Master of Science

Assessing Compliance with the X-minute City Concept: A Bikeability and Accessibility Approach in Münster

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Declaration of Originality

I, Hager Abdelwahid, declare that the thesis titled ”**Assessing Compliance with the X-minute City Concept: A Bikeability and Accessibility Approach in Münster**” is entirely my own work, carried out and written independently with guidance from my supervisors. Any assistance I have received is acknowledged, and all sources, whether published or unpublished, are accurately cited. This thesis has not been submitted for any other degree and is not currently under consideration for any other qualification.

Additionally, I used the large language model GPT-4o to correct language and find word synonyms. However, the content, analysis, and conclusions presented in this thesis remain entirely my own.

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Abstract

The x-minute city concept ensures that residents can access essential services within a short walking or cycling distance, promoting sustainable urban mobility. While previous research has primarily focused on walkability, bikeability remains underexplored. This study aims to develop a framework to assess compliance with the x-minute city concept by integrating accessibility, bikeability, and service diversity while addressing social inequalities. The methodology combines multiple indicators into a composite x-minute city index. Accessibility is evaluated using a cumulative-opportunity measure across six essential service categories. Bikeability is assessed through an index evaluating infrastructure, safety, comfort, and environmental factors, with weights determined by experts using the Analytic Hierarchy Process. Service diversity is analyzed using the Shannon index, while social inequalities are assessed through sufficiency criteria and the Gini index to measure disparities in aligning with the x-minute city concept..

Applying this framework to Münster reveals that 99.5%, 99.2%, and 98.3% of residents can access at least one essential destination within 15, 10 and 5 minutes, respectively. The results indicate that aligning with the x-minute concept is well distributed across different population groups, including foreigners, the elderly, and children. While most residents have access to a sufficient variety of amenities within 15 minutes, availability decreases at the 10- and 5-minute thresholds. Peripheral areas have limited access to diverse amenities and bike-friendly infrastructure, highlighting the need for targeted improvements. Overall, Münster aligns with the 15-minute city model and has the potential to transition toward a 10-minute city with further enhancements in accessibility and service distribution in underserved areas. A key contribution of this study is the development of a digital tool that provides real-time, location-specific insights into x-minute city compliance. By supporting urban planners and policymakers, this tool helps optimize accessibility and offers insights into the importance of the x-minute city concept.

Keywords: x-minute city, composite index, bikeability, accessibility, urban diversity, urban mobility, active transportation, social inequalities.

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Abbreviations

Abbreviation	Definition
OSM	Open Street Map.
POIs	Points of Interest.
LTS	Level of Traffic Stress.
AHP	Analytic Hierarchy Process.
AIJ	Aggregation of Individual Judgments.
AIP	Aggregation of Individual Priorities.
CR	Consistency Ratio
NDVI	Normalized Difference Vegetation Index
HDBSCAN	Hierarchical Density-Based Spatial Clustering of Applications with Noise.
HTML	Hypertext Mark-up Language.
CSS	Cascading Style Sheet.
Js	JavaScript.
API	Application Programming Interface.
GSV	Google Street View.

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Introduction

The 15-minute city concept, developed by the Franco-Colombian scientist Carlos Moreno in 2016, gained global attention during the COVID-19 pandemic. The core idea behind the 15-minute city is to ensure access to essential amenities within a short distance, either by walking or biking, thereby promoting short-distance accessibility [1]. Previous studies have used the term ”x-minute city” to account for the varying scales at which the concept can be implemented, as city size significantly influences its practical application [4] [5].

Several European cities have adopted the x-minute city concept to promote car independence and enhance global warming mitigation policies. A notable example is Paris, where Mayor Anne Hidalgo has promoted the ”Ville du Quart d'Heure” concept, advocating for short-distance travel and sustainable mobility [6]. Furthermore, urban planning policies have been shifting toward a safer accessibility approach that prioritizes land-use diversity over merely increasing traffic speed [7]. As a result, active mobility has become a key component of policy agendas in many European cities.

Since the x-minute city relies on active transportation, cities promoting cycling as a primary mode need a bikeability assessment method to ensure essential services remain accessible. Bikeability is defined as ”an assessment of an entire bikeway network for perceived comfort, convenience, and access to important destinations” [8]. Various index-based models quantify bike-friendliness, integrating diverse data sources and statistical modeling for a comprehensive, objective evaluation of bikeable zones. These assessments support urban planning and policy decisions, promoting cycling as a sustainable transport mode [9] [10].

1.1 Research Overview

1.1.1 Problem Definition and Research Gap

In exploring transportation methods within the x-minute city framework, most existing research has focused on walkability, while only a few studies have considered cycling [11]. As an active mode of transport, cycling contributes to well-being and mobility justice by being an environmentally friendly and inclusive transportation option. Moreover, cycling enhances local accessibility in cities due to its ability to cover longer distances efficiently.

Regarding cycling assessment, bikeability has emerged as a method for evaluating cycling conditions based on infrastructure, accessibility, and environmental indicators. However, there is a gap in research regarding the identification of bikeability indicators within the x-minute city framework [11]. While the x-minute city has gained global recognition, even well-planned cities can still experience social segregation. Therefore, there remains a need to assess bikeability indicators to ensure equitable access to essential services. Factors such as infrastructure quality, safety, comfort, and the environment, which are often overlooked in x-minute city discussions, must be addressed [5].

Therefore, a comprehensive bikeability assessment is crucial for improving accessibility within the concept framework. Evaluating diversity and sufficiency of essential amenities is equally important to prevent social inequalities [12]. To address this, both bikeability and access to essential services must be assessed. This approach enhances decision-making and promotes cycling as a key transport mode in the x-minute city.

In light of the identified research gap, this study aims to evaluate the applicability of the x-minute city concept within the case study area, with a particular focus on bikeability and accessibility. Münster, known as the cycling capital of Germany, has been selected due to its strong potential as a city of short distances.

To achieve this aim, the study sets out several key objectives. First, it seeks to assess compliance with the x-minute city framework by developing assessment criteria to quantify how well the case study area aligns with the concept, particularly regarding amenity accessibility and diversity. Second, it aims to evaluate bikeability by identifying key factors such as cycling infrastructure, comfort, safety, and environmental conditions, ultimately developing a composite bikeability index tailored to the x-minute city framework.

Additionally, the study addresses spatial inequalities by identifying regions that require further improvements to foster a more inclusive urban environment. Lastly, a customized, and equitable digital mapping tool will be developed to support urban planning and decision-making processes within the x-minute city framework.

The main research questions are as follows:

- ***1) How can accessibility by bike be measured and assessed, and what indicators influence bikeability in the context of the x-minute city?***
- ***2) How can compliance with the x-minute city concept be measured, and how can social inequalities be addressed using Münster as the case study?***
- ***3) How can digital tools enhance the assessment process through data visualization and customized interactive mapping?***

1.2 Thesis Structure

This thesis examines the x-minute city concept through the lens of bikeability and accessibility, using Münster as a case study. It is organized into six chapters:

- **Introduction** – Presents the x-minute city concept, identifies the research gap, and outlines the study's objectives and methodology.
- **Literature Review** – Discusses accessibility measures, bikeability assessment and indicators, approaches to evaluating x-minute city compliance, and ways to address social inequalities.
- **Methodology** – Details the development of a composite bikeability index for Münster. It also introduces an x-minute city index to evaluate concept compliance and a method for assessing social inequalities.
- **Results** – Presents findings on x-minute city compliance, including accessibility, bikeability, and social inequalities.
- **Discussion** – Interprets the results in an urban planning context, and acknowledges research limitations. Future research directions to refine x-minute city assessment models are also proposed.
- **Conclusion** – Summarizes the key findings and methods used to assess the x-minute city.

2

Literature Review

This chapter reviews the x-minute city concept, its origins, key dimensions, and debates on its applicability. It explores accessibility measurement methods, the diversity of destinations, and bikeability assessment, including indicators and indices. Additionally, it examines social inequalities in accessibility and digital tools for evaluating the x-minute city. By analyzing these aspects, the chapter highlights the potential of cycling within the x-minute city framework and how to assess it through bikeability evaluation methods. This review provides a foundation for tackling the research gap.

2.1 The X-minute City Concept as an Urban Planning Model

2.1.1 The State of the Art of the X-minute City

The ”x-minute city” concept was first introduced in 2016 by Carlos Moreno, a scientist and professor at the Sorbonne University. Moreno defines the x-minute city as a city where basic human needs are accessible within a 15-minute walk or bike ride [1]. The concept mainly proposes to reduce the time needed to travel between urban nodes, with the aim of eliminating car dependency [13]. Moreno categorized the essential daily needs to: (a) living, (b) working, (c) commerce, (d) healthcare, (e) education and (f) entertainment [1]. At its core, the concept is based on four key dimensions: proximity, density, diversity, and digitalization (see Figure 2.1).

The core element of the x-minute city is proximity, ensuring that essential services are accessible within the 15-minute threshold[1]. This proximity-based framework emphasizes decentralization and polycentricity, allowing neighborhoods to function as self-sufficient units while promoting equitable distribution of resources [14]. The model includes density, promoting compact urban areas where resources and amenities are efficiently concentrated, reducing car dependency. In addition to proximity and density, the x-minute city concept integrates diversity and digitalization.

Diversity involves a mixed land-use approach, combining residential, commercial, and cultural spaces to maximize urban vitality and social cohesion [13]. Meanwhile, digitalization facilitates the efficient implementation of the model through smart technologies, such as sensors and automation. Digitalization enhance service delivery, optimize urban resource use, and monitor public spaces for improved user experiences [1]. These components together create a framework that supports sustainable, equitable, and resilient urban development.

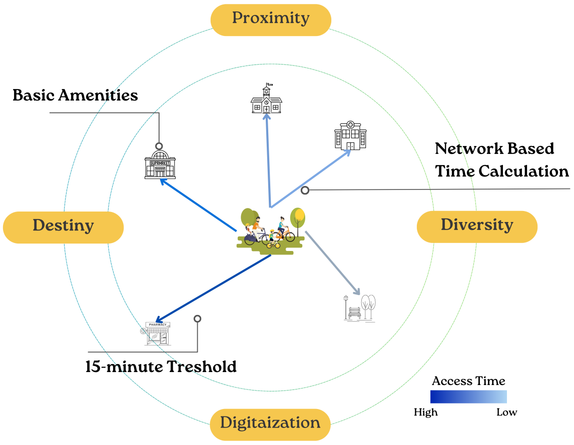

Figure 2.1: Note: Own figure: The State-of-the-art of the X-minute City Concept, based on Moreno et al. [1]

2.1.2 The Current Debate on the X-minute City

The current debate is whether the concept is novel or not. Studies proved that the principles underlying the x-minute city concept are deeply rooted in historical and contemporary urban planning frameworks. Mouratidis (2024) states that Moreno was interpreting another concepts. Ideas such as Krier's "City within the City" (1977) emphasize self-sufficient neighborhoods. While "New Urbanism" (Duany et al., 2001; Grant, 2005) promotes transit-oriented development to counter urban sprawl and car dependency[12].

Moreover, "complete communities" concept focuses on diverse land uses linked by sustainable transport[15]. The concept is quantified by measuring accessibiliy that people need in their daily lives [16] [17]. Chrono-urbanism, which connects quality of life to reducing transport time and costs, which is very similar to the x-minute city[18] [16]. Additionally, the 20-minute Neighborhood concept which is promoting for accessibility within 20 minutes [19]. These ideas closely align with the concept, demonstrating that the x-minute city concept has evolved from earlier urban planning models.

Furtheremore, the x-minute city as an urban planning model could not fit for all cities. For instance, the concept may not be fully adaptable to cities in the Global South due to differing urban structures, cultural contexts, and socioeconomic conditions [20]. On the contrary, it could be applicable for compacted cities such as European cities. Poorthuis and Zook (2023) highlight that the 15-minute city concept originates from European urban planning and may overly prioritize large, high-density urban areas [21].

While previous studies have explored key aspects and the applicability of the x-minute city, we can conclude that the concept itself is not entirely new. However, its global popularity and the attention it has received underscore the importance of urban planning approaches that enhance accessibility through active mobility.

2.2 Accessibility in the Context X-minute City

2.2.1 Accessibility Definition

Accessibility is a core concept in transport and urban planning, focusing on how transport systems and land use policies shape people's ability to access various opportunities like jobs, education, and health services [22]. Fundamentally, accessibility, which was introduced by Hansen in 1959, involves the complex ways in which people interact with transportation, adding a social dimension to transport planning [23] [2]. Accessibility-based planning takes into account elements of both the land-use and transportation systems, in contrast to mobility-based planning, which solely takes into account the transportation systems [3].

Access to activities depends on three main factors: infrastructure, land use, and people. Infrastructure includes how well transportation systems like buses, trains, and streets are connected. Land use refers to where people live and where important places like schools, hospitals, and parks are located. The closer these places are to where people live, the easier it is to reach them. Additionally, people's characteristics such as age, mobility, income, and background influence how easily they can move around the city and use different transportation options safely and comfortably [24]. Based on this, it explains why assessing accessibility is crucial in the context of the x-minute city.

At its core, the x-minute city concept has been primarily linked to proximity. However, recent research has shifted the focus to accessibility, emphasizing the role of accessibility, the diversity of services, and transportation conditions [20, 25]. This shift raises important questions, such as how the variable ”x” is defined within the x-minute framework and how it can be determined. Another is which essential destinations should be included to meet people's daily needs.

In exploring these aspects, studies have examined trip origins and the types of amenities that should be provided within an appropriate threshold. Furthermore, most research has primarily focused on walking as the main mode of transport [26, 27], while fewer studies have considered a combination of walking and cycling in both global and local contexts [28]. Among these, Knap et al. (2023) appears to be the only study that proposed a composite accessibility metric, using Utrecht, the Netherlands, as a case study [5].

2.2.2 Accessibility Measurements

To quantify accessibility, four main methods are commonly used. Based on Geurs and van Wee (2004), these methods are categorized into , location-based, person-based, and utility-based measures. The infrastructure-based approach examines how transportation systems influence people's ability to reach opportunities. The person-based and utility-based approaches focus on the individual level, considering people's participation in activities and the benefits gained from accessing different opportunities. Finally, the location-based approach evaluates how many opportunities a person can reach within a given distance or travel time [24].

Location-based measures analyze accessibility on a larger scale, assessing each area within the study region and often distinguishing between different population groups. These measures are widely used to examine access to amenities and inequalities in accessibility [29] [3]. A common method is the cumulative opportunity measure, which counts the number of opportunities accessible within a specified travel time [2]. Another widely used approach is the gravity-based method, where accessibility decreases as travel costs increase. In this method, closer opportunities are given higher weight, while those further away contribute less.

To quantitatively assess accessibility, Hansen's accessibility formuls is often used. The accessibility A_i for a particular area i is calculated by summing up the size of activities O_j in all other areas j, weighted by a function $f(t_{ij})$ that accounts for the travel time t_{ij} between areas i and j. The formula is expressed as:

$$A_i = \sum_j O_j f(t_{ij})$$

In this equation:

- A_i: Accessibility in zone i
- O_j: Size of activity in zone j (e.g., number of amenities)
- t_{ij}: Travel time between zones i and j
- $f(t_{ij})$: A function used to weight destination opportunities by the travel time required to reach them

A common choice for the impedance function is an exponential decay function:

$$f(t_{ij}) = e^{-\beta t_{ij}}$$

where β is a parameter that determines how quickly accessibility decreases as travel time increases.
This formula helps evaluate how easily individuals can access various opportunities based on factors like transportation infrastructure and travel time.

2.2.3 Trip Origins

Defining trip origins is a critical component in evaluating accessibility within the x-minute city framework. The selection of spatial scale directly impacts the accuracy of this evaluation. Some studies considered the origin of the trip as the centroid of the smallest geographical areas such as the census block in the USA or the Statistical Area SA1 in New Zealand [4]. Other studies aggregated the population distribution based on cell-based grid and considered the cell centriod as the trip origin. For example, Knap et al. (2023) identified the trip center by calculating the population-weighted geometric mean of residential buildings in the city of Utrecht [5].

By using disaggregated spatial units, such as small neighborhood blocks or individual buildings, to represent trip origins, the analysis becomes more precise and reflective of actual urban experiences [11]. This finer spatial resolution enables a detailed understanding of how residents access essential services within the designated x-minute thresholds (e.g., 5, 10, 15, and 20 minutes). It also helps identify specific areas where accessibility may be insufficient, ensuring that the x-minute city concept serves all residents.

2.2.4 Selection of Amenities

In the context of the x-minute city, the selection of urban amenities as trip destinations is crucial. Deciding which amenities to include in this assessment requires careful consideration, as the x-minute city concept aims to ensure that residents can access essential services within a short travel time. As identified by Moreno et al. (2021), people need to access commerce, living, healthcare, education, work, and entertainment within a 15-minute threshold. However, studies vary in identifying the specific types of services that should be included, as shown in Table 2.1.

Some studies maintain a broad perspective, including cultural and leisure opportunities [18] or an extensive range of amenities such as sports facilities, restaurants, and banks [26]. Others focus more on destinations required for daily needs, such as education, commercial stores, food, recreation, and healthcare [5]. On the other hand, some studies included access to job opportunities as a requirement for the x-minute city [20] [5].

Table 2.1: X-Minute City Services as Destinations

Source	Amenities
Moreno et al. [1]	Categories: commerce, living, healthcare, education, working, entertainment.
Allam et al. [13]	Amenities such as parks and recreation centres, and public services (post offices, banks, etc.).
Pozoukidou & Chatziyiannaki [18]	Cultural and recreational opportunities, work, and basic healthcare.
Abdelfattah et al. [26]	Commercial stores (including clothes shops, electronics shops, etc.), food/grocery stores, health facilities, educational facilities, cultural venues, parks and green spaces, restaurants, sports facilities, and other services (post offices, banks, etc.).
T.M. Logan et al. [4]	Supermarkets, pharmacies, parks, primary schools, (doctors/GPs and dentists).
David Vale et al. [30]	10 categories: (1) Healthcare, (2) Supermarkets, markets, and food shops, (3) Education, (4) Sports and recreation, (5) Culture and leisure, (6) Parks and other green areas, (7) Eating and drinking establishments, (8) Retail, (9) Religious, and (10) Public service.

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Source	Amenities
Knap et al. [5]	Education, jobs, commercial, food, recreation, bars and restaurants, parks, entertainment, healthcare, and sports.
Guzman et al. [20]	Care, Enjoyment, education, provision, labor, and habitation. Extension: access to transport and opportunities available (jobs).
Yu et al. [3]	Health, education, recreation, commercial, and food establishments.

A key consideration in defining the scope of the x-minute city is the inclusion of high-level services such as universities, hospitals, airports, and museums. While these facilities play an important role in urban life, they are usually visited less frequently and are less suitable for short-distance accessibility assessments [12]. Therefore, studies emphasize that the x-minute city framework should focus on essential services that residents rely on daily rather than including all possible urban functions [4] [3]. Employment centers, for example, are crucial but are not necessarily expected to fall within a short-travel threshold [12]. As a result, the x-minute city concept prioritizes amenities that meet residents' frequent needs, ensuring a more practical and effective urban planning approach.

2.2.5 Accessibility for Cycling as the Mode of Transport

2.2.5.1 Assignment of X-minute City Threshold, Cycling Speed and Travel Time Calculation:

The definition of time thresholds, or proximity time ranges, is a critical element in the x-minute city concept. These thresholds determine the maximum time residents should spend traveling to access essential services, typically set at 5, 10, 15, and 20 minutes by walking or cycling [11, 31].

Studies assigned different speed for different types of cyclists based on their gender, age and the purpose of cycling trips, as shown in Table 2.2. Some studies conducted in Europe have found that the average speed of conventional cyclists ranges between 12 km/hr and 14 km/hr [32] [33] [34]. Other studies used existing cycling trajocty data like Strava and survey recorded trips to assign different values for low, fast and average cyclists [35]. In a case study in Utrecht, the author adapted the use of an average cycling speed, around 15 km/hr to account for different population groups in the x-minute city [5].

Table 2.2: Speed Categories for Slow, Average and Fast Riders

Reference	Speed (km/h)	Context
[32], [33], [34]	12-14 km/h for fast, average, and slow riders, respectively.	Mean speed in a European context.
[35]	20, 14, and 13 km/h for fast, average, and slow riders, respectively.	Note: speed for fast riders under optimal conditions.
[5]	15 km/h (Average speed)	Typical speed for average riders on flat terrain.
[14]	14 km/h (Average speed)	Mean recorded speed.

2.2.6 Tools to Measure Accessibility for Cycling

R5py and r5r are commonly used in the literature to assess urban accessibility. R5py is a recently developed Python library based on r5r, developed for R [36]. r5py and r5r provides an interface to R5, the Rapid Realistic Routing on Real-world and Reimagined Networks, which is known for its fast routing performance [37]. These packages provides routing on multimodal networks including walking, cycling, car, and public transport[36] [38].

One study, using Helsinki as a case study, used r5py to calculate the travel time matrix between origins and destinations by walking, cycling, public transport and car[37]. The authors created a grid covering the study area and calculated the travel matrix from each centroid to all other cells, taking into account different cycling speeds to account for different abilities of different age groups of the population [37]. The R5py could also consider the Level of Traffic Stress (LTS) based on the experience of the rider.

2.3 Bikeability as a Key Factor of the Accessible X-minute City

2.3.1 Bikeability Definition

The definition of bikeability varies based on the field, the scale, the indicators to be assessed, and the assessment methods [39]. At its core, Bikeability describe how suitable or friendly an area is for cycling [40]. In the field of urban planning and transport, bikeability widely addresses the suitability of the urban environment and the road network for cycling and commuting trips [41].

2.3.2 Bikeability Assessments

The assessment of bikeability involves three key steps: identifying relevant indicators, categorizing them into domains, and defining evaluation criteria [41] [42]. Indicators represent measurable aspects of the cycling environment, such as infrastructure quality, safety, and accessibility, while domains group these indicators into broader categories. Evaluation criteria establish how each indicator is assessed to ensure consistency in measurement. To quantify and compare cycling conditions across different areas, bikeability indices are commonly used, providing a structured framework for assessing network suitability and informing urban planning decisions.

2.3.2.1 Bikeability Indicators

Bikeability indicators can be categorized into two types: objective and subjective, as shown in Table 2.3. Objective indicators are obtained from measurable data collected through observations and systematic surveys, often integrating spatial analysis to assess cycling conditions. These indicators provide a standardized evaluation of the built environment, such as infrastructure quality, road safety, and network connectivity. On the other hand, subjective indicators capture individual perceptions of bikeability and are assessed through surveys and stated preference models. These indicators reflect how cyclists personally experience and interpret their environment, influenced by factors such as past experiences, personal preferences, and social interactions [41].

Table 2.3: Bikeability Indicators Assessment Criteria

Domain	Component	Type	References
Infrastructure	Availability of bike paths.	subjective or objective.	[9] [43] [44]
	Multimodal features and proximity to public transport	subjective or objective.	[45]
	Availability of Parking	subjective or objective.	[9]
	Quality of cycle infrastructure	subjective or objective.	[43]
Accessibility	Land use, types of activities, origins-destinations	subjective or objective.	[44] [45]
	Network features: Density, connectivity, directness	subjective or objective.	[45]

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Domain	Component	Type	References
Safety	Traffic Volume, speed	subjective or objective.	[9] [43] [39] [44]
	Segregation from vehicles and pedestrians.	subjective or objective.	[44]
	Conflicts: interaction with other transport modes and barriers	subjective or objective.	[45]
	Accident rates.	objective.	[9]
	Cyclist and driver behavior	subjective	[39]
Environment	Landscape: Green areas, tree cover, water bodies.	subjective or objective.	[43] [44]
	Pollution: Exposure to air and noise pollution	subjective or objective.	[46]
Comfort	Surface quality	subjective or objective.	[39]
	Traffic stress	subjective or objective.	[47]
	Width of bike lanes	subjective or objective.	[45]
	Slope and gradient comfort	subjective or objective.	[9] [43] [39]

2.3.2.2 Bikeability Index (BI)

Bikeability indices can be categorized as either segment-based or cell-based. Some studies divided the study area into a grid of uniformly sized cells and calculated the bikeability index for each cell [44]. For example, one study used a 100×100m grid to develop a bikeability index for Barcelona, assessing factors such as traffic, infrastructure presence, parking facilities, topography, and connectivity [9]. Another approach was applied in Munich to develop a segment-based index at the road network scale to assess bikeability indicators, including bicycle infrastructure (bike paths and lanes), the existence of structurally separated bike paths, green areas and water surfaces, topography, land use, bicycle facilities, and traffic load [44].

The most commonly used metrics are bicycle level of service (BLOS), Level of Traffic Stress (LTS), and the bikeability index (BI) [8] [10] [43]. The Bicycle Level of Service (BLOS) for a route assesses a cyclist's perceived comfort, security, traffic safety, and overall convenience when sharing the roadway with motorized traffic [8]. Meanwhile, the Bikeability Index (BI) measures how easily cyclists can reach desirable destinations using bicycles as a mode of transport [43].

In addition, LTS is an indicator that assess the stress people experience while cycling [48]. The LTS framework categorizes cycling infrastructure based on its suitability for different cyclist groups. LTS 1 represents low-stress conditions that most children can tolerate, while LTS 2 is acceptable for the general adult population, providing a comfortable and safe cycling environment. LTS 3 is suited for “confident” cyclists who prefer dedicated bike infrastructure but can manage some traffic exposure, whereas LTS 4 is only suitable for “fearless” cyclists who are comfortable riding in high-traffic environments with minimal cycling infrastructure. [49]. Studies have also included LTS as a sub-indicator as part of Bikeability Index (BI). In the context of the x-minute city, a study identified a LTS of 2 to represent the average adults [3].

Bikeability Index (BI) Formula

Early studies customized the bikeability index based on their target indicators. For instance, Krenn et al. (2015) developed a simple additive formula to assess bikeability in Graz [40]. Their bikeability index was formulated as:

$$\begin{aligned}\text{Bikeability Index} = {} & \text{cycling infrastructure} + \text{presence of separated bicycle pathways} \\ & + \text{main roads without parallel bicycle lanes} + \text{green and aquatic areas} \\ & + \text{topography}\end{aligned} \tag{2.1}$$

Researchers have further refined indices by adding coefficients as weighting schemes to assign importance to each indicator [50] [51]. The Bikeability Index (BI) can now be formulated as a linear equation:

$$BI = \alpha_1 x_1 + \alpha_2 x_2 + \alpha_3 x_3 + \cdots + \alpha_n x_n \tag{2.2}$$

where:

- α_i represents the weight assigned to each bikeability indicator.
- x_i reprecents the i^{th} normalized indicator.

2.3.2.3 Analytic Heirarchy process (AHP): Addresseing the Importance of Bikeability Indicators

While early bikeability indices used simple additive models, recent approaches have introduced weighting schemes to reflect the varying importance of different indicators. To address this, structured decision-making methods such as the Analytic Hierarchy Process (AHP) are used. AHP provides a framework for determining the relative importance of bikeability indicators through pairwise comparisons, ensuring that the index reflects expert knowledge and real-world conditions.

AHP is a common used technique for addressing multi-criteria decision-making [52]. It was first developed by Thomas L. Saaty between 1971 and 1975 [53]. AHP relies on pairwise comparisons between different factors, assigning each factor a rank relative to others based on its importance [54]. In this process, planners and decision-makers actively participate in ranking the factors through these comparisons. AHP is particularly common in transportation-related applications [55].

The AHP follows a structured approach, beginning with defining the scope and considering all relevant stakeholders, objectives, and outcomes [52]. The problem is then organized into a hierarchical structure consisting of a goal, criteria, sub-criteria, and alternatives [53]. Next, pairwise comparisons are conducted, where each element is evaluated against the others using a numerical scale. The number of required comparisons is calculated using the formula $\frac{n(n-1)}{2}$, where n represents the number of elements being compared [52]. During the pairwise comparison process, decision-makers are required to provide their evaluations. A verbal scale is used to assess both quantitative and qualitative criteria, ranging from ”equal” (1) to ”absolutely more important than” (9)[54].

These pairwise comparisons are structured into a matrix, where diagonal elements are always assigned a value of 1, while the remaining values are the inverse of their corresponding comparisons [52]. Repeating these comparisons enhances accuracy and provides a clearer understanding of the relationships between different factors [56]. Following this, mathematical calculations are conducted to determine the maximum eigenvalue, consistency ratio (CR), and normalized values for each criterion or alternative. If the calculated CR values fall within an acceptable range, the decision is made based on the normalized values [53]. Otherwise, the process is repeated until the consistency measures meet the required threshold. According to Saaty (1990), a CR of 0.10 or lower is considered acceptable for continuing the analysis [57].

AHP Group Aggregation Techniques

When determining the weights from more than one decision makers, the next step involves selecting an aggregation method. The two common aggregation approaches in AHP group decision-making are the aggregation of individual judgments (AIJ) and the aggregation of individual priorities (AIP) [58]. AIJ combines individual pairwise comparison matrices before calculating priorities, typically using the geometric mean to aggregate judgments. In contrast, AIP derives priorities for each individual first and then aggregates them into a final group priority, often using the arithmetic mean [59].

AHP in Cycling Context

In the context of cycling, previous studies applied AHP for cycling and bikeability indicators. For instance, Beck, L., & Özdal Oktay, S. (2023) applied the AHP to assess priorities for sustainable cycling infrastructure in Münster. The results informed the visualization settings of a cycling dashboard designed to support urban planning and decision-making [60]. Another study used AHP to prioritize bikeability indicators for on-road bicycle facilities, focusing on expert evaluations. The indicators emphasized infrastructure quality, safety measures, network connectivity, and facility accessibility [61]. The study highlights AHP's role in conducting decision-making and aligning infrastructure improvements with expert insights to enhance cycling safety and efficiency [61].

2.4 Diversity and Sufficiency for the X-minute City

While diversity is a core dimension of the x-minute city, studies have examined its influence on residents' travel behavior. Research has found that people living in more diverse areas are more likely to prefer active transportation modes [3]. By analyzing the impact of land-use diversity and built environment density, studies have shown that vehicle miles traveled decrease in more diverse and densely populated areas [62] [3].

In the context of the x-minute city, Guzman et al. (2024) incorporated a diversity index to evaluate access to different categories of services. Their proposed x-minute city index accounted for both walkability conditions and the diversity of available services [20]. Therefore, it is crucial to address diversity as a core dimension of the x-minute city concept.

To quantify the level of diversity, indexes such as the Shannon Diversity Index are potential techniques. The Shannon Diversity Index is a metric commonly used in ecology; however, it has also been applied in urban contexts [63]. Graells-Garrido et al. (2021) used the Shannon Entropy Index to measure diversity in a 15-minute city analysis in Barcelona [64]. Notably, Shannon Entropy has been applied indirectly in some studies to assess diversity. This suggests that the dimension has been overlooked [11].

In essence, the x-minute city concept highlights the importance of meeting residents' needs with an adequate number and type of amenities. While studies tend to focus on the quantity of accessible services, the sufficiency of these services is less frequently examined [12]. The concept of access sufficiency shifts the focus from general accessibility measures to an evaluation of whether essential amenities are adequately available within a defined travel time.

Sufficiency analysis methods sets minimum access thresholds for different amenity categories, ensuring that locations meet essential service requirements [65]. Calafiore et al. (2022) applied this approach in Liverpool, UK, using binary indicators to assess whether key services were reachable within a 10-minute walk, summarizing them into a composite access measure [66]. In Toronto, a similar framework was used to classify neighborhoods based on their 15-minute accessibility by various travel modes, further linking sufficient access to reduced car dependency for non-work trips [3]. This framework emphasizes the role of sufficiency in ensuring that residents can meet their daily needs by assigning a binary score in case population have access to basic necessities within a short distance.

2.5 Social Inequalities Assessment

Equitable accessibility to services is a critical theme in urban studies, as cities exhibit inherent heterogeneity in service distribution, leading to unequal access [28]. Accessibility inequalities even within 15-minute city frameworks, raising concerns about equity in urban planning.

To quantify the degree of inequality in accessibility across the city, the Gini inequality index G is commonly used. The Gini index is a well-established measure of statistical dispersion, widely applied in urban studies to assess disparities in access to essential services. In the context of the x-minute City, Bruno et al (2024) adapted the original formula to evaluate inequalities at a universal level. Their study provides a global assessment of how close cities are to achieving the 15-minute city ideal, revealing strong heterogeneity in accessibility and highlighting the role of population density in shaping urban equity. The level of equity using the Gini Index is computed as:

$$G = 1 - 2\frac{\sum_{p=1}^{N_{pop}} \sum_{p' \leq p} PT_{p'}}{N_{pop} \sum_{p=1}^{N_{pop}} PT_p} \tag{2.3}$$

where:

- PT_p represents the proximity time measure for the p-th individual in the city, sorted in non-decreasing order.
- N_{pop} denotes the total population of the city.

The Gini index value is between 0 to 1, where 0 indicates perfect equality in accessibility, meaning all individuals have equal access, while values closer to 1 suggest significant disparities [67]. The index is particularly useful for analyzing the spatial distribution of accessibility and identifying population groups experiencing reduced access to key urban opportunities.

2.6 Existing Digital Tools for the X-minute City

Existing tools for assessing cities' alignment with the x-minute city concept employ diverse methodologies and transport modes to quantify accessibility to essential amenities. We investigated three tools that provide accessibility approach for the x-minute city. The first tool, Sony CSL's open-access platform (`http://whatif.sonycsl.it/15mincity`), calculates walking and cycling times to critical services—such as healthcare, education, and cultural venues. The tool visualizes neighborhoods as "15-minute" as H3 cells based on an x-minute city score. It emphasizes multimodal accessibility by averaging travel times across eight categories, including parks, schools, and transit hubs [28].

The second tool, Urban Intelligence NZ's interactive dashboard (`http://projects.urbanintelligence.co.nz/x-minute-city`), evaluates access via walking, cycling, and driving to policy-aligned amenities like pharmacies and supermarkets. Designed for planners, its radar plots and static maps highlight areas within 10- or 15-minute thresholds, though it prioritizes walking and cycling in support of health-centric urban design. The third tool, Aino's AI-powered analyzer (`http://15mincity.ai`), focuses exclusively on walking to assess global locations against the 15-minute ideal, covering groceries, healthcare, and leisure. While limited to pedestrian access, its AI-driven insights provide instant, scalable evaluations of urban walkability [68].

These tools are the available ones investigated in this study and collectively address the x-minute city's core goal—equitable access to daily needs. The tools' shared focus on walking and cycling underscores the shift toward sustainable urban mobility, although the inclusion of driving metrics in the NZ tool reflects practical compromises in car-dependent regions. However, while these tools are important for decision-making, none currently address the differences in cycling speeds among diverse population groups. For instance, children and older adults typically cycle at slower speeds than other groups, and assuming a uniform cycling speed may not accurately reflect real-world accessibility scenarios.

2.7 Conclusion of Literature Review

This literature review highlights the evolution of the x-minute city concept and the role of cycling in promoting equitable urban accessibility. While previous studies have extensively examined walkability, fewer have focused on cycling as a core element of proximity planning. Additionally, although various accessibility metrics exist, there is still a gap in integrating bikeability indicators into the x-minute city framework, particularly key factors such as infrastructure, safety, comfort, and environment.

Moreover, the diversity and sufficiency of essential amenities required for daily life must be assessed within this framework. Given the ongoing debate on social inequalities in the x-minute city concept, studies emphasize the need to address social aspects and levels of inequality. By tackling these issues, this research develops a methodology to bridge the identified gap and proposes an approach to assess compliance with the x-minute city concept

3

Methodology

This chapter introduces our methodology framework. We explain the main framework to answer the 3 research questions we introduced in our introduction. Consequently, we apply the methodology to Münster as a case study area.

Methodology Overview

The thesis will address how to determine the components of the x-minute city. Bikeability will be assessed as a means of examining cycling as a potential transport mode for the x-minute concept (see Figure 3.1). Moreover, we address the social dimension to ensure the inclusivity of the concept. The methodology is structured to answer the research questions as follows:

1) How can accessibility by bike be measured and assessed, and what indicators influence bikeability in the context of the x-minute city?
We will answer the first question by defining accessibility as the core principle of the x-minute city. In addition, we define the characteristics of an accessible x-minute city, along with a list of fundamental components and dimensions to be addressed within this framework. Our objective is to explore the potential of cycling as a transport mode within the x-minute city context. We, therefore, introduce a bikeability index to assess factors that align with the concept.

2) How can compliance with the x-minute city concept be measured, and how can social inequalities be addressed using Münster as the case study?
We build on the framework by identifying the key factors necessary for ensuring compliance with the x-minute city concept. To achieve this objective, we introduce a criterion that captures three key indicators. First, we assess whether population groups have access to the bikeable network within the x-minute city isochrones. Second, we examine the main dimensions of the concept: diversity, density, and destinations. Furthermore, we address the social dimension to determine the proportion of the population that has access to basic amenities within the x-minute city thresholds (5, 10, and 15 minutes of cycling time). By addressing these aspects, we aim to emphasize the importance of inclusivity within the x-minute city concept.

3) How can digital tools enhance the assessment process through data visualization and customized interactive mapping?

To address this question, we propose an approach for designing a user-friendly tool. Information and statistics on accessibility, bikeability, and the extent to which people's locations comply with the x-minute city concept are essential for the public and decision-makers. Therefore, we aim to develop a tool that provides insights into the level of compliance with the x-minute city concept.

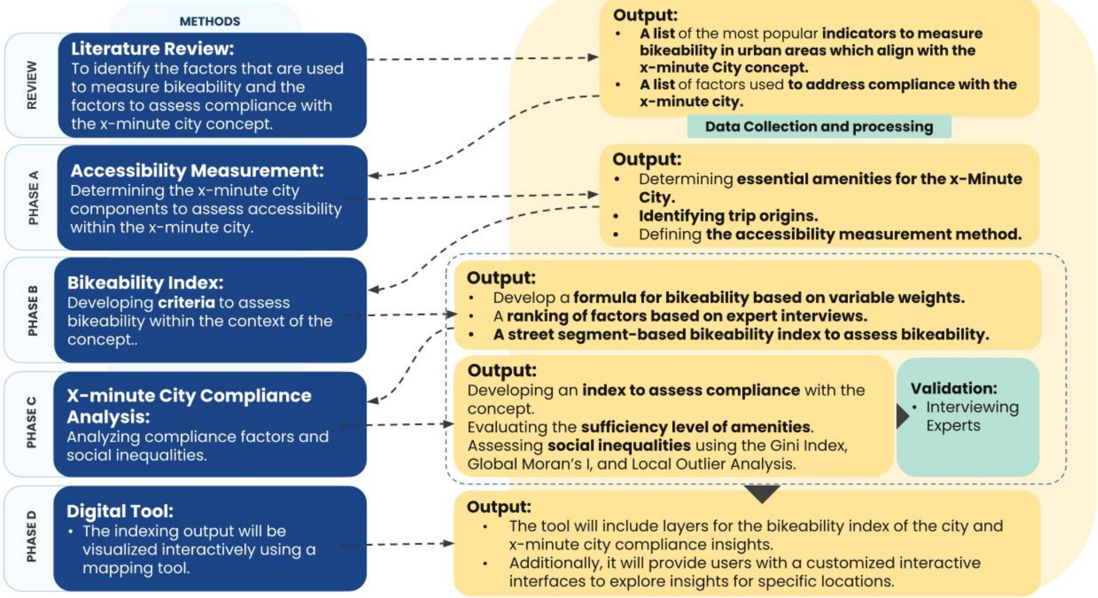


Figure 3.1: Methodology Overview.

3.1 The Case Study Area: Münster

Münster is located in the German state of North Rhine-Westphalia. The city has the highest proportion of cycling in Germany, which made it earning the title of "Germany's cycling capital" [60]. Münster has a well-connected and hierarchical cycling network. A key part of this network is the 4.5 km car-free promenade, a vital green cycling route around the city center. By the end of 2023, Münster's population was around 321,421, but the city is home to more than 500,000 bicycles, according to Stadt Münster. Interestingly, the city's Masterplan +2035 includes an inclusive concept known as the "the city of short distances," which closely aligns with promoting active mobility as the primary mode of accessibility on the municipal agenda.

Public transport also plays a crucial role in the city's mobility system. Since Münster lacks rail-based transit, such as trams or subways—an uncommon feature for a city of its size—buses serve as the primary mode of public transport. Münster has been conducting regular mobility surveys since 1982 to understand how residents travel, using responses from randomly selected households to analyze how different modes of transport are used. The 2022 survey showed that cycling remains the dominant mode at 47%, while car use dropped to 26%, walking increased to 19%, and public transport usage declined to 8%. Overall, environmentally friendly transport options (walking, cycling, and public transport) now account for 74% of all trips, reflecting a shift toward more sustainable mobility, as highlighted in the Masterplan Mobilität Münster 2035+ vision.

Münster was chosen as the case study area due to its strong cycling culture and potential for being an x-minute city. This study presents a framework to assess the "x-minute city" concept in Münster. Furthermore, our study examines the current situation of the city with regard to population distribution, diversity of amenities, and overall compliance with the principles of the concept.

3.2 Data Collection and Processing

Data Collection

Data collection for Münster involved gathering various datasets to assess the x-minute city concept. Table 3.1 provides an overview of the collected data, including the street network, points of interest representing amenities, population distribution, and environmental factors. Each dataset is described by its content, format, and source. These datasets were collected for use in the x-minute city analysis.

Table 3.1: Data Description and Sources

Data	Description	Type	Source
Street Network	Münster street network, including all road types.	Shapefile and PBF	OSM
POIs in Münster	A representation of the main amenities.	Shapefile	OSM

Continued on next page

Data	Description	Type	Source
Transportation Dataset	Includes bus stations.	Shapefile	OSM
Water Bodies	Includes rivers and lakes.	Shapefile	OSM
Population Dataset	Includes total population, share of foreigners, and the number of different age groups aggregated by 100×100m cells.	CSV	Census Data Bank (Zensus Datenbank)
Bike Incidents	Includes bicycle-related incidents recorded in 2023.	CSV	The Federal Statistical Office (DE Statistisches Bundesamt)
Digital Elevation Model	Covers Münster to calculate the slope.	Raster (.tif)	Sentinel-2
Satellite Imagery	Covers Münster to calculate the Normalized Difference Vegetation Index (NDVI).	Raster (.tif)	Sentinel-2
Air Quality Sensor Data	PM2.5 data recorded by bike sensors.	CSV	Open Sense Map
Station-Based Air Quality Data	Includes air quality index and PM2.5 readings from the Münster Weseler Straße and Münster-Geist stations.	CSV	The German Environment Agency

Data Processing

Regarding the OpenStreetMap (OSM) street network data, the raw dataset initially contained over 400 fields. We cleaned the data by removing attributes with only null values and retained only the fields relevant to our analysis. Fields with unreliable or incomplete data, where most entries were null, were also excluded. Additionally, we incorporated promenade routes as a separate category, recognizing their importance in Münster.

In order to analyze the street network dataset, we filtered the street types to include only specific types: promenade, cycleway, primary, secondary, residential, tertiary, track, and unclassified. Cyclists could navigate these types of roads regardless of the existence of bike lanes. We also included service and living streets, as cyclists could access these types of roads. We strictly excluded roads that are categorized as motorways.

The population data that we obtained from the German Census Data Bank (Zensus Datenbank) is in 100 × 100 m cells. Data from different layers have attributes representing total population and foreigners per cell. In particular, the data is part of the social aspects of the x-minute city analysis. We have therefore only processed variables that are relevant to our analysis.

All the datasets have been clipped to the city boundaries. We created a 3 km buffer around Münster [5]. This buffer accounts for residents living near the boundary who may travel to destinations just outside Münster within the defined x-minute thresholds (5, 10, and 15 minutes). The data was projected to UTM Zone 32N for consistency in spatial analysis.

3.3 Phase A: Accessibility Measurement: Determination of the X-minute City Components

3.3.1 The X-minute City Destinations and Trip Origins

3.3.1.1 Selected Essential Amenities

Based on the literature review, we define the amenities of an x-minute city as destinations offering services that people require on a daily basis [1] [13]. Higher-order facilities—such as large hospitals and museums—that people tend to travel to for reasons like better opportunities or their specialized nature are excluded from our selection criteria [12]. Additionally, local public transport serves have been included, ensuring that people have access to various locations extending beyond the x-minute threshold [12].

To address essential amenities, we aggregated the destinations into main categories, as shown in Table 3.2. The purpose of this aggregation is to provide insights into the targeted activities at each destination. Furthermore, the main categories are further classified by the type of amenities. The primary destinations are grouped into six main daily needs: food, education, healthcare, sports, leisure, and transportation. The main sub-categories are the amenities that exist in Münster,.

Table 3.2: Destination Categories for X-minute City Assessment

Category	Basic Amenities
Food	Supermarkets, grocery shops, bakeries, butchers, restaurants, cafes and bars.
Healthcare	General practitioners, clinics and pharmacies.
Education	Schools and kindergartens.
Sports	Sport centers and gyms.
Leisure	Parks, gardens, community and arts centers.
Transportation	Transport destinations within the city.

To analyze the distribution of essential amenities in Münster and determine whether the city has a polycentric structure, the Hierarchical Density-Based Spatial Clustering of Applications with Noise (HDBSCAN) algorithm was used. HDBSCAN is an unsupervised clustering method that identifies spatial patterns by detecting clusters of varying densities while filtering out noise points [69]. Unlike traditional clustering methods, HDBSCAN does not require a predefined number of clusters and adapts to the natural distribution of amenities. The analysis was implemented using the `sklearn.cluster.HDBSCAN()` function from the `scikit-learn` library. This approach provides an understanding of urban centers and sub-centers in Münster.

3.3.1.2 Trip Origin of the X-minute City

To identify the x-minute city population distribution, studies have identified trip origins to represent the location of population. One of the most common approaches in the literature involves mapping the aggregated census tracts in a form of cell-based grid. The center of each cell is identified as the origin of trips for the x-minute city [26] [28].

In our case study, we calculated the mean geometric center of residential buildings to represent trip origins, following the method proposed by Knap et al. [5]. This approach provides more accurate results compared to other aggregated methods based on the cell centroids. We utilized OSM building data to identify and filter buildings categorized as residential, such as houses and apartments. Some cells lacked residential buildings, but the census data indicated the existence of population. Therefore, in order to identify the trip origins for these cells , we assigned the mean center of these cells as trip origins. The mean center was calculated using the mean center tool in ArcGIS Pro.

In order to process trip origins, we decided to aggregate the case study area into a 100×100 m cell-based grid, which will provide an accurate analysis (see Figure 3.2). Fortunately, the Census Data Bank provides 100×100 m cell-based social data. The German census, conducted on May 15, 2022, used a register-based method, using public administration records to determine population distribution. To enhance accuracy, supplementary measures were implemented, including multiple case checks to remove duplicates and statistical corrections through sample-based household surveys and surveys of dormitories and shared accommodations [70] [71]. The data is aggregated by population total count, share of foreigners, and the number of people in five age groups: below 18, 18–29, 30–49, 50–64, and above 65. This dataset, obtained for Münster, forms the population distribution for the x-minute city analysis.

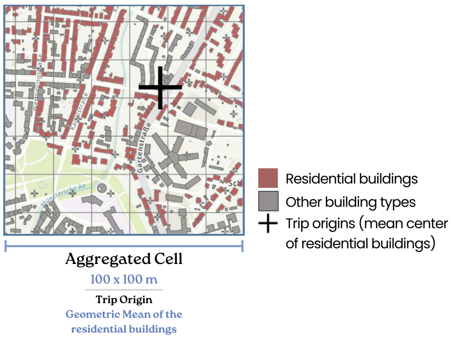


Figure 3.2: Trip Origins of the X-minute City.

3.3.2 Accessibility Measurement

As mentioned in the literature review chapter, the cumulative opportunities measure is a method used to assess accessibility levels from origins to destinations. This approach counts the number of opportunities available within a defined time threshold based on the chosen travel mode [2]. In the context of the x-minute city, the objective is to determine the number of amenities accessible within 5, 10, and 15 minutes of cycling. The cumulative opportunities measure was chosen due to its ease of interpretation and practical applicability [3] [72].

In order to measure accessibility we use the equation from Hansen (1959). The measure of accessibility in zone i, denoted as A_i, is defined by the following [23]:

$$A_i = \sum_j O_j \cdot f(C_{ij}) \tag{3.1}$$

where:

- A_i is the accessibility of the origin Census Tract (CT) of the x-minute city i,
- O_j represents the number of opportunities at the destination CT j,
- C_{ij} is the travel time between the origin and destination CTs.
- $f(C_{ij})$ is a binary impedance function that assigns the values 0 or 1, depending on the travel cost between origin and destination relative to the x-minute City thresholds– 5, 10, and 15 minutes. t.

The impedance function $f(C_{ij})$ for cumulative accessibility is defined as follows:

$$f(C_{ij}) = \begin{cases} 1 & \text{if } C_{ij} \leq t \\ 0 & \text{otherwise} \end{cases} \tag{3.2}$$

To quantitatively measure the cumulative opportunities measure, we calculate travel time matrices from the trip origins to destinations using the R5py python library. The R5py function `TravelTimeMatrixComputer()` is used to calculate the travel time matrix from trip origins to destinations using the street network from OSM [37]. To tackle the the rider personal differences, we assigned different speed and level of traffic stress (LTS). The cumulative opportunities measure is then calculated using the Accessibility R package [73]. The Accessibility R package includes the function `cumulative_cutoff()`, which calculates the number of opportunities within a specified cutoff. In our context, the cutoff is the x minutes threshold– 5, 10 and 15 minutes. The function requires the travel time matrix and the opportunities dataframes and results in a score reflects cumulative accessibility at a specific location (see Figure 3.3).

In our study, we did not aggregate destinations into cells. Instead, we calculated the travel time from each origin to the exact location of each destination. The accessibility R package function `cumulative_cutoff()` requires the number of opportunities at each destination, and studies typically assign the total number to an aggregated location [74]. However, since our destinations are not aggregated, we assigned a value of 1 as the number of total opportunities at each location j. This approach provides more accurate insights into the number of each category and subcategory separately. Consequently, we address the issue of aggregated destinations that could introduce bias in calculating travel time from origin to destination by ensuring that all opportunities at a destination point are not aggregated into a single location.

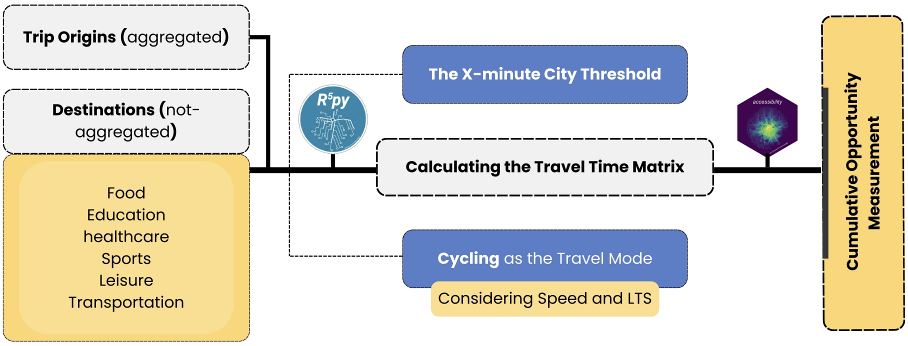


Figure 3.3: Cumulative Opportunity Measurement, based on Boisjoly & El-Geneidy [2].

To assess the suitability of cycling routes for different user groups, we classified the types of riders based on their average cycling speed and tolerance for their level traffic stress (LTS), as shown in Table 3.3. The classification defines three rider types: slow riders, characterized by an average speed of 12 km/h, are associated with LTS 1, suitable for vulnerable groups such as children and the elderly. Average riders, cycling at a speed of 14 km/h, align with LTS 2, catering to regular riders with moderate traffic tolerance [75] [76]. Lastly, fast riders, with an average speed of 20 km/h, correspond to LTS 4, designed for experienced and confident cyclists who are comfortable navigating higher-stress traffic environments [37]. This rider classification ensures that the analysis of cycling infrastructure considers the varying needs and safety requirements of diverse user groups, enhancing the inclusivity of the x-minute city concept.

Table 3.3: Characteristics of Riders by Type, Speed, Stress Level, and Suitability.

Rider Type	Speed (km/h)	Level of Traffic Stress (LTS)	Suitable For
Slow	12	1	Children and elderly
Average	14	2	Average riders
Fast	20	4	Experienced and confident riders

3.4 Phase B: Bikeability Segment-based Index

To assess whether the cycling network is bikeable for accessing essential amenities, it is necessary to evaluate its suitability based on specific bikeability indicators. The bikeability indicators workflow follows three main steps: (1) identifying relevant indicators, (2) categorizing them into domains, and (3) defining evaluation criteria [41] [42]. The bikeability evaluation process involves several key steps. First, the different bikeability domains and their corresponding indicators must be identified. Then, a bikeability formula is applied to assess the bikeability of each network edge. The indicators are normalized, and a weight is assigned to each one using the Analytic Hierarchy Process, based on expert interviews (see Figure 3.4).

For the x-minute short trips, we limit our bikeability assessment to address infrastructure, safety, comfort, and environment. There domains are chosen as being the most crucial indicators to assess bikeability and align with the inclusivity concept of the x-minute city. In order to map indicators, we utilize a street segment-based assessment criteria to assure a high resolution assessment level for the study area, as shown in Table 3.4. Accordingly, we map the bikeability indicators by assigning values to each road segment.

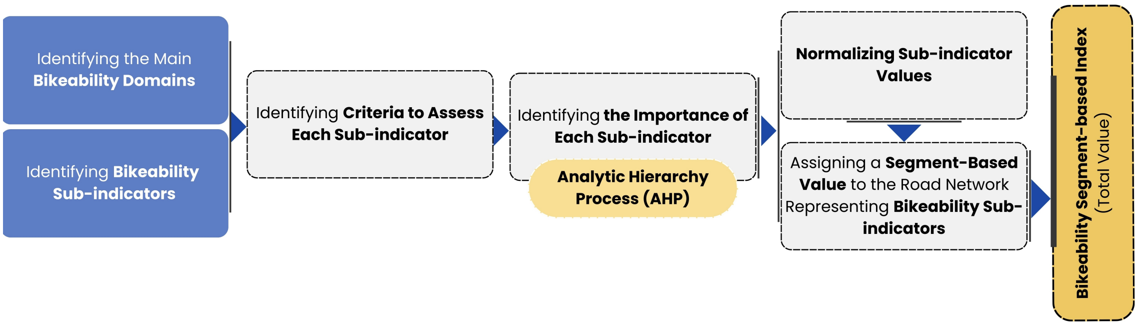


Figure 3.4: Bikeability Segment-based Index process.

3.4.1 Bikeability Sub-Indicators Assessment Criteria

We evaluate each of the domains and apply a bikeability index formula to assign a value for each street segment, representing a bikeability index. The general equation to assess each of the bikeability index based on street segment level is calculated using the formula:

$$BI(e) = \sum_{i=1}^{n} \omega_i \cdot f_i(e) \tag{3.3}$$

where:

- $BI(e)$: Bikeability Indicator for each edge.
- n: The total number of sub-indicators (factors) being considered.
- ω_i: The weight assigned to each sub-indicator i (where i ranges from 1 to n).
- $f_i(e)$: Calculates a value based on specific criteria for each indicator i.

This approach ensures a comprehensive evaluation of bikeability and the relative importance of its indicators. The same formula will be applied to the main domains: infrastructure, safety, comfort, and environment. It will then be adapted to the sub-indicators associated with these main domains as follows:

3.4.1.1 Infrastructure Indicator

The **Infrastructure** indicator evaluates the physical elements that support cycling within the urban environment, including the presence of bike paths, and bike facilities. The Bikeability Infrastructure Indicator for each street segment is calculated as:

$$\begin{aligned} BI_i(e) infrastructure = {} & \alpha \cdot \textit{Bike\_Infrastructure\_Presence} \\ & + \beta \cdot \textit{Bike\_Facilities\_Presence} \end{aligned} \tag{3.4}$$

Where:

- α, β: Coefficients representing the weight of each sub-indicator.

To evaluate bike paths presence, we utilized OSM data to identify and categorize existing cycleways, bike lanes, and cycle tracks (see Appendix 6.2). A binary classification was applied, where the presence of bike paths was scored as 1 and their absence as 0, following the criteria established by Kren et al. and Arellana et al. [40] [43]. Similarly, the presence of bike facilities, such as bike parking, was assessed using OSM data. Bike parking is a crucial component of bike infrastructure indicators, as it protects bicycles against theft and shields them from harsh weather conditions [44]. Roads with bike parking amenities were assigned a score of 1, while those without were given a score of 0, based on the approach from Werner et al. [39].

3.4.1.2 Safety Indicator

The **Safety** indicator includes various elements that influence the security and well-being of cyclists on the road. The Bikeability Safety Indicator for each street segment is calculated as:

$$\begin{aligned} BI_i(e)safety = {} & \alpha \cdot \textit{Road\_Speed\_Limit} \\ & + \beta \cdot \textit{Road\_Bike\_Incidents} \\ & + \gamma \cdot \textit{Cycleway\_Separation} \\ & + \delta \cdot \textit{Conflict\_Points} \end{aligned} \tag{3.5}$$

Where:

- $\alpha, \beta, \gamma, \delta$: Coefficients representing the weight of each sub-indicator.

Key safety sub-indicators include the road speed limit, road bike incidents, level of cycleway separation, and conflict points. Road speed limits were obtained from OSM data, assigning range value based on the speed, as per Arellana et al., as shown in Table 3.4 [43]. Road bike incidents were measured by the number of reported cycling accidents using the dataset of road accidents by The Federal Statisti- cal Office (DE Statis- tisches Bundesamt). Roads with locations experiencing incidents receiving scale range from 0 to a range value based on the accident counts, following the methodology of Werner et al. [39].

The level of cycleway separation was evaluated based on the availability of physical barriers between bike lanes and vehicular traffic, again using OSM data to assign scores of 1 or 0. The OSM data contained missing values for the separation level of the cycleway. Therefore, we added the missing values manually by evaluating the cycleway using Satellite imagery and Google Street View (GSV) imagery comparisons. Lastly, conflict points, such as the presence of bus stops along road segments, were identified and scored similarly. By evaluating these safety-related factors, we can identify critical areas that may require infrastructural or policy interventions to enhance cyclist safety.

3.4.1.3 Comfort Indicator

The **Comfort** indicator assesses conditions that affect the ease of cycling, focusing on road slope percentage and bike path width. The Bikeability Comfort Indicator for each street segment is calculated as:

$$\begin{aligned} BI_i(e)comfort = \alpha \cdot \textit{Road\_Slope\_Percentage} \\ + \beta \cdot \textit{Bike\_Path\_Width} \end{aligned} \tag{3.6}$$

Where:

- α, β: Coefficients representing the weight of each sub-indicator.

Road slope percentage was categorized into three levels: low (0%–5%), moderate (6%–9%), and steep (>9%), based on studies by Arellana et al. and Pardo & Sanz [43] [77]. These categories were assigned scores of 1, 0.5, and 0, respectively, to reflect the varying degrees of cycling comfort associated with each slope level. To calculate the slope percentage, we obtained terrain raster and used the 'Add Surface Information' tool in ArcGIS to calculate the average slope.

Additionally, the bike path width was assessed by measuring the width of cycleways, bike lanes, and cycle tracks using OSM data. Paths with widths of ≥1.4 meters (one way) or ≥2.6 meters (double way) were deemed adequate and scored as 1, while narrower paths were scored as 0, in accordance with the criteria set by Arellana et al. and Pardo & Sanz [43] [77].

It is worth mentioning that, although some studies consider bike lane width as an indicator of safety, we assess it as an indicator of comfort. We argue this based on the correlation between the bike accident risk map and bike lane widths. Our findings conclude that there is no association between accident rates and bike lane width. Considering the assessment, the width values were not available for the entire OSM dataset. The dataset has to be investigated in terms of cycleway existence and assigned a value manually based on aerial imagery comparisons.

3.4.1.4 Environment Indicator

The **Indicator** factor includes environmental factors that are essential for short trips. Air quality, exposure to green areas and water bodies have been included in our environment indicators as being the most important factors in the literature. The Bikeability Environment Indicator for each street segment is calculated as:

$$\begin{aligned} BI_i(e)environment = {} & \alpha \cdot \mathit{Air\_Quality} \\ & + \gamma \cdot \mathit{Green\_Areas\_Exposure} \\ & + \delta \cdot \mathit{Water\_Bodies\_Exposure} \end{aligned} \tag{3.7}$$

Where:

- $\alpha, \beta, \gamma, \delta$: Coefficients representing the weight of each sub-indicator.

Green Spaces:
To assess the presence of green spaces, we acquired Sentinel-2 Band 4 and Band 8 imagery over the city of Münster to calculate the Normalized Difference Vegetation Index (NDVI). The data were clipped to the city boundary with a 3 km buffer to cover the whole street network. Sentinel-2 bands were retrieved using Google Earth Engine for different seasons throughout the past year.

To assign NDVI values to street segments, a 10 m buffer was created around each street edge to capture exposure to green spaces. The mean NDVI value within this buffer was then calculated and assigned to the corresponding street segment using zonal statistics technique with the Rasterstats Python library.

Water Bodies:

To quantify cyclists' exposure to water bodies, a larger buffer of 50 m was created for each street edge. This decision was based on the fact that lakes and rivers typically have surrounding buffer spaces, making a wider buffer more appropriate. We utilized OSM data to extract waterways and water bodies, assigning a value of 1 for streets with exposure and 0 for streets without exposure.

Air Quality:

We assessed cyclists' exposure to air pollution using OpenSenseMap data, focusing specifically on PM2.5 concentrations. Several SenseBox sensors are distributed throughout Münster, providing air quality measurements. Additionally, citizen science campaigns have recorded bike rides, contributing valuable sensor data.

First, OpenSenseMap data were extracted for mobile OpenSenseBox sensors mounted on bicycles. The "Fine Dust PM2.5" sensor type was selected to reflect air quality along the street network while cycling. We obtained data from bike-mounted sensors recorded between January 1, 2024, and December 31, 2024.

Notably, the recorded data contained outliers and anomalies. To eliminate outliers, this dataset was compared against air quality data from two stationary monitoring stations that continuously record the air quality index. The data were aggregated temporally to compute the daily mean PM2.5 concentration for 2024. A box plot analysis was conducted to identify and remove abnormal values from each sensor dataset.

Following data cleaning, we applied Ordinary Kriging to interpolate the PM2.5 concentrations and generate a surface raster. The ordinary kriging was conducted using the pykrige Python toolkit. Finally, the ArcGIS ”Add Surface Information” tool was used to assign the mean PM2.5 value to each street segment.

Table 3.4: Bikeability Sub-indicator Assessment Criteria

Factor	**Component**	**Variables**	**Range Value**	**Source**
Infrastructure	Presence of bike paths	Presence of bike paths. No presence of bike paths, according to Krenn et al. and Arellana et al. [40][43]	Yes: 1 No: 0	OSM
	Presence of bike facilities	Presence of bike parking. No presence of bike parking, according to Werner et al. [39]	>0: 1 =0: 0	OSM
Safety	Road Speed Limit	Speed limit for cycling street network in (Km/hr), according to Arellana et al. [43]	Value range	OSM
	Road Bike Incidents	Number of bike incidents.	Value range	OSM
	Level of Cycle Way Separation	Presence of bike separation. No presence of bike separation, according to Werner et al. [39]	Yes: 1 No: 0	OSM
	Conflict Points	Existence of bus stops along the road segment	Value range	OSM
Comfort	Road slope percentage	0%–5% slope: Low 6%–9% slope: Moderate >9% slope: Steep, according to Arellana et al. and Pardo & Sanz [43] [77]	1 0.5 0	OSM

Factor	Component	Variables	Range Value	Source
	Bike Path Width	Width ≥ 1.4 m (one way) Width ≥ 2.6 m (double way) Width < 1.4 m (one way) Width < 2.6 m (double way) No bike path presence, according to Arellana et al. and Pardo & Sanz [43] [77]	1 1 0 0 0	OSM
Environment	Green areas	NDVI values average for the 4 seasons	Mean NDVI	OSM
	Water Bodies	Exposure No exposure	1 0	OSM
	Air Pollution Exposure	PM 2.5 mean along street segment, according to Werner et al. [39]	Mean PM 2.5	Open-Sense-Map

3.4.2 Analytic Hierarchy Process (AHP): Addressing the weights of Bikeability sub-indicators

To evaluate the importance of each bikeability sub-indicator, an Analytic Hierarchy Process (AHP) was conducted using pairwise comparisons. These comparisons were divided into four categories: infrastructure, safety, comfort, and the surrounding environment. A survey was designed to capture expert preferences using the same ranking scale described in the previous chapter, where a score of 1 meant equal importance and a score of 9 represented the highest level of importance. The survey was structured to assess the relative importance of sub-indicators within each category. Invitations were sent through the University of Münster to experts from the Municipality of Münster, the Municipality of Osnabrück, and professionals in the cycling industry.

To combine expert judgments, the Aggregation of Individual Judgments (AIJ) method was used to calculate the geometric mean [58]. In AHP, AIJ brings together multiple experts' pairwise comparisons into a single, consistent comparison matrix. The geometric mean is applied to the individual judgments for each pairwise comparison, ensuring a fair and balanced weighting of sub-indicators.

By applying the Bikeability Index (BI) formula to the street network, the four bikeability indicators—infrastructure, safety, comfort, and the environment—were mapped. This allowed for the calculation of a segment-based bikeability index for each street.

3.5 Phase C: X-minute City Compliance Analysis

To evaluate compliance with the x-minute city concept, we propose an index that integrates both the bikeability level and the diversity of amenities within the x-minute thresholds. We emphasize that assessing accessibility through the cumulative opportunity measure must be combined with evaluating the diversity of these amenities.

Through this framework, we highlight the importance of accessibility to a diverse range of amenities. Simply having access to a high number of amenities is insufficient if they lack diversity or if the street network is not bike-friendly. Since diversity is closely linked to accessibility measurement, we focus on an approach that captures the core dimensions of the x-minute city—accessibility and diversity (see Figure 3.5). Additionally, we address social inequalities by examining disparities across the study area, considering both sufficiency (having access to a minimum set of essential amenities) and equity (whether different social groups have fair access). By evaluating these aspects together, we assess the overall level of compliance with the x-minute city concept and determine how inclusive it is.

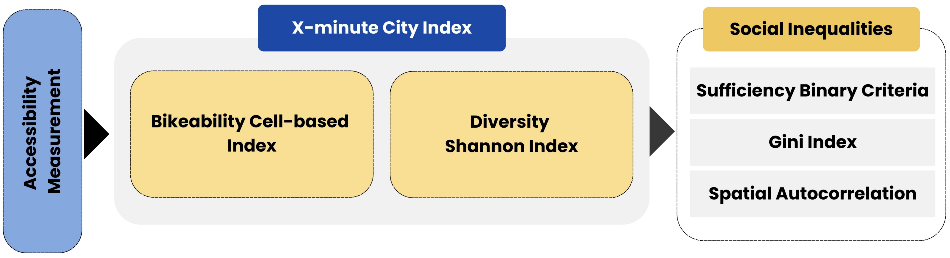


Figure 3.5: X-minute City Assessment including Accessibility, Bikeability, Diversity, Sufficiency and Social Inequalities

3.5.1 Bikeability Index in the Context of X-minute City

To calculate an aggregated bikeability index based on a cell-based approach, we used the formula provided by the work of Guzmán et al., who included a walkability index as part of their x-minute city assessment [20]. The index assigns a value between 0 and 1, where values closer to 1 indicate better walkability. By calculating a weighted average walkability value for each 15-minute walk isochrone, their study highlights the importance of safe and attractive streets in achieving the 15-minute city concept. Building upon this methodology, we have adapted a similar framework to develop a bikeability indicator for our research, applying similar criteria for a 5, 10, and 15-minute cycling isochrones. The bikeability indicator (BI) for a given cell i is calculated as a weighted average of the bikeability values of all street segments s within the cycling time isochrones. The formula is given as:

$$BI_i = \frac{\sum_{s \in i} (BI_{s,i} \cdot L_{s,i})}{\sum_{s \in i} L_{s,i}} \tag{3.8}$$

where:

- BI_i: Average bikeability value for the 15-minute cycling isochrone of cell i.
- $BI_{s,i}$: Bikeability value of street segment s within the isochrone of cell$i$.
- $L_{s,i}$: Length of the street segment s within the isochrone of cell i.

3.5.2 Diversity Index: Shannon Entropy

Diversity is one of the main dimensions of the x-minute city [1]. It is also a predictor of the level of development of places[78]. For this reason, we include a diversity index as a sub-index in the assessment of the x-minute city. We were inspired by Graells-Garrido et al.[64] to examine whether the city is monocentric or offers a diverse range of amenities. The Shannon Index is calculated and is adapted, based on our approach to the examined amenities within the x-minute city, as follows.:

$$H = -\sum_{c \in C} p_c \log p_c \tag{3.9}$$

where:

- H is the Shannon Entropy.
- C is the set of amenity sub-categories, including food (e.g., supermarkets, bakeries), healthcare (e.g., clinics, doctors), education (e.g., schools), sports (e.g., sports centers), and leisure (e.g., arts centers).
- p_c is the frequency of an amenity of each category $c \in C$.

The Shannon Index formula was applied using the cumulative opportunity measure, which quantifies the number of reachable amenities within specific cycling time thresholds. Transportation destinations were excluded from the diversity index to focus solely on essential amenities [20].

3.5.3 The X-minute City Complaince Index

To evaluate compliance with the x-minute city, we propose a 100 × 100 m cell-based approach. The resulting C_x index quantifies a city's performance based on accessibility to diverse services via cycling within 5-, 10-, and 15-minute isochrones. This composite index integrates two dimensions: the diversity of essential services and the bikeability of each cell. To ensure inclusivity, we assign a cycling speed of 12 km/h for slower riders and use LTS 1 as the most convenient condition for elderly people and children.

The formula is adapted from Guzman et al., who originally developed it in a walkability context. Higher values of the (C_x index) indicate better compliance with the x-minute city concept, highlighting areas where diverse opportunities are accessible under safe, comfortable, and efficient biking conditions. Conversely, if a particular cell has high accessibility and diversity but a low bikeability score, the C_x index will be low because, even though the cell has a wide range of nearby opportunities, they are not easily reachable by bike.

$$Cx_i = \sum_k D_{ik} \cdot BI_i \tag{3.10}$$

This formula is adapted from Guzman et al. in a context of walkability evaluation.[20].
where:

- D_{ik}: Diversity score of essential service category k accessible within a 5, 10, and 15-minute biking isochrones from the trip origin for each cell i.
- BI_i: Bikeability index of the specific cell i.

A city generalized index is also specified by considering the population values. The city-level index will be applied to different age groups and foreign residents to evaluate whether each group meets the concept equally. The city-scale compliance index (Cx_{city}) is calculated as the population-weighted average of block-level indices:

$$Cx_{city} = \frac{\sum_i Cx_i \cdot p_i}{\sum_i p_i} \tag{3.11}$$

where:

- Cx_i: Compliance index for cell i.
- p_i: Population within cell i.

3.5.4 Social Inequalities in The Case Study Area

We examine social inequalities by assessing whether all segments of the population have access to a minimum set of sufficient amenities using sufficiency binary criteria. Additionally, we apply the Gini index and statistical modeling to determine social inequality levels and map differences in x-minute city compliance across the city.

3.5.4.1 The X-minute City Sufficiency Score

To assess sufficiency in access to essential amenities, we employ a binary sufficiency score criteria, where access is considered sufficient if the minimum threshold of services is met. The criteria were first introduced by Yu et al. (2024) to define the essential services people need within x-minute thresholds (5, 10, and 15 minutes). We adapted this approach by including key amenities specific to Münster, ensuring relevance to the local context.

Table 3.5 presents the binary sufficiency assessment criteria.If the specified conditions are met, access is considered sufficient (1), and if not, it is considered insufficient (0). This framework helps identify disparities in service availability and accessibility to daily necessities.By addressing this, we ensure that residents have access to a minimum, complete set of essential daily amenities.

Table 3.5: Sufficient Access Criteria for Various Necessity Categories. Note: The table is based on Yu et al. [3]

Necessity Category	Sufficient Access Criteria
Food	$\geq$ 1 Supermarket/Grocery Store **OR** $\geq$ 3 Specialty Food Stores **AND** $\geq$ 1 Restaurant
Health	$\geq$ 1 Doctor's Office **OR** $\geq$ 1 Clinic **AND** $\geq$ 1 Pharmacy
Sports	$\geq$ 1 Sports Center
Leisure	$\geq$ 1 Park **OR** $\geq$ 1 Garden **AND** $\geq$ 1 Arts/Community Center
Education	$\geq$ 1 School **AND** $\geq$ 1 Kindergarten

3.5.4.2 Gini Index

To gain insights into the level of inequality and how different population groups deviate from equity within the x-minute city at various thresholds, we apply both the Gini index and a Lorenz curve. The Gini index is computed using the R package `Accessibility`, which provides the function `gini_index()` [79]. This function calculates the index based on population characteristics and another targeted measure. In our study, we computed the Gini index for the entire population to assess equity in the x-minute city compliance scores and accessibility scores. Low Gini index values indicate minimal inequality in access to amenities and high compliance with the concept. Conversely, high Gini index values reveal greater levels of social inequality.

3.5.4.3 Spatial Autocorrelation

To examine spatial patterns in accessibility, diversity, and bikeability within the X-minute city framework, we employ the Global Moran's Index. This metric assesses spatial autocorrelation, determining whether these attributes exhibit clustering, dissimilarity, or random distribution across the study area [80]. A positive Moran's Index value indicates clustering of similar values, while a negative value suggests spatial dissimilarity. A value close to zero implies a random spatial distribution.

To identify clusters and outliers, we first assess local spatial autocorrelation. Spatial outliers indicate local negative spatial autocorrelation, while local clusters of high or low values signify positive spatial autocorrelation[81]. To confirm these patterns, significance testing is conducted, with a p-value below 0.05 indicating statistically significant spatial autocorrelation [66]. The Auto-correlation Global Moran's test was implemented in ArcGIS, followed by the use of the Cluster and Outlier Analysis (Anselin Local Moran's I) tool to visualize outliers within significant clusters. The Hot Spot Analysis (Getis-Ord Gi*) ArcGIS tool was also used to visualize the confidence level of the clustering pattern.

3.6 Phase D: The X-minute City Digital Tool

3.6.1 Tool Purpose

One of the main objectives of this study is to develop a digital interactive interface that represents Münster's compliance with the x-minute city concept. This tool helps the community and decision-makers better understand the importance of the concept and provides a more realistic perspective on the current situation.

To develop this digital tool, we utilize open-source data and technologies to create a user-friendly interface. The interactive mapping platform will display the x-minute city and bikeability indices, allowing users to gain statistical insights. Our approach focuses on designing a workflow that gives users the flexibility to customize the tool based on specific locations, enabling them to analyze accessibility statistics effectively.

3.6.2 Tool Implementation, Architecture, and Selected Technologies

The implementation of the proposed digital tool follows a structured architecture that integrates both client-side and server-side technologies (see Figure 3.6). The front-end is developed using HTML, CSS, and JavaScript. Chart.js is utilized for dynamic data visualization, enabling users to interpret the x-minute city statistics through interactive charts, while Leaflet is used for interactive mapping and visualizations. The back-end is handled by Flask, a lightweight web framework that facilitates API request handling, data processing, and communication between the front-end and the database. PostgreSQL is used for storing and managing both spatial and non-spatial data, while psycopg ensures seamless integration between Flask and PostgreSQL for efficient data retrieval and manipulation.

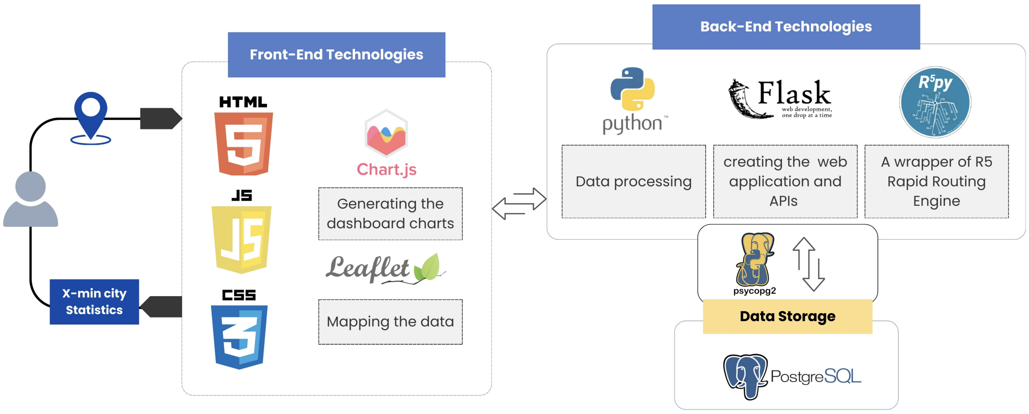


Figure 3.6: Digital Tool Architecture Diagram.

To process spatial data, the tool utilizes OSMnx, which enables the retrieval of street networks and relevant urban features from OSM. The system is designed to be interactive, allowing users to input their x and y coordinates (location) and preferred amenity categories for analysis. These inputs ensure that the accessibility assessment is tailored to the user's specific area of interest. A function assigns a single category (e.g. Food, Education, etc), based on the user's selection, ensuring a focused evaluation of accessibility metrics. Additionally, the tool allows users to select their cycling speed preference—categorized as slow (12 km/hr), average (14 km/hr), or fast (20 km/hr)—to account for variations in individual travel behavior and ensure a more realistic estimation of cycling accessibility.

The accessibility analysis is conducted using r5py, which computes a travel time matrix to estimate the time required to reach various destinations within 5-, 10-, and 15-minute thresholds [36]. The system then analyzes the number of accessible amenities and services within these thresholds, categorizing them by type. Additionally, the tool calculates the average travel time required to reach different subcategories of amenities, providing a more detailed understanding of accessibility patterns.

The robust design outlined in this implementation enables a detailed and customizable analysis of Münster's compliance with the x-minute city concept. Furthermore, it demonstrates significant potential for adaptation to other urban environments, particularly within European contexts.

3.7 Conclusion of the Methodology

Our methodology evaluates accessibility and bikeability within the x-minute city framework. Bikeability is assessed by developing a composite bikeability index based on four key indicators: infrastructure, safety, comfort, and environment. We assess accessibility using cumulative opportunity metrics, measuring the number of essential amenities reachable within a given threshold. To determine the importance of bikeability subindicators, we apply the Analytic Hierarchy Process (AHP), involving decision-makers and cycling experts. The bikeability index is implemented on a segment-based street network, providing a high-resolution assessment.

To evaluate compliance with the x-minute city concept, we use the x-minute city compliance index, which examines amenity diversity (Shannon index) and bikeability quality. Additionally, we address inclusivity by assessing essential service sufficiency and inequality in access (Gini index). Finally, we introduce a scalable digital tool that offers real-time insights into Münster's alignment with x-minute city principles, supporting both public engagement and decision-making.

4

Results

This section presents the results of the accessibility measurement, bikeability evaluation, and x-minute city compliance analysis for Münster. It also addresses the research questions guiding this study and examines social factors to characterize Münster's current situation.

4.1 Results Interpretation

4.1.1 Research Question 1

The results address two key aspects: (1) how accessibility to essential amenities is measured in Münster, and (2) how the cycling network is evaluated using a bikeability index.

4.1.1.1 Accessibility Measurement

Selected Destinations and Distribution

The OpenStreetMap (OSM) Points of Interest (POIs) data were processed to classify destination categories in Münster. Additionally, the HDBSCAN algorithm was applied to detect spatial distribution patterns of essential destinations across the city.

The results reveal a high population concentration in the city center, with a gradual decline toward the surrounding districts. As illustrated in Figure 4.1, the clustering of essential amenities closely corresponds to population density, indicating that these amenities are primarily located in areas with higher residential concentrations. Conversely, the outskirts of Münster exhibit lower population densities and a sparse distribution of essential amenities, suggesting limited existence of services in these areas.

Cumulative-opportunity Accessibility Measurement

To measure accessibility, travel time matrices were firstly computed for six destination categories—Food, Healthcare, Education, Leisure, Sports, and Transportation—using r5py. Table 4.1 shows that the median cycling travel time remains consistently at 10 minutes

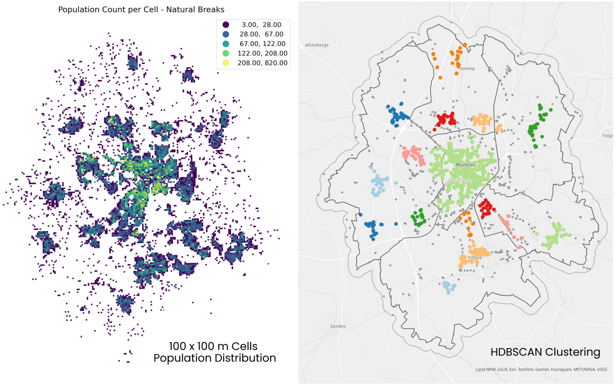


Figure 4.1: Population and Essential Amenities Distribution - Clustering using HDBSCAN

across all categories, meaning half of the accessible trips are completed within this timeframe. The mean travel times (9.23–9.72 minutes) closely align with the median, indicating a relatively symmetric distribution with minimal variation among categories. The standard deviations (3.53–3.71 minutes) suggest similar variability across destination types. First quartile (Q1) values of 6–7 minutes indicate that a significant portion of trips falls on the lower end, while third quartile (Q3) values of 12–13 minutes show that most trips are clustered around the median. The consistent minimum value of 0.0 minutes across categories likely reflects cases where origins and destinations are extremely close.

Table 4.1: Descriptive Statistics of Travel Times by Destination Category for the 15-minute City- speed of 12km/hr and LTS 1

Category	Mean (min)	Median (min)	Std. (min)	Min (min)	Q1 (min)	Q3 (min)
Food	9.63	10.00	3.53	0.00	7.00	13.00
Healthcare	9.30	10.00	3.61	0.00	7.00	12.00
Education	9.23	10.00	3.66	0.00	6.00	12.00
Leisure	9.26	10.00	3.71	0.00	6.00	12.00
Sports	9.72	10.00	3.53	0.00	7.00	13.00
Transportation	9.40	10.00	3.66	0.00	7.00	13.00

The cumulative-opportunity accessibility measurement was calculated with a focus on considering accessibility at the lowest travel speed (12km/hr) and routes classified as Level of Traffic Stress (LTS) 1. This approach ensures that results reflect the most equitable and safe access conditions for all users, including vulnerable groups such as children, elderly individuals, and inexperienced cyclists.

By mapping accessibility within the 15-minute cycling threshold (Figure 4.2), a similar spatial pattern emerges across all destination categories. The maps illustrate a high concentration of destinations in the city center. Accessibility gradually decreases toward the outskirts, where accessibility is absent. Despite these variations, most grid cells can access at least one destination from each category, ensuring a baseline level of accessibility among population. Next, we examine the population distribution and identify areas absence of accessibility .

Figure 4.2: Spatial Distribution of Cumulative-Accessibility across Six Destination Categories within a 15-minute Cycling Time.

In terms of population distribution, access to urban services remains uneven, with some residents having higher accessibility to essential categories than others, as shown in Appendix 6.2. However, focusing on those without access, Table 4.2 shows that only 1,391 residents (0.46% of the total population) lack access to essential destinations within a 15-minute travel time. This indicates that the 15-minute threshold provides very good overall accessibility in Münster. Although the 10-minute (0.83%) and 5-minute (1.71%) thresholds apply slightly stricter criteria, they still reflect strong levels of service accessibility.

Table 4.2: Population with No Accessibility within 5, 10, and 15-minutes

Count	15 min	10 min	5 min
Residents with No Access	1391	2532	5193
Percentage of Total Population	0.46%	0.83%	1.71%

4.1.1.2 Bikeability Street Segment-based Index

The bikeability assessment begins with constructing a street segment-based index. As mentioned in the methodology chapter, criteria were established to evaluate the importance of sub-indicators across four primary indicators: infrastructure, safety, comfort, and environment. Consequently, the Analytic Hierarchy Process (AHP) is applied to quantify the relative importance of these sub-indicators, forming the basis for the bikeability evaluation.

Analytic Hierarchy Process Results (AHP)

We consulted four experts with cycling network planning and urban mobility backgrounds for a detailed pairwise comparison. The interviewed group included: (1) a Naviki Cycling App co-founder, providing insights on user experience in cycling technology; (2) a representative from Münster's Bicycle Office, offering expertise in cycling infrastructure and planning; (3) a contributor to Münster's Master Plan for Mobility 2035+, overseeing the "City of Short Distances" vision, which aligns with the x-minute city concept; and (4) a bicycle traffic specialist from Osnabrück's Department of Urban Development and Traffic Planning. Their diverse perspectives ensured a well-rounded evaluation of bikeability sub-indicator weights.

The experts were asked to complete the survey (see Survey, 6), and we conducted interviews with three of them. The interviews included open-ended questions about the reasoning behind their importance rankings and their insights on the x-minute city concept and bikeability in Münster. To process the data, individual weights were calculated separately using the SuperDecisions software, which automatically computes the weights and the consistency ratio (CR) for each expert. Additionally, expert judgments for each indicator were combined using the geometric mean (AIJ) method. This produced consistent weights for the bikeability index. The AIJ calculations were conducted using Excel.

The AHP results underscore the significance of Münster-specific bikeability sub-indicators. Table 4.3 shows that for infrastructure, experts assigned a dominant weight of 0.874 to bike paths presence compared to 0.126 for bike facilities presence. In safety, traffic speed was prioritized (0.510), followed by bike accidents rate (0.182), bike paths separation (0.157), and conflict points (0.152). Regarding comfort, bike paths width received a weight of 0.590, surpassing road slope at 0.410. In environment, air quality was most critical (0.473), with green spaces and water bodies weighted at 0.295 and 0.232, respectively. These values indicate the relative contribution of each indicator to a bike-friendly environment, as evaluated by experts in Münster.

Table 4.3: Aggregated (AIJ) Weights by Classification and Indicator

Bikeability Indicator	Sub-indicator	AIJ Weight
Infrastructure	Presence of Bike Paths	0.874
	Presence of Bike Facilities	0.126
Safety	Bike Accidents Rate	0.182
	bike paths Separation	0.157
	Conflict Points	0.152
	Traffic Speed	0.510
Comfort	Bike Paths Width	0.590
	Road Slope	0.410
Environment	Air Quality	0.473
	Green Area Exposure	0.295
	Water Bodies Exposure	0.232

Segment-based Bikeability Index

The bikeability index formula was applied to the bike network of Münster using the AHP aggregated weights (see Equation 3.3). As shown in Figure 4.3, the maps highlight that high infrastructure values significantly align with the existence of cycle ways, indicating well-developed cycling infrastructure in these areas. In terms of the safety indicator, the initial results provide insights into the good level of safety across the majority of the bike network, suggesting that most cycling routes are secure for users.

As observed, areas with dedicated cycleways scored highest on the comfort indicator, ensuring a more pleasant cycling experience. Bike paths near water bodies also performed well, benefiting from better air quality and greater green space exposure. In contrast, the central train station area received the lowest scores on the bikeability environment index and safety (see Appendix 6.4). This is mainly due to a lack of green spaces, poorer air quality, and lower safety indicators. Interestingly, the promenade, a key cycling route, achieved higher overall scores than other streets in the city center, reinforcing the importance of well-designed cycling infrastructure.

Figure 4.3: Bikeability Segment-based Indicators: Infrastructure, Safety, Comfort, and Environment

4.1.2 Research Question 2

The results address two key aspects: (1) how to access compliance with the x-minute city concept, and (2) how to address social inequalities within the concept.

4.1.2.1 X-minute City Index

Using the x-minute City Index, we assess compliance with this concept at a cell-based level (100 × 100 m). Compliance for each cell is determined using Equation 3.10. Bikeability is evaluated within x-minute city isochrones (5, 10, and 15 minutes cycling time), and a cell-based bikeability index was calculated for each cell (see Appendix Figure 6.5).

The diversity of accessible amenities is assessed using Equation 3.9, which directly reflects accessibility to amenities variations by measuring the existence and frequency of amenities within each threshold.

Bikeability Cell-Based Index Clusters

Following the assessment of the bikeability cell-based index, the Anselin Local Moran's I analysis was applied to detect clustering patterns and outliers (see Figure 4.4). The results reveal a notable high-high cluster in the central area of the city, extending to surrounding districts such as Gievenbeck. However, this clustering decreases in some areas when the travel time is reduced to 10 and 5 minutes. An exception in the central area is the central station and its surroundings, which are not classified as a high-high cluster. A particularly interesting insight is that the area around Ludgeriplatz appears as a low-low cluster in the 5-minute isochrone, indicating that bikeability quality in this location remains significantly low (see Appendix 6.4). This outcome highlights localized deficiencies in cycling infrastructure or conditions that require targeted interventions to support the x-minute city objective.

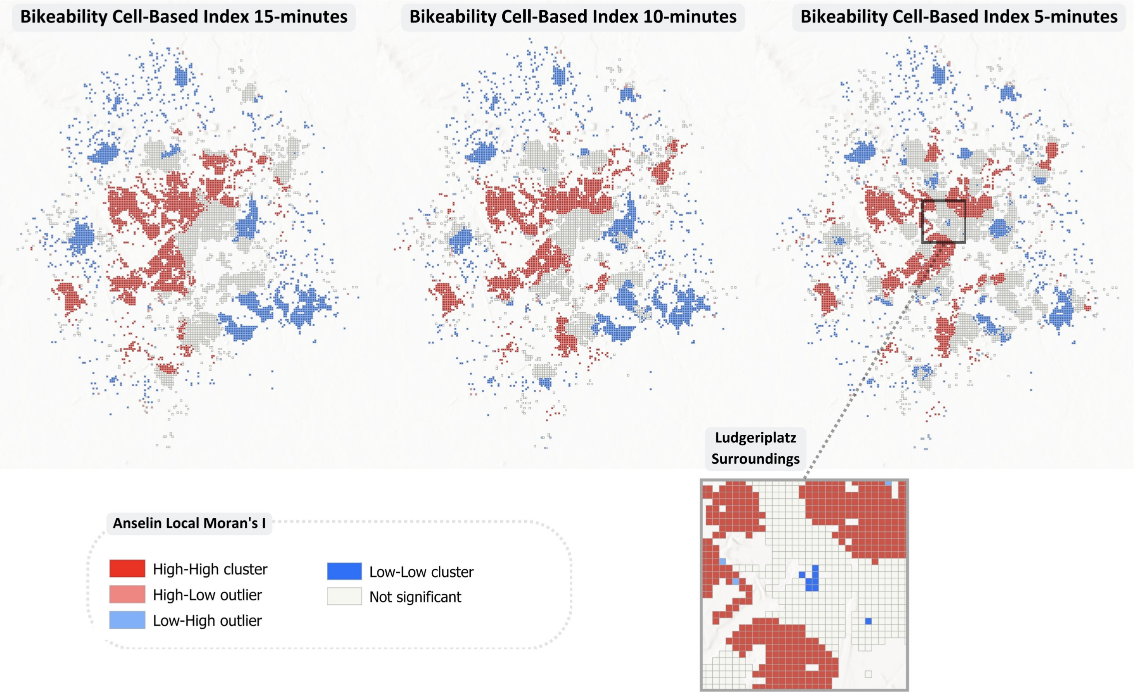


Figure 4.4: Bikeability Cell-based Index Clusters and Outliers- Anselin Local Moran's I

Diversity Index

To evaluate how well the x-minute city framework provides access to diverse services, we calculated the diversity index for Münster. The findings reveal significant variations in diversity across destination categories (see Figure 4.5). The city center has the highest

Shannon Index values, indicating a well-balanced distribution of essential services. Even at the lowest cycling speeds and safest (LTS 1) routes, residents can access shopping, education, healthcare, transportation, and leisure facilities conveniently.

In contrast, peripheral areas show lower Shannon Index values, with some outskirts recording a value of 0, indicating no access to amenities. This highlights accessibility gaps and the challenges residents face in meeting the x-minute city concept in these areas.

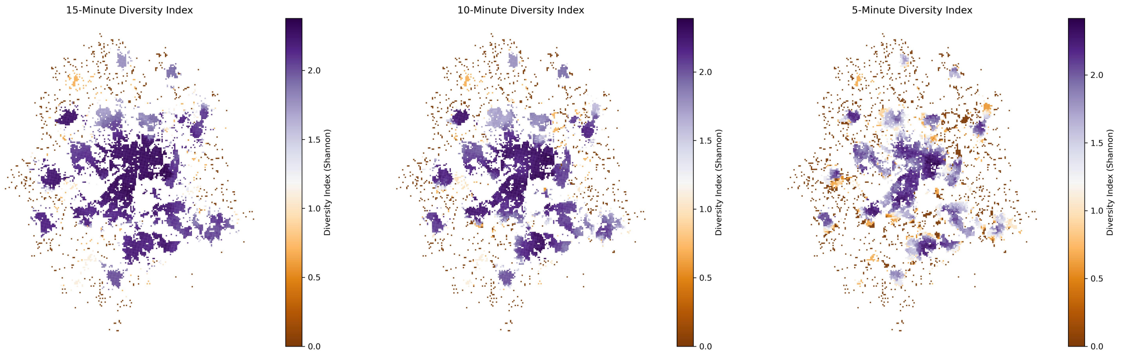


Figure 4.5: Diversity Shannon Index for 5, 10, 15-minutes for an X-minute Inclusive City.

Table 4.4 summarizes the Shannon Index statistics for each cell at 5, 10, and 15-minute travel thresholds. At 5 minutes, the mean index is 1.29 (median = 1.58, Std. Dev. = 0.81), indicating moderate diversity with high variability. As travel time extends to 10 minutes, diversity increases (mean = 1.72, median = 2.04) while variability decreases (Std. Dev. = 0.74). This suggests that longer cycling times allow access to a wider range of services, leading to a more balanced distribution of destinations. At 15 minutes, diversity further improves (mean = 1.89, median = 2.13) with lower variability (Std. Dev. = 0.65), reflecting greater and more uniform accessibility across cells. These trends indicate that longer travel times enhance both diversity and spatial consistency in accessibility.

Table 4.4: Descriptive Statistics of the Shannon Index- Diversity of Essential Amenities

Category	Mean	Median	Std. Dev.	Min	Q1	Q3	Max
5-min	1.29	1.58	0.81	0.00	0.64	1.98	2.42
10-min	1.72	2.04	0.74	0.00	1.68	2.20	2.39
15-min	1.89	2.13	0.65	0.00	1.92	2.25	2.38

X-minute City Spatial Clustering Analysis

The x-minute city index was calculated by integrating diversity and bikeability indexes for each cell. To further analyze the spatial distribution of the x-minute City Index, we conducted a Global Moran's I test to assess the presence of spatial autocorrelation for cycling clusters at 5, 10, and 15-minute thresholds (see Appendix 6.8). Following this, we applied a Getis-Ord hotspot analysis to identify clusters of high and low confidence levels and used Anselin Local Moran's I to detect spatial outliers.

The results reveal a clear pattern, as shown in Figure 4.6, with significant hot spot clusters in the city center, indicating high compliance with the x-minute city concept. Surrounding districts mostly exhibit average values, while the outskirts display cold spots, reflecting significantly lower x-minute city index values. A particularly notable hotspot emerges around the central train station in the 15-minute map, but its significance slightly declines in the 10- and 5-minute maps due to lower bikeability scores in the area. Additionally, in the 5-minute map, a low outlier is observed near Ludgeriplatz, where low bikeability reduces accessibility.

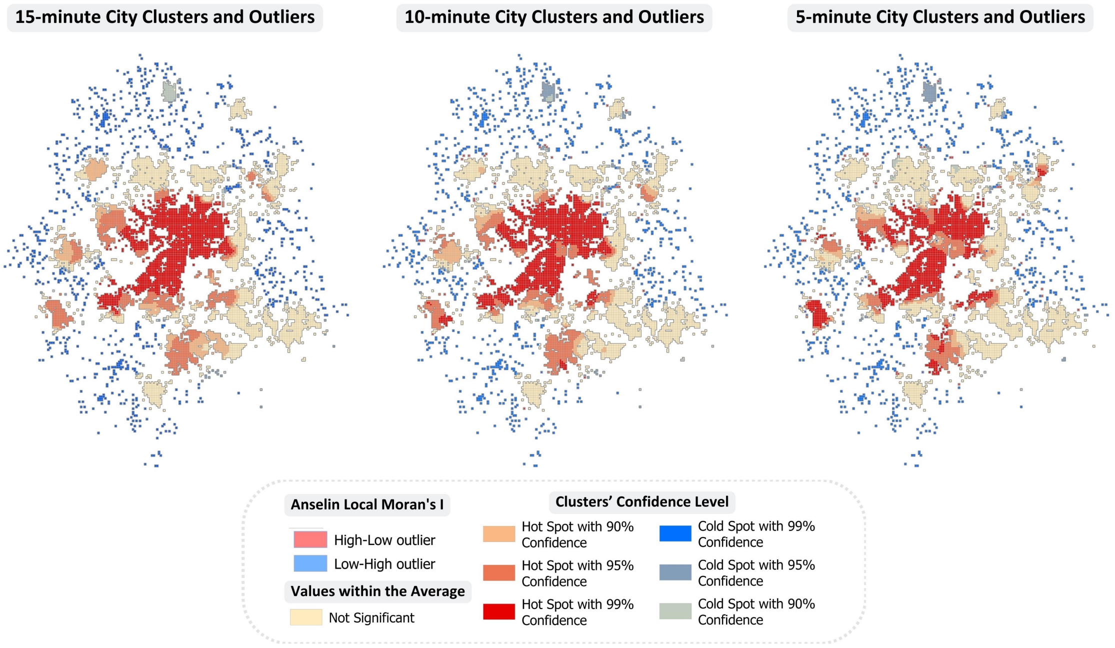


Figure 4.6: The X-minute City Index Clusters (Hot and Cold Spots) and Outliers

Beyond the city center, clusters of high compliance appear in Hiltrup and Albachten, distinguishing them from other peripheral areas with cold spots. This suggests that these districts maintain a relatively balanced distribution of accessibility and bikeability.

These findings emphasize the importance of integrating bikeability into the x-minute city assessment, ensuring that the evaluation promotes equality in accessibility analysis.

4.1.2.2 Social Inequalities within the X-minute City Index

To assess social inequalities, we calculated the Gini index and evaluated the sufficiency of essential amenities to measure the distribution of accessibility across the population. Additionally, the x-minute city index and spatial statistical analyses identified areas with varying levels of compliance. Ensuring equitable access to necessities is crucial, as outlined in the criteria presented in the methodology (Table 3.5). The results are as follows:

Social Inequalities: Gini Index

We calculate the Gini index to assess the distribution of accessibility across the population, where lower values indicate greater equity. As shown in Figure 4.7, the Lorenz curve closely follows the equity line, with only a minimal area behind it, indicating a highly equitable distribution across the population. This is reflected in the Gini index values for the x-minute city index, which remain consistently low across all thresholds: 0.059 at 5 minutes, 0.065 at 10 minutes, and 0.073 at 15 minutes. Since the x-minute city index integrates diversity and bikeability, these results suggest that their combined effect contributes to a more balanced and equitable distribution across the population.

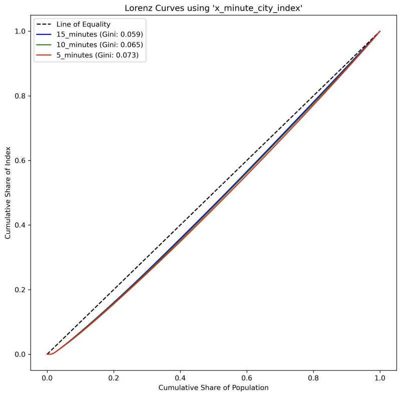


Figure 4.7: Lorenz Curve Illustrating the Distribution of the X-Minute City Index Across the Population.

Sufficient Access to Necessities

The analysis of sufficiency criteria reveals a consistent spatial pattern across essential services, including food, education, sports, and healthcare (see Figure 4.8). Areas meeting the sufficiency criteria represent completeness of amenities. The results indicates the areas have access to complete amenities remain concentrated in the city center and key districts, while the outskirts generally experience inadequate accessibility to essential services. This pattern holds across all five destination categories, except for leisure, where sufficiency is observed only in central districts. An exception is Münster-Hiltrup, where leisure amenities are also well distributed.

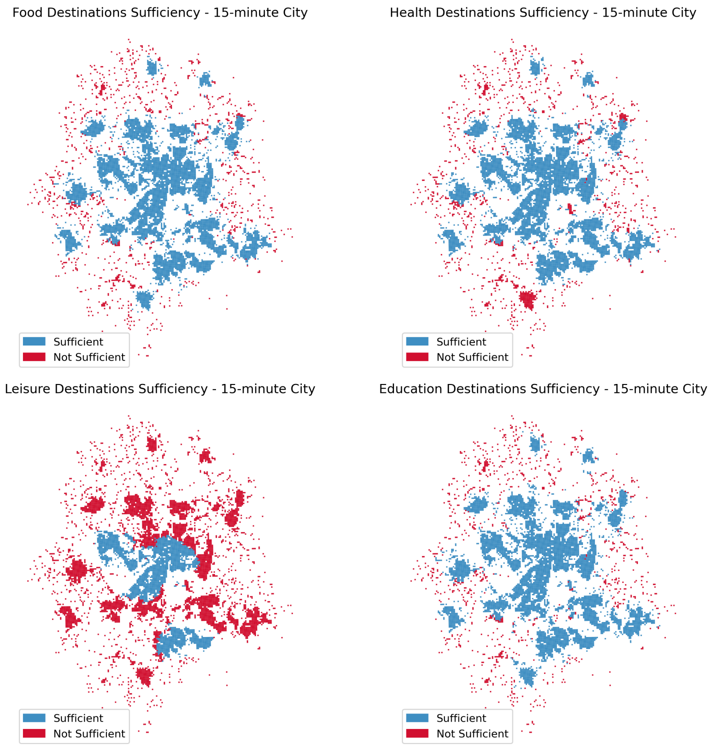


Figure 4.8: Sufficient Access to the 5 Destination Category based on the Proposed Sufficiency Criteria- 15-minutes Cycling Time

Table 4.5: Population Without Access Based on the Sufficiency Criteria at Different Thresholds

	4 Criteria			**5 Criteria**		
Threshold	**5-min**	**10-min**	**15-min**	**5-min**	**10-min**	**15-min**
Population	196,226	40,631	16,248	289,940	219,125	163,531
% Insufficient	64.63%	13.38%	5.35%	95.50%	72.18%	53.86%

While the x-minute city index and Gini index address social inequalities, the sufficiency criteria reveal additional details not fully captured by these measures. Table 4.5 shows that under the four-criteria evaluation, the 15-minute threshold meets sufficiency, with only 5.35% and 13.38% of the population lacking access at 15 and 10 minutes, respectively. However, applying the five-criteria assessment significantly increases the share of the population without sufficient access across all thresholds, reaching 53.9% and 72% at 15 and 10 minutes, respectively (see Appendix 6). The number rises even more sharply for shorter travel times, with the results indicating that the majority of the population fails to meet the criteria at the 5-minute threshold.

Social Inequalities: Population Groups

Following the population-weighted approach described in the methodology (see Equation 3.11), we computed the city-wide compliance index to capture the overall alignment of Münster with the x-minute city concept. By aggregating cell-level indices weighted by local population, this measure accounts for the fact that more densely populated areas have a greater influence on the city's overall compliance level.

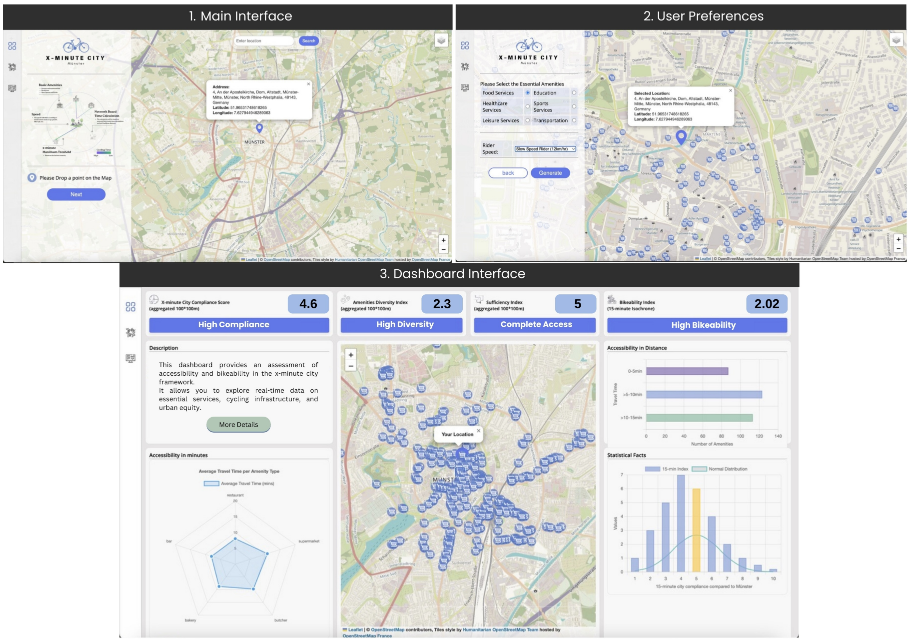
Appendix 6 presents the weighted mean indices across various travel time thresholds. The results show that most age groups have similar access levels, although the 18–29 group scores slightly higher. Notably, vulnerable populations such as children (below 18) and the elderly (above 65) do not experience a significant drop in their indices, indicating a relatively inclusive x-minute city distribution. A similar trend appears when comparing foreigners and Germans, with both groups displaying similar mean values. These findings suggest that, under the (Cx_{city}) compliance calculation, Münster's short-distance accessibility remains largely equitable across different age segments and nationalities.

4.1.3 Research Question 3

4.1.3.1 The X-minute City Digital Tool

To assist urban planners and the public in evaluating accessibility within the x-minute city framework, we developed a digital tool. The tool was implemented to give insights about the x-minute city different indices and provides the user with a customized experience based on their preferences. The design of the interfaces is as follows:

a) The First and The Second interface The first interface offers users a straightforward workflow, allowing them to either pin or search for their location (see Figure 4.9). By clicking "Next," they can proceed to the next interface, where they can select the amenities they are interested in and visualize the POIs. Additionally, users can choose their cycling speed from three categories: 12 km/h for slow riders, 14 km/h for average riders, and 20 km/h for fast riders.



Selected Location:
4, An der Apostelkirche, Dom, Altstadt, Münster-Mitte, Münster, North Rhine-Westphalia, 48143, Germany
Latitude: 51.96531748618265
Longitude: 7.627944946289063

This dashboard provides an assessment of accessibility and bikeability in the x-minute city framework.
It allows you to explore real-time data on essential services, cycling infrastructure, and urban equity.

Figure 4.9: X-minute City Digital Tool User Interfaces

b) The Third Interface: A Dashboard Once the user presses ”Generate,” the dashboard is displayed. Initially, the dashboard provides insights into the four indices calculated for the x-minute city: the X-minute City Compliance Index, Diversity Index, Sufficiency Score, and Bikeability Index. These indices are visualized in the upper section of the dashboard, with values aggregated to a 100x100m cell-based resolution for the case study.

The radar chart presents the average travel time for each amenity sub-category. For instance, if the user selects the food category, the chart visualizes the average travel time to supermarkets, butcher shops, bakeries, restaurants, and bars, provided they exist within the specified threshold from the selected location.

Additionally, the histogram displays the x-minute city Index z-score and p-value for the selected location, offering insights into how this location compares to other areas in Münster. Meanwhile, a bar chart represents the number of amenities accessible within the 5, 10, and 15-minute thresholds, providing a clear overview of service availability in the specified area.

4.2 Results Validation

The experts who participated in the AHP survey were asked to validate the research results through interviews. They were invited to assess the results of amenity accessibility and distribution, the bikeability index outcomes, and overall compliance with the x-minute city framework in Münster. Additionally, we presented a demo of the digital tool to gather their insights on its importance for public use and the decision-making process.

Accessibility and Amenities Distribution: The experts emphasized the planning department's efforts of Münster Municipality in establishing a polycentric urban structure in Münster. They found that Figures (4.1, 4.2) are aligned with their expectations, as the amenity distribution shows that a high concentration of services is centralized in the city center, giving its residents greater accessibility compared to those in other centers. One expert remarked that ”The other centers are considered little lives around the city center,” which explains the gradual decline in accessibility in these areas. They also noted that peripheral areas in Münster have lower accessibility levels, which contributes to the high dependence on cars in these areas.

Bikeability Index: The experts stated that ”Ludgeriplatz and the central train station surroundings are likely lower in bikeability compared to their surroundings.” They acknowledged the critical safety concerns in these locations, stating that ”people have died in these places.” Despite some safety measures being implemented, the experts noted that these areas remain unfriendly and unsafe for cyclists to navigate. On the other hand, roads like Promenade logically receive higher scores compared to other roads.

X-minute City Compliance Index: Regarding amenity diversity, the experts agreed that the maps accurately represent the distribution of services (see Figures 4.5 and 4.6). They confirmed that districts like Hiltrup exhibit high diversity, attributing this to Hiltrup's history as a formerly independent city, which contributed to a richer mix of services and amenities. The experts also stated that it makes a lot of sense that peripheral areas have low x-minute city scores, as these areas have limited access to cycling infrastructure and often require traveling more than 15 minutes to reach essential amenities. Regarding social inequalities, the experts emphasized that gender and income should be considered when assessing compliance with the x-minute city concept.

X-minute City Digital Tool: The experts validated the digital tool as user-friendly and widely accessible to a broad range of users. They also highlighted that ”it is quite good to use OSM APIs because they are updated frequently,” ensuring real-time updates to amenities. This feature enhances the tool's accuracy and relevance, providing up-to-date data for users.

5

Discussions

5.1 Results Discussion

The study results indicate that Münster excels in both accessibility and bikeability, featuring a dense concentration of essential amenities and a well-developed cycling network. Regarding accessibility. The findings show that 99.5% and 99.2% of the population have access to at least one essential destination within 15- and 10-minute thresholds, respectively. For the 5-minute threshold, this figure slightly declines to 98.3%, indicating that most of the population still has access within a shorter timeframe.

The AHP confirms that key factors such as bike path availability, traffic speed limits, path width, slope, and air quality play a crucial role in shaping the cycling experience. Experts identified these as the most influential factors. Roads with higher bikeability scores tend to have well-developed infrastructure, lower exposure to high-speed traffic, good road quality, and better air conditions. While Münster's cycling network generally provides high-quality infrastructure, some locations—such as peripheral areas, Ludgeriplatz, and the surroundings of the central train station—scored lower. These findings, supported by expert interviews, highlight the need for targeted interventions in these zones.

The analysis of x-minute city compliance reveals a notable spatial clustering of high-value index cells around the city center, with surrounding districts also aligning with the concept. This pattern indicates high accessibility to diverse amenities and a bike-friendly network. The findings also align with previous urban planning studies that associate higher population densities with better service accessibility [26] [5]. By contrast, peripheral areas exhibit lower x-minute scores, reflecting limited amenity diversity and lower bikeability. As a result, some residents must travel more than 15 minutes to access essential amenities. Overall, x-minute city compliance slightly decreases at the 10-minute threshold and declines further at the 5-minute threshold.

While the Gini index remains relatively low, indicating broad equity, the results also show that vulnerable groups, including foreigners, children, and the elderly, have similar x-minute access to essential services as other groups. However, analyzing the sufficiency criteria provided additional insights. The findings indicate that 95% of the population can access most daily necessities within the 15-minute threshold. On the other hand, applying stricter sufficiency criteria reveals additional gaps in access to essential services. These discrepancies underscore the importance of using multiple measures—such as sufficiency scores and diversity indices—to capture nuances in service distribution rather than relying solely on accessibility metrics.

This study suggests that most of Münster's population has access to diverse amenities, essential services, and a bikeable network within 15 minutes. Addressing gaps in amenity accessibility, diversity, and sufficiency could facilitate a transition toward a 10-minute city. Enhancing cycling infrastructure, particularly in peripheral areas, would improve mobility for those traveling beyond 15 minutes and promote greater urban equity.

5.2 Research Limitations

This study relies on a quantitative approach to assess compliance with the x-minute city concept, which, while effective for measuring accessibility and bikeability, does not capture the lived experiences of residents. The methodology does not include a public participatory approach, meaning user preferences, perceptions, and real-world mobility challenges are not directly captured. Integrating qualitative insights could provide a more holistic understanding of urban accessibility and the x-minute city.

Regarding accessibility, due to data limitations, service quality and capacity (e.g., schools and hospitals) were not assessed, though high accessibility does not guarantee service availability if facilities exceed capacity. Additionally, computational constraints led to the use of aggregated trip origins instead of precise residential addresses. Furthermore, average cycling speeds were derived from literature rather than real travel data (e.g., Strava or travel surveys), which could improve accuracy. In addressing social inequalities, Income and gender as social factors were also excluded due to lack of the data on the scale of 100 x 100 m cells.

In evaluating the bikeability index, we validated the results by interviewing experts due to certain limitations. However, community engagement through public surveys would be essential for obtaining more detailed validation of the index. Regarding bikeability indicators, road conditions—especially at night—were difficult to capture. Therefore, these aspects have to be considered to enhance the framework of assessing the x-minute city concept.

5.3 Recommendations and Future Research

Future research should integrate qualitative methods and public participation to better capture public needs. Surveys and participatory mapping could enhance accessibility and bikeability assessments, offering insights into local mobility patterns. Additionally, integrating public transportation in x-minute assessments would address the needs of individuals unable to rely on active travel due to age, disabilities, or preferences. Moreover, Social factors such as gender and income disparities should also be considered to ensure equitable access.

Regarding accessibility measurement, future research could compare accessibility measurements, such as cumulative opportunity and gravity-based accessibility, to determine their effectiveness in different urban contexts. Refining these methods would improve x-minute city evaluations and support more informed planning decisions. Since cities are dynamic, accessibility varies over time. Future studies should analyze spatial and temporal changes and assess policy effectiveness in achieving x-minute city goals. This would provide valuable insights for long-term urban planning.

For policymakers, ensuring inclusivity requires addressing mobility needs, service quality, and infrastructure capacity. While city centers often offer high accessibility, peripheral areas require targeted improvements in bikeability and amenity distribution to promote equity.

Digital tools play a crucial role in assessing and monitoring x-minute city compliance. Future research should enhance their accuracy by integrating real-time data on congestion, weather, parking, and user preferences, such as perceived safety and scenic routes. This would make the tools more adaptable and user-centric, improving their practical applicability for both planners and the public.

Overall, achieving the x-minute city concept requires a data-driven, inclusive approach. By refining accessibility assessments, incorporating real-time data, and addressing social inequalities, future research can guide the development of more equitable and livable urban environments.

6

Conclusion

This research highlights the potential of cycling as a mode of transport for the x-minute city, contributing to the development of inclusive, and accessible urban environments. The study aimed to develop a framework that integrates bikeability and accessibility while addressing social inequalities to assess the x-minute city, using Münster as a case study.

To assess bikeability, this study developed a composite bikeability index that integrates infrastructure, safety, comfort, and environmental indicators. To address the importance of the sub-indicators, we utilized an Analytic Hierarchy Process (AHP) to involve decision makers and cycling experts in the process. The bikeability index is applied to a segment-based street network to provide a high-resolution assessment and offer more insights than aggregated methods. The experts highlighted the importance of bike paths, low speed traffic exposure, and air quality in assessing bikeability. Accessibility was evaluated using the cumulative opportunity measure across six destination categories. The study focused on essential destinations that people require in their daily lives while excluding high-level destinations such as hospitals and universities.

The study revealed that assessing compliance with the x-minute city concept requires not only accessibility to amenities but also amenity diversity and bikeability as part of the assessment. Therefore, we applied the Shannon index to measure the degree of amenity diversity within cycling isochrones. To address social inequalities, we developed sufficiency criteria to assess the minimum necessities people need within an x-minute city threshold for their daily needs, while the Gini index quantified inequalities in aligning with the x-minute city concept.

The findings show that Münster excels strongly in accessibility and bikeability, with 99.5% of residents having access to at least one essential destination within 15 minutes, 99.2% within 10 minutes, and 98.3% within 5 minutes. Furthermore, the majority of the population has access to a bike-friendly network within 15 minutes, with accessibility slightly higher than at the 10-minute threshold, while the 5-minute threshold has the lowest accessibility. The Gini index further suggests that the city provides equitable access to the x-minute city, and the analysis shows that vulnerable groups do not experience lower x-minute scores. Additionally, 95% of residents can access a diverse and sufficiently large number of amenities within 15 minutes.

These results position Münster within the 15-minute city framework and highlight its potential transition toward a 10-minute city. While city center residents benefit from 5-minute access, peripheral areas—where travel times exceed 15 minutes—require improvements due to limited accessibility, diversity, and bikeability. These findings underscore the need to integrate diversity, bikeability, and sufficiency criteria into x-minute city assessments for a more comprehensive understanding of the concept.

A key contribution of this study is the development of a digital tool, which provides insights for the public and decision-makers with statistics on how Münster complies with the concept. While, Münster serves as a strong case study proving that cycling serve as an efficient mode of transport for the x-minute city, the proposed framework can be adapted and applied to other cities, supporting future efforts to create equitable, and well-connected urban spaces.

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Appendix

Accessibility Measurement

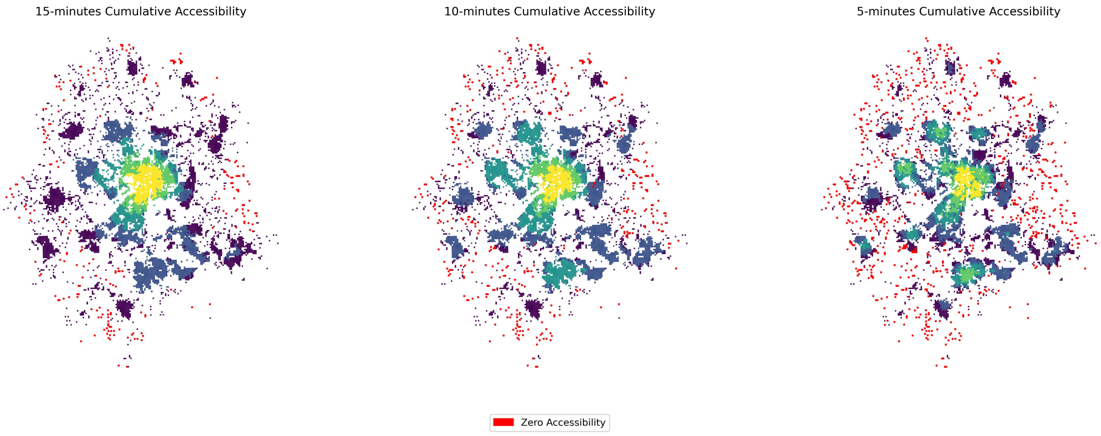


Figure 6.1: Cumulative Accessibility Measurement for the Six X-minute City Destinations Combined within 15, 10, and 5-minute Threshold

Accessibility Inequalities

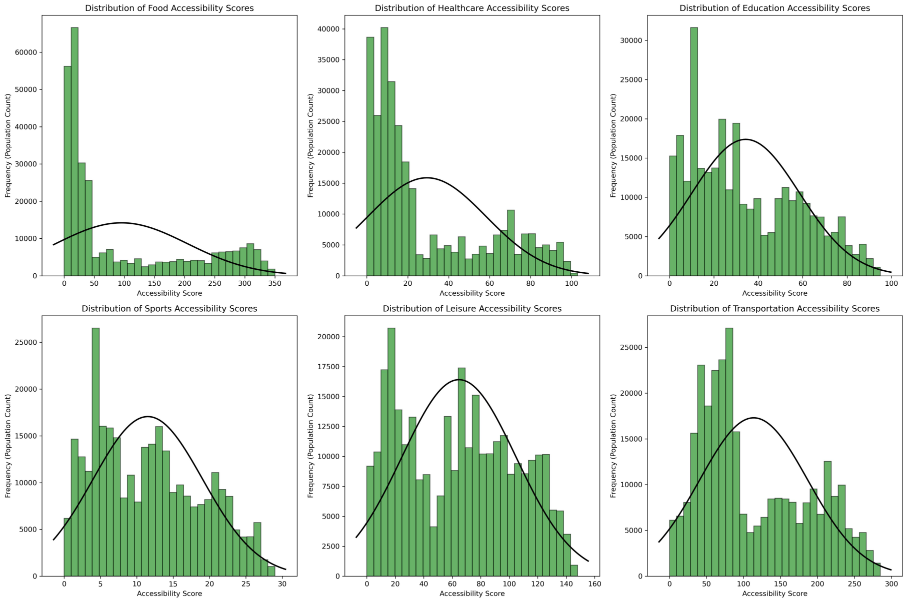


Figure 6.2: Distribution Curves of the Population's Accessibility (15-minute Cycling Time) for the Six Essential Destination Categories.

Table 6.1: Population with No Access by Category within 15-minutes

Category	**Food**	**Healthcare**	**Education**	**Sports**	**Leisure**	**Transportation**
Number of People	5,056	7,014	5,036	6,190	3,492	1,937
Percentage (%)	1.67%	2.31%	1.66%	2.04%	1.15%	0.64%

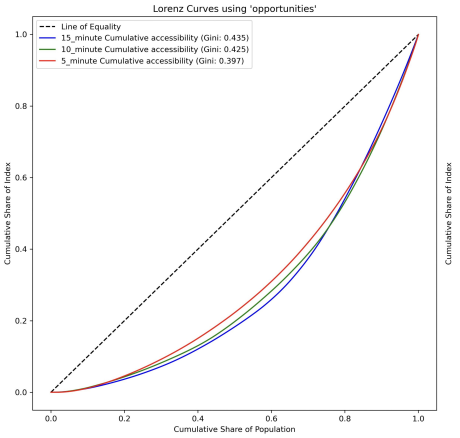


Figure 6.3: Lorenz Curve Illustrating the Distribution of the Cumulative Accessibility Measurements Across the Population.

Bikeability Index

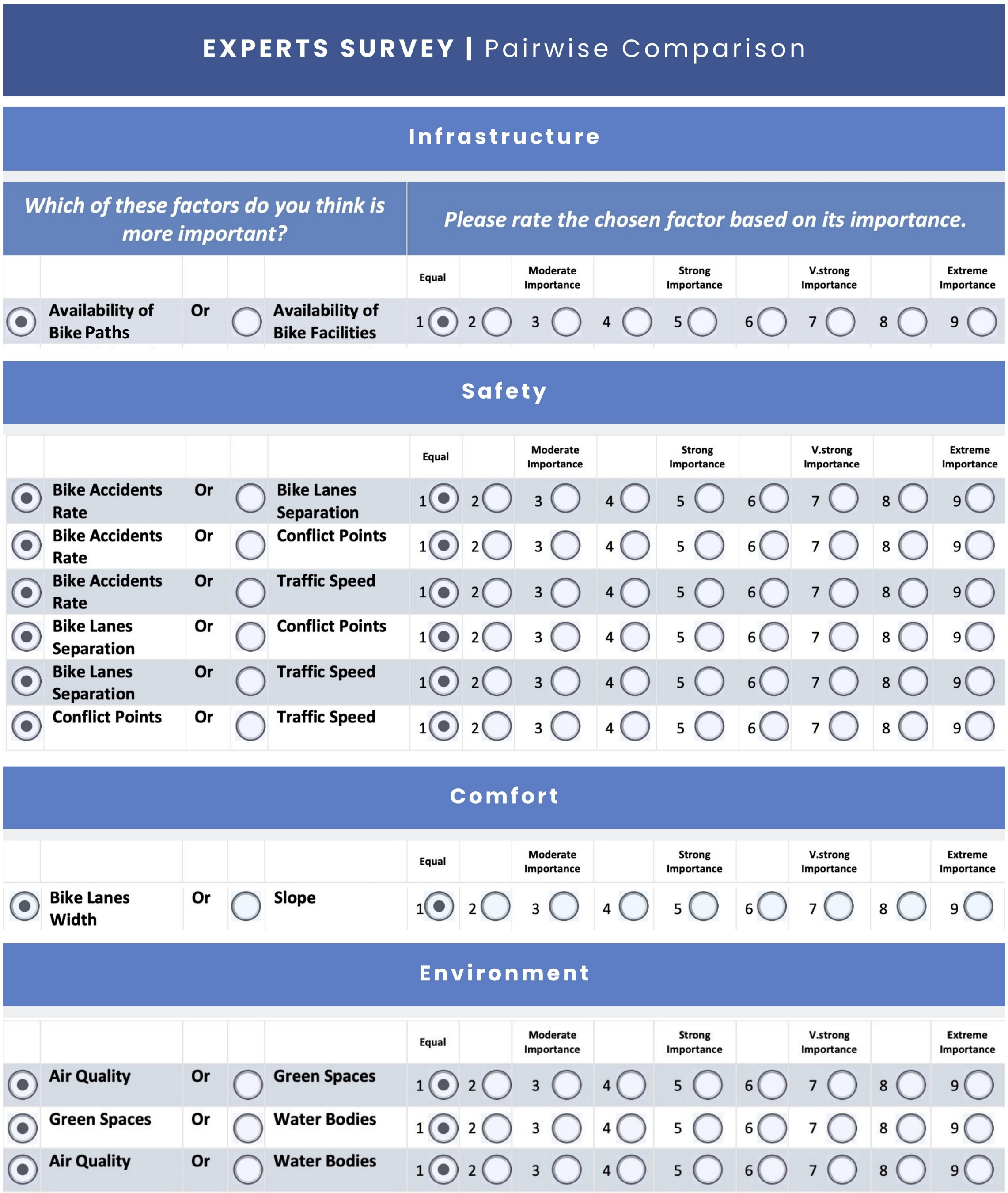
Open Street Map Street Network Data Processing(Filtered OSM Tags)

Table 6.2: OSM Tag Filters for Cycling Network

Bike Network Filtration	Availability of Bike Infrastructure
bicycle=designated	fclass=cycleway
bicycle=yes	cycleway=lane
fclass=cycleway	cycleway=track
cycleway=lane	cycleway=yes
cycleway=track	cycleway:both=lane
cycleway=yes	cycleway=separate*
cycleway:both=lane	cycleway:lane=exclusive
cycleway=separate*	cycleway:left=lane
cycleway:lane=exclusive	cycleway:left=track
cycleway:left=lane	cycleway:right=lane
cycleway:left=track	cycleway:right=track
cycleway:right=lane	cycleway:track=exclusive
cycleway:right=track	
cycleway:track=exclusive	

[*] representing physically separated cycleways.

Bikeability Indicators Pairwise Comparisons Survey



EXPERTS SURVEY | Pairwise Comparison

Infrastructure

Which of these factors do you think is more important?

Please rate the chosen factor based on its importance.

					Equal		Moderate Importance		Strong Importance		V.strong Importance		Extreme Importance
●	Availability of Bike Paths	Or	○	Availability of Bike Facilities	1 ●	2 ○	3 ○	4 ○	5 ○	6 ○	7 ○	8 ○	9 ○

Safety

					Equal		Moderate Importance		Strong Importance		V.strong Importance		Extreme Importance
●	Bike Accidents Rate	Or	○	Bike Lanes Separation	1 ●	2 ○	3 ○	4 ○	5 ○	6 ○	7 ○	8 ○	9 ○
●	Bike Accidents Rate	Or	○	Conflict Points	1 ●	2 ○	3 ○	4 ○	5 ○	6 ○	7 ○	8 ○	9 ○
●	Bike Accidents Rate	Or	○	Traffic Speed	1 ●	2 ○	3 ○	4 ○	5 ○	6 ○	7 ○	8 ○	9 ○
●	Bike Lanes Separation	Or	○	Conflict Points	1 ●	2 ○	3 ○	4 ○	5 ○	6 ○	7 ○	8 ○	9 ○
●	Bike Lanes Separation	Or	○	Traffic Speed	1 ●	2 ○	3 ○	4 ○	5 ○	6 ○	7 ○	8 ○	9 ○
●	Conflict Points	Or	○	Traffic Speed	1 ●	2 ○	3 ○	4 ○	5 ○	6 ○	7 ○	8 ○	9 ○

Comfort

					Equal		Moderate Importance		Strong Importance		V.strong Importance		Extreme Importance
●	Bike Lanes Width	Or	○	Slope	1 ●	2 ○	3 ○	4 ○	5 ○	6 ○	7 ○	8 ○	9 ○

Environment

					Equal		Moderate Importance		Strong Importance		V.strong Importance		Extreme Importance
●	Air Quality	Or	○	Green Spaces	1 ●	2 ○	3 ○	4 ○	5 ○	6 ○	7 ○	8 ○	9 ○
●	Green Spaces	Or	○	Water Bodies	1 ●	2 ○	3 ○	4 ○	5 ○	6 ○	7 ○	8 ○	9 ○
●	Air Quality	Or	○	Water Bodies	1 ●	2 ○	3 ○	4 ○	5 ○	6 ○	7 ○	8 ○	9 ○

Figure 6.4: Low Bikeability Index Streets- Pictures by the Author

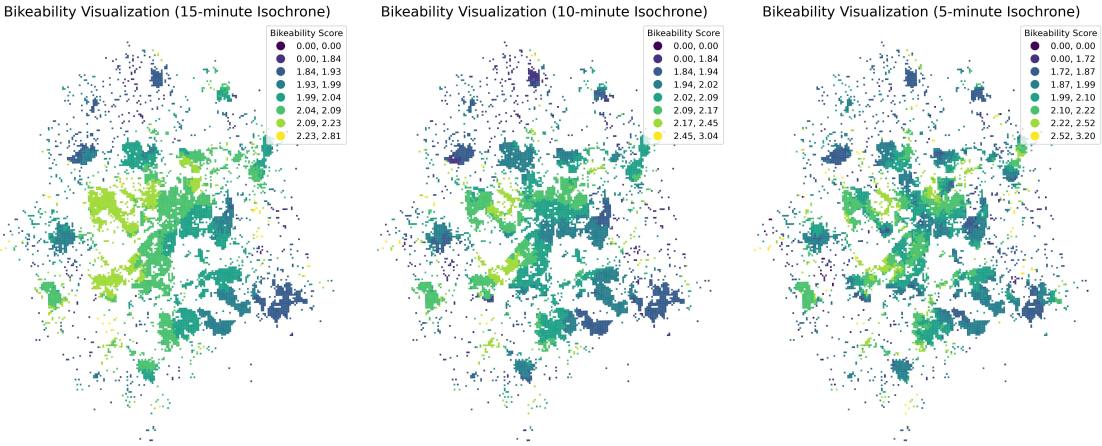
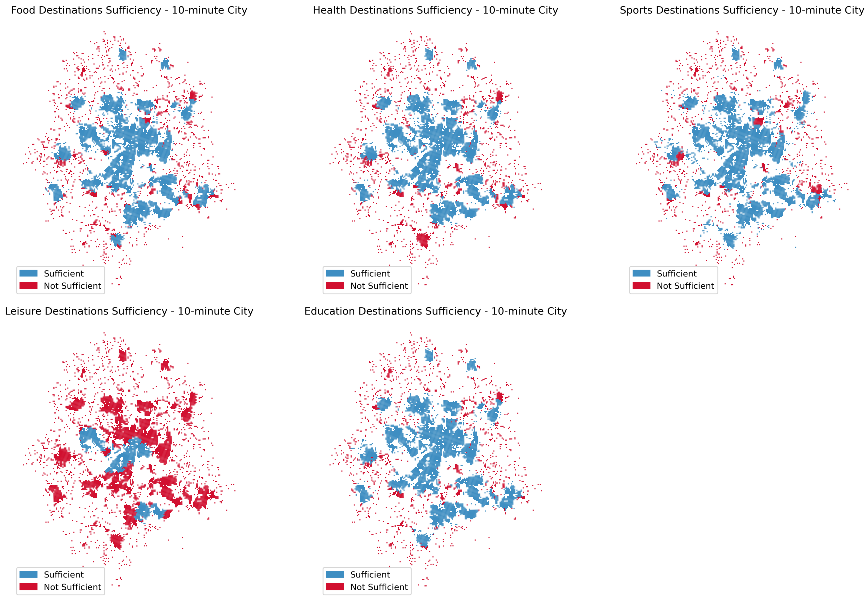


Figure 6.5: Bikeability Cell-based Index for 15, 10, and 5-minutes Isochrones

X-minute City Sufficiency Level



Food Destinations Sufficiency - 10-minute City

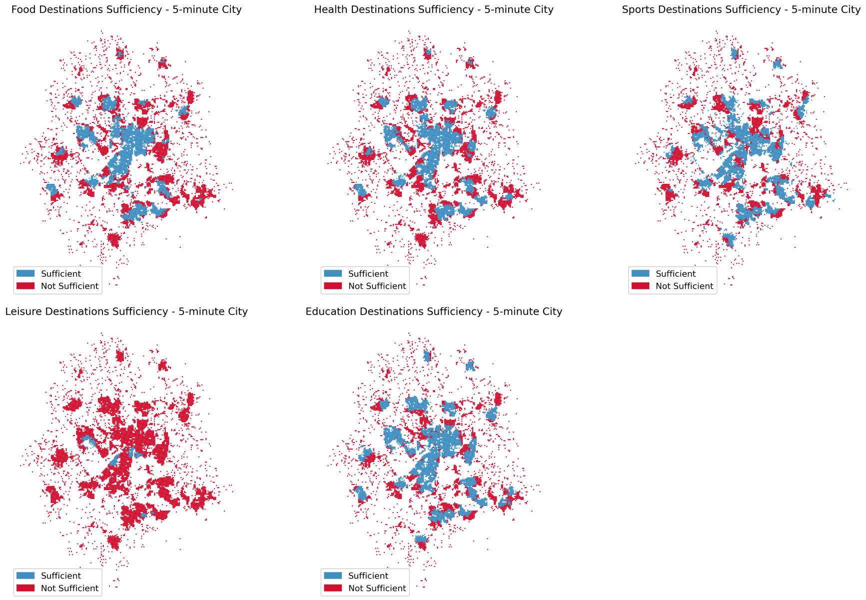
Health Destinations Sufficiency - 10-minute City

Sports Destinations Sufficiency - 10-minute City

Leisure Destinations Sufficiency - 10-minute City

Education Destinations Sufficiency - 10-minute City

Figure 6.6: Sufficient Access to the 5 Destination Category based on the Proposed Sufficiency Criteria- 10-minutes Cycling Time



Food Destinations Sufficiency - 5-minute City

Health Destinations Sufficiency - 5-minute City

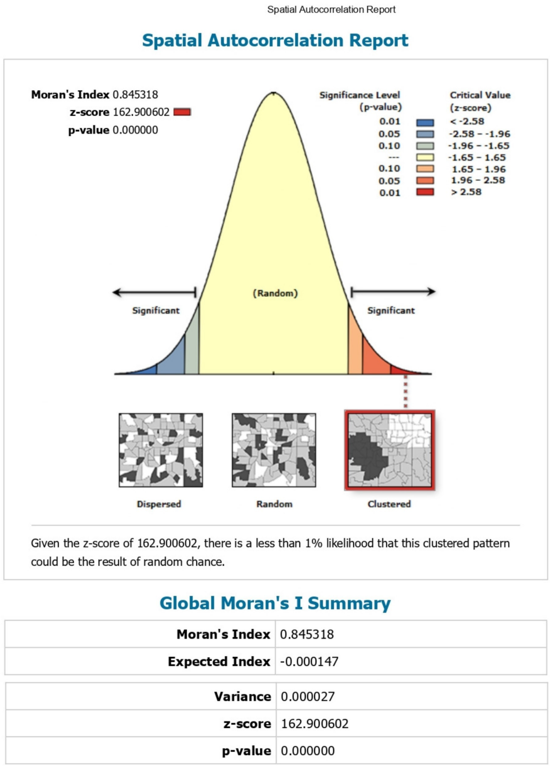
Sports Destinations Sufficiency - 5-minute City

Leisure Destinations Sufficiency - 5-minute City

Education Destinations Sufficiency - 5-minute City

Figure 6.7: Sufficient Access to the 5 Destination Category based on the Proposed Sufficiency Criteria- 5-minutes Cycling Time

Spatial Autocorrelation



Spatial Autocorrelation Report

Spatial Autocorrelation Report

Moran's Index 0.845318
z-score 162.900602 🟥
p-value 0.000000

Significance Level (p-value)		Critical Value (z-score)
0.01	🟦	< -2.58
0.05	🟦	-2.58 - -1.96
0.10	🟩	-1.96 - -1.65
---	🟨	-1.65 - 1.65
0.10	🟧	1.65 - 1.96
0.05	🟧	1.96 - 2.58
0.01	🟥	> 2.58

Given the z-score of 162.900602, there is a less than 1% likelihood that this clustered pattern could be the result of random chance.

Global Moran's I Summary

Moran's Index	0.845318
Expected Index	-0.000147

Variance	0.000027
z-score	162.900602
p-value	0.000000

Figure 6.8: Spatial Autocorrelation- Global Moran's I Test Result for the 15-minute Index

Threshold (minutes)	below_18	18_29	30_49	50_64	above_65
15	4.270771	4.487331	4.366448	4.305148	4.323171
10	4.264418	4.497333	4.364248	4.304132	4.320339
5	4.251075	4.503390	4.361808	4.294950	4.303358

Table 6.3: Weighted Mean X-minute City Index Values for Different Age Groups Across Different Travel Time Thresholds.

Threshold (minutes)	Weighted Mean- Foreigners	Weighted Mean- Germans
15	4.315712	4.350554
10	4.303999	4.351821
5	4.293215	4.345886

Table 6.4: Weighted Mean X-minute City Index Values for Foreigners and Germans Across Different Travel Time Thresholds.

Extra Sources

X-minute City Digital Tool for Münster

GitHub: `https://github.com/Hager-ali-m/X-minute-City-Tool.git`
License: MIT License

Data Processing and Analysis Scripts

Data Processing: `https://drive.google.com/drive/folders/1EqFMLNGvzZpJHI7L8Z6n-JS0JnYMMX84?usp=drive_link`

Analysis Scripts including Python Jupyter Notebooks and R files: `https://drive.google.com/drive/folders/1y-wJO9lWRSvAGih38wI7kMVYBEd64HPq?usp=sharing`