also plays an important role in addressing climate change. In Austria, the transport sector is the largest emitter of greenhouse gases (without emission trading), highlighting the potential for improvement by enhancing PT and convincing more people to use that mode of transport. Furthermore, urbanization continues rapidly, which is why it becomes increasingly important to effectively assess PT networks in cities (Saif et al., 2018, p. 49; Umweltbundesamt, n.d.).

Reducing greenhouse gas emissions from traffic not only benefits the environment but also contributes to public health. Higher car traffic leads to increased pollution, which has been linked to a rise in hospitalizations among young children due to respiratory diseases (Bauernschuster, Hener, & Rainer, 2017, p. 31).

This thesis not only outlines the relevance of public transport and provides a technical and theoretical background for PT data (i.e., schedule and network data) storage and usage but also discusses methodologies for PT analysis. Based on this knowledge an empirical examination of Vienna's public transport network takes place to (1) find transit deserts (places with relatively low PT connectivity – details are given in Chapter 2.4) and (2) discover directional dependencies and patterns.

The methodology employed in this thesis is based on GTFS (General Transit Feed Specification) data and an OSM (OpenStreetMap) street network which enables the creation of a PT network. Based on that a network analysis is conducted and isochrones (lines connecting points that can be reached in equal travel time from a specific location) are generated to identify transit deserts and directional dependencies.

1.1 Motivation and Background

The preceding findings illustrate the social and environmental significance of PT and provide the motivation for analyzing PT connectivity, identifying transit deserts, and revealing underlying structural issues.

The city examined in this study, Vienna, is known worldwide as the most livable city (Economist Intelligence Unit Limited, 2023). One contribution to that reputation is its PT network consisting of multiple different modalities. However, questions remain about the spatial equity of this network: How evenly is the PT network distributed? Are there underserved areas with limited connectivity?

To answer these questions and to address potential service deficiencies, the PT network must be analyzed to identify irregularities and find transit deserts. Knowing where underserved areas are, understanding why they are underserved, and identifying structural imbalances is essential for informed planning and improving the existing network.

For example, a person can live near a subway station which has a high interval, but the route will just go into the city center. This dynamic can prove beneficial in certain scenarios, such as when an individual wishes to go shopping. However, it can also be limiting in other situations, such as when one needs to visit a nearby neighbor, or a doctor located in the adjacent district. This kind of directional dependence – where direction, not just distance affects accessibility – remains unexplored in transport research.

1.2 State of Research and Research Gap

Previous research has investigated accessibility in Vienna and across Austria. Notable examples include the ÖV-Güteklassen and the recently published ÖV-Erreichbarkeitsanalyse 2024 by the Österreichische Raumordnungskonferenz (ÖROK).

The ÖV-Güteklassen evaluates PT quality based on the proximity to stops and service frequency but does not analyze which destinations are reachable or the geographic extent of reachable area (ÖROK, 2022). For instance, a stop might have a frequent and fast service yet provide limited network coverage depending on the connected lines. Overall accessibility could be better if the frequency at one stop is lower but connects to a wider range of areas in the city. In contrast, the ÖV-Erreichbarkeitsanalyse 2024, assesses accessibility based on the access to Points of Interest (POI), including regional centers, supra-regional centers, and educational institutions (ÖROK, 2024). POI-based approaches are widely used (Boisjoly & El-Geneidy, 2017; Karner, Pereira, & Farber, 2024; Zhu, Liu, & Yeow, 2005) because they focus on access to actual opportunities. However, they conflate transport planning and urban planning, making it difficult to determine whether high or low accessibility results from transport infrastructure or the spatial distribution of destinations (Martens, 2015, p. 19).

For example, a region may score highly because many POIs are nearby and accessible by foot, even if public transport is minimal. Alternatively, strong PT service may connect people to more distant POIs. While both situations yield similar scores, their implications for planning are very different.

This does not imply that POI-based approaches are inadequate but that combining a network-based approach and a POI-based approach would provide a more holistic understanding of accessibility.

Furthermore, neither the ÖV-Güteklassen nor the POI-based ÖV-Erreichbarkeitsanalyse 2024 can show the underlying reason why a region becomes a transit desert nor identify directional dependencies. The research gap can thus be summarized as follows: existing methods capable of detecting transit deserts do not provide insights into the underlying spatial patterns or directional dependencies that contribute to accessibility deficits, and they offer no visual explanations to support the interpretation of the results.

1.3 Objectives and Research Questions

In response to the identified research gap the objectives are to:

- Identify transit deserts within the public transport network.
- Reveal and demonstrate directional dependencies that influence connectivity.
- Develop visualizations that illustrate these spatial patterns and directional effects, thereby improving interpretability and communication of accessibility issues.

These objectives will guide the investigation and help answer the following research questions:

1. How can transit deserts be detected?
2. Where are transit deserts located?
3. How can directional dependence be analyzed and visualized?
4. How can a method be developed which addresses the previous questions and can be applied to multiple cities?

1.4 Relevance

The relevance of this work stems directly from the identified research gap. By analyzing directional dependencies, this thesis provides deeper insights into the structural issues and imbalances within the public transport network. This enhanced understanding offers valuable information that supports more informed decision-making in PT planning.

Moreover, the ability to visualize underlying spatial patterns and the reasons why certain regions are underserved by public transport improve communication with decision-makers. Clear visual explanations help communicate complex accessibility challenges effectively, facilitating better planning and policy development.

1.5 Structure

Chapter 2 provides essential background information and reviews work relevant to this study. It begins with a discussion of the importance of PT and outlines various measures used to assess accessibility. Based on these measures, the concept of transit deserts is introduced and explained within the context of this thesis. The chapter then explores the concept of directionality, providing an explanation of directional dependencies and their role in public transport analysis. Finally, a technical foundation on public transport data and network data is given, including fundamental principles of graph theory relevant to the study.

Chapter 3 details the methodology and the used data sources employed in the analysis. The various steps to evaluate PT in Vienna are described, focusing on the identification of transit deserts and directional dependencies.

Chapter 4 presents the results of the analysis, illustrated with multiple maps that show key findings.

Chapter 5 offers a discussion of the results, describing the implications of the findings as well as the limitations and shortcomings of the study.

The Conclusion, Chapter 6, summarizes the main findings, addresses the initial research questions and objectives, and suggests directions for future research.

2 Background and Related Work

This chapter offers background information on the topic and reviews existing research relevant to this study. The first subchapter begins by clarifying the distinction between mobility and accessibility. It then highlights the importance of PT and reviews measures to quantify accessibility. Following this, concepts of transit deserts and directional dependence are introduced. At the end of this chapter a technical overview of PT and network data relevant to the analysis is given.

2.1 Mobility vs. Accessibility

As Geurs and van Wee (2004, p. 127) state, accessibility is often misunderstood and poorly defined. Additionally, mobility is used interchangeably with accessibility, even by researches and planners despite their different meaning (Pereira & Herszenhut, 2023). Therefore, the following section clarifies what mobility and accessibility mean in this work.

The concept of mobility describes people's travel behavior including the number of trips taken per day and the modes of transport used (e.g., bus and walking). The modal split is one result of a mobility-evaluation and describes the taken share of transport mode in a society. In Figure 1 the modal split of Vienna in the year 2023 is visible as an example.

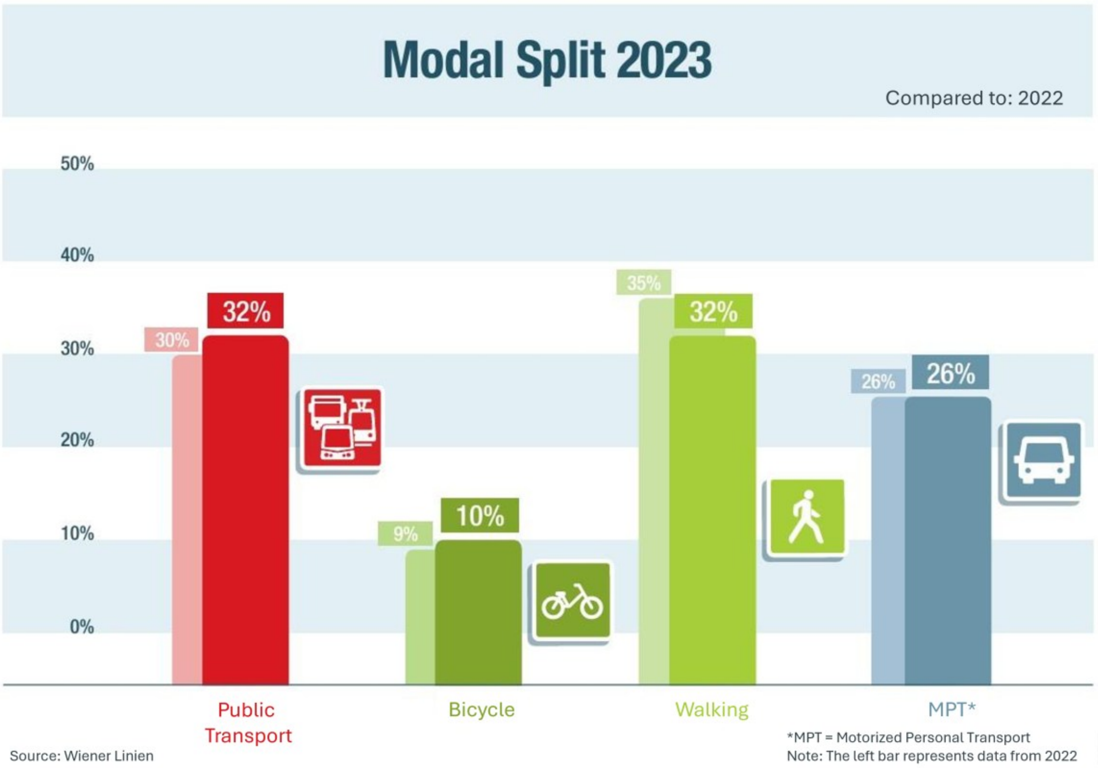


Figure 1: Modal Split Vienna (Wiener Linien, 2024).

Accessibility on the other hand describes "[…] the ease with which people can reach places and opportunities […]" as Pereira and Herszenhut (2023) say. In short, while mobility describes the actual travel behavior of people, accessibility describes the ease with which individuals can reach various opportunities within space. Consequently, accessibility has an important impact on the activities one can do depending on which places are reachable.

The degree of accessibility depends on three different aspects (Pereira & Herszenhut, 2023):

i. **Infrastructure.** The infrastructure of public transport plays a key role since access to activities depends on it. This includes coverage, connectivity of public transport and street networks, and the distribution of fast types of public transport like subways.

ii. **Land use.** The distribution of activities (e.g., schools and health services) is closely linked to accessibility, as those located farther away are more challenging to reach. Therefore, urban planning and transport planning depend on each other (more about that in Chapter 2.3.5).

   This idea aligns with Tobler's first law of geography, which states that the proximity of places plays a crucial role in their relation: "[…] everything is related to everything else, but near things are more related than distant things." (Tobler, 1970, p. 236). In other words, proximity plays a key role in how places interact,

iii. **People**. Also, personal characteristics affect access to activities. Factors such as gender, age, race or income affect the possibilities to move in space and use certain modes of transport significantly. For example, individuals with motor or cognitive difficulties could be excluded from using PT because it is not handicapped accessible. Furthermore, people of a specific race could be exposed to some kind of violence or discrimination and therefore cannot travel without fear. These factors can lead to social exclusion (see Chapter 2.2.2) and often receive little attention in large-scale transport analysis. This is because personal characteristics are better assessed through qualitative surveys due to computational challenges.

2.2 Relevance of Public Transport

"Accessibility is one of the most important outcomes of the transportation system." (Saif et al., 2018, p. 36). This importance arises from the impacts accessibility can have on individuals. However, a well-established public transport network enriches not only the lives of the directly affected people but also produces environmental benefits which affect everyone. The next subchapters examine these effects in more detail.

2.2.1 Health

In 2019, 34.5 % of the population in Austria were classified as overweight, which increases the risk of developing various diseases, including Type 2 diabetes and cardiovascular disorder (Statistik Austria, 2023). Obesity is, amongst other factors, a result of an excess calorie intake, which can occur due to either excessive food consumption or insufficient physical activity. Even small reductions in physical movements put individuals at risk. At the same time small improvements in activity lower the risk of becoming overweight. Because less vigorous forms of activity are easier for individuals to sustain, promoting daily walking can help individuals achieve their activity goals. Since the use of public transport increases the likelihood of walking, well established public transport which is available for many citizens helps more people to not get overweight (MacDonald, Stokes, Cohen, Kofner, & Ridgeway, 2010, pp. 105–106).

Furthermore, Bauernschuster et al. (2017, p. 31) could show that public transport has multiple other positive impacts on health by examining strikes in public transport in Germany. Public transport strikes lead to pollution shocks due to the increase in motorized individual transport which is needed for individuals to still travel. This results in a rise in pollution-related health issues. For example, hospital admissions among young children increase by 11 % on strike days because of respiratory diseases. In addition, during strikes the risk of being injured by a motored vehicle increases by 20 %. Basagaña et al. (2018, p. 1076) also show the increase of pollution during strikes, pointing out the impact of public transport on air quality. An increase in NOx between 4.1 % and 7.7 % was measured and the same was observed for black carbon. These examples show the importance of PT in relation to health by explaining the negative impacts the lack of this mode of transport entails.

2.2.2 Social Exclusion

The access to a well-functioning public transport system enables people to participate in various societal activities. Therefore, it is essential to ensure equitable access to transport. However, that is not always the case, as certain groups are more affected by transport-related social exclusion (Mackett & Thoreau, 2015, p. 611).

Social exclusion is a term used to describe "[…] circumstances where individuals or groups of people are unable to participate in activities or to access goods, services and opportunities that are available to others as a fundamental part of belonging to society.", as Mackett and Thoreau (2015, p. 610) explain. This can affect individuals with physical disabilities, those facing language barriers, or people who simply lack access to public transport. If certain areas are poorly connected – or not connected at all – to the wider transport network, individuals without alternative means of travel (e.g., private vehicle) are unable to reach essential destinations. For instance, if job opportunities are located in these areas, residents cannot attend an interview or secure employment due to limited travel possibilities (Mackett & Thoreau, 2015, p. 611).

2.2.3 Employment

Various studies have shown a connection between employment rates and access to public transport. PT plays a crucial role in job accessibility and, consequently, an individual's income. Greater access to job opportunities can improve a person's performance in the labor market and increase employment options that would otherwise be unavailable due to commuting constraints (Saif et al., 2018, p. 38).

2.2.4 Environmental Impact

But there are not just impacts on one's quality of life but also on the environment. Cities have an important role in the climate discussion by representing 70 % of all energy consumption and greenhouse gas emissions worldwide although they just cover 1 % of the total land mass. Despite this small number, cities house over half of the world's population (Cohen & Muñoz, 2016, p. 87; United Nations, 2007, p. 1).

In Austria in 2023, 44.8 % of greenhouse gas emissions derive from the transport sector making it the largest sector in terms of the amount of emission caused as shown in Figure 2 (without emission trading). Transport is a key challenge for climate, which is why Vienna aims to reduce per capita emissions by 50 % through improvements in public transport, among other initiatives (Stadt Wien, n.d.a; Umweltbundesamt, n.d.).

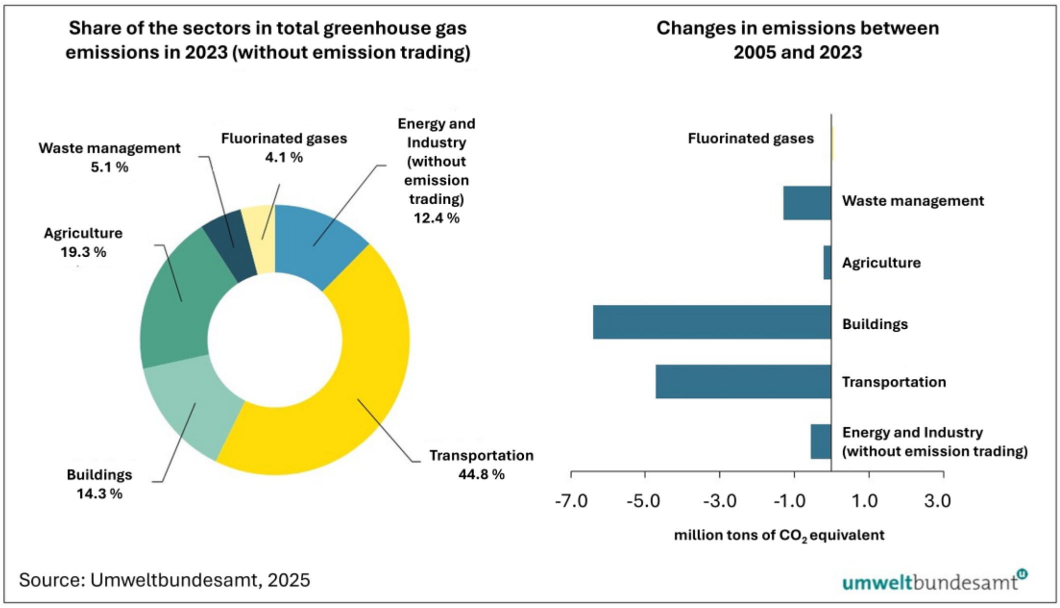


Figure 2: Greenhouse gas emissions in Austria (Umweltbundesamt, n.d.).

Given the mentioned impacts of public transport, it is important to improve this mode of transport where necessary. The first step is examining the network to discover possible shortcomings. The next chapter outlines different opportunities to do so.

2.3 How Can Accessibility Be Measured?

Accessibility can be measured in various ways. Two of the most commonly used measures focus on and how many points of interest are reachable (discussed in Chapter 2.3.1).
In Austria, the most renowned (based on the author's assumption) accessibility analysis, called ÖV-Güteklassen, has been conducted by the Österreichische Raumordnungskonferenz (ÖROK), which evaluates the accessibility in terms of the proximity to public transport stops and the types of services available at these stops (more details in Chapter 2.3.2). In 2024 an updated study has been published by the ÖROK which evaluates the accessibility of regional and supra-regional centers.
The following subchapters present an overview of different approaches used in scientific research and practical public transport planning. First, POI-based approaches will be described, including the cumulative opportunity measure, the gravity-based measure and the recent 2024 study by ÖROK. After that non-POI-based studies, which rely solely on network configuration, will be explained, including the ÖV-Güteklassen, the potential mobility index and the isochrone approach. At the end of this chapter a discussion of the various measures is provided, explaining the purpose of each measure and the reasons for choosing a particular one in this study.

2.3.1 Accessibility of POIs

The two most widely applied accessibility measures are based on the availability of reachable opportunities (POIs) and are explained in the following sections.

Cumulative Opportunity Measure

The Cumulative Opportunity Measure (COM) considers the number of POIs that can be reached in a given time as shown in Formula 1 (Pereira & Herszenhut, 2023). The more POIs are accessible in this period, the higher the accessibility score. While the distance to the POIs is not considered, the size (or weight) of the POIs is represented by O_j. For instance, if the accessibility of supermarkets is assessed, the size could be measured by the number of products or the square meters. POIs are thus weighted in the calculation. If O_j = 1, the POIs are not weighted (Kapatsila, Palacios, Grisé, & El-Geneidy, 2023, p. 3; Verduzco Torres & McArthur, 2024, p. 2).

One advantage of this method is that it is easy to grasp and can therefore be communicated well with decision-makers. However, it is "[…] believed to be a poor approximation to the way opportunities are perceived […]" (Kapatsila et al., 2023, p. 1) since POIs that are farther away are weighted the same as those that are closer.

$$A_i = \sum_{j=1}^{n} O_j \times \mathrm{f}(c_{ij})$$

$$\mathrm{f}(c_{ij}) = f(x) = \begin{cases} 1, & if\, c_{ij} \leq C \\ 0, & otherwise \end{cases}$$

Formula 1: Cumulative Opportunity Measure (Pereira & Herszenhut, 2023)

A_i… accessibility at origin i

O_j… number of opportunities at destination j

n… number of destinations in study area

$\mathrm{f}(c_{ij})$… binary function. 0 or 1, depending on the travel cost c_{ij} between i and j

C… travel cost threshold

Gravity-Based Measure

The gravity-based measure offers a more sophisticated assessment by incorporating both the number of reachable POIs and a distance-decay factor. It is based on the gravity model which assumes that the level of interaction between two activities depends positively on their size and negatively on the distance between them (Hansen, 1959, p. 73).

Formula 2 (Pereira & Herszenhut, 2023) shows the calculation of that measure and a linear decay function which could also be replaced by an exponential one. POIs which are farther away and thus more difficult to reach receive lower weights than closer ones. As Hansen (1959, p. 74) states, adjusting the exponent based on the type of POI is reasonable, since people's willingness to travel varies depending on the opportunity. For example, individuals are more willing to travel farther for jobs than for shopping. Therefore, for opportunities where longer travel is more acceptable, the exponent should be decreased to reflect a slower decline in accessibility. Additionally, similar to the COM, POIs are weighted by their size (e.g., number of products in a supermarket) in the gravity-based measure (Hansen, 1959, pp. 73–74).

While this method is based on a more refined understanding of accessibility, more sophisticated analytical skills are needed and communication challenges can arise when explaining results to non-expert decision-makers (Kapatsila et al., 2023, pp. 1–2).

Furthermore the findings of Santana Palacios and El-Geneidy (2022, p. 5) “[…] strongly suggest that estimating access to jobs by public transport using the cumulative opportunities approach highly approximates the best performing gravity-based access measures promoted in transport planning and geography scholarship.”

$$A_i = \sum_{j=1}^{n} O_j \times \mathrm{f}(c_{ij})$$

$$f_{lin}(c_{ij}) = f(x) = \begin{cases} 1 - \frac{c_{ij}}{C}, & if\, c_{ij} \leq C \\ 0, & otherwise \end{cases}$$

Formula 2: Gravity-based measure (Pereira & Herszenhut, 2023)

A_i… accessibility at origin i

O_j… number of opportunities at destination j

n… number of destinations in study area

$f_{lin}(c_{ij})$… linear decay function depending on the travel cost c_{ij} between i and j

C… travel cost limit

ÖROK Accessibility Analysis

The ÖROK Accessibility Analysis, conducted in 2024, can be classified as a POI accessibility study. The focus of this study lies on the accessibility of regional and supra-regional centers as well as educational institutions. In this context, regional centers refer to Bezirkshauptstädte, and supra-regional centers to Landeshauptstädte. For Vienna, multiple regional and supra-regional destinations are defined (ÖROK, 2024, pp. 13–14).

These central regions are identified as key destinations due to their provision of essential central facilities. Since such facilities can be seen as POIs, the study can be considered POI-based.

To carry out the analysis, a 100 m x 100 m raster grid is applied across Austria. For each cell, accessibility to the defined destinations – which are the highest-ranking PT nodes of central regions (regional and supra-regional centers) – is assessed using both PT and walking. A regional center is classified as accessible if it can be reached within 30 minutes, and a supra-regional center if it is accessible in 50 minutes (ÖROK, 2024, pp. 7–14).

2.3.2 Stops and Types of Transport – ÖV-Güteklassen

The ÖV-Güteklassen (public transport quality classes) were developed by ÖROK as part of the “ÖREK Partnerschaft Plattform Raumordnung und Verkehr” and serve as a tool to assess public transport accessibility in Austria. These quality classes aid in analyzing, evaluating and planning to determine standards for settlement- and public transport development (ÖROK, 2017, p. 5).

The ÖV-Güteklassen evaluate public transport accessibility based on two key factors: (1) the accessibility of stops by walking and (2) the operating quality available at these stops. The classification depends on the following aspects:

i. **Accessibility of stops:**
   - Walking distance to stops

ii. **Operating Quality:**
   - Type of public transport (e.g., train, bus)
   - Frequency of service

The accessibility of stops in combination with the operating quality results in the classification (ÖROK, 2017, pp. 7–15).

2.3.3 Potential Mobility Index (PMI)

Another approach to measure accessibility is the Potential Mobility Index (PMI). The PMI is a measure of potential mobility and "For one origin destination pair, the PMI is defined as the quotient of the aerial or Euclidean distance ('as the crow flies') and the travel time on the transport network between that origin and that destination." (Martens, 2017, pp. 154–155). In Formula 3 (Martens, 2017, p. 155) the calculation is visible. As mentioned in Chapter 2, the terms "mobility" and "accessibility" are often used interchangeably in the field of public transport. Potential mobility, in this case, can be understood as a form of accessibility analysis since the result is comparable to the reachable surface area, similar to the concept explained in the next section.

$$PMI(i) = \frac{1}{n} * \sum_{i=1}^{n} \frac{d(i, j, \dots n)}{T(i, j, \dots n)}$$

Formula 3: Calculation of the PMI (Martens, 2017, p. 155)

$PMI(i)$… average areal speed for zone i

$d(i, j, \dots, n)$… aerial distance between zone i and zone j

$T(i, j, \dots, n)$… travel time in the transport network between zone i and zone j

2.3.4 Accessibility of Area using Isochrones

A further method of measuring accessibility is using isochrones, which represent the area that can be reached within a given time. Instead of counting the number of POIs, the accessible area in square meters is evaluated. That provides advantages and disadvantages which are mentioned in Chapter 2.3.5 (O'Sullivan, Morrison, & Shearer, 2000, pp. 85–86).

Compared to the PMI, the isochrone-based method provides additional insights and offers enhanced opportunities for visualization, as it produces not just a single index but also isochrones for each evaluated origin point. Furthermore, the isochrone approach can be easily expanded, reusing the calculated areas. This measure will be explained in more detail in Chapter 3 since it plays a key role in the methodology (O'Sullivan et al., 2000, p. 89).

2.3.5 What is the Best Measure?

No single measure can comprehensively account for all factors simultaneously. The choice of the most appropriate measure depends on the goal, and in many cases, a combination of multiple measures may be necessary. Also, each measure has its own strengths and limitations.

The Importance of the Objective

The suitability of a measure depends on what should be discovered. For example, while the ÖV-Güteklassen, isochrones and PMI only consider the public transport network, the COM, the gravity-based measure and the ÖROK accessibility analysis 2024 depend on the spatial distribution of opportunities and the infrastructure of the PT network. This is because the last three approaches are also dependent on the spatial distribution of POIs. Thus, these methods analyze aspects of urban planning and transport planning together. The disadvantage is that the result does not reveal which factor contributes to the score.

For instance, when using the COM, a high accessibility score means that many POIs are reachable. The underlying cause of this result cannot be discovered by that score. There are three distinct scenarios which can lead to the same high score, illustrating the limitations of solely applying the COM (Martens, 2015, p. 19).

- **i.** A high density of POIs near the origin suggests that the public transport network is less critical, as these points may be accessible on foot.
- **ii.** A well-established PT network enables the reachability of distant POIs because one can travel far easily and reach many places. The score will also be high in that case even if all POIs are far away.
- **iii.** The last reason for a high score is that the PT network is relatively good, and the POIs are relatively well distributed.

In contrast, the ÖV-Güteklassen, PMI and isochrones do not depend on POIs because they solely focus on the PT network itself. Consequently, the disadvantage is that nothing can be stated about reachable opportunities.

The previous examples illustrate that no single measure is universally applicable, and the appropriate approach depends on the specific objectives. For a comprehensive examination of a PT network, multiple measures should be used in combination.

Martens (2015, pp. 20–21) addressed this by introducing the POMA (Potential Mobility and Accessibility) framework, which integrates transport planning and urban planning. As shown in Figure 3, this framework combines two measures: the accessibility of POIs on the x-axis (“accPOI”, which reflects urban planning) and the accessibility of area on the y-axis (“accA”, which reflects the transport planning).

The grey dots in Figure 3 represent examples for analyzed regions, where both accPOI and accA values have been calculated to explain the figure.

Quadrant 1 describes a scenario where the spatial coverage (accessibility of area) is below the average, and the accessibility of POIs is below the POI accessibility poverty line. Accessibility poverty occurs when individuals are unable to meet their daily needs due to a lack of available transport and access to opportunities. This can result from different causes, such as poor PT or the lack of an automobile. The poverty line should be set by decision-makers, but it can be challenging to define due to the limited literature on this subject (Karner et al., 2024).

Quadrant 1 indicates not only poorly developed urban planning (low accPOI) but also poor PT connectivity (low accA). Quadrant 2 describes a situation where the accessibility of POIs is above the poverty line, but the accessibility of area is below average, indicating well-developed urban planning and weaker transport planning. Quadrant 3 shows regions with both high accA and accPOI, reflecting strong transport and urban planning. Quadrant 4 shows regions with high accA but low accPOI, indicating a well-established transport system but a low number of reachable POIs.

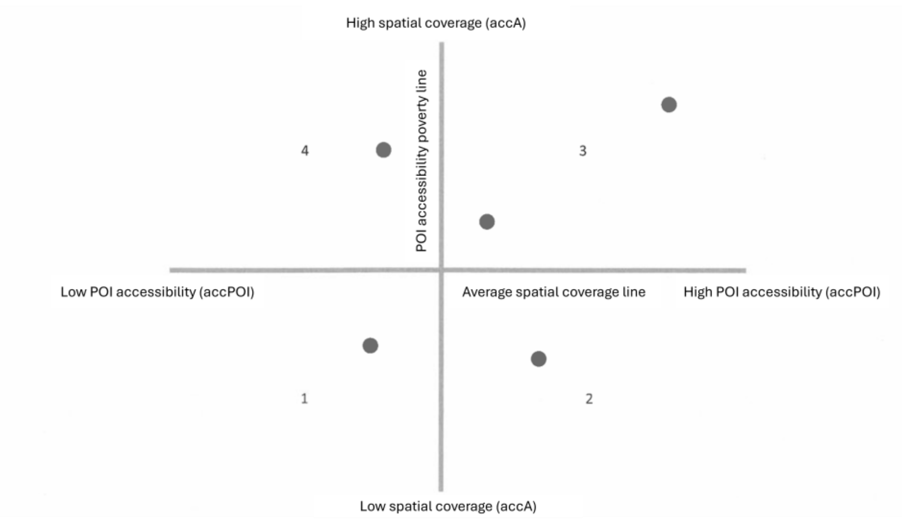


Figure 3: POMA framework (Martens, 2015, p. 22).

Depending on the goal, improvement of the PT network should be considered in areas with low spatial coverage, even when accPOI is high, because individual and subjective destinations (e.g., a friend's place) are not taken into consideration using POIs. Better overall accessibility could provide sufficient connectivity. Furthermore, if accPOI is below the poverty line but accA is high, the distribution of opportunities should be considered (urban planning) (author's assumption).

Since there is no universally agreed-upon minimum threshold for accessibility, situations must be evaluated individually. However, accessibility scores can help identifying outliers and provide an overview of the situation (Karner et al., 2024).

A New Approach

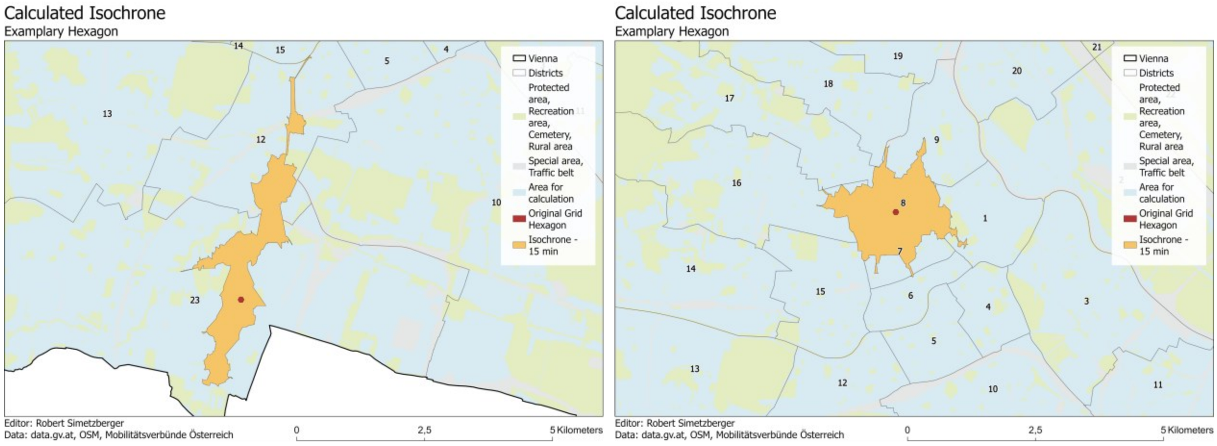
The POMA framework holistically examines PT networks and can deliver information not just about transport planning but also urban planning. However, there are also limitations:

i. **Communication Challenges:** The PMI is not trivial and thus not easy to communicate with decision-makers. It can be interpreted as the area accessible in space, but no visual representation is available since it is never calculated. Since transport and urban planning highly rely on decision-makers, clear communication plays a key role in any measure.
ii. **Lack of Spatial Insights:** The PMI cannot reveal spatial tendencies, such as varying accessibility in different directions. As mentioned in the introduction, no existing research has explored how to incorporate directional dependencies into accessibility measures. The POMA framework also does not take that into account.

To address these gaps, this thesis proposes a new approach leveraging the existing isochrone measure within the POMA framework. This approach focuses on the calculation of the area-based accessibility (accA) and the potential of this measure to analyze public transport networks. Visualizing directional dependencies and isochrones offer deeper insights, leading to better communication and understanding.

Figure 4 illustrates this using two example isochrones that cover the same area in terms of square meters. At first, accessibility appears equal. However, visual inspection reveals strong differences. In map (a), accessibility is highly directional, with limited spatial coverage. In contrast, map (b) shows broader, more evenly distributed coverage. These visual distinctions offer valuable insights into how accessibility varies across regions.

Figure 27 further demonstrates that reachability is strongly direction dependent in Vienna’s PT network. Furthermore, the COM is just one processing step away, requiring only the intersection of data. More details will be explained in Chapter 3.



(a) (b)

Figure 4: Comparison of two isochrones with equal area (15-minute travel time) but different spatial distributions. Map (a) shows limited directional accessibility, primarily along a transport corridor, while map (b) demonstrates more balanced coverage across multiple directions. This highlights the added value of visual analysis when assessing public transport accessibility.

2.4 What Are Transit Deserts and How Can They Be Detected?

Transit deserts were first described by Jiao and Dillivan (2013, p. 23) as the gap between transit supply and demand (see Chapter 2.4.1). In this thesis, the term “transit desert” refers to regions that are underserved by PT compared to other regions included in the analysis. Whether a region is classified as a transit desert depends on its relative performance within the study area, as no universally accepted threshold currently exists to define underserved transit access. Further details are provided in Chapter 3.2.3.

After calculating accessibility for different origins using one of the previously mentioned measures, further analysis is needed to identify transit deserts in the PT network. When only using the accessibility score, these results can be visualized on a map, and concentration of high and low accessibility can already be observed. This is demonstrated in Figure 5, where areas with very good (dark green) connectivity and bad (light green) connectivity are already apparent. At this point, however, nothing can be said about the extent of accessibility poverty – the distance between actual accessibility and an acceptable threshold of accessibility. Therefore, it is unclear if a region is underserved by PT and qualifies as a transit desert.

The goal is to quantify this accessibility poverty gap for each region and visualize it on a map. The FGT_2 index, which will be explained in Chapter 2.4.1, not only offers a comprehensive measure of overall inequality, which will be used to assess overall accessibility poverty, but also measures the accessibility poverty gap for each cell. This focuses on the individual shortfalls in accessibility at specific locations. Chapter 2.4.1 provides an explanation of the FGT_2 measure and other possibilities to calculate accessibility inequalities.

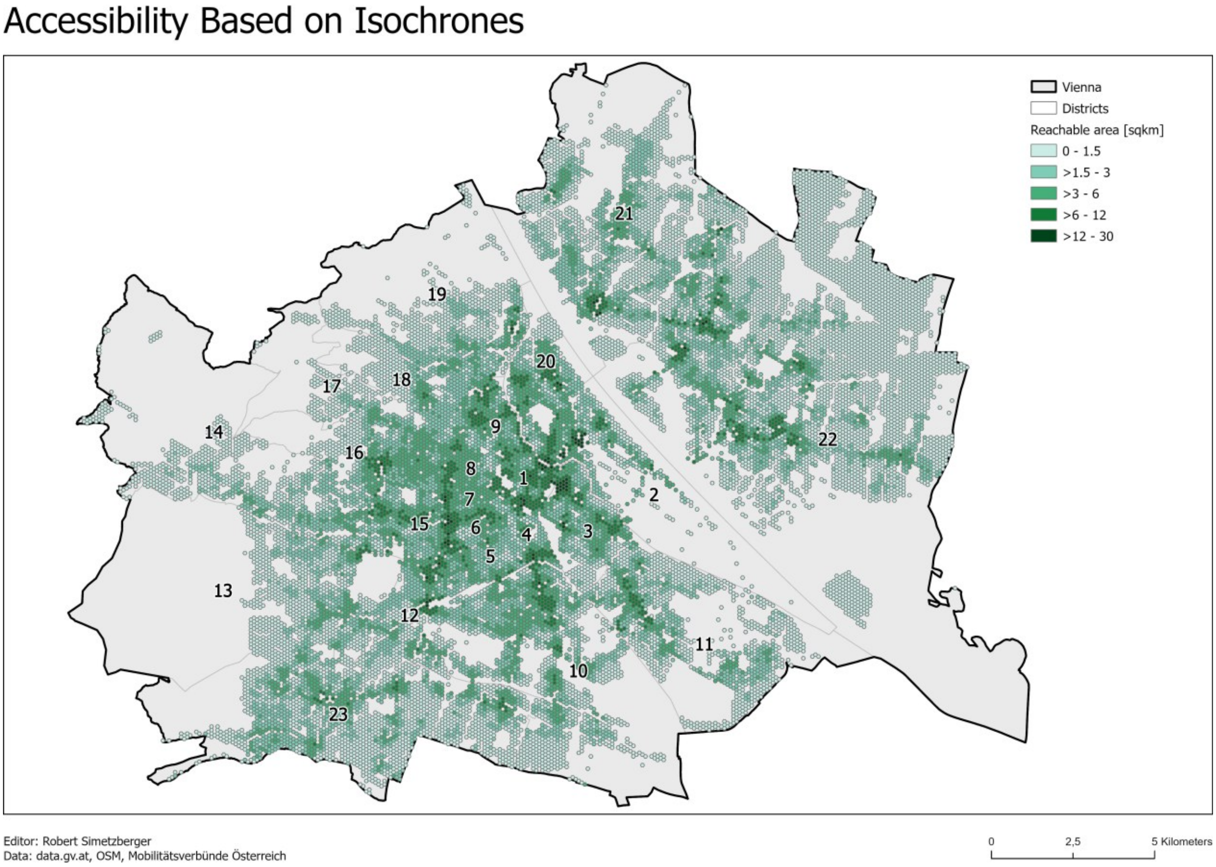


Figure 5: Accessibility scores for reachable area per hexagon.

2.4.1 How to Measure Accessibility Poverty?

There are different possibilities to identify inequalities and poorly connected places in a transport network. The most widely used approaches to identify accessibility poverty are the Gini coefficient/Lorenz Curves and the needs-gap method (Karner et al., 2024).

Lorenz Curve and Gini Coefficient

Originally, the Lorenz curve was used to represent income inequalities by plotting the accumulated distribution of income on the y-axis and the accumulated distribution of the population, ranked by the income, on the x-axis. An example is visible in Figure 6 (Karner et al., 2024).

The Gini coefficient is then calculated by the area between the Lorenz curve and the line of equal distribution. The higher the coefficient, which reaches from zero to one, the more unequal the distribution (Karner et al., 2024).

Since the 2000s, the Lorenz curve and Gini coefficient have been used more frequently in research on transport inequalities including accessibility inequalities (e.g., access to transit stops) (Delbosc & Currie, 2011; Karner et al., 2024).

Among other limitations discussed in Karner et al. (2024), one disadvantage of this measure is that it assesses overall inequality without accounting for the distribution of accessibility shortfalls. As a result, it does not capture the severity (i.e., the distance below the poverty threshold) of accessibility gaps at individual locations. Therefore, the specific distribution of transit deserts cannot be visualized on a map, making it impossible to identify and highlight these areas.

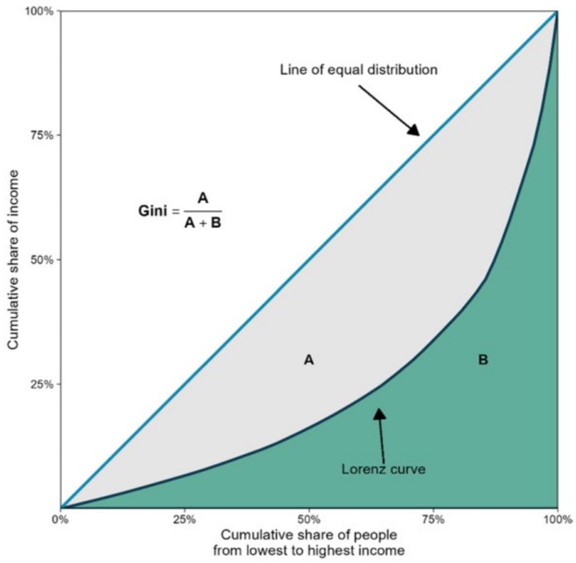


Figure 6: Lorenz-Curve (Karner et al., 2024).

Needs-Gap

The needs-gap approach quantifies gaps between potential transit (transit supply) and accessibility needs (transit demand). Locations where transit demands exceed transit supply can be referred to as needs-gaps or transit deserts (Currie, 2010; Karner et al., 2024).

A key limitation is that measures of supply (e.g., proximity to stops and frequency) and demand (e.g., population density and travel patterns) are often mismatched, meaning that they do not capture concepts which are similar enough to compare. Therefore, calculating the difference to discover balance or imbalance does not bring valuable insights, making it impossible to accurately identify accessibility poverty in transport networks (Karner et al., 2024).

Foster-Greer-Thorbecke

In contrast to the previously mentioned approaches there is a more promising alternative, the transport adapted Foster-Greer-Thorbecke (FGT) measure, which is independent of supply and demand values and takes both the number of individuals below a poverty line and also the size of the accessibility shortfall relative to it into account. The FGT was originally designed to measure income poverty and has first been used in the field of transport equity by Martens (2017, pp. 158–159).

The FGT, defined in Formula 4, not only considers the number of individuals below the poverty line but also captures the distribution of income among the poor.

$$FGT_\alpha = \frac{1}{N}\sum_{i=1}^{H}(\frac{z - y_i}{z})^\alpha$$

Formula 4: Calculation of FGT measure (Karner et al., 2024)

N … size of the population
z … poverty line
H … number of individuals below the poverty line z
y_i… "income" or accessibility level of individual i
α… parameter determining the sensitivity to poverty gap changes

There are three different FGT indices, based on parameter α. If α = 0, the proportion of individuals below the threshold is calculated. When α = 1, the FGT measures the average percentage distance between the poverty line and each individual's accessibility level. The most used variation in economics is when α = 2. FGT_2 assigns a weight to each poor person or group depending on the income shortfall (the difference between the poverty line and the person's income). The greater the shortfall, the greater the weight is given in the overall measurement of poverty. Thus, the measure generates an index for severity which not only considers the number of people below the poverty line but also the size of the shortfall relative to it, making it sensitive to the depth of poverty. The assigned weight is the size of the shortfall itself (Karner et al., 2024; Martens, 2017, pp. 158–160).

As previously mentioned, the FGT_2 has been adapted by Martens (2017, pp. 158–159) for use in transport research where it measures the extent and severity of accessibility poverty instead of income poverty.

The term in the summation ($(\frac{z-y_i}{z})^2$) refers to the poverty gap for each respective region/individual i. By squaring this result, regions with especially low accessibility are emphasized. These interim results allow for the identification of transit deserts, which can be visualized on a map.

The result of the FGT_2 describes the overall inequality, providing a broader view that allows for comparisons between different groups (e.g., districts). When the entire population is below the poverty line, FGT_2 reaches 1 and if every individual is above this threshold, it reaches 0.

A key challenge with the FGT is defining the poverty line, ideally set by decision-makers and residents. Since such standards do not exist yet, determining an appropriate threshold can be difficult, partially explaining the little use of this measure (Karner et al., 2024).

2.4.2 Which Measure is The Best for Identifying Transit Deserts?

Since one objective of this study is to identify transit deserts, a measure to quantify the poverty gap in each analyzed region is required. The FGT_2 is the preferred measure for this purpose. It provides individual results for each region, weighing them according to their accessibility shortfall. This allows for the identification of regions with particularly poor connectivity. Additionally, it offers an overall measure of inequality, which can be used for comparison across regions.

2.5 Directional Dependencies in Public Transport Networks

In addition to identifying transit deserts, this study aims to reveal directional dependencies – spatial tendencies where travel efficiency varies based on direction. Understanding these tendencies is essential for a more comprehensive analysis of transit deserts, as some areas may not only be poorly connected but also have unequal connectivity depending on the direction of travel. Moreover, locations that appear well-connected may be highly directionally dependent, meaning individuals can only reach certain destinations quickly in specific directions.

The detection and quantification of spatial patterns have been of great interest in various fields, with Tobler's first law of geography (see Chapter 2.1.2) guiding much of this research. However, as Zhu, Janowicz, and Mai (2019, p. 413) point out, this law only considers distance while ignoring directional influences, known as anisotropicity (rotation variance). This represents a fundamental concept in GISience. Zhu et al. (2019, p. 413) propose a generalized version of this law, which integrates anisotropicity and makes directionality a first-class citizen.

2.5.1 What Are Directional Dependencies?

As already mentioned in Chapter 2.3, directional dependence (rotation variance) is also known as anisotropicity, meaning that the value and change of an attribute depends on the direction. For example, the impact of wildfires on air quality is heavily influenced by wind direction as shown in Figure 7 – individuals far from the fire may experience higher pollution than those nearby, depending on the wind direction (Zhu et al., 2019, p. 399).

Figure 7: Smoke streams in Madeira, 2024 (Dauphin, 2024).

In public transport networks a similar effect can occur: two locations that are physically similar close may have vastly different travel times based on the structure of the network, illustrating the importance of directionality.

2.5.2 Why Does Directionality Matter?

"One could argue that anisotropic patterns are the rule, not the exception." (Zhu et al., 2019, p. 399).

Directionality matters in various fields due to its different impacts it has. In transport planning, directional dependencies play a crucial role in determining how easily different areas can be reached. Due to the network's configuration, geographically closer locations may take longer to reach than more distant ones due to the lack of isotropicity. For instance, if the city center is well-connected from a starting point in an outer district, but an adjacent district is not, traveling to the city center might take only 10 minutes, while reaching the adjacent district could take twice as long, despite its proximity.

As already mentioned in the previous chapter, public transport planning mostly focuses on the identification of transit deserts but not on the underlying tendencies which can affect these deserts. By considering both directional tendencies and overall accessibility, deeper insights can be gained into how people perceive their ability to reach destinations and how transit deserts emerge.

2.6 Public Transport Data

To perform the various analyses described in the previous sections, data that contains public transport and road network information is needed. The following chapters explain the technical background of these data, including the structure and format in which they are stored.

2.6.1 Historical Background

Public transport data, including schedules and routes, has been around for a long time. However, before 2005 it was often difficult to access. Transit agencies stored the data and provided it on their own platforms, making it difficult for the average citizen to find and use, particularly in foreign cities and countries. Therefore, using public transport in unfamiliar cities was not as user-friendly as it could have been (McHugh, 2013, p. 125).

In 2005, Bibiana McHugh, an IT manager for Geographic Information Systems (GIS), identified this issue while travelling, where she came up with the idea of creating a general standard for public transport information. Collaborating with Google, McHugh helped develop the Google Transit Feed Specification in 2005, an open standard data format that quickly gained traction. One of the biggest advantages is its accessibility and ease of use. By making public transit data easily available in a standardized format, millions of users worldwide can now access transit information through familiar applications (McHugh, 2013, pp. 125–127).

The introduction of GTFS removed the need for users to search the web for information provided by local transit agencies, which improves the user experience of public transport. Routing, using public transport is now as easy as routing for traveling by car. As a result, public transit became more convenient and competitive with other modes of transport (McHugh, 2013, pp. 125–127).

Today GTFS stands for General Transit Feed Specification. The replacement of the word Google with General reflects its widespread adoption. Hughs (2009) stated: "Given the wide use of the format, and the community process that this group uses to develop new extensions to the format, the 'Google' in GTFS is increasingly a misnomer, one that makes some potential users shy away from adopting GTFS. A data format becomes useful as more people use it, so if there are simple things that we can do to make GTFS more appealing to potential users, we should do them."

2.6.2 Technical Background on GTFS Data

GTFS schedule data is stored in simple csv files with a .txt file extension. These files are linked to each other with cross-referenced fields and are contained in a zip file. At its most basic form seven files create the GTFS dataset, shown in Table 1, which can be described as follows: "A GTFS schedule dataset has one or more routes (routes.txt), each route has one or more trips (trips.txt), each trip visits a series of stops (stops.txt) at specified times (stop_times.txt). Trips and stop times only contain time of day information; the calendar is used to determine on which days a given trip runs (calendar.txt and calendar_dates.txt). Additionally, multiple agencies (agency.txt) can operate multiple routes." (Mobility Data, 2024). The relation between the basic files is illustrated in Figure 8.

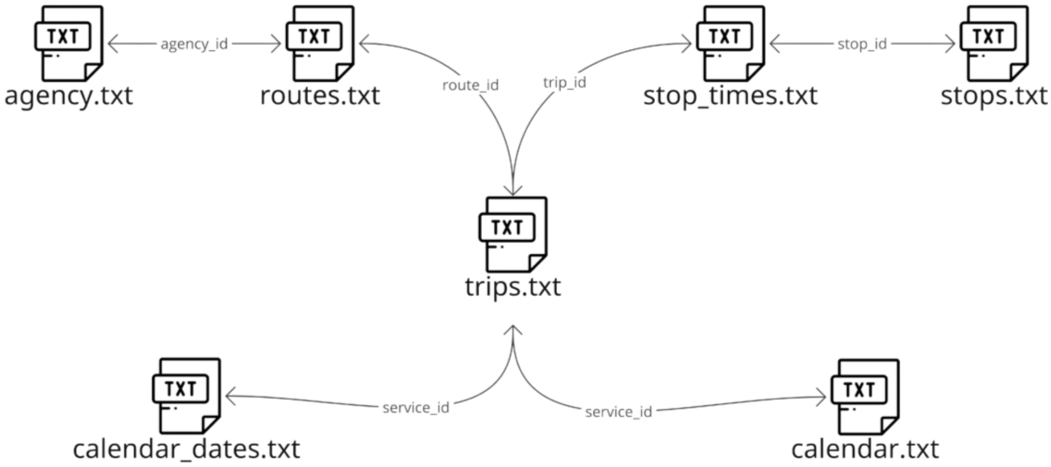


Figure 8: Relationship between the basic files of a GTFS schedule dataset (Mobility Data, 2024).

Additionally, to the basic set of files, optional files can be added to provide more information. For example, the shapes.txt file contains geographic information about the paths. For more optional files see Mobility Data (2024).

Filename	**Description**
agency.txt	"Transit agencies with service represented in this dataset."
routes.txt	"Transit routes. A route is a group of trips that are displayed to riders as a single service."
trips.txt	"Trips for each route. A trip is a sequence of two or more stops that occur during a specific time period."
stops.txt	"Stops where vehicles pick up or drop off riders. Also defines stations and station entrances."
stop_times.txt	"Times that a vehicle arrives at and departs from stops for each trip."
calendar.txt	"Service dates specified using a weekly schedule with start and end dates."
calendar_dates.txt	"Exceptions for the services defined in the calendar.txt."

Table 1: The basic files of a GTFS dataset (Mobility Data, 2024).

2.7 Graph Theory – Networks

GTFS data enables the storage of schedule information data for public transport systems. All the approaches discussed in the previous sections rely on a routable network. This means structuring the data so that directions between two points can be generated. Graph theory lays the foundation for creating such routable networks.

2.7.1 Basics of Graph Theory

Graph theory is a fast-evolving discipline of discrete mathematics and has a significant impact on both mathematical and non-mathematical fields. Its methodologies and concepts are fundamental in fields such as computer science, biology, and logistics. Graph theory offers the possibility to study systems composed of interconnected components. This includes applications in navigation systems, transport networks, and social network analysis, where understanding relationships and connectivity is essential. One real world example for such a system can be a public transport network. It consists of interconnected components where the components are stops and the connection is given by the routes between those stops (Nickel, Rebennack, Stein, & Waldmann, 2022, p. 119).

A common and practical problem faced by millions of people daily is determining how to travel from a starting location to a destination. Whether it involves walking, driving, or using public transport, solving this problem efficiently depends on understanding and analyzing the structure of the underlying transport network. This is where graph theory becomes essential. It provides the mathematical foundation for representing such networks and developing algorithms that can solve routing, scheduling, or optimization problems within them.

Mathematical Representation of a Graph

In essence, a graph is a mathematical representation of a network. Formally, a graph is defined as a pair $G = (V, E)$, where:

- $V = \{v_1, \dots, v_n\}$ is a finite set of nodes, which represent entities or locations and
- $E = \{e_1, \dots, e_m\}$ is a set of edges, which represent the connections or relationship between the nodes.

Edges consist of elements that are either unordered pairs $\{v_1, v_2\}$ or ordered pairs $\{v_1, v_2\}$ where $v_1, v_2 \in V$. If the edges are unordered pairs the graph is called undirected and if they are ordered it is called directed. Thus, in an undirected graph, the order of nodes does not matter, while in a directed graph, the order indicates the direction of the edge. Illustrative examples are shown in Figure 9. A real-world example of directed graphs in transport is one-way streets, where movement is only permitted in one direction (Iwanowski & Lang, 2021, p. 257; Nickel et al., 2022, p. 120).

Furthermore, edges in a graph can be assigned weights, which are numerical values that represent quantities such as distance or travel time. Generally speaking, this weight is called the cost in graph theory. Such graphs are referred to as weighted graphs or networks and an example is also shown in Figure 9.

Graph Theory in Transport

Weighted graphs play an important role in real-world applications like transport networks where different paths may vary in travel duration. In such cases, algorithms that operate on weighted graphs help identify the fastest route from one point to another. The following example should illustrate that: Assuming that the network given in Figure 9 is a PT network and the weights correspond to travel times in minutes. There are multiple options to reach Point F from Point A but only one is the fastest option, the option with the lowest total cost. One possibility is following the route A → B → D → E → G → F which has a total cost of 15 min. The fastest route on the other hand is A → C → E → G → F with a total cost of 11 min. As shown in this example multiple options exist to travel from Point A to Point F but only one option is the fastest. In this example it is relatively easy to identify the route with the lowest total cost but in real world applications, which can be much larger, this task becomes increasingly complex. Therefore different algorithms exist to identify routes depending on different objectives (Iwanowski & Lang, 2021, p. 278).

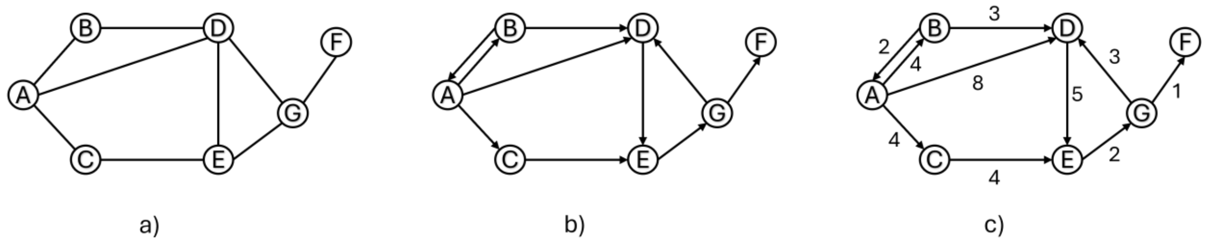


Figure 9: a) not directed and b) directed and c) directed weighted graph (own representation, 2024).

2.7.2 Algorithms in Graph Theory

As already mentioned, a common challenge in the field of public transport is determining the shortest path between two points. This problem is typically solved using a weighted graph where the edges present either travel times or distances. Different algorithms can compute the shortest path, with the Dijkstra algorithm being used in this thesis.

Dijkstra's-Algorithm

The Dijkstra algorithm is widely used to identify the shortest path in networks and plays a crucial role in transport navigation. It works by calculating the minimum cost from a start point to an end point, where the cost corresponds to the edge weight, such as distance or travel time (Dijkstra, 1959, pp. 269–271; Nickel et al., 2022, pp. 125–126).

The algorithm is explained in the following steps (Delling, Pajor, & Werneck, 2015; Iwanowski & Lang, 2021, pp. 281–282; Nickel et al., 2022, pp. 126–127):

i. **Initializing:** Assign all nodes an initial distance of ∞ (infinity) except for the starting node, which is set to 0. Every node is marked as unvisited and saved in a priority queue, which is ordered by distance so that the node with the smallest distance is always at the front.

ii. **Update Neighbors:** For the current node (starting with the starting node), examine all its unvisited neighbors. For each neighbor, calculate the new cost which is the current node's distance plus the edge weight from the current node to the neighbor. If this new cost is smaller than the neighbor's current cost, update the neighbor's cost with this lower value in the priority queue.

iii. **Select Next Node:** Mark the current node as visited, remove it from the priority queue and select the unvisited node with the smallest known cost (the one at the front of the priority queue). This node becomes the new current node.

iv. **Repeat:** Repeat steps 2 and 3 until the target node is reached or the priority queue is empty (meaning no path exists).

v. **Result:** Since the shortest path is always chosen during the updates, the shortest path for the starting point to the target node is determined.

RAPTOR-Algorithm

Another important algorithm in this thesis is RAPTOR (Round bAsed Public Transit Optimized Router), which is specifically designed for routing along public transport networks. While Dijkstra's algorithm can solve routing problems in transit networks, it faces significant challenges when transfers, schedules and more information (e.g., fares) are considered. Incorporating that information in the Dijkstra algorithm increases computational complexity, making it impractical for large transit systems. Furthermore, schedules are not fixed and change over time, making the Dijkstra algorithm even more impractical, as it relies on preprocessing (Delling et al., 2015).

Delling et al. (2015) studied the problem of computing best journeys in PT networks and introduced RAPTOR to identify the best journeys by minimizing arrival time and the number of transfers. RAPTOR is not Dijkstra-based and operates in rounds, where each round corresponds to a specific number of transfers allowed. In each round, arrival times for all reachable stops are calculated by traversing each route no more than once. This round-based design makes RAPTOR easy to parallelize, distributing routes across multiple CPU cores. Additionally, RAPTOR requires no preprocessing, allowing it to handle schedule changes and delays efficiently, and it eliminates the need for a priority queue, which can slow down calculations.

The RAPTOR algorithm is explained in the following steps (Delling et al., 2015):

i. **Initializing:** Create an array with the length of the transfers allowed to store the arrival times for each stop. Set every arrival time at each stop to ∞ except for the source stop, which is assigned the departure time.

ii. **First Round (0 Transfers):** Starting at the source stop, all reachable stops are evaluated and the arrival times are updated.

iii. **Next Rounds (1 or more transfers):** In the following rounds, the stops reached in the previous round are considered. Starting from these stops, all possible trips are evaluated, and the arrival times at each stop are updated.
If two stops are connected by walking, the arrival time at the second stop is updated based on the walking time.

iv. **Stopping Condition:** If no improvement is made to the arrival times at any stop in a round, no better journey can be found, and the algorithm stops.

Explaining more algorithms in detail would (1) go beyond the scope of this study and (2) not be helpful for further understanding of this work. For further information on computational foundations of shortest path algorithms and more see Nickel et al. (2022) and Delling et al. (2015)

3 Identifying Transit Deserts and Directional Dependencies – Method

This chapter outlines the methodology and procedures used to achieve the objectives mentioned in the introduction: (1) identifying transit deserts and (2) analyzing directional dependencies within Vienna's public transport network.

This chapter is structured as follows: first, the process of data collection and data preprocessing are explained. Next, the method developed to identify transit deserts and directional dependencies is described.

3.1 Data

The methodology in this thesis relies on analyzing accessibility using two transport modes: public transport and walking. Therefore, a network capable of facilitating routing for these modes is constructed by integrating GTFS data and a street network. The combination of these datasets enables multimodal routing, leveraging the GTFS data for PT routes and schedules, and OSM data for walking routes. The following sections provide an overview of the data sources used and preprocessing steps applied.

3.1.1 Data Collection

First, to define the study area, the administrative boundary of Vienna is used. Additionally, to delimit the area for which the calculations are performed within Vienna, the land use plan (Flächenwidmungsplan*)* is used. To carry out accessibility calculations, a routable network is required, which was generated using OSM and GTFS data. The used data is shown in Table 2.

Data	Format	Functions	Source
Polygon Vienna	.shp	To delimit the study area.	Data.gv.at 04.2024
Land use plan	.shp	To exclude areas where PT is irrelevant.	Data.gv.at 03.2024
OSM data Vienna	.pbf	To build the network (representing the street network).	Geofabrik 06.2024
GTFS Wien VOR	gtfs (.zip)	GTFS data for PT in Vienna without ÖBB, WESTbahn, Raaberbahn, Niederösterreich Bahnen and CityAirportTrain Vienna	data.mobilitaetsverbuende.at 06.2024
GTFS Fahrplandaten Eisenbahn	gtfs (.zip)	GTFS data for PT in Vienna consisting of ÖBB, CityAirportTrain Vienna, Niederösterreich Bahnen, Raaberbahn/GYSEV, Montafonerbahn, WESTbahn and Bahnen der Österreichischen Gesellschaft für Eisenbahngeschichte.	data.mobilitaetsverbuende.at 06.2024

Table 2: Data sources.

3.1.2 Data Preprocessing

Before implementing the main methodology, data preprocessing is conducted. The Polygon of Vienna's boundary is used to define the study area. Within this boundary, areas not relevant to calculate accessibility in this study are excluded. The focus is on areas where people live, so the categories protected area (Schutzgebiet), recreation area (Erholungsgebiet), cemetery (Friedhof), special area (Sondergebiet), rural area (Ländliches Gebiet), and traffic belt (Verkehrsband) are excluded for the set of origins for accessibility calculations. These categories are illustrated in Figure 10. The blue region, labeled "Area for calculation" is the resulting residential area where origins (start nodes) are placed for analysis. Other regions are excluded as origins but are considered as potential destinations.

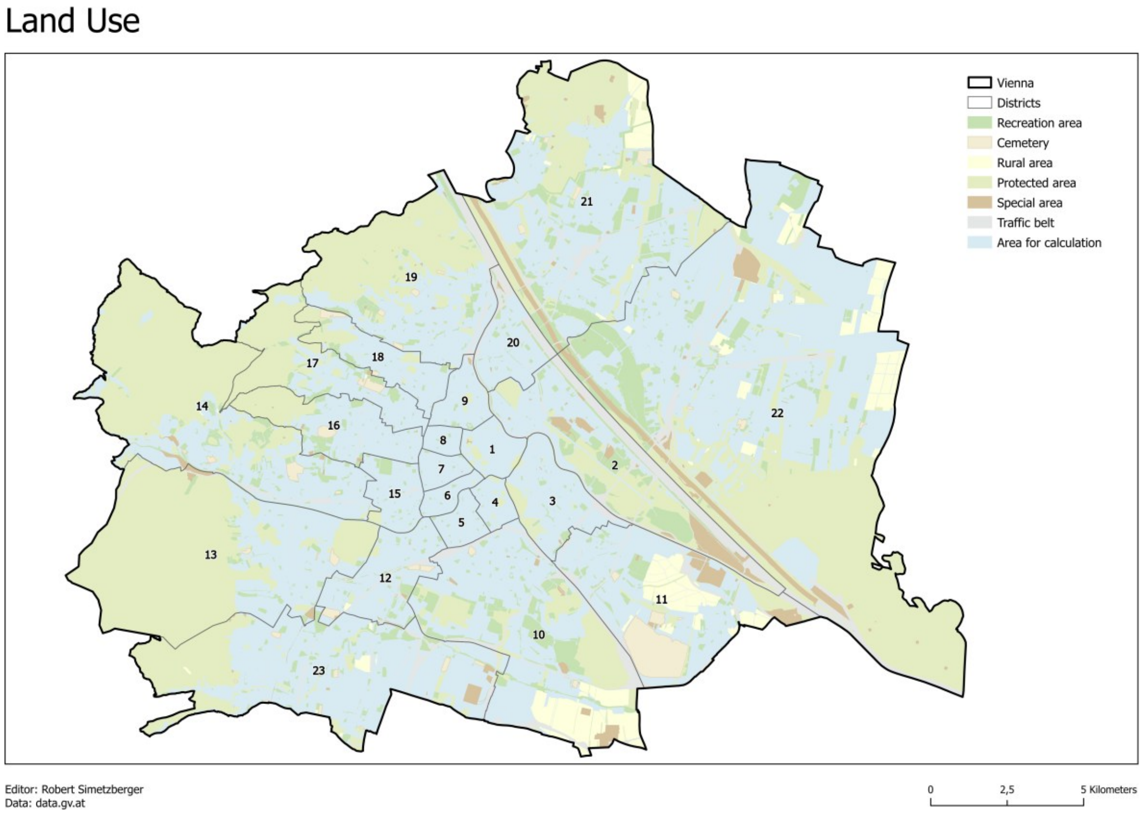


Figure 10: Land use in Vienna.

Additionally, before implementing the main method, the residential area is divided into regions, each of which will have its accessibility calculated. To facilitate the accessibility calculation a starting point in each region is identified. This is achieved through hexagonal tessellation. The residential area is divided into 19,832 hexagons with an area of approximately 9,000 m^2 and an edge length of 60 m. The centroid of each hexagon serves as a starting node for accessibility analysis and the result for this point represents the corresponding cell.

Hexagonal tessellation is chosen over square grids because the distance from the centroid to the edges is more similarly distributed in hexagons than in squares. In squares, regions near the vertices are farther from the centroid, leading to less accurate representation. Since the centroid is representative for the entire hexagon, a uniform distribution of distances from the centroid to the edges is essential for ensuring greater accuracy (Birch, Oom, & Beecham, 2007, p. 350; ESRI, n.d.c).

There are also options for selecting starting nodes without relying on geometrical forms:

i. **Using every house.** As the accessibility of residential areas is of interest it would also be possible to calculate the accessibility for every address. However, with more than 190,000 addresses in Vienna the computational complexity would increase significantly (compared to 19,832 cells with hexagonal tessellation) (Prinz & Herbst, 2008, p. 8).

ii. **Using building blocks.** Prinz and Herbst (2008) use building blocks and calculate a representative starting point for each building block based on the average location of addresses within the block. However, varying block sizes can lead to inconsistent resolutions in the results.

To address the challenges of differently sized building blocks and computational complexity, hexagonal tessellation is selected as the most appropriate approach. Figure 11 illustrates the hexagons used in this study and therefore the area of calculation.

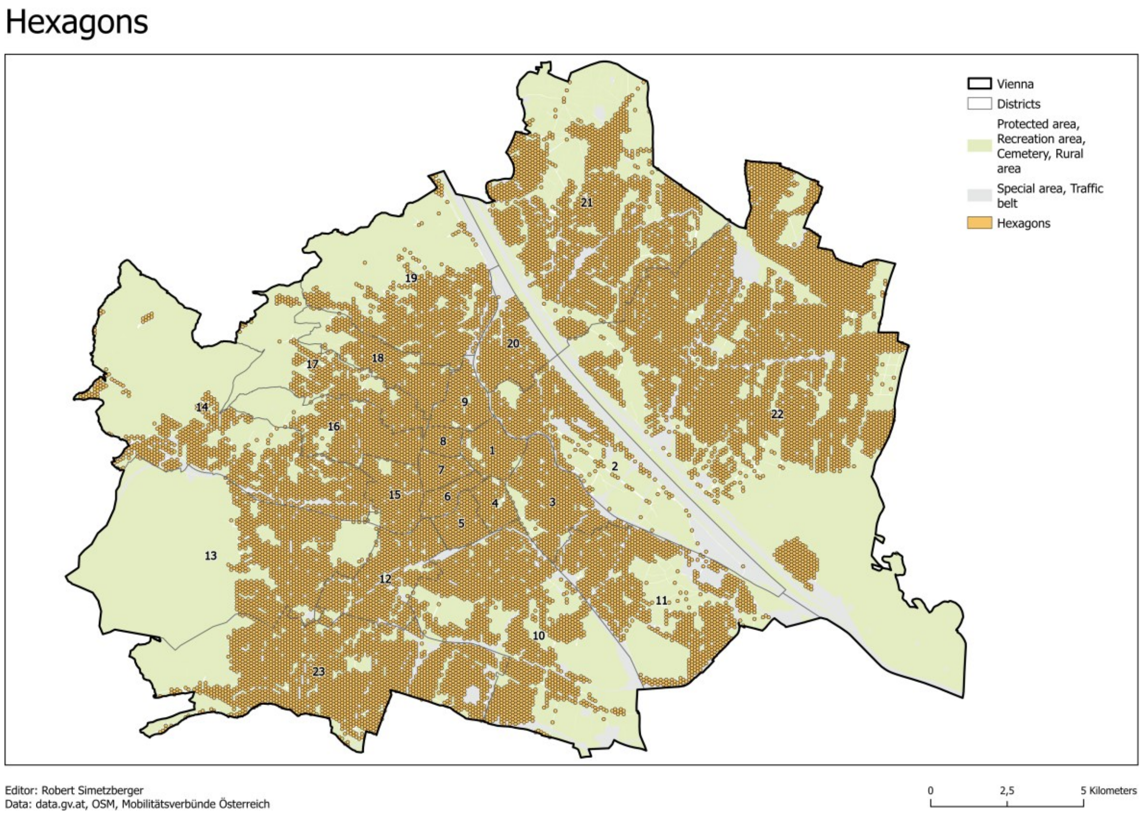


Figure 11: Hexagons for the accessibility calculation.

3.2 Method

Once the area of interest for the accessibility calculation is determined and the hexagons, including their centroids, are generated, the main methodology begins. This method aims to identify transit deserts and directional dependencies using isochrones. Different reasons for using isochrones are discussed in the previous chapters. To summarize briefly, isochrones allow for an independent examination of the public transport network without relying on POIs and provide additional insights, such as directional dependencies and offer clear visual representations compared to other approaches.

There are multiple approaches to generate isochrones:

ArcGIS Pro offers a tool to calculate isochrones using the ArcGIS Network Analyst extension. However, since this thesis aims to create a reproducible method that can be applied by other researchers, the objective is to use open-source resources. Furthermore, the pre- and post-processing steps require programming capabilities, making it more practical to use programming languages. Additionally, the calculations in ArcGIS Pro are Dijkstra-based, which is less efficient than RAPTOR and ArcGIS Pro does not allow to set the walking time parameter independently of the total travel time (ESRI, n.d.a, n.d.b).

Open Trip Planner (OTP) provides the possibility to generate Isochrones at a given departure time and location using their API. Testing the API confirmed that it is capable of generating isochrones. However, OTP has stopped the support of this feature and there are several shortcomings compared to other methods. The calculation speed is slower compared to other options and the isochrones generated reflect only a single, fixed departure time. Given that schedule data varies significantly on the time of the day, a time window offers a more robust approach for capturing realistic travel patterns (more on time windows in Chapter 3.2.1) (OpenTripPlanner, n.d.).

R5 (Rapid Realistic Routing on Real-world and Reimagined networks) is a routing engine used by conveyal, "[…] a web-based system that allows users to create transport scenarios and evaluate them in terms of cumulative opportunities accessibility indicators." (Conveyal, 2024). The routing method is called "realistic" because it allows for multiple different departure times within a given time window. This better reflects how people use PT compared to planning a trip at one exact time. More details of R5 are provided in the next section (Conveyal, 2024).

3.2.1 Tools and Libraries

To carry out the method, different tools and libraries are used. The study uses the programming languages Python and R. The reasons for the use of these two languages is the wide range of application possibilities of Python, including its spatial possibilities, and the availability of the r5r package, which is a wrapper for R5 in R (Pereira, Saraiva, Herszenhut, Braga, & Conway, 2021). Therefore, the isochrones are calculated using R and the remaining tasks using Python. There is also a wrapper for R5 in Python, called r5py (Fink, Klumpenhouwer, Saraiva, Pereira, & Tenkanen, 2022), but this package does not yet include the method to generate isochrones.

r5r is a wrapper for R5 which makes it possible to use R5 locally within the R environment. This enables users to easily incorporate methods developed by Conveyal for various transport analyses. The package provides seven fundamental functions, such as "accessibility()" for calculating access to opportunities or "isochrone()" to generate isochrones.

Before performing any calculations, users must run the “setup_r5()” function, which downloads and stores an R5 Jar file locally. This function builds a multimodal transport network using an OpenStreetMap (OSM) street network and one or more PT networks in GTFS format (Pereira et al., 2021).
The isochrone function calculates isochrones for multiple origins using different modes of transport within a given travel time. One key advantage compared to other tools is its ability to use time windows, eliminating the need to rely on a single, fixed departure time. For example, the start time can be set to 10:00 but with a time window of 10 minutes. Without a time window, if no bus leaves at 10:00 there will be no connection. Similarly, if a bus departs at 10:00 and an express service at 10:02, the slower one at 10:00 would be used for the calculation, ignoring the faster option. Using a time window ensures that trips are calculated every minute within the window, with the resulting median being used.
The median is preferred over the mean because it is more robust, explained by the following example: If there is an existing service connecting A and B and an express service is added that operates infrequently but falls within the time window, the mean would overestimate accessibility due to its sensitivity on the magnitude of the considered values. The median, on the other hand, focuses solely on the position of the values, making it less sensitive to such outliers and more representative of typical travel times (Conway, Byrd, & van der Linden, 2017, pp. 4–5).
Another advantage of R5 is that it is not solely Dijkstra-based. The approach uses Dijkstra for routing along the street network for walking and RAPTOR for routing along the PT network which significantly improves computational efficiency (see explanations of the algorithms in Chapter 2.7.2) (Conway et al., 2017, p. 6).
Furthermore, several packages in Python are utilized, such as geohexgrid to generate hexagons and multiple libraries to work with spatial data. The used libraries are shown in the tables in the next chapters.

3.2.2 Accessibility Calculation

The accessibility calculation is carried out using R and Python, as mentioned previously. The Isochrones are calculated in R and the grid generation, preprocessing and evaluation of the resulting isochrones are done in Python. This chapter provides an overview of the working steps in a summary table and explains the steps and tools used in detail. Also, the used libraries will be stated in the tables. At the end of this chapter a flow chart is presented in Figure 13 for further illustration and explanation.

Defining the Area of Interest and Generating the Grid

As mentioned, at first a hexagonal grid is generated to define the origins for the calculation before the actual accessibility analysis is carried out. The necessary working steps are summarized in Table 3, including the required libraries.

Working steps	Procedure	Libraries
1. Read data	The border and land use plan of Vienna are read.	geopandas
2. Determination of the area of interest	The area of interest is determined by the border of Vienna and the residential areas of the land use plan.	geopandas
3. Hexagonal tessellation	Hexagonal tessellation is done.	geohexgrid
4. Identify origins	Add a column and save the centroid of each cell.	geopandas
5. Clip hexagonal grid	Extract cells where the centroid is within the area of interest.	geopandas

Table 3: Hexagonal tessellation.

First, the area of interest for the analysis is defined by overlaying Vienna's boundary which is clipped by the land use plan using the categories protected area, recreational area, cemetery, special use area, rural area, and traffic belt.

A hexagonal grid is then generated using python and the geohexgrid package, which minimally covers the specified area. The result is visible in Figure 11. After creating the grid, which is a geodataframe, the centroid of each hexagon is calculated and added to the table in a new column.

The centroids serve as the origins of the accessibility analysis. Since the geohexgrid package creates a grid that covers the input area entirely, the centroids of hexagons at the edges of the grid may fall outside the area of interest. Therefore, each centroid is checked to confirm it lies within the research area. Hexagons with centroids outside the area are removed from the geodataframe. The resulting grid consists of 19,832 cells with an individual area of approximately 9,000 m^2.

Calculating Isochrones and Accessibility

Once the grid is prepared, the isochrones and therefore the accessibility are calculated in R using the r5r package. This step involves creating a PT network and generating isochrones for the specified origins, shown in Table 4.

Working steps	Procedure	Libraries
1. Create network	Create a routable network using OSM street network and GTFS data within the setup_r5 function.	r5r
2. Read data	Read the hexagonal grid data for the centroids as origins.	data.table
3. Calculate isochrones	Calculate isochrones using the isochrone function.	r5r

Table 4: Calculation of isochrones.

To begin, a multimodal transport network is built by using OSM street data and GTFS data, processed through the "setup_r5()" function.

For the isochrone calculation, which is conducted using that network, a table containing the origins for the calculation is needed. This table is the hexagonal grid table, generated in Python beforehand, where the centroids of each hexagon are stored, serving as origins. This table is passed to the "isochrone()" function, which requires several parameters to generate isochrones.

Explanation of the Isochrone Parameters

The parameters are explained in the r5r documentation (Pereira et al., 2021) and the specific values used in this analysis are shown in Table 5 and explained in this section. To summarize, the centroids of the grid are used as origins/starting nodes for the calculation. Isochrones are generated for the defined cutoff times using the specified modes of transport. The departure time, in combination with the time window, determines the range of possible departures and the maximum walking time and walk speed determine the allowed walkable distance, as distance is velocity multiplied by time.

In general, the aim of this analysis is to represent the largest possible number of people in one set of parameters. The selected group of individuals are people in the age group of 20-74, which mostly represents the working society and people in education. In Vienna in 2024, 1,454,008 people fall within the 20-74 age group, making up 72 % of the total city's population (Stadt Wien, 2024). However, basing key parameters on this age group inherently means that certain parts of the population – such as the elderly or individuals with disabilities – are less represented. For example, the average gait speed of individuals aged 80 and above declines compared to people between 20-69, meaning they cannot cover the same distances by walking in the same time period. Consequently, stops that are reachable for a younger person may not be reachable for a person above 80 in the given walking time (Bohannon & Williams Andrews, 2011, p. 183).

Since the selected group are people in education or working people, the departure time is set to 08:00 in the morning of a weekday. This represents peak hours where a lot of individuals in this group travel. The time window is set to 30 minutes which means that every possible departure between 08:00 and 08:30 is considered. The advantage of this approach is that no single departure time must be set, which can significantly influence accessibility, as explained in Chapter 3.2.1. If the departure time is set to 08:00 but a much faster connection leaves at 08:10, this would not be taken into account if there is a fixed single departure time. Therefore, the time window creates a more realistic scenario, because individuals may prefer to leave their home 10 minutes later when they arrive at their destination at the same time.
The walk speed is set to 4.86 km/h, based on Bohannon and Williams Andrews (2011, p. 183) who identified this as the average walking speed for women and men aged 20-69. The maximum walking time is set to 6.33 minutes, following Tennøy, Knapskog, and Wolday (2022, p. 1), who discovered this to be the average time employed people spend walking to PT stops, across all PT types and various cities in Norway, for the same age group defined in the previous study. While there is a slight difference in the age group ranges between the studies and Vienna's demographic data, the overlap remains substantial.
The walking time of 6.33 minutes also aligns with the general rule of thumb that assumes walking distances of 400 m to local bus stops and 800 m to railway stops. In this study all stops are considered, so the average of the identified times for local bus stops and railway stops is used. The result is an allowed walking distance of 513 m (Tennøy et al., 2022, p. 2).
The allowed number of transfers is set to 2, despite findings by Grisé and El-Geneidy (2019, p. 259) showing that satisfaction decreases with the number of transfers. While trips with one transfer are similarly satisfactory as zero transfers, two or more transfers result in a satisfaction decrease of 32 %. Nevertheless, their study of 1342 individuals of the McGill university (students and staff) revealed that 20 % of trips transferred two times (only 3 % more than two times), suggesting that while satisfaction declines, two transfers remain a common and acceptable part of daily travel.
The cutoff values, which describe the maximum travel time allowed, are set to 15 minutes and 30 minutes. These two cutoff values are used to analyze how accessibility and the occurrence of transit deserts changes when the travel time is increased.

Parameter	Value	Description
origins	Hexagonal grid	Each origin is used as the starting node for the isochrone calculation
mode	Walk, Transit	Walk and Transit are used to route by walking and public transport.
cutoffs [min]	15, 30	For each cutoff, an isochrone is calculated.
departure_datetime	06.05.2024 08:00:00	This is the departure time, used for the calculation of the isochrone.
max_walk_time [min]	6.33	The maximum walking time to reach a stop.
walk_speed [km/h]	4.86	The walking speed of individuals.
max_trip_duration [min]	30	The time when the trip must be finished.
time_window [min]	30	The time window allows the calculation to consider multiple departure possibilities, not just at one specific time.
max_rides	3	Specifies the allowed PT rides in the same trip and therefore the allowed transfers.

Table 5: r5r parameters.

Result of the Isochrone Calculation

The isochrone calculation outputs a table where each row represents an origin (hexagon) and includes the isochrone geometry for a given cutoff time. Since two cutoff values are used, the table consists of 39,964 rows in total – two rows for each hexagon. Each row includes three columns: the id, the cutoff duration, and the geometry of the isochrone. As a result, each id appears twice in each table, once for each cutoff value. Figure 12 illustrates an example of a single grid cell along with its respective isochrones in a map. This cell, with id 14862a, will serve as an example in multiple tables throughout the explanation of the method.

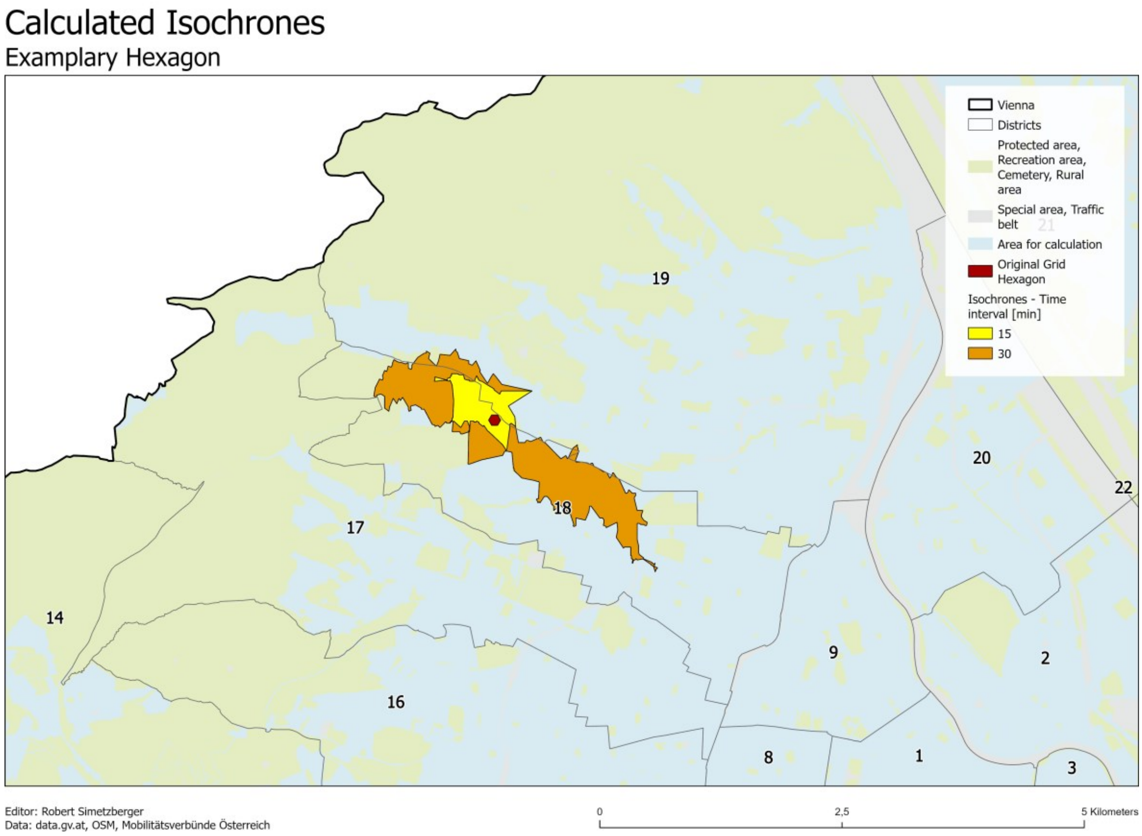


Figure 12: Calculated isochrones and grid cell 14862a.

At this point, two separate tables exist: (1) The grid table, consisting of 19,832 rows with an id, the hexagon geometry and the centroid and (2) the isochrones table, consisting of 39,664 rows with an id, a cutoff value and the isochrone geometry.

Calculating Accessibility

After the isochrones are generated, they are analyzed to evaluate accessibility. The working steps needed, and the used libraries are shown in Table 6.

Working steps	Procedure	Libraries
Read data	Read the grid and isochrone files.	os, pandas, geopandas
Check geometries	Check geometries (self-intersection occurs).	shapely
Validate geometries	Make the affected geometries valid.	shapely
Merge data	The grid and isochrone tables are merged using the id.	geopandas
Add area column	Calculate the area for each isochrone.	geopandas

Table 6: Analyzing the calculated isochrones.

First, the grid and isochrones tables are read into Python. The geometry column of the isochrones table is validated using the is_valid() function, as self-intersecting geometries can cause issues in further calculations. Invalid geometries are corrected using the make_valid() function.

Next, the isochrones and grid table are merged using the id column. This merge is necessary because the isochrones are required for further analysis and the grid cells are needed for visualizing the results.

The next step involves calculating the area of the isochrones, as the reachable area serves as the indicator of accessibility. This new column represents accessibility. Table 7 shows the merged table, including the area values for the example in Figure 12. To minimize edge effects, the transport network data used for the analysis includes not only Vienna but also surrounding regions. This approach better reflects real-world travel patterns. To further clarify the explanation, a flowchart of the described steps is shown in Figure 13.

id	**geometry_grid**	**centroid_31256 _grid**	**isochrone_cutoff _isochrones**	**geometry_is ochrones**	**area isochrones [m^2]**
14862a	Polygon	Point	30	Poygon	1,622,555
14862a	Polygon	Point	15	Poygon	313,410

Table 7: Excerpt of the merged table using grid cell 14862a as an example. Columns originating from the grid table are labeled with the "_grid" suffix, and columns from the isochrones use the "_isochrones" suffix.

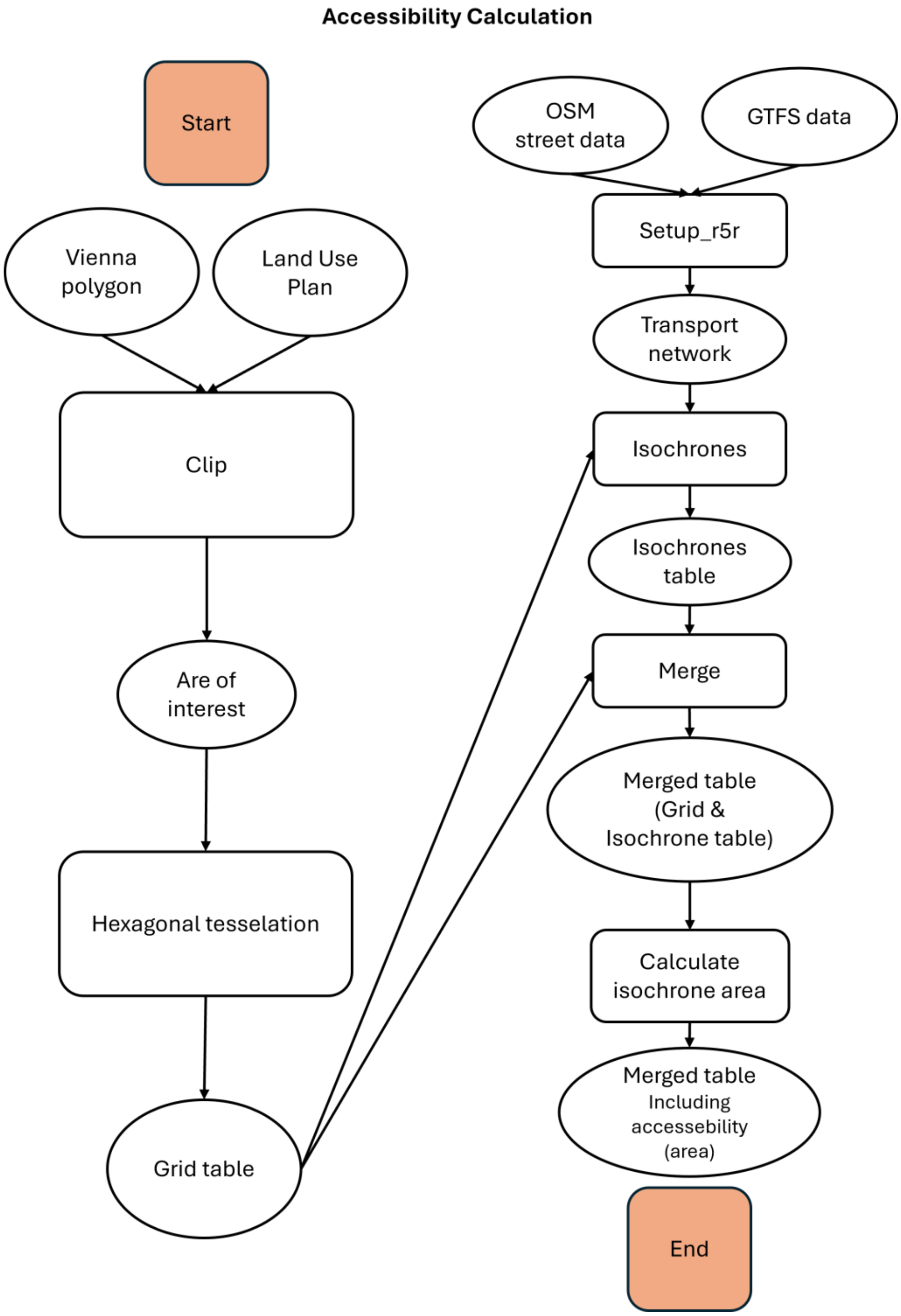


Figure 13: Accessibility calculation (own representation, 2025).

3.2.3 Identification of Transit Deserts

After calculating the reachable area for each origin, transit deserts can be identified based on these values. This is done for each cutoff time individual, meaning that for the identification of transit deserts the existing merged table is now split into two tables. One for the cutoff value of 15 minutes and one for 30 minutes. As already mentioned, this is done to analyze how accessibility and the occurrence of transit deserts changes when the travel time is increased.

This means that the following working steps are always done twice, once for each table. At the end of this chapter a flowchart represents the working steps for further illustration and explanation in Figure 15.

Using the FGT_2 Measure for the Identification of Transit Deserts

In this study, the FGT_2 measure is applied. This measure not only considers the number of cells below a specified threshold (the poverty line) but also reflects the distribution of accessibility among the “poor” and calculates a poverty gap for each individual cell. Therefore, both the number of cells below the threshold and the severity are captured.

As shown in Formula 4, several values are required to calculate the FGT_2. The size of the Population N corresponds to the number of origins. The poverty line z is defined as the median accessibility/reachable area and H represents the number of cells where the reachable area falls below z. The variable y_i is the accessibility level of origin i.

The poverty gap (interim result, see Chapter 2.4.1) for each cell is calculated and stored in a new column. This gap is the squared normalized difference between the median accessibility and the accessibility level of each individual cell. These interim results enable the identification of transit deserts based on this value, with higher values indicating worse connectivity. If the poverty gap is zero, it means that the cell’s accessibility is above the poverty line, and if the poverty gap is 1, the accessibility of that cell is zero. The FGT_2 result is used for further interpretation which will be explained in the Results Chapter.

Defining Transit Deserts

As discussed in Chapter 2.4.1, defining the poverty line is a key challenge when applying the FGT_2 measure. As Karner et al. (2024) state, the definition of a minimum acceptable accessibility level is context-dependent and not universally established. Once there is evidence for a baseline FGT_2, measures can incorporate that threshold into the calculation compared to the needs-gap approach, for which that is not possible. As there is no common poverty line already, the median is a solid data driven threshold as it is robust to outliers. Using the median as the poverty line means that every cell with an accessibility below this value is classified as a transit desert.

However, since there still is a significant variation in accessibility below the median, further distinctions are needed. The greater the difference between a cell’s accessibility and the poverty line, the worse its connectivity and the more severe the transit desert. Therefore, the cells identified as transit deserts are further categorized by dividing the poverty gaps into four severity classes using quantiles: mild transit desert (Q1), moderate transit desert (Q2), severe transit desert (Q3) and extreme transit desert (Q4).

Calculating the FGT_2 and the Poverty Gaps

The FGT_2 is calculated for isochrones with a cutoff of 15 minutes and 30 minutes travel time separately. Both the FGT_2 score and the individual poverty gaps for each origin are computed, and the poverty gaps are stored in a new column in the respective merged table. Then another column is added, assigning the rows to their respective quantiles based on their poverty gap. This enables visualization based on the poverty gap. Table 8 shows a summary of the procedure and Table 9 an exemplary row for the resulting table.

Working steps	Procedure	Libraries
Split merged table	Split the merged table into one for each time interval.	
Define FGT_2 parameters	The poverty line z is defined as the median accessibility. N := Number of cells; H := Number of cells with an accessibility below z. y_i := accessibility level of cell i.	geopandas
Create function to calculate FGT_2	Write a function to calculate the FGT_2 and the corresponding poverty gaps. The function takes a dataframe as input – either for the 15-minute or the 30-minute time interval. All necessary variables are derived from the dataframe. The function computes the FGT_2 value and returns a list of individual poverty gaps. It is called separately for each time interval.	geopandas, numpy, math
Call function	Apply the function to each table. The poverty gaps are stored in a new column.	
Categorize transit deserts	Categorize the transit deserts (poverty gap > 0) by the assignment of quantiles. This information is stored in a new column.	numpy

Table 8: Identification of transit deserts

id	**geometry_grid**	**centroid_31256_grid**	**isochrone_cutoff_ isochrones**	**geometry_ isochrones**	**area isochrones [m^2]**	**poverty gap**	**quantile membership**
14862a	Polygon	Point	15	Poygon	313410	0.64	Q3

Table 9: An examplary row of the merged table for the 15 min cutoff value including the poverty gap and the quantile membership.

Reachable Area as a Metric for Transit Deserts

The reachable area was chosen as the primary metric for the identification of transit deserts over the maximum reachable distance, which would have also been an option, as it better captures accessibility to dispersed opportunities. While distance-based measures highlight how far one can travel, the area-based approach is more representative for real-world accessibility, given that opportunities are typically distributed spatially rather than concentrated linearly along transit routes. This is explained in Figure 14. While this exemplary cell is not identified as a transit desert if the maximum reachable distance is used as the accessibility metric, it is classified as one if the reachable area is used. As the impact of reachable distance is investigated in the next step, using the reachable area is more appropriate here because as shown, one can only move very close to the PT line here.

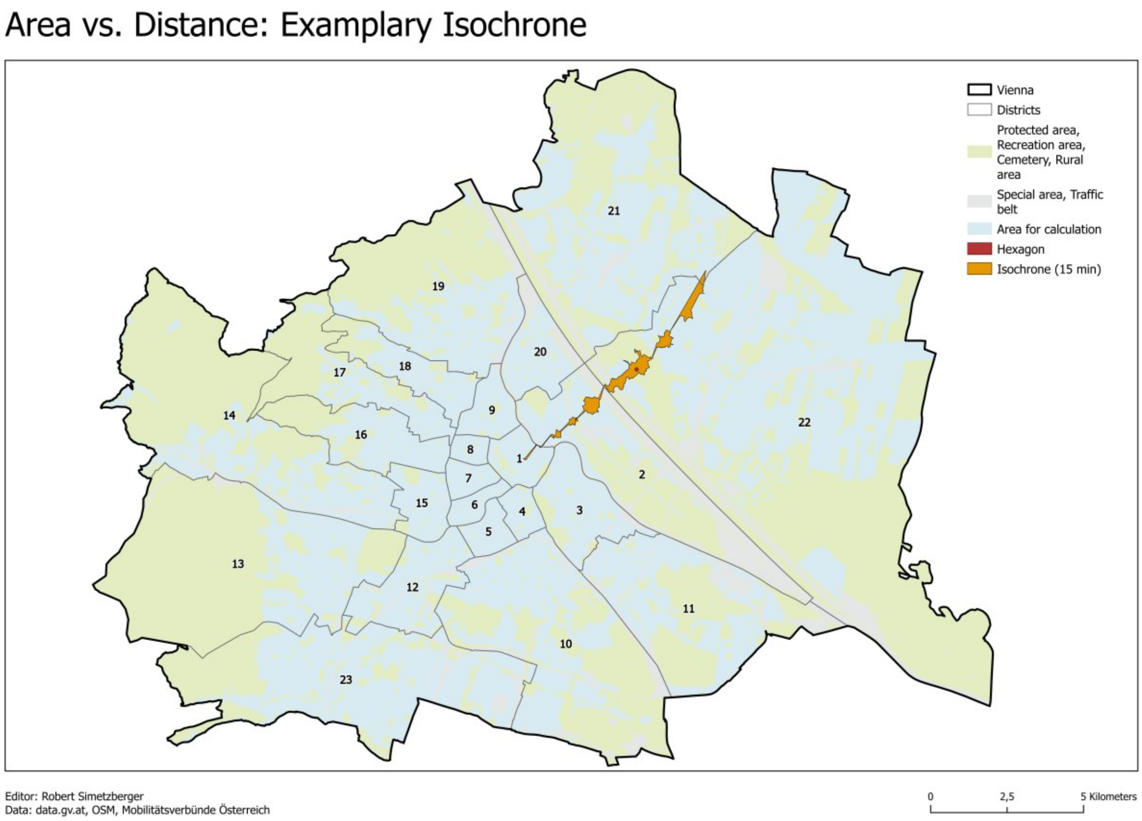


Figure 14: Area vs. Distance.

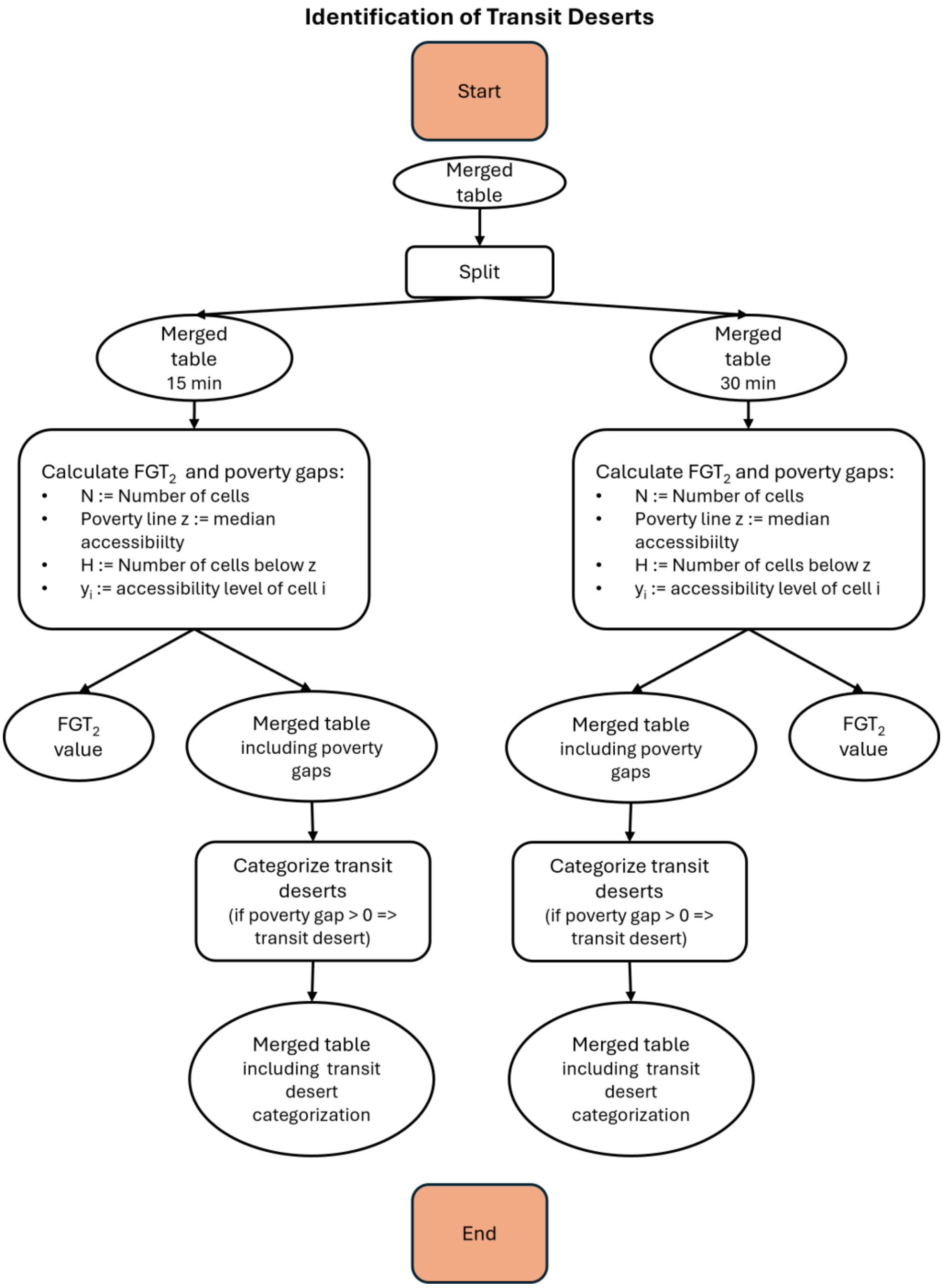


Figure 15: Identification of transit deserts (own representation, 2025).

3.2.4 Detecting Directional Dependencies

After identifying transit deserts, the goal was to detect directional dependencies to gain deeper insights into the structure of Vienna's public transport network. Directional dependency refers to the phenomenon where accessibility from a location varies depending on the direction of travel. This can provide valuable information about how accessible certain areas are in different directions, revealing potential imbalances in the network, such as cases where certain areas are well-connected to the city center but poorly connected to adjacent neighborhoods. This type of analysis is particularly useful for understanding spatial inequities and planning more balanced transport systems because public transport users don’t always travel toward central hubs – they may need to reach nearby districts for work, healthcare, or social visits. If the network favors radial movement (e.g., toward the center) over lateral movement (e.g., between adjacent districts), some people may face barriers despite geographic proximity.

As shown in Figure 4, traveling in Vienna can be highly influenced by the direction a person wants to travel to. Figure 27 and Figure 31 in the Results Chapter show how accessibility is influenced by the direction for Vienna entirely. This asymmetry can result in situations where, for example, a person can easily reach central Vienna but struggles to access a neighboring district, which may be critical for daily needs like visiting a doctor or a friend. Identifying and addressing such directional gaps is essential for promoting equitable and efficient mobility.

Explanation of the Methodology

To identify directional dependencies, the underlying assumption is that the more an isochrone deviates from a circular shape, the more directionality influences travel. A perfectly circular isochrone would suggest uniform reachability in all directions, implying no directional bias. However, simply measuring this deviation does not reveal information about the geographical extent of the isochrone, and thus no insights into reachability in particular directions. To address this, the maximum reachable distance in defined directions is calculated. Unlike the area-based approach, which focuses on the total spatial coverage, this method captures directional differences by identifying how far one can travel in specific orientations. This provides additional insights into potential imbalances in the network, which are not captured by the area-based approach.

For uncovering these underlying patterns, a new methodology was developed. Table 10 summarizes the procedure and in Figure 18 a flowchart is represented.

Working steps	Procedure	Libraries
Add column and calculate expanded hexagon	Create a hexagon for each isochrone which works as a bounding shape.	shapely, math
Create triangles	Load the hexagonal grid data for the centroids as origins.	shapely
Intersect expanded triangles	Intersect the triangles with the isochrone.	shapely
Save maximum distance to small triangles	Save the maximum reachable distances to the respective triangles of the grid.	shapely, math

Table 10: Detecting directional dependencies

As already mentioned, the goal is to identify reachability in different directions to show directional dependencies. To achieve this, six directions are determined as shown in Figure 17. The detailed approach is explained in the following. First, a new column called "expanded_hexagon" is added to the merged table (which consists of the isochrones and grid data). This column stores hexagons which act as a bounding shape for the isochrones as shown in Figure 16. For each isochrone (i.e., each row), this hexagon is calculated using the distance between the centroid and the furthest vertex of the isochrone, which serves as the apothem length. Based on this the corresponding radius is derived. Then, the vertices of each expanded hexagon are calculated in a loop by projecting points from the centroid outward at fixed angles, starting at 0° and increasing by 60° for each subsequent vertex. The radius determines the distance from the centroid to each vertex.

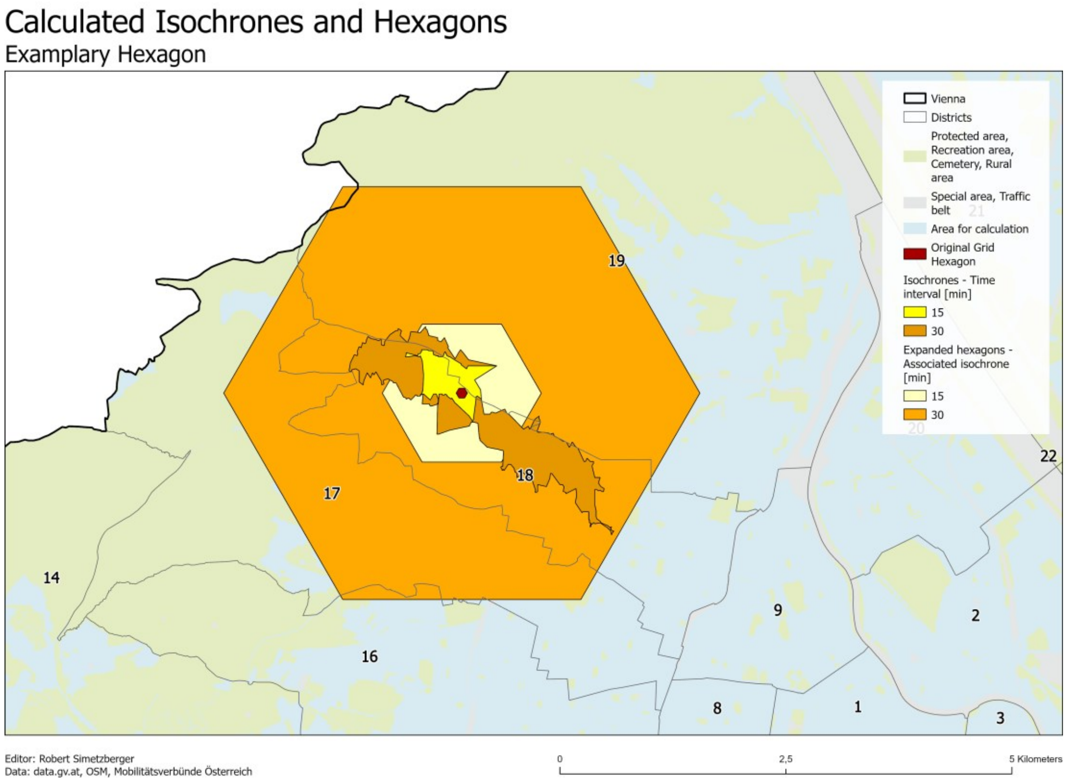


Figure 16: Expanded hexagons.

Then, the expanded hexagon is split into triangles by connecting the centroid of the hexagon with two adjacent vertices each, as shown in Figure 17. The result is six triangles with each triangle representing a directional segment of the hexagon.

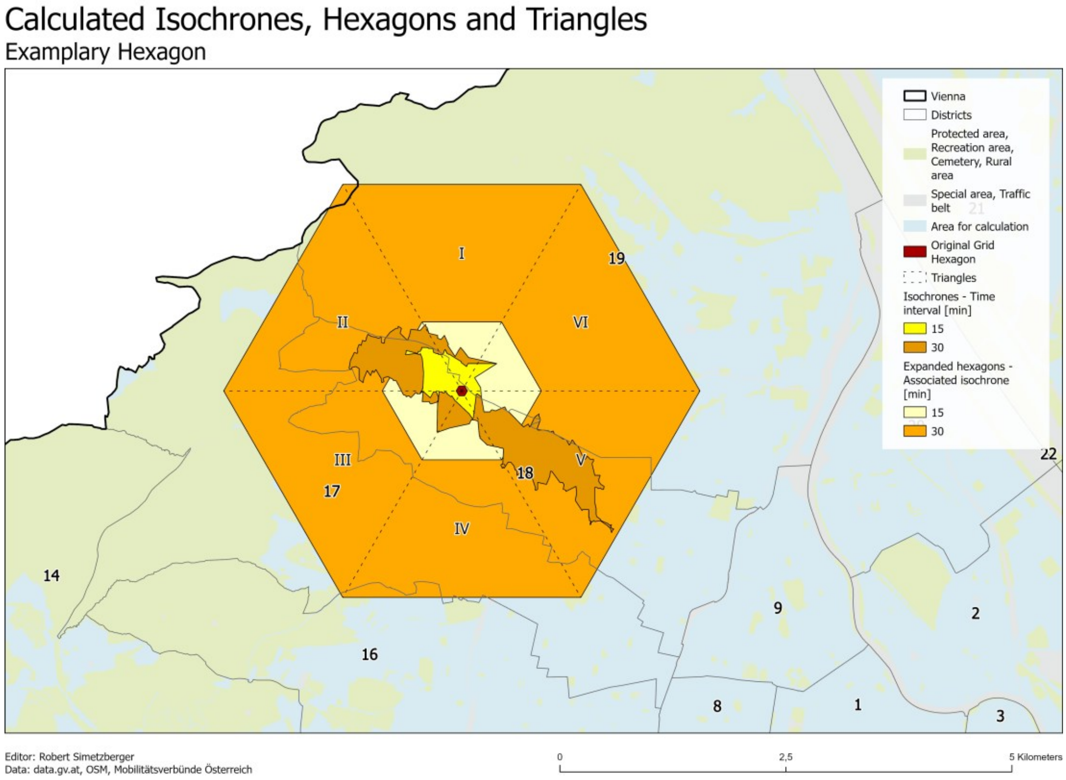


Figure 17: Triangles to analyze directionality.

The next step is intersecting the triangles of the expanded hexagon with the corresponding isochrone to determine the maximum reachable distance within the defined time interval in each direction. This step is crucial for isolating accessibility patterns within specific directional segments.

For each triangle, the vertex furthest away from the centroid is identified. This vertex represents the maximum reachable distance in that direction for the given cell. The resulting maximum distance values are each stored in a new column.

Example

Table 11 shows an excerpt from the table of this calculation for an exemplary row, in particular the exemplary row which is used through the explanation and shown in Figure 17 on a map. As visible in Figure 17, reachability for the 30 minutes time interval is very good in direction V but very low in the other directions, especially in direction I, III, IV and VI. This is also shown in Table 11, which presents the reachability values in each direction in meters.

id	geometry_ grid	isochrone_ cutoff	Dist_I	Dist_II	Dist_III	Dist_IV	Dist_V	Dist_VI
14862a	Polygon	30	837	1277	668	974	2280	490

Table 11: This table shows the reachability values in meters for each direction ("Dist_X"). The "isochrone_cutoff" column represents the travel time and the "id" the specific hexagon cell.

This methodology makes it possible to quantify accessibility in different directions for each grid cell, uncovering patterns of directional dependence. These findings offer valuable insights into how well Vienna's public transport network supports balanced accessibility and can help guide future network improvements. To further clarify the explanation, a flowchart of the described steps is shown in Figure 18.

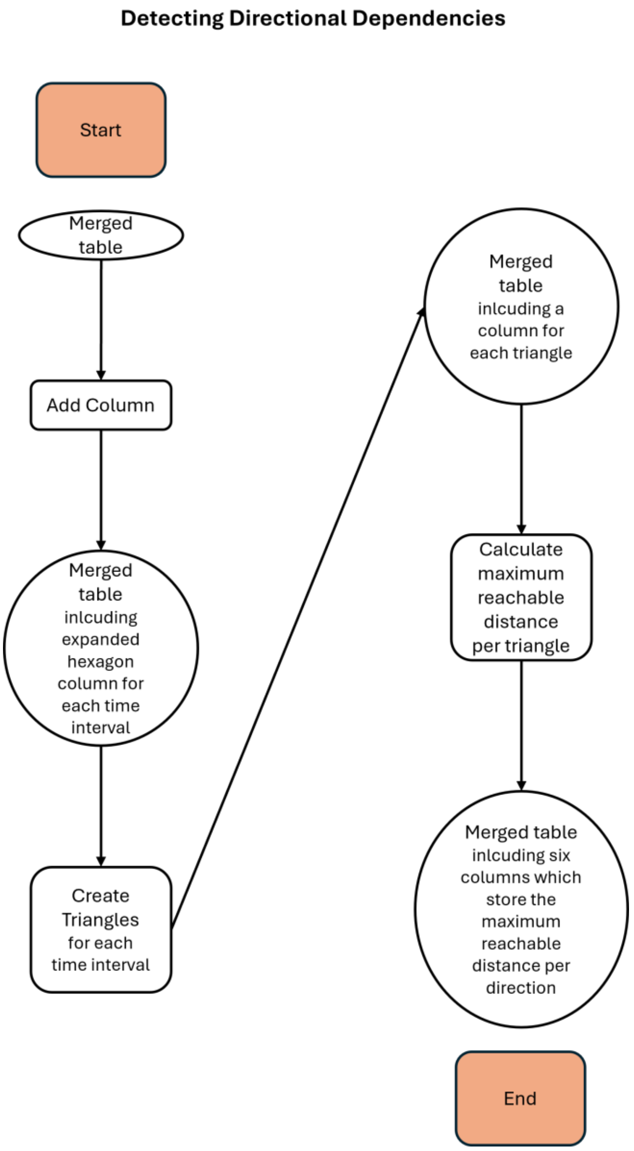


Figure 18: Detecting directional dependencies (own representation, 2025).

By combining area- and distance-based approaches, this study provides a more holistic understanding of PT accessibility. The area-based approach identifies regions with limited overall accessibility and the distance-based approach detects directional dependencies that may reveal imbalances in the network.

4 Results

This chapter presents the results of the accessibility analysis conducted in the previous chapter. It is divided into two subchapters, the identification of transit deserts and the detection of directional dependencies. Together, these analyses offer a comprehensive view of spatial imbalances within Vienna's transport network.

The results show spatial disparities in accessibility across the city, highlighting the existence of transit deserts – areas with lower public transport connectivity compared to the median. In addition, the study reveals directional dependencies, illustrating how accessibility levels depend on the direction of travel.

Both findings are critical for understanding how the transport network shapes mobility options for residents. These insights can inform planning decisions aimed at reducing spatial inequality and enhancing equitable access to opportunities.

4.1 Identification of Transit Deserts

This section focuses on spatial differences in PT accessibility across Vienna, with emphasis on identifying transit deserts. Transit deserts, defined as cells with accessibility levels below the citywide median accessibility, are visualized by categorizing the calculated poverty gaps into four quantile-based classes (see Chapter 3.2.3), reflecting the depth of accessibility poverty within each cell. Depending on which quantile a cell is assigned to by its poverty gap, it is visualized as shown in Figure 19 and Figure 21.

The analysis shows that transit deserts are predominantly located closer to the outer edges of the city. Peripheral districts tend to have lower accessibility scores, whereas central districts and areas along major transit corridors benefit from more frequent and diverse service. This pattern shows the concentration of high-quality services in core areas.

Further details on the severity and distribution of these deserts are provided in the following Chapter 4.1.1, which focuses on the results for the 15-minute time interval.

4.1.1 FGT_2 – 15-Minute Time Interval

Figure 19 visualizes the spatial distribution of transit deserts using the poverty gaps for the 15-minute time interval during the morning peak. As already mentioned, the cells are assigned to four different classes by the use of quantiles based on the poverty gaps. These quantiles are:

- Q1 mild transit desert: ≤ 0.10
- Q2 moderate transit desert: > 10 - 0.42
- Q3 severe transit desert: > 0.42 - 0.77

- Q4 extreme transit desert: > 0.77 – 1.0

The results show that the areas with the highest poverty gaps – indicating extreme transit deserts – are predominantly located at the outer edges of the city, while central districts and areas along major transit corridors show lower poverty gaps, benefiting from higher service. The computed FGT_2 value of 0.22 indicates a moderate overall degree of accessibility poverty, suggesting that while central Vienna is well-connected, disparities remain in peripheral zones.

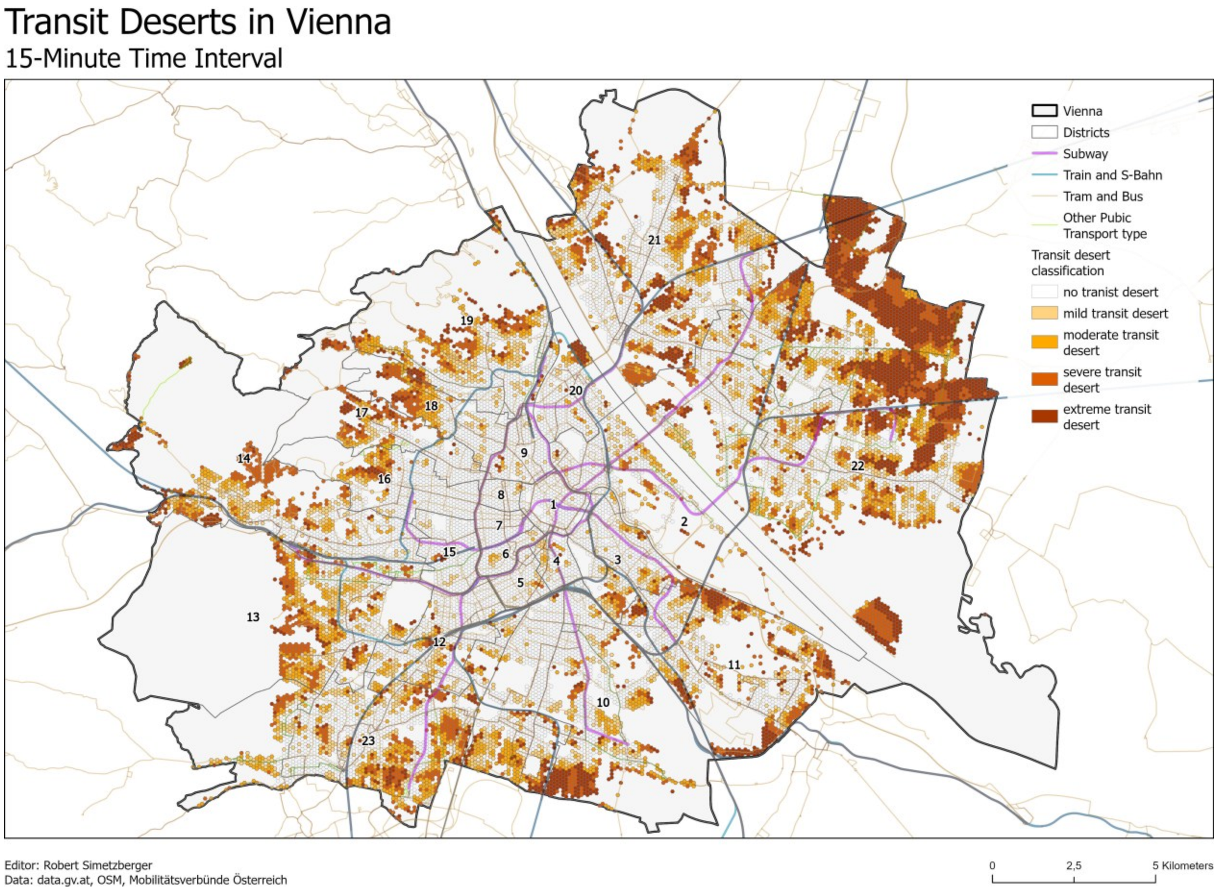


Figure 19: Transit deserts in Vienna – 15-minute time interval. The transit desert classification is based on the quantile membership of each cell.

One illustrative case is the southern part of Vienna, where an accumulation of transit deserts is given around Rothneusiedel and Inzersdorf, near the planned U1 extension (Figure 20). This region exemplifies areas with extremely poor public transport connections to other parts of the city. The affected region, highlighted by a black circle, is largely uninhabited at present. However, construction is set to begin in 2030, and by completion, the area is expected to accommodate approximately 21,000 residents. Without the U1 extension, future inhabitants would face significant public transport shortages. Thus, the extension is being developed in parallel with the housing project to ensure adequate connectivity, directly addressing this problem.

This example underscores the importance of quantifying accessibility when planning new residential developments to guarantee sufficient public transport access. However, not all areas classified as severe or extreme transit deserts are currently unpopulated or scheduled for improvement. Several already inhabited regions remain underserved, with no planned expansion of the PT network. For instance, residents in the northwest of district 18 (green circle) or the western part of district 13 (purple circle) must contend with low connectivity and limited access to high-frequency services.

Further examination of the northwest part of district 18 reveals poverty gaps up to 0.97 (1 meaning worst accessibility and 0 above the poverty line) and a FGT_2 value of 0.57, indicating that accessibility there is substantially lower than the city median. Also, the mean maximum reachable distance across all directions of 506 meters is significantly lower than the mean of the entire city with 1164 meters. The values of maximum reachable distance are used here as it is easier to comprehend. But also, the mean reachable area of 446,064 m^2 is significantly lower than the average of the entire city with 2,082,413 m^2.

A similar pattern is given for the western part of district 13 which shows poverty gaps up to 0.96 and a FGT_2 value of 0.46. Again, this shows lower accessibility levels than the city's median. Also, for this region, the mean maximum reachable distance across all directions of 614 meters and the reachable area of 614,489 m^2 are significantly lower than the city's means.

The identification of such disparities highlights areas where existing infrastructure may fall short of providing effective travel options. These findings will be further discussed in the Discussion in relation to its implications.

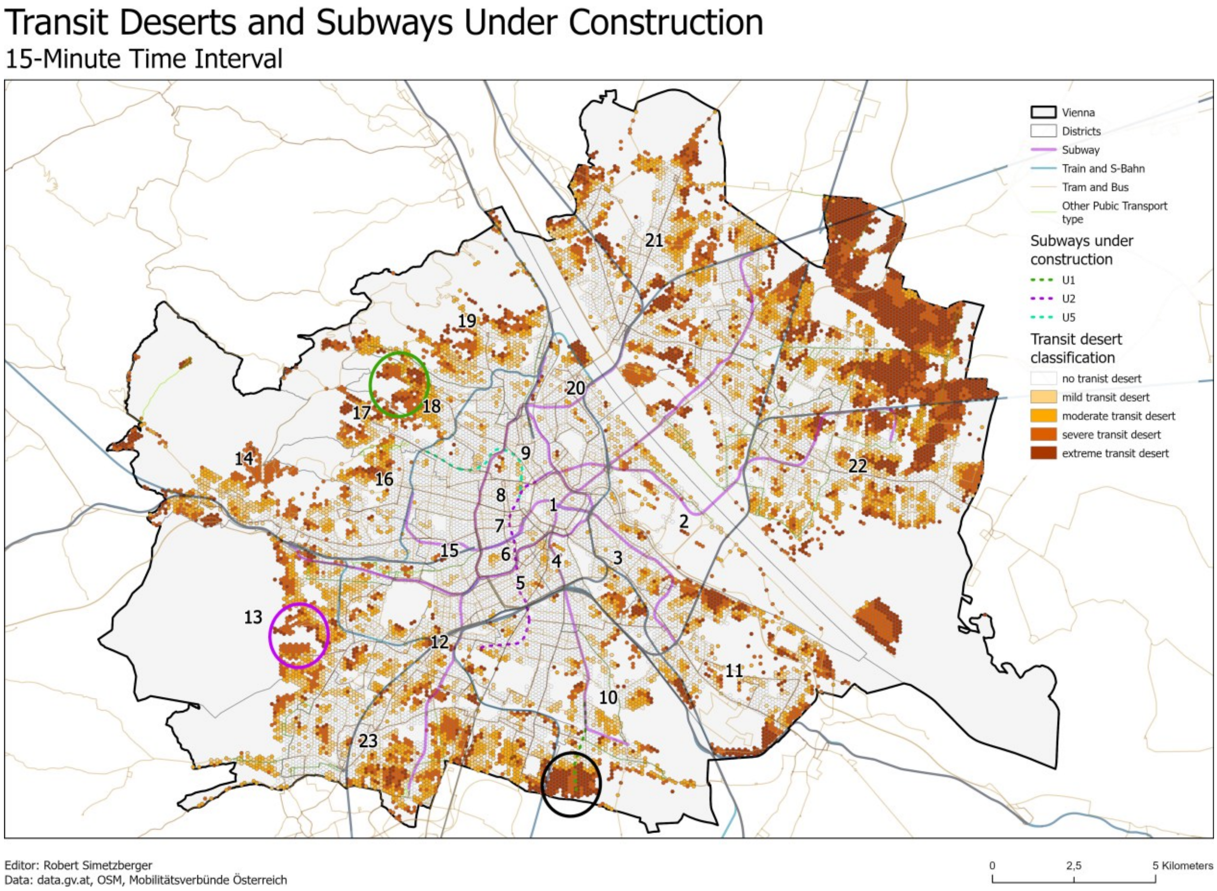


Figure 20: Transit deserts and subways under construction.

4.1.2 FGT_2 – 30-Minute Time Interval

The results of the 30-minute time interval are shown in Figure 21, using the poverty gaps of the calculation of this time interval also during the morning peak. Also here, the cells are assigned to four different classes using quantiles. For this time interval these are:

- Q1 mild transit desert: ≤ 0.10
- Q2 moderate transit desert: > 0.10 - 0.40
- Q3 severe transit desert: > 0.40 - 0.97
- Q4 extreme transit desert: > 0.97 – 1.0

The results exhibit a similar distribution compared to the 15-minutes time interval. Transit deserts are primarily located closer to the city boundaries than the city center and the FGT_2 value is 0.24. However, on a closer look significant differences are shown and will be discussed in the following Chapter 4.1.3.

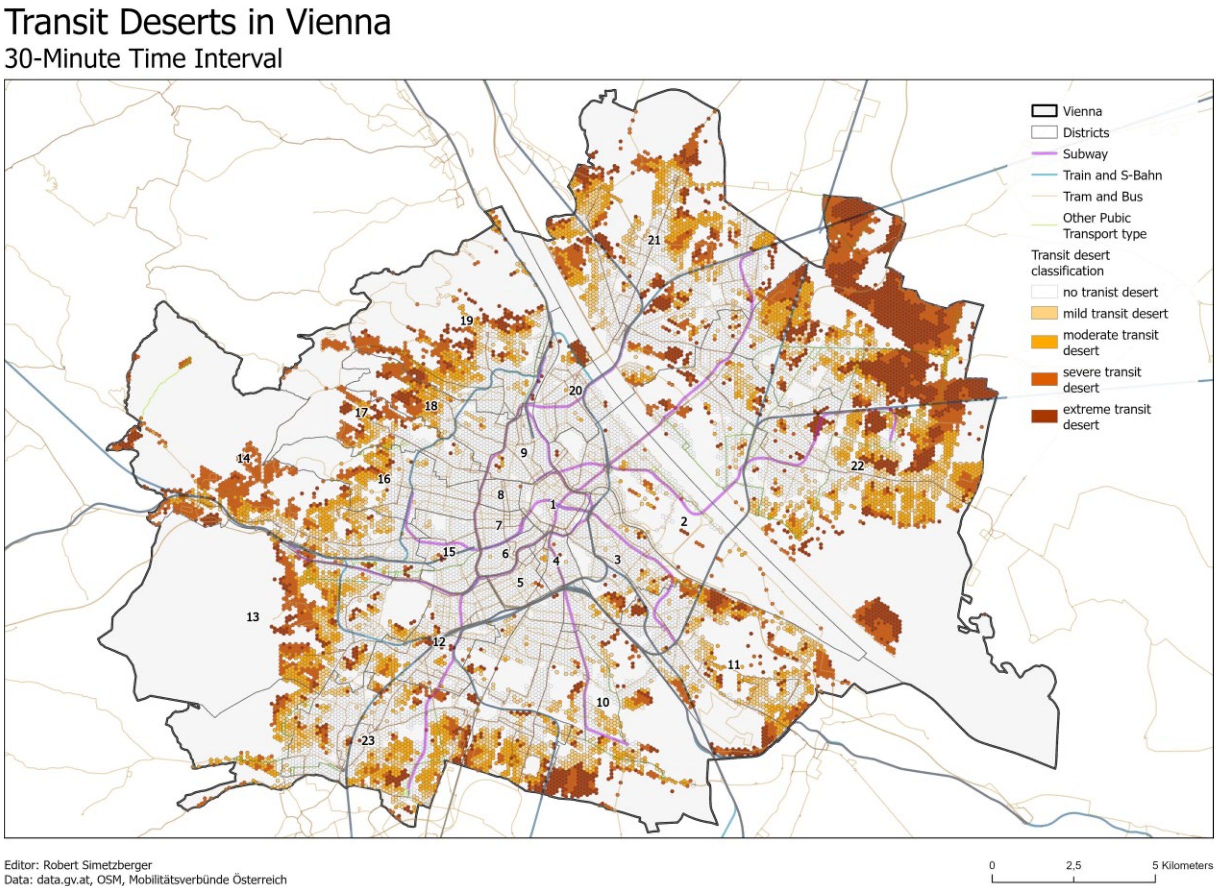


Figure 21: Transit deserts in Vienna – 30-minute time interval. The transit desert classification is based on the quantile membership of each cell.

4.1.3 Comparison of the FGT_2 for the 15-Minute and 30-Minute Time Interval

As already mentioned previously, the results for the 15-minute and 30-minute time intervals are visually similar, but differences are visible upon closer analysis. In general, the number of transit deserts are the same for both intervals because the identification of transit deserts is performed separately for each time interval using their own accessibility poverty gap thresholds. These thresholds are based on the median accessibility level within each interval's dataset. This approach, detailed in Chapter 3.2.3, is necessary because there is no universally accepted common accessibility poverty line. By classifying deserts relative to each interval's distribution, the focus lies on the relative severity and the spatial patterns of transit deserts rather than absolute counts, enabling meaningful comparison across time intervals.

For the 30-minute interval, more deserts are located further from the city center compared to the 15-minute time interval. This can also be shown by calculating the average Euclidian distance between the centroid of the first district and the centroid of the transit deserts. While the average distance between those two points is 8459 m for the 15-minute time interval, the average distance for the 30-minute time interval is 8769 m, indicating a difference of 310 m.

Figure 22 illustrates this pattern using a scatterplot, where each point represents a district. The x-axis displays the average Euclidean distance of transit deserts in a district from the centroid of the first district (reference point), while the y-axis represents the number of transit deserts per km^2 within that district. Blue dots correspond to the 15-minute time interval, and red dots represent the 30-minute time interval. The scatterplot reveals a clear trend: as the distance from the first district increases, the number of transit deserts per km^2 also rises. Consequently, areas closer to the first district exhibit fewer transit deserts.

This can further be illustrated by comparing the inner districts to the outer districts. As visible in Figure 22, inner districts, such as 4, 5 and 9, which are closer to the first district, lose transit deserts when the travel time increases. Outer districts on the other hand, such as 11, 14 and 21, which are further away from the city center, gain transit deserts.

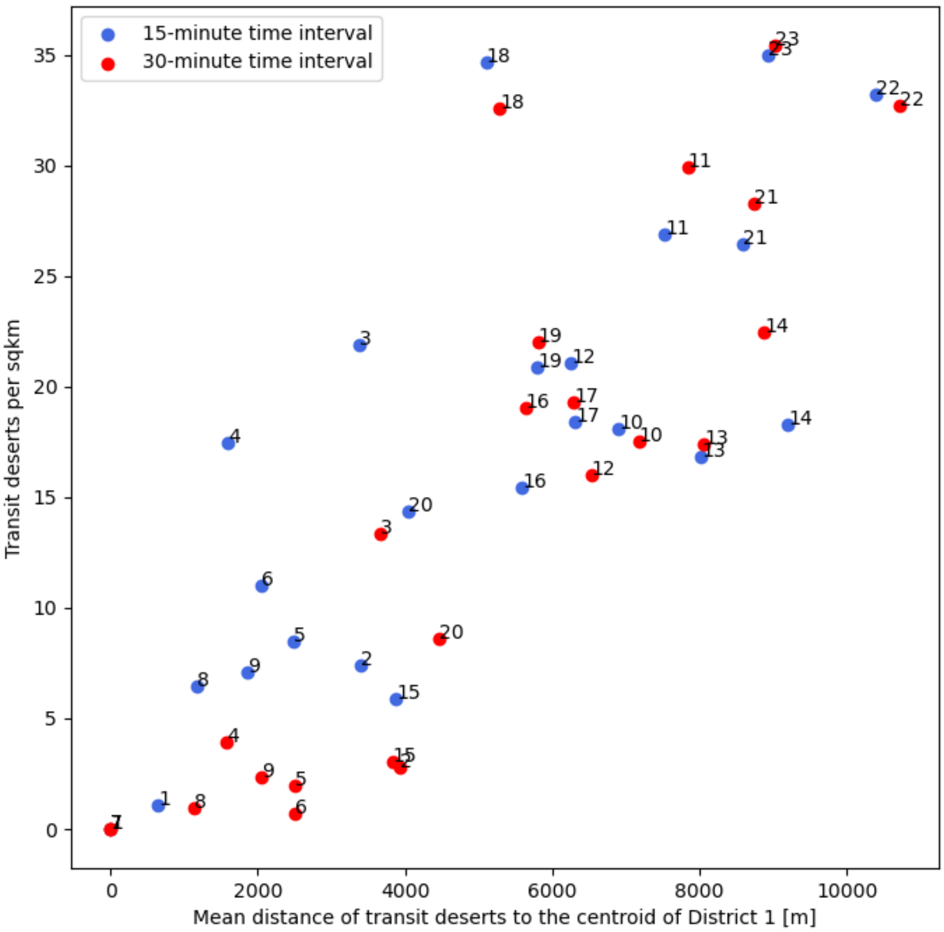


Figure 22: Mean distance of transit deserts to the first district on the x-axis and the number of transit deserts per km^2 on the y-axis. The dots represent districts, and the color represents the time interval.

Additionally, the FGT_2 value is higher for the 30-minute time interval, reflecting greater accessibility inequality when the travel time increases. This does not mean that the absolute accessibility decreases but rather a widening disparity in accessibility levels across different regions.

This can further be supported by comparing the quantile thresholds of the transit desert categorization. While the thresholds for the first two quantiles are approximately the same for the two time intervals, the upper threshold of Q3 for the 15-minute time interval is 0.77 and for the 30-minute time interval 0.97, showing a greater disparity at the higher end. This suggests that the worst-off areas are more severely underserved, leading to a widening disparity in accessibility levels.

For example, the FGT_2 value of the purple circle region in district 13 in Figure 20 increases from 0.46 for the 15-minute time interval to 0.77 for the 30-minute time interval, indicating a strong rise in inequality for this region. This means that other cells for the 30-minutes time interval benefit more from the extended time than this region.

Consequently, this region does not experience the same level of benefit, making it one of the regions contributing to the increasing disparity. In contrast, the green area in district 18 in Figure 20 has a FGT_2 value of 0.58, showing only a slight increase in inequality compared to the shorter interval value of 0.57. This highlights the need for detailed examinations because, although the overall trend is apparent when comparing the quantile thresholds, not every region is affected to the same extent.

4.1.4 District Analysis

For the district-level analysis, the FGT_2 is calculated per district. The poverty line is being kept the same and the remaining variables are adjusted to the district specific values. That enables a comparison between each district. This analysis reveals that outer districts, such as 14, 17, 21 and 22, exhibit the highest FGT_2 values for both the 15-minute and 30-minute time intervals. In contrast, inner districts like 1, 6, and 9 show the lowest FGT_2 values. Figure 23 displays the FGT_2 values. Districts with fewer than 20 transit deserts are marked with a hatched line to indicate lower statistical robustness.

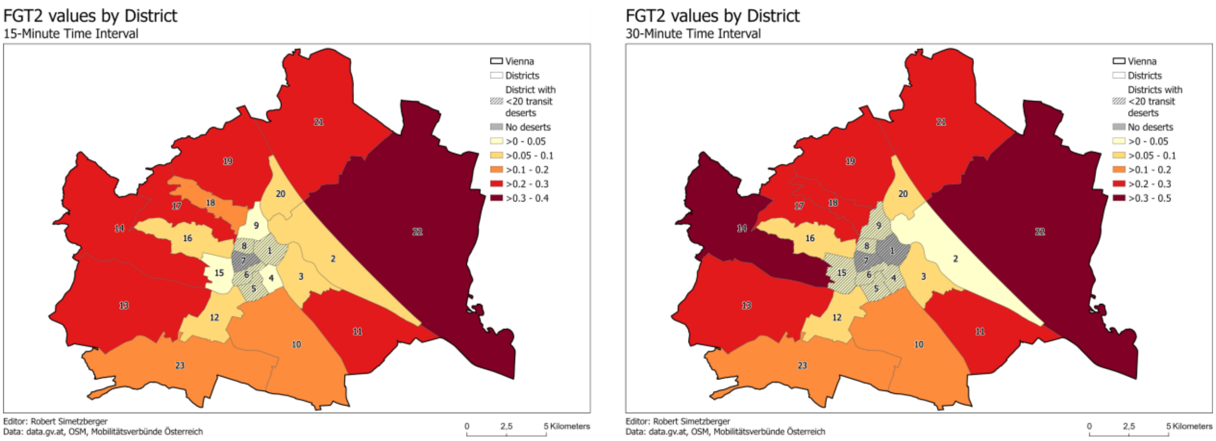


Figure 23: FGT_2-values by district.

To provide a more comprehensive view, Figure 24 shows the density of transit deserts by dividing the number of transit deserts by the area of each district. The results show that outer districts exhibit the highest number of transit deserts per km^2, highlighting the unequal distribution of accessibility across Vienna.

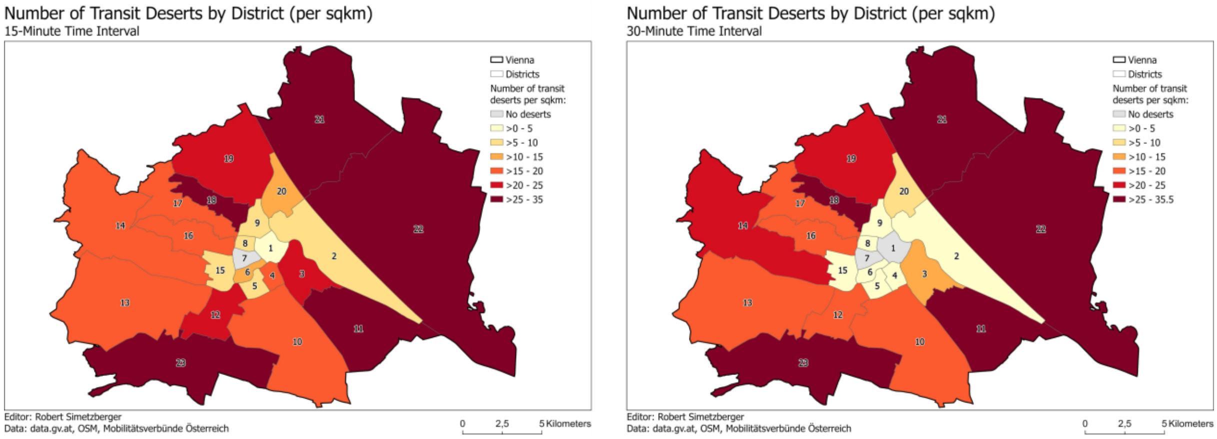


Figure 24: Number of transit deserts by district per km^2.

It is important to note that this representation does not account for the number of people affected, as population densities vary across districts. The main indicators in this study are intentionally spatial and not population weighted, as the goal is to assess geographic accessibility inequality.

However, to provide a complementary perspective on social exposure to accessibility poverty, the number of transit deserts per 10,000 inhabitants is also presented in Figure 25. This analysis reveals a pattern similar to the spatial distribution shown in Figure 24.

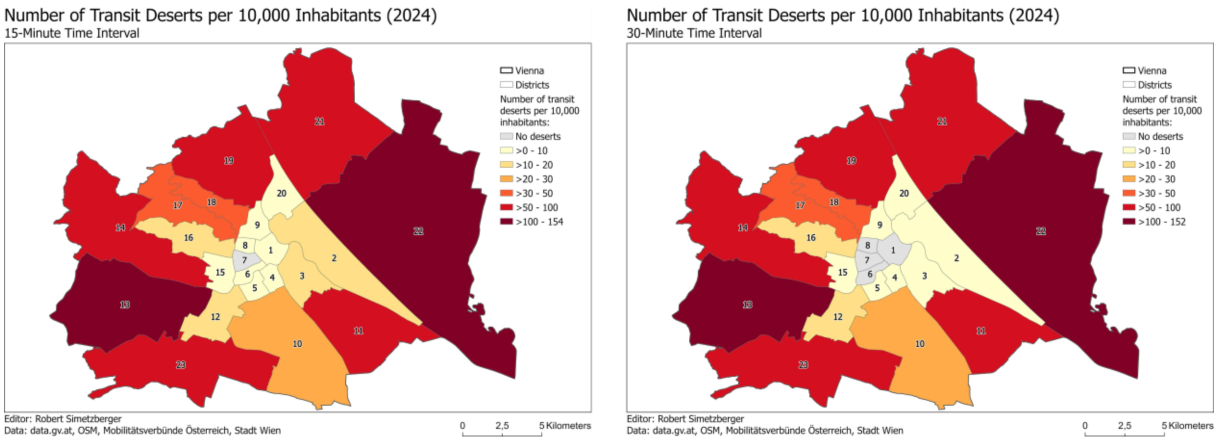


Figure 25: Number of transit deserts by district per 10,000 inhabitants

A comparison of the two time intervals reveals differences in the spatial distribution of transit deserts. The number of transit deserts per km^2 decreases for central and mid-range districts such as 3, 4, 5, 6, and 12, while outer districts such as 11, 14 and 16 gain transit deserts, as shown in

Figure 26. This pattern aligns with the earlier results that the mean distance of transit deserts to the city center is greater for the 30-minute time interval.

Most of the outer districts gain more transit deserts in the 30-minute time interval, and the FGT_2 increases for them as well as illustrated in Figure 26. Calculating the Spearman correlation between the number of transit deserts per km^2 and the FGT_2 by district indicates a moderate, statistically significant positive relationship ($\rho = 0.45$, $p = 0.03$). The Spearman correlation is chosen due to the non-normal distribution of the data.

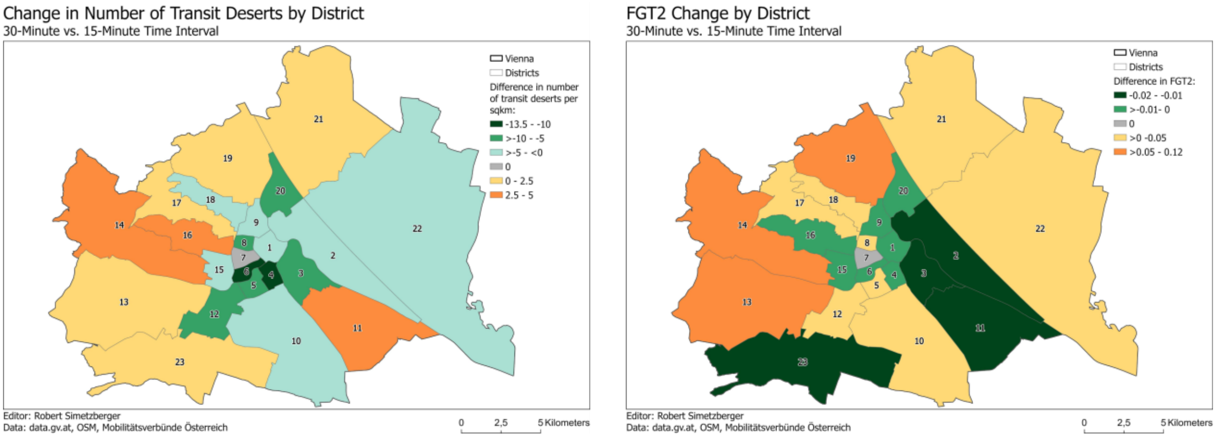


Figure 26:Change in number of transit deserts (left) and change in FGT_2 (right).

When analyzing and interpreting maps based on aggregated spatial units, such as the district level figures shown, it is crucial to consider the Modifiable Areal Unit Problem (MAUP). MAUP refers to the sensitivity of spatial analysis results to the choice of spatial scale and zoning:

- The scale effect occurs when results vary depending on the level of spatial aggregation (e.g., districts vs. smaller units like Zählsprengel).
- The zoning effect refers to changes in results caused by using different boundaries or configurations for the same level of aggregation.

In both cases, statistical patterns and visual representations can shift significantly. This phenomenon is inherent to spatial analysis and should always be considered when analyzing and interpreting aggregated geographic data (Openshaw, 1983; Openshaw & Taylor, 1979).

4.2 Directional Dependencies

This section is dedicated to describing the results of the analysis of directional dependencies in Vienna’s PT network. The results show spatial imbalances in reachability based on directionality, showing differences in the distances one can travel depending on the direction from a given origin. These results provide additional insights into the structure of Vienna’s PT network beyond the transit desert analysis.

4.2.1 15-Minute Time Interval

Figure 27 visualizes the maximum reachable distance from each grid centroid in six directions within the 15-minute time interval. The results show that the highest reachability occurs along subway lines, followed by train corridors. In areas where these types of PT are not present, bus lines become especially important for connectivity, as they often represent the best-connected locations in those areas.

This demonstrates that the direction with the highest reachability from a given point is strongly influenced by the type of available PT and the orientation of those lines. In other words, travel speed and distance depend not only on the location, but also on the direction of travel, because of the structure of transport corridors.

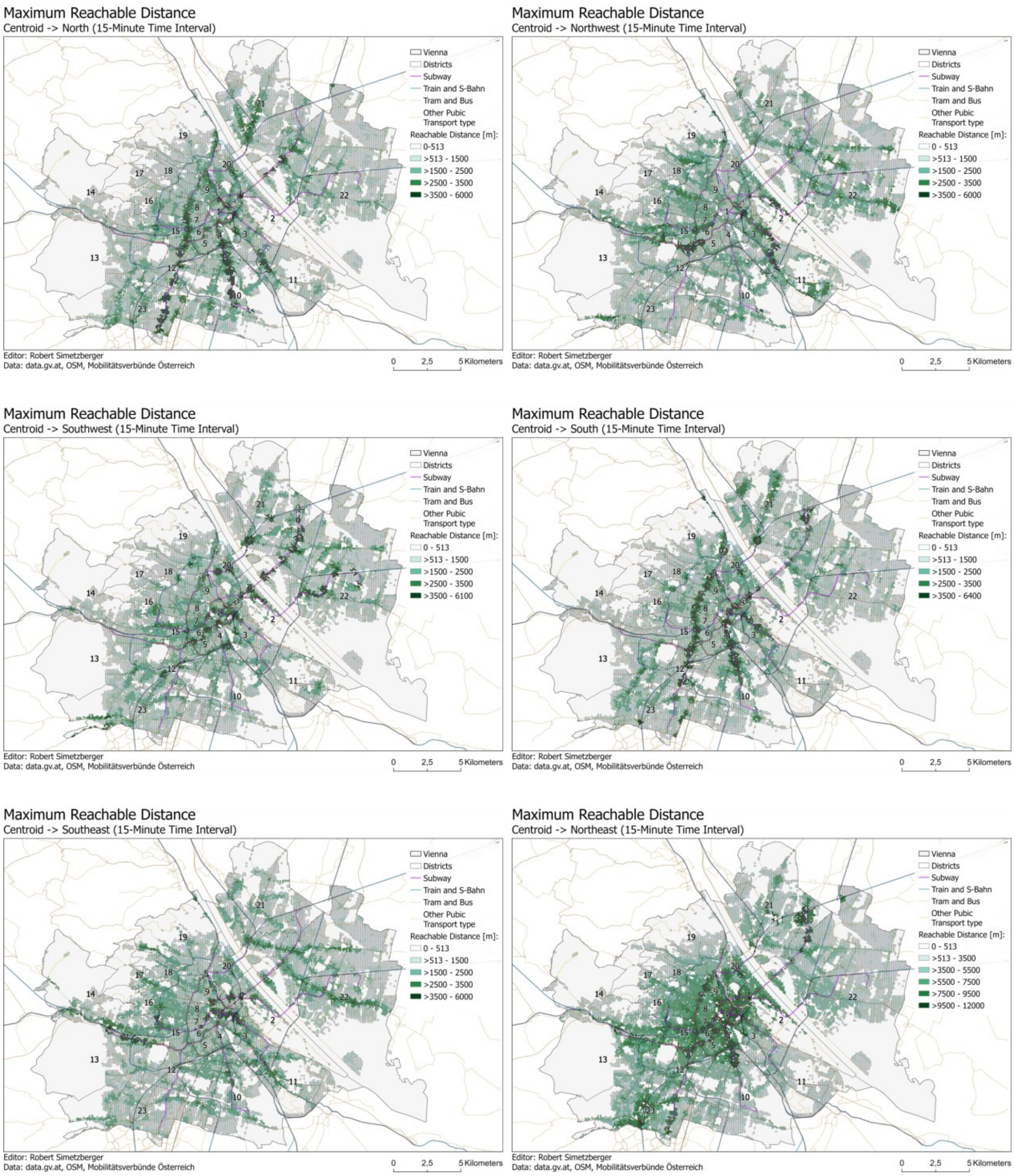


Figure 27: Directional dependencies – 15-minute time interval. Directionality is visualized by showing the reachability in meters for each cell. The centroid is the origin of the respective cell.

The analysis of individual maps delivers additional insights. For example, when examining the Centroid → South Direction (Figure 27), it is clearly visible that the highest reachability is given along the U6 and U1 subway. Figure 28 shows the Subways in Vienna for orientation.

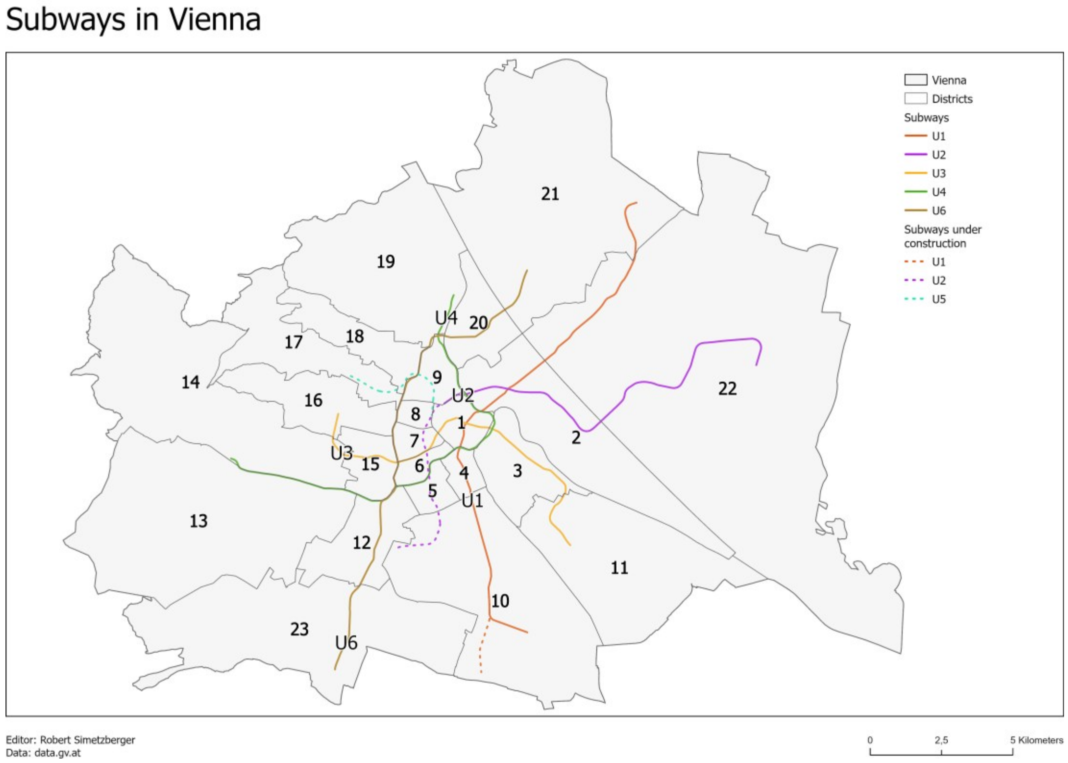


Figure 28: Subways in Vienna.

In contrast, closer to the western and eastern parts of Vienna Centroid → South reachability decreases. Furthermore, when comparing the subway lines under construction to the Centroid → South directionality map it is visible that reachability in that direction at the area close to the U2 extension is significantly lower than at the existing U6 and U1. Additionally, the cells near the areas of the planned U1 extension show lower reachability than the cells where the U1 line already exists. Figure 29 illustrates these findings by combining the directionality data with the subway infrastructure data.

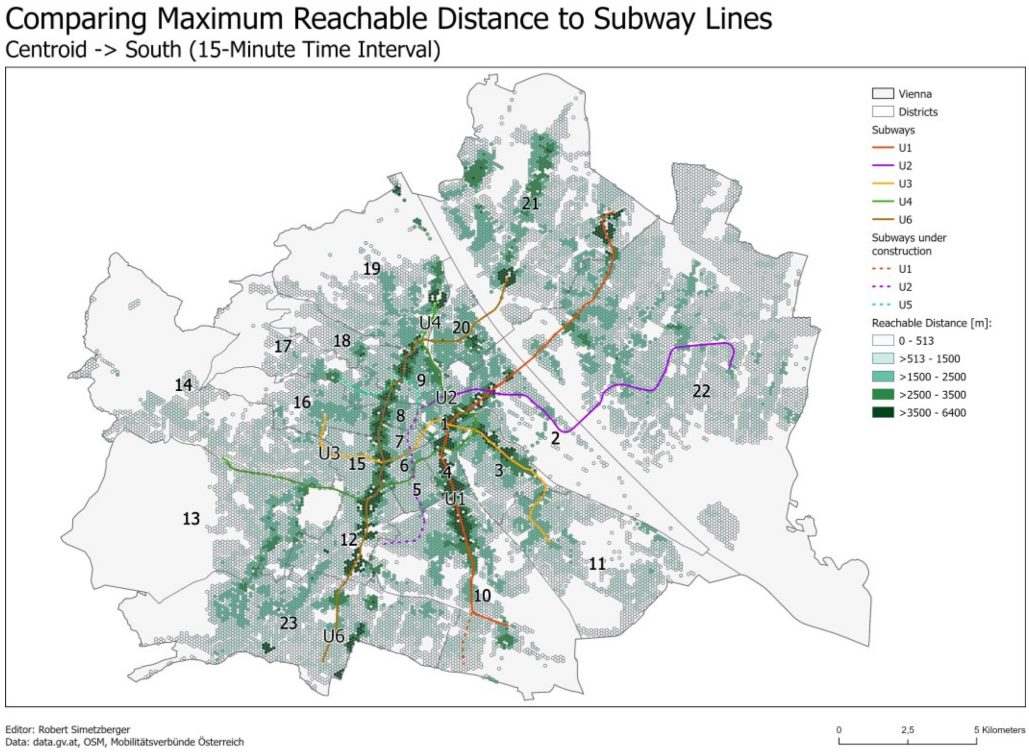


Figure 29: Comparing maximum reachable distance to subway lines. Directionality is visualized by showing the reachability in meters for each cell. The centroid is the origin of the respective cell.

A similar picture is given when comparing the U5 extension to the directionality map for the direction Centroid → Southwest, as shown in Figure 30. Reachability is relatively low in that future transit corridor.

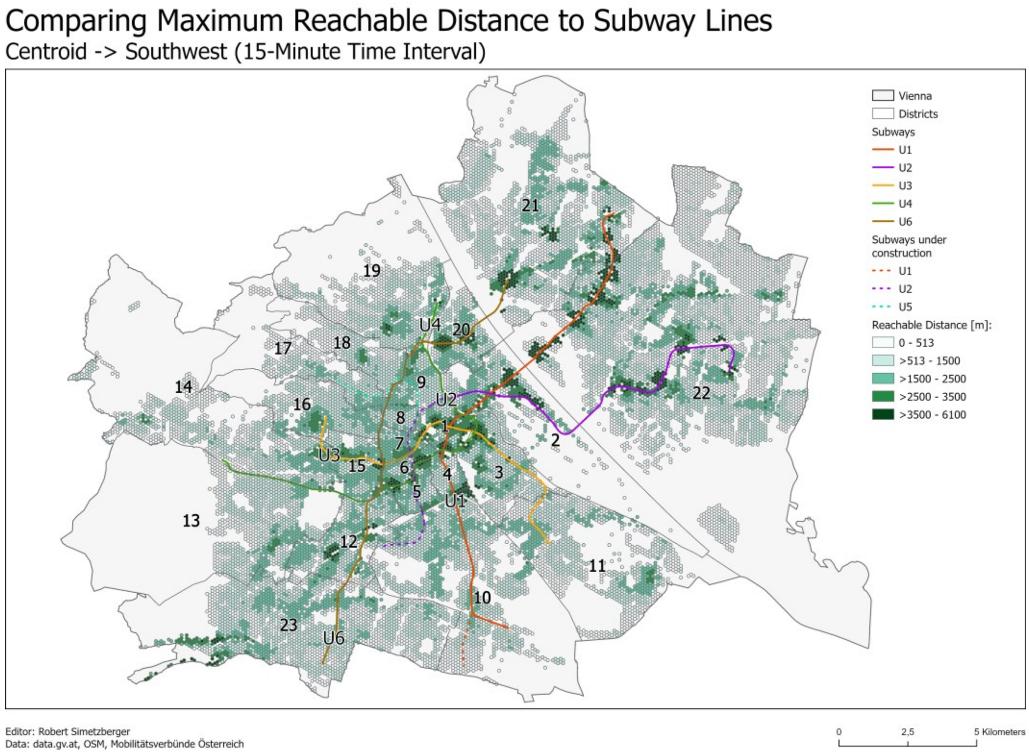


Figure 30: Comparing maximum reachable distance to subway lines. Directionality is visualized by showing the reachability in meters for each cell. The centroid is the origin of the respective cell.

4.2.2 30-Minute Time Interval

Figure 31 shows directional dependencies for the 30-minute time interval. Directionality continues to play a role, but visual inspection shows less spatial concentration compared to the 15-minute time interval.

However, the highest reachability is still given along major transit corridors, such as subway lines. This shows the dependence of reachability on different types of PT and, therefore, the directions to which they are going.

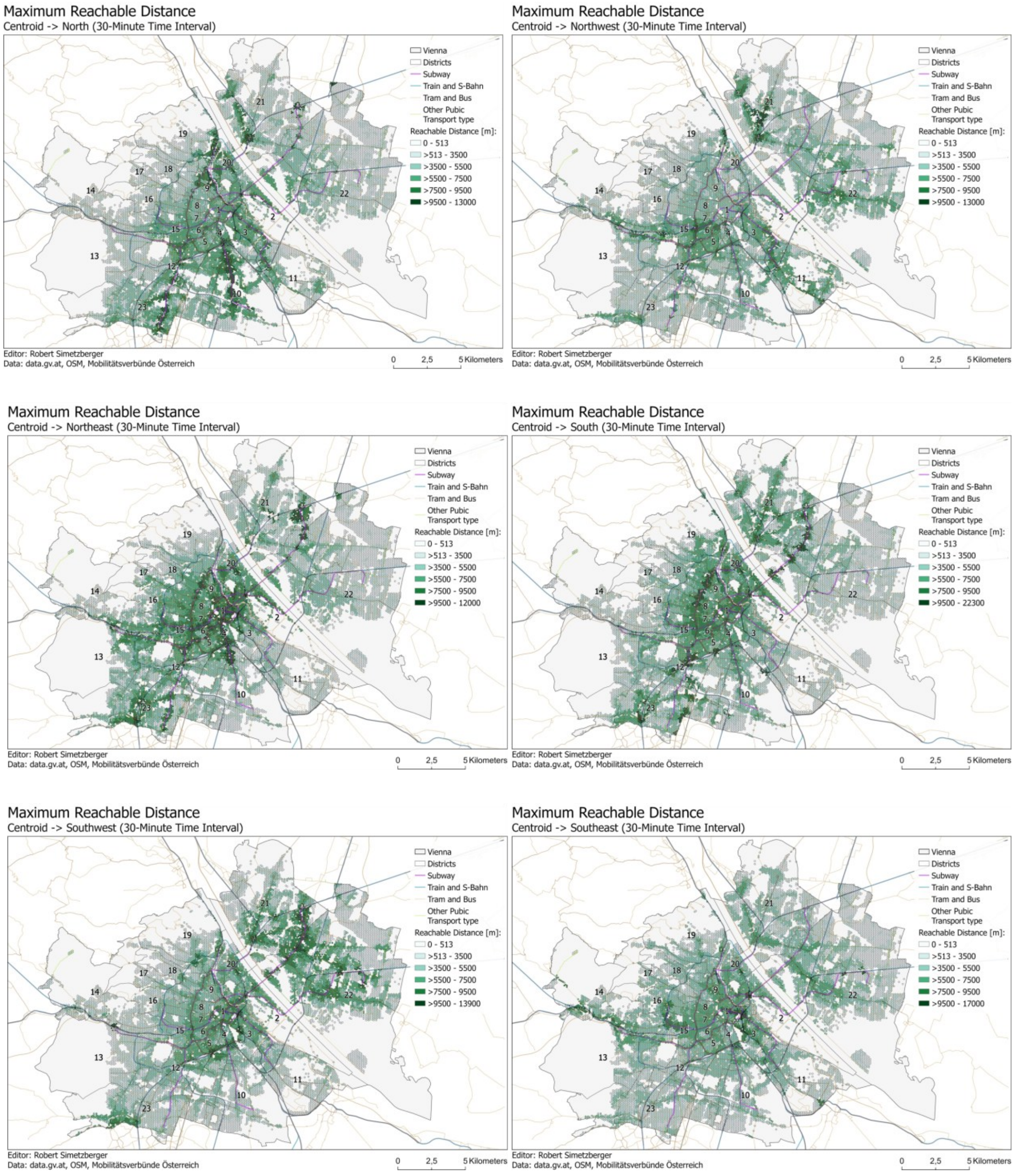


Figure 31: Directional dependencies – 30-minute time interval. Directionality is visualized by showing the reachability in meters for each cell. The centroid is the origin of the respective cell.

4.2.3 Comparing 15-Minute Time Interval to 30-Minute Time Interval

When comparing the two time intervals, directional dependencies appear more significant in the 15-minute time interval than in the 30-minute time interval. Visual inspection shows more clustering of high reachability cells in the 15-minute maps compared to the 30-minute maps. This observation is supported statistically by correlating the isochrone area with the range of maximum reachable distances across all directions. The correlation measures the relationship between the reachable area and the deviation in maximum reachable distances, which indicates the degree of directional dependence. The higher the range, the more directionality matters as different directions are differently well connected.

The Spearman correlation, chosen due to the non-normal distribution of the data, reveals a significant positive relationship between reachable area and directional dependence: 0.67 ($p = 0.00$) for the 15-minute interval and 0.51 ($p = 0.00$) for the 30-minute interval. These results suggest that directionality plays a stronger role in accessibility at shorter travel times. As travel time increases, directional dependence decreases, indicating that reachability becomes more evenly distributed across all directions.

5 Discussion and Shortcomings

This chapter provides a discussion to reflect on the results of this thesis. Furthermore, the shortcomings of the study are addressed.

5.1 Discussion

The results in Chapter 4 reveal spatial patterns and accessibility inequalities across Vienna, providing insights into transit deserts and directional dependencies. This section is split into subchapters to interpret these findings in relation to the two objectives.

5.1.1 Transit Deserts

The results in Chapter 4.1 reveal a pattern of accessibility inequality and show that transit deserts are predominantly located closer to the boundaries of Vienna. The district analysis supports this finding, showing that the outer districts, such as 14, 19, 21 and 22 not only have the highest number of transit deserts per square kilometer but also exhibit the highest FGT_2 values.

One possible reason for the accumulation of transit deserts in outer districts is the proximity of these areas to natural barriers, such as forests, where public transport is either nonexistent or sparse because there are not many destinations to reach. However, this appears not to be the only reason when comparing the results to the directional dependencies maps. This analysis shows that even in directions away from the forests, these outer districts often exhibit lower reachability. This represents a structural issue, as outer districts are less integrated into the city's PT network, particularly in terms of high-speed modes like subways, which often do not reach the boundaries of Vienna.

The comparison of the FGT_2 values for the 15-minute and 30-minute time interval provides further insights into accessibility inequality in the city. For the 30-minute time interval, the FGT_2 value increases, indicating greater inequality. This can be explained by the fact that well-connected cells benefit more from the extended travel time, as they can access additional PT lines or travel farther using fast modes such as subways. In contrast, cells with already low connectivity, especially those far from PT stops or only served by slower bus lines, fail to gain as much accessibility. Since the walking time does not increase with the longer time interval, cells that do not reach a PT stop by walking will also fail to do so for the 30-minute time interval. Furthermore, regions which are only served by low-speed bus lines and with low PT density may still not access faster modes like subways or even other bus lines. The outer districts are especially affected by that, shown in Figure 26. The FGT_2 increases for most of the

outer districts while it decreases for the inner ones, indicating a rise in inequality for the outer districts. This is further supported by the example of the purple region in district 13 in Figure 20. When increasing the travel time from 15 to 30 minutes the FGT_2 increases from 0.46 to 0.77, highlighting a rise in inequality.
The comparison of the number of transit deserts per square kilometer between the 15-minute and 30-minute time interval shows an increase in transit deserts in outer districts, and thus a shift in accessibility inequality towards the boundaries. This is further supported by comparing the mean distance between PT transit desert cells and the city center, which increases for the longer time interval.
These disparities in accessibility likely stem from the higher density of stops and high-speed PT (especially subways) in central areas. The unequal distribution of infrastructure also explains why transit deserts are shifted to the outer districts when the travel time is increased. Outer districts fail to improve in accessibility on the same level as the inner districts, which benefit more from the extended time.
As already explained in Chapter 2.2, higher accessibility levels correlate with social inclusion and employment rates, indicating the importance of PT. Inhabitants of these underserved regions are either exposed to lower possibilities on the job market and social exclusion or have to find different forms of commuting, such as traveling by car, which has negative impacts on health and the environment.

5.1.2 Directional Dependencies

The analysis of directional dependencies adds another layer of understanding, leading to a more comprehensive perspective on Vienna's public transport network. The results reveal anisotropicity, indicating imbalances in reachability across different directions.
For the 15-minute time interval, clear concentration is visible along major transit lines, the subway and train lines, highlighting their important role in the network. These modes enable high reachability, especially towards the city center, while bus lines are important connectors in areas with no subway access, despite their lower reachability. For the 30-minute time interval, however, directionality appears less influential, as the maps do not exhibit such strong concentration patterns. These visual findings are supported by the correlation between the isochrone area and the range of the maximum reachable distance values. The result is higher for the shorter travel time, indicating stronger directional dependence. The longer travel time allows for more diversified journeys by enabling transfers and extending walking distances both

after using a public transport mode and between transfers, which leads to more evenly distributed accessibility across multiple directions.

Additionally, areas with relatively low reachability in specific directions can be detected using this methodology. For example, the area between the U6 and U1 where the U2 will be extended shows relatively low North-South reachability, while other directions in this region are better connected. The fact that this is the region where the U2 is being extended in the North-South direction indicates that this is an existing problem which decision-makers have already discovered. This alignment validates the methodology and demonstrates the potential for identifying problematic regions in the network.

As the Stadt Wien (n.d.b) and the Wiener Linien (n.d.) write, the extension of the U2, together with the development of the U5 does not only create an important transfer node in the city center but also connects a fast growing urban development area in the south of Vienna, the Wienerberg. Furthermore, the new North-South connection, provided by the U2, will make PT more attractive for commuters. In summary, not just the Viennese will profit from this subway development but also commuters, which will have a positive environmental and societal impact. As explained in Chapter 2.2 well-connected public transport can lower social exclusion and reduce greenhouse gas emissions.

In summary, the directional dependence analysis not only highlights the strengths and weaknesses of Vienna's PT network but also offers a tool for detecting areas of directional imbalance, supporting targeted interventions in transport planning.

5.2 Shortcomings

The implementation of the methodology comes with certain limitations. First, the analysis is carried out for a single time interval on a single weekday. The results may differ for other days of the week or times of the day. However, by selecting a weekday morning, the study considers a time period when a large portion of the population is traveling – children commuting to school and adults to work. Nonetheless, individuals outside these groups are not represented. This limitation is given in any study that does not consider all possible travel scenarios, but expanding the temporal scope would not improve the development of this methodological approach.

Another factor to consider is the presence of areas where construction is currently prohibited. These zones in the land use plan indicate regions where development is restricted but people could live already (see Figure 32). Since some of these areas may already contain housing, they are included in the evaluation. But, if no one lives in these zones, this could skew the results.

Therefore, it is crucial to be aware of these areas and consider their potential impact. However, district 22 is the only one with a substantial number of such regions.

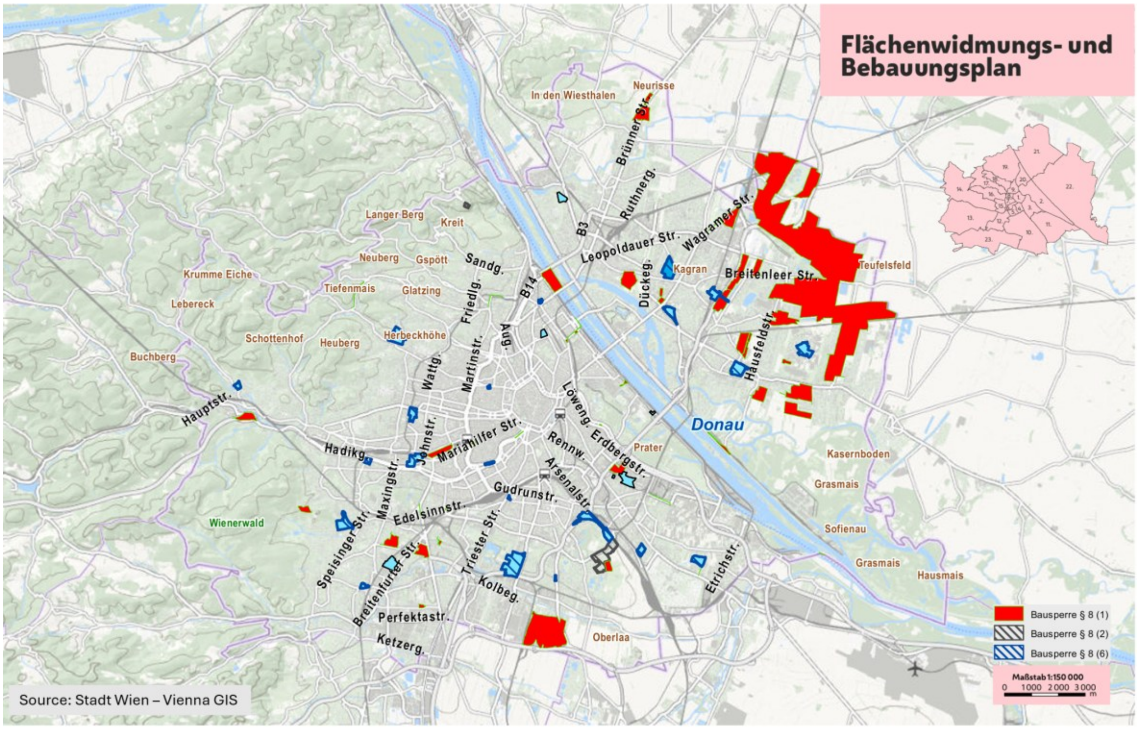


Figure 32: Land use plan showing regions with restricted development (own representation, 2025).

6 Conclusion

This study highlights the relevance of public transport and measuring accessibility. It proposes a definition of transit deserts as areas that are underserved by PT relative to other parts of the city. To provide a more differentiated understanding, transit deserts are further categorized by severity. These areas are identified, using the introduced isochrone-based approach and are visualized on maps. To gain further insights into the network, directional dependencies are examined after the term is introduced. Multiple maps show these dependencies as the result of this approach and reveal that the possibility of travelling in the city is not just determined by distance but also by direction.

Referring back to the research questions presented in the Introduction, this study has successfully addressed all four:

1. **How can transit deserts be detected?**

   Transit deserts can be detected using various accessibility measures, such as the cumulative opportunity measure (COM), the potential mobility index (PMI), the categorization of available stops (ÖV-Güteklassen) and the isochronal analysis. Some indicators, such as COM or gravity-based measures, are POI-based and reflect both public transport accessibility and the spatial distribution of opportunities. Others, like the PMI and the isochronal analysis, are solely based on the network's configuration.

   These indicators are further evaluated using the FGT_2 measure, enabling the identification of severely underserved regions.

2. **Where are transit deserts located?**

   The results show that most transit deserts are located at the outer edges of Vienna. This is detailed in the Results chapter through several illustrative maps.

3. **How can directional dependence be analyzed and visualized?**

   Directional dependence is analyzed by dividing each cell's isochrone into six directions and measuring the maximum reachable distance in each direction. This enables the identification of directional dependence by extracting the possible travel distance in each direction. Six maps visualize these patterns (one per direction), revealing clear travel corridors and highlighting that accessibility is strongly influenced by direction.

4. **How can a method be developed which addresses the previous questions and can be applied to multiple cities?**

   Several methodological approaches were considered, but the isochrone-based approach was chosen for its ability to identify both transit deserts and directional dependencies independently of POI distribution. This approach only requires GTFS data and a street network, both widely available and open-source, making the method transferable to other cities. This was also the reason for working with open-source programming languages to ensure reproducibility and accessibility.

These answers address the previously identified research gap: existing methods capable of detecting transit deserts do not provide insights into the underlying spatial patterns or directional dependencies that contribute to accessibility deficits, and they offer no visual explanations to support the interpretation of the results.

The findings offer valuable insights and demonstrate the potential of the isochrone-based approach. Transit deserts were identified using the FGT_2 measure, highlighting areas with low connectivity. Additionally, the analysis on directional dependencies revealed imbalances in Vienna's PT network and helps detect regions where new transit lines may be needed, as demonstrated by the example of the U2 extension.

Isochrones not only facilitate the detection of transit deserts but also provide deeper insights into directional dependencies. Unlike conventional accessibility analyses that rely on POIs – combining urban and transport planning factors – the isochrone-based approach evaluates the network itself, independent of specific destination points. This distinction makes isochrones an effective tool for assessing structural imbalances in public transport. Furthermore, by incorporating accessibility and directional factors, this study demonstrates that isochrones contribute to a more comprehensive understanding of a city's transit network than transit desert analysis alone.

This does not imply that POI-based approaches are inadequate. On the contrary, combining network-based and POI-based approaches would provide a more holistic understanding of accessibility. For future research, integrating additional information, such as POIs, could further combine transport and urban planning perspectives. An accessibility analysis based on POIs would offer a more comprehensive view of service availability, with the POMA framework offering an effective way to interpret the results.

In addition, comparing the findings to additional census data in a resolution similar to the hexagonal grid of the study could provide insights into transport justice by showing if transit deserts occur along with specific groups, such as people with lower income or migration backgrounds.

Another interesting direction would be to analyze temporal variations in transit deserts and directional dependencies. While this analysis focused on peak hours, accessibility patterns may

differ significantly during off peak times like weekends or public holidays, when service levels are typically reduced.
Furthermore, integrating additional modes of transport, such as cycling, could enrich the analysis. One limiting factor in accessibility is the walking distance and time to stops. If cycling were considered as well, it could significantly increase the range from which people can access the public transport network.

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Declaration on the Use of AI

ChatGPT (including the GPT-3.5-based Assistant on Poe.com) and Claude (on Poe.com) were used during the writing of this master's thesis to improve the style, grammar, and spelling of the text.