Bachelor's Degree in Industrial Technologies

Bachelor's final project

Creation and Implementation of the BIKE (Bicycle Integration Key Elements) Index: Assessing Bicycle Integration in European Cities.

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Madrid
Jul 2025

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Declaro, bajo mi responsabilidad, que el Proyecto presentado con el título

Creación y aplicación del BIKE (Bicycle Integration Key Elements) Index: Evaluando la Integración de la Bicicleta en Ciudades Europeas

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Abstract

This thesis introduces the BIKE Index, a multi-dimensional and reproducible framework for evaluating urban cycling conditions across cities, developed in response to the lack of standardized tools for assessing bikeability. The index integrates four key dimensions into a composite score: Cycling Infrastructure, Cyclist Services, Environmental Constraints, and Safety and Street Quality. Each dimension is measured using open data sources and consistent spatial methods, including an urban perimeter derived from Local Administrative Units and a standardized set of 210 cycling routes per city.

The methodology is applied to thirteen European capital cities using harmonized data from OpenStreetMap, OpenRouteService, Eurostat, and E-OBS climate datasets. Indicators are normalized using a modified Z-score to ensure comparability across cities. The results reveal significant disparities in cycling conditions, with scores ranging from 65.6 (Amsterdam) to 30.3 (Rome). While infrastructure emerges as the primary differentiator, services, environmental factors, and safety also play critical roles. These findings suggest that creating cycling-friendly cities requires coordinated progress across all four areas. The BIKE Index offers a transparent and scalable methodology for benchmarking cycling conditions, enabling consistent comparisons and supporting evidence-based planning and policy.

Creation and Implementation of the BIKE (Bicycle Integration Key Elements) Index: Assessing Bicycle Integration in European Cities.

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Abstract

This thesis presents the BIKE Index, a composite indicator developed to assess how effectively cities integrate cycling into their urban systems and to compare their overall level of bicycle adaptation. The index aggregates four key dimensions: cycling infrastructure, cyclist services, environmental constraints, and safety; and nine different indicators into a single score, based entirely on open data sources and a fixed set of 210 simulated cycling routes per city. The outcome is a transparent, reproducible, and scalable methodology that enables consistent benchmarking of cycling conditions in cities worldwide, supporting evidence-based planning and policy evaluation.

Key Words: Mobility, bicycle, composite indicator, cycling, infrastructure, sustainability, urban planning.

1. Introduction

European cities face unprecedented pressure to reduce transport emissions by 90% by 2050 [1] as part of the European Green Deal. Transport currently accounts for around 25% of the EU's total greenhouse gas emissions, and unlike other sectors, its contribution continues to rise [2]. Cycling has emerged as a key solution, offering a low-cost, low-carbon alternative for everyday mobility. Recent figures confirm this momentum: cycling to work in the Netherlands increased by 57% between 2024 and 2025 [3], and Paris recorded a 166% growth in cycling traffic following targeted infrastructure investment [4]. Despite these gains, large disparities remain in how cities support cycling. Daily cycling rates range from 51% in the Netherlands [5] to less than 1% in Greece and Portugal [6], revealing a persistent implementation gap.

While cycling is increasingly prioritized in urban agendas, cities still lack rigorous tools to evaluate their progress or benchmark their cycling conditions against others. The most widely cited reference, the Copenhagenize Index[7], has not been updated since 2019 and relies on subjective expert judgment. Other indices are often qualitative or lack transparency, while academic approaches tend to focus on local case studies that are hard to scale. The BIKE Index addresses this gap by proposing a transparent, multi-dimensional, and reproducible methodology based entirely on open data.

2. Project Definition

The BIKE Index aims to provide both policymakers and researchers with a reliable, evidence-based tool to assess the level of bicycle integration in urban transport systems. The project pursues four objectives: to design a standardized index, build a fully open-data methodology, apply it to a city sample, and generate clear, comparable outputs.

To capture the multifaceted nature of bicycle integration, the index is structured around four core dimensions, as shown in Figure 1. **Cycling Infrastructure** evaluates the physical layout of the cycling network; **Cyclist Services** measures access to bike shops and shared mobility stations; **Environmental Constraints** considers natural factors such as topography and climate; and **Safety and Street Quality** captures cyclists' exposure to risk and the presence of traffic-calming measures.

The methodology was applied and validated in a sample of thirteen European capital cities, selected for their diversity in geography, size, and cycling maturity. Although developed and tested in this small sample, the BIKE Index is designed to be fully transparent, reproducible, and scalable, relying exclusively on a standardized workflow that can be applied to any city worldwide.

3. Description of the Methodology

The BIKE Index is based on a reproducible geospatial methodology that simulates urban cycling conditions through 210 representative routes per city. These routes model internal city movement and are generated using OpenRouteService. Along each route, attributes such as surface type, infrastructure presence, and slope are extracted. Additional data is obtained from Google Maps, Copernicus, E-OBS, and Eurostat databases.

These sources provide the basis for constructing nine indicators grouped into four dimensions:

1. **Cycling Infrastructure** includes: 1a, the proportion of route on dedicated bike lanes; 1b, the connectivity of the city's cycling network; and 1c, the efficiency of each route.

2. **Cyclist Services** covers: 2a, the access to repair shops and bike-related services; and 2b, the spatial coverage of bike-sharing stations.

3. **Environmental Constraints** includes: 3a, the influence of terrain topography; and 3b, the number of climatically unfavorable days.

4. **Safety and Street Quality** integrates: 4a, cyclist fatality rate; and 4b, the degree of street-level protection and traffic calming on the routes.

All indicators are normalized using the Median Absolute Deviation (MAD) z-score method, and then aggregated into a single composite score through weighted averaging.

4. Results

The BIKE Index was applied to thirteen European capital cities, generating composite and dimension-level scores that reveal substantial disparities in cycling conditions across the continent. Final scores range from 30.3 in Rome to 65.6 in Amsterdam, with cities like Paris and Copenhagen also ranking high, while Athens, Dublin, and Luxembourg fall toward the bottom. The analysis highlights a clear gap between cycling-leading cities and those with structural challenges.

Differences between cities are most pronounced in the Infrastructure and Safety dimensions. Infrastructure scores range from 18 to 83, reflecting uneven development of protected cycling networks. Safety scores are even more critical, with cities like Rome scoring 0, and Luxembourg achieving the highest score despite underperforming elsewhere. Service provision shows moderate variation, with Paris and Copenhagen leading in repair and bike-sharing access. Environmental constraints vary less overall, but penalize cities with steep terrain or adverse climates. These results enable clear benchmarking, expose policy gaps, and illustrate contrasting development strategies—such as Paris's service-led model versus Amsterdam's infrastructure-first approach.

These findings are illustrated in a set of representative visual outputs. Figure 2 shows the dimension-level breakdown for all cities. Figure 3 displays the complete cycling network in Stockholm. Finally, Figure 4 maps the bike-sharing stations density in Madrid.

5. Conclusion

The BIKE Index proves to be an effective tool for systematically assessing and comparing how cities support everyday cycling. The results show that infrastructure remains the strongest driver of cycling success, while supportive services, environmental constraints, and safety play complementary but critical roles. Cities such as Amsterdam and Paris demonstrate that different development strategies can both yield high scores. Meanwhile, cities like Madrid illustrate how balanced progress across dimensions can compensate for geographic limitations and deliver strong overall results.

The BIKE Index offers a scalable and transparent methodology built entirely on open data. Although the study is limited by data quality, city perimeter definitions, and the sample size, it lays the foundation for broader applications. Future research should extend the analysis to more cities, incorporate more dimensions, and track performance over time. As cities worldwide seek to decarbonize transport and improve urban livability, the BIKE Index provides a practical tool for guiding and measuring progress in cycling integration.

Creación y aplicación del BIKE (Bicycle Integration Key Elements) Index: Evaluando la Integración de la Bicicleta en Ciudades Europeas

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Resumen del Proyecto

Esta tesis presenta el BIKE Index, un indicador compuesto diseñado para evaluar el nivel de adaptación de las ciudades europeas al uso de la bicicleta y comparar su nivel de adaptación al uso cotidiano del transporte ciclista. El índice se estructura en torno a cuatro dimensiones: —infraestructura ciclista, servicios al ciclista, condicionantes ambientales y seguridad, las cuales se concretan en nueve indicadores agregados en una única puntuación por ciudad. La metodología empleada se basa íntegramente en fuentes de datos abiertas y en un conjunto estandarizado de 210 rutas simuladas por ciudad. El resultado es una herramienta transparente, reproducible y escalable que permite realizar comparaciones consistentes de las condiciones del ciclismo urbano a escala global, facilitando la planificación y evaluación de políticas públicas fundamentadas en evidencia.

Palabras clave: Movilidad, bicicleta, indicador compuesto, ciclismo, infraestructura, sostenibilidad, planificación urbana.

1. Introducción

Las ciudades europeas afrontan una presión sin precedentes para reducir en un 90% las emisiones del transporte de cara a 2050, tal y como dicta el Pacto Verde Europeo [1]. El transporte representa el 25% de emisiones en la Unión Europea y, a diferencia de otros sectores, su contribución sigue aumentando [2]. En este contexto, la bicicleta se ha consolidado como una solución clave, ofreciendo una alternativa con bajo coste económico y mínimo impacto ambiental. Las cifras más recientes confirman esta tendencia: el número de personas que se desplazan al trabajo en bicicleta aumentó un 57% en los Países Bajos entre 2024 y 2025 [3], y París ha registrado un crecimiento del 166% en el tráfico unipersonal tras una gran inversión en infraestructura [4]. No obstante, persisten grandes desigualdades: la tasa de uso diario de la bicicleta alcanza el 51% en los Países Bajos [5], mientras que en países como Grecia y Portugal apenas supera el 1% [6], lo que evudencia una brecha entre las aspiraciones políticas y su implementación práctica.

Pese al creciente protagonismo de la bicicleta en las agendas urbanas, las ciudades siguen careciendo de herramientas rigurosas para evaluar su progreso o comparar objetivamente sus condiciones ciclistas. El principal referente, el Copenhagenize Index [7], no se actualiza desde 2019 y se basa en evaluaciones subjetivas realizadas por expertos.

Otros índices tienden a ser cualitativos o poco transparentes, mientras que los enfoques académicos se centran habitualmente en estudios de casos locales difíciles de replicar a gran escala. El BIKE Index aborda esta necesidad mediante una metodología transparente, multidimensional y reproducible, basada exclusivamente en datos abiertos.

2. Definición del Proyecto

El BIKE Index desea proveer a entes públicos y a la investigación de una herramienta fiable y cuantitativa para evaluar el grado de integración de la bicicleta en los sistemas de transporte urbano. El proyecto persigue cuatro objetivos principales: diseñar un índice estandarizado, desarrollar una metodología íntegramente basada en datos abiertos, aplicarla a una muestra de ciudades y generar resultados visuales y comparables.

Con el fin de reflejar la naturaleza multifacética de la integración ciclista, el índice se estructura en torno a cuatro dimensiones principales, como se muestra en la Figura 1. La dimensión de **Infraestructura Ciclista** evalúa la disposición física de la red de carriles bici; **Servicios al Ciclista** mide el acceso a talleres, tiendas especializadas y sistemas de bike-sharing; **Condicionantes Ambientales** considera factores naturales como la topografía y el clima; y **Seguridad y Calidad Vial** refleja la exposición al riesgo y la presencia de medidas de calmado de tráfico.

La metodología fue aplicada y validada en una muestra de trece capitales europeas, seleccionadas por su diversidad geográfica, tamaño y cultura ciclista. Aunque se ha desarrollado y testado en este conjunto reducido de ciudades, el BIKE Index está diseñado para ser plenamente transparente, reproducible y escalable, basándose en un flujo de trabajo estandarizado aplicable a cualquier ciudad del mundo.

3. Descripción de la Metodología

El BIKE Index se basa en una metodología geoespacial que simula las condiciones reales del ciclismo urbano mediante 210 rutas representativas por ciudad. Estas rutas modelan los desplazamientos internos dentro del área urbana y se generan a través de OpenRouteService. A lo largo de cada trayecto se extraen atributos como la vía o la pendiente del terreno. Información adicional se obtiene de las bases de datos de Google Maps, Copernicus, E-OBS y Eurostat.

Estas fuentes permiten construir nueve indicadores, agrupados en cuatro dimensiones:

1. **Infraestructura Ciclista**: incluye 1a, la proporción del recorrido que transcurre por carriles bici; 1b, la conectividad de la totalidad de la red ciclista; y 1c, la eficiencia de cada ruta en comparación con la distancia más corta.

2. **Servicios al Ciclista**: abarca 2a, el acceso a talleres y servicios relacionados con la bicicleta; y 2b, la cobertura de estaciones de bicicleta compartida.

3. **Condicionantes Ambientales**: incluye 3a, la influencia de la topografía del terreno; y 3b, el número de días climáticamente desfavorables.

4. **Seguridad y Calidad Vial**: integra 4a, la tasa de mortalidad ciclista; y 4b, el grado de protección vial y presencia de medidas de calmado de tráfico.

Todos los indicadores se normalizan mediante el método de z-score basada en la Desviación Absoluta Mediana (MAD), y se agregan posteriormente en una única puntuación compuesta utilizando promedios ponderados.

4. Resultados

El BIKE Index fue aplicado a trece capitales europeas, generando puntuaciones compuestas y por dimensión que revelan importantes disparidades en las condiciones para el ciclismo urbano. Las puntuaciones finales oscilan entre 30.3 (Roma) y 65.6 (Ámsterdam), con ciudades como París y Copenhague también en las primeras posiciones, mientras que Atenas, Dublín y Luxemburgo se sitúan en la parte baja del ranking. El análisis muestra una brecha clara entre las ciudades líderes en ciclismo y aquellas que enfrentan desafíos estructurales.

Las diferencias más marcadas se observan en las dimensiones de Infraestructura y Seguridad. Las puntuaciones de infraestructura varían entre 18 y 83, reflejando el desarrollo desigual de redes ciclistas protegidas. Las de seguridad son aún más críticas: Roma obtiene una puntuación de 0, mientras que Luxemburgo alcanza el valor más alto pese a su bajo rendimiento en otras dimensiones. La oferta de servicios presenta una variación moderada, con París y Copenhague destacando por su acceso a sistemas de bicicleta compartida. Por su parte, los condicionantes ambientales muestran menos variación, aunque penalizan a ciudades con orografía pronunciada o clima adverso. Estos resultados permiten establecer comparaciones claras y evidenciar estrategias urbanas contrapuestas, como el modelo basado en servicios de París frente al enfoque centrado en infraestructura de Ámsterdam.

Estos hallazgos se ilustran mediante una serie de salidas visuales representativas. La Figura 2 muestra los resultados por dimensión para todas las ciudades. La Figura 3 presenta la red ciclista completa en Estocolmo. Por último, la Figura 4 recoge la densidad de estaciones de bicicleta compartida en Madrid.

5. Conclusiones

El BIKE Index ha demostrado ser una herramienta eficaz para evaluar y comparar de forma sistemática cómo las ciudades fomentan el uso cotidiano de la bicicleta. Los resultados indican que la infraestructura sigue siendo el principal motor del éxito ciclista, mientras que los servicios, las condiciones ambientales y la seguridad desempeñan un papel complementario pero igualmente crucial. Ciudades como Ámsterdam y París demuestran que diferentes estrategias de desarrollo pueden conducir a buenos resultados. Por su parte, casos como el de Madrid muestran cómo un progreso equilibrado en todas las dimensiones puede compensar limitaciones geográficas y dar lugar a resultados sólidos.

Aunque el estudio presenta limitaciones en cuanto a la calidad de los datos, la definición de los perímetros urbanos y el tamaño de la muestra, sienta las bases para futuras aplicaciones más amplias. Investigaciones posteriores deberían ampliar el análisis a más ciudades, incorporar nuevas dimensiones y realizar un seguimiento temporal de los resultados. En un contexto global donde las ciudades buscan descarbonizar el transporte y mejorar su habitabilidad, el BIKE Index se perfila como una herramienta útil para guiar y medir el avance en la integración de la bicicleta.

Bibliography

1. European Commission. *Urban Mobility and Accessibility.* `https://commission.europa.eu/eu-regional-and-urban-development/topics/cities-and-urban-development/priority-themes-eu-cities/urban-mobilityand-accessibility_ro`. Accessed on June 28, 2025. 2025.

2. European Environment Agency. *Sustainability of Europe's Mobility Systems.* `https://www.eea.europa.eu/en/analysis/publications/sustainability-of-europes-mobility-systems`. Accessed on June 28, 2025. 2023.

3. EU Urban Mobility Observatory. *Cycling to work on the rise in the Netherlands: 57% increase in one year.* `https://urban-mobility-observatory.transport.ec.europa.eu/news-events/news/cycling-work-rise-netherlands-57-increase-one-year-2025-06-02_en`. Accessed on June 28, 2025. 2025.

4. European Cyclists' Federation. *European cities are improving cycling for citizens.* `https://www.ecf.com/en/news/european-cities-are-improving-cycling-for-citizens/`. Accessed on June 28, 2025. 2025.

5. Cycling Industry News. *Netherlands further builds on cycling's modal share, hitting 51% in Utrecht.* `https://cyclingindustry.news/netherlands-further-builds-on-cyclings-modal-share-hitting-51-in-utrecht/`. Accessed on July 6, 2025. 2024.

6. João Monteiro et al. "The Potential Impact of Cycling on Urban Transport Energy and Modal Share: A GIS-Based Methodology". *ISPRS International Journal of Geo-Information* 12 (Feb. 2023). doi: `10.3390/ijgi12020048`.

7. Copenhagenize Design Co. *Our Methodology.* `https://copenhagenizeindex.eu/about/methodology/`. Accessed on June 28, 2025. 2025.

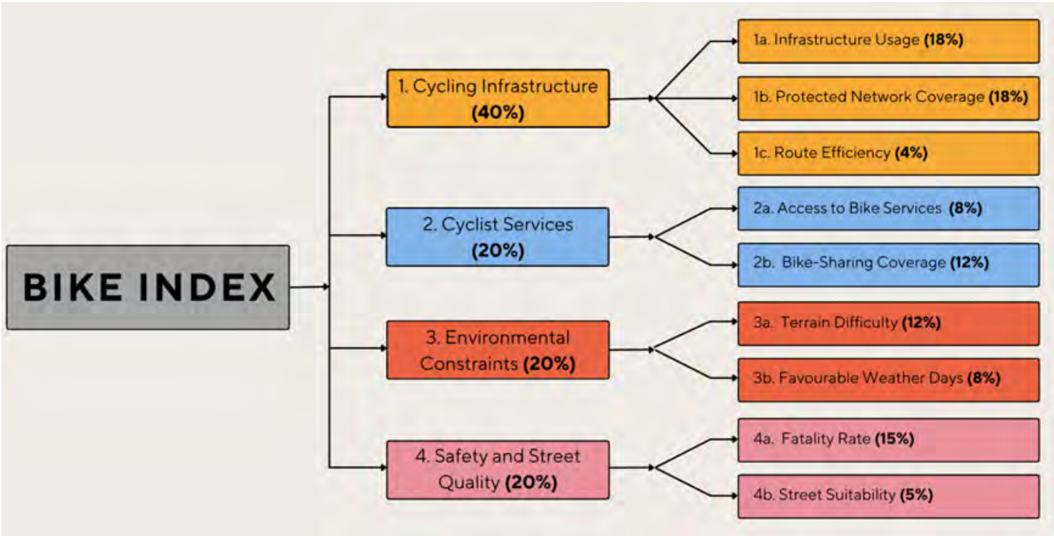

Figure 1: Hierarchical structure of the BIKE Index, comprising four dimensions and nine underlying indicators with their respective weights.

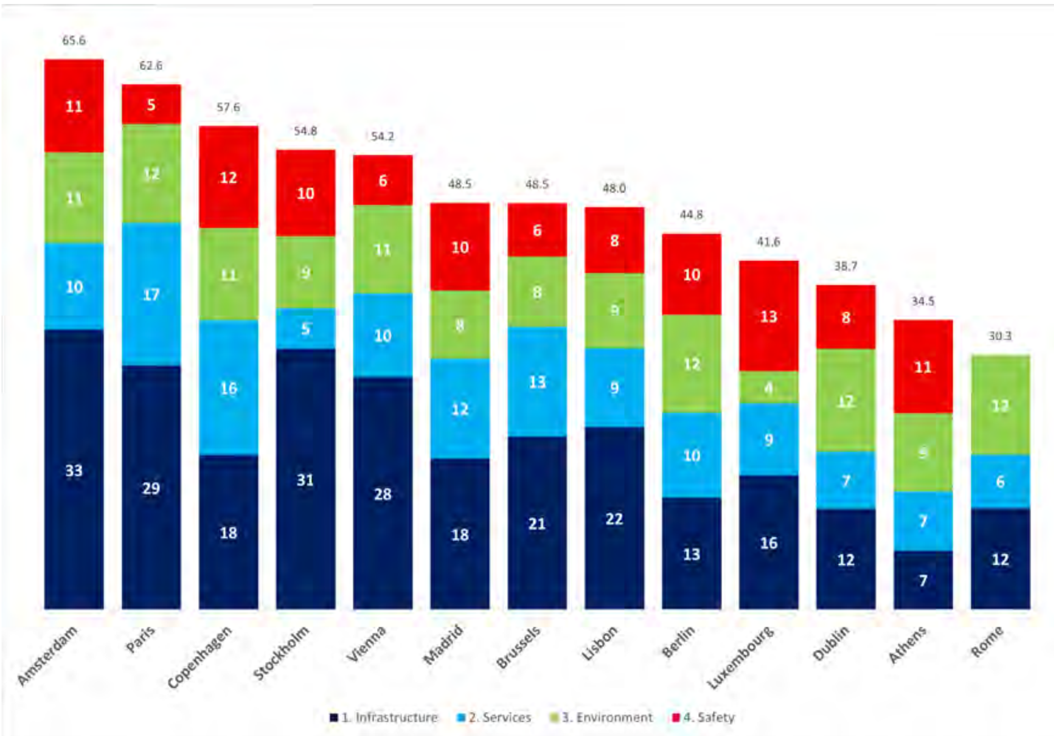

Figure 2: BIKE Index final scores by city, disaggregated into the four main dimensions: Infrastructure, Services, Environment, and Safety.

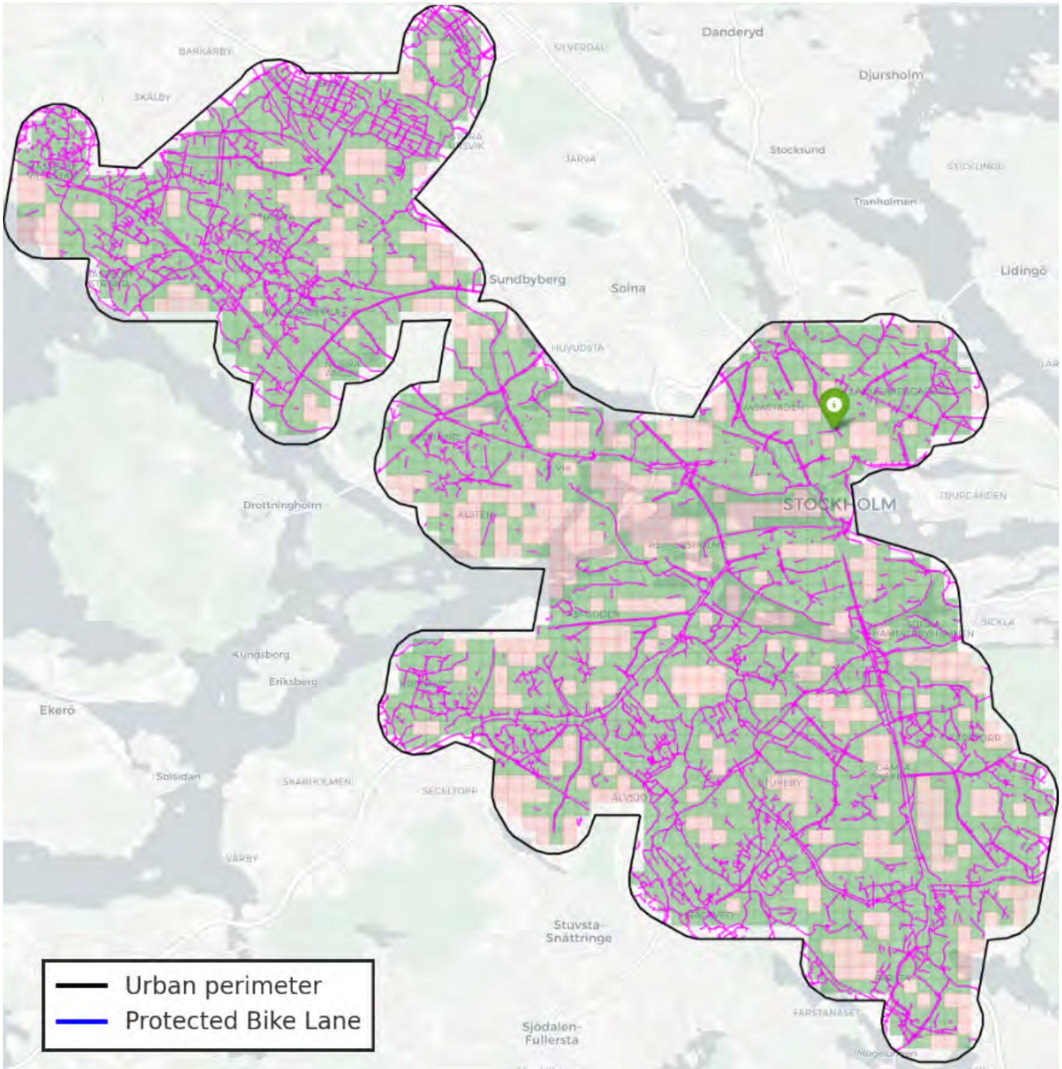

Figure 3: Results of indicator 1b for Stockholm, showing the urban perimeter and the protected cycling network.

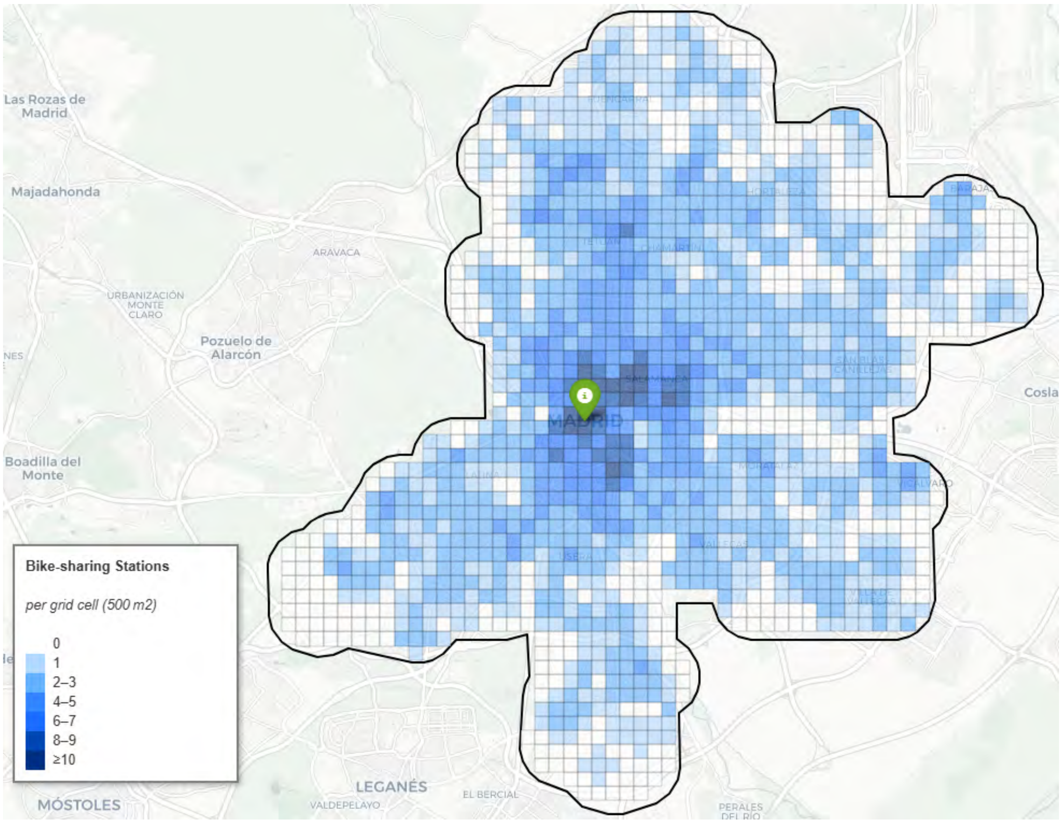

Figure 4: Results of indicator 2b for Madrid, showing the density of bike-sharing stations per $500m^2$ grid cell.

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Chapter 1

Introduction

1.1 Overall Context

European cities stand at a pivotal moment in urban transportation planning. With over 70% of EU citizens living in urban areas that generate 23% of all transport greenhouse gas emissions [1], the urgency for sustainable mobility solutions has never been more pressing. The European Green Deal seeks an ambitious 90% reduction in transport emissions by 2050 [8], positioning cycling as a cornerstone of this transformation [9]. Transport currently accounts for approximately 25% of the EU's greenhouse gas emissions, with these figures continuing to rise despite overall emission reductions across other sectors [2].

The momentum behind cycling as a sustainable transport solution is undeniable. Recent data shows remarkable growth trends: cycling to work in the Netherlands has increased by 57% in just one year (March 2024-2025) [3], while bike-sharing systems across Europe have grown by 4% from 2016 to 2023 [10]. In Paris alone, cycling traffic has increased by 166% thanks to strategic political leadership and infrastructure investment [4]. This surge reflects a broader European recognition that cycling adds €150 billion annually to the European economy, with over €90 billion attributed to environmental, health, and mobility benefits [11].

However, the gap between ambition and implementation remains significant. Despite record funding—with over $800 million in state and local funding allocated to cycling projects in 2023 in the United States alone [12]—substantial disparities exist across European cities in their cycling infrastructure quality, safety conditions, and accessibility. The modal share of cycling varies dramatically between Northern and Southern Europe, ranging from 51% of Dutch citizens using bikes in their daily routine [5]to only 0-1% in Greece and Portugal [6]. Cities investing in cycling infrastructure are experiencing huge increases in bike use [13], yet many urban areas lack the systematic assessment tools necessary to guide evidence-based policy decisions.

The research and policy communities increasingly acknowledge that promoting cycling effectively requires rigorous, data-driven evaluation frameworks. Traditional assessment methods often rely on qualitative judgments or focus on isolated factors, leading to limited comparability and constrained scalability. Moreover, differences in data collection standards and a lack of integration between databases hinder robust cross-city analysis. This fragmentation is particularly problematic given that urban mobility policies are often guided by legacy approaches grounded in expert intuition rather than systematic, quantitative evidence. [14]

The **BIKE Index** (Bicycle Integration Key Elements) is designed to fill this gap. It provides a standardized, transparent framework for evaluating urban cycling conditions across European cities. The index combines multiple dimensions—including infrastructure quality, safety, service accessibility, and environmental constraints—through the systematic analysis of over 200 cycling routes per city. Built entirely on open data and documented methods, the BIKE Index offers a reproducible tool that bridges academic research and practical policymaking, supporting cities in planning and prioritizing investments to strengthen everyday cycling conditions.

1.2 Motivation

The BIKE Index project emerges from both practical and academic motivations grounded in current gaps in urban mobility research and policymaking.

Methodological Gaps in Current Frameworks

From a practical perspective, European cities face growing pressure to demonstrate measurable progress toward climate and sustainability challenges, particularly in the transport sector. While cycling is recognized as a key component of reducing emissions, congestion, and unhealthy habits, many cities continue to plan and implement cycling infrastructure without standardized, data-driven evaluation tools. Existing assessment frameworks either focus on isolated elements—such as infrastructure length or safety statistics—or rely on subjective expert evaluations that lack transparency and reproducibility. The Copenhagenize Index [7], for instance, provided an influential benchmark but has not been updated since 2019, leaving a significant gap in current comparative knowledge of urban cycling conditions.

Beyond limitations in individual tools, there are broader challenges related to data harmonization and methodological consistency. Differences in data collection practices, incomplete integration of databases, and a lack of comparable indicators prevent researchers and policymakers from evaluating cycling conditions systematically across cities. This methodological gap is especially critical given the commitments of numerous European cities to climate neutrality targets and to serving as experimental hubs for sustainable mobility innovation.

Policy Development and Implementation Needs

There is also a clear research need for frameworks that combine methodological rigor with practical usability. Many academic studies offer in-depth local analyses but are not easily transferable across geographical contexts. Conversely, broader rankings often sacrifice precision and detail. The BIKE Index seeks to address these issues by developing a transparent, route-based assessment framework that integrates multiple dimensions—cycling infrastructure quality, safety conditions, service accessibility, and environmental constraints—using only open data sources and reproducible methods. In doing so, it provides a tool that can bridge the gap between academic research and urban policy planning.

Personal Motivation

On a personal level, this project reflects a long-standing interest in urban sustainability and planning. I have always been fascinated by how cities function—how infrastructure design, policy choices, and human behavior intersect to shape daily life. This curiosity has evolved into a practical motivation: I would like to live one day in a city where cycling to work is not only possible but safe, convenient, and supported by public policy. As a cycling enthusiast, I believe strongly in the role of bicycles as a viable mode of everyday transport, not just a leisure activity.

Working on the BIKE Index represents a small step toward making that vision a reality. By producing a rigorous, data-driven tool that helps governments and planners understand the real conditions of urban cycling, I hope this thesis can contribute to better decisions and more effective policies that put bicycles at the center of urban mobility planning. Beyond the technical challenge, the project is personally rewarding: it combines my interest in quantitative analysis with a topic I care about deeply, offering a chance to apply academic work to a problem with real-world impact.

1.3 Objectives

This thesis pursues four specific, measurable objectives that address identified gaps in cycling assessment methodologies and contribute to evidence-based urban planning practices.

1. **Design and validate a standarized methodology for assesing bikeability:** The first objective is to design and formalize the BIKE Index methodology, combining multiple assessment dimensions relevant to cycling into a single composite score. This involves defining the normalization and weighting procedures, ensuring that the index accurately reflects differences in urban cycling conditions, and validating the approach through statistical analysis of route-level data. The aim is to establish a robust framework that can serve as a foundation for comparative analysis across European cities.

2. **Build an open-data methodology for transparent analysis:** The goal here is to develop and implement a complete process—from data collection to indicator calculation—based entirely on public, open sources. This involves designing workflows to process and clean data from sources like OpenStreetMap and Eurostat, and structuring the data so that other researchers or practitioners can replicate the analysis or extend it to new cities. A key part of this objective is demonstrating that rigorous urban mobility evaluation is possible without relying on proprietary or closed datasets. Equally important is ensuring the interpretability of the BIKE Index's dimensions and sub-dimensions, which are designed to reflect real-world components of cycling conditions in a clear and intuitive manner. This makes the results actionable and suitable for decision-making, allowing urban planners, policymakers, and stakeholders to identify specific areas for improvement and compare progress across cities using a consistent and transparent framework.

3. **Demonstrate the policy relevance by applying the BIKE index to multiple European Cities:** Beyond purely technical development, the thesis seeks to show how the index can serve as a foundation for future policy work and comparative research. By analyzing strengths, weaknesses, and specific challenges in each city, the BIKE Index helps identify where public investment and planning efforts could be most effectively targeted. The ultimate goal is to bridge rigorous analysis with real-world decisions that improve urban conditions for everyday cycling.

4. **Generate comparative results and clear visual outputs for interactive comprehension of the indicator :** This objective centers on producing

rankings, indicator profiles, and visualizations that clearly communicate differences in cycling conditions. The work aims to not only build the index but also translate its outputs into accessible, practical information that can inform planning decisions, identify gaps in infrastructure or services, and highlight best practices that may be transferable between cities.

Chapter 2

Literature Review

Urban cycling has become a central focus in transportation research and policy discussions over the past two decades. As cities worldwide face rising challenges of traffic congestion, climate change mitigation, and public health concerns, the promotion of cycling emerges as a cost-effective, environmentally sustainable, and socially equitable solution. However, understanding how well cities support cycling—beyond anecdotal impressions or isolated statistics—requires rigorous and comparable measurement frameworks.

A substantial body of literature has developed various approaches to assess the *bikeability* or bicycle-friendliness of urban areas. These range from qualitative expert evaluations to quantitative network analyses using geospatial data. Despite this progress, existing indices and methodologies often exhibit significant limitations. Some frameworks emphasize infrastructure presence without examining its functional performance; others focus on user perceptions but lack spatial comparability; still others limit their scope to specific geographic regions or omit critical contextual factors such as topography or climate.

In contrast to this background, the BIKE Index proposes a new standard in cycling assessment. It combines high-resolution geospatial data, standardized route-based analysis, and a transparent methodology that integrates multiple dimensions of cycling conditions. This chapter reviews the main frameworks and indices that have shaped the field, identifies persistent gaps in current literature, and positions the BIKE Index as a response to those methodological challenges.

2.1 Review of Existing Methodologies

Over the past two decades, several prominent indices and frameworks have been developed to assess how well cities support cycling. These initiatives vary widely in their methodological approaches, geographic scope, and data sources.

The Copenhagenize Index

The Copenhagenize Index represents the most established and comprehensive global ranking system. First launched in 2011 and updated biennially until 2019, it evaluates cities based on fourteen parameters including bicycle infrastructure, facilities, traffic calming measures, modal share, gender balance, safety, advocacy, political commitment, bike-sharing systems, and urban planning practices [7]. The methodology emphasized holistic assessment, recognizing that bicycle friendliness extends beyond infrastructure to encompass political will, cultural acceptance, and safety metrics. While influential and widely cited, the Copenhagenize Index relies significantly on expert judgment and qualitative assessments, making its weighting methodology partially opaque and difficult to reproduce in academic research. Additionally, it has not been updated since 2019, leaving a gap in current comparative data.

PeopleForBikes City Ratings

The PeopleForBikes City Ratings represent a shift toward data-driven quantitative analysis. This framework evaluates cities using five key criteria: ridership, safety, network quality, network growth (acceleration), and network equity (reach) [15]. Its methodology centres on network connectivity and low-stress access to key destinations using data from OpenStreetMap and other public sources. While innovative in its approach and transparent in publishing its methodology and code, the City Ratings have been primarily applied to a limited number of countries, with a strong focus on North America. In contrast, the BIKE Index is designed for international comparability, enabling robust assessment across cities from different countries under a unified methodological framework.

Global Bicycle Cities Index by Luko

The Global Bicycle Cities Index by Luko, published in 2022, evaluated 90 cities globally across six categories: weather, bicycle usage rates, crime and safety, infrastructure quality, bike-sharing opportunities, and cycling awareness events [16]. Although broader in scope than some previous efforts, its methodology lacks detailed documentation and transparency, making it difficult to reproduce or adapt for detailed urban planning applications. Furthermore, today this study is non-existent, as Luko Insurance has been acquired by GetSafe [17].

Academic Approaches to Bikeability

The concept of *bikeability* has become central to evaluating urban cycling conditions. Winters et al. [18] established a foundational framework, developing a bikeability index based on factors such as facility availability and quality, street connectivity, topography, and land use. Their work produced high-resolution bikeability maps using widely available spatial data, making it adaptable across different urban contexts.

Hardinghaus et al. [19] expanded this approach by integrating multiple parameters through a multifactorial index weighted by expert surveys, combining empirical data and professional judgment to achieve realistic and transferable evaluations. Their research demonstrated that joint assessment of different parameters provides more realistic evaluations than analyzing individual components separately.

Weikl and Mayer [20] refined bikeability assessment further by distinguishing between local, route-wide, and network-wide indicators based on European design standards, enabling a nuanced view of network quality and connectivity.

Other academic studies have developed bikeability indices tailored to specific urban areas or used tools like Bicycle Level of Service (BLOS) [21] to evaluate segment-level conditions. While rigorous, these efforts often remain local in scope, highlighting the need for frameworks that enable broader, comparable analysis across cities. Although these studies provide robust methodologies, they frequently focus on specific contexts or prototypes and rarely support large-scale comparative analysis. Nonetheless, they establish critical theoretical foundations on the factors influencing bikeability—from street design to socio-demographic variables. A 2020 review by Kellstedt et al. [22] highlighted this diversity of approaches and underscored the need for globally transferable, open-data-based tools.

2.2 Limitations and Gaps in Existing Literature

Despite significant progress, the literature on cycling assessment continues to exhibit important methodological limitations that constrain its applicability and comparability across contexts.

- **Lack of Multi-Dimensional Integration:** Many existing frameworks focus on a single dimension—such as infrastructure length, safety statistics, or network connectivity—without integrating them into comprehensive composite indices. This limits their capacity to capture the complex, multifactorial nature of cycling environments, where infrastructure, safety, services, environmental conditions, and policy context all interact to shape cyclist experiences.

- **Limited Environmental Evaluation:** A persistent gap in much of the literature is the absence of systematic evaluation of environmental constraints, particularly topography and climate. These factors have been shown to significantly influence cycling behavior, yet are often treated as external variables or ignored altogether in standard bikeability assessments.

- **Spatial and Temporal Constraints:** Many methodologies remain constrained to specific urban areas or time periods, limiting their utility for broad cross-city comparisons or longitudinal monitoring. Some indices rely on static data snapshots or case studies, rather than reproducible methods that can be updated and applied consistently across multiple cities and years.
- **Deficit in Cross-City Comparability:** Differences in data sources, measurement scales, and weighting schemes make direct comparison between cities difficult in many existing frameworks. This undermines the potential of cycling assessment tools to inform policy or benchmarking at broader scales.
- **Dependence on Subjective Data and Scalability Issues:** Several indices depend on expert judgment, perception surveys, or qualitative evaluations, which can introduce biases and limit replicability. In addition, methods that require extensive manual data collection or processing are difficult to scale to larger datasets or multiple cities simultaneously.

These limitations highlight the need for integrated, reproducible, and scalable frameworks that combine multiple dimensions using objective, publicly available data sources—addressing the complexity of urban cycling environments while supporting systematic comparison across contexts.

2.3 Contribution of the BIKE Index

The BIKE Index introduces several methodological innovations that directly address gaps identified in previous literature.

- **Route-Based, Data-Driven Methodology:** Unlike approaches that rely solely on static network mapping or abstract connectivity metrics, the BIKE Index employs a route-based methodology. It generates a standardized set of simulated cycling routes per city using tools like the OpenRouteService API [23]. This allows extraction of detailed segment-level attributes—including waytype classification, surface conditions, slope categories, and suitability scores—capturing actual cycling conditions along recommended paths rather than theoretical network properties.
- **Integration of Environmental and Service Factors:** The BIKE Index uniquely incorporates environmental constraints (such as slope-induced effort and climatic conditions) and service-related indicators (like accessibility to

bike shops and bike-sharing stations). These dimensions are often missing or treated superficially in other indices, yet are crucial determinants of practical bikeability across diverse urban contexts.

- **Standardization and Comparative Normalization:** The methodology establishes a uniform framework for data collection, normalization, weighting and aggregation. Indicators are normalized against theoretical or empirical reference values, ensuring comparability between cities regardless of size, morphology, or baseline cycling conditions. This systematic approach tries to address longstanding challenges of cross-city comparability and standardization seen in earlier work.

- **Reproducible, Open, and Comprehensive Framework:** The BIKE Index is built entirely on open data sources and employs documented, transparent procedures. The use of high-resolution spatial analysis (e.g., 500-meter urban grids) enables fine-grained assessment and mapping of cycling conditions within cities, supporting both research reproducibility and practical planning applications. This contrasts with many previous indices that relied on proprietary data, expert judgment, or closed methodologies.

In sum, the BIKE Index contributes an integrated, scalable, and rigorously documented framework that advances the state of the art in urban cycling assessment.

Framework	Main Characteristics	Strengths	Limitations
Copenhagenize Index	Combines infrastructure, culture, and policy factors with qualitative expert assessment.	Holistic view; widely cited benchmark.	Subjective weighting; limited transparency; outdated since 2019.
PeopleForBikes City Ratings	Data-driven focus on network connectivity and equity, primarily North American cities.	Transparent methodology; open tools.	Initially limited European coverage; emphasis on network structure over environment.
Winters et al. (2013)	High-resolution bikeability surfaces based on five factors (facility, connectivity, topography, land use).	Adaptable; visual mapping supports planning.	Local case studies; limited cross-city comparability.
Hardinghaus et al. (2021)	Multifactorial index using expert weighting and open geodata.	Integrates multiple parameters; transferable.	Requires expert input; model validation needed.
Weikl and Mayer (2023)	Differentiates local, route, and network-wide indicators based on European guidelines.	Nuanced assessment; data-driven.	Depends on data quality; scope local.
BIKE Index	Route-based assessment integrating infrastructure, services, environment, and safety using open data.	Multi-dimensional; reproducible; high spatial resolution; standardized normalization.	Currently applied to European cities; further expansion needed.

Table 2.1: Comparison of Major Cycling Assessment Frameworks

Chapter 3

Structure of the Composite Index

3.1 Dimensions and Indicators

The BIKE Index is structured around four core dimensions that collectively provide a comprehensive assessment of urban cycling conditions. This framework was designed to be both mutually exclusive—ensuring no overlap between dimensions—and collectively exhaustive, capturing all fundamental aspects that influence cycling viability in urban environments. Each dimension addresses a distinct component of the cycling experience, from the physical infrastructure available to cyclists to the environmental constraints they face.

Figure 3.2 and Figure 3.3 are presented at the end of the chapter to illustrate the internal structure of the index: a hierarchical diagram displaying the dimensions and their associated indicators, and a sunburst chart visualizing the relative weights assigned to each component.

Theoretical Foundation and Weighting Rationale

The weighting methodology follows established principles for composite indicator construction, balancing theoretical soundness with practical applicability. The allocation prioritizes infrastructure as the foundational element while ensuring equal representation of other critical dimensions. This approach aligns with OECD guidelines that recommend weighting schemes based on "analytical soundness, measurability, and relevance to the phenomenon being measured" [24].

The framework distributes weights as follows: Cycling Infrastructure receives the highest allocation at 40%, reflecting its documented role as the primary determinant of cycling uptake [25]. The remaining three dimensions—Cyclist Services, Environmental Constraints, and Safety and Street Quality—each receive equal weight at 20%, simplifying interpretation while acknowledging their collective importance for comprehensive cycling assessment.

3.1.1 Dimension 1: Cycling Infrastructure (40%)

Cycling infrastructure forms the backbone of any cycling-friendly city, providing the physical foundation that enables safe, convenient, and attractive bicycle mobility. This dimension receives the highest weight based on overwhelming empirical evidence demonstrating that infrastructure quality is the strongest predictor of cycling uptake and safety outcomes. Research consistently shows that infrastructure has the highest weights in bikeability models, with studies reporting coefficients as high as 0.75 [26]. The seminal work by Schoner and Levinson found that "connectivity and directness are important factors in predicting bicycle commuting," with network density showing the strongest relationship to cycling rates [27]. Similarly, studies across European cities demonstrate that "cities investing in cycling infrastructure are experiencing huge increases in bike use" [28].

1a – Infrastructure Usage (18%)

This indicator measures the share of route segments that pass through cycling-friendly infrastructure, providing a user-centered perspective on infrastructure accessibility. It receives the highest weight in the composite indicator (along with Indicator 1b) as it most directly reflects the cyclist's experience of infrastructure quality and continuity.

1b – Protected Network Coverage (18%)

This indicator evaluates the spatial distribution of dedicated cycling infrastructure across the urban territory, capturing how well protected cycling facilities reach different neighborhoods. Similarly to Indicator 1a, it is considered to be one of the two most important factors to bikeability.

1c – Route Efficiency (4%)

While geometric efficiency affects cycling convenience, it receives reduced weight as empirical evidence suggests that safety and protection are more influential factors in cycling decisions than route directness [29]. The lower allocation reflects that cyclists often accept longer routes if they provide better safety and comfort conditions.

3.1.2 Dimension 2: Cyclist Services (20%)

This dimension captures the supporting infrastructure that enables practical bicycle use, focusing on maintenance services and flexible access options. The equal 20% weight with other non-infrastructure dimensions reflects the growing recognition that cycling promotion requires ecosystem-level support beyond dedicated lanes. Services are important for convenience and accessibility, especially in emerging cycling cities. They are less critical than infrastructure or safety, but increasingly present in modern indices [30].

2a – Access to Bike Services (8%)

Measuring access to bike repair shops and retail services, this indicator reflects the maintenance infrastructure necessary for bicycle ownership and use. Research indicates that access to maintenance infrastructure has been shown to influence bicycle ownership, perceived reliability, and overall frequency of use [31].

2b – Bike-Sharing Coverage (12%)

This indicator receives a higher weight within the dimension based on evidence that bike-sharing systems have significant impact on cycling modal share and public perception. Studies show that bike sharing schemes have been shown to increasing cycling modal share in areas with low cycling uptake [32]. The higher allocation reflects bike-sharing's role in building cycling culture and providing accessible entry points for new cyclists.

3.1.3 Dimension 3: Environmental Constraints (20%)

Environmental factors represent structural conditions that influence cycling feasibility but cannot be easily modified through policy interventions. This dimension does not directly inform decision-making or policy prioritization, but it provides essential context for interpreting infrastructure performance and cycling uptake across different geographic settings. By accounting for these fixed constraints, the indicator ensures fairer comparisons between cities and avoids penalizing those facing unfavorable terrain or climate conditions.

3a – Terrain Difficulty (12%)

Topographical constraints receive higher weight as they represent immutable geographic barriers that fundamentally shape cycling accessibility. Research demonstrates that hilly terrain is known to reduce cycling uptake, influence route choice, and affect perceived accessibility [29]. Unlike climate, terrain cannot be mitigated through infrastructure adaptations, making it a more fundamental constraint.

3b – Favourable Weather Days (8%)

While climate affects cycling behavior, it receives lower weight because infrastructure and policy interventions can partially mitigate weather impacts through covered facilities, maintenance protocols, and complementary services. Studies show that weather sensitivity varies significantly based on infrastructure quality and cycling culture development [33].

3.1.4 Dimension 4: Safety and Street Quality (20%)

Safety concerns consistently rank as the top barrier to cycling adoption [34], making this dimension critical for comprehensive assessment. The equal weight with services and environmental factors reflects safety's fundamental importance while recognizing that it intersects with infrastructure quality.

4a – Fatality Rate (15%)

This indicator receives higher weight as it provides objective, empirical data on actual cycling risk based on systematic exposure measurement. Studies emphasize that exposure-adjusted crash rates are equally essential for international comparisons and for setting local planning priorities [35]. Objective data provides more reliable comparative basis than subjective assessments.

4b – Street Suitability (5%)

While important for capturing nuanced infrastructure quality, this indicator receives lower weight as it represents inferred rather than directly observed safety outcomes. Research shows that cyclists' safety may be biased when assessed by objective measures only but notes that subjective measures can be influenced by factors beyond actual risk [36].

3.2 Sample Cities and Reproducibility

The BIKE Index was applied to thirteen European capital cities: Amsterdam, Athens, Berlin, Brussels, Copenhagen, Dublin, Stockholm, Lisbon, Luxembourg, Madrid, Paris, Rome, and Vienna. These cities were selected to represent diverse geographic, climatic, and urban contexts across Europe, enabling a robust comparative analysis of cycling conditions.

While this sample provides valuable insights into European cycling infrastructure, services, environmental constraints, and safety, the BIKE Index methodology is designed for global reproducibility. The framework relies exclusively on:

- Open data sources (OpenStreetMap, OpenRouteService, Copernicus, etc.)
- Transparent computational workflows
- Standardized spatial analysis techniques

As such, the index can be applied to any city worldwide where comparable open geospatial and statistical data are available. This flexibility ensures the BIKE Index serves as a scalable tool for researchers, planners, and policymakers seeking evidence-based cycling assessments beyond the initial sample.

For full transparency and reproducibility, all scripts used to calculate the indicators are included in Appendix A, structured and annotated by phase and dimension.

3.3 Normalization Methodology

3.3.1 Need for Normalization

The construction of a composite indicator requires the integration of multiple individual dimensions that often exhibit different scales, units, and distributions. Without proper normalization, indicators with larger numerical ranges would disproportionately influence the final composite score, leading to misleading results and compromised comparability across cities.

In the BIKE Index, this challenge is particularly pronounced given the diverse nature of the component indicators. For instance, the cyclable infrastructure coverage indicator (see Section 4.1.1) produces values ranging from 6.9% to 73.7%, while the slope-induced effort indicator (see Section 4.3.1) generates scores between 0 and 0.81. Similarly, safety metrics such as exposure-adjusted fatality rates (see Section 4.4.1) span from 0.2 to 5.1 deaths per 100 million kilometers cycled. Without normalization, an indicator like fatality rate would be systematically underweighted compared to coverage percentages, distorting the composite assessment.

Moreover, the presence of outliers in several indicators compounds this issue. Cities with extreme values—such as Luxembourg's 25-fold difference in slope effort compared to Amsterdam (Section 4.3.1), or Athens' minimal cycling infrastructure coverage (Section 4.1.1)—would skew traditional normalization methods like min-max scaling, compressing the meaningful variation among non-extreme cities into narrow ranges.

3.3.2 Selection of Normalization Method

After evaluating multiple normalization approaches, including min-max scaling, standard z-score normalization, and robust scaling methods, the Modified Z-Score normalization using Median Absolute Deviation (MAD) was selected as the optimal method for the BIKE Index. This choice is grounded in several methodological and practical considerations specific to the characteristics of our indicator dataset [24].

The Modified Z-Score method addresses the critical limitation encountered with min-max normalization during preliminary analysis: sensitivity to extreme outliers. Traditional min-max scaling proved inadequate when confronted with the substantial range variations we observed in this study in indicators such as cycling safety (25-point differences) and bike-sharing coverage (near-zero values versus 100% coverage). These extreme values would concentrate the distribution of non-outlier cities into narrow bands, obscuring meaningful differences in cycling conditions. Figure 3.1 visualizes the difference between min-max scaling and z-score using MAD.

The Modified Z-Score approach uses the median and Median Absolute Deviation (MAD) instead of the mean and standard deviation employed in traditional z-score normalization. This substitution provides several advantages aligned with the requirements of composite indicator construction:

- **Robustness to outliers:** The median and MAD are resistant statistics that remain stable even when extreme values are present, ensuring that normalization parameters accurately reflect the central tendency and dispersion of the majority of observations rather than being distorted by outliers.

- **Theoretical foundation:** The method is well-established in the statistical literature on robust normalization [18] [37] and is specifically recommended by the OECD and European Commission guidelines for composite indicator construction when dealing with non-normal distributions or extreme values [24].

3.3.3 Mathematical Formulation

The Modified Z-Score normalization follows a two-step process for each indicator:

Step 1: Calculate the Modified Z-Score

For each indicator i with observed values $x_1, x_2, \ldots, x_n$ across the n cities, the *Modified Z-Score* is computed as shown in Equation 3.1:

$$Z_i^* = 0.6745 \times \frac{x_i - \mathrm{median}(x)}{\mathrm{MAD}} \tag{3.1}$$

where:

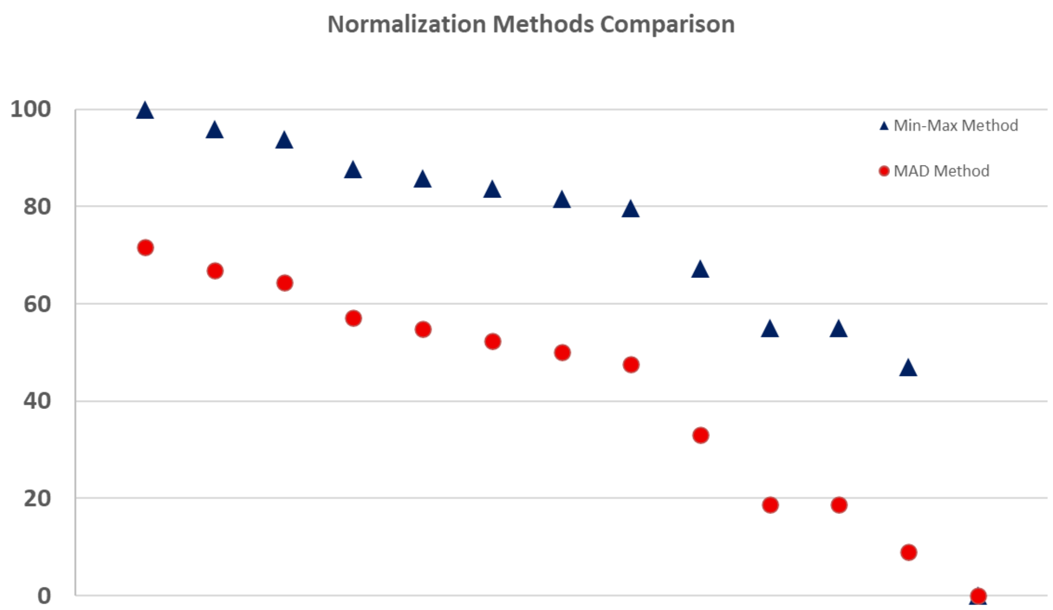


Figure 3.1: Comparison of Normalization Methods: Min-Max vs MAD z-score

- median(x) is the median value of the indicator across all cities,
- MAD is the Median Absolute Deviation, calculated as shown in Equation 3.2:

$$\text{MAD} = \text{median}(|x_i - \text{median}(x)|) \tag{3.2}$$

- The constant 0.6745 adjusts the MAD to be comparable to the standard deviation under a normal distribution, making Z_i^* comparable with traditional z-scores. This number is used because, for a normal distribution, the 75th percentile is at $z = 0.6745$.

Step 2: Transform to 0–100 Range

To bound the scores and make them suitable for composite indicator aggregation, each modified z-score is transformed as follows in Equation 3.3:

$$N_i = \frac{Z_i^* + k}{2k} * 100 \tag{3.3}$$

where $k = 2$ is used to approximate the range ± 2 standard deviations. This ensures that most values fall within the $[0, 100]$ interval while preserving the relative differences among cities. Any result that falls outside this range will be considered an outlier and bounded to this $[0, 100]$ range.

This systematic approach ensures methodological consistency across all dimensions of the BIKE Index while maintaining the interpretability and comparability essential for cross-city analysis. The normalized indicators can then be aggregated using the weighting scheme described in Section 3.1 to produce the final composite scores.

3.3.4 Advantages and Limitations

The Modified Z-Score normalization provides several methodological advantages for the BIKE Index. Its robustness to outliers ensures that cities with extreme values—whether exceptionally high-performing or severely constrained—do not distort the normalization parameters for the broader sample. This characteristic is particularly valuable given the diverse cycling development stages represented across European capitals. Additionally, the method maintains the relative distances between cities more faithfully than min-max scaling in the presence of outliers, preserving meaningful differentiation among cities with intermediate performance levels.

However, certain limitations must be acknowledged. The choice of k = 2 for the range transformation, while statistically grounded, introduces a degree of arbitrariness that could affect the final composite scores. Cities with Modified Z-Scores exceeding ± 2 may be compressed toward the bounds of the 0-1 scale, potentially underestimating their true relative position. However, in our sample, this only happened to 3 (out of the 117) results. Furthermore, the method assumes that the underlying indicator distributions, while potentially skewed, remain sufficiently concentrated around the median to make MAD-based scaling appropriate.

Despite these limitations, the Modified Z-Score approach represents the most suitable normalization method for the BIKE Index given the characteristics of the indicator dataset and the requirements of robust composite indicator construction. The method successfully addresses the outlier sensitivity issues encountered with alternative approaches while maintaining the theoretical rigor and transparency essential for academic research and policy application.

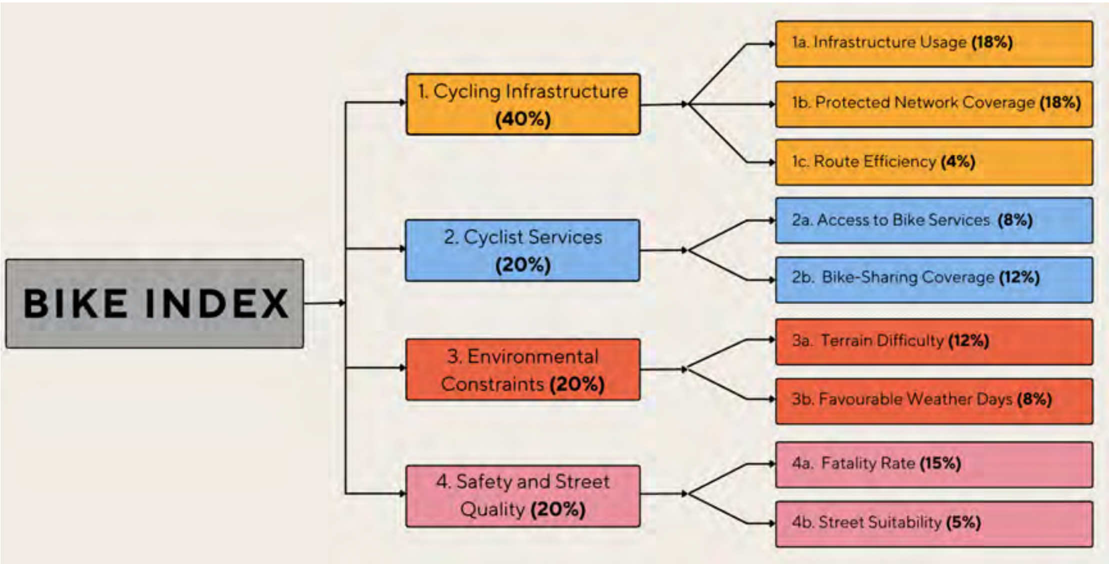


Figure 3.2: Hierarchical structure of the BIKE Index, showing the four dimensions and their corresponding indicators.

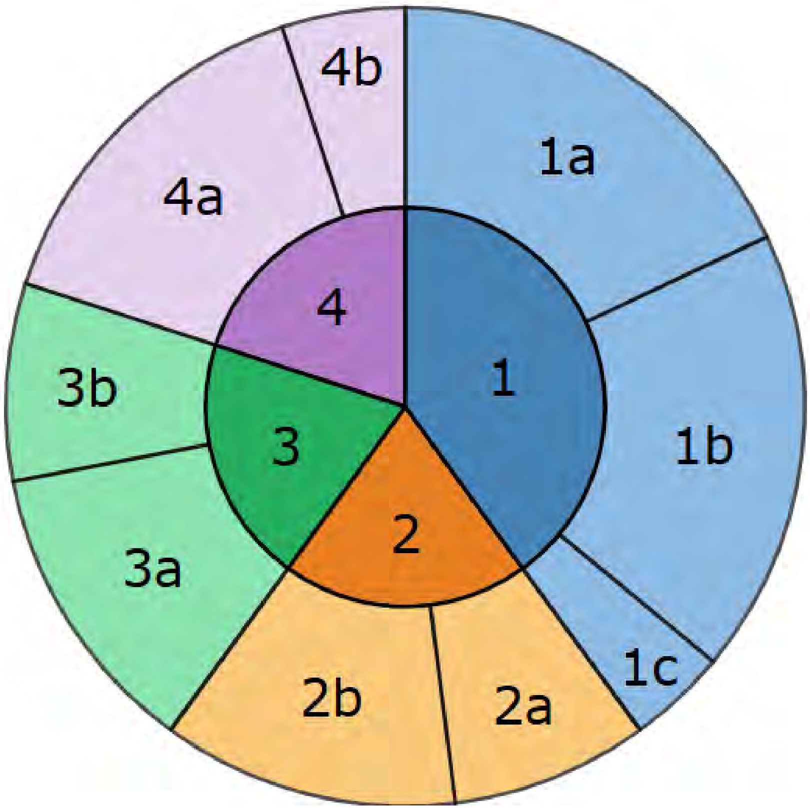


Figure 3.3: Visual representation of the relative weights assigned to each dimension and indicator within the BIKE Index.

Chapter 4

Methodology

4.0 Methodology common for all indicators

Before presenting the individual indicators that compose the BIKE Index, it is essential to explain the common methodological foundations that apply to all cities and across all dimensions of analysis. These procedures define how each urban area is spatially delimited, how routes and proximity are computed, and how urban territory is divided into comparable analytical units. Without a consistent baseline, cross-city comparisons would be unreliable, and indicator results could be misleading due to differences in spatial extent, data resolution, or measurement scale.

This section presents the shared steps that precede and support the indicator-specific calculations:

1. The construction of a unified urban perimeter.

2. The generation of cardinal cycling routes.

3. The creation of a $500m^2$ analytical grid over each city.

These spatial layers serve as the structural backbone of the index, ensuring that every indicator is evaluated using a harmonized and equitable spatial framework.

4.0.1 Urban Area Delimitation

Accurate delimitation of the urban area is essential for consistent and comparable analysis across cities. Since all indicators in this study rely on spatial interactions—whether based on street segments, cycling routes, or service coverage—the definition of a common and realistic perimeter is a foundational step.

To achieve this, we implemented a two-stage methodology combining administrative boundaries with population density data:

1. Administrative Reference Perimeter

First, the official *administrative perimeter* was obtained using the *Core City Boundaries* layer provided by Copernicus Urban Atlas [38]. These boundaries correspond to Local Administrative Units (LAU level) and are widely used in European spatial analysis due to their standardization, legal validity, and direct alignment with municipal governance structures [39].

2. Density-based Adjustment

Administrative boundaries alone are not always a faithful representation of the actual inhabited urban fabric. In cities such as Madrid or Rome, the LAU perimeter includes large uninhabited areas—such as natural parks, reservoirs, or agricultural zones—that are irrelevant for active mobility planning. To correct this, we applied a refinement procedure based on population density, using the Global Human Settlement Layer (GHSL) population raster at 1000ṁ resolution, downloaded from the Copernicus Emergency Management Service [40, 41]. Density-based refinement follows Freire et al. (2016) [42], where population is redistributed using built-up land cover to exclude non-residential zones.

Specifically, we:

1. Selected raster tiles with population density greater than 1000 inhabitants/km^2, a threshold consistent with definitions of urban concentration zones in Europe [43].

2. Clipped the selected high-density areas to the LAU perimeter using spatial intersection.

3. Merged the resulting geometries into a single polygon using a unary union operation. Only the largest contiguous area was retained to avoid fragmented peripheries; this choice was validated case by case to ensure no relevant zones were not taken into account.

4. A morphological smoothing operation was applied: a negative buffer of 1500m followed by a positive buffer of the same size, using projection EPSG:3857 to ensure metric accuracy. This process effectively eliminated narrow protrusions ("spikes" or "horns") from the geometry while preserving the core shape of the inhabited area. The buffer size was verified: tests across multiple cities showed that this value consistently removed geometric artefacts without eroding meaningful urban territory.

   This step is crucial to avoid bias in the simulated bike routes presented in Section 4.0.2, since sharp angles or isolated corridors at the boundary could

distort routing patterns, travel distances, or infrastructure proportions.
Figure 4.2 shows a comparison of the urban perimeter before and after applying the smoothing procedure, highlighting how unwanted geometric irregularities that could affect the study are removed without altering the overall urban extent.

The result is a **curated urban perimeter** that better represents the actual urban core relevant to cycling mobility. This geometry, saved as GeoJSON in EPSG:4326, was used as the spatial boundary for grid generation, routing calculations, and service coverage in all subsequent indicators.

In a few cases, the standard procedure based on single LAU units was not sufficient to capture the actual urban core of the city. For instance, *Dublin* and *Athens* do not have a unique LAU that fully encompasses the central urban fabric. Instead, their functional urban areas are composed of multiple adjacent administrative districts. In these cases, a manual composition was performed by merging a predefined set of relevant sub-units—such as *North Inner City* and *South East Inner City* for Dublin, or *Central Athens*, *West Athens*, and *Piraeus* for Athens—based on Eurostat's definition of "Core Cities" [44].

Similarly, *Brussels* presents a case of fragmented governance and overlapping jurisdictions. Although the metropolitan region is composed of multiple LAU units (municipalities), the urban perimeter was limited to the most central and densely populated units to ensure analytical consistency. In all such cases, the selection criteria followed Eurostat's Core City definition, prioritizing the spatial extent of the municipal core over the broader metropolitan region.

A visual comparison between the administrative boundary and the final curated perimeter for Madrid is shown in Figure 4.1.

Finally, the curated perimeter was discretized into 30 equidistant points along its boundary. This allowed the generation of origin–destination pairs for simulated bike routes across the urban space (see Section 4.0.2).

Limitations

A major limitation in any cross-city urban analysis is the lack of a consistent and universal definition of "city perimeter" across Europe. While some municipalities—such as Berlin—are governed as unified metropolitan units, others—such as Paris—consist of a relatively small administrative core surrounded by dozens of densely populated suburban communes that operate independently. As a result, the analytical perimeter of Berlin covers over 1500km^2, while that of Paris remains restricted to just its core (202.88km^2), as shown in Figure 4.3, despite both urban areas hosting similar population sizes and functional footprints. This structural asymmetry leads to unavoidable biases when comparing indicators related to infrastructure density, service coverage, or average route length.

Throughout this work, we have attempted to minimize size-related distortions by focusing on densely inhabited zones and applying a uniform population density threshold (1000inhab/km^2) for all cities [43]. The smoothing and fragment removal steps also aimed to eliminate non-urban artefacts, especially in edge cases. However, it is important to note that some indicators—such as coverage percentages—are inherently sensitive to the spatial extent defined. Efforts to mitigate this through normalization and relative metrics have had good results, but perfect comparability is not always attainable [45].

For transparency, Table 4.1 shows the final curated perimeter area and length for all cities included in the index.

City	**Area (km^2)**	**Perimeter Length (km)**
Berlin	1574.57	287.71
Stockholm	582.71	178.83
Vienna	535.86	132.53
Rome	458.19	179.48
Athens	451.12	120.44
Madrid	421.52	110.31
Amsterdam	384.97	125.86
Brussels	324.85	85.26
Dublin	274.97	89.24
Copenhagen	248.10	71.16
Paris	202.88	54.04
Lisbon	106.86	42.13
Luxembourg	57.97	30.90

Table 4.1: Curated urban perimeter area and length for the 13 cities included in the BIKE Index.

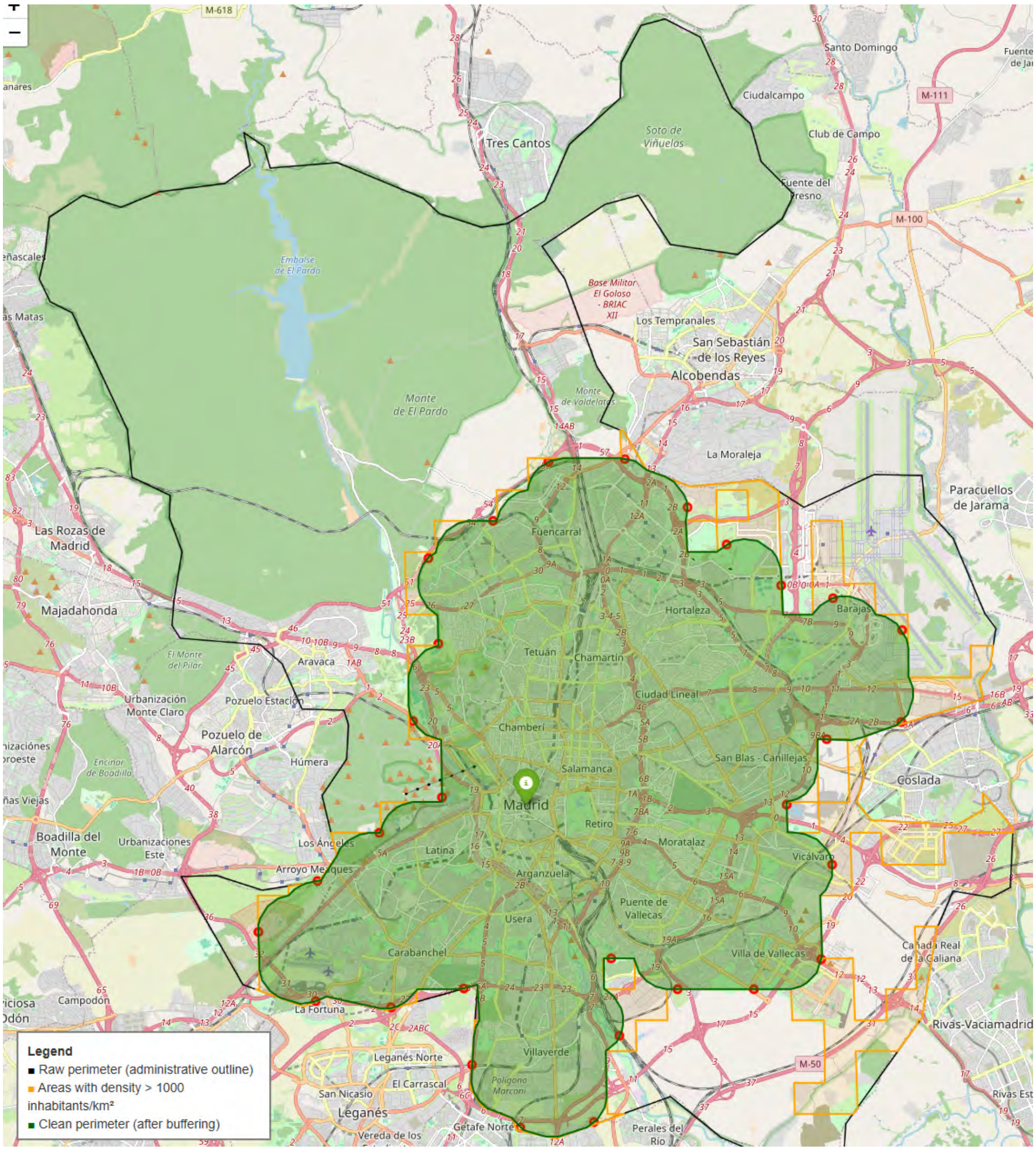


Figure 4.1: Comparison between administrative, high-density, and clean urban perimeters for Madrid.

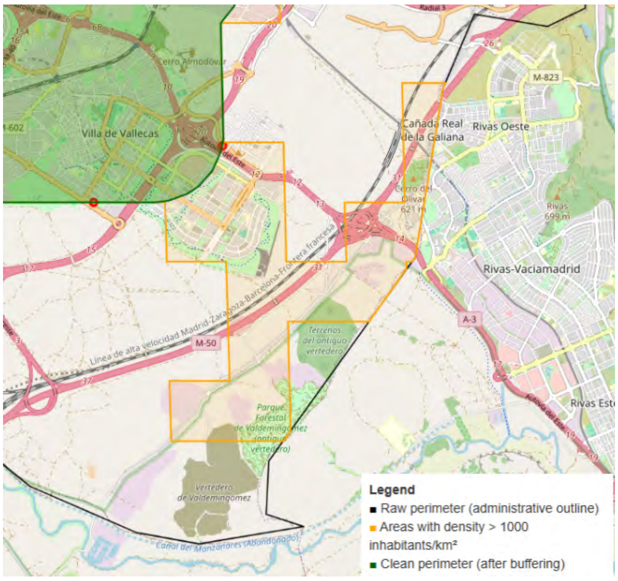


Figure 4.2: Effect of morphological smoothing on the urban perimeter - Example of Cañada Real in Madrid *(detail)*.

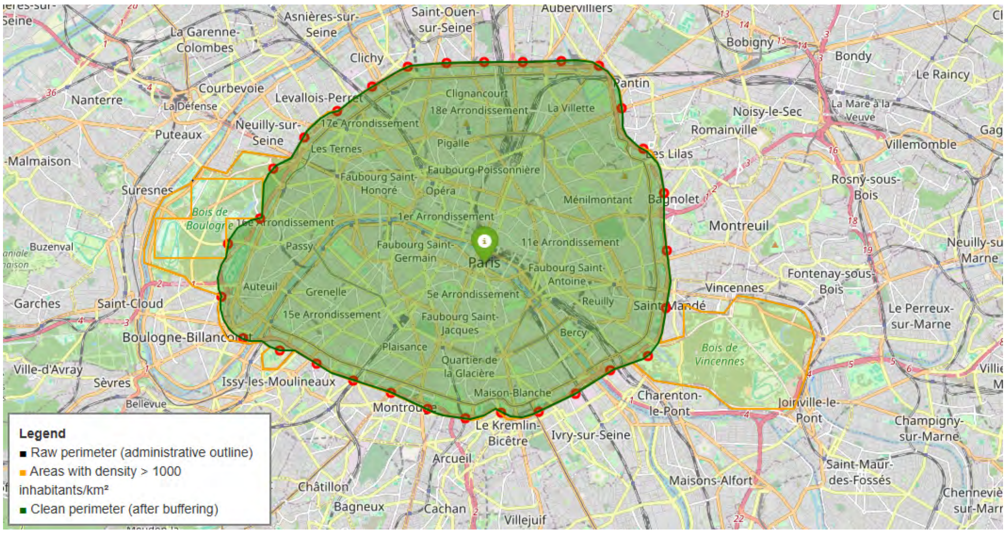


Figure 4.3: Perimeter for Paris used in following sections.

4.0.2 Route Network Design

To analyze cycling infrastructure and accessibility in a spatially realistic and methodologically consistent way, this study simulates urban bicycle mobility through a standardized set of routes for each city. Rather than relying on abstract network metrics or arbitrary origin–destination pairs, the method generates concrete, georeferenced cycling routes that represent plausible everyday journeys under typical conditions.

The route network is constructed using 30 equally spaced points along the curated urban perimeter (see Section 4.0.1 and Figure 4.1). These points are distributed with uniform geodesic spacing, ensuring full coverage of the urban edge without clustering or directional bias. Each point serves as an origin for seven simulated routes, resulting in a total of 210 routes per city. This number was chosen to balance spatial representativeness and computational feasibility, following similar scales used in mobility modeling literature [46, 47].

The seven routes per point follow two primary patterns of urban movement:

- **Radial mobility:** Four routes are directed inward from each perimeter point toward central destinations, mimicking typical commutes for work, education, or services.
- **Tangential mobility:** Three routes connect the origin to other points on the perimeter, located at angular offsets of 90°, 180°, and 270°, capturing circumferential flows across districts.

To generate radial routes, a secondary circle of interior points is created around the city center. These 30 points are aligned angularly with their respective perimeter counterparts, ensuring that each radial route follows a consistent heading (e.g., toward 0°, 90°, 180°, or 270°). The radius of this inner circle is defined as:

$$r_{\text{inner}} = \max\left(\frac{1}{2}\min_i\left(d(c, p_i)\right),\ 1.5\text{km}\right) \tag{4.1}$$

where $d(c, p_i)$ is the geodesic distance between the city center c and each perimeter point p_i. This ensures that the inner circle remains fully contained within the urban area, even in cities with asymmetric geographies (e.g., Lisbon or Stockholm), and avoids collapsing all destinations into a central cluster.

The diagram presented in Figure 4.4 illustrates the route generation scheme described above. From each of the 30 perimeter points, seven routes are created: three toward opposite points on the outer perimeter (90°, 180°, 270° offsets) and four toward the inner circle (0°, 90°, 180°, 270°). Combined with the 30 evenly distributed exterior points, this approach yields a highly connected route network that ensures broad coverage across the city.

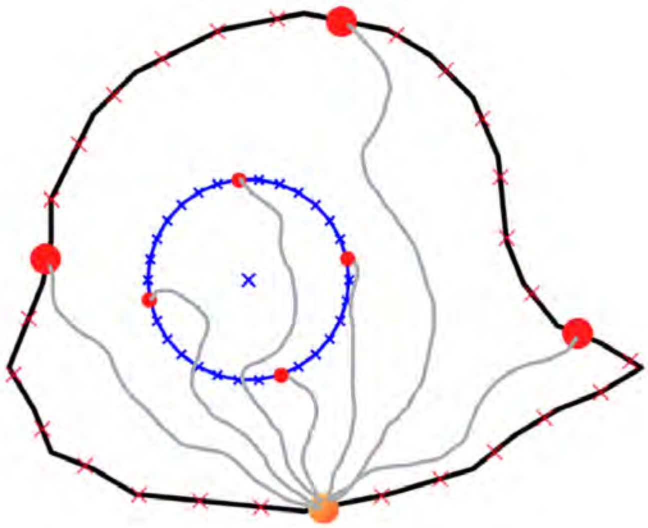


Figure 4.4: Schematic representation of the seven cardinal routes generated from 1 of the 30 perimeter points.

All routes are calculated using the OpenRouteService (ORS) API, a widely used open-source platform for geospatial routing and transport modeling [23]. The `cycling-regular` profile is selected to prioritize realistic bicycle recommendations based on infrastructure, slope, road hierarchy, and traffic rules.

In addition to the route geometry, the API provides detailed segment-level metadata via its `extra_info` endpoint. These properties are obtained using the ORS extra information endpoint, as documented in the official API specification [48]. This ensures that the resulting routes reflect both the structure and the conditions of real-world cycling infrastructure. The data includes:

- `steepness`: Categorical slope intensity.
- `waytype`: Infrastructure type (e.g., dedicated bike lane, residential street).
- `waycategory`: Road classification (e.g., local, collector, primary).
- `surface`: Pavement quality.
- `suitability`: Overall cycling suitability index (0 to 1).

These attributes form the empirical foundation for multiple indicators in this study, including effort estimation (Section 4.3.1) or infrastructure quality (Section 4.1.1), between others.

Although most routes are successfully generated, any route targeting a destination with no valid nearby segment in the cycling network is discarded.

Figure 4.5 and Figure 4.6 show the complete set of 210 generated routes for Berlin and Vienna. The resulting pattern reveals a diverse and realistic mesh of urban trajectories, combining radial flows with lateral connections across the city. This synthetic but empirically grounded network is used as the input base for all subsequent indicators. The green circle may appear distorted due to differences in vertical and horizontal scaling during map rendering, but it is geometrically circular in the original coordinate system.

Limitations

Although this method provides a consistent and reproducible mobility model, several simplifications and biases must be acknowledged. Most notably, the fixed design of 30 perimeter points and 210 total routes may under-represent the complexity of mobility patterns in very large or poly-centric cities.

A more structural limitation stems from the origin–destination design: all routes begin at the urban edge and lead either to the center or to other perimeter locations. This configuration inherently focuses traffic on main radial corridors, which—although realistic for long-distance trips—means that many inner neighborhoods, especially those located far from both the center and the perimeter, may not be intersected by any route. This spatial bias may exclude certain urban zones from direct evaluation. However, the design choice was deliberate: by emphasizing cross-city connections, the model captures the routes that most cyclists would use to traverse the city, thereby reflecting the actual performance of strategic cycling infrastructure.

Finally, while the ORS API provides rich segment-level metadata, its accuracy is dependent on the underlying quality of OpenStreetMap data, which may vary across regions [49].

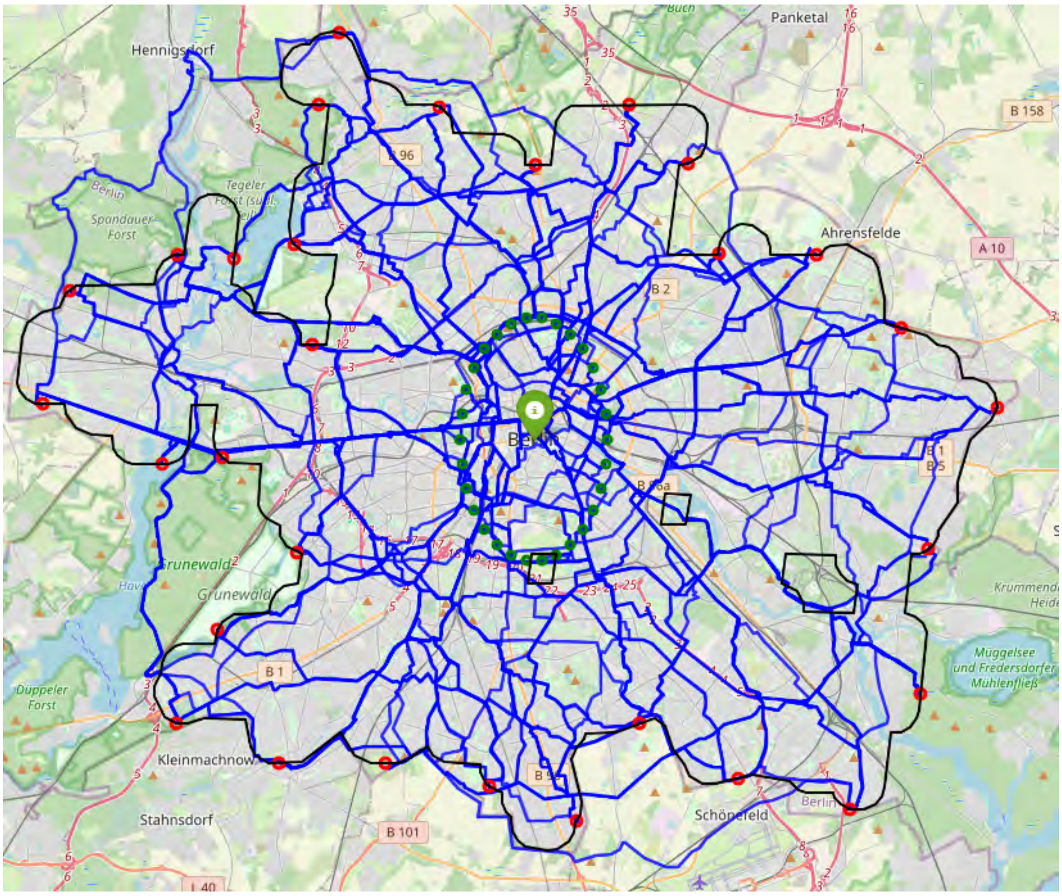


Figure 4.5: Full set of 210 generated cycling routes in Berlin, combining perimeter-perimeter and perimeter-center connections.

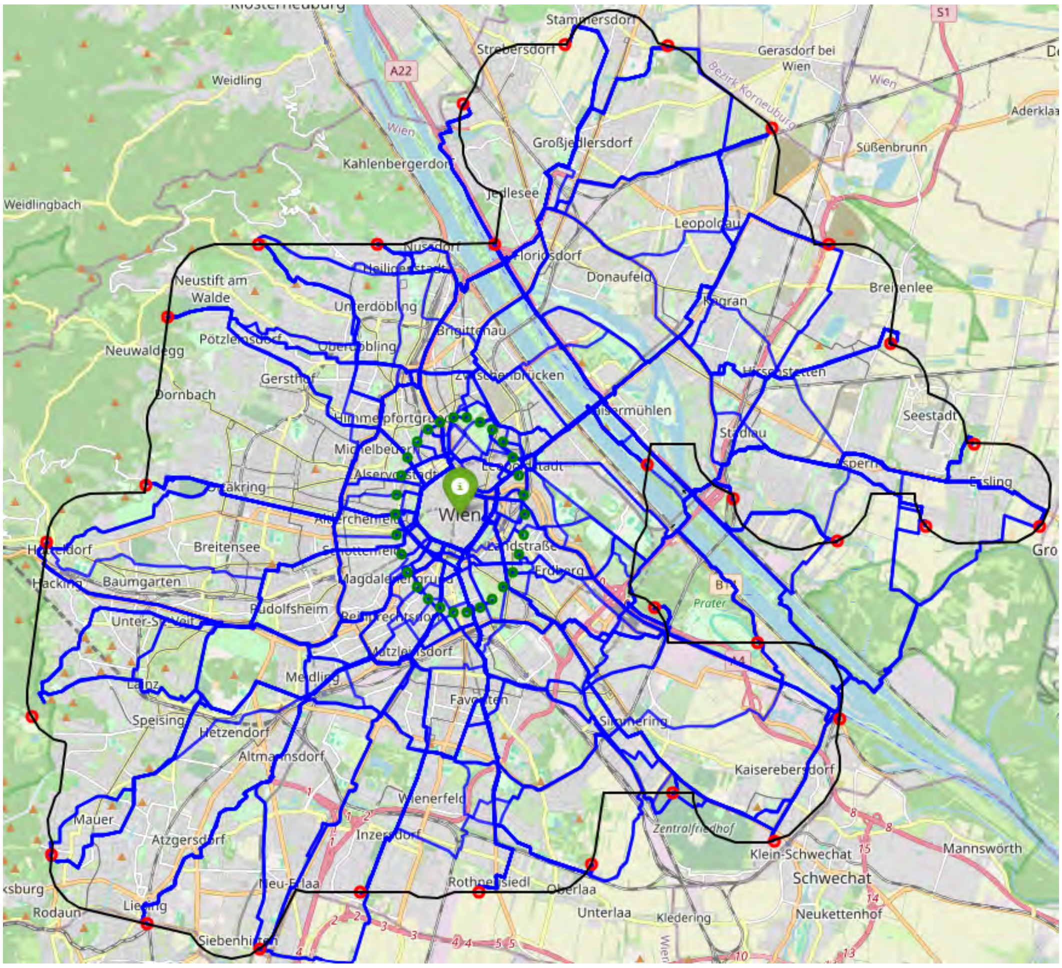


Figure 4.6: Full set of 210 generated cycling routes in Vienna, combining perimeter-perimeter and perimeter-center connections.

4.0.3 Generation of the Urban Grid

To spatially quantify proximity-based cycling indicators, a regular grid of 500-meter tiles is generated over each city's curated urban perimeter. This grid serves as the analytical framework for evaluating infrastructure coverage, service density, and local accessibility. Each tile approximates a walkable unit of urban space, allowing indicators to capture whether services or cycling facilities are present within a reasonable distance.

The tile size—$500m^2$—is selected based on established thresholds in urban planning literature, which commonly define this distance as a comfortable 5–7 minute walk for most users [50, 51]. This granularity ensures a realistic and human-centered representation of urban proximity, aligned with the scale of daily mobility.

Technically, the process consists of the following steps:

1. The curated urban perimeter (see Section 4.0.1) is projected into a metric coordinate system (EPSG:3857) to guarantee accurate distances.

2. A rectangular bounding box is calculated, and square tiles of 500 meters are generated across its full extent. Only tiles that fall entirely within the perimeter are retained, ensuring analytical consistency.

3. The grid is reprojected to geographic coordinates (EPSG:4326) and saved as a GeoJSON file for further spatial analysis and map visualization.

The decision to retain only those tiles that are entirely enclosed within the curated urban perimeter is a deliberate methodological constraint. This approach ensures that all spatial analysis is conducted within the limits of valid and consistently available data. Since all geospatial inputs—cycling routes, service locations, and infrastructure attributes—have been collected or computed strictly within each city's defined urban boundary, extending the grid beyond this perimeter would introduce unsupported and potentially misleading results. Tiles that only partially intersect the perimeter may fall outside the known dataset coverage and thus cannot be reliably assessed. While this decision slightly reduces spatial coverage at the edges of each city, it guarantees analytical consistency and prevents the inclusion of incomplete or unverifiable observations.

The result of the grid for the city of Lisbon can be visualized in Figure 4.7

Limitations

While the 500-meter til size provides a human-scale unit of analysis, it introduces certain biases across cities of varying size. In particularly extensive cities such as Berlin or Rome, the total number of tils is much higher than in compact urban cores like Lisbon or Luxembourg. As many indicators are calculated as a percentage of grid tils with coverage, larger cities are implicitly penalized: even with substantial absolute infrastructure or services, the relative proportion of covered tils tends to be lower. This reflects a real spatial constraint—the greater difficulty of achieving high proximity across vast urban areas—but also limits comparability between cities with significantly different urban morphologies.

Alternative approaches, such as using variable til sizes based on total area, were considered. However, the 500-meter resolution was retained for all cities to maintain conceptual consistency with pedestrian-scale accessibility thresholds widely supported in the literature [50, 51]. This ensures that "proximity" retains a stable and interpretable meaning across contexts.

Finally, it should be noted that the exclusion of tils that only partially intersect the urban boundary results in a slight underestimation of total coverage near the city edges. This is a conservative design choice made to avoid including areas beyond the perimeter where no route, climate, or service data are available.

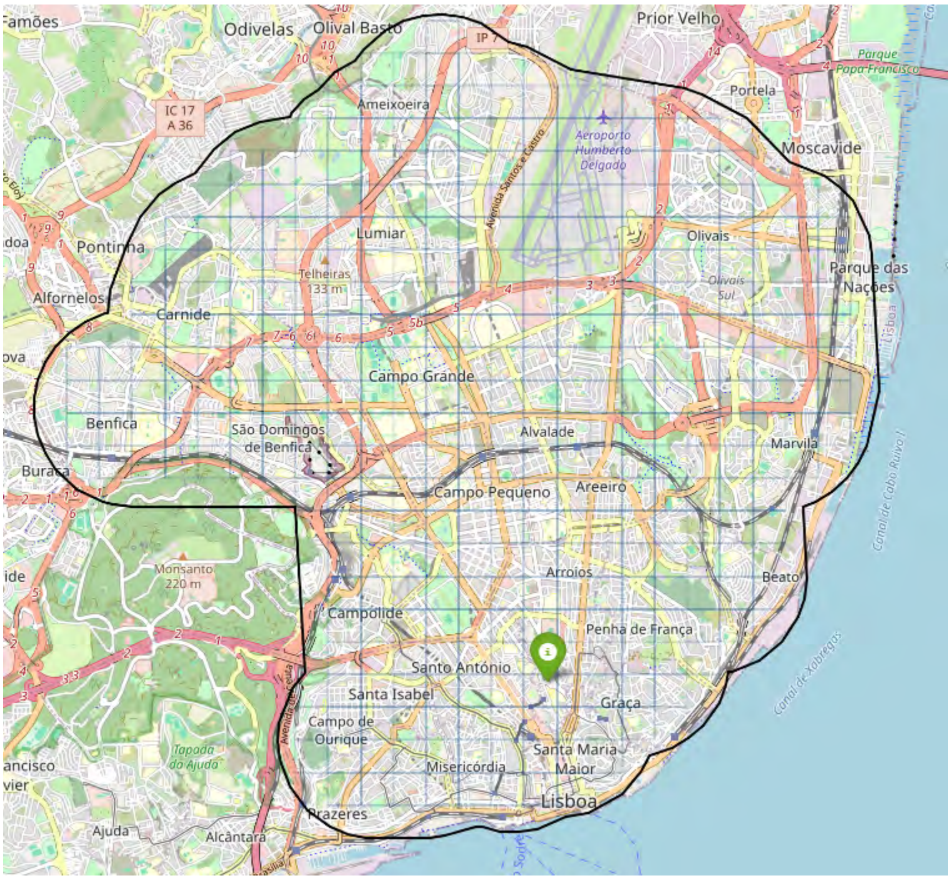


Figure 4.7: Example of 500 m urban analysis grid over the city of Lisbon.

4.1 Dimension 1 – Cycling Infrastructure

This dimension evaluates the physical and spatial characteristics of the dedicated cycling network in each city. It focuses on how much infrastructure is available, how well it is distributed and connected across the urban area, and how efficiently it supports direct movement.

The analysis is structured around three complementary indicators:

- Indicator1.a measures the percentage of each route that runs on cycling-friendly infrastructure
- Indicator1.b evaluates how well the infrastructure covers the city and whether it forms a connected network
- Indicator 1.c assesses how direct cycling routes are compared to straight-line distance

Together, these indicators offer a robust overview of the structural quality of cycling infrastructure: from its sheer presence to its spatial deployment and real-world performance in route planning.

4.1.1 Indicator 1.a – Infrastructure Usage

Methodology

This indicator evaluates the effective coverage of cyclist-friendly infrastructure across the city's recommended route network. It aims to measure not just the existence of cycling infrastructure, but its practical presence along the routes that a typical cyclist might use. This approach recognises that infrastructure must be usable, continuous, and safe to effectively support everyday cycling.

The theoretical foundation for this indicator lies in the growing consensus that high-quality cycling infrastructure is a key enabler of sustainable mobility. Numerous studies highlight how the availability, design, and continuity of dedicated lanes, tracks, and shared paths directly influence modal choice, especially for new or cautious cyclists [51, 52]. As such, the indicator focuses not only on quantity but on functional accessibility, aligning with cyclist-centered urban design principles [53].

The methodology is based on the set of 210 radial routes described in Section 4.0.2, which connect equidistant points along the urban perimeter. These routes are computed using the `cycling-regular` profile of the OpenRouteService (ORS) API, which prioritises safety and infrastructure continuity for cyclists. Each route is decomposed into segments, and each segment is classified using ORS's waytype metadata, which reflects the underlying road or path type [54].

To quantify the share of infrastructure suitable for cycling, all segments are grouped into four categories, as defined by OpenStreetMaps (OSM) documentation [55, 56, 57]. In addition, each segment is weighted according to its level of suitability for cycling:

- **Dedicated bike lanes**, typically physically segregated or clearly marked. They receive full weight (*1.0*), reflecting their safety and clarity.
- **Paths and tracks**, such as park trails or rural connectors with low traffic. They are weighted at *0.8*.
- **Shared footways**, where cyclists are legally allowed to ride in pedestrian zones. Shared footways receive a lower weight of *0.5* due to potential conflicts with pedestrians.
- All other segments—such as main roads, stairs, or unclassified routes—are considered non-cyclable for the purposes of this indicator, and are weighted at 0.0.

The different weights are informed by literature on infrastructure typologies and cyclist comfort, allowing the indicator to account for qualitative differences in the cycling environment.

The final score is calculated as the ratio between the weighted sum of segment distances and the total route distance. Formally, if d_i denotes the length of segment i, and w_i its corresponding weight, the indicator is computed as shown in Equation 4.2:

$$\text{Infrastructure Usage} = \frac{\sum d_i \cdot w_i}{\sum d_i} \cdot 100 \tag{4.2}$$

The result is a continuous score between 0 and 100, with higher values indicating broader and higher-quality coverage of infrastructure suitable for cycling. This formulation ensures consistency across cities and enables comparative assessment based on actual network usability, not just infrastructure mapping.

Results

When applied to the set of thirteen European capitals, the indicator reveals sharp differences in the effective quality of cycling infrastructure. Amsterdam and Stockholm lead the ranking with scores of 73.7% and 71.9%, respectively, due to the overwhelming predominance of dedicated cycleways in their networks (over 69% of route distance). Vienna and Paris also perform well, albeit with slightly more heterogeneous networks. In Vienna's case, 6.5% of the network consists of paths and tracks, while in Paris, the strong performance is partially offset by segments along higher-traffic roads.

Lisbon marks a turning point, with a score of 39.6%. Although over one third of its network is made up of cycleways, this is diluted by a high proportion of streets and roads not considered bike-friendly. From Luxembourg downwards, the indicator drops below 40%. In Luxembourg's case, 17.5% of the infrastructure corresponds to paths, a typology that receives a lower weight due to comfort and continuity concerns. Similarly, Brussels, Madrid, and Copenhagen show a relatively high presence of marked or visually identifiable infrastructure, but much of it lies on streets or general-purpose roads without cyclist priority.

The lower end of the ranking includes Berlin, Rome, and Athens. These cities fall below 30%, with Berlin scoring just 25.8% despite having a visible cycling culture. The key issue lies in the predominance of shared footways and road segments that do not meet the criteria for safe cycling infrastructure. Athens ranks last with only 6.9% of infrastructure deemed cyclist-friendly. More than 85% of the routes in Athens traverse regular streets or major roads, indicating a lack of formal support for urban cycling.

These results highlight not only the quantity of infrastructure available, but also the typology that composes it. Cities like Amsterdam and Stockholm achieve high scores through the continuity and dominance of segregated cycleways, while others rely heavily on lower-quality infrastructure types that reduce the overall usability and comfort of the network.

The full results of this indicator are provided in Figure 4.8, which shows the breakdown of infrastructure types and the weighted score for each city. In addition, Figure 4.9 and Figure 4.10 offer a visual comparison between two extreme cases: Amsterdam and Athens. The analysis was implemented in Python using publicly available tools and APIs, and the full codebase is available in the project repository for reproducibility and audit purposes.

Limitations

This type of analysis, while powerful, also carries important limitations. First, the indicator reflects only the infrastructure found along the predefined radial routes. It does not capture internal or peripheral cycling corridors that may serve local traffic. Second, the classification of segments depends on OpenRouteService metadata, which in turn relies on the quality and completeness of OpenStreetMap data. In cities where OSM tagging is inconsistent or outdated, the results may underestimate real-world infrastructure. Additionally, weighting choices—though grounded in literature—inevitably involve a degree of subjectivity.

	Weight	1	0.8	0.5	0	0	0	0
City	1a - Infrastructure Level	Cycleway	Path	Footway	Street	Road	State Road	Other
Amsterdam	73.7%	71.8%	0.3%	3.4%	8.3%	14.6%	1.1%	0.6%
Stockholm	71.9%	69.8%	0.9%	2.7%	14.9%	11.2%	0.0%	0.5%
Vienna	64.8%	59.0%	6.5%	1.2%	23.2%	7.9%	0.6%	1.7%
Paris	58.2%	56.9%	0.3%	2.2%	12.5%	13.6%	14.5%	0.0%
Lisbon	39.6%	35.5%	1.2%	6.3%	29.0%	23.5%	4.2%	0.3%
Luxembourg	38.3%	21.5%	17.5%	5.5%	30.5%	17.6%	5.1%	2.3%
Brussels	37.8%	34.4%	1.1%	5.1%	31.7%	24.7%	2.5%	0.7%
Madrid	34.7%	31.1%	1.2%	5.4%	26.7%	28.4%	5.1%	2.1%
Copenhagen	30.4%	28.4%	1.9%	0.8%	17.3%	47.7%	3.7%	0.2%
Dublin	28.2%	26.6%	0.2%	2.8%	10.7%	59.7%	0.0%	0.0%
Berlin	25.8%	15.7%	8.1%	7.4%	33.5%	28.3%	6.5%	0.6%
Rome	24.8%	20.7%	1.7%	5.5%	25.4%	43.3%	2.1%	1.2%
Athens	6.9%	3.1%	2.0%	4.3%	34.1%	52.0%	3.0%	1.5%

Figure 4.8: Results of Indicator 1a - Infrastructure Usage

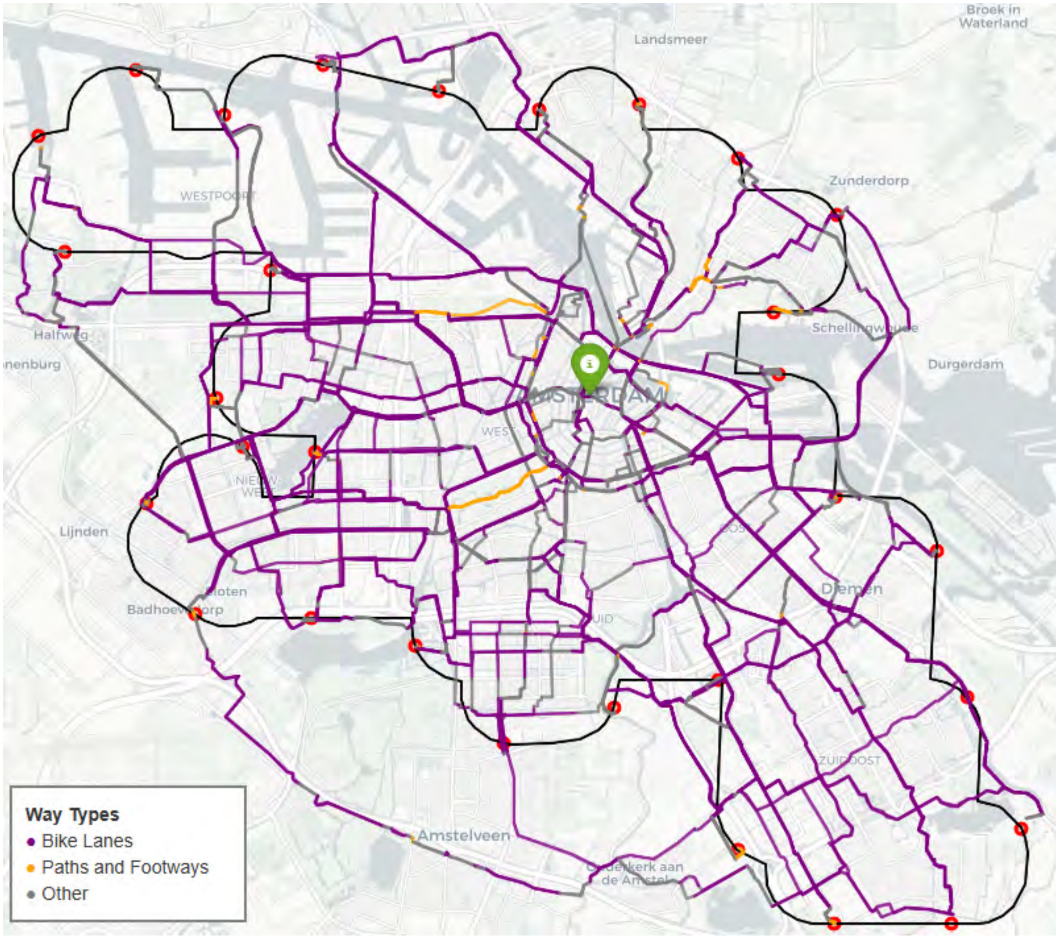


Figure 4.9: Results of Indicator 1a for Amsterdam

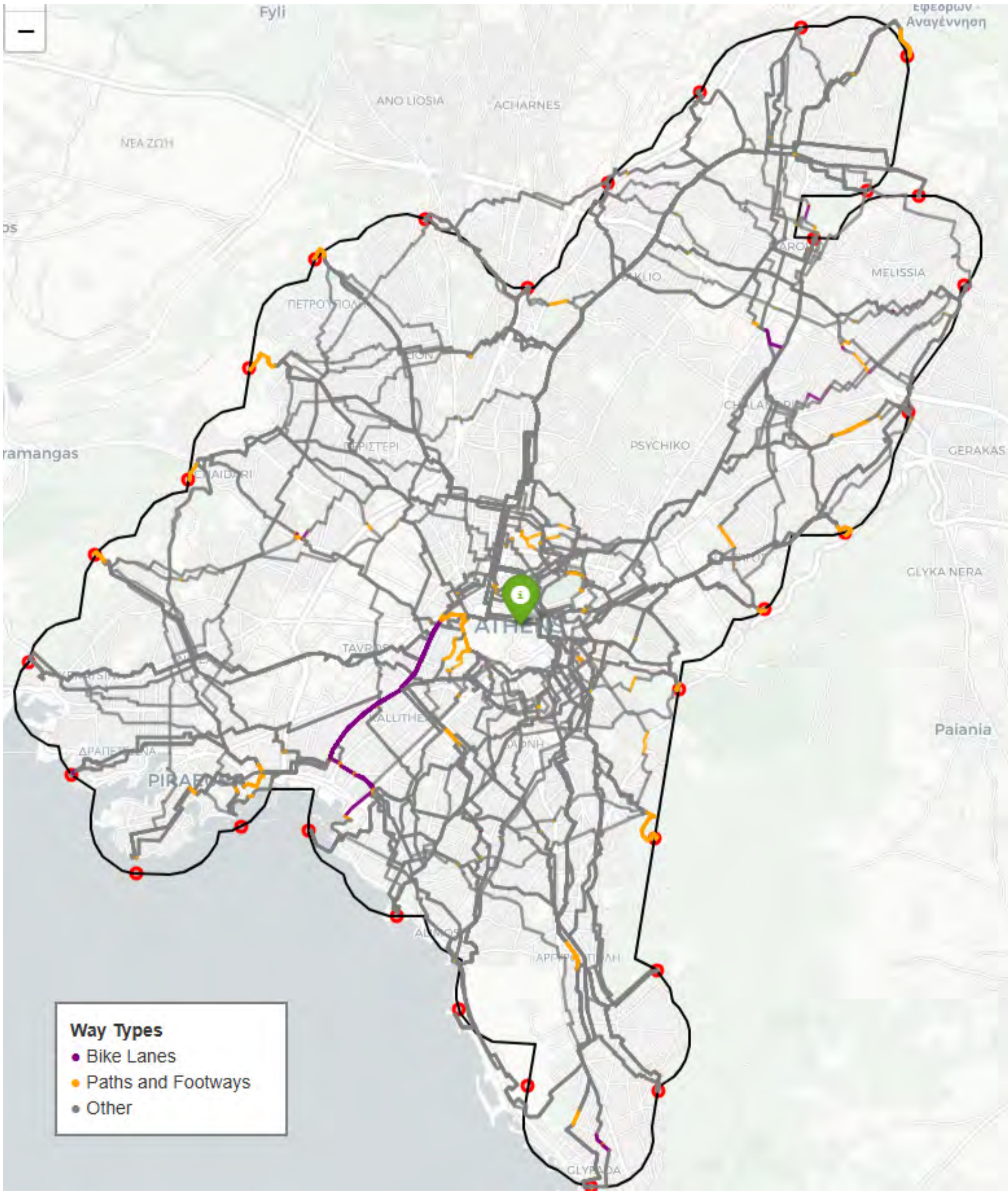


Figure 4.10: Results of indicator 1a for Athens

4.1.2 Indicator 1.b - Protected Network Coverage

Methodology

This indicator evaluates how extensively dedicated cycling infrastructure is spatially distributed throughout the urban area. Unlike Indicator 1a in Section 4.0.2 that focus on infrastructure quality along specific routes, this measure captures how well the formal cycling network reaches across the entire city. The analysis focuses exclusively on *physically segregated bike lanes*—road segments explicitly tagged as `highway=cycleway` in OpenStreetMap [58]. This excludes mixed-traffic streets or shared lanes where bicycles and vehicles coexist without physical separation, as such environments have been shown to significantly reduce perceived and actual safety for cyclists [59, 52]. The scope is therefore limited to infrastructure clearly intended for exclusive cycling use, such as protected lanes, greenways, or dedicated paths.

To calculate the indicator, all dedicated cycling segments within the cleaned urban perimeter (as defined in Section 4.0.1) were extracted and projected onto a uniform 500-meter grid (see Section 4.0.3). Each tile was evaluated for spatial intersection with the infrastructure. tiles intersecting at least one dedicated segment—regardless of length—were marked as *cycling-covered*. The final indicator value is computed as the percentage of covered tiles over the total number of tiles in the urban grid, as shown in Equation 4.3:

$$\text{Protected Network Coverage} = \frac{n_{\text{covered}}}{n_{\text{total}}} \times 100 \tag{4.3}$$

This metric provides a simple but effective proxy for spatial accessibility: the higher the percentage of grid tiles with dedicated infrastructure, the greater the probability that residents across the city live or travel within reach of a safe cycling corridor.

In addition to the main coverage metric, the analysis also calculated: (i) the *connectivity* of the cycling network—measured as the proportion of cycling-covered tiles that form part of the largest connected component in the grid—and (ii) the *total length* of dedicated infrastructure in kilometers. However, these values are not included in the composite BIKE Index. Connectivity was found to be highly polarized—either close to fully connected or substantially fragmented—and thus limited in comparative value. As for total length, normalization by population or surface area introduces systematic bias by favoring cities that are either densely populated or geographically compact, without capturing true functional coverage. For this reason, both metrics are reported as supporting statistics but excluded from the index calculation.

Results

The results reveal a pronounced gap in spatial cycling infrastructure coverage among the analysed cities. Amsterdam leads the ranking with 81.8% of its urban grid covered by dedicated cycleways. It is followed closely by Stockholm (78.7%) and Paris (70.0%), both of which also show complete network connectivity, with all cycling-covered tiles forming a single connected component. These cities combine dense infrastructure with spatial continuity, ensuring that most urban areas are within short reach of a dedicated cycling corridor.

A second cluster of cities—including Copenhagen, Vienna, Lisbon, and Brussels—achieve intermediate values ranging from 50% to 55%. While these cities present generally well-connected networks (connectivity above 94%), their coverage does not yet extend evenly across the full urban territory. This may reflect historical patterns of network expansion or spatial inequality in infrastructure investment. For instance, Lisbon covers over half its grid despite a smaller total network length, suggesting a compact and spatially efficient cycling system.

Madrid and Luxembourg score below 40%, with 37.4% and 34.5% of grid coverage respectively. Both show relatively high connectivity, but their networks remain spatially limited in absolute terms. Berlin stands out as an outlier: despite a very large total length of cycling infrastructure (over 1,000 km), it achieves only 29.4% grid coverage. This suggests a high degree of spatial concentration, with infrastructure clustered in specific areas rather than spread uniformly across the city. Its low connectivity score (61.0%) further reflects fragmentation.

At the lower end of the spectrum, Rome (21.1%), Dublin (19.0%), and Athens (6.6%) display sparse and disconnected networks. These cities combine low infrastructure density (less than 0.4 km of cycleway per km^2) with poor connectivity: less than half of the covered grid tiles are connected in a single component. Athens, in particular, shows minimal presence of dedicated infrastructure, with only 43.5 km of cycleways covering just 6.6% of the city's grid and a fragmented layout.

These results suggest that strong performance in this indicator depends not only on total infrastructure investment, but on how evenly and coherently it is distributed across the city. Cities like Paris and Lisbon achieve relatively high coverage with moderate total lengths, while others like Berlin or Madrid are penalised by spatial concentration or urban sprawl. Overall, the indicator highlights spatial accessibility as a crucial, and often overlooked, dimension of cycling policy.

The full dataset, including supporting statistics on connectivity and infrastructure length, is presented in Figure 4.11. Figure 4.13 and Figure 4.14 contrast two cities with opposite profiles: Stockholm features dense, connected infrastructure with broad reach, while Dublin displays a sparse and fragmented layout with limited spatial coverage. Figure 4.14 represents Rome's network, and 3 completely separate and segregated networks can be observed, portraying how disconnected Rome's cyclist network is.

Limitations

As with any spatial metric, some limitations must be acknowledged. The use of grid tiles introduces edge effects near the urban boundary. These have been mitigated through careful perimeter cleaning and manual inspection of anomalous components, but cannot be eliminated entirely. Besides, the indicator exclusively considers dedicated cycling infrastructure. Shared-use roads or lanes without explicit segregation—even if marked for cyclists—are excluded by design. This choice was intentional, reflecting a conservative interpretation of what constitutes safe and cyclist-friendly infrastructure. However, it may penalize cities that have invested in shared solutions. Future iterations of the index could introduce a weighting scheme to partially credit this type of infrastructure while maintaining a focus on safety and network quality. Finally, the connectivity measure assumes topological adjacency and does not capture the actual ease of movement between tiles—only their geometric contiguity.

City	Indicator 1b	Connectivity	Length / City Area	Total Length (km)	City Area (km^2)
Amsterdam	81.8%	100.0%	3.09	1,187.8	385.0
Stockholm	78.7%	99.4%	2.55	1,486.8	582.7
Paris	70.0%	100.0%	2.13	432.8	202.9
Copenhagen	54.5%	95.2%	1.08	267.6	248.1
Vienna	54.2%	96.3%	1.22	655.9	535.9
Lisbon	53.3%	95.4%	1.30	139.0	106.9
Brussels	50.6%	94.8%	0.91	296.0	324.9
Madrid	37.4%	97.1%	0.78	327.4	421.5
Luxembourg	34.5%	88.1%	0.56	32.4	58.0
Berlin	29.4%	61.0%	0.64	1,001.4	1,574.6
Rome	21.1%	32.4%	0.36	165.8	458.2
Dublin	19.0%	44.1%	0.35	95.4	275.0
Athens	6.6%	30.3%	0.10	43.5	451.1

Figure 4.11: Results of Indicator 1b - Protected Network Coverage

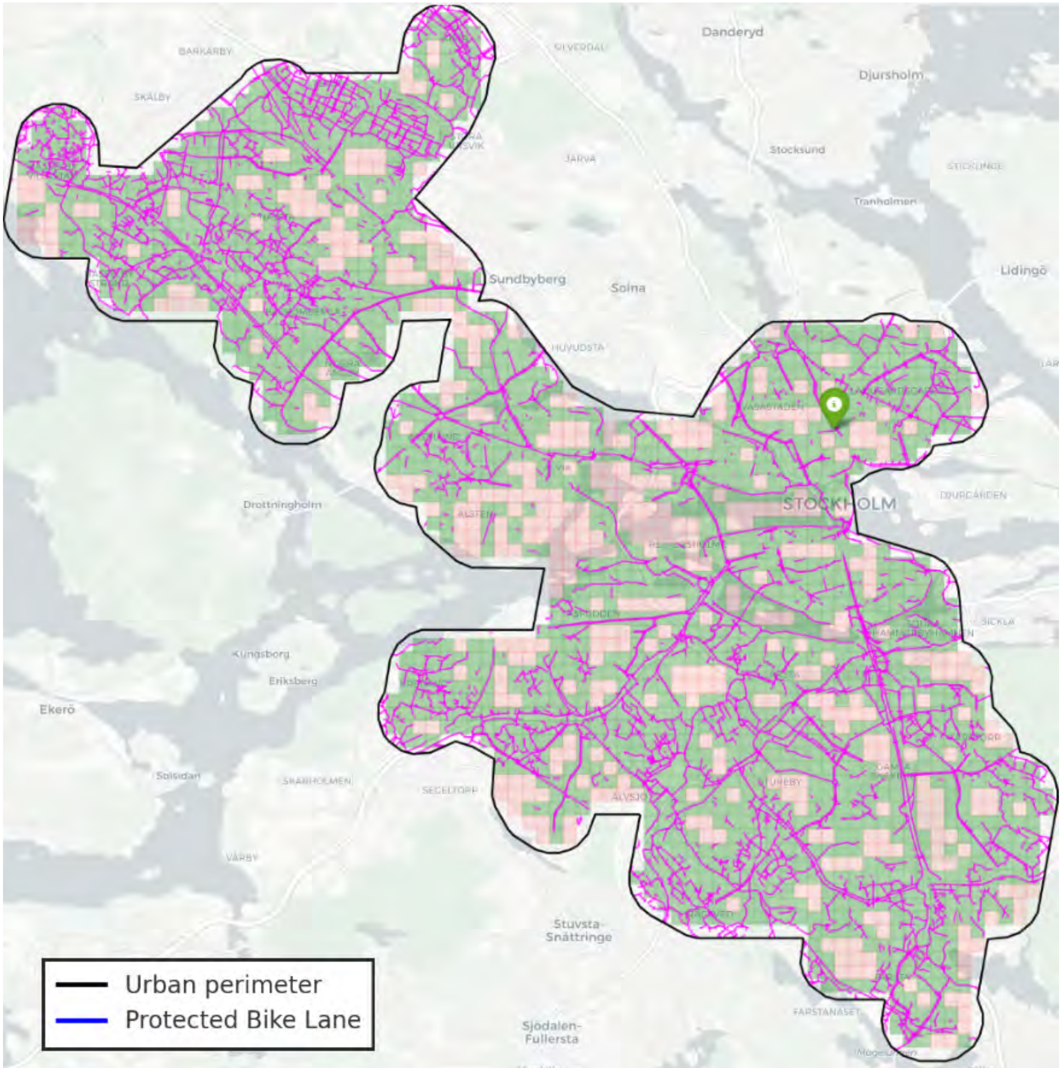


Figure 4.12: Results of indicator 1b for Stockholm

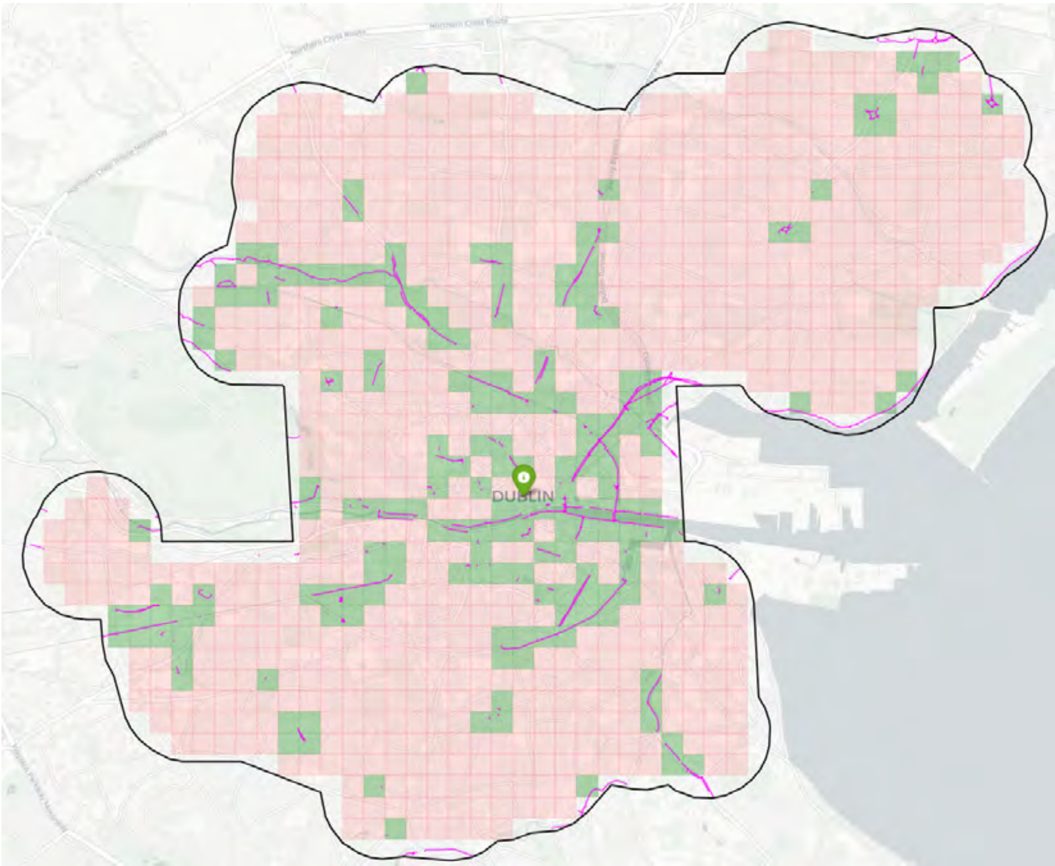


Figure 4.13: Results of indicator 1b for Dublin

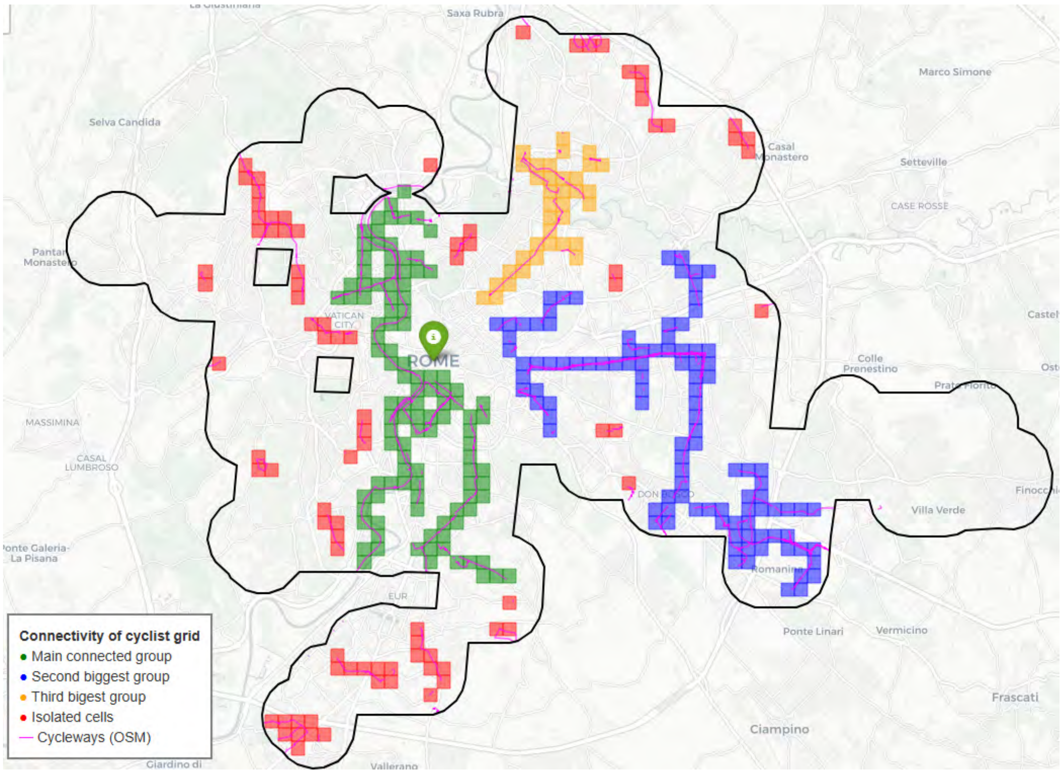


Figure 4.14: Results of indicator 1b for Rome

4.1.3 Indicator 1.c – Route Efficiency

Methodology

This indicator assesses the geometric efficiency of cycling infrastructure by measuring how closely recommended cycling routes follow the shortest possible path between two points. It captures the extent to which the network enables direct and convenient travel, an essential characteristic of high-functioning transport systems. More direct routes reduce effort, time, and uncertainty for cyclists, and are associated with increased likelihood of bicycle use [60].

While previous indicators focus on infrastructure quality or spatial coverage, this metric introduces a functional dimension to the BIKE Index. It reflects how effectively a cyclist can move through the city, independent of whether the infrastructure is present or how widely it is distributed.

The analysis is based on the same set of 210 radial routes described in Section 4.0.2. For each route, the straight-line (geodesic) distance between the start and end points is divided by the actual travel distance returned by the routing engine. This ratio captures how closely the path resembles an ideal straight trajectory, as shown in Equation 4.4:

$$\text{Route Efficiency} = \frac{d_{\text{straight}}}{d_{\text{real}}} \tag{4.4}$$

Values closer to 1 indicate highly efficient routes with minimal detours, while lower values suggest fragmented networks, poor continuity, or routing over suboptimal infrastructure. The final indicator is computed as the mean of all route-level efficiency scores for each city.

By construction, the metric is sensitive to the structural properties of the network—such as grid regularity, barriers, and street hierarchy—but remains independent of topography, street width, or infrastructure type. It therefore complements other indicators by offering a neutral lens on network performance from the cyclist's perspective.

Results

The results reveal moderate variability in Route Efficiency across European capitals. Athens scores highest with an average ratio of 0.68, followed by Lisbon, Paris, and Madrid (all at 0.64). These cities demonstrate relatively direct routing between perimeter points, despite differing infrastructure levels. This can often be attributed to their compact urban form and dense central layouts, which favour radial or grid-like street patterns that enable more direct connections across the city.

In contrast, Luxembourg and Stockholm fall below 0.52, suggesting a less geometrically efficient cycling network. In these cases, geographical constraints (such as waterways, uneven topography, or islands), fragmented development, and car-centric urban planning likely lead to longer, more indirect routes. Figure 4.16 illustrates this contrast using the route distributions for Athens and Stockholm, and the differences in urban planning are evident.

Figure 4.15 presents the full set of results for Indicator 1.c across all cities.

Limitations

Despite its mathematical clarity, the indicator has important limitations. It is strongly influenced by the underlying morphology of the urban fabric, regardless of whether cycling infrastructure exists. A compact, orthogonal city layout may yield high scores even in the absence of dedicated lanes, while fragmented or historic urban forms might penalize otherwise high-performing networks.

Moreover, the metric does not explicitly measure cycling conditions, safety, or comfort. As such, its value lies more in offering a functional reference than a direct measure of infrastructure quality.

A more informative approach might involve comparing cycling travel time or distance to equivalent car routes, providing insight into competitive travel efficiency. However, implementing this would require detailed car routing data, consistent traffic models, and careful interpretation. Preliminary tests across a small subset of cities showed highly correlated results with the current metric, leading to the decision to maintain the simpler formulation without compromising overall insight.

City	Indicator 1c	Median	Std deviation	Max	Min
Athens	**0.68**	0.68	0.06	0.83	0.56
Lisbon	**0.64**	0.65	0.09	0.84	0.31
Paris	**0.64**	0.63	0.06	0.82	0.50
Madrid	**0.64**	0.63	0.06	0.79	0.42
Brussels	**0.63**	0.62	0.07	0.78	0.45
Vienna	**0.61**	0.61	0.06	0.77	0.39
Rome	**0.59**	0.59	0.07	0.80	0.40
Copenhagen	**0.58**	0.57	0.07	0.77	0.39
Berlin	**0.58**	0.57	0.05	0.71	0.40
Amsterdam	**0.57**	0.56	0.07	0.76	0.32
Dublin	**0.56**	0.56	0.08	0.79	0.21
Luxembourg	**0.51**	0.52	0.10	0.79	0.23
Stockholm	**0.49**	0.50	0.09	0.75	0.20

Figure 4.15: Results of Indicator 1c - Route Efficiency

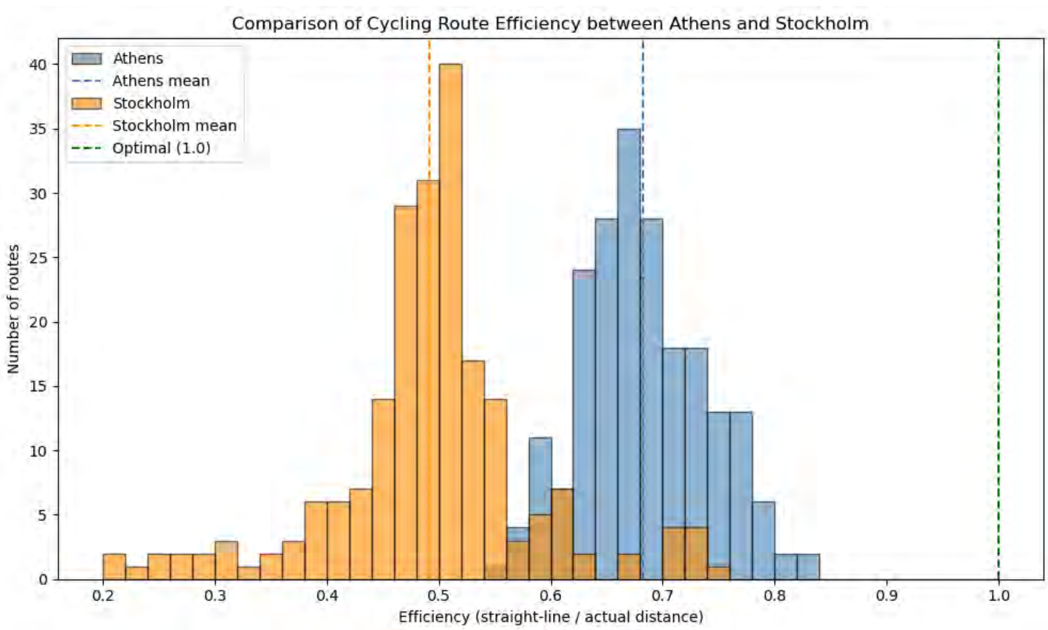


Figure 4.16: Indicator 1c: Distribution of route efficiency across all 210 routes in Athens and Stockholm

4.2 Dimension 2 – Cyclist Services

This dimension evaluates the availability and spatial accessibility of key services that support daily cycling, focusing on two essential components: maintenance infrastructure and bike-sharing systems. Unlike purely infrastructural measures, these indicators capture how service provision enables or limits practical bicycle use, reflecting the broader urban ecosystem necessary for a robust cycling culture.

The dimension is defined by two indicators:

- Indicator 2a captures the market's support infrastructure for ownership and maintenance.

- Indicator 2a quantifies coverage by public bike-sharing stations, representing flexible access options for residents who do not own a bicycle.

Together, these indicators highlight how well a city sustains and complements cycling as a mode of transport beyond dedicated infrastructure, revealing differences in how supportive the service environment is for existing and potential cyclists.

4.2.1 Indicator 2a - Access to Bike Services

This indicator quantifies the spatial accessibility of cyclist-specific services—namely, bike shops and repair workshops—across the urban area. It measures whether citizens have access to at least one of these services within a walkable distance, thereby reflecting the availability of essential infrastructure for bicycle maintenance and usability.

The indicator is grounded in urban accessibility theory, which stresses the importance of proximity to services for promoting sustainable mobility and reducing spatial inequality [51]. Access to maintenance infrastructure, in particular, has been shown to influence bicycle ownership, perceived reliability, and overall frequency of use [61].

The analysis is conducted over the grid calculated in Section 4.0.3. Each tile is treated as a spatial unit and evaluated for intersection with the buffer area of cyclist services. Buffers are circular zones with a radius of 500 metres, centred on the location of each service point. This threshold aligns with commonly accepted standards for walkable access in mobility and public health studies [50].

Service locations were obtained from a dedicated dataset compiled through geolocated queries to Google Maps. Since no public harmonized database exists for cyclist services across European cities, a custom data extraction procedure was developed. For each city, all tiles of the urban grid were scanned using search queries such as “bike sharing”, “bicycle repair shop”, and “bicycle rental” near each coordinate. The results were parsed from the HTML content using a web scraping script, collecting the name, coordinates, and service-related tags of each entry.

Entries were classified into three categories:

- Workshop if the tag included "Bicycle repair shop"
- Store if it included tags like "Bicycle store", "Electric bicycle store", or "Used bicycle shop"
- Both if tags of both types were present

All duplicates were removed by comparing names and coordinates across overlapping queries. The final dataset includes unique, georeferenced service points, which were reprojected to metric coordinates (EPSG:3857) and buffered. Then, each grid tile was evaluated for intersection with the service buffers. A tile is marked as "covered" if any part of its geometry intersects the buffer area of at least one valid service point.

The final value of the indicator is calculated as shown in Equation 4.5:

$$\text{Access of Bike Services} = \frac{n_{\text{covered}}}{n_{\text{total}}} \times 100 \tag{4.5}$$

This method ensures a consistent and reproducible measure of service coverage. It captures real spatial influence zones rather than assigning services to fixed administrative units, and allows cross-city comparisons under a standardised framework.

In parallel, a Gini index was calculated to assess the spatial inequality of service distribution across the urban grid. The Gini index is a well-established measure of statistical dispersion, often used to evaluate spatial equity in access to urban resources [62]. In this context, it reflects how evenly bike services are distributed within the urban area: a lower Gini value indicates a more uniform spatial distribution, while higher values reveal clusters of services in specific neighborhood. Preliminary analysis showed a strong correlation between the Gini index and population density patterns, as well as an inverse relationship between the total number of services and their spatial uniformity—cities with more services tend to exhibit greater spatial concentration. For these reasons, the Gini index is reported as a complementary measure but is not incorporated into the composite BIKE Index.

The Gini index was computed using the standard formula for discrete spatial units, based on the Lorenz curve of cumulative service distribution across grid tiles, as shown in Equation 4.6:

$$G = \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} |x_i - x_j|}{2n^2 \bar{x}} \tag{4.6}$$

Results

The results reveal notable differences in service accessibility across cities. Paris ranks highest, with 89.3% of the urban grid covered by at least one cyclist-specific service. Figure 4.20 shows that although services are denser in central districts, overall coverage extends well into peripheral areas, supporting widespread access. The relatively low Gini index (0.49) indicates a more even distribution of services across the city, reinforcing the high coverage score.

As Figure 4.18 Copenhagen follows with 76.3% coverage and a moderate Gini (0.60), reflecting a fairly balanced network with some concentration in key districts. Amsterdam and Lisbon achieve similar coverage (55.6% and 55.2% respectively), but have higher Gini values (0.73 and 0.74 respectively), suggesting more uneven service distribution and greater clustering in certain zones.

At the lower end, Stockholm and Luxembourg show limited coverage (24.9% and 34.0%), with large portions of the urban grid lacking services. Figure 4.19 illustrates this sparse pattern in Stockholm, where services are relatively concentrated in specific areas. Their higher Gini indices (0.84 and 0.80 respectively) reflect this unevenness in spatial distribution.

Across the sample, headline coverage percentages provide the clearest picture of practical accessibility for cyclists. Meanwhile, the Gini index offers complementary insight on whether services are spread evenly across the city or clustered in select areas.

These findings confirm our preliminary analysis of the relationship between coverage and spatial inequality. Cities with more services often show lower Gini values, reflecting broader distribution, while cities with fewer services tend to exhibit more uneven clustering (higher Gini values). For this reason, the Gini index is reported as a supporting measure but not included in the composite BIKE Index.

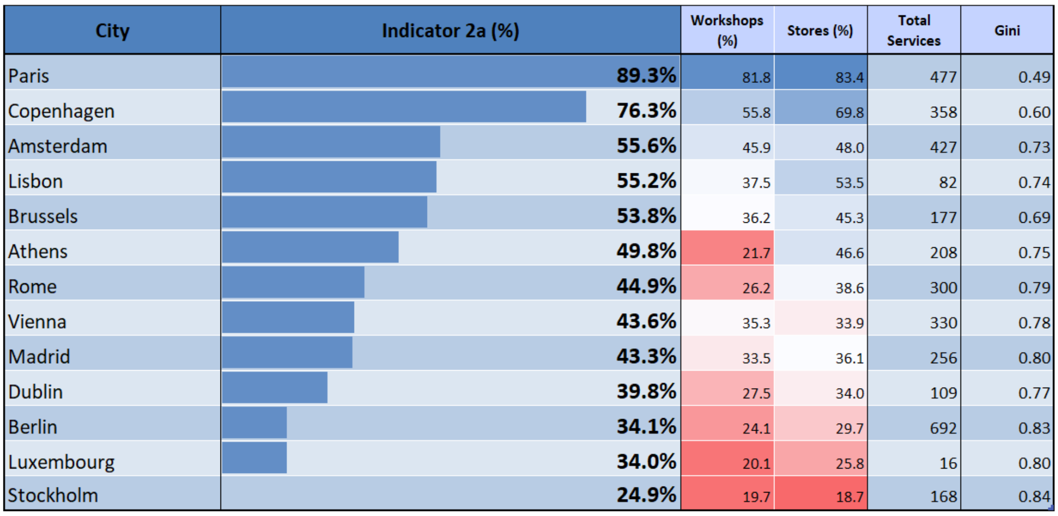
Full results, including coverage rates, service counts, and Gini indices, are presented in Figure 4.17.

Limitations

This indicator focuses solely on physical proximity to workshops and stores, without considering qualitative aspects such as service quality, capacity, or specialization. Additionally, data was compiled through automated queries to Google Maps; although deduplication and cleaning were applied, some inaccuracies in classification or missing points may persist.

Another limitation is that the chosen 500-meter threshold for access is somewhat arbitrary. While it reflects a commonly accepted walkable distance in urban studies, cyclists with a mechanical issue might be willing (or forced) to travel much farther to find a suitable workshop or store. Therefore, the indicator may underestimate real-world service accessibility for some users who do not depend strictly on close proximity.

Furthermore, cities with lower population density may appear disadvantaged in this analysis, as their urban form naturally leads to larger distances between services and fewer workshops overall. This reflects genuine differences in service environment, but also highlights the difficulty of comparing dense and less dense cities using a uniform spatial threshold.



City	Indicator 2a (%)	Workshops (%)	Stores (%)	Total Services	Gini
Paris	89.3%	81.8	83.4	477	0.49
Copenhagen	76.3%	55.8	69.8	358	0.60
Amsterdam	55.6%	45.9	48.0	427	0.73
Lisbon	55.2%	37.5	53.5	82	0.74
Brussels	53.8%	36.2	45.3	177	0.69
Athens	49.8%	21.7	46.6	208	0.75
Rome	44.9%	26.2	38.6	300	0.79
Vienna	43.6%	35.3	33.9	330	0.78
Madrid	43.3%	33.5	36.1	256	0.80
Dublin	39.8%	27.5	34.0	109	0.77
Berlin	34.1%	24.1	29.7	692	0.83
Luxembourg	34.0%	20.1	25.8	16	0.80
Stockholm	24.9%	19.7	18.7	168	0.84

Figure 4.17: Results of Indicator 2a - Access to Bike Services

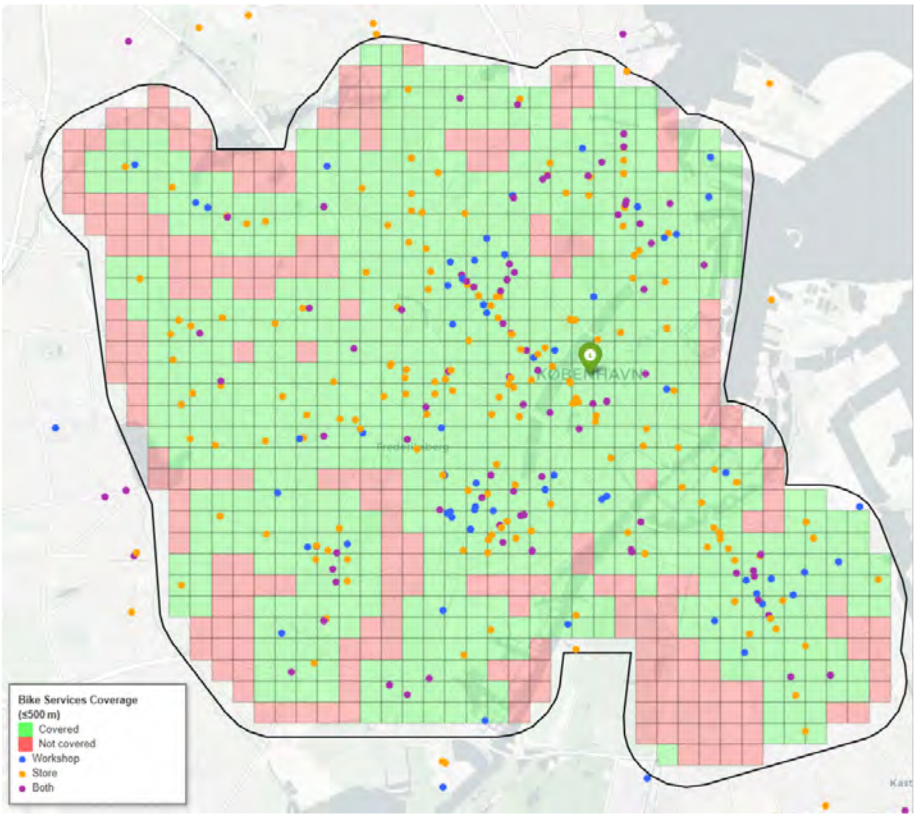


Figure 4.18: Indicator 2a: Bike services coverage in Copenhagen

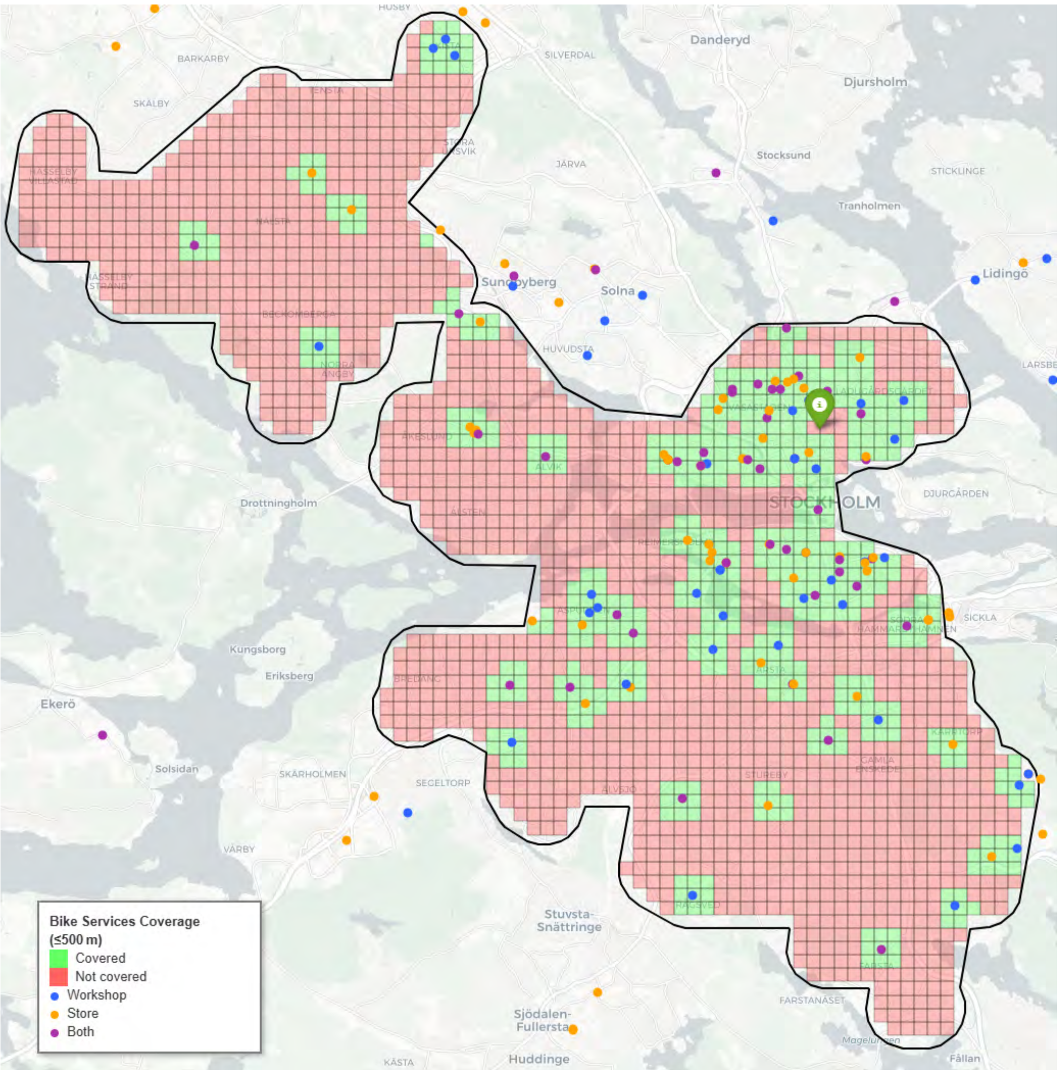


Figure 4.19: Indicator 2a: Bike services coverage in Stockholm

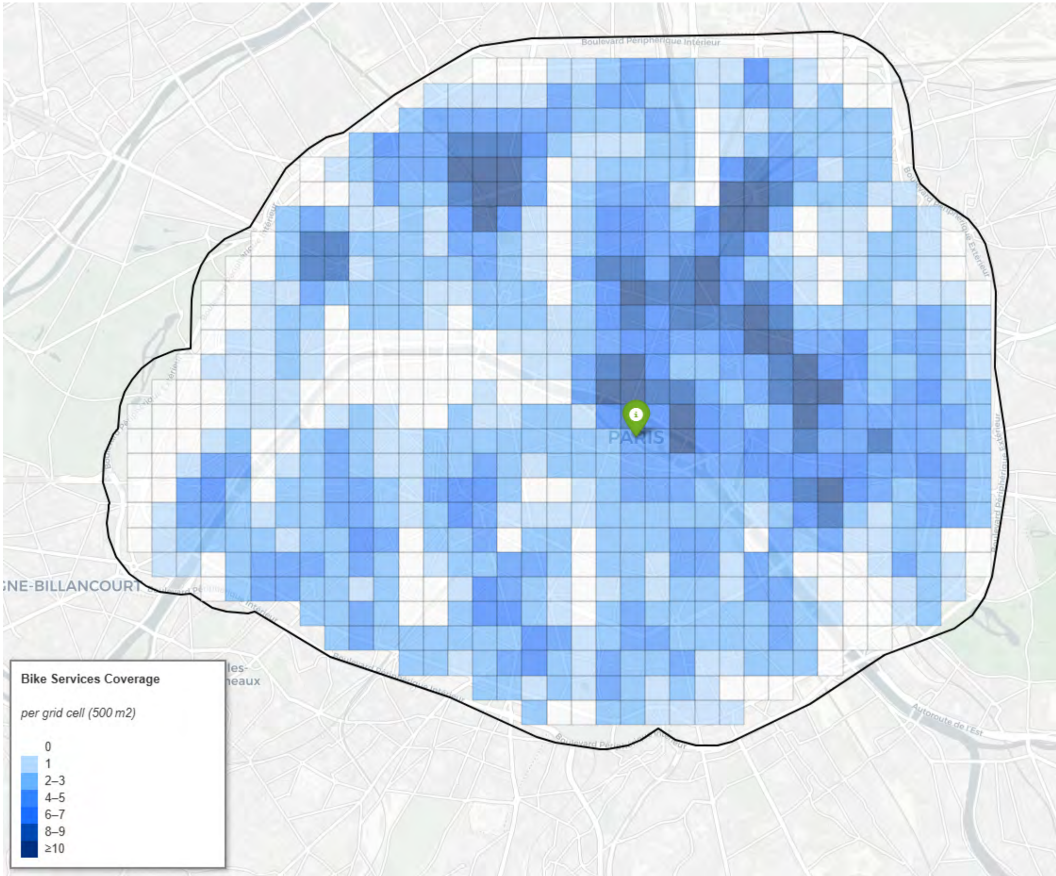


Figure 4.20: Indicator 2a: Bike services density in Paris

4.2.2 Indicator 2b - Bike-Sharing Coverage

This indicator measures the percentage of the urban area covered by at least one public bike-sharing station within 500 metres. The objective is to evaluate the territorial presence of bike-sharing systems, which play a critical role in supporting flexible and frequent cycling among urban residents. As with other indicators in this study, the analysis uses the grid defined in Section 4.0.3, ensuring methodological consistency across the BIKE Index.

The theoretical basis for this indicator lies in extensive literature linking the presence and spatial accessibility of bike-sharing stations with increased system adoption, modal shift, and higher daily cycling rates [63, 64]. A distance of 500 metres is commonly used in studies on urban service accessibility and walkability standards, representing a reasonable expectation for users seeking convenient and reliable bike-sharing services.

Methodologically, the approach follows the process detailed in Section 4.2.1. First, a dataset of service points was filtered to include only those tagged as "Bike sharing station". Each station was transformed into a metric coordinate reference system (EPSG:3857) and buffered by 500 metres to simulate its effective area of influence. The urban grid was then intersected with these buffers, and a tile was marked as covered if any part of its geometry overlapped with the buffer area of at least one station.

To complement the main metric, a Gini index was calculated over this distribution to assess spatial inequality in station availability, using Equation 4.6. However, as discussed in Section 4.2.1, the Gini index is reported only as a supporting measure and is not integrated into the composite indicator.

The final indicator value is calculated as the percentage of covered tiles over the total number of tiles in the urban grid, following Equation 4.7:

$$\text{Bike-Sharing Coverage (\%)} = \frac{n_{\text{covered}}}{n_{\text{total}}} \times 100 \tag{4.7}$$

where n_{covered} is the number of tiles intersecting at least one buffer, and n_{total} is the total number of tiles in the grid. This approach yields an objective and comparable measure of the spatial coverage of bike-sharing services across cities.

Results

The results reveal substantial variation in bike-sharing station coverage across cities. Paris achieves full coverage (100%), reflecting a dense network of stations concentrated within the central urban core—the area defined by our perimeter method (see Section 4.0.1). This methodological choice, which focuses on the dense inner zone, partly explains Paris's perfect score.

Madrid and Copenhagen follow with high coverage values of 86.7% and 85.0% respectively. Both cities show relatively moderate Gini indices (0.51 in each), indicating that stations are reasonably well distributed across the urban area. Figure 4.22 represents the density and distributation of stations of Madrid, where it can be noticed that Madrid offers a bike-sharing service to all of its population, and places with more population density have more stations, intuitively.

Berlin and Brussels also perform strongly (78.8% and 83.6%), but Berlin displays a higher Gini index (0.68), reflecting notable clustering of stations in certain corridors and neighborhoods. Vienna and Luxembourg achieve mid-range scores (57.4% and 55.1%), while Amsterdam, Lisbon, and Dublin fall below 40%. Dublin in particular shows strong central clustering but poor peripheral coverage, as seen in Figure 4.24. In contrast, Figure 4.23 illustrates Brussels's balanced network structure, with stations covering central and peripheral zones.

At the lower end, Stockholm, Athens, and Rome report limited coverage (16.2%, 0.5%, and 0.4% respectively), with Gini indices of 0.90 or higher. These high values reflect extreme spatial concentration, with stations located in few zones and large peripheral gaps in service.

Overall, the results confirm that while many cities have developed extensive bike-sharing systems, their spatial distribution remains uneven in several cases. Complementary measures such as the Gini index and spatial maps provide crucial insights into where systems might be expanded to improve equitable access. Detailed figures and full results by city are presented in Figure 4.21.

Limitations

A key limitation is that cities with a strong cycling culture—such as Amsterdam or Stockholm—exhibit high rates of private bike ownership (e.g., approximately 1.3 bicycles per person in the Netherlands [65], with similar trends in Dutch cities). This widespread ownership reduces reliance on public bike-sharing systems, meaning low coverage values in these contexts do not necessarily indicate poor cycling accessibility.

Besides, as with other grid-based coverage indicators, the measure is constrained by the defined urban perimeter. In cities like Paris, focusing on the dense core inflates perceived coverage, potentially overstating the reach of bike-sharing services beyond that zone. In addition, the 500-metre buffer threshold, while consistent with walk-ability standards, is a simplification. Many users may be willing to travel farther, especially in lower-density areas where stations are more widely spaced.

City	Indicator 2b (%)	Gini	Total Stations
Paris	100.0%	0.24	1061
Madrid	86.7%	0.51	663
Copenhagen	85.1%	0.51	2205
Brussels	83.6%	0.43	362
Berlin	78.8%	0.68	5225
Vienna	57.4%	0.67	300
Luxembourg	55.2%	0.69	47
Amsterdam	38.7%	0.77	155
Lisbon	24.5%	0.89	63
Dublin	16.9%	0.88	119
Stockholm	16.2%	0.90	112
Athens	0.6%	1.00	1
Rome	0.4%	1.00	3

Figure 4.21: Results of Indicator 2b - Bike-Sharing Coverage

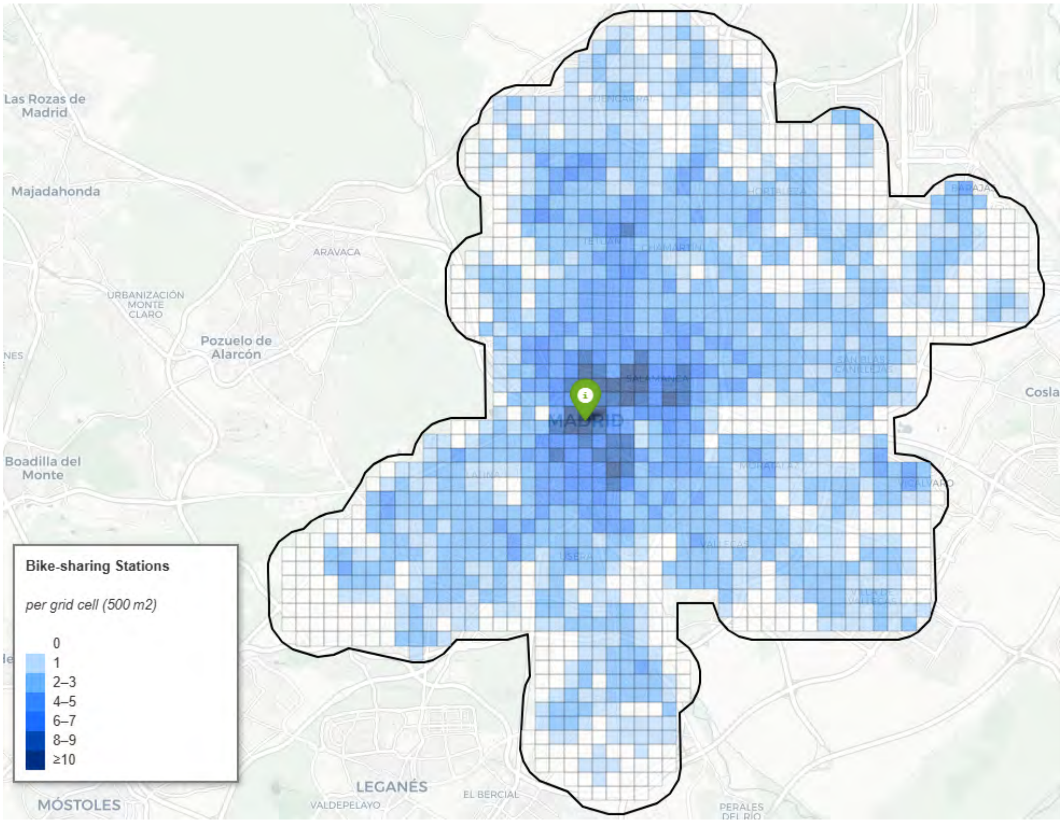


Figure 4.22: Indicator 2b: Bike-Sharing Stations density in Madrid

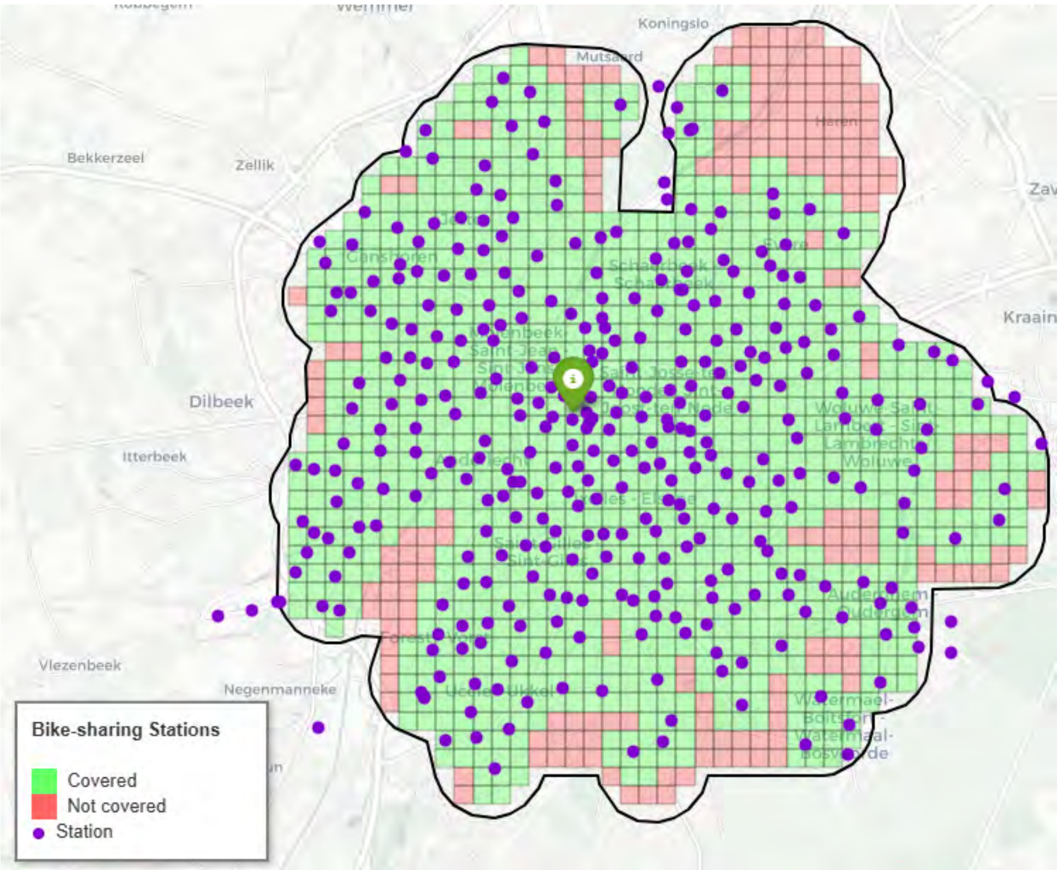


Figure 4.23: Indicator 2b: Bike-Sharing Stations coverage in Brussels

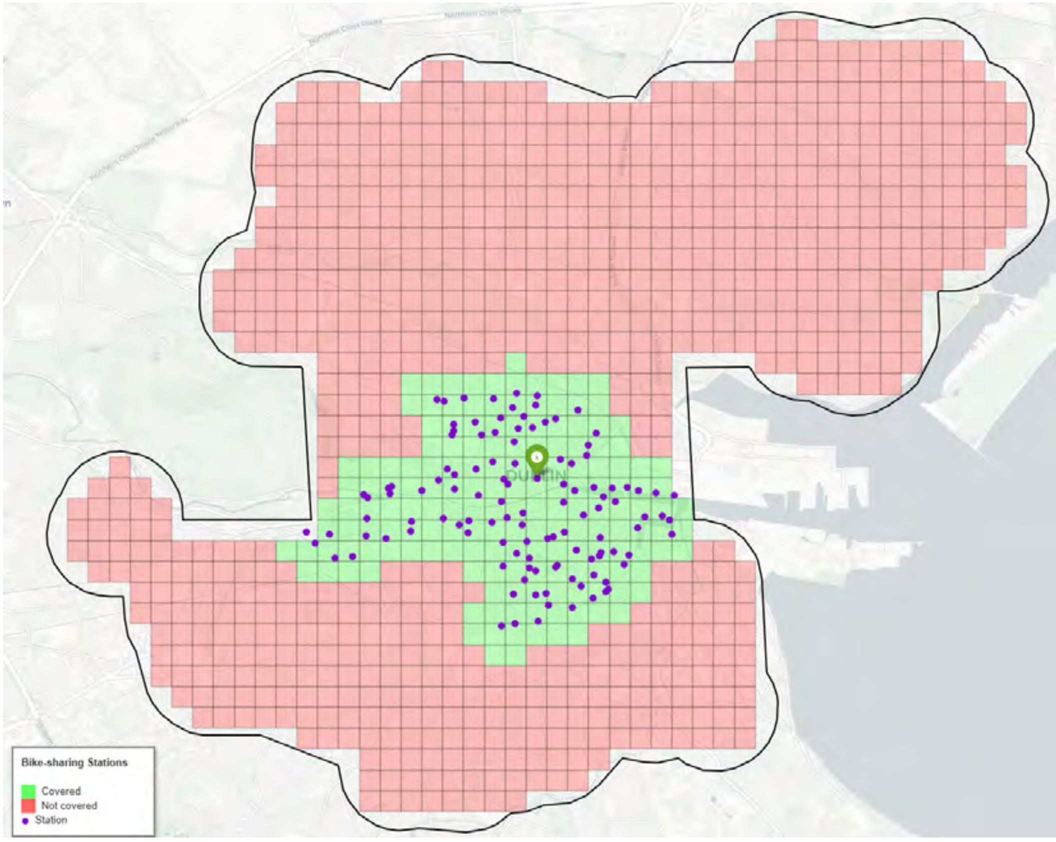


Figure 4.24: Indicator 2b: Bike-Sharing Station coverage in Dublin

4.3 Dimension 3 – Environmental Constraints

This dimension captures how the natural environment constrains or enables everyday cycling, focusing on two key variables: topography and climate. Unlike infrastructure or service-related metrics, these indicators reflect structural conditions that cannot be easily modified by policy, but which exert a strong influence on cycling behaviour and feasibility. Steep slopes and adverse weather are well-documented deterrents to cycling uptake, particularly among less experienced users or in cities with limited mitigation measures. It combines two complementary perspectives:

- Indicator 3a quantifies the slope-induced physical effort required to traverse the city's cycling network, offering a measure of vertical accessibility.
- Indicator 3b calculates the percentage of climatically favorable days per year based on temperature and precipitation thresholds.

Together, these indicators provide essential context for interpreting differences in cycling infrastructure performance, recognizing that some cities face harsher environmental constraints than others.

4.3.1 Indicator 3a - Terrain Difficulty

Methodology

This indicator quantifies the physical effort imposed by topography along cycling routes within each city. While most infrastructure indicators focus on network coverage or spatial connectivity, this metric addresses the vertical dimension of cycling mobility—capturing how steep segments can become invisible barriers to certain users. Hilly terrain is known to reduce cycling uptake, influence route choice, and affect perceived accessibility, particularly among less fit or experienced cyclists [66]. By measuring elevation-related effort, this indicator offers a complementary perspective on cycling infrastructure quality.

The methodology relies on the `steepness` attribute provided by the OpenRouteService (ORS) API, which classifies each segment of a route according to its elevation. Each slope category is mapped to a numerical weight reflecting the relative exertion required to traverse that range, defined as follows:

$$\begin{gathered}\textit{0} \text{ for 0–1\% (flat)}, \quad \textit{1} \text{ for 1–4\% (mild)}, \quad \textit{2} \text{ for 4–7\% (moderate)}, \\ \textit{3} \text{ for 7–10\% (steep)}, \quad \textit{4} \text{ for 10–16\% (very steep)}, \quad \textit{5} \text{ for >16\% (extreme)}.\end{gathered}$$

These weights were designed to ensure interpretability and proportionality across the slope range, allowing a single effort score to be computed per route. Since each ORS route is computed in only one direction, the absolute value of the slope category is used to capture the total elevation challenge a cyclist would experience when travelling both ways. This symmetric approach avoids underestimating effort in downhill-only segments and better reflects perceived accessibility.

The slope-induced effort for a given route is computed as a length-weighted average of the steepness weights, as shown in Equation 4.8:

$$\text{Terrain Difficulty} = \frac{\sum(\text{length}_i \times \text{weight}_i)}{\text{total route length}} \tag{4.8}$$

The indicator is applied to the full set of simulated routes generated in Section 4.0.2, where each city is modeled with 210 routes distributed evenly across the urban perimeter. Although routes are not inherently bidirectional, they were treated as such for analysis, considering both directions between each pair of points. The final city-level score corresponds to the average effort across all routes. This produces a continuous variable where higher values indicate greater physical demand and lower network accessibility, reflecting more topographically challenging conditions for cyclists. While the weights are heuristic in nature, they allow consistent comparisons across cities and are based on the full distribution of slope categories observed in the data.

Results

The indicator reveals substantial variation in slope-induced cycling effort across the analysed cities. As shown in Figure 4.25, cities such as Amsterdam, Copenhagen, and Berlin exhibit near-zero average scores, with over 97% of their network segments falling within the flat [0–1%] slope category. These networks are essentially flat and thus offer optimal accessibility regardless of user physical condition.

In contrast, cities such as Lisbon, Athens, and Luxembourg present considerably higher average effort scores—ranging from 0.77 to 0.81. These scores reflect significant elevation differences and frequent occurrences of moderate to extreme slope segments. Luxembourg in particular stands out, with over 10% of its route network featuring slopes above 7%, and more than 2% exceeding the 16% category.

Intermediate cases include Madrid, Rome, and Brussels, where average scores range from 0.32 to 0.57. These cities combine mostly accessible terrain with isolated steep zones, suggesting heterogeneous topographic barriers depending on neighborhood.

Standard deviation values are consistent with this pattern: flat cities such as Amsterdam and Copenhagen present negligible internal variation, while hilly cities such as Lisbon or Luxembourg exhibit standard deviations above 0.4, indicating a diverse and sometimes abrupt slope profile within the same urban network.

To better illustrate these differences, Figure 4.27 visualises the segment-level steepness classification in Luxembourg. This spatialised view confirms the presence of steep slopes across multiple corridors and highlights the physical challenges faced by cyclists in topographically constrained environments.

Figure 4.27 shows a comparison of the distribution of slope-induced efforts across all routes in Vienna and Luxembourg. The result is clear: whereas in Luxembourg you should expect to go up and down hills in every direction you want to go, in Vienna, only a portion of the routes present significant elevation.

Limitations

This indicator presents two key limitations. First, terrain is an immutable geographic constraint: cities built on hilly or mountainous landscapes have limited capacity to reduce slope-induced effort through policy or infrastructure alone. As such, the indicator captures a structural challenge rather than a dimension of active planning or intervention, and should be interpreted accordingly.

Second, the slope weights assigned to each category are heuristic and subjective. Although they are proportional and based on observed distributions of slope classes, the model assumes a linear relationship between slope and effort that has not been empirically calibrated. Future refinements could incorporate non-linear physiological models or adjust weights based on empirical studies of effort or user perception.

City	Indicator 3a (Average)	Median	Std Deviation	Min	Max	[0 -1) %	[1 - 4) %	[4 - 7) %	[7 - 10) %	[10 - 16) %	[16 + %
Amsterdam	0.00	0.00	0.00	0.00	0.00	100%	0	0	0	0	0
Copenhagen	0.01	0.00	0.03	0.00	0.20	99.0%	1.0%	0	0	0	0
Berlin	0.03	0.00	0.08	0.00	0.44	97.2%	2.5%	0.2%	0	0.1%	0
Dublin	0.11	0.00	0.17	0.00	0.81	88.7%	10.8%	0.5%	0	0	0
Paris	0.18	0.09	0.22	0.00	1.00	82.9%	16.4%	0.6%	0	0	0
Vienna	0.24	0.12	0.29	0.00	1.34	79.9%	16.7%	2.6%	0.5%	0.3%	0.1%
Stockholm	0.31	0.25	0.28	0.00	1.61	73.2%	26.0%	0.6%	0.1%	0.1%	0.1%
Rome	0.32	0.24	0.26	0.00	1.02	72.2%	26.0%	1.4%	0.3%	0.1%	0.1%
Brussels	0.35	0.34	0.25	0.00	1.19	67.8%	29.4%	2.5%	0.2%	0	0
Madrid	0.57	0.57	0.26	0.00	1.39	49.6%	46.8%	2.7%	0.8%	0.2%	0
Athens	0.77	0.74	0.32	0.14	2.00	40.3%	50.3%	6.7%	1.4%	0.7%	0.5%
Lisbon	0.78	0.74	0.44	0.00	2.08	45.4%	43.1%	8.6%	1.2%	0.9%	0.8%
Luxembourg	0.81	0.77	0.48	0.00	2.33	42.5%	44.5%	7.1%	2.4%	1.5%	2.1%

Figure 4.25: Results of Indicator 3a - Terrain Difficulty. Higher scores reflect greater slope-induced effort.

4.3.2 Indicator 3b - Favourable Weather Days

Methodology

This indicator estimates the proportion of days per year in which weather conditions are suitable for urban cycling, based on daily temperature and precipitation values. While climate is an exogenous factor and cannot be influenced by municipal policies, it exerts a direct influence on cycling rates, comfort, and feasibility. Including this indicator allows the BIKE Index to account for structural climatic constraints and provides context for interpreting other infrastructure-related scores.

A day is considered unfavourable if it meets at least one of the following criteria, derived from previous literature on cycling behaviour under adverse conditions [67, 68]:

- Minimum temperature below 0°C
- Maximum temperature above 35°C
- Total precipitation exceeding 2mm

These thresholds capture the most frequent deterrents to everyday cycling: cold stress, heat exhaustion, and wet conditions that impair safety or comfort. Rain alone can reduce cycling activity by 25–36%, and thermal extremes are known to particularly affect vulnerable users [67].

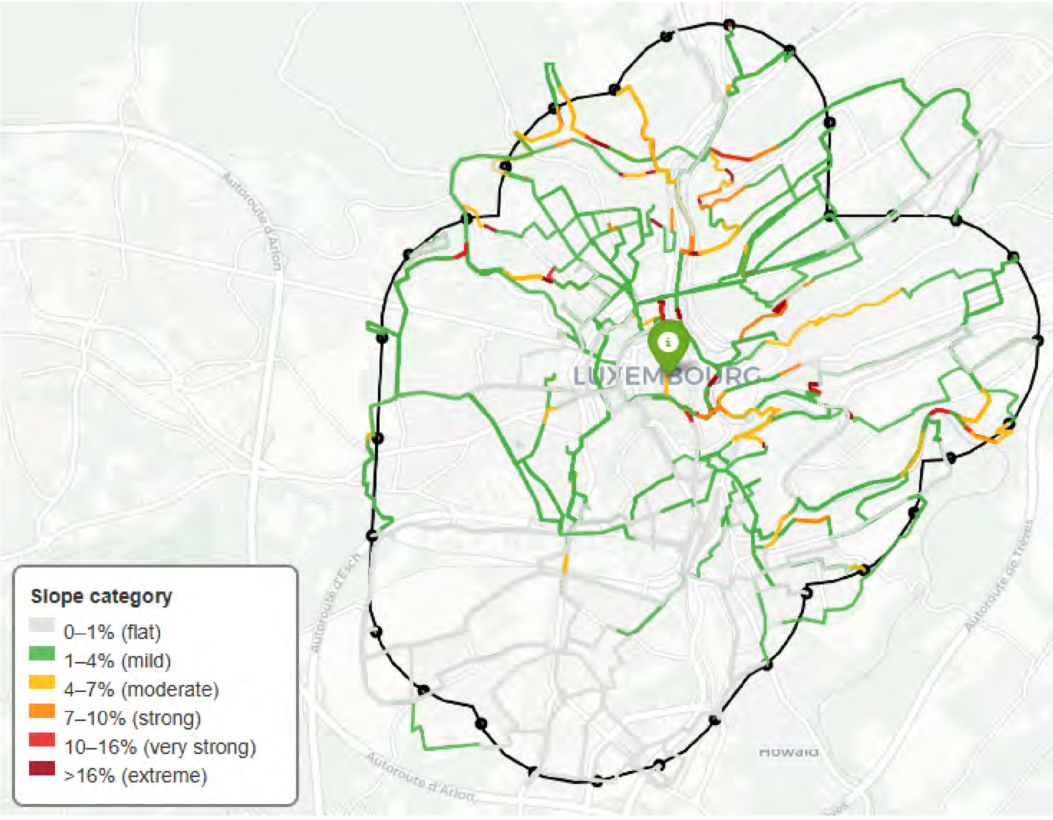


Figure 4.26: Slope categories along cycling routes in Luxembourg

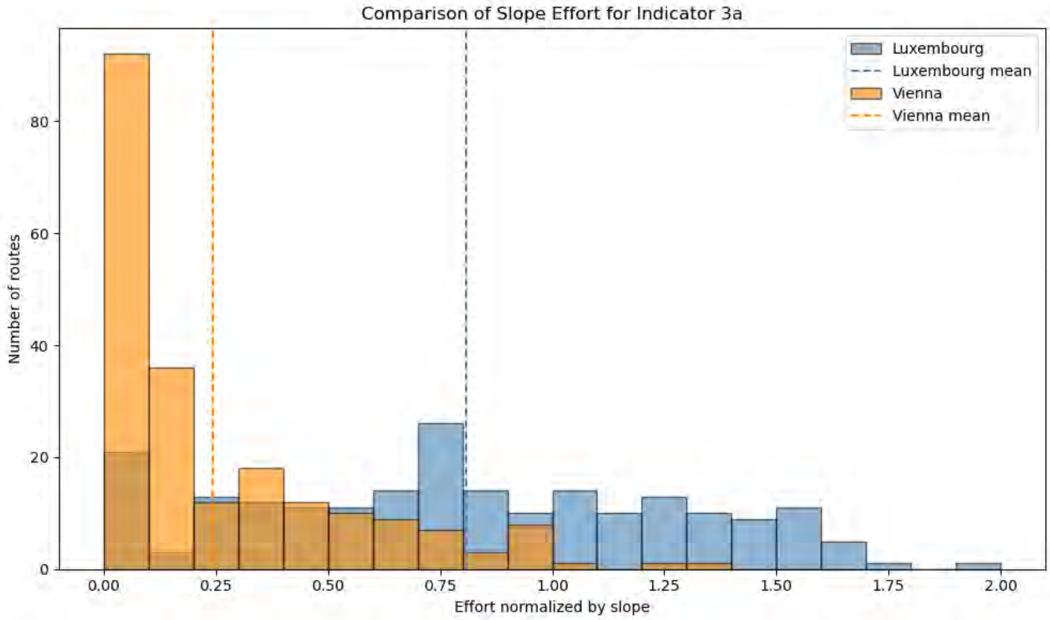


Figure 4.27: Indicator 3a: Distribution of slope-induced effort across all 210 routes in Vienna and Luxembourg

Daily data were obtained from the *ENSEMBLES observational dataset for European climate* (E-OBS ensemble mean dataset) (`v31.0e`) at 0.1° spatial resolution, a standard open-access climate product for Europe [69]. For each city, the grid point closest to the defined city center was selected, and daily values of minimum temperature (tn), maximum temperature (tx), and total precipitation (rr) were extracted for the period 2015–2024.

Each day is evaluated independently. If any of the three unfavorable thresholds is met, the day is flagged as unsuitable for cycling. The percentage of favorable days is then computed for each valid year and averaged across the period, as shown in Equation 4.9:

$$\text{Favourable Weather Days} = 1 - \left(\frac{\text{Number of Unfavourable Days}}{\text{Total Days}} \right) \tag{4.9}$$

The final result is a single percentage per city, representing the long-term climatic potential for urban cycling. This metric is stable, reproducible, and directly comparable across cities, as it is based on standardised thresholds and harmonised data sources.

Results

The results confirm strong climatic differences across European capitals in terms of cycling suitability. As summarised in Figure 4.28, **Athens**, Lisbon, and Rome lead the ranking, with over 78% of the year classified as favourable for cycling. These cities benefit from dry, temperate climates with very few cold or rainy days, although occasional hot days above 35°C are observed.

In contrast, cities such as Amsterdam, Stockholm, and especially Luxembourg report far lower scores—between 56% and 60%—primarily due to frequent rainfall and cold spells. For instance, Amsterdam registers 119 rainy days per year on average, and Stockholm faces more than 80 days below 0°C, which limits daily cycling conditions even when infrastructure is present.

Madrid presents a notable duality: while rain and snow are relatively rare, it accumulates more than 30 cold days and 38 hot days per year, reducing its share of favourable days to under 70%. Mid-range cities like Paris, Dublin, and Vienna show more balanced conditions, with values close to 70%, affected by moderate winters and variable precipitation.

Standard deviation values range from 2.2 to 5.4 percentage points across cities, indicating that interannual variability is limited and the indicator captures a stable climatic baseline. These values are averaged over 10 years (2015–2024), using only years with at least 250 valid daily observations per variable (which resulted to be all years).

Figure 4.29, Figure 4.30 and Figure 4.31 show the daily climate profile for Amsterdam, Stockholm and Madrid, in 2022, with thresholds visually overlaid. These are the cities with the most average cold, hot and rainy days in our sample, respectively. The temperature and precipitation ranges illustrate how extreme values are distributed throughout the year, providing an intuitive interpretation of how climatic factors affect daily cycling feasibility.

Limitations

This indicator is constrained by several factors. First, while weather and climate are generally exogenous, some cities have developed mitigation strategies that partially reduce their impact. Examples include covered cycling lanes, underground corridors, or maintenance protocols that improve cycling viability under light rain or cold temperatures. These adaptations are not captured by the indicator and may lead to underestimation of effective cycling conditions in well-adapted cities.

Second, the thresholds used to define unfavourable conditions—0°C, 35°C, and 2mm of precipitation—are based on documented behavioural responses but remain discretionary simplifications. Slight variations in these limits (e.g. using

5°C instead of 0°C) could affect the classification of marginal days and shift the resulting percentages.

Third, although the use of harmonised climate data ensures consistency, the method does not differentiate between intensity or duration of adverse events within the same day. A short, light shower is treated the same as continuous rainfall, which may overestimate the number of truly prohibitive days. Moreover, selecting a single grid point per city ignores possible intra-urban climatic diversity, particularly in large or topographically complex areas. Finally, the indicator does not account for perceived thermal conditions such as wind chill or heat index, which can significantly affect cycling comfort even when temperature thresholds are not exceeded.

City	Indicator 3b	Std Deviation	Rainy Days / Yr	Cold Days / Yr	Hot Days / Yr
Athens	84.4%	2.34	36	9	13
Lisbon	82.8%	3.38	57	0	5
Rome	78.5%	3.68	62	2	15
Paris	72.9%	3.92	82	16	3
Dublin	71.9%	3.05	91	15	0
Madrid	69.4%	3.79	46	30	38
Vienna	68.7%	2.24	70	48	4
Berlin	65.7%	3.81	70	59	2
Brussels	61.7%	2.63	102	41	2
Copenhagen	61.6%	5.42	105	44	0
Stockholm	61.4%	4.81	71	84	0
Amsterdam	60.1%	3.89	119	33	0
Luxembourg	56.3%	4.1	99	69	2

Figure 4.28: Results of Indicator 3b - Favourable Weather Days

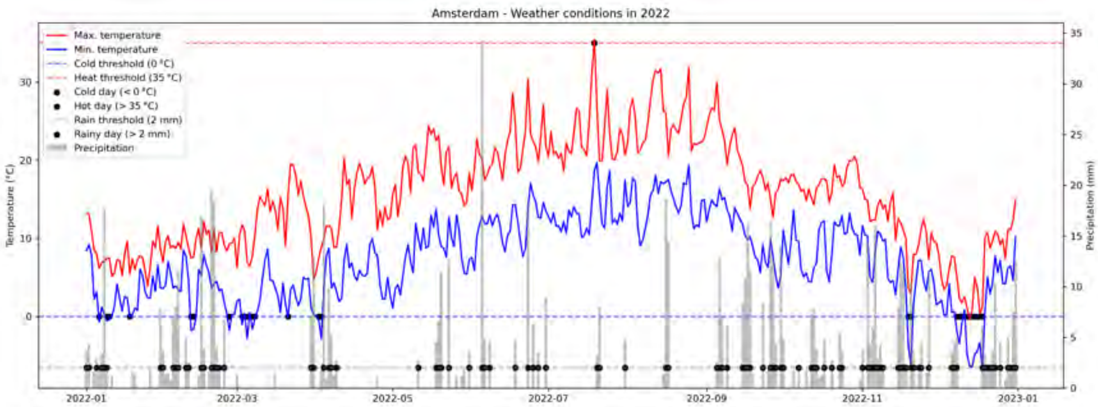


Figure 4.29: Climatic Conditions in Amsterdam (2022) – Daily Temperature and Precipitation

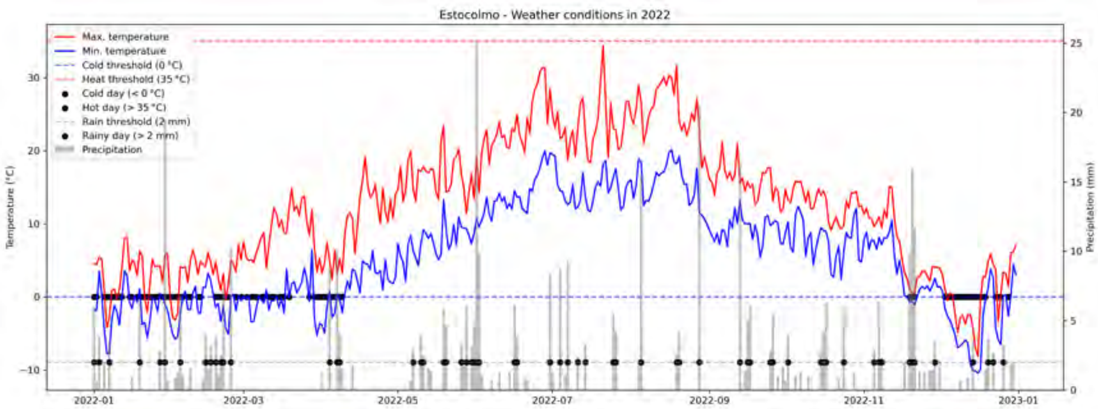


Figure 4.30: Climatic Conditions in Stockholm (2022) – Daily Temperature and Precipitation

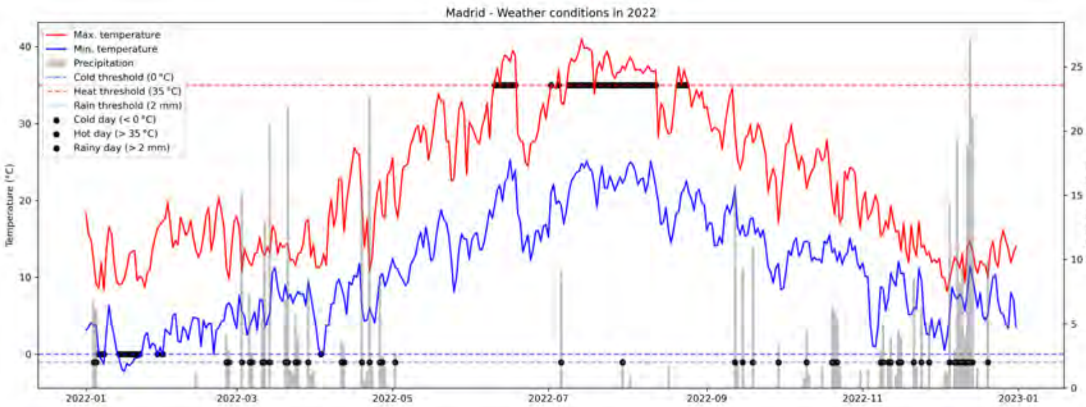


Figure 4.31: Climatic Conditions in Madrid (2022) – Daily Temperature and Precipitation

4.4 Dimension 4 – Safety and Street Quality

This dimension captures the conditions that affect how safe and comfortable it is to cycle in each city, beyond infrastructure provision. It combines two complementary perspectives:

- Indicator 4a: The objective risk of fatal accidents, adjusted for cycling exposure.
- Indicator 4b: The effective quality of the street network used by cyclists.

Together, they reflect whether the cycling environment is not only well designed on paper, but also safe, connected, and legally accessible in practice. While one indicator is based on national statistics and the other on segment-level routing data, both aim to represent the day-to-day experience of navigating the city by bike.

4.4.1 Indicator 4a – Fatality Rate

This dimension captures the conditions that affect how safe and comfortable it is to cycle in each city, beyond infrastructure provision. It combines two complementary perspectives: the objective risk of fatal accidents, adjusted for cycling exposure (Indicator 4a), and the effective quality of the street network used by cyclists (Indicator 4b). Together, they reflect whether the cycling environment is not only well designed on paper, but also safe, connected, and legally accessible in practice. While one indicator is based on national statistics and the other on segment-level routing data, both aim to represent the day-to-day experience of navigating the city by bike.

Methodology

This indicator estimates the real risk of fatal cycling crashes, adjusting for exposure by incorporating how much cycling is done in each country. Unlike raw fatality counts, exposure-adjusted rates enable meaningful comparisons of cycling safety across countries with widely different levels of bicycle use. The indicator serves as a proxy for the objective safety of the cycling environment, particularly in the absence of reliable and harmonized data at the city level.

The fatality rate is defined as the number of annual cyclist deaths per 100 million kilometers cycled, as shown in Equation 4.10:

$$\text{Fatality rate} = \frac{\text{Annual cyclist deaths}}{\text{Million km cycled per year}} \times 100 \tag{4.10}$$

This metric is endorsed by the OECD and the International Transport Forum (ITF), and is widely used in cross-country comparisons of road safety performance [35]. A lower value indicates a safer environment for cyclists per unit of exposure, independent of population size or cycling uptake.

Data were extracted from Table 4 of the 2018 Discussion Paper jointly produced by the International Transport Forum (ITF), the World Health Organization (WHO), and the Physical Activity through Sustainable Transport Approaches (PASTA) project [35]. The authors compiled data for 47 countries by combining fatality records and travel surveys, applying a standardized exposure metric and classifying each country's reliability level.

Where national travel surveys were unavailable, exposure was estimated using average trip lengths and mode share assumptions at the regional level. This approach introduces uncertainty but remains the best available method for estimating cycling risk consistently across Europe.

For the purposes of the BIKE Index, the national fatality rate is assigned to each capital city. This is an approximation, but considered justifiable and sufficiently robust given the strong correlation between national and urban safety trends. Moreover, this is the only indicator in the index derived at national scale, and it is clearly marked as contextual rather than infrastructure-based.

All values refer to the period 2011–2015, averaged over five years to minimise annual fluctuations and reporting bias. The final indicator is expressed in cyclist fatalities per 100 million kilometers cycled, without further transformation or scaling.

Results

The indicator reveals substantial differences in cycling safety across the studied countries. As shown in Figure 4.32, national fatality rates range from just 0.2 deaths per 100 million kilometres cycled in Luxembourg to 5.1 in Italy, representing a 25-fold difference in exposure-adjusted risk.

At the safer end of the scale, countries such as Spain, Greece, Luxembourg, and the Netherlands report fatality rates below 1.0. These low values reflect a combination of favorable traffic conditions, higher infrastructure quality, or more developed safety cultures. For instance, the Netherlands maintains a low fatality rate (0.8) despite its extremely high cycling exposure, with over 15 billion kilometers cycled annually.

Conversely, France, Austria, and particularly Italy show substantially higher fatality rates, with Italy exceeding 5 deaths per 100 million kilometres. In these cases, low modal shares, high traffic speeds, or a lack of dedicated infrastructure may contribute to greater objective risk for cyclists.

Intermediate cases include Germany, Sweden, and Portugal, which cluster between 1.0 and 1.2. These results illustrate the gradient between cycling-rich, safety-oriented environments and less protective contexts. It is also notable that high fatality rates are not necessarily linked to low exposure: for example, Germany reports over 35 billion kilometres cycled annually with a moderate risk level of 1.1.

In the BIKE Index, each capital city inherits the national value of its respective country as a contextual proxy. While this introduces some limitations (discussed below), it ensures consistency and comparability across cities in the absence of harmonised urban-level data.

Limitations

The most significant limitation of this indicator is the age of the data. All fatality rates are based on five-year averages covering the period 2011–2015, meaning they may no longer reflect current conditions. Since then, many European cities have expanded their cycling infrastructure, introduced speed-reduction measures, or implemented Vision Zero strategies. Using outdated figures may therefore underestimate recent safety improvements or misrepresent present-day risk levels.

Second, the indicator uses national-level values as proxies for capital cities, due to the lack of consistent, exposure-adjusted data at the urban scale. While national rates offer a stable and comparable baseline, they may smooth over the typically safer conditions found in dense, infrastructure-rich capitals.

Third, although exposure-adjusted rates are statistically sound, their accuracy depends on the quality of both fatality and exposure data. Several countries rely on estimated cycling distances derived from assumptions on trip frequency and mode share [35], introducing a degree of uncertainty.

Finally, the indicator only accounts for fatalities, excluding injuries and subjective risk perception—factors that also shape cycling behavior and public support for cycling policies.

City	Country	Fatality rate (per 100M km)	Avg Fatalities / year	Exposure (million km/year)
Luxembourg	Luxembourg	0.2	0.4	178
Madrid	Spain	0.4	64.6	14,494
Athens	Greece	0.5	15.8	3,443
Amsterdam	Netherlands	0.8	125.4	15,080
Copenhagen	Denmark	0.9	28.2	3,079
Lisbon	Portugal	1.0	32.6	3,253
Berlin	Germany	1.1	387.6	35,367
Stockholm	Sweden	1.2	22.6	1,934
Dublin	Ireland	1.8	8.8	482
Brussels	Belgium	2.4	74.0	3,033
Vienna	Austria	2.4	45.8	1,898
Paris	France	2.8	152.0	5,468
Rome	Italy	5.1	269.8	5,294

Figure 4.32: Results of Indicator 4a - Fatality Rate. Source: OECD [35]

4.4.2 Indicator 4b - Street Suitability

Methodology

This indicator assesses the overall street-level suitability of the cycling network, reflecting how well the urban environment supports safe, legal, and comfortable cycling—regardless of whether dedicated infrastructure is present. Unlike binary infrastructure metrics, this indicator captures the nuanced reality of where cyclists are actually routed and how appropriate those segments are in practice.

The metric relies on the `suitability` value provided by the OpenRouteService (ORS) API, which is returned when explicitly requested in a route calculation [70, 71]. For each segment, ORS assigns a normalised score between 0 (least suitable) and 1 (most suitable), based on attributes relevant to the selected travel profile. In the case of cycling, suitability considers the following factors:

- Road classification (e.g. cycleways, primary, tertiary, residential)
- Legal access for cyclists
- Surface type and pavement quality

- Presence or absence of cycle infrastructure
- Traffic characteristics and network context

Although the internal algorithm is not fully disclosed, documentation and developer discussions indicate that "suitability for cycling generally reflects how well the segment matches the needs of the profile (cycling, in this case)"[72, 73]. The score integrates information from OpenStreetMap (OSM), and is designed to favour segments that are segregated, calm, or legally accessible[23]. According to the developers, for cycling and walking profiles, suitability values are derived from path type, surface, and accessibility—"how suitable the way is based on characteristics of the route and the profile" [72].

This enables a more nuanced assessment than infrastructure-only maps. For instance, low-speed residential streets may score near 1.0 even without dedicated lanes, while major arterial roads with no protections or poor surface may fall below 0.6. Shared-use paths or mixed-traffic segments may also receive moderate values depending on legal access and surface conditions.

The indicator is computed using the 210 cross-city cycling routes defined in Section 4.0.1, ensuring consistency across cities. Each route is decomposed into segments, and a length-weighted mean of the suitability scores is calculated as shown in Equation 4.10:

$$\text{Street Suitability} = \frac{\sum_i \text{suitability}_i \cdot \text{length}_i}{\sum_i \text{length}_i} \tag{4.11}$$

The final result is a single value between 0 and 1 for each city. In practice, observed values range between 0.78 and 0.91, forming a tight distribution that still reflects meaningful differences in how cycle-friendly each urban network is. Based on empirical inspection of these values, the following thresholds are proposed:

- Above 0.85: consistently high suitability
- 0.80–0.85: moderately supportive conditions
- Below 0.80: fragmented or suboptimal environments

Because the suitability parameter is automatically computed by ORS using OSM data, the indicator is fully reproducible, scalable, and independent of manual classification. It provides a robust measure of the effective quality of streets actually used by cyclists, including segments not formally classified as cycle infrastructure.

Results

The results reveal significant variation in the street-level quality of cycling routes across cities. As shown in Figure 4.33, suitability scores range from a high of 0.91 in Copenhagen to a low of 0.78 in Lisbon, suggesting meaningful differences in how well urban street networks support cycling.

The top-performing cities—Copenhagen, Brussels, Paris, and Stockholm—consistently exceed a score of 0.89. In these cities, over 75% of all route segments are rated above 0.9, and more than 90% surpass 0.8. This indicates that the vast majority of streets used by cyclists offer very high levels of comfort, accessibility, and legal support.

Mid-range performers include Vienna, Dublin, Amsterdam, and Berlin, with scores between 0.86 and 0.89. These cities display more heterogeneity: although they include many highly rated segments, they also show a larger share of routes in the 0.8–0.9 or even 0.7–0.8 intervals. For example, Amsterdam's high suitability (0.87) is achieved despite having almost no segments rated 1.0, with the bulk concentrated between 0.9 and 0.95.

Lower-scoring cities—Athens, Madrid, Rome, and Lisbon—exhibit more fragmented networks. In Lisbon, the overall suitability score drops to 0.78, with 84.2% of segments rated between 0.8 and 0.9, and a non-negligible share (5.9%) below 0.5. Rome also reports over 6% of segments in the lowest suitability band. These patterns suggest that cyclists in these cities are often routed through legally accessible but sub-optimally designed or exposed streets, even when infrastructure coverage may appear sufficient.

The distribution patterns highlight that even cities with high modal shares (e.g. Amsterdam or Berlin) can contain notable internal variation, and that suitability scores are sensitive to local tagging accuracy, street context, and infrastructure quality beyond simple presence.

Figure 4.35 and Figure 4.34 provide a spatial example of the indicator output in the city of Copenhagen and Rome. The colored segments represent individual route sections, colored according to their suitability score. It clearly shows that most high-scoring segments are concentrated along a few principal cycling axes, particularly those near the city center and main arteries where dedicated infrastructure or legal cycling access exists.

In contrast, segments located outside these primary corridors tend to display lower suitability scores, especially when crossing peripheral or arterial roads without protective features. This confirms the fragmented nature of Rome's cycling environment, where even within the urban perimeter, route quality varies substantially depending on alignment. The visual map complements the distributional statistics by revealing spatial patterns and highlighting structural gaps in the usable cycling network.

Limitations

The main limitation of this indicator lies in the opacity of the suitability algorithm used by ORS. Although the parameter is documented and empirically consistent, the exact weighting and logic behind its calculation for the cycling profile is not based upon a conventional framework. [72]. This restricts the interpretability of score thresholds and makes it difficult to audit the influence of individual attributes such as surface type or traffic volume.

Second, suitability scores are sensitive to OpenStreetMap (OSM) data quality, particularly regarding surface, access, and road classification tags. While OSM coverage is generally reliable in European capitals, local inconsistencies or outdated edits can affect the computed score without reflecting real-world conditions. However, this risk is mitigated by the high density and frequency of community-contributions in most urban centres.

City	Indicator 4b	[1.0]	[0.9-1.0)	[0.8-0.9)	[0.7-0.8)	[0.6-0.7)	[0.5-0.0]
Copenhagen	0.91	35.0%	37.8%	25.8%	0.3%	1.1%	0.1%
Brussels	0.90	20.1%	59.5%	19.3%	0.2%	0.8%	0.3%
Paris	0.89	17.2%	61.6%	18.9%	0.1%	1.8%	0.4%
Stockholm	0.89	12.0%	65.7%	20.5%	0.5%	1.1%	0.2%
Vienna	0.89	17.1%	57.6%	22.2%	1.0%	1.6%	0.6%
Dublin	0.87	25.7%	31.9%	38.7%	0.1%	1.5%	2.1%
Amsterdam	0.87	1.4%	70.9%	26.4%	0.2%	0.9%	0.3%
Luxembourg	0.87	40.7%	5.6%	45.2%	2.6%	3.0%	3.0%
Berlin	0.86	22.2%	24.4%	50.9%	0.5%	0.8%	1.3%
Athens	0.84	29.3%	2.0%	61.4%	1.7%	2.0%	3.7%
Madrid	0.82	40.4%	50.6%	2.9%	1.7%	4.4%	0.0%
Rome	0.80	11.3%	4.3%	75.4%	1.4%	1.5%	6.1%
Lisbon	0.78	0.3%	6.2%	84.2%	0.6%	2.9%	5.9%

Figure 4.33: Results of Indicator 4b - Street Suitability

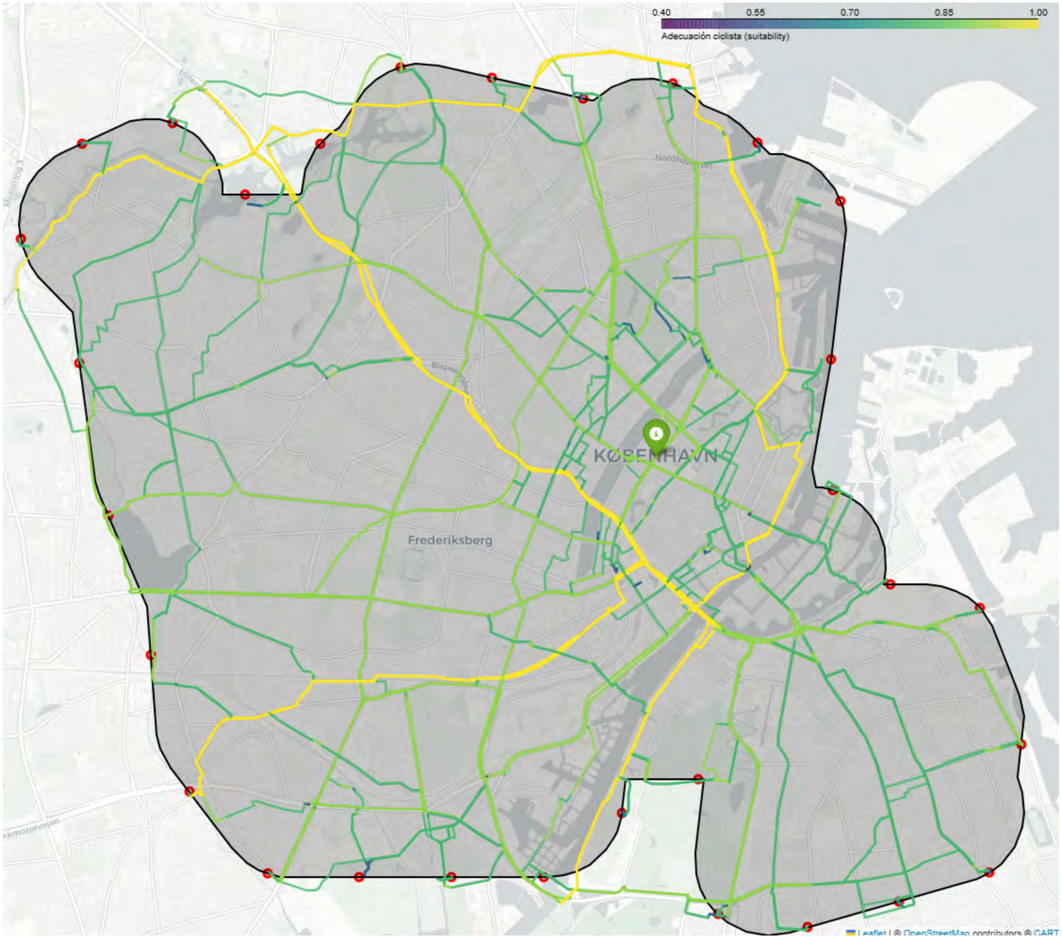


Figure 4.34: Indicator 4b: Cycling suitability along simulated routes in Copenhagen.

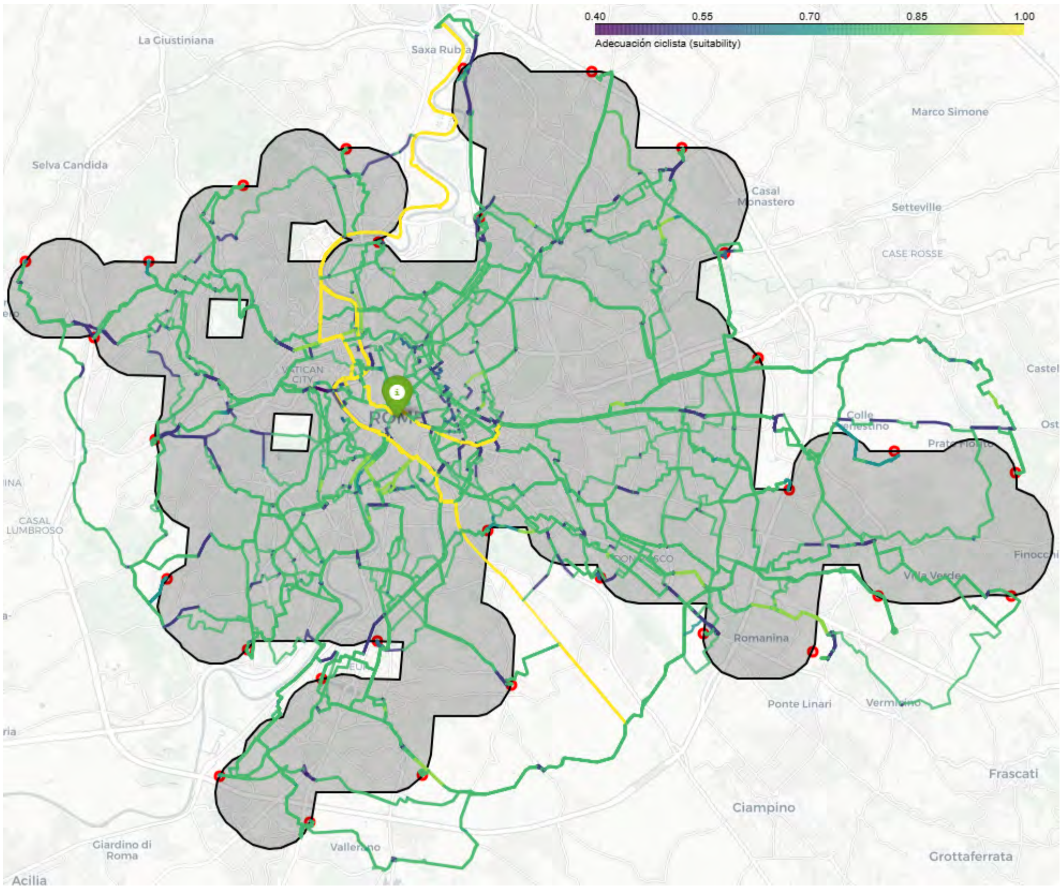


Figure 4.35: Indicator 4b:: Cycling suitability along simulated routes in Rome.

Chapter 5

Results

This section presents the composite results of the BIKE Index applied to the 13 European capital cities chosen in our sample (see Section 3.2), showing aggregated scores at both the dimension and overall index levels. The analysis reveals the relative performance of cities across the four main dimensions of cycling conditions: Infrastructure, Services, Environment, and Safety.

At the end of the chapter, the complete results are shown. Figure 5.9 presents the normalized results for all individual indicators included in the BIKE Index, following the procedure described in Section 3.3. To complement this, Figure 5.10 aggregates the results at the dimension level, offering a broader view of performance across the four core components of the index.

5.1 Overall BIKE Index Scores

Figure 5.1 visualizes the final results after adding together all the indicators. The composite BIKE Index scores range from 65.6 (Amsterdam) to 30.3 (Rome), representing a substantial spread in cycling conditions across the analyzed European capitals. Amsterdam achieves the highest overall score, followed by Paris (62.6) and Copenhagen (57.6) in the top tier of performance. The middle tier includes Stockholm (54.8), Vienna (54.2), Madrid (48.5), Brussels (48.5), Lisbon (48.0), and Berlin (44.8). The bottom tier comprises Luxembourg (41.6), Dublin (38.7), Athens (34.5), and Rome (30.3).

The results demonstrate a clear stratification in cycling friendliness, with a 35.3-point gap between the highest and lowest performers. Three cities achieve scores above 55, representing the most bike-friendly environments in the sample. Six cities cluster in the middle range between 40-55 points, while four cities fall below 40, indicating significant challenges in their cycling environments.

It is important to emphasise that the BIKE Index is relative: a score of 50 represents the median performance within the sample, not an absolute standard. Cities like Stockholm or Vienna score near this midpoint, reflecting balanced but not exceptional conditions. Notably, low scores in southern cities such as Rome or Athens are mainly driven by gaps in infrastructure and safety, despite their favourable climate. Conversely, Stockholm's moderate score despite harsh winters suggests that strong policies and infrastructure can mitigate environmental barriers.

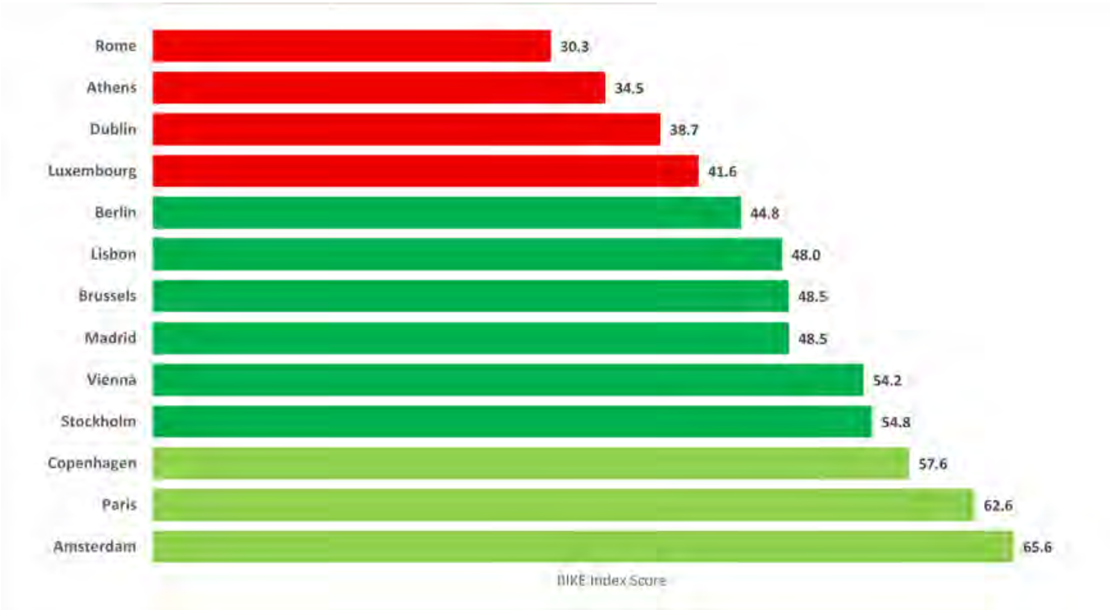


Figure 5.1: Overall BIKE Index Rankings for 13 European Capital Cities

5.2 Dimension-Level Results

5.2.1 Infrastructure Dimension

The Infrastructure dimension shows the largest variation among all dimensions, with scores ranging from 83 (Amsterdam) to 18 (Athens). Amsterdam leads this dimension with exceptional performance, followed by Stockholm (78) and Paris (73). Copenhagen, despite its overall high ranking, achieves only 46 points in infrastructure, suggesting room for improvement in dedicated cycling infrastructure coverage and quality.

At the lower end of the infrastructure spectrum, Athens (18), Berlin (33), Dublin (30), and Rome (30) demonstrate substantial infrastructure deficits. The large range of 65 points in this dimension reflects the fundamental differences in cycling infrastructure development across European capitals.

These results highlight the critical role of infrastructure in shaping overall cycling conditions. High-scoring cities combine dense, high-quality networks with supportive planning policies. In contrast, cities at the bottom show structural deficiencies that directly limit safe and convenient cycling. The unexpectedly low score of Berlin suggests that cycling culture alone does not guarantee strong infrastructure provision.

5.2.2 Services Dimension

Paris dominates the Services dimension with a near-perfect score of 85, followed closely by Copenhagen (80). This dimension shows more moderate variation than Infrastructure, with scores ranging from 85 to 24. Brussels (65), Madrid (59), and Amsterdam (52) achieve mid-range performance in services provision.

Stockholm presents a notable contrast, scoring only 24 in Services despite achieving 78 in Infrastructure. This pattern suggests that high infrastructure scores do not necessarily correlate with comprehensive service provision. Rome (32), Dublin (34), Athens (35), and Luxembourg (43) cluster at the lower end of service accessibility.

The moderate variation in this dimension suggests a more consistent baseline of service provision across cities, though notable gaps remain. The case of Stockholm illustrates that strong infrastructure does not always translate into accessible services, pointing to different policy priorities or implementation stages. Similarly, the low scores in southern cities reinforce broader structural lags in cycling ecosystem development beyond just infrastructure.

5.2.3 Environment Dimension

The Environment dimension exhibits the most compressed distribution, with scores ranging from 61 (Dublin) to 19 (Luxembourg). Most cities cluster between 40-60 points, indicating relatively similar environmental constraints across the sample. Rome (59), Paris (59), Berlin (58), and Copenhagen (55) achieve above-average environmental scores.

Luxembourg emerges as a clear outlier with only 19 points, reflecting significant topographical and meteorological challenges that constrain cycling accessibility. Madrid (41), Brussels (42), and Stockholm (43) show below-average environmental conditions among the analyzed cities.

The narrow range of scores in this dimension suggests that environmental conditions, while important, vary less dramatically than infrastructure or services. Luxembourg stands out as a clear exception, where steep terrain and weather act as major deterrents. Overall, this dimension appears to play a more secondary role in explaining cross-city differences in cycling conditions.

5.2.4 Safety Dimension

The Safety dimension displays significant variation, ranging from 66 (Luxembourg) to 0 (Rome). Luxembourg leads this dimension despite poor performance in other areas. Copenhagen (61), Amsterdam (55), and Athens (55) also achieve strong safety scores. Madrid (52) and Stockholm (51) perform moderately in this dimension.

Rome receives a score of 0 in Safety, representing the most extreme performance gap observed across all dimensions and cities. Paris scores particularly low (24) in Safety despite strong overall performance, highlighting dimension-specific challenges even among top-performing cities.

The wide spread in Safety scores underscores its critical and uneven role across cities. High-performing cities like Luxembourg and Copenhagen show that strong safety outcomes are achievable regardless of overall index rank. In contrast, Rome's score of 0 reveals severe safety deficiencies, which likely undermine all other efforts to promote cycling. The low score of Paris highlights that strong infrastructure and services do not always guarantee safe cycling conditions.

5.2.5 Cross-Dimensional Performance Patterns

The analysis reveals distinct performance profiles among cities. Amsterdam demonstrates balanced excellence with high Infrastructure (83) and moderate scores across other dimensions. Paris exhibits service-oriented strength (Services: 85) but shows weakness in Safety (24). Copenhagen achieves consistent mid-to-high performance across all dimensions except Infrastructure.

Several cities show highly unbalanced profiles. Stockholm combines exceptional Infrastructure (78) with poor Services (24), while Luxembourg pairs strong Safety (66) with poor Environment (19). Rome displays consistently low performance across most dimensions, with critical Safety deficiencies.

The middle-tier cities generally show more balanced profiles with smaller standard deviations across dimensions. Madrid demonstrates the most balanced performance profile among all cities, with dimension scores ranging only from 41 to 59.

These patterns suggest that each city's performance is shaped by a unique combination of policy priorities, historical investment, and geographic constraints. Amsterdam's balanced profile reflects decades of integrated planning and a mature cycling culture. Paris's strong services but low safety may result from rapid recent investment in infrastructure and services without parallel improvements in traffic safety. Copenhagen's relatively low Infrastructure score likely reflects limitations in infrastructure density rather than quality, while Stockholm's imbalance suggests a focus on physical infrastructure without equivalent investment in support services. Luxembourg's strong Safety but poor Environment likely stems from low traffic volumes offset by steep terrain and adverse weather. Rome's consistently low scores point to structural neglect of cycling across all dimensions. Madrid's balanced profile may indicate steady, moderate progress without major gaps or standout strengths.

Figure 5.2 offers a comparison of the final results for all dimensions. Figure 5.3, Figure 5.4, Figure 5.5 and Figure 5.6 show the ranking for each dimension separately.

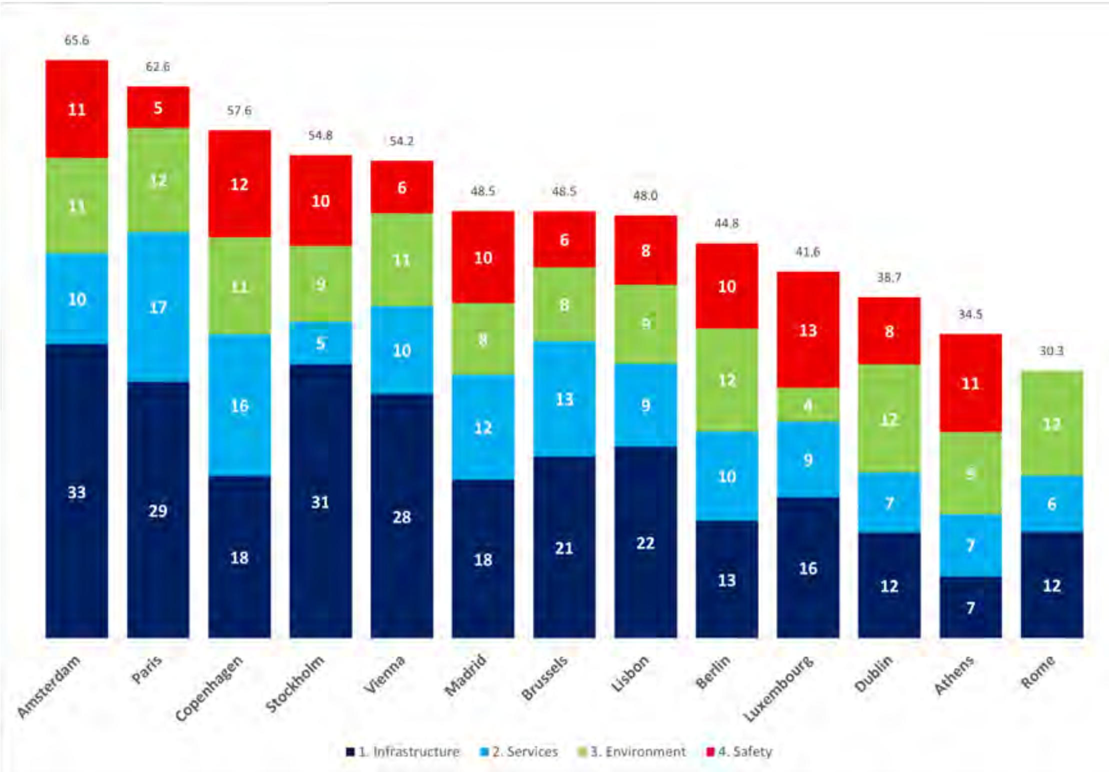


Figure 5.2: BIKE Index Dimension Scores by City

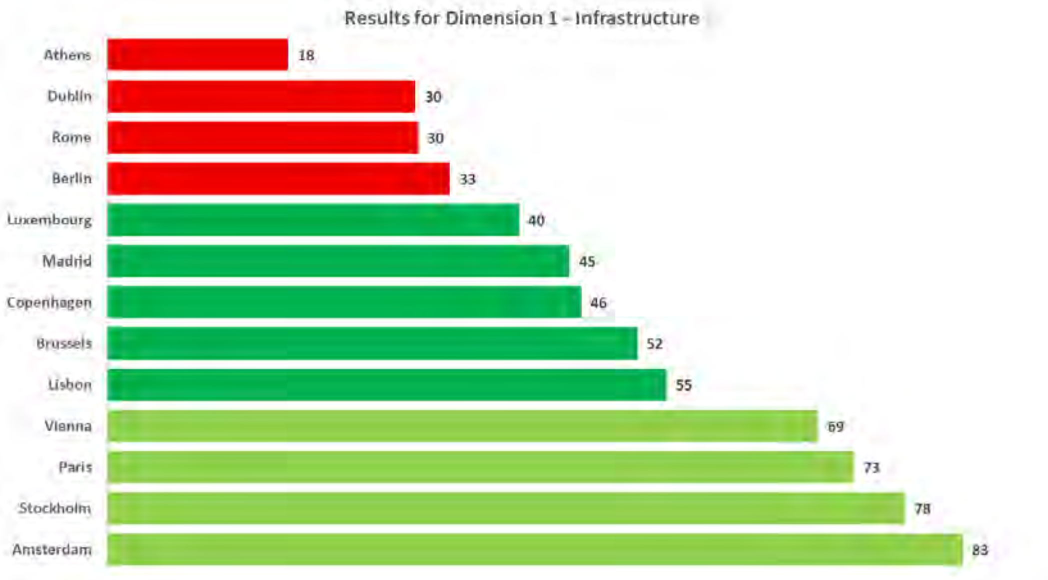


Figure 5.3: Results for Dimension 1 - Cycling Infrastructure (40%)

Figure 5.4: Results for Dimension 2 - Environmental Constraints (20%)

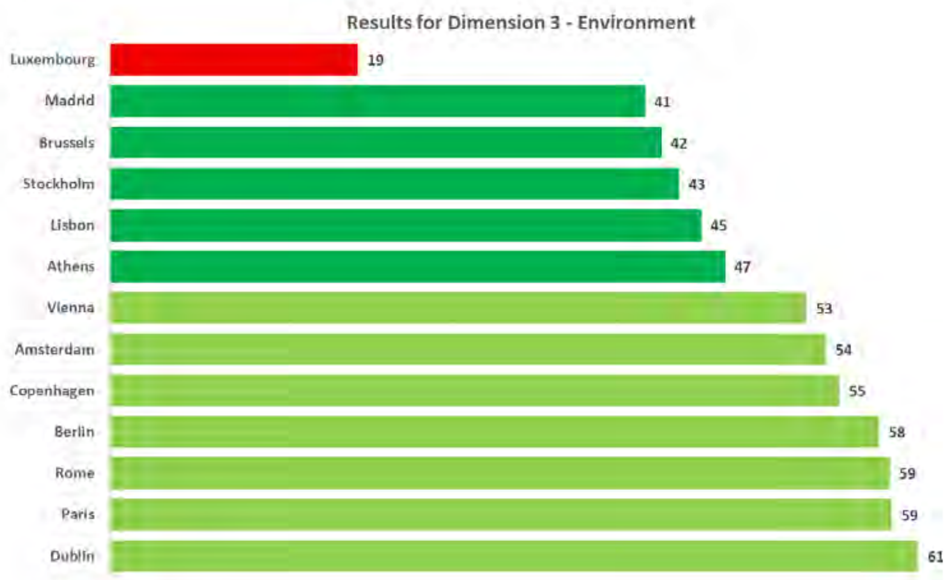


Figure 5.5: Results for Dimension 3 - Environmental Constraints (20%)

Figure 5.6: Results for Dimension 4 - Safety and Street Quality (20%)

5.3 Case Studies

To further illustrate the practical application of the BIKE Index, this section includes two case studies. The first explores in detail the cycling conditions of a single city, while the second compares two contrasting cities to highlight how the index can reveal differences in cycling performance and guide targeted improvements.

5.3.1 Madrid Case Study: A Balanced Middle-Tier Performer

Madrid achieves an overall BIKE Index score of 48.5, positioning it in 6th place among the 13 analyzed European capitals, tied with Brussels. This score places Madrid squarely in the middle tier of cycling performance, below the top-performing Nordic and Dutch cities but significantly above the bottom quartile.

Cycling Infrastructure

Cycling Infrastructure is one of Madrid's main limitations, with a dimension score of 45, ranking 8th among the 13 cities. This is due in part to only 46% of route kilometers using cycling-friendly infrastructure and just 39% of the urban grid being covered by protected bike lanes. While Madrid's network offers relatively high route efficiency (scoring 72), indicating that cycling routes are fairly direct, the lack of widespread, high-quality infrastructure means that cyclists still spend much of their journeys sharing space with motor vehicles or navigating fragmented corridors. This reflects both historical underinvestment and a focus on flagship projects rather than citywide coverage. Compared to the top three cities (Amsterdam, Paris, Copenhagen), which average 73% infrastructure coverage and 66% protected network coverage, Madrid's network remains patchy and less protective.

Cyclist Services

In Cyclist Services, Madrid performs notably well, scoring 59 and ranking 4th overall. The city's bike-sharing system, BiciMAD, covers 67% of the urban grid—on par with or above the top cities—and is widely accessible across central and peripheral neighborhoods. However, access to bike repair shops and retail services, while decent (47), still lags behind leaders like Paris and Copenhagen, where service density and spatial equity are higher. This suggests that while Madrid has invested heavily in public bike-sharing, the private service ecosystem is still catching up, particularly in outlying districts.

Environmental Constraints

Environmental Constraints present Madrid's most significant structural barrier, with a dimension score of 41 (12th place). The city's topography is challenging: hills and elevation changes are common, as reflected by a terrain difficulty score of 33—well below the top cities, where flatness is the norm. While Madrid enjoys more favorable weather days (52) than many northern cities, the combination of summer heat and steep routes creates a real deterrent for everyday cycling. This means that, despite the city's relatively dry and mild climate, the physical effort required to cycle across much of the city is considerably higher than in Amsterdam or Copenhagen.

Safety and Street Quality

On Safety and Street Quality, Madrid scores 52, ranking 5th. Its fatality rate is low (67), thanks in part to Spain's national road safety policies and the adoption of 30 km/h speed limits in urban areas. However, the city's street suitability score is just 9, indicating that many cycling routes traverse streets with suboptimal conditions—narrow lanes, parked cars, and inconsistent markings. This gap between objective safety and perceived comfort highlights a common pattern: while Madrid is relatively safe statistically, the day-to-day experience for cyclists is still undermined by street design and traffic stress.

When compared at the indicator level to the average of the top three cities, Madrid's strengths are most visible in route efficiency and bike-sharing coverage, while its biggest gaps are in protected network coverage, terrain, and street suitability. The radar chart in Figure 5.7 visualizes this comparison, showing Madrid's profile (blue) against the top-three average (green).

Conclusions

Madrid presents a balanced performance across the BIKE Index dimensions, yet this apparent equilibrium masks deep internal contrasts. The city combines a Europe-leading bike-sharing system and relatively strong safety outcomes with a fragmented, hilly, and car-dominated street network. To fully capitalize on its favorable climate and robust service provision, Madrid would benefit from expanding continuous, protected cycling corridors—especially into working-class peripheral areas. Enhancing street-level comfort through parking space removal and surface improvements could also raise its infrastructure suitability (notably the 4b score), responding to the latent demand evident in the widespread use of BiciMAD. In this sense, Madrid exemplifies a "service-rich but infrastructure-constrained" cycling city—well positioned for substantial growth if its physical networks align with its policy ambition and emerging cycling culture.

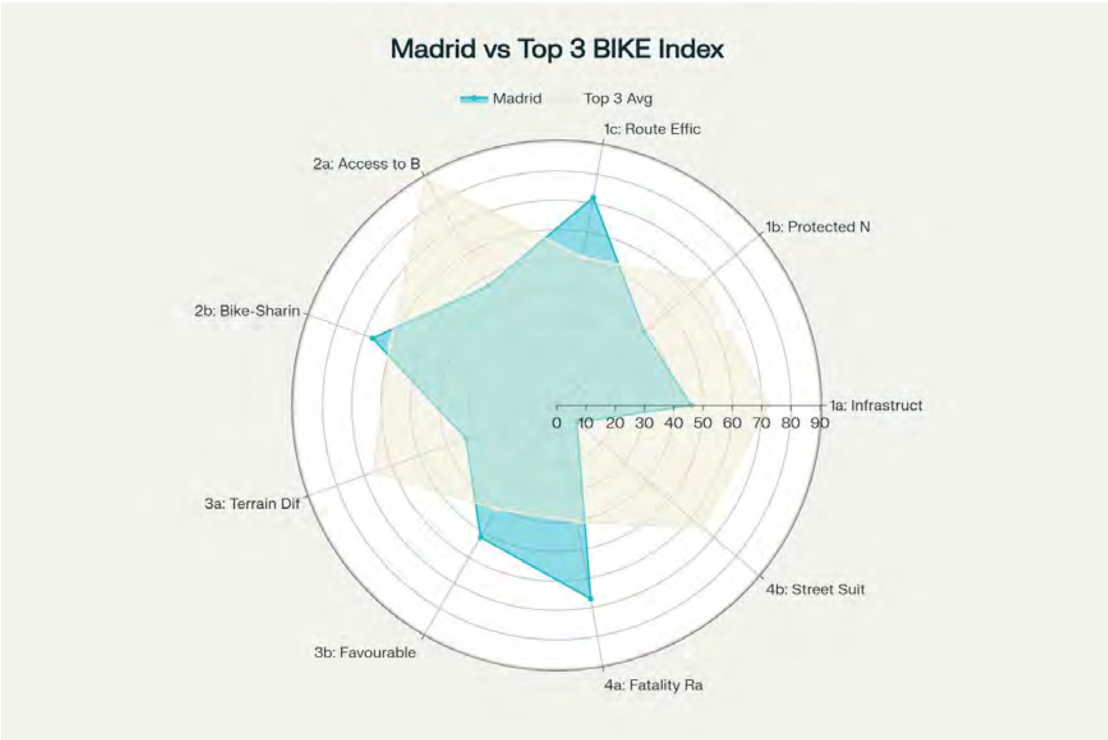


Figure 5.7: Radar chart comparing Madrid to the average of the top-3 cities on each indicator

5.3.2 Amsterdam vs Paris: A Tale of Two Cycling Capitals

Amsterdam and Paris represent the pinnacle of European cycling achievement, securing the top two positions in the BIKE Index with scores of 65.6 and 62.6 respectively. Despite their close overall rankings, these cities exemplify fundamentally different approaches to cycling infrastructure and urban mobility. Amsterdam represents the "infrastructure-first" model with unparalleled dedicated cycling networks, while Paris embodies the "service-integrated" approach with comprehensive support systems and rapid infrastructure expansion. The radar chart in Figure 5.8 visualizes the comparison across the two cities.

Infrastructure: Amsterdam's Dominance vs Paris's Balanced Growth

Amsterdam establishes clear supremacy in the Infrastructure dimension, scoring 83 compared to Paris's 73, yet the underlying patterns reveal distinct strategic approaches. Amsterdam achieves a perfect infrastructure usage score of 100, meaning most of recommended cycling routes utilize dedicated, high-quality cycling infrastructure. This reflects decades of systematic investment in protected cycleways that form a comprehensive, city-wide network. The city's protected network coverage score of 77 demonstrates extensive spatial reach, ensuring that cyclists across Amsterdam benefit from segregated infrastructure.

Paris, while trailing in absolute infrastructure metrics, demonstrates remarkable route efficiency with a score of 73—nearly double Amsterdam's 37. This indicates that Paris's cycling network, though less comprehensive in coverage, provides more direct connections across the city. Paris's infrastructure usage score of 79 and protected network coverage of 67 reflect a rapidly developing but still incomplete network.

The contrast highlights two successful but different evolutionary paths: Amsterdam's mature, blanket coverage versus Paris's strategic, corridor-focused development that maximizes connectivity with targeted investments.

Services: Paris's Excellence vs Amsterdam's Moderate Performance

The Services dimension reveals a complete reversal of leadership, with Paris achieving a perfect score of 85 while Amsterdam manages only 52. Paris excels across both service indicators: a perfect bike services accessibility score of 100 and exceptional bike-sharing coverage of 75. The city's dense network of repair shops, retailers, and Vélib' stations creates an ecosystem where cycling is supported at every level—from maintenance to flexible access options.

Paris's bike-sharing system deserves particular recognition, covering three-quarters of the urban grid and providing accessible entry points for residents without private bicycles. This extensive coverage reflects strategic public investment in shared mobility infrastructure that complements rather than competes with private bicycle ownership. However, note that only Paris's city center is considered in this study, which would skew the results.

Amsterdam's more modest performance (bike services score of 68, bike-sharing coverage of 41) reflects a different urban context. In a city where bicycle ownership approaches 1.3 bikes per resident [74], the demand for extensive bike-sharing networks is naturally lower. Amsterdam's cycling culture has developed around private ownership supported by a robust but less dense service infrastructure. The city's approach prioritizes long-term bicycle ownership over flexible access, reflecting its deeper cycling integration into daily life.

Environmental Constraints: Geographic Realities Shape Performance

Both cities face significant environmental challenges, though of different types. Amsterdam scores 54 in the Environment dimension compared to Paris's 59, reflecting their distinct geographic contexts.

Terrain presents Amsterdam's primary advantage, scoring 71 compared to Paris's 59. Amsterdam benefits from its famously flat topography, where elevation changes are literally non-existent. This geographic gift eliminates physical barriers to cycling and makes the city accessible to users of all fitness levels and ages. The flat terrain also enables efficient cycling across long distances, supporting Amsterdam's role as a cycling-commuting capital.

Weather conditions, however, favor Paris significantly. Amsterdam's harsh climate results in only 60% favorable cycling days annually, compared to Paris's 73%. Amsterdam faces over 119 rainy days per year and frequent cold spells that challenge even committed cyclists. Paris's more temperate climate provides twice as many suitable cycling days, reducing weather-related barriers to everyday cycling.

These environmental differences help explain the cities' strategic approaches: Amsterdam's infrastructure investment partly compensates for climate challenges, while Paris can rely more on favorable weather to encourage cycling adoption.

Safety and Street Quality: A Study in Contrasts

The Safety dimension reveals the starkest difference between the two cities, with Amsterdam scoring 55 compared to Paris's alarming 24. This gap stems from dramatically different safety profiles across both indicators.

Amsterdam benefits from Netherlands' excellent national safety record, with a fatality rate score of 57 reflecting the country's systematic approach to cycling safety through infrastructure design, traffic law enforcement, and cultural integration. However, Amsterdam's street suitability score of only 50 suggests that even in this cycling-friendly city, not all streets provide optimal cycling conditions.

Paris faces significant safety challenges, most notably an extremely poor fatality rate score of 9, reflecting France's higher exposure-adjusted cycling fatality statistics. This poor safety performance undermines Paris's otherwise strong infrastructure and service development. However, Paris partially compensates with a street suitability score of 67, indicating that where cycling does occur, the street-level conditions are generally appropriate.

The safety contrast highlights a critical difference: Amsterdam's safety emerges from systematic, long-term infrastructure development and cultural change, while Paris's rapid cycling expansion has outpaced safety infrastructure development, creating temporary mismatches between cycling demand and protective measures.

Conclusion

The Amsterdam–Paris comparison highlights two distinct but effective models for developing cycling-friendly cities. Amsterdam reflects a long-term, infrastructure-led approach grounded in cultural integration and systematic network coverage, while Paris showcases a rapid expansion model driven by strong service provision and dynamic policymaking. Each city faces limitations—Amsterdam in service density and weather, Paris in safety and infrastructure consistency—but together they illustrate that different strategies can lead to cycling success. An optimal model may lie in combining Amsterdam's infrastructure depth with Paris's service innovation and proactive safety planning.

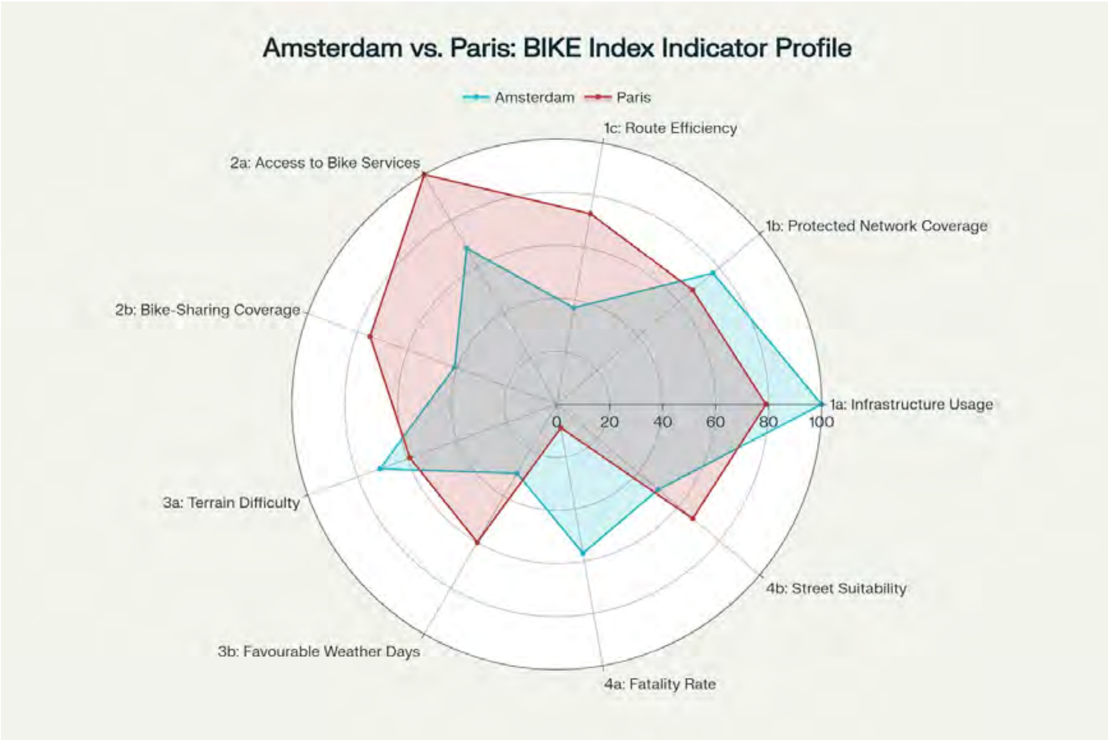


Figure 5.8: Radar chart comparing Amsterdam and Paris at indicator-level scores.

	Weights	0.4	0.2	0.2	0.2
City	**FINAL VALUE**	**1. Infrastructure**	**2. Services**	**3. Environment**	**4. Safety**
Amsterdam	65.6	83	52	54	55
Paris	62.6	73	85	59	24
Copenhagen	57.6	46	80	55	61
Stockholm	54.8	78	24	43	51
Vienna	54.2	69	50	53	30
Madrid	48.5	45	59	41	52
Brussels	48.5	52	65	42	32
Lisbon	48.0	55	47	45	39
Berlin	44.8	33	51	58	48
Luxembourg	41.6	40	43	19	66
Dublin	38.7	30	34	61	38
Athens	34.5	18	35	47	55
Rome	30.3	30	32	59	0

Figure 5.9: Full Results for the BIKE Index, broke down in dimensions.

City	FINAL VALUE	1a	1b	1c	2a	2b	3a	3b	4a	4b
	Weights	0.18	0.18	0.04	0.08	0.12	0.12	0.08	0.15	0.05
Amsterdam	65.6	100	77	37	68	41	71	30	57	50
Paris	62.6	79	67	73	100	75	59	60	9	67
Copenhagen	57.6	40	53	44	100	66	70	33	55	78
Stockholm	54.8	98	74	2	17	29	50	33	48	63
Vienna	54.2	88	53	58	48	51	55	50	19	62
Madrid	48.5	46	39	72	47	67	33	52	67	9
Brussels	48.5	50	50	67	65	66	47	33	19	72
Lisbon	48.0	53	52	74	67	33	19	83	52	0
Berlin	44.8	33	32	43	32	63	69	43	50	43
Luxembourg	41.6	51	36	11	32	50	17	21	72	49
Dublin	38.7	37	23	35	42	29	64	58	33	53
Athens	34.5	7	12	94	58	20	20	87	64	28
Rome	30.3	32	24	50	50	20	50	73	0	0

Figure 5.10: Full Results for the BIKE Index, broke down in indicators.

Chapter 6

Conclusions

The final chapter of this thesis presents the main conclusions derived from the development and application of the BIKE Index across thirteen European capital cities. It synthesizes the work conducted, evaluates the degree to which the project's objectives have been fulfilled, and reflects on the most important comparative insights. It also discusses the study's limitations and proposes avenues for future research and methodological refinement. The chapter is organized into five sections:

- **Summary of the Work Conducted**, offering a recap of the methodological process;
- **Degree of Objective Fulfillment**, assessing how each of the project's aims was achieved;
- **Main Conclusions**, presenting the global results, notable city cases, and key patterns;
- **Limitations of the Study**, outlining methodological and data-related constraints;
- **Future Research**, suggesting improvements and extensions for subsequent work.

This structure provides a comprehensive closure to the thesis, consolidating key findings while identifying the conditions for future progress.

6.1 Summary of the Work Conducted

This thesis has developed and applied the BIKE Index, a comprehensive and reproducible framework for evaluating urban cycling conditions across European cities. The project was structured in several key phases, each contributing to the methodological rigor and practical relevance of the final results.

The work began with the methodological design of the index, establishing a hierarchical structure based on four core dimensions: infrastructure, cyclist services, environmental constraints, and safety and street quality. Each dimension was defined through a set of carefully selected indicators, chosen for their empirical relevance, policy applicability, and support in the academic literature. A weighting scheme was established to reflect the relative importance of each dimension in shaping cycling conditions.

Following the conceptual framework, an extensive data collection and processing phase was carried out. This involved harmonizing geospatial, climatic, and statistical data from open-access sources for a sample of thirteen European capital cities. Particular attention was given to ensuring transparency and replicability, with all data sourced from public repositories and all processing steps implemented through documented computational procedures.

The next phase focused on the calculation of the index. All indicators were normalized to a standard 0–100 scale using robust normalization techniques, and then aggregated dimension by dimension following the established weights. This approach ensured comparability across cities while preserving the distinct contribution of each variable. The composite BIKE Index score for each city was derived from the weighted sum of its dimension scores.

Lastly, the thesis applied the index to produce a comparative assessment of the selected cities. This included rankings, dimension-level breakdowns, indicator visualizations, and city-level case studies. The analysis captured both general trends and individual profiles, highlighting the diversity of cycling conditions across Europe. The BIKE Index proved effective in synthesizing complex urban data into actionable insights, offering a structured tool for benchmarking and supporting cycling-related planning decisions.

6.2 Degree of objective fulfillment

This thesis successfully accomplished all four objectives stated in Section 1.3, confirming both the methodological soundness and practical value of a standardised, open-data approach to urban cycling assessment. Each objective has been addressed through a structured sequence of design, implementation, and application phases, resulting in a replicable framework and actionable insights.

1. **Objective 1: Design and validate a standardized methodology for assessing bike-ability** has been fully achieved. The BIKE Index establishes a robust four-dimensional framework encompassing Infrastructure (40%),

Services (20%), Environmental Constraints (20%), and Safety and Street Quality (20%). The methodology employs Modified Z-Score normalization using Median Absolute Deviation to handle outliers effectively, ensuring reliable cross-city comparisons. Validation through statistical analysis of over 2,700 routes (210 per city $\times$ 13 cities) across diverse European contexts confirms the framework's ability to accurately capture meaningful differences in urban cycling conditions. The systematic integration of multiple assessment dimensions into a single composite score provides the foundation for comparative analysis that was previously lacking in the field.

2. **Objective 2: Build an open-data methodology for transparent analysis** has been fully achieved. The entire analytical framework relies exclusively on publicly available data sources, including OpenStreetMap, OpenRouteService API, Eurostat, and Copernicus satellite data. All computational workflows are documented and reproducible, from urban perimeter delimitation through route generation to indicator calculation. The standardized spatial analysis framework—featuring 500-meter grids and systematic route networks—enables researchers and practitioners to replicate the analysis or extend it to new cities without requiring proprietary datasets or closed methodologies. This demonstrates that rigorous urban mobility evaluation is indeed possible using only open sources.

3. **Objective 3: Demonstrate policy relevance through application to European cities** has been fully achieved. The application to 13 diverse European capitals reveals clear performance patterns and actionable insights for urban planning. The analysis identifies specific strengths and challenges for each city: Amsterdam's infrastructure excellence but weather constraints, Paris's service integration success alongside safety gaps, and Madrid's balanced profile with topographical limitations. The case studies provide concrete examples of how cities can leverage their strengths and address weaknesses, bridging rigorous analysis with real-world policy decisions that can improve cycling conditions.

4. **Objective 4: Generate comparative results and clear visual outputs** has been fully achieved. The thesis produces comprehensive rankings, detailed indicator profiles, and accessible visualizations that clearly communicate differences in cycling conditions across cities. Radar charts enable intuitive comparison of city performance profiles, while dimension-level analysis highlights where public investment might be most effectively targeted. The visual outputs successfully translate complex, multi-dimensional data into practical information that supports evidence-based planning decisions and identifies transferable best practices.

Besides, the alignment of this work with the United Nations Sustainable Development Goals (SDGs) is discussed in detail in Appendix A, which provides a comprehensive reflection on how the methodology, results, and policy relevance of the BIKE Index contribute to sustainable urban development objectives.

6.3 Main Conclusions

6.3.1 Global Analysis of Results

The application of the BIKE Index to thirteen European capitals reveals a pronounced stratification in cycling conditions, with overall scores ranging from 65.6 (Amsterdam) to 30.3 (Rome)—a 35-point gap that demonstrates substantial differences in how well cities support everyday cycling. This range suggests that policy choices, investment priorities, and urban planning approaches have measurable and significant impacts on cycling environments across European contexts.

The city hierarchy emerges in three distinct tiers. The top tier consists of Amsterdam (65.6), Paris (62.6), and Copenhagen (57.6), representing cities that have achieved comprehensive cycling-friendly environments through different pathways. The middle tier includes Stockholm (54.8), Vienna (54.2), Madrid (48.5), Brussels (48.5), Lisbon (48.0), and Berlin (44.8), showing cities with developing but incomplete cycling systems. The bottom tier comprises Luxembourg (41.6), Dublin (38.7), Athens (34.5), and Rome (30.3), indicating cities facing significant structural challenges in cycling provision.

Cycling Infrastructure

Infrastructure emerges as the primary differentiator across all dimensions, exhibiting the largest variation with scores ranging from 83 (Amsterdam) to 18 (Athens)—a 65-point spread that reflects fundamental differences in cycling infrastructure development. This dimension alone accounts for much of the overall ranking variation, confirming empirical evidence that infrastructure quality serves as the strongest predictor of cycling uptake and safety outcomes.

Cities such as Amsterdam, Stockholm, and Paris demonstrate dense and coherent networks of protected cycling infrastructure, often covering more than 70% of the urban grid. In contrast, Rome, Dublin, and especially Athens offer minimal and fragmented infrastructure, often disconnected and poorly integrated into the urban fabric. Some cities, like Berlin, have long cycling networks in absolute terms but limited spatial coverage, indicating an uneven distribution concentrated in specific districts. Overall, the leading cities combine high network density with citywide coherence, while lower-scoring cities lack both coverage and continuity.

Cyclist Services

The availability of supporting services (bike shops, repair stations, and public bike-share systems) also varied widely (85 to 24 points). Paris ranked highest in service coverage, which reflects an aggressive expansion of cycling services. Amsterdam and Lisbon showed more moderate service provision (about 55% coverage by shops), and they suffered from uneven spatial distribution – services tend to cluster in central or affluent areas. Stockholm and Luxembourg lag in this dimension: only 25–34% of their urban area has nearby bike services. Stockholm demonstrates that strong infrastructure does not automatically translate to robust service provision.

Likewise, bike-sharing systems are absent or minimal in some cities: for instance, Athens and Rome have virtually no public bike-share (covering <1% of the city). These findings underscore that Paris's recent investments in cycling amenities have paid off, giving it a service edge even over Amsterdam. Meanwhile, cities with lower cycling cultures generally have fewer shops and stations, which can further hinder bicycle use.

It is important to note, however, that this dimension is particularly sensitive to city size and the definition of the urban perimeter adopted in Section 4.0.1. Paris's outstanding performance partly reflects the decision to analyze only its central administrative area, rather than the full metropolitan region. This methodological choice may have amplified density-related indicators and should be reconsidered in future iterations of the index to improve consistency across cities of varying spatial structures.

Environmental Constraints

The analysis confirms that geography and climate create very different backdrops for urban cycling. Southern European capitals enjoy the most favorable conditions: for example, Athens, Lisbon, and Rome each have over 78% of days per year with weather suitable for cycling. These cities' dry, temperate climates mean rain is infrequent and winters are mild (though they do experience occasional heat waves in summer). In contrast, frequent rainfall and extended cold periods limit bike activity in northern cities; for instance, Amsterdam has 119 rainy days annually, and Stockholm endures over 80 sub-freezing days. Madrid presents an interesting case: despite its reputation for good weather, it suffers from both extremes—intense summer heat and freezing cold temperatures in the winter—placing structural limits on year-round cycling comfort.

Terrain is another crucial factor: flat cities like Amsterdam, Copenhagen, and Berlin are essentially flat, imposing virtually no extra effort on cyclists. By contrast, Lisbon, Athens, and Luxembourg are very hilly, registering high terrain difficulty scores. Even Madrid, Rome, and Brussels have pockets of steep terrain that can impede cycling in certain neighborhoods. In summary, cities with flat topography and mild, dry weather (e.g. Amsterdam) have an inherent advantage, while those with mountainous terrain or severe weather (e.g. Athens for hills, Stockholm for climate) face natural challenges to cycling. Importantly, these environmental disadvantages are largely beyond immediate policy control – they underscore why adaptation strategies (like e-bikes for hills or winter maintenance for snow) are essential in some contexts.

Safety and Street Quality

The index's safety dimension reveals profound disparities in cyclist risk and route quality across European capitals. Cities in cycling-centric countries like the Netherlands and Denmark benefit from strong safety cultures, shaped by infrastructure design, enforcement, and long-standing cycling traditions. At the other end of the spectrum, cities such as Rome and, to a lesser extent, Athens and Lisbon present far more hazardous environments for cyclists. Rome's safety score stands out as a significant outlier, scoring zero in this dimension despite the normalization process used to minimize the effect of extreme values. This suggests a genuine and critical deficiency that may still distort intercity comparisons, particularly in composite averages.

Beyond fatality statistics, the quality of streets used by cyclists also varies considerably. High-scoring cities like Copenhagen and Amsterdam offer safe, comfortable, and continuous cycling routes, often fully separated from traffic. In contrast, lower-performing cities tend to funnel cyclists through fragmented networks and high-traffic roads without protection, leading to both higher risk and lower perceived comfort. Athens and Madrid exemplify this issue, where infrastructure gaps force riders onto unsuitable streets, dragging down their safety evaluations. In sum, the most successful cities combine low objective risk with street environments that feel consistently safe to navigate—while lagging cities struggle not just with safety outcomes, but with the daily experience of cycling.

In summary, the comparative results of the BIKE Index reveal that cycling success is shaped by several patterns. Infrastructure acts as the foundation, providing the essential backbone for safe and accessible cycling, but on its own is not enough. Service integration functions as a multiplier, expanding the usability and reach of cycling networks, particularly through bike-sharing and maintenance availability. Meanwhile, geographic constraints impose structural limitations that cities must adapt to rather than overcome—terrain, heat, and urban form directly affect cycling feasibility regardless of policy ambition. Finally, safety emerges as an independent variable, often requiring targeted interventions beyond general investment. Together, these patterns show that top-tier performance arises not from a single strength, but from a coordinated strategy that balances infrastructure, services, environment, and safety.

6.3.2 Notable Cases

A special examination of Madrid and a comparison between Amsterdam and Paris provide additional insight into these findings.

Madrid as a Balanced Middle-Tier Performer

Madrid emerged as a balanced performer in the index – it did not top any single category, but it maintained consistently average-to-good performance across all dimensions. Madrid's protected bike network remains modest, yet it is spatially cohesive and complemented by other strengths: the city has invested in a comprehensive e-bike sharing system (BiciMad), achieving 86% coverage of its urban area with bike-share stations – one of the highest rates among the cities studied. Its service coverage (bike shops, etc.) is likewise around the middle of the pack.

In terms of safety, Spain's cyclist fatality rate is moderate (neither especially low nor high), and Madrid in particular has implemented traffic calming (e.g. citywide 30 km/h zones) that likely improve urban cycling safety. The net effect is that Madrid's well-rounded profile secures a solid overall index ranking – its profile suggests that cities can achieve respectable cycling performance through systematic attention to all dimensions rather than dramatic excellence in specific areas. (infrastructure, services, slow-speed traffic management, etc.) have made Madrid a comparatively cycle-friendly city given its geography.

Amsterdam vs. Paris: Contrasting Pathways to Excellence:

The Amsterdam vs. Paris comparison highlights two successful but contrasting pathways to urban cycling improvement. Amsterdam, long dubbed a cycling capital, leads thanks to over 40 years of continuous pro-bike policies. It boasts an expansive, mature infrastructure network and very high cycling mode share. Its culture of cycling is deeply embedded – nearly 40% of all trips in Amsterdam are made by bicycle [75]. This legacy translates into strong performance in nearly every index dimension: Amsterdam's streets are highly safe by design and dominated by cyclists, and basic cycling services (parking, shops) are abundant.

However, Amsterdam's dominance is not absolute. The city's one relative shortcoming is in the services dimension, particularly bike-sharing: because private bike ownership is so ubiquitous (with 1.3 bikes per resident [74]), Amsterdam has a very limited public bike-share system, yielding a low coverage score for that specific indicator. Additionally, Amsterdam's massive cycling population means that collision counts remain non-trivial – in fact, in one global index Amsterdam's safety rating was affected by a high absolute number of incidents, even if the per-kilometer risk is low.

Paris, on the other hand, has seen a more recent transformation. Historically, Paris was car-dominated and lagged far behind Amsterdam in cycling provision. But in the past decade – especially under its current mayor – Paris has aggressively reallocated street space to bikes and expanded cycle lanes citywide. As a result, Paris now registers about 70% infrastructure coverage, rapidly closing the gap with Amsterdam. Paris truly excels in the services dimension: it leads the entire sample in bike-shop coverage and achieved 100% bike-share coverage within the dense city, thanks to the hugely successful Vélib' system and its successors. The impact is evident in usage: bicycle traffic in Paris has surged by over 160% in recent years, and by 2023 bikes even outnumber cars in Paris's daily center-city trips [76]. This is a remarkable shift.

Nevertheless, Paris still faces challenges that Amsterdam solved long ago. Parisians frequently note that the "spirit is willing but the infrastructure is not" [76] – meaning that demand for cycling sometimes exceeds the capacity or quality of the bike network. Indeed, Paris's safety metrics remain weaker: France's cyclist fatality rate is higher than the Netherlands', and Paris's on-street conflict between cars, bikes, and scooters has been an adjustment. Many of Paris's new lanes are unsegregated or semi-protected, and intersections can be daunting compared to Amsterdam's strictly calmed, bike-prioritized junctions.

In short, Amsterdam represents the gold standard of a fully consolidated cycling city, whereas Paris is an ambitious newcomer making rapid progress. Paris demonstrates that a large metropolis can fundamentally change course towards bike-friendliness within a decade – but also that policy momentum must be sustained to address second-order issues like network connectivity, safety enforcement, and cultural adaptation. The comparison underscores that there are multiple paths to improvement: Amsterdam relied on long-term, bottom-up cycling culture and infrastructure saturation, while Paris leveraged strong political leadership and investment to kick-start change. For other cities, both lessons are valuable.

6.3.3 Common Patterns Identified

Several consistent patterns emerge from the cross-city analysis that illuminate the fundamental drivers of cycling performance:

Interdependencies between dimensions

The results indicate that high scores in different BIKE Index dimensions tend to reinforce each other, but correlations are not absolute. In general, cities that invested heavily in infrastructure also enjoy better safety outcomes – a reflection of safer street design and the "safety-in-numbers" effect as more people cycle. For instance, the countries with the best protected bike networks (Netherlands, Denmark) also exhibit very low cyclist fatality rates. Similarly, a dense infrastructure grid often correlates with high service accessibility, since pro-cycling cities also attract more bike shops and support facilities.

However, there are notable exceptions. One is the case of Amsterdam's safety: despite world-class infrastructure, the sheer volume of cyclists means total incident counts remain appreciable. Conversely, Luxembourg scored poorly on infrastructure but topped the safety metric (its national risk rate is the lowest), likely due to factors external to urban infrastructure (e.g. fewer cyclists and generally safer national roads). These examples show that while a virtuous cycle often exists between infrastructure, usage, and safety, each dimension also has unique influences. Policy integration is key – improvements are strongest when all factors advance in parallel.

Trade-offs between infrastructure and services

An interesting asymmetry observed is that some cities focus resources on hard infrastructure whereas others emphasize soft services and promotion – and an imbalance can limit overall cycling gains. For example, Paris initially pushed bike-sharing and saw ridership jump, even when its bike lane network was still catching up. This led to a period where enthusiastic new cyclists were using the service (Vélib') but still lacked safe routes, highlighting a mismatch. Conversely, Berlin has a large nominal bike network but until recently offered relatively sparse bike-share coverage and fewer cycling events or training programs, potentially limiting the utility of its infrastructure.

Our findings suggest that infrastructure and services should be developed together: infrastructure provides the backbone, while services amplify the network's usability. Notably, Madrid's balanced approach – moderate infrastructure coupled with a robust e-bike share system – illustrates how services can help overcome infrastructure gaps (in Madrid's case, electric bike-share mitigates its hilly terrain). Another insight is that private bicycle ownership vs. public bike-share can be inversely related: cities with high personal bike ownership (e.g. Amsterdam, Copenhagen) often have less demand for bike-sharing, whereas cities newer to cycling (Paris, Lisbon) lean heavily on bike-share to lower entry barriers. Thus, the optimal mix of interventions may differ by city maturity, but ultimately a synergy between building bike lanes and providing convenient services yields the best outcome for cycling rates.

Role of geography and urban form

The diversity of the 13 capitals underscores how physical geography and city layout influence cycling feasibility. Topography emerged as a decisive factor: flat cities achieved high bikeability scores relatively easily, whereas hilly cities face intrinsic challenges. For example, Lisbon and Athens would require extra effort (such as e-bikes, funiculars, or zigzag route planning) to attain the same level of cycle comfort that Amsterdam naturally has. We observed that some hilly cities are starting to adapt – Madrid's deployment of e-bikes is one such adaptation – but steep terrain remains a physical barrier that can't be fully eliminated.

Urban form and size are also important: compact, high-density cities (like Paris or Copenhagen) can blanket their area with bike infrastructure more readily, whereas sprawling or polycentric cities (like Berlin) struggled to achieve high coverage despite long networks. The data revealed that smaller cities can attain higher network density with less infrastructure – for instance, Lisbon covers half its grid with a relatively short network, reflecting a compact urban core. In larger metros, cyclists may face longer travel distances and more heterogeneous conditions between center and periphery.

Additionally, climate influences seasonal cycling patterns: northern cities have had to invest in winter maintenance, lighting, and all-weather gear culture to keep people riding year-round, whereas southern cities don't face cold winters but must address heat and different schedules. One positive pattern is that climate constraints can be mitigated – for example, Copenhagen's high cycling rate persists through harsh winters due to strong civic commitment and infrastructure that is cleared of snow promptly.

In sum, while geography sets the stage, smart planning can alleviate some natural disadvantages. Cities with less favorable geography might focus even more on infrastructure quality (e.g. protected lanes on hilly routes) and technology (e.g. e-bikes, shade for heat), whereas cities blessed with flat, temperate environments have no excuse not to excel in cycling with the right policies.

6.4 Limitations of the Study

It is important to acknowledge the study's limitations. These mostly stem from data availability constraints and methodological choices made to ensure consistency across the 13 European capital cities. The key limitations are detailed in the following sub-sections.

Heavy reliance on OpenStreetMap and Google Maps data

This study's methodology depends heavily on third-party open data sources, notably OpenStreetMap (OSM) for infrastructure data and Google Maps for various cycling-related services. While using open platforms ensures broad coverage and reproducibility, it also introduces uncertainties. OSM, which is the source of 50% of the indicator data is a crowd-sourced map and lacks formal quality control, so data completeness and consistency can vary by location. Mapping conventions (for example, what qualifies as a "cycle lane" vs. a "cycle track") are not fully standardized across all countries, which can lead to uneven or incomparable data inputs.

Similarly, information sourced from Google Maps (such as bike shop locations or bike-sharing stations) may be incomplete or outdated if local data are not regularly updated. In short, the accuracy of the BIKE Index is constrained by the reliability and granularity of these external data sources – any gaps or errors in OSM or Google data will propagate into the results.

Missing dimensions and indicators

The custom BIKE Index focuses on measurable infrastructure and service indicators, but it omits certain qualitative or policy-related dimensions due to a lack of open, reproducible data. In particular, factors such as a city's cycling culture, public attitudes, or the political commitment to cycling were not included, even though these can significantly influence cycling conditions. Some well-known city ranking indices account for such aspects – for example, the Copenhagenize Index qualitatively scores cities on Advocacy and Politics, rewarding strong cycling NGOs and pro-cycling political leadership. Incorporating similar measures in our study was not feasible because no standardized data exist across all cities for cultural or political commitment.

Moreover, even certain physical factors had to be left out: for instance, motor traffic speed and volume (which strongly affect cyclist comfort and safety) are barely documented in OSM and thus could not be used. The exclusion of these dimensions means the BIKE Index provides a "narrower" (but still valid) view of bike-friendliness – primarily capturing infrastructure and basic services – and may overlook softer influences like community support, enforcement of bike-friendly policies, or funding commitment, simply because consistent data on these are unavailable publicly.

Dependence on city perimeter definitions

The results of the BIKE Index are sensitive to how the boundaries of each city are defined. Different cities have different administrative perimeters – some encompass extensive suburban or rural areas, while others cover only a dense urban core. These discrepancies affect the comparability of the index outcomes. For example, a city with a broad administrative area may appear to have lower cycling infrastructure density or coverage, not necessarily because it is less bike-friendly, but because its boundary includes large sparsely populated zones.

In our analysis we used the official city limits for each capital, which means the indicators (especially coverage-based ones like infrastructure per square kilometre or population served) are calculated over areas of varying size and urbanisation. This is a known limitation in multi-city studies: if one city's "footprint" is much larger or differently defined than another's, direct comparisons can be misleading. Some approaches address this by standardising the evaluated area (e.g. focusing only on the continuous urbanised area), but in our study the data and grid system adhere to the given administrative boundaries. This decision was deliberate: using official administrative units was the only way to apply a consistent and reproducible definition across all cities, avoiding subjective interpretation or manual selection of urban footprints.

This issue is particularly relevant in the case of Paris. Unlike other cities, the analysis was limited strictly to its central municipal area (Ville de Paris), which covers just over 200 km²—much smaller than its functional urban region. As a result, many coverage-based indicators (such as bike service density or infrastructure reach) appear inflated, simply because they are measured over a compact, infrastructure-dense territory. While this provides useful insights into the core city, it limits comparability with capitals like Berlin or Madrid, where the administrative perimeter covers a much broader and more heterogeneous space. Consequently, grid-based results and coverage metrics may be partially skewed by boundary effects, and interpretations must account for these contextual differences.

Small sample size

Another clear limitation is the small sample of cities examined. The study covers only 13 European capital cities, which is a limited subset of all urban areas and even of European capitals. Although these cities provide valuable case studies and the methodology could be replicated for others, the limited sample size restricts the representativeness of the findings. The results cannot be generalized to all European cities or beyond – they are specific to the selected capitals, which tend to have relatively high profiles and possibly better cycling infrastructure than smaller cities or towns.

With such a small cohort, statistical generalization is not robust; patterns observed (for example, regional trends or correlations between indicators) are indicative but not definitive. In essence, the BIKE Index results serve as a comparative insight into these 13 cities rather than a comprehensive assessment of urban cycling conditions across Europe. Future research applying the same index to a larger and more diverse set of cities would be needed to draw broader conclusions.

Imperfect proxies for key concepts

Finally, some of the indicators used in the BIKE Index are recognized as imperfect proxies for the underlying concepts we aimed to measure. In an ideal scenario, each aspect of cycling conditions (safety, comfort, etc.) would be captured by a direct metric; in practice, data limitations required us to use approximations. For example, due to the absence of city-level cycling safety statistics in open data, our index relies on national-level cyclist casualty rates as a surrogate for the safety risk in each city. This proxy is an oversimplification – a particular city's safety record can differ from the national average, so using national data may misrepresent the true local risk.

We acknowledge that such approximations, while methodologically justified to fill data gaps, do not fully capture the nuance of the concepts in question. This issue is not unique to our study: in cycling research, indirect measures are often used when direct data are lacking (for instance, the share of women among cyclists is sometimes used as a proxy for perceived safety). Similarly, our index's proxy indicators (like using a coverage of infrastructure as a stand-in for "comfort" or using national data for local safety) provide only a rough picture. They introduce an additional layer of uncertainty in interpretation, since improvements or deterioration in these proxy metrics might not correspond neatly to real-world experience. Therefore, results involving such proxy-based indicators should be viewed as indicative estimates of the concept rather than precise measurements.

Composite Scoring and Weighting Constraints

One of the limitations of the BIKE Index lies in its weighting and aggregation structure. The index assigns fixed weights to each dimension—40% for Infrastructure and 20% for Services, Environment, and Safety—based on interpretability rather than empirical optimization. While this structure is transparent and grounded in literature-informed priorities, it lacks a rigorous theoretical foundation and may not reflect the actual relevance of each dimension across different urban contexts. Applying the same weighting scheme to all cities assumes uniform importance of each factor, which is unlikely in practice. For example, safety concerns may be more critical in cities with high baseline risk, while environmental constraints could dominate in hilly or extreme-climate regions. This static approach, although simple and reproducible, may overlook local nuance.

In addition, the additive nature of the composite score allows strong performance in one dimension to offset critical weaknesses in another. A city with excellent infrastructure but severe safety issues might still rank favorably, potentially masking significant risks for cyclists. This compensation logic is an inherent drawback of most composite indices. Although the BIKE Index offers a coherent way to summarize complex conditions, future versions could explore more adaptive weighting or alternative aggregation methods to reduce these structural biases.

6.5 Future Research

The findings and limitations of this study open several avenues for further research and methodological enhancement. In particular, future work can expand the scope of the BIKE Index and refine its methodology to improve robustness and comparability. The following sub-sections outline key directions for future investigation.

Expansion of the Sample

A priority for future research is to apply the BIKE Index to a larger and more diverse set of cities, both within Europe and globally. The current evaluation of 13 European capitals could be extended to include a broader range of city sizes and geographies in Europe (e.g. medium-sized cities or additional capital and regional cities) to test the index's generalizability. Expanding beyond Europe is equally important, as it would allow validation of the BIKE Index under different cultural and infrastructural contexts.

Comparative analyses across continents could reveal whether the factors influencing bikeability are consistent or if new context-specific variables emerge. By enlarging the sample, future studies can increase the statistical robustness of the index, enable benchmarking across a wider spectrum of urban environments, and potentially uncover outlier cases that challenge or enrich the current framework.

Sensitivity Analysis of Index Construction

Another crucial direction is to conduct a comprehensive sensitivity analysis of the BIKE Index construction. The index is built on multiple methodological choices – including the normalization of indicators, the weighting scheme assigned to each factor, and the technique used for aggregating indicators into a composite score – and each of these choices can influence the results. Even slight changes in the normalization method (e.g. using z-scores vs. min–max scaling), the weights of individual indicators, or the aggregation formula (additive versus multiplicative) may alter city rankings and scores.

It is well documented that such assumptions can significantly sway the message conveyed by a composite indicator. Future work should therefore systematically test how different normalization approaches, weight configurations, and aggregation methods impact the BIKE Index outcomes. This could involve techniques like Monte Carlo simulations or scenario analysis to observe the robustness of city scores under varying parameter settings. A thorough sensitivity analysis will identify which components of the index have the greatest influence on the results and ensure that the conclusions drawn are not an artifact of a particular methodological choice. In turn, this will enhance the credibility and transparency of the index, as recommended in composite indicator best-practice guidelines, and may suggest an optimal set of methodological choices that balance fairness and reliability.

Improvement of Urban Perimeter Definition

For meaningful inter-city comparisons, it is vital to clearly and consistently define the urban area or "perimeter" for each city in the study. Differences in how these boundaries are defined can introduce bias. Cities vary widely in their administrative limits and the extent of their functional urbanized area, which makes direct comparison challenging. For instance, comparing a city that is defined strictly by a small municipal boundary with another defined by a broad metropolitan region could skew the index values due to population and area differences rather than true cycling conditions.

By improving the urban perimeter definition in this way, the BIKE Index can achieve fairer comparisons – evaluating like-with-like in terms of urban scale – and the results will be more consistently interpretable. This refinement addresses known issues in bikeability comparisons, where varying levels of urbanization and city layout demand careful alignment of study areas for each city.

Integration of Additional Dimensions and Indicators

While the current BIKE Index focuses primarily on measurable factors such as infrastructure and perhaps safety or network connectivity, urban cycling conditions are also shaped by broader policy and cultural dimensions. A valuable extension of this research would be to incorporate additional indicators that capture the political commitment to cycling, the cycling culture of the populace, financial budget allocations for cycling, and experiential factors like traffic stress. For example, political commitment might be quantified by the presence of an official cycling strategy, the level of investment in bike programs, or the existence of pro-cycling regulations and leadership. Cycling culture and social acceptance of biking could be reflected in survey-based measures of public attitude, the prevalence of cycling events, or the proportion of people who cycle regularly beyond mere infrastructure availability. Including such qualitative or semi-quantitative measures would address aspects of “bicycle friendliness” that go beyond infrastructure alone.

In the same vein, tracking municipal budgets or per-capita spending on cycling infrastructure can indicate the priority given to cycling in urban transport funding, and thus serve as a proxy for commitment. Additionally, integrating a measure of traffic stress or comfort – for instance, using a Level of Traffic Stress (LTS) analysis or cyclist perception surveys – would account for the quality of the cycling experience (how safe or relaxed cyclists feel amid traffic), complementing the physical indicators of infrastructure. By broadening the index to include these dimensions, future studies will produce a more holistic assessment of bikeability.

Other city ranking initiatives have likewise recognized the importance of such factors; for instance, the well-known Copenhagenize Index evaluates cities on a range of criteria that span infrastructure and the ambition of local actors and policies towards cycling [7]. Therefore, incorporating political, cultural, and budgetary indicators alongside traditional metrics would enrich the BIKE Index, allowing it to capture the enabling environment for cycling. This multi-dimensional approach would improve the explanatory power of the index and make it a more useful tool for policymakers seeking to understand both the hard and soft factors that drive cycling success.

Temporal Analysis for Longitudinal Insights

Future applications of the BIKE Index would benefit greatly from adopting a longitudinal perspective. Rather than relying on a one-time evaluation, repeating the index periodically would allow researchers to monitor how urban cycling conditions evolve over time. This would provide valuable insight into the effectiveness of specific policy interventions and infrastructure investments, while also highlighting cities that are making continuous progress—or those where improvements have stalled. Longitudinal data could also uncover broader trends, such as the impact of technological adoption (like e-bikes) or policy shifts on cycling environments across Europe.

Appendix A

Alignment with the United Nations Sustainable Development Goals (SDGs)

This annex provides a reflection on how this project aligns with the United Nations Sustainable Development Goals (SDGs). The project develops an index to evaluate urban cycling environments, directly supporting several SDGs—particularly those related to sustainable cities, health, climate action, and inequality reduction.

A.1 Main SDGs Addressed

A.1.1 SDG 11: Sustainable Cities and Communities

- The core objective of the BIKE Index is to assess and promote urban cycling, which is a key element in making cities more inclusive, safe, resilient, and sustainable.

- The index evaluates the quality and coverage of cycling infrastructure, the accessibility of cyclist services, and the safety of urban cycling, all of which contribute to more sustainable urban mobility systems.

- By enabling policymakers and planners to identify gaps and prioritize interventions, the project supports the development of transport systems that are accessible and sustainable for all residents.

A.1.2 SDG 3: Good Health and Well-being

- Promoting cycling as a daily mode of transport has direct health benefits, including increased physical activity, reduced risk of chronic diseases, and improved mental health.

- The project's indicators address both the physical safety of cyclists and the environmental factors (such as air quality and climate) that influence the health impacts of urban mobility choices.

- By encouraging safer, more widespread cycling, the index contributes to healthier urban populations.

A.1.3 SDG 13: Climate Action

- Cycling is a zero-emission mode of transport. By facilitating modal shift from cars to bicycles, cities can directly reduce greenhouse gas emissions.

- The BIKE Index includes environmental indicators (terrain and climate suitability) and highlights the potential for cycling to mitigate the urban contribution to climate change

A.1.4 SDG 10: Reduced Inequalities

- The index evaluates the spatial distribution of cycling infrastructure and services, highlighting disparities in access between neighborhoods and demographic groups.

- By identifying areas with poor coverage or accessibility, the project supports efforts to make sustainable mobility options available to all, regardless of income, age, or ability

A.2 Secondary SDGs Supported

A.2.1 SDG 9: Industry, Innovation and Infrastructure

- The project introduces an innovative, reproducible methodology for evaluating urban cycling conditions using open data and scalable computational tools.

- By advancing the state of the art in urban mobility assessment, the thesis supports the development of modern, resilient infrastructure.

A.2.2 SDG 8: Decent Work and Economic Growth

- Improved cycling infrastructure and services can stimulate local economies, create jobs in the cycling sector, and support retail activity in urban areas.

A.3 Conclusion

The BIKE Index project is closely aligned with the United Nations SDGs, particularly SDGs 11, 3, 13, and 10. By providing a comprehensive, transparent, and policy-relevant assessment of urban cycling conditions, the thesis supports the transition toward healthier, more sustainable, and more equitable cities. The methodology and findings offer practical tools for decision-makers and contribute to the broader global agenda of sustainable urban development.

Appendix B – Visual Summary of City-Level Indicators

Indicator 1a

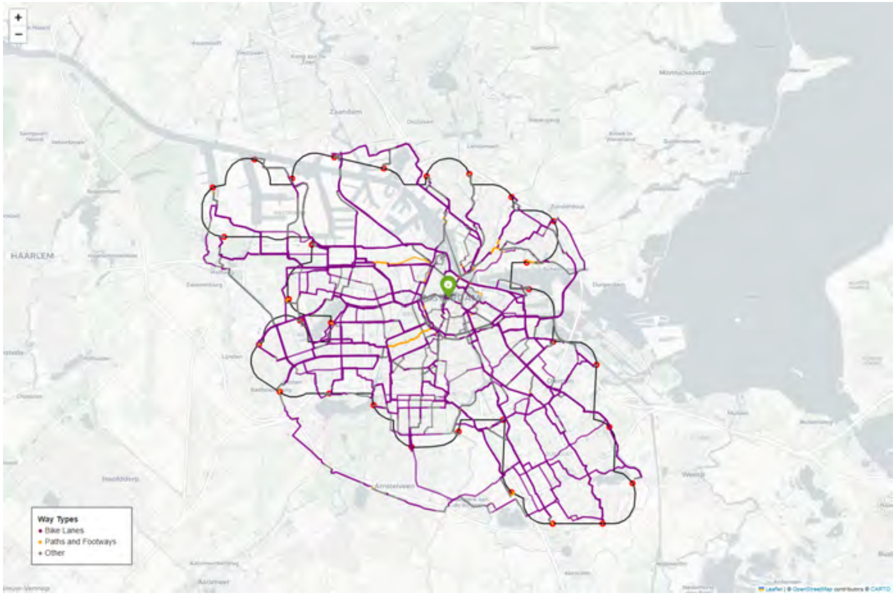


Figure 1: Amsterdam – Indicator 1A

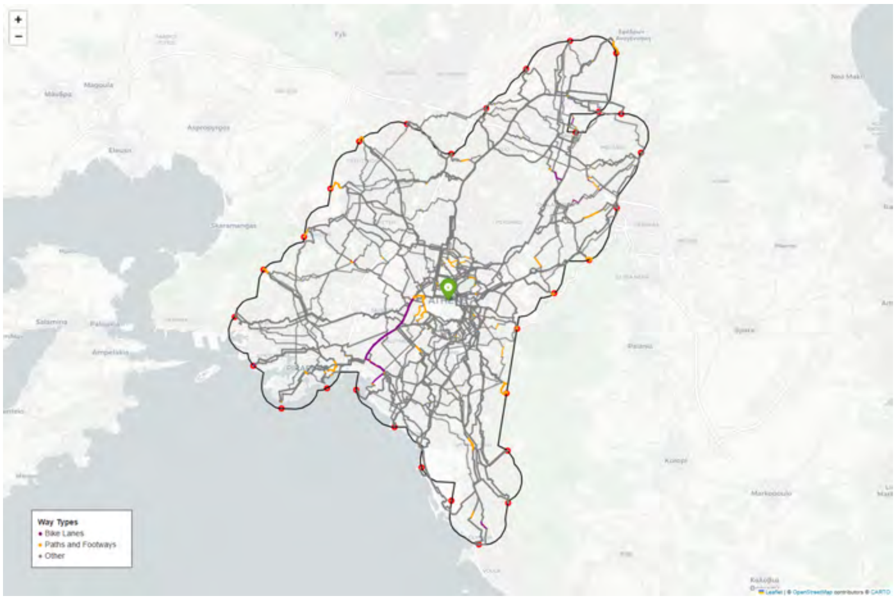


Figure 2: Atenas – Indicator 1A

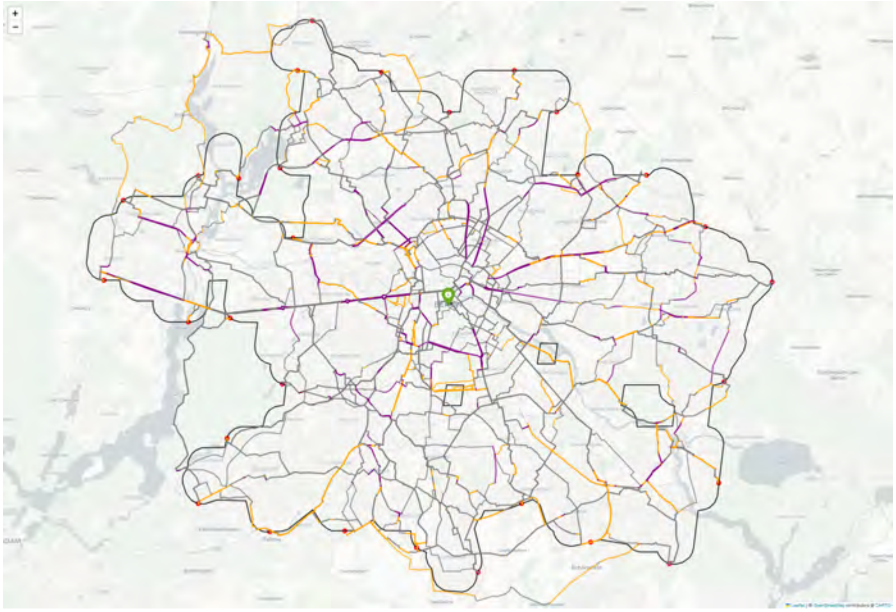


Figure 3: Berlin – Indicator 1A

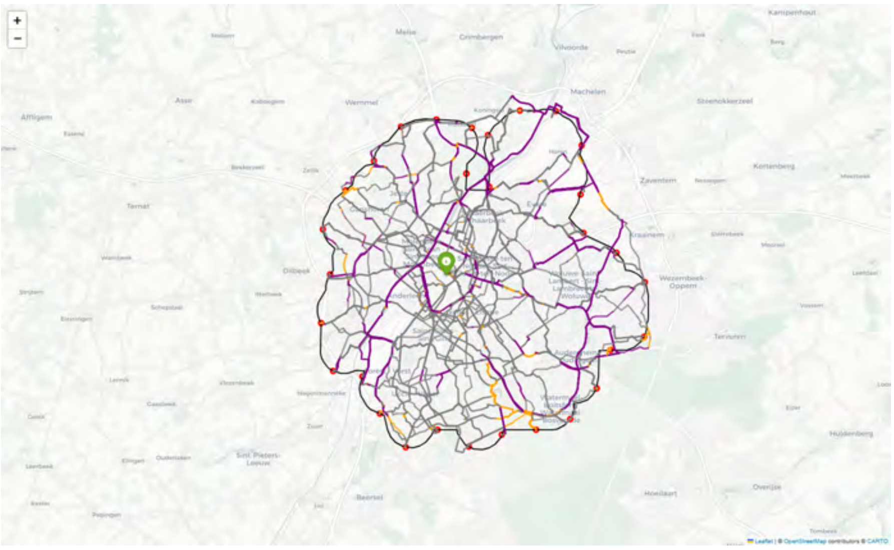


Figure 4: Brussels – Indicator 1A

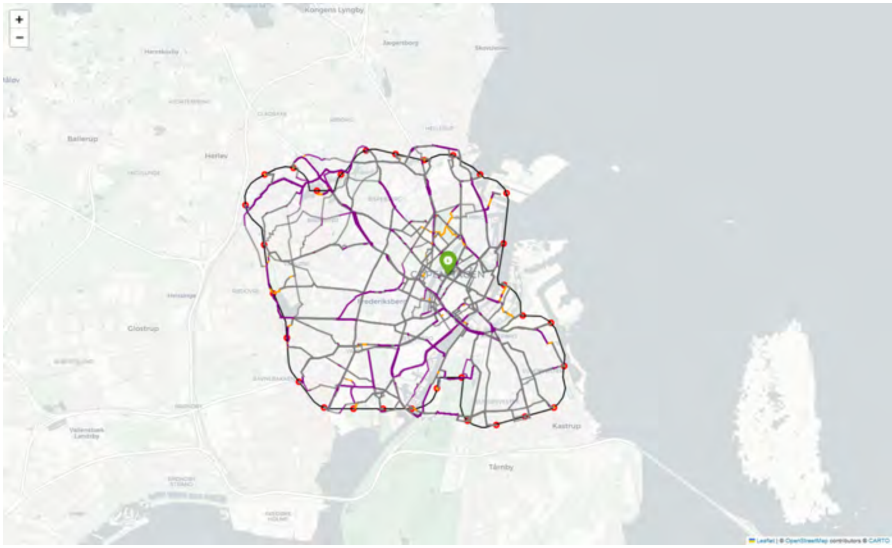


Figure 5: Copenhague – Indicator 1A

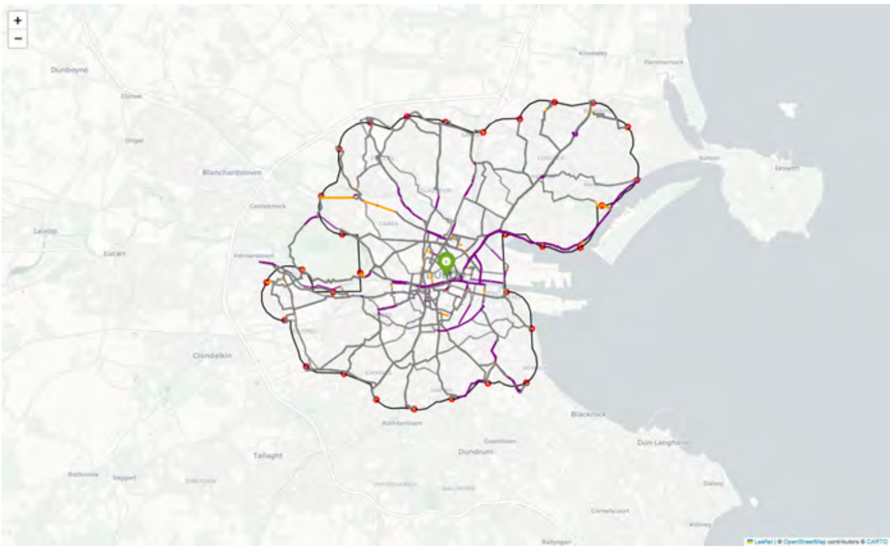


Figure 6: Dublin – Indicator 1A

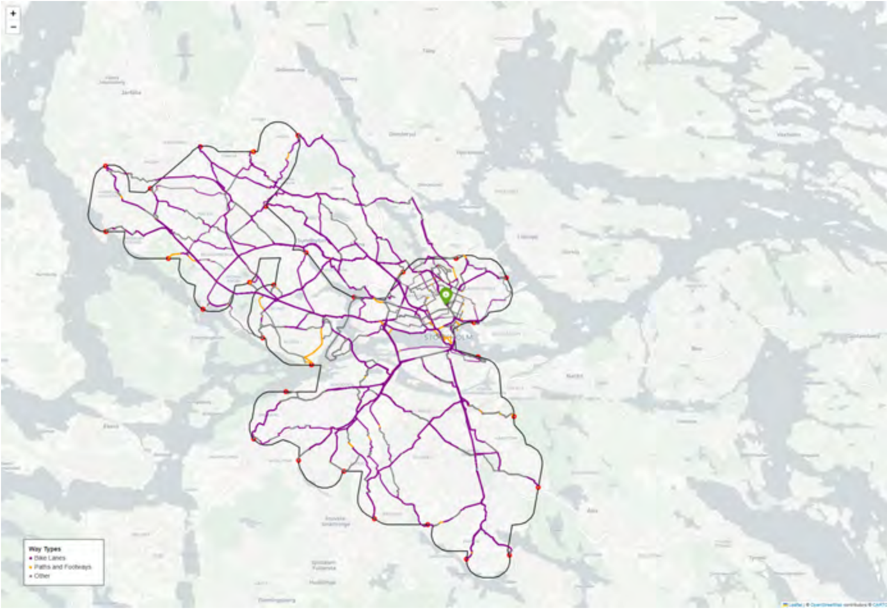


Figure 7: Estocolmo – Indicator 1A

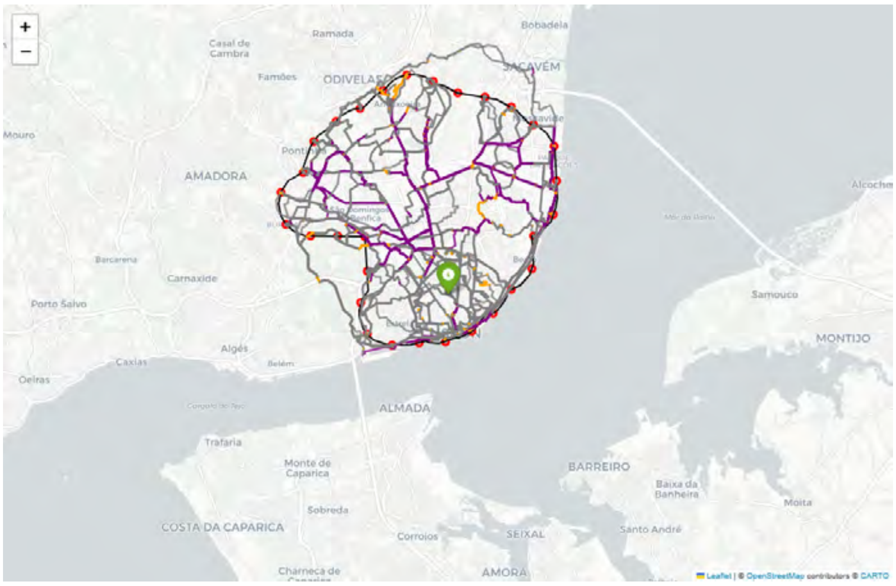


Figure 8: Lisbon – Indicator 1A

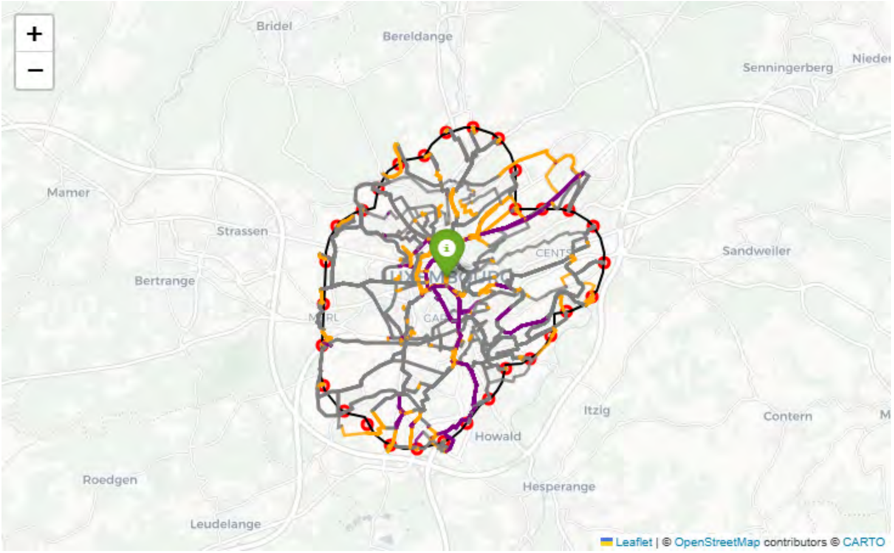


Figure 9: Luxemburgo – Indicator 1A

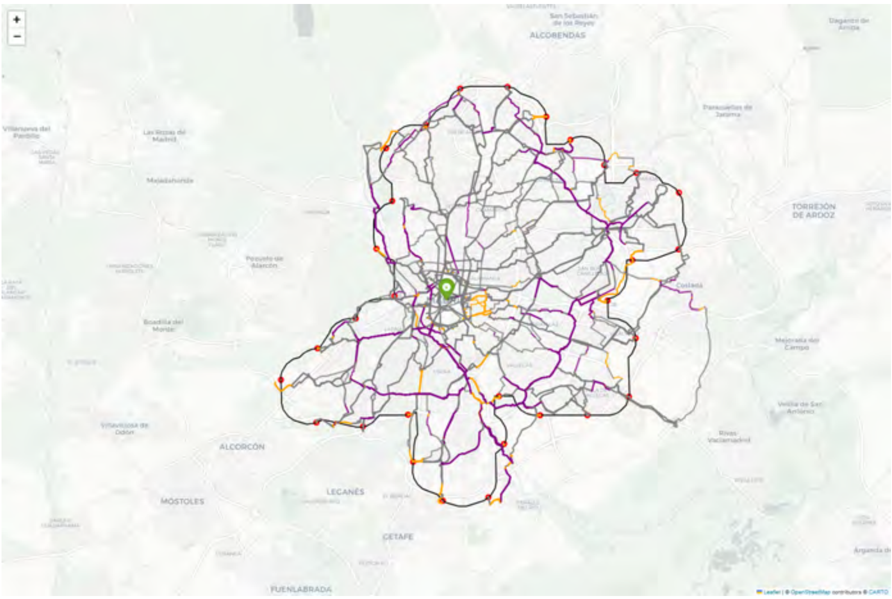


Figure 10: Madrid – Indicator 1A

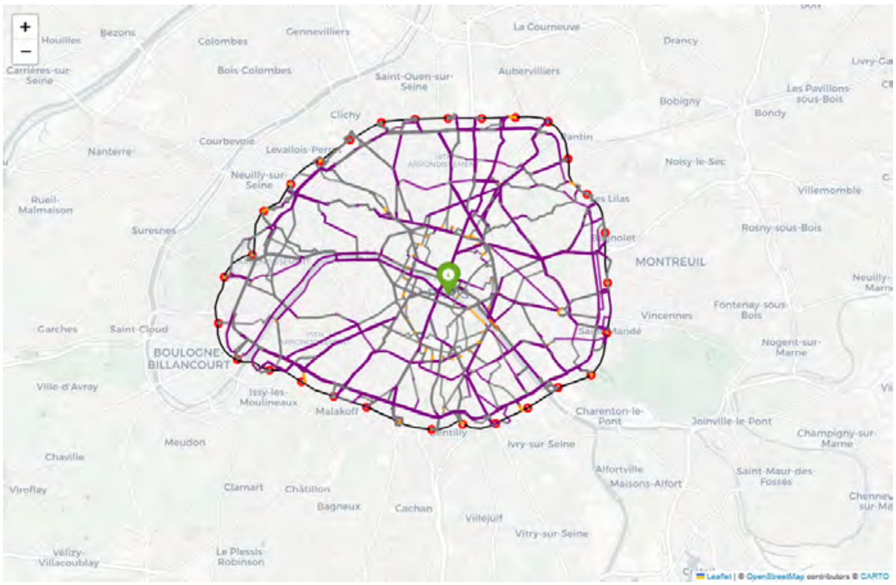


Figure 11: Paris – Indicator 1A

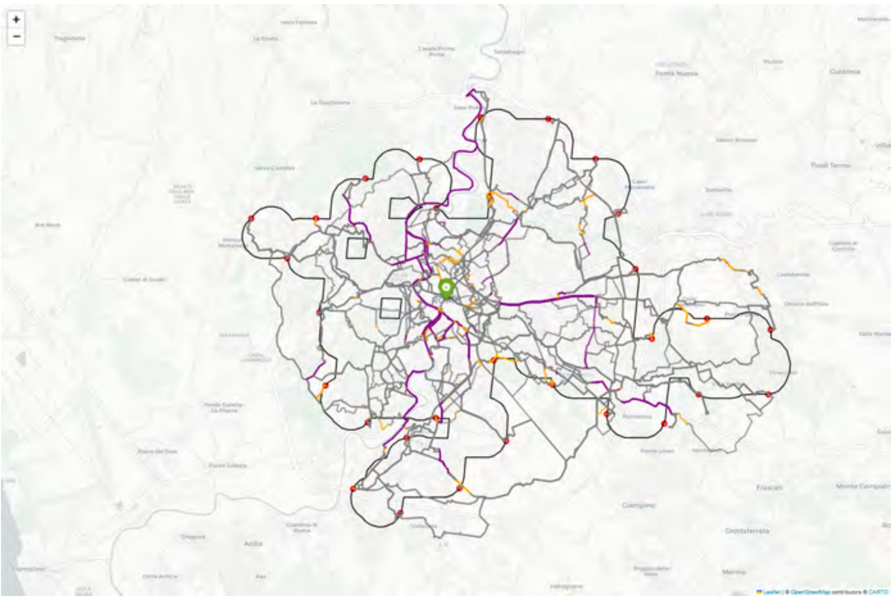


Figure 12: Rome – Indicator 1A

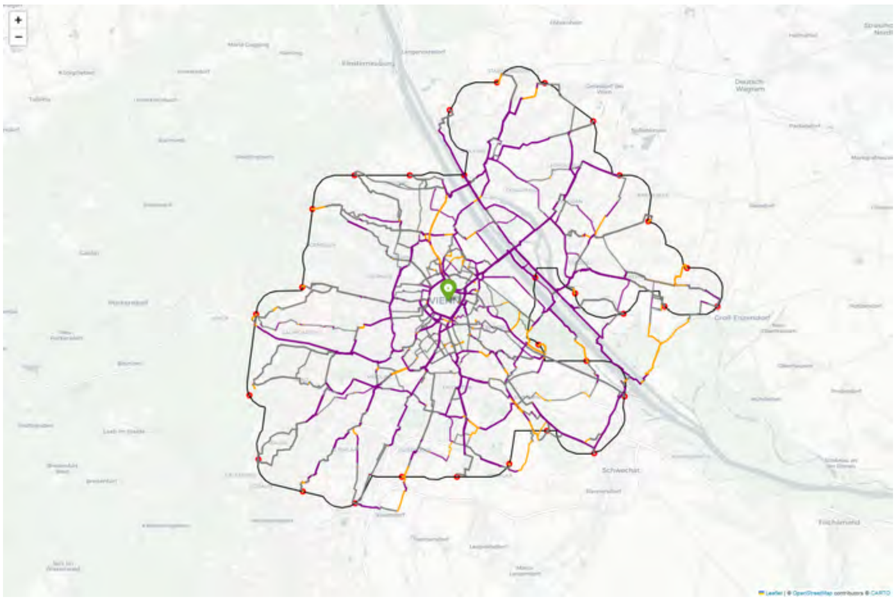


Figure 13: Viena – Indicator 1A

Indicator 1b

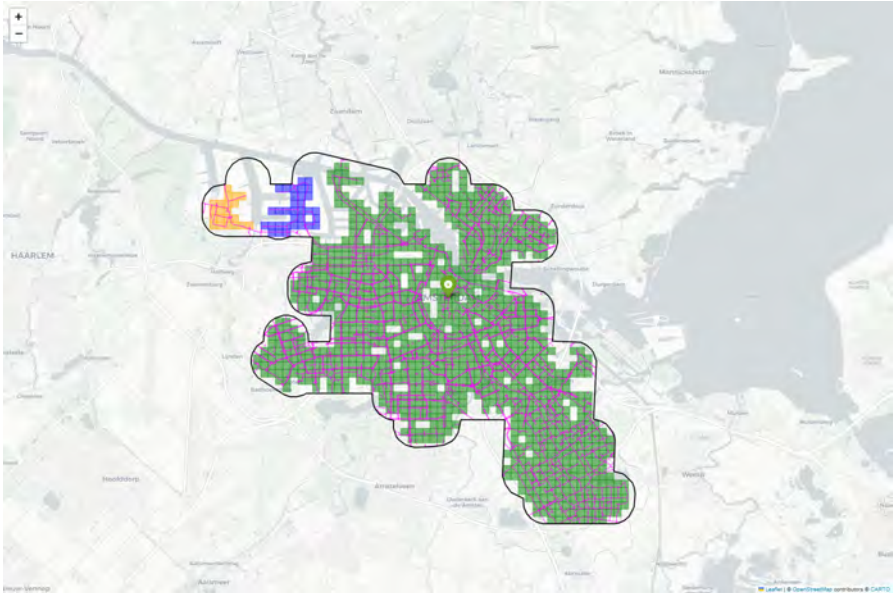


Figure 14: Amsterdam – Indicator 1B

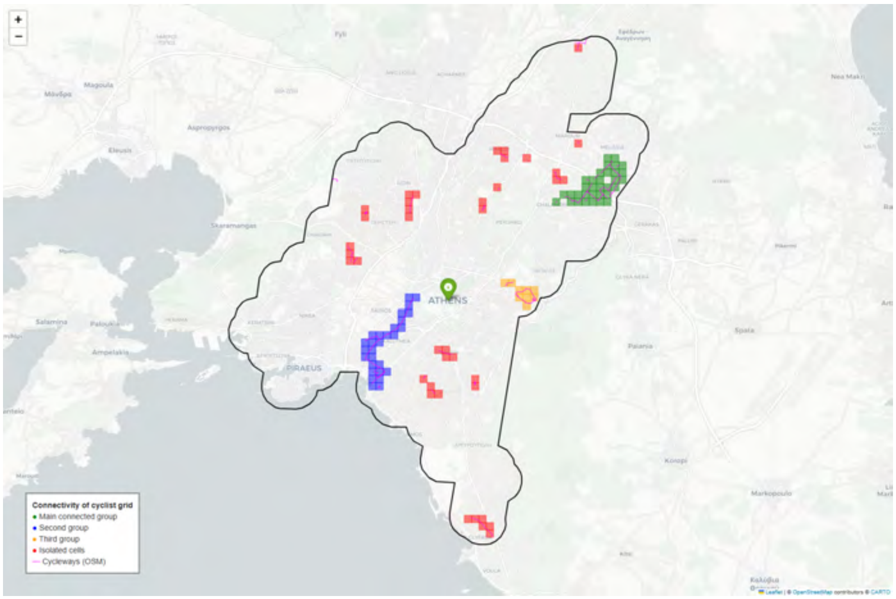


Figure 15: Atenas – Indicator 1B

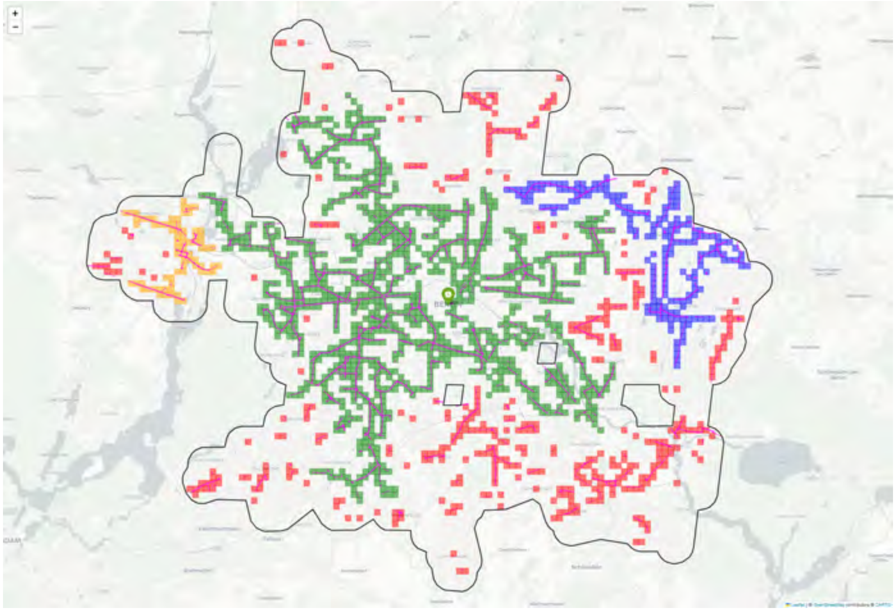


Figure 16: Berlin – Indicator 1B

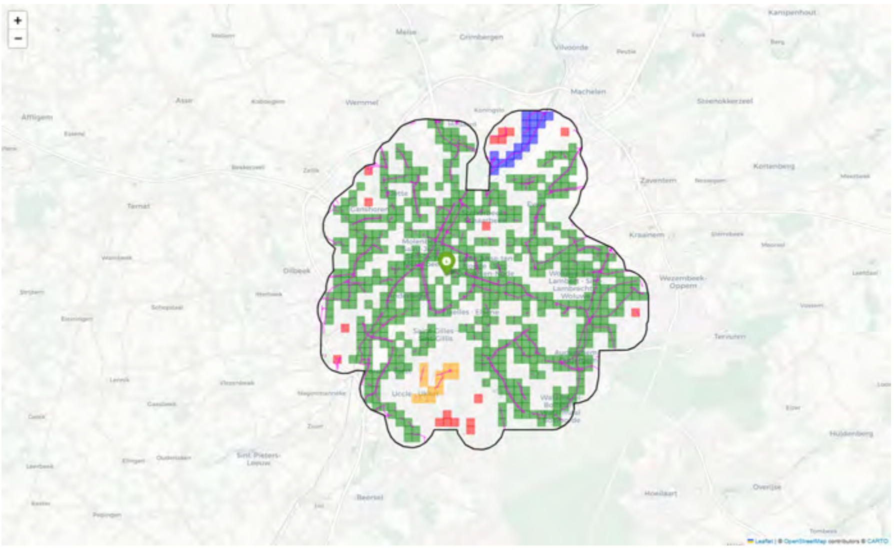


Figure 17: Brussels – Indicator 1B

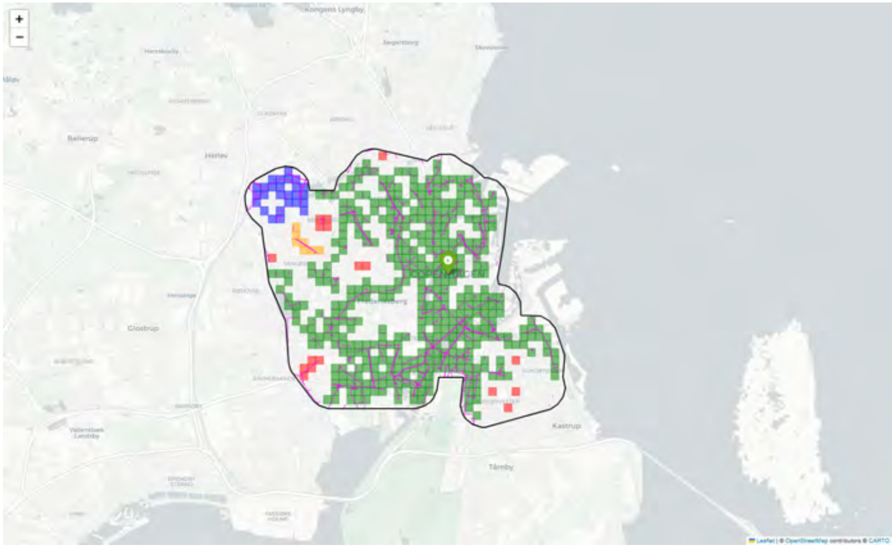


Figure 18: Copenhague – Indicator 1B

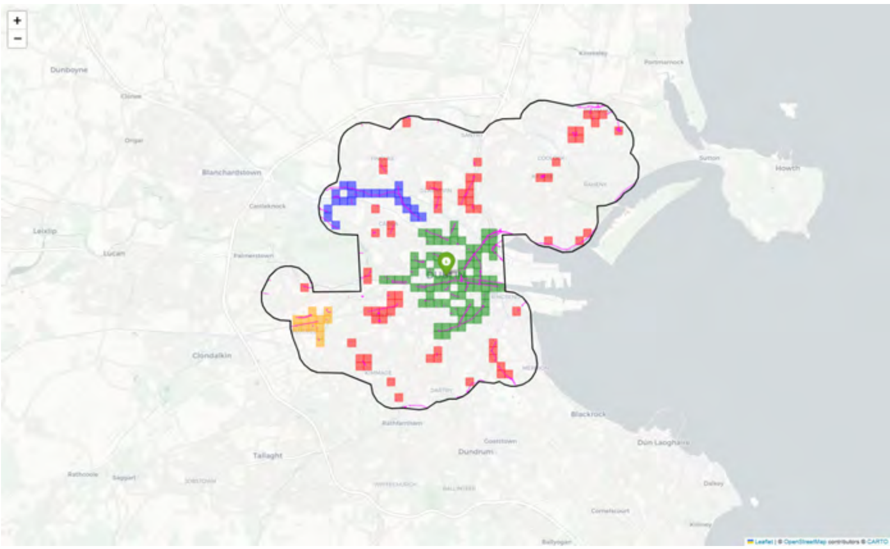


Figure 19: Dublin – Indicator 1B

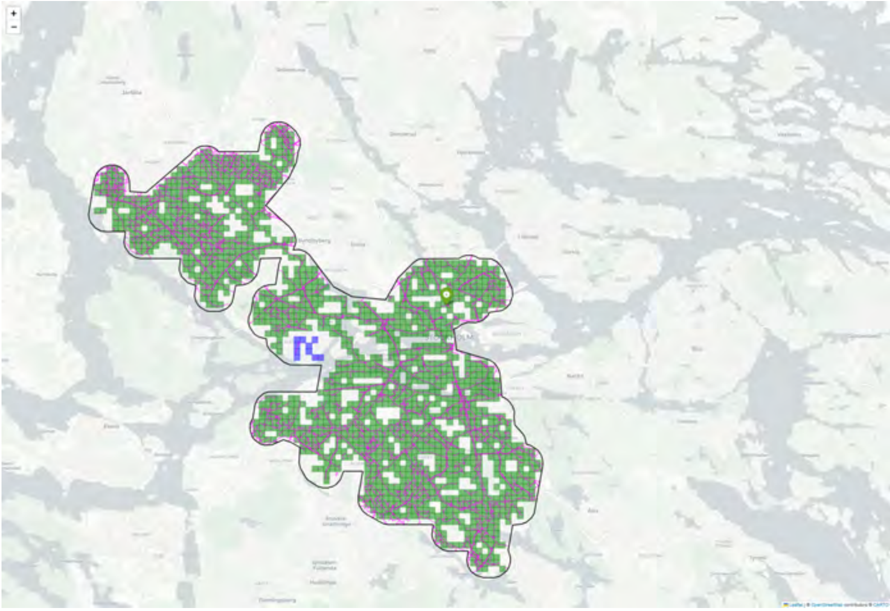


Figure 20: Estocolmo – Indicator 1B

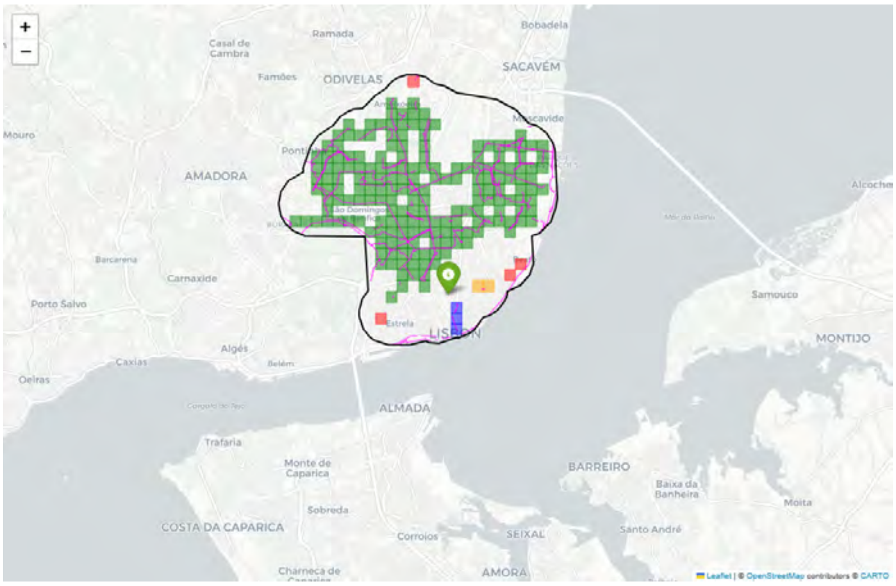


Figure 21: Lisbon – Indicator 1B

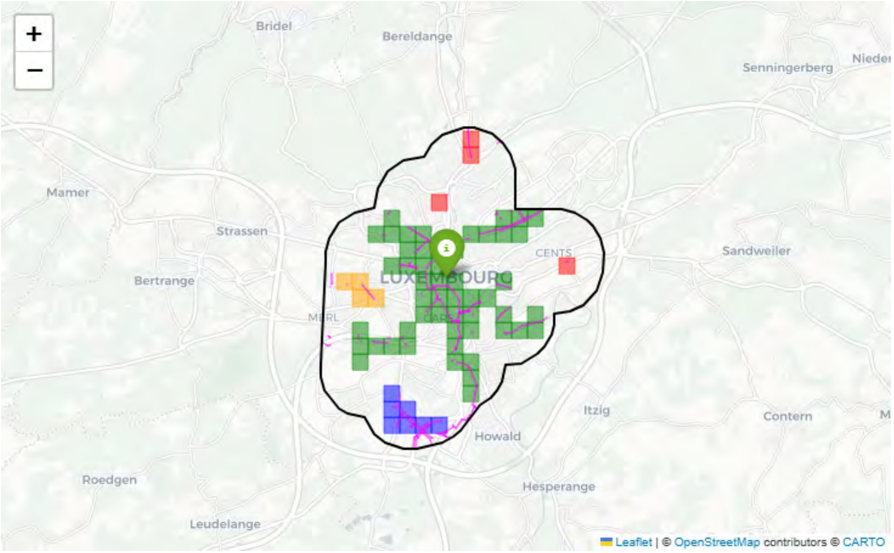


Figure 22: Luxemburgo – Indicator 1B

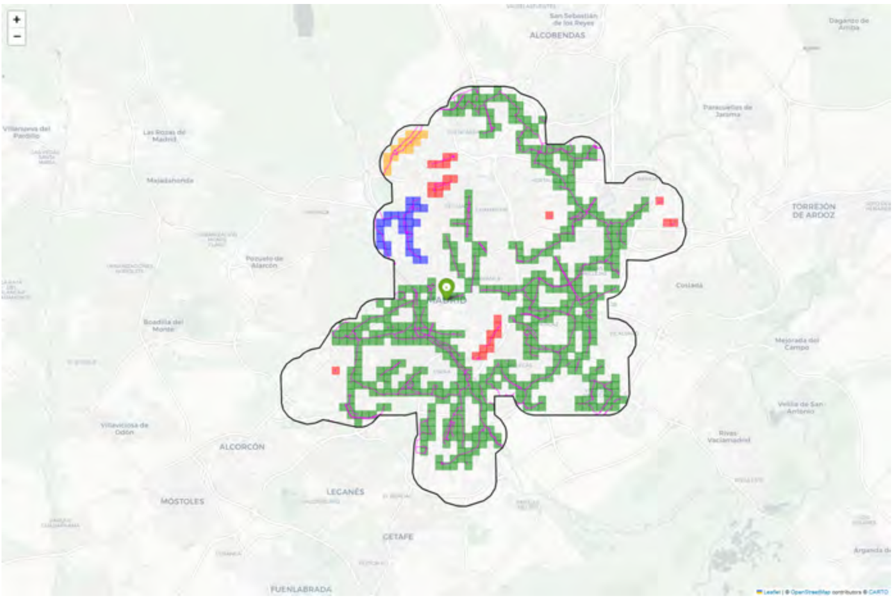


Figure 23: Madrid – Indicator 1B

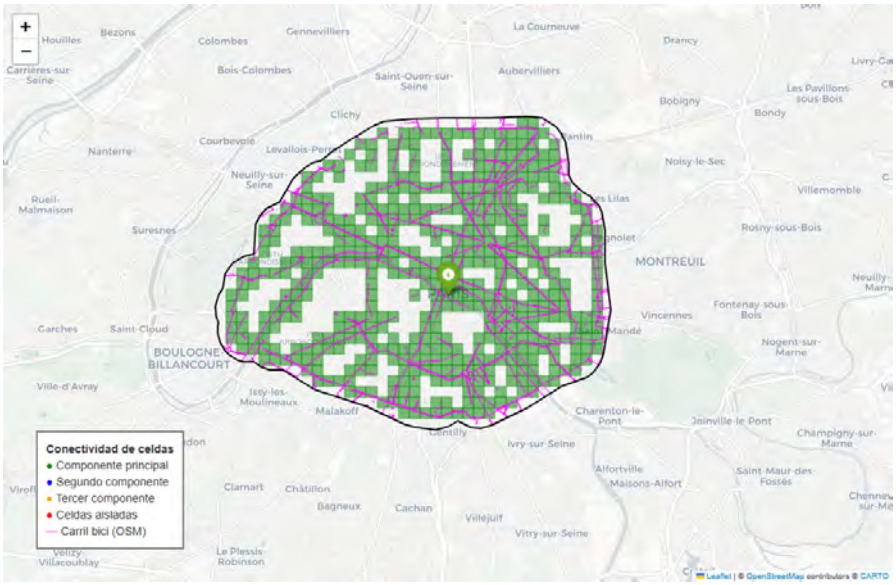


Figure 24: Paris – Indicator 1B

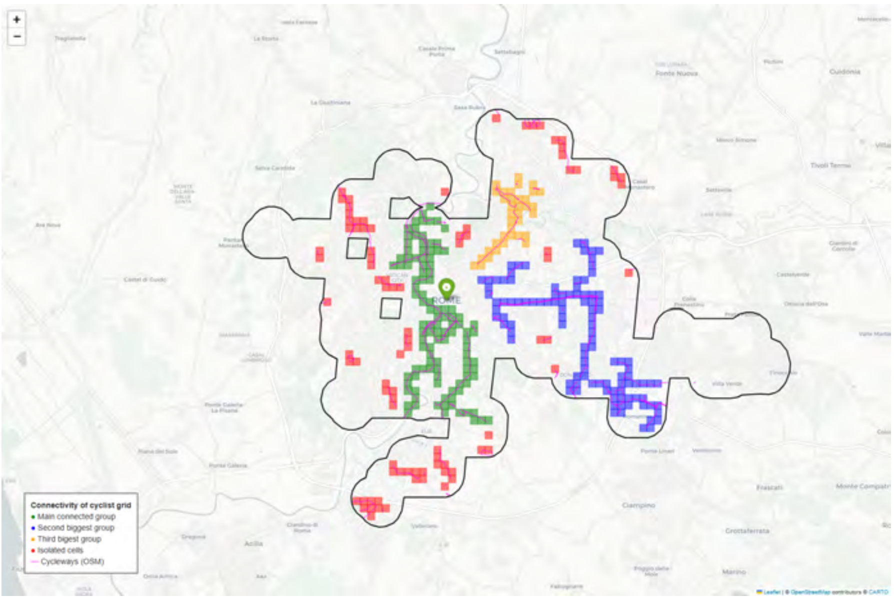


Figure 25: Rome – Indicator 1B

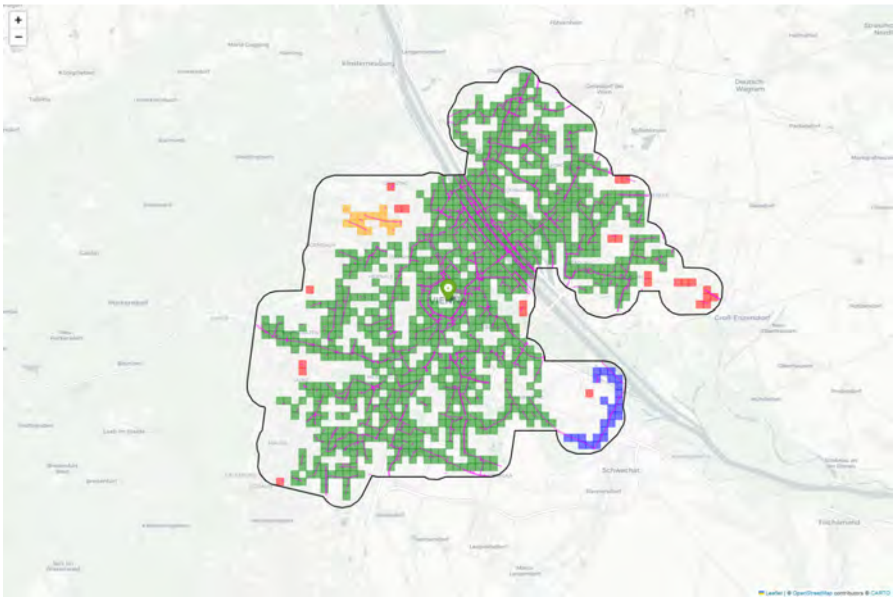


Figure 26: Viena – Indicator 1B

Indicator 1c

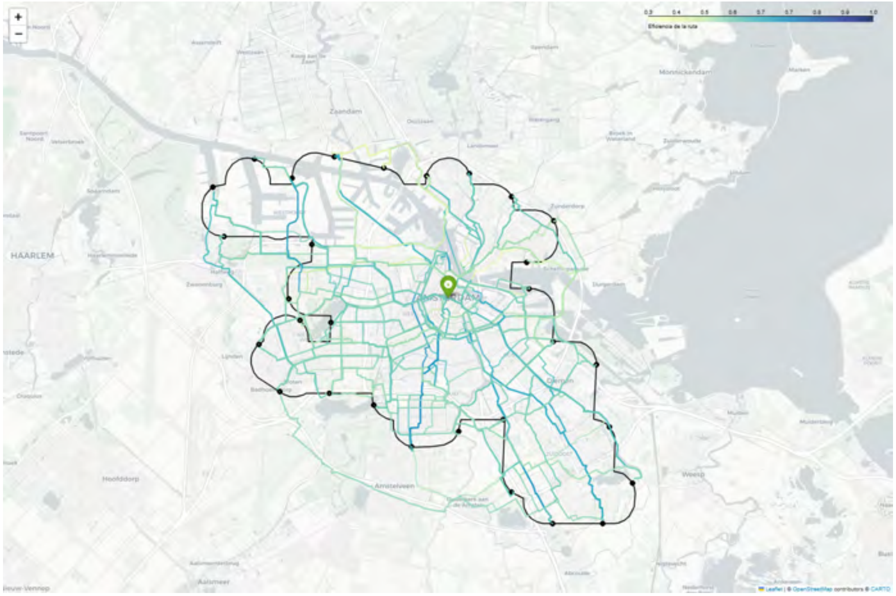
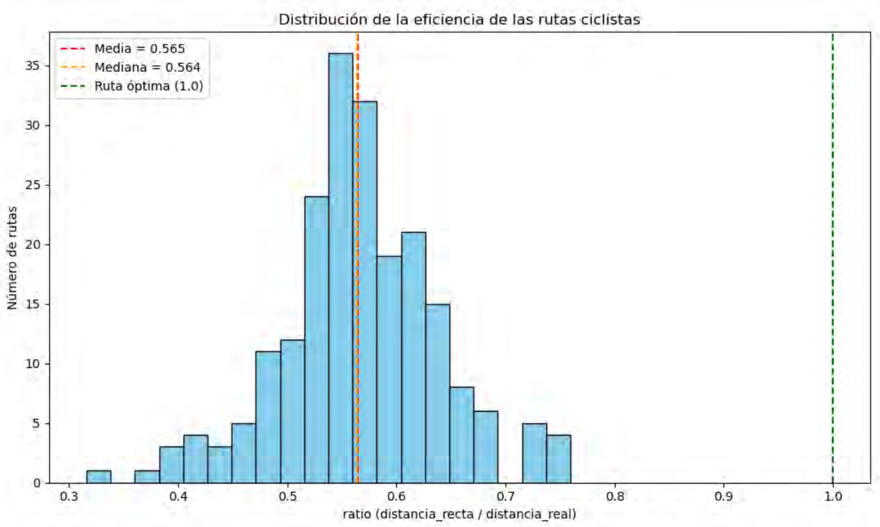


Figure 27: Amsterdam – Indicator 1C



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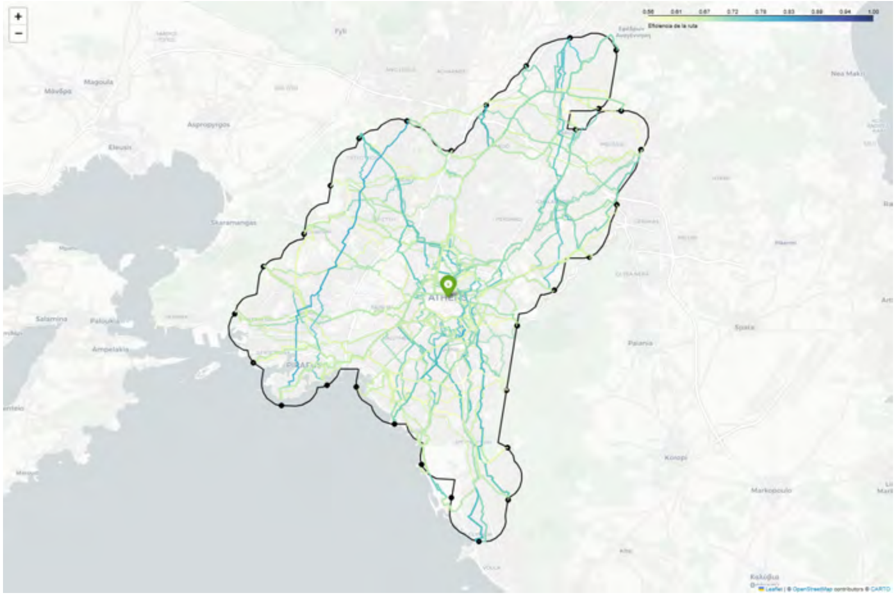
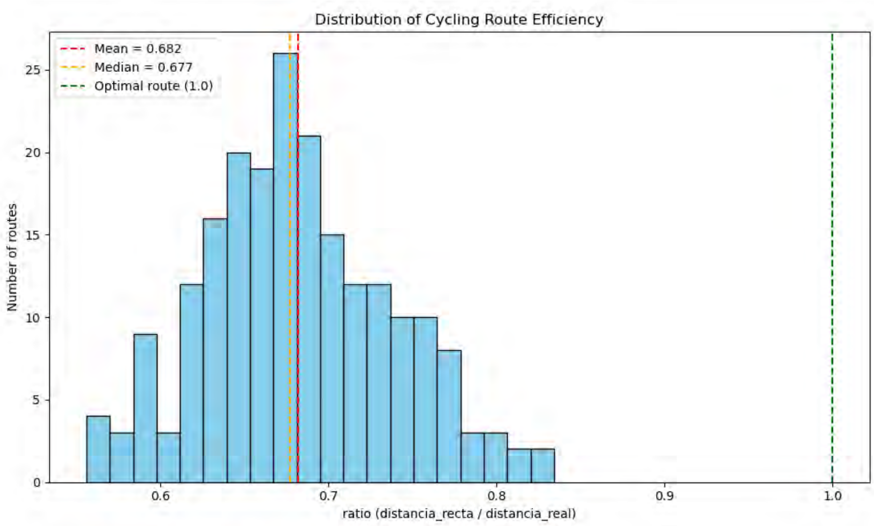


Figure 29: Atenas – Indicator 1C



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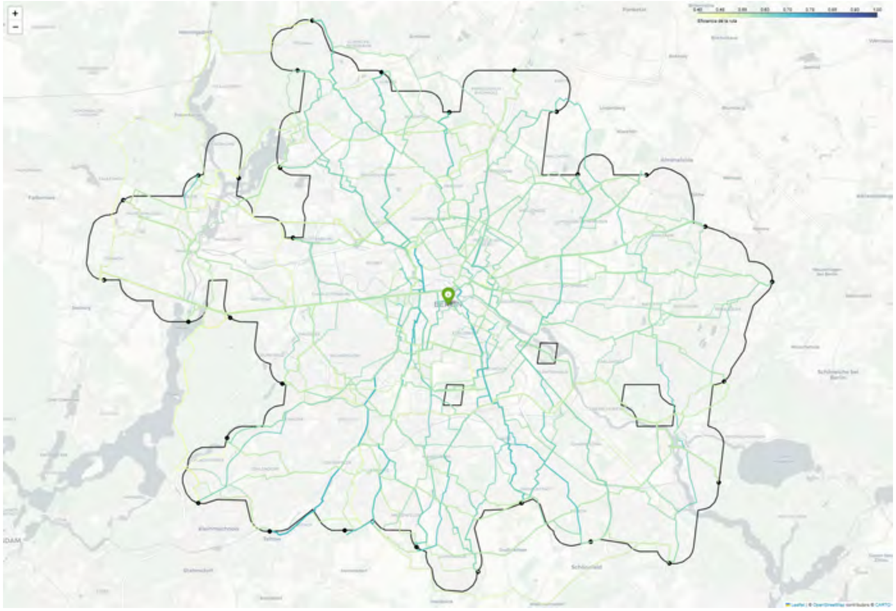
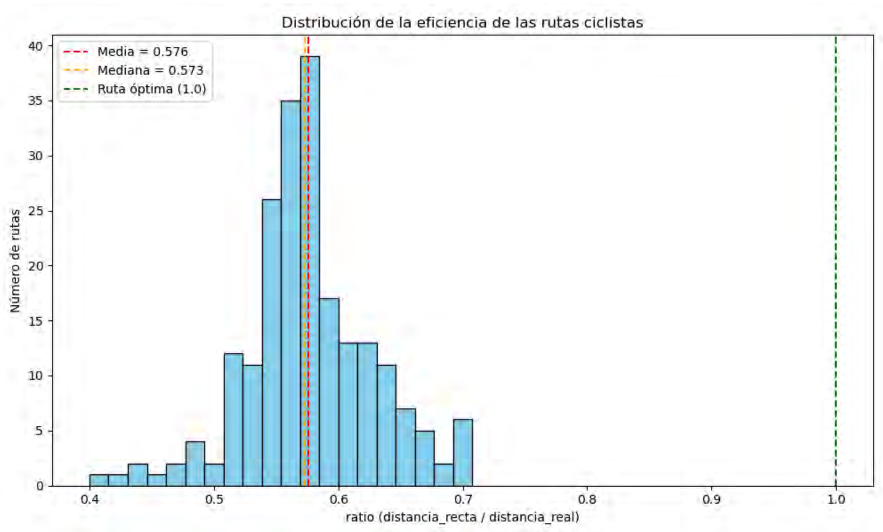


Figure 31: Berlin – Indicator 1C



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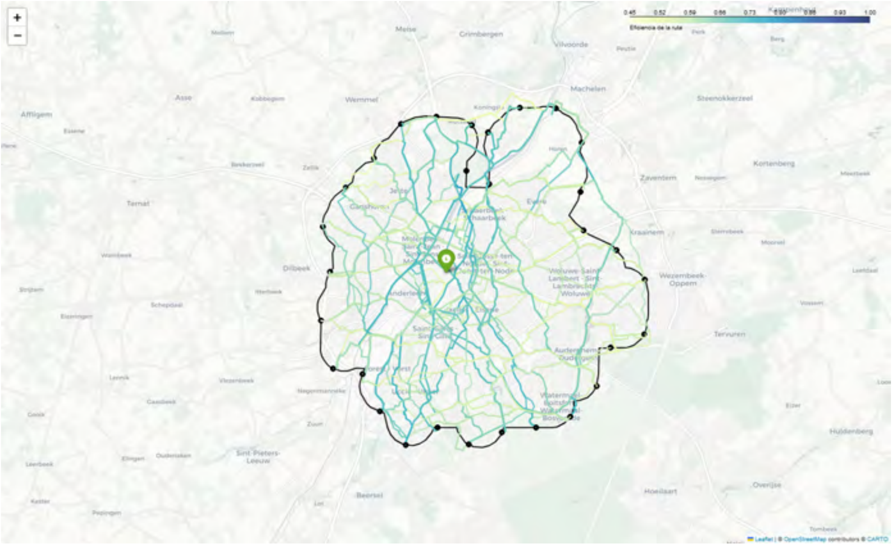
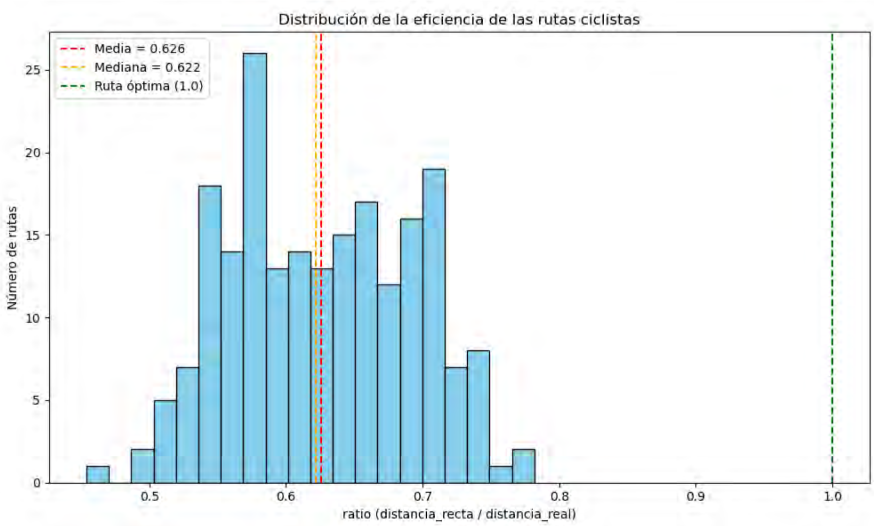


Figure 33: Brussels – Indicator 1C



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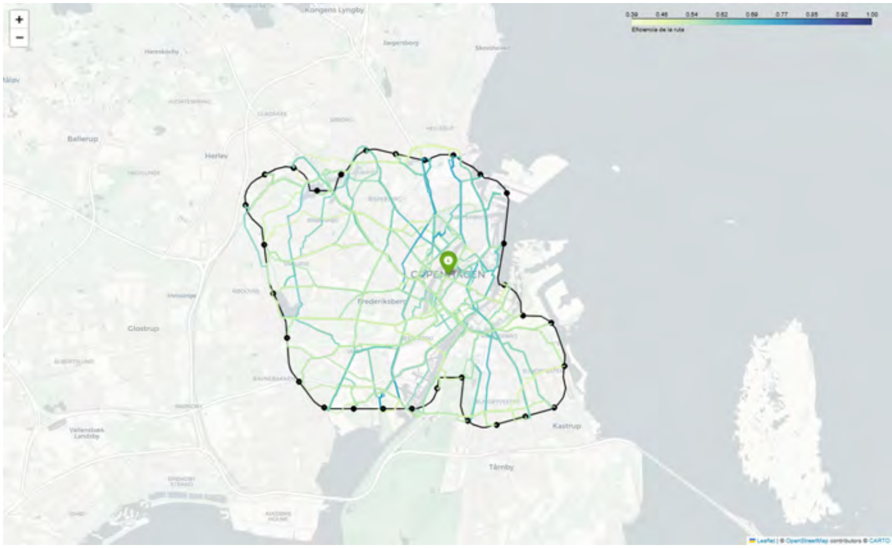


Figure 35: Copenhague – Indicator 1C

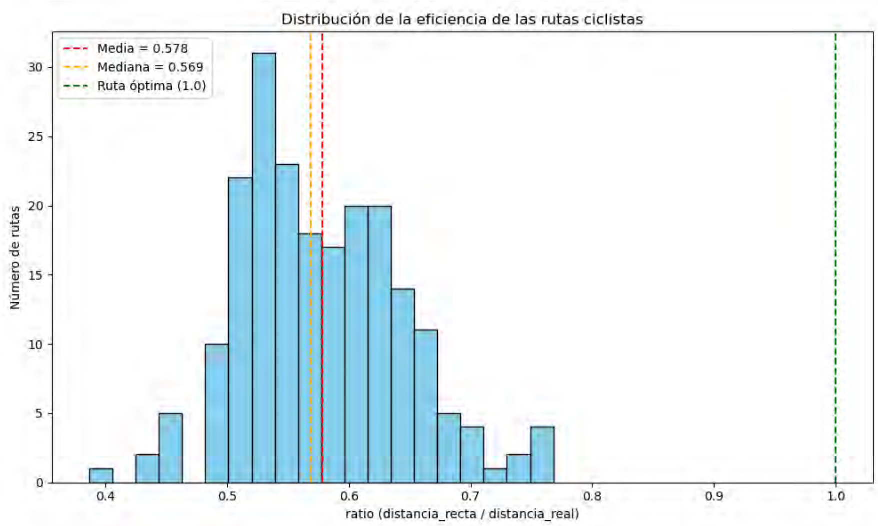
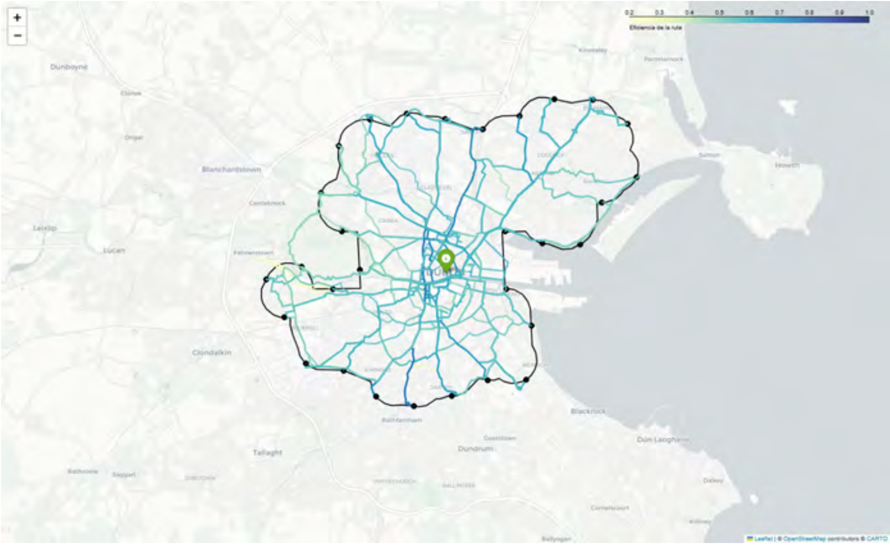


Figure 36: Copenhague – Indicator 1C



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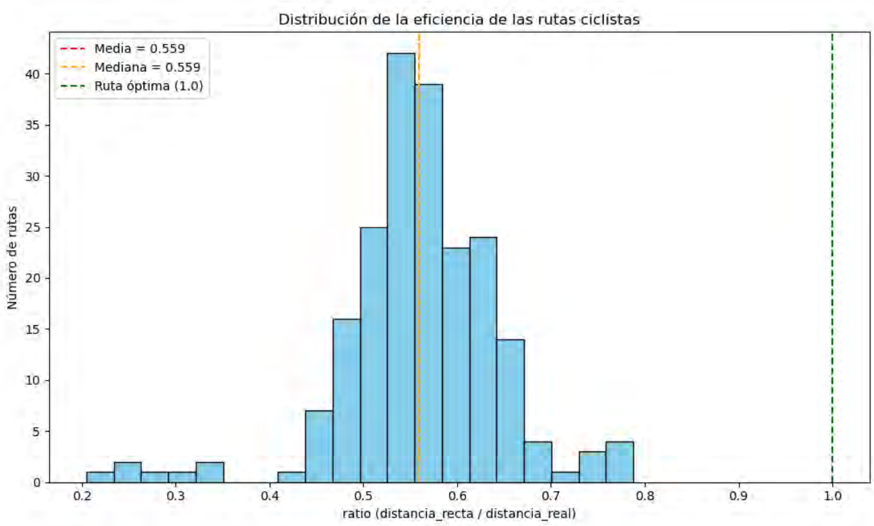

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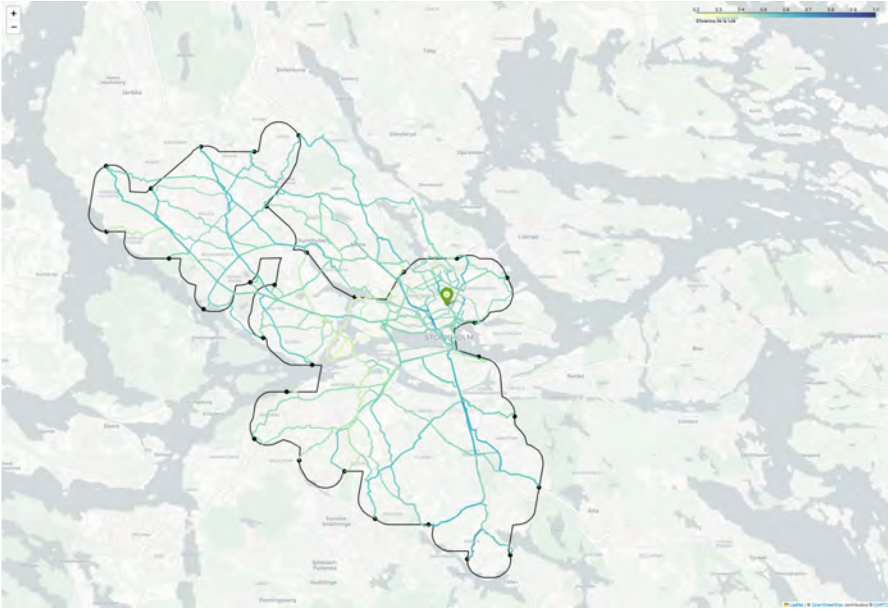

Figure 39: Estocolmo – Indicator 1C

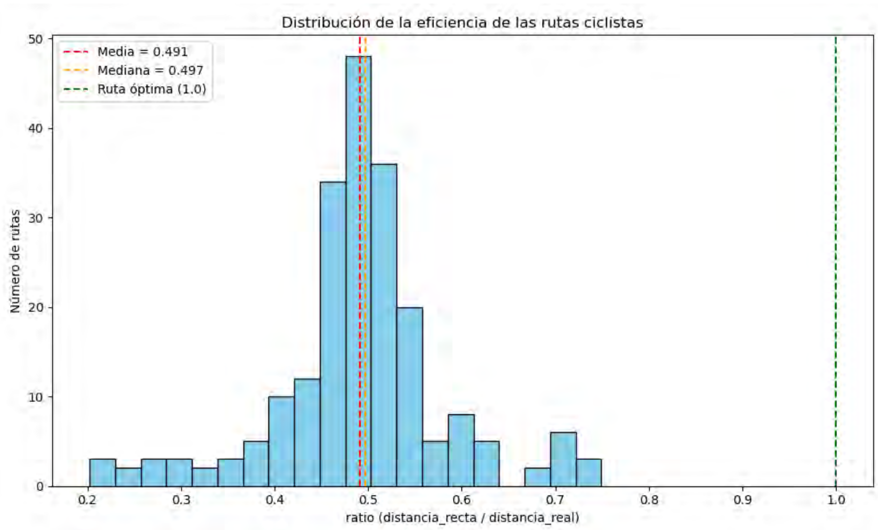

Figure 40: Estocolmo – Indicator 1C

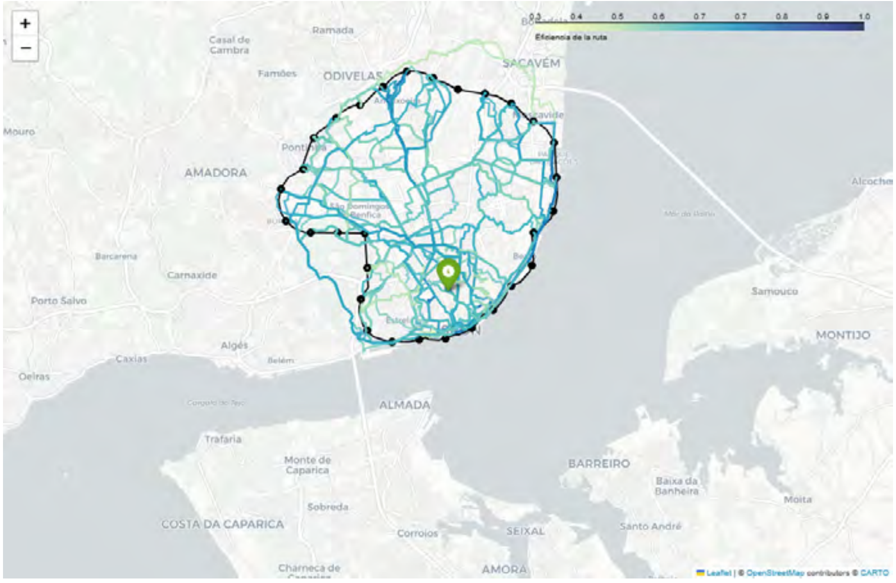

Figure 41: Lisbon – Indicator 1C

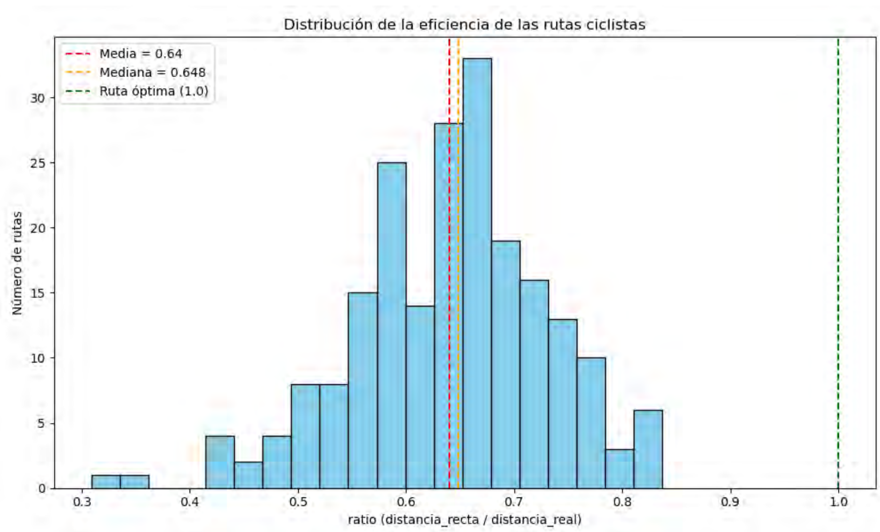

Figure 42: Lisbon – Indicator 1C

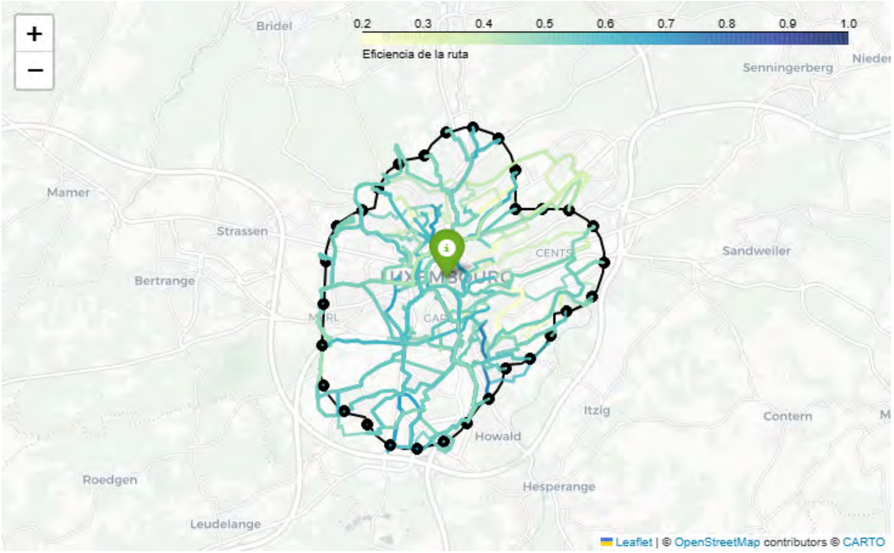

Figure 43: Luxemburgo – Indicator 1C

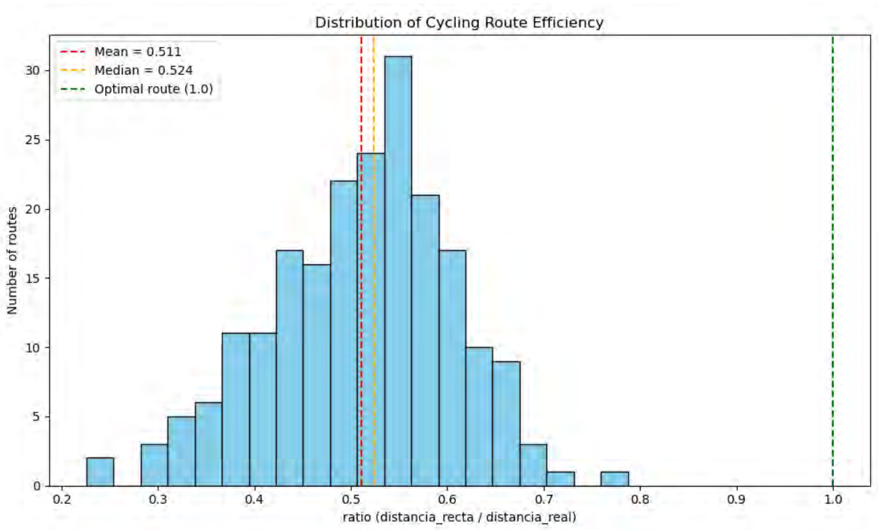

Figure 44: Luxemburgo – Indicator 1C

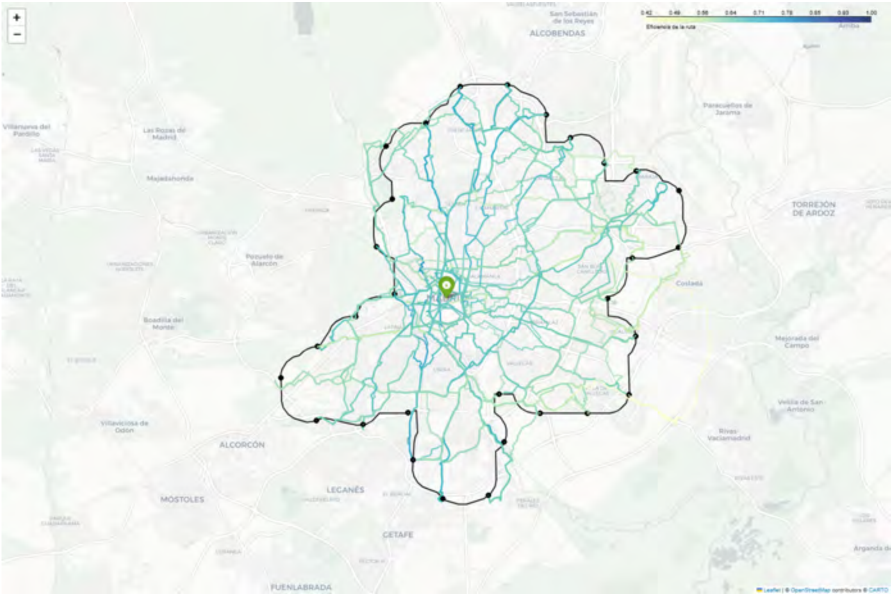

Figure 45: Madrid – Indicator 1C

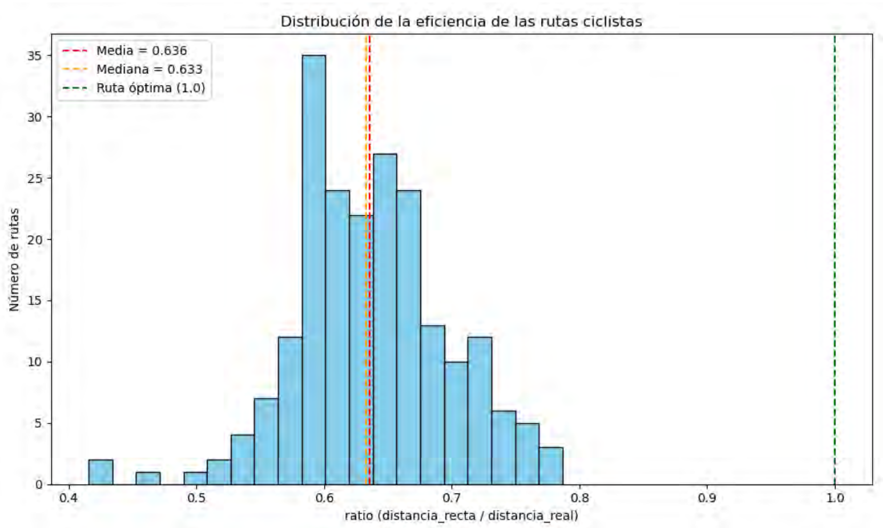

Figure 46: Madrid – Indicator 1C

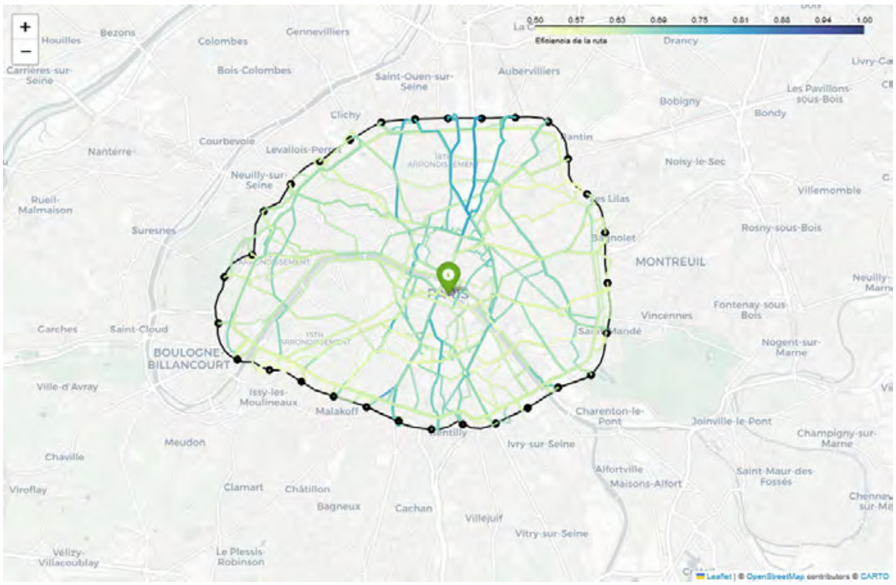

Figure 47: Paris – Indicator 1C

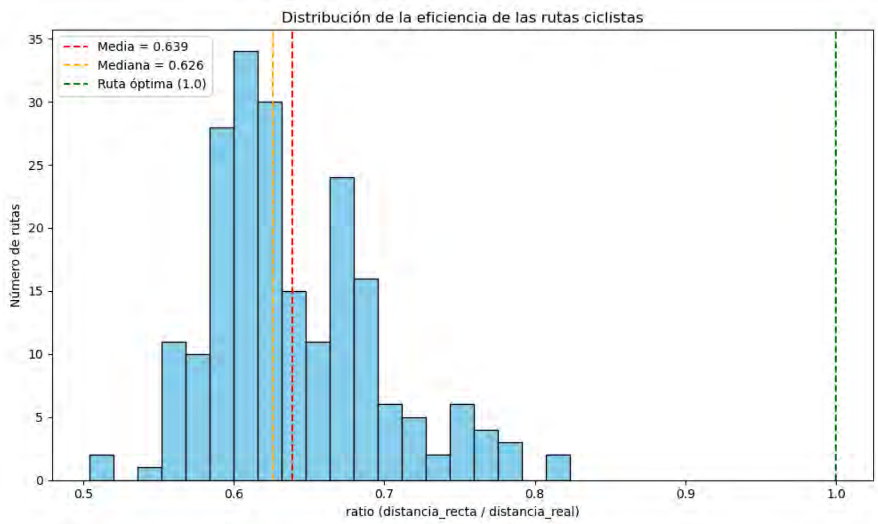

Figure 48: Paris – Indicator 1C

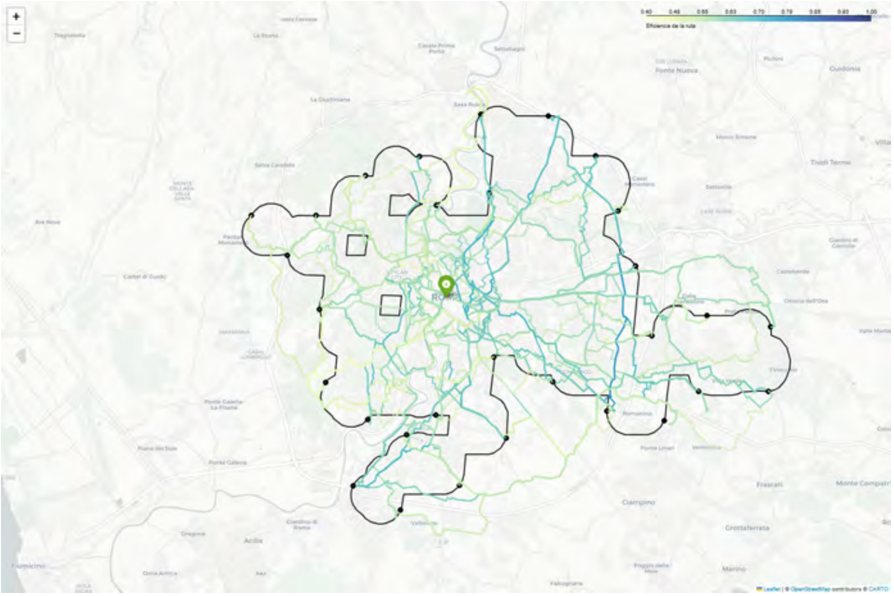

Figure 49: Rome – Indicator 1C

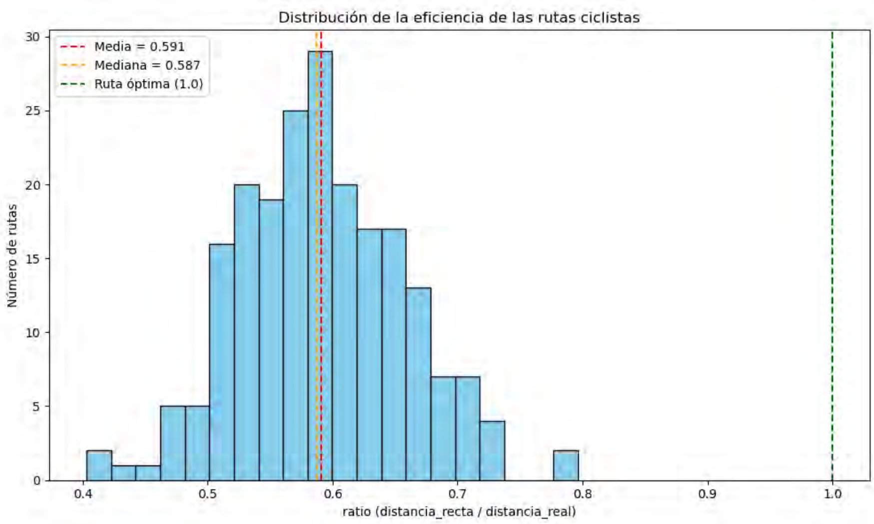

Figure 50: Rome – Indicator 1C

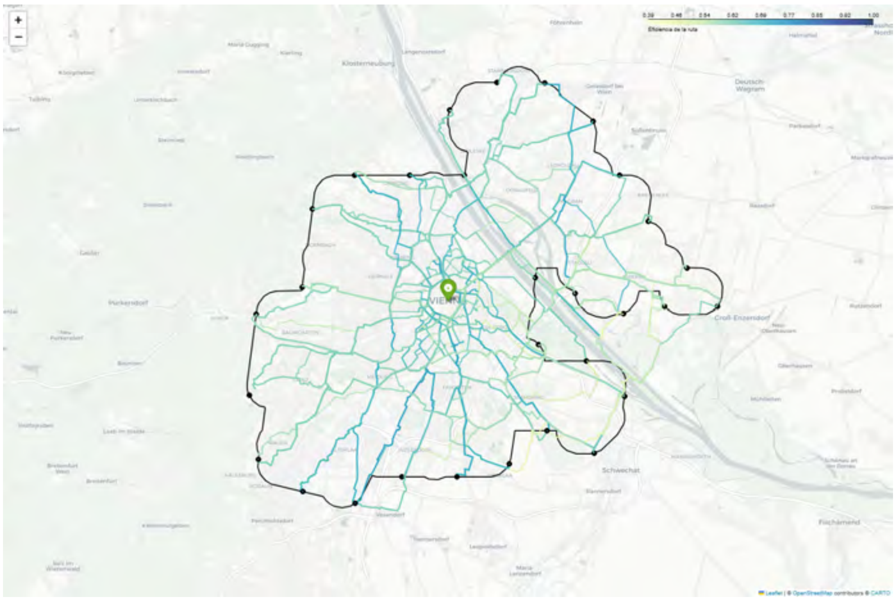

Figure 51: Viena – Indicator 1C

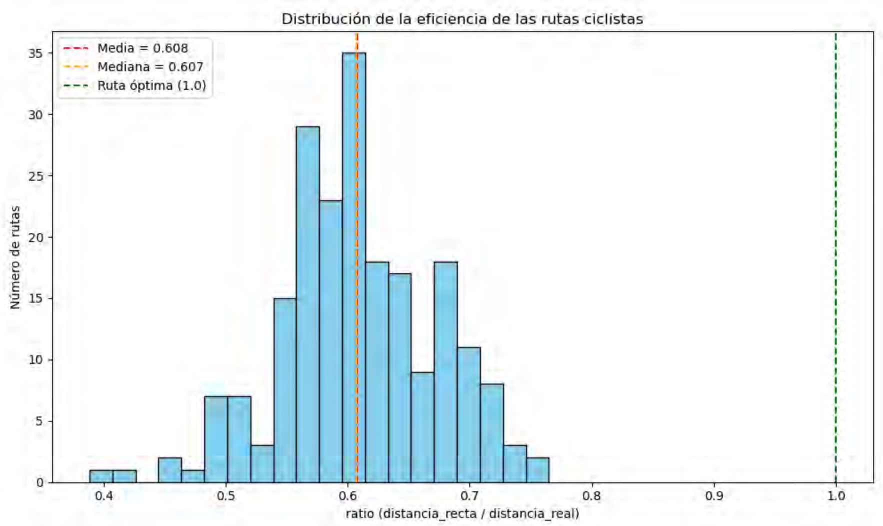

Figure 52: Viena – Indicator 1C

Indicator 2a

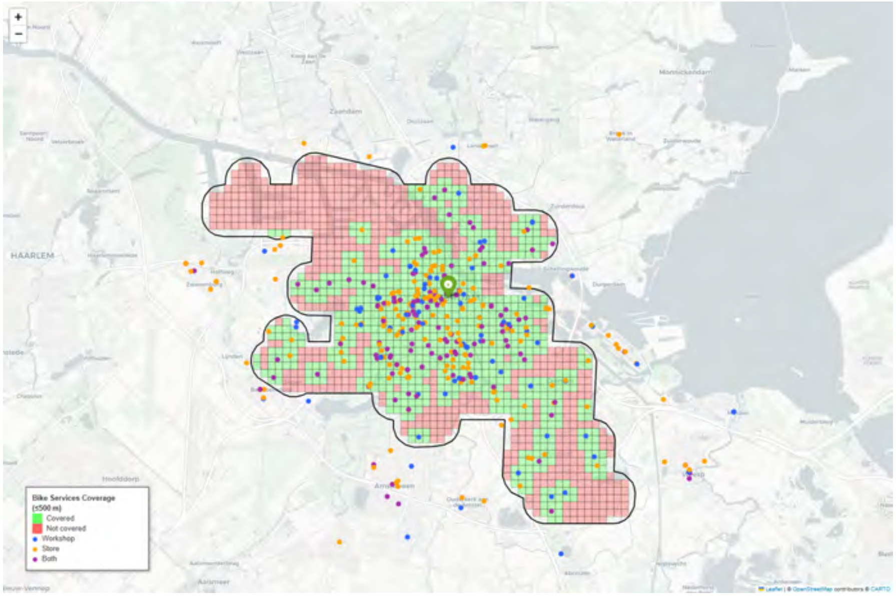

Figure 53: Amsterdam – Indicator 2A

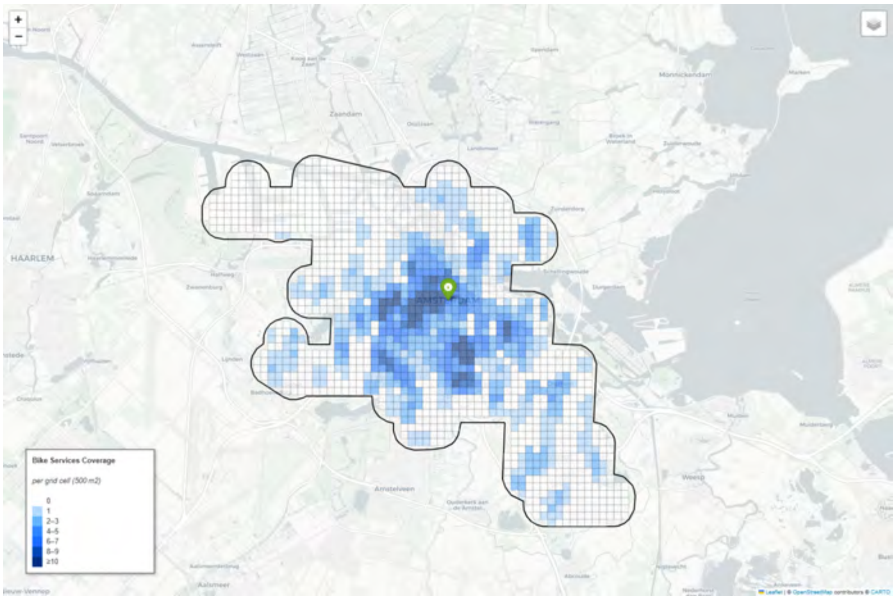

Figure 54: Amsterdam – Indicator 2A

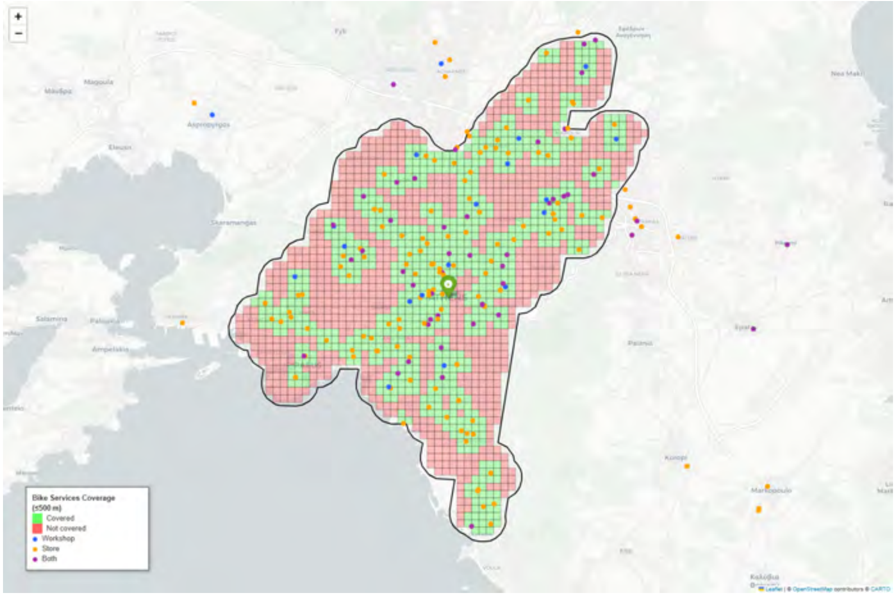

Figure 55: Atenas – Indicator 2A

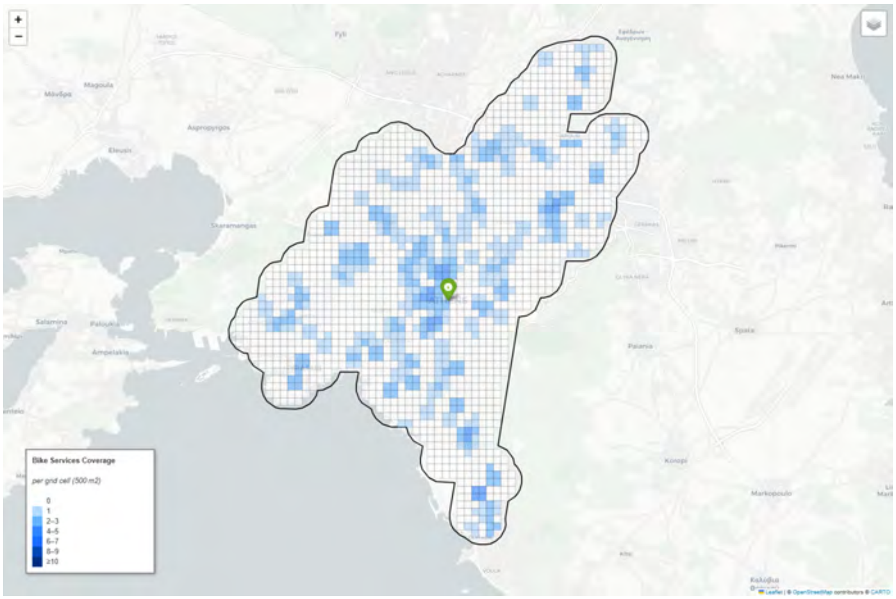

Figure 56: Atenas – Indicator 2A

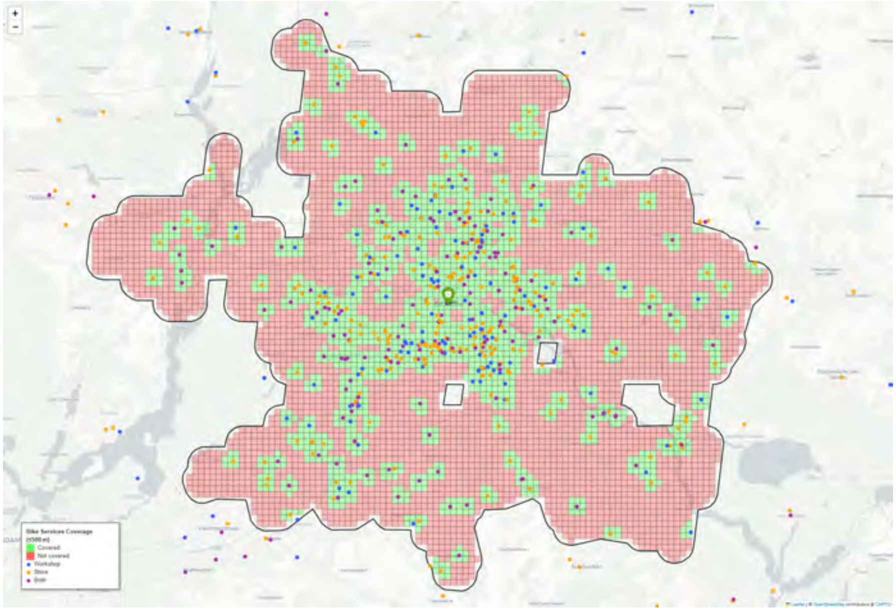

Figure 57: Berlin – Indicator 2A

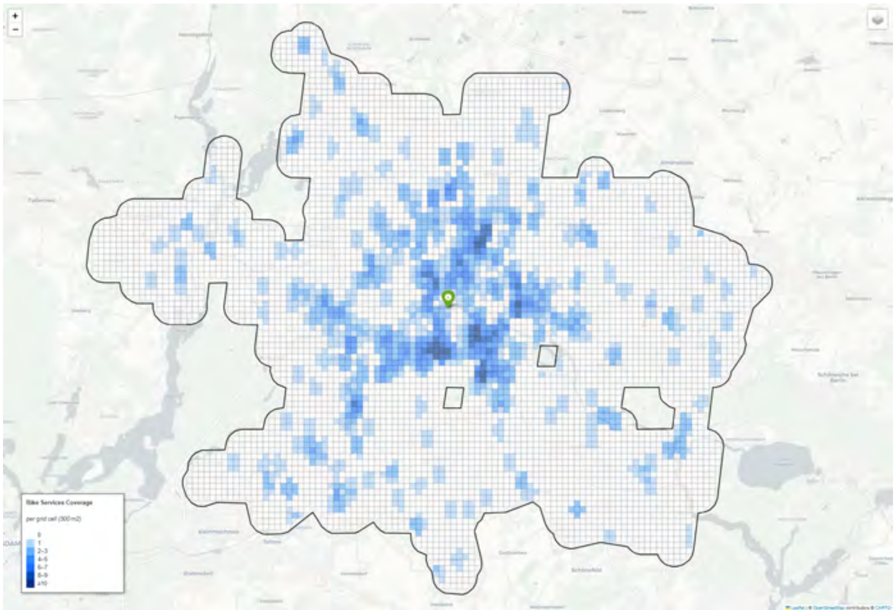

Figure 58: Berlin – Indicator 2A

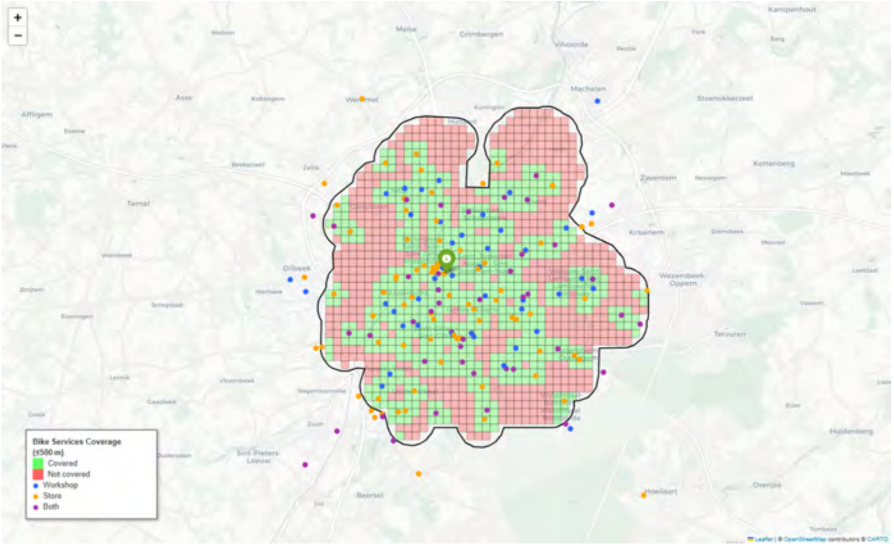

Figure 59: Brussels – Indicator 2A

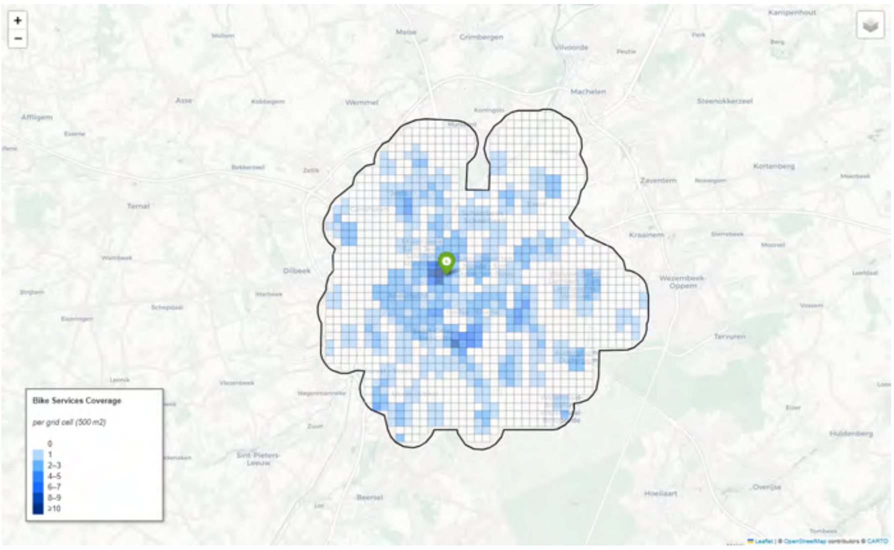

Figure 60: Brussels – Indicator 2A

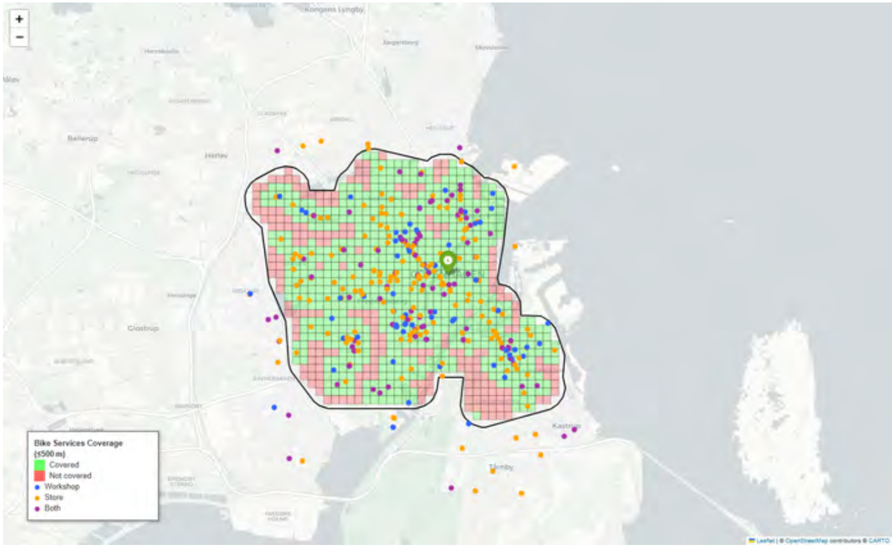

Figure 61: Copenhague – Indicator 2A

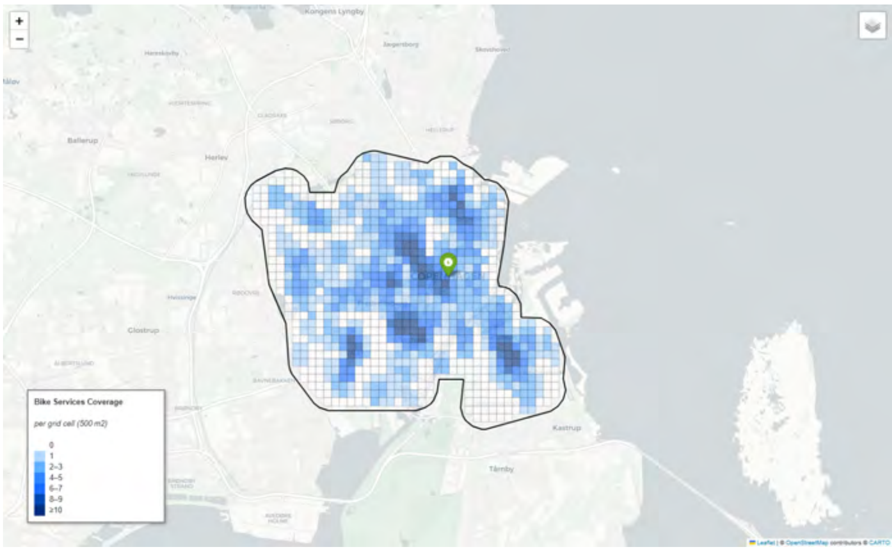

Figure 62: Copenhague – Indicator 2A

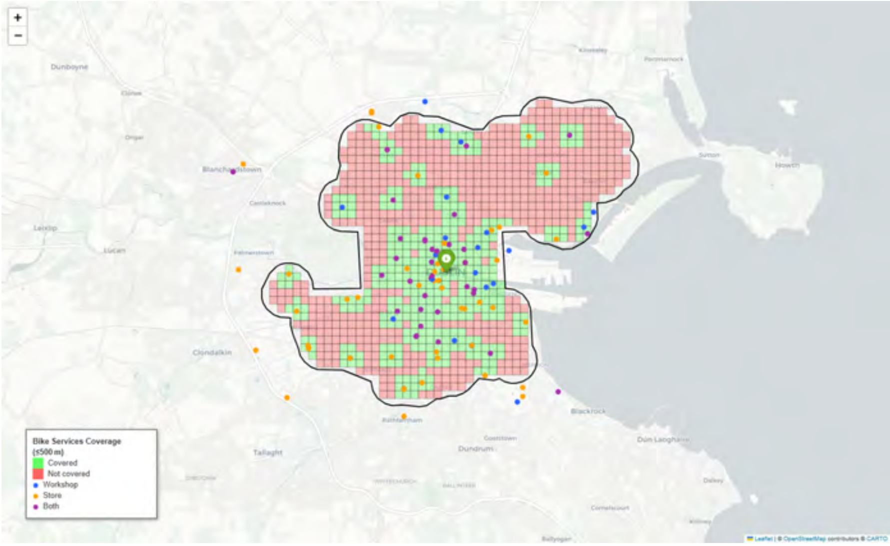

Figure 63: Dublin – Indicator 2A

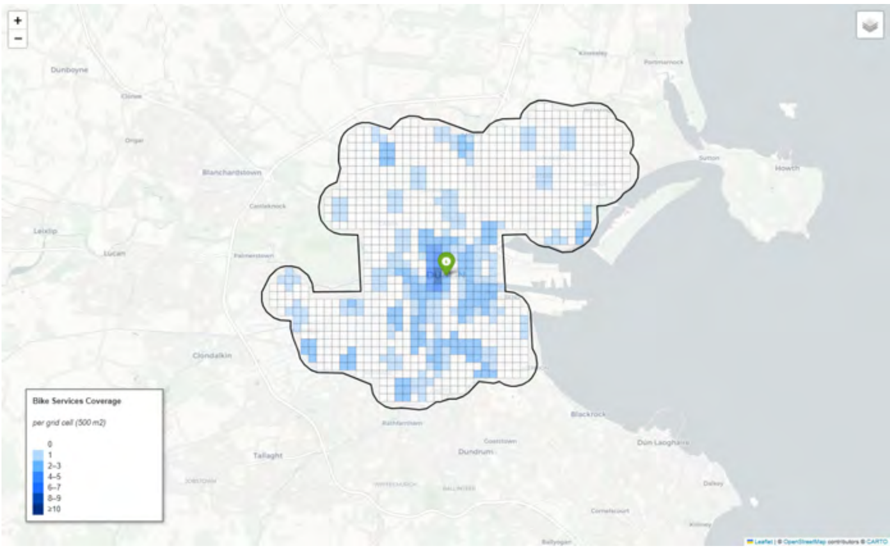

Figure 64: Dublin – Indicator 2A

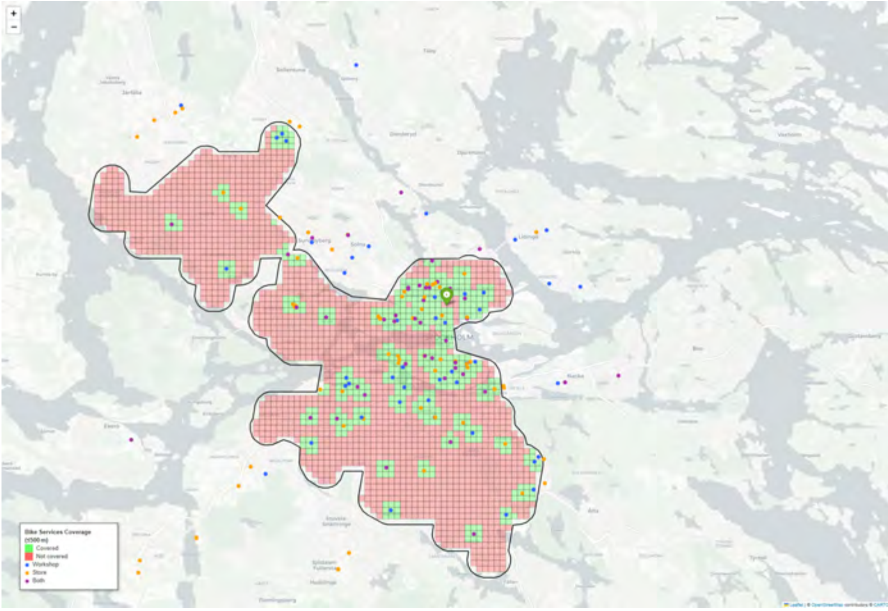

Figure 65: Estocolmo – Indicator 2A

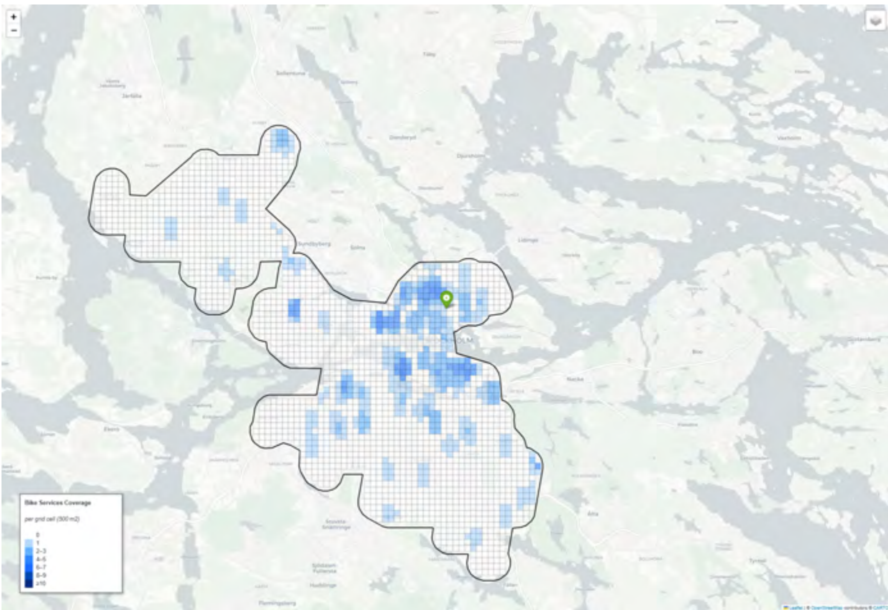

Figure 66: Estocolmo – Indicator 2A

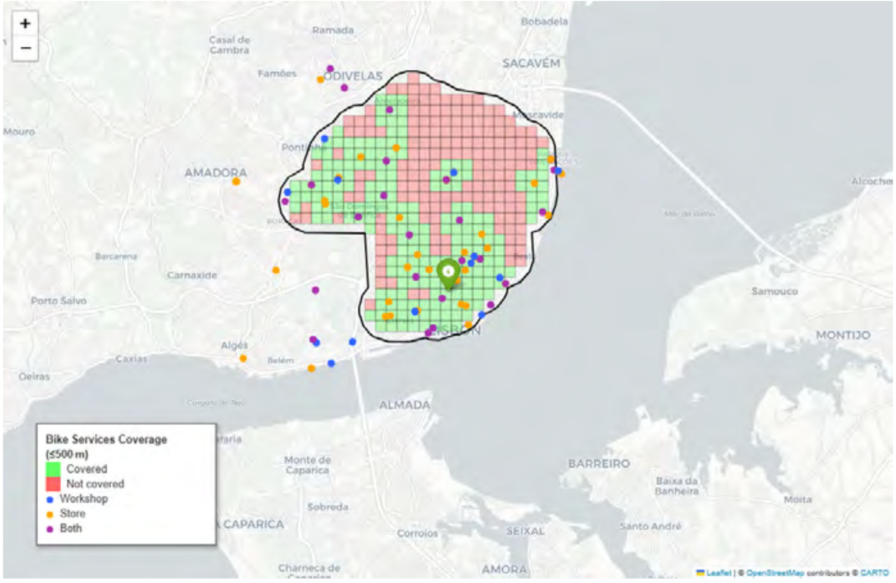

Figure 67: Lisbon – Indicator 2A

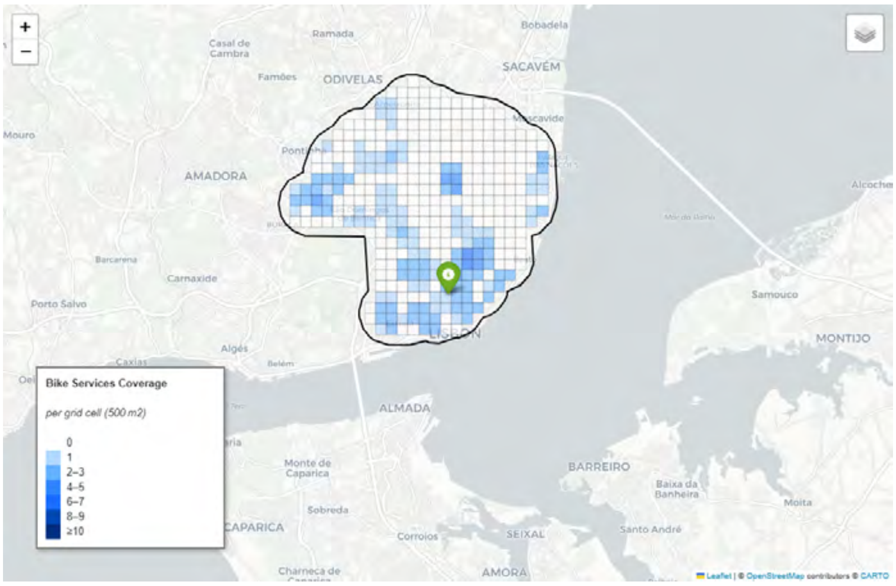

Figure 68: Lisbon – Indicator 2A

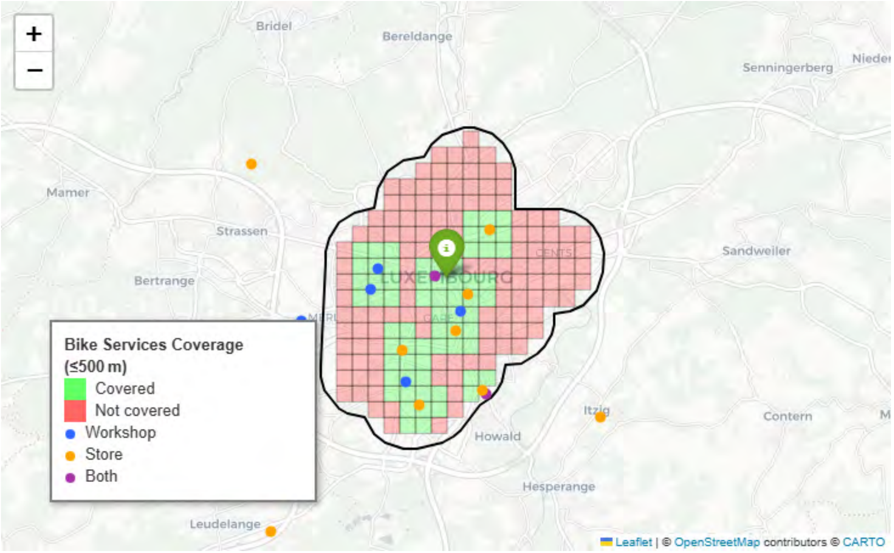

Figure 69: Luxemburgo – Indicator 2A

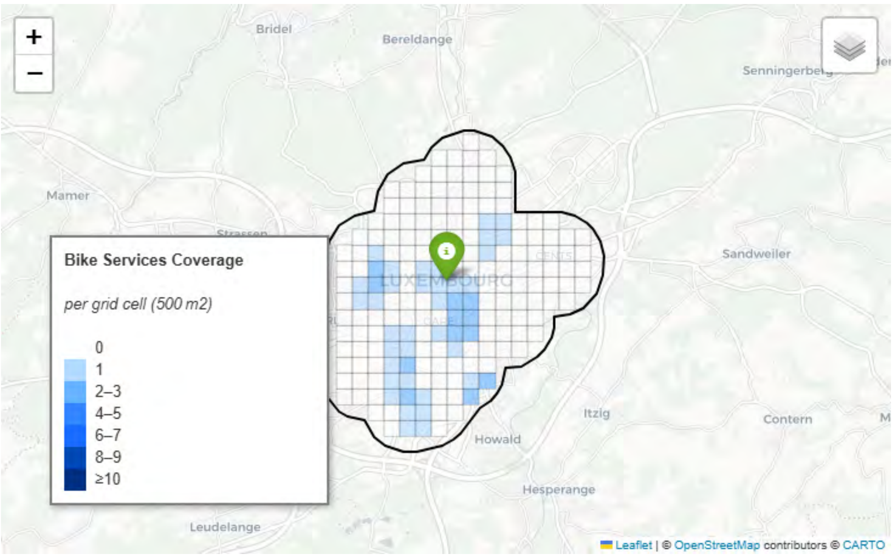

Figure 70: Luxemburgo – Indicator 2A

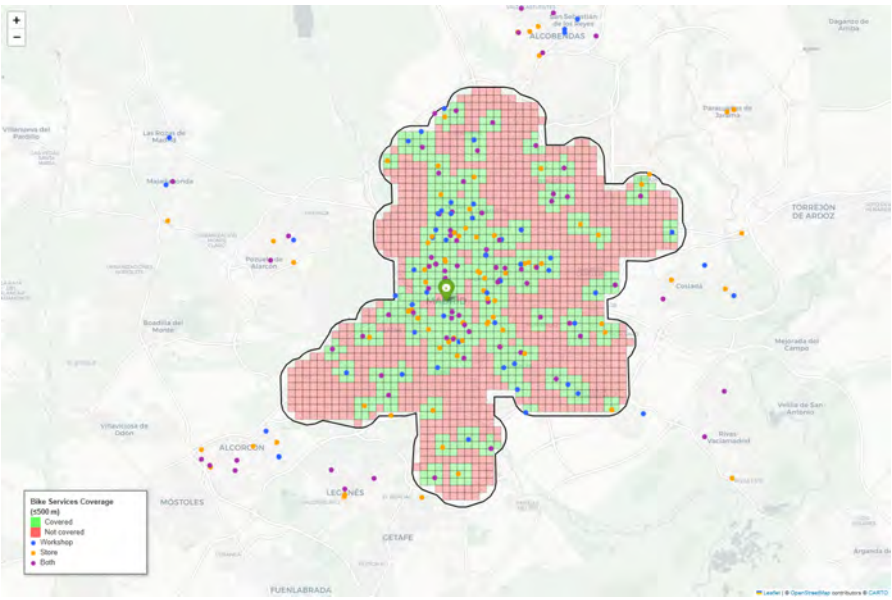

Figure 71: Madrid – Indicator 2A

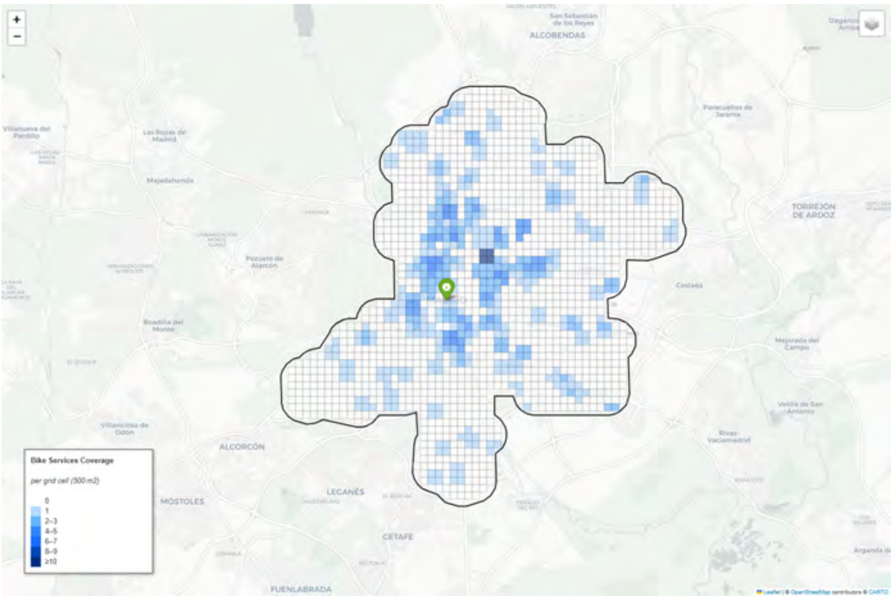

Figure 72: Madrid – Indicator 2A

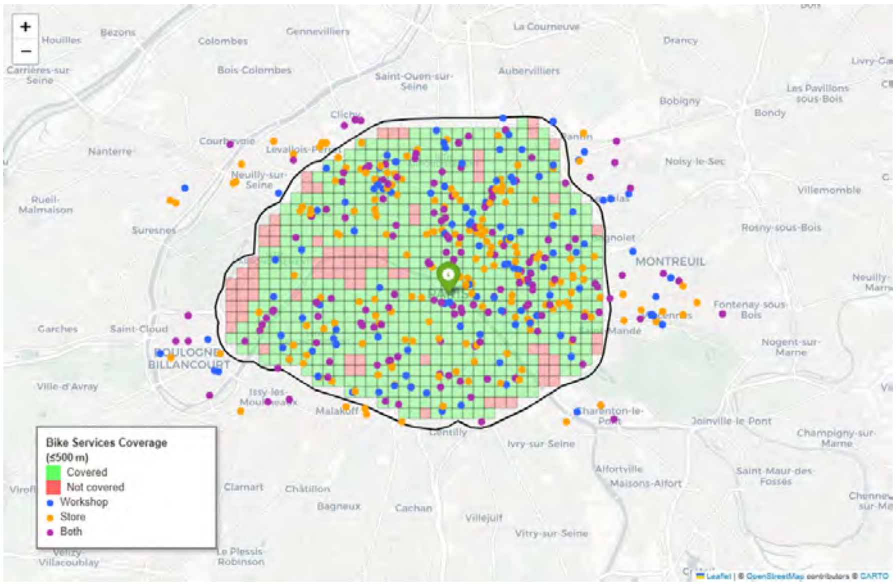

Figure 73: Paris – Indicator 2A

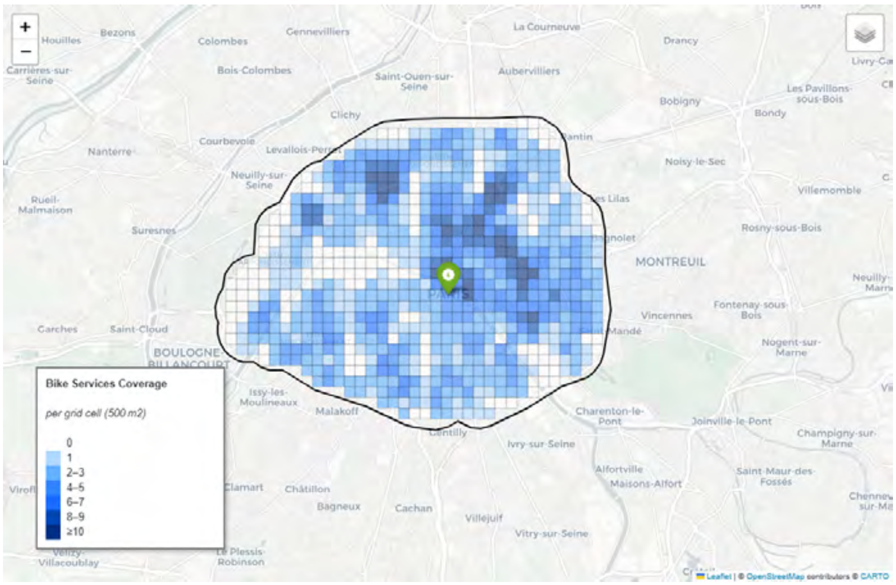

Figure 74: Paris – Indicator 2A

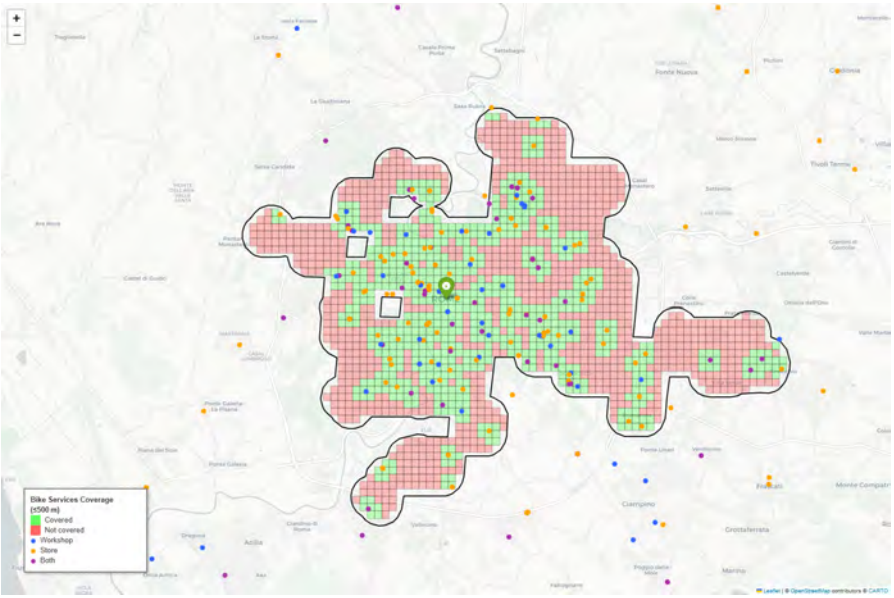

Figure 75: Rome – Indicator 2A

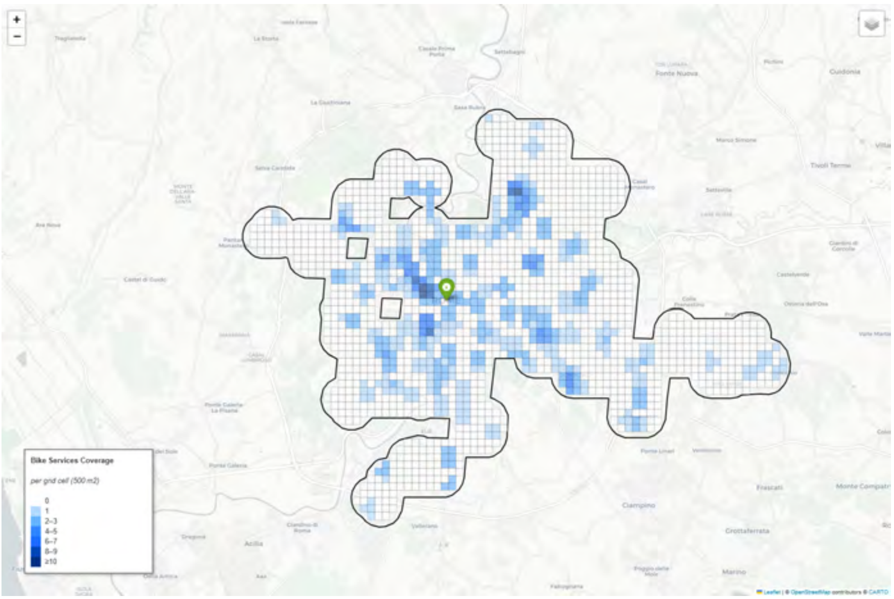

Figure 76: Rome – Indicator 2A

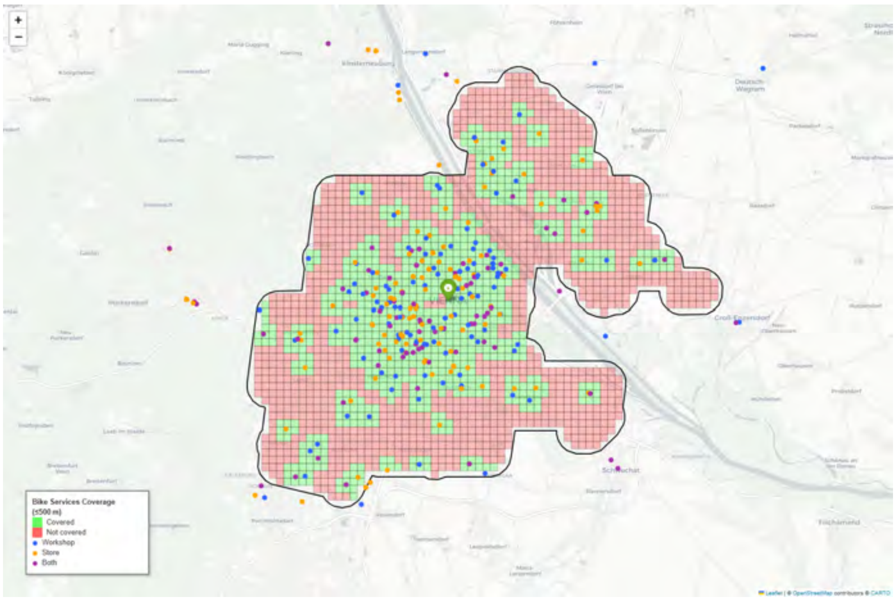

Figure 77: Viena – Indicator 2A

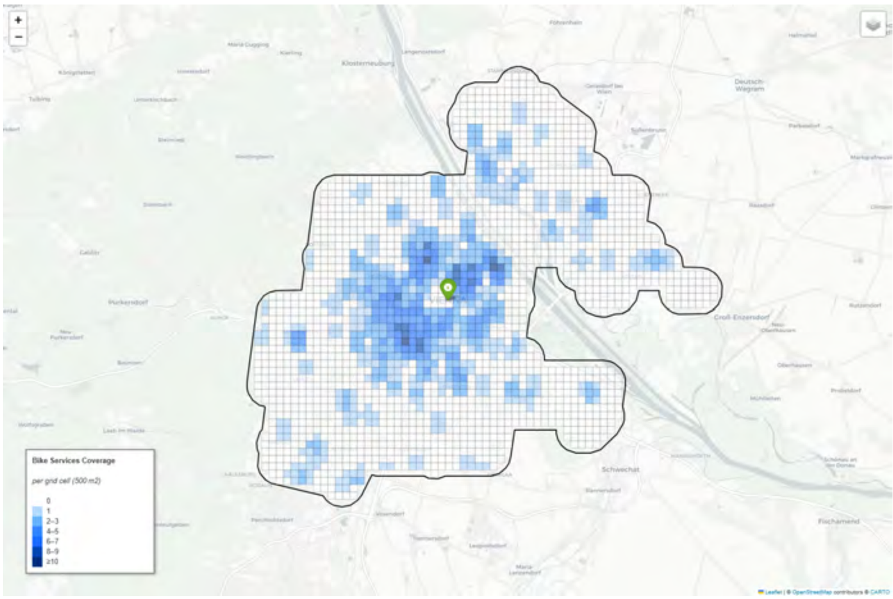

Figure 78: Viena – Indicator 2A

Indicator 2b

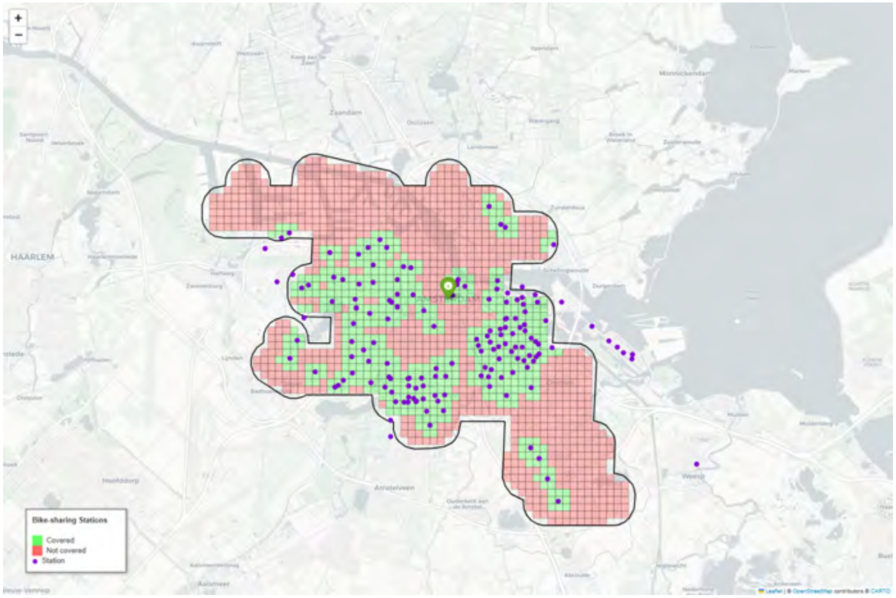

Figure 79: Amsterdam – Indicator 2B

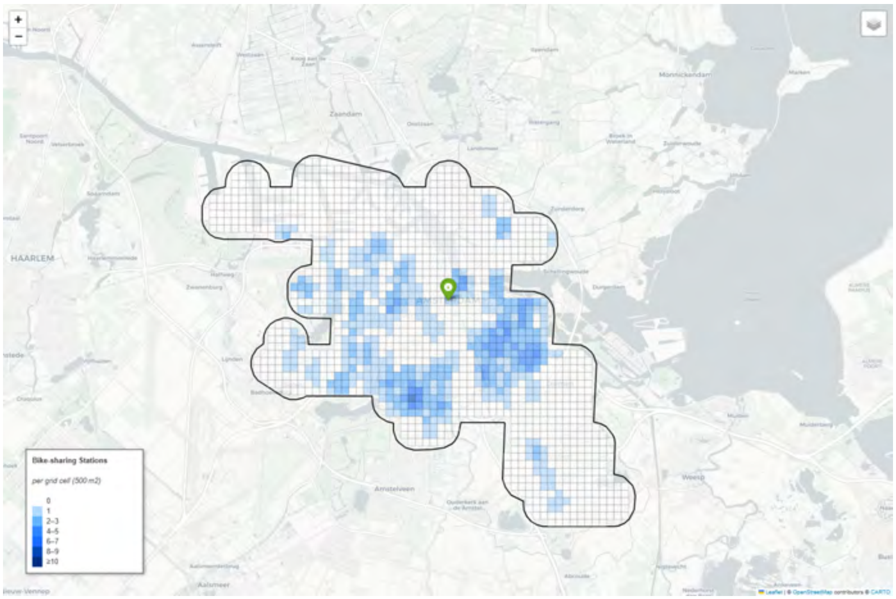

Figure 80: Amsterdam – Indicator 2B

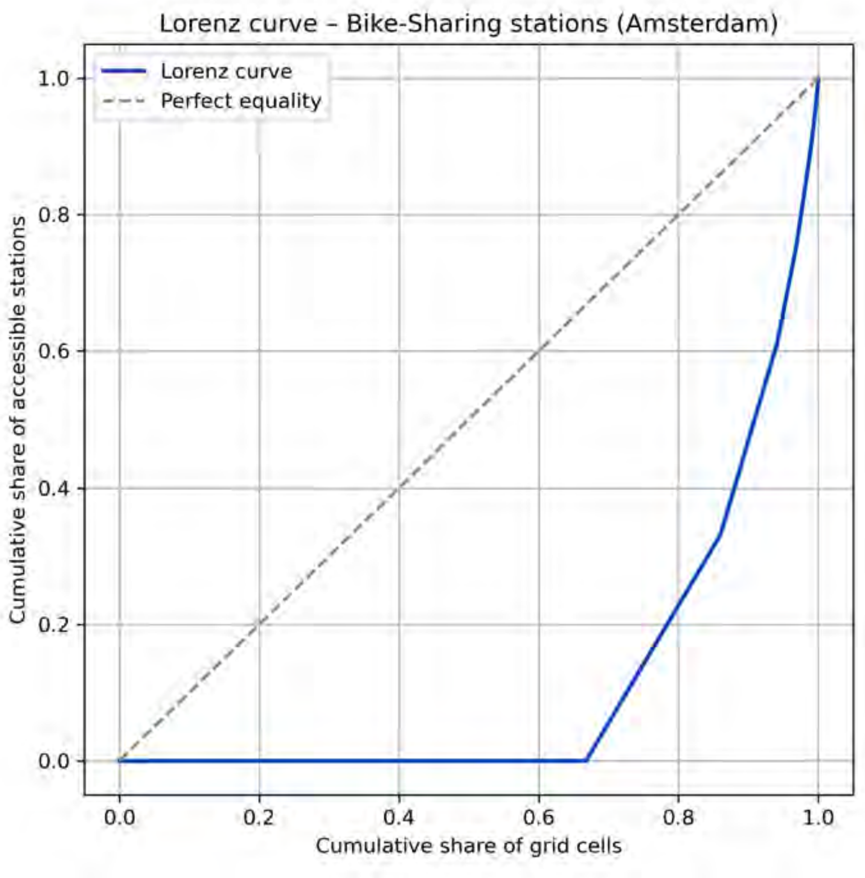

Figure 81: Amsterdam – Indicator 2B

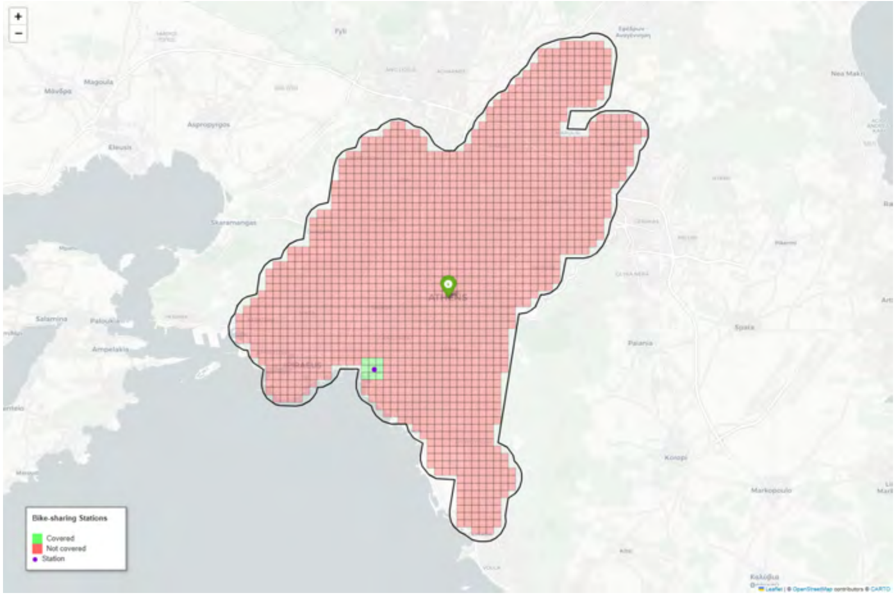

Figure 82: Atenas – Indicator 2B

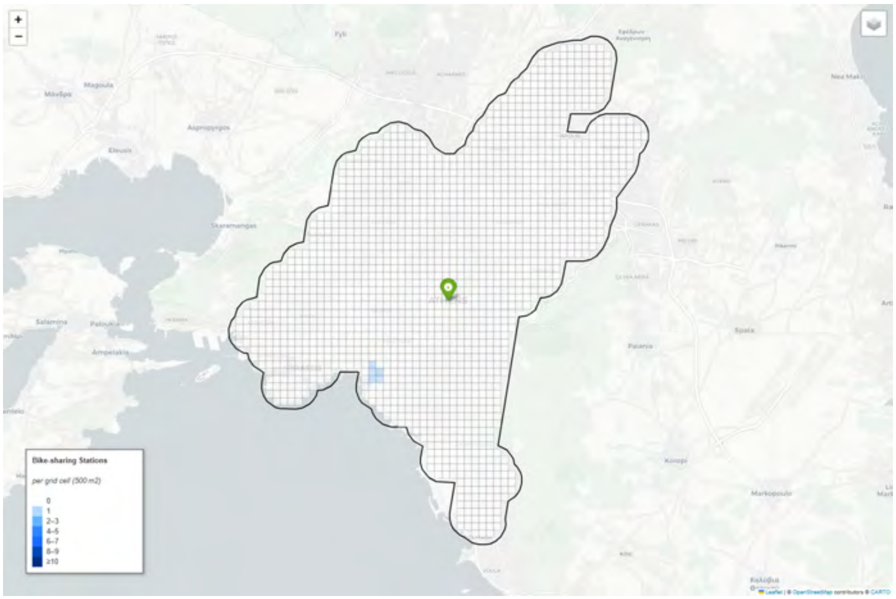

Figure 83: Atenas – Indicator 2B

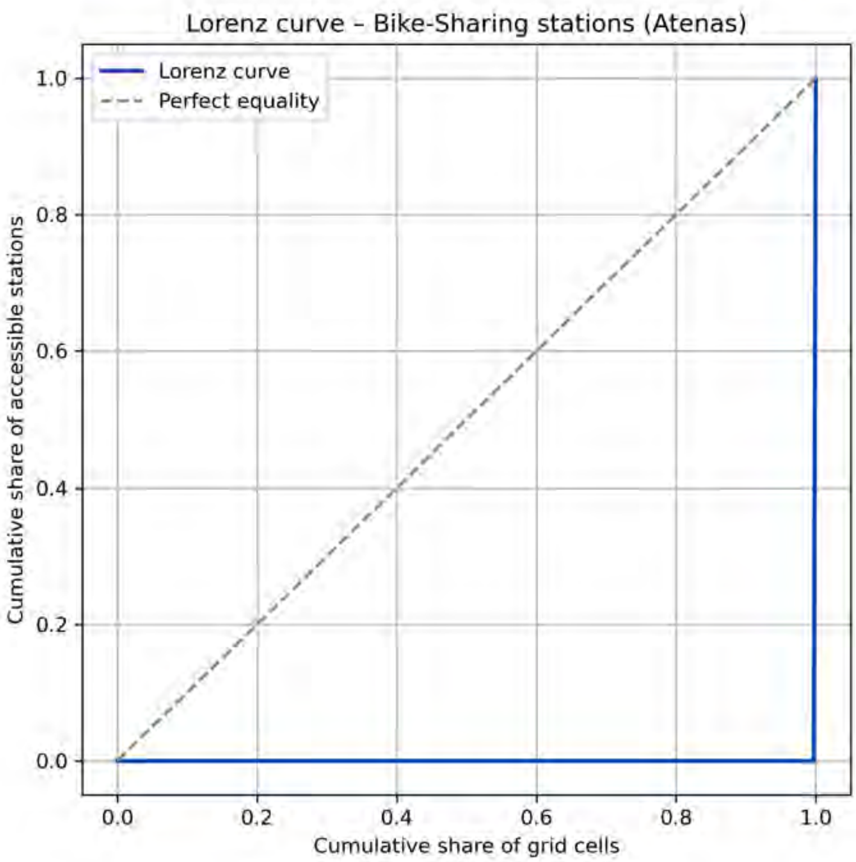

Figure 84: Atenas – Indicator 2B

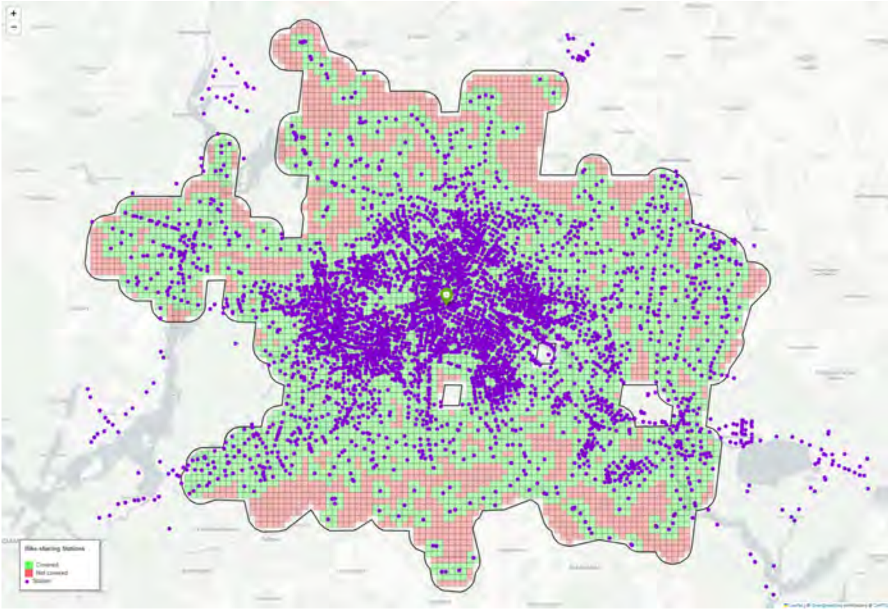

Figure 85: Berlin – Indicator 2B

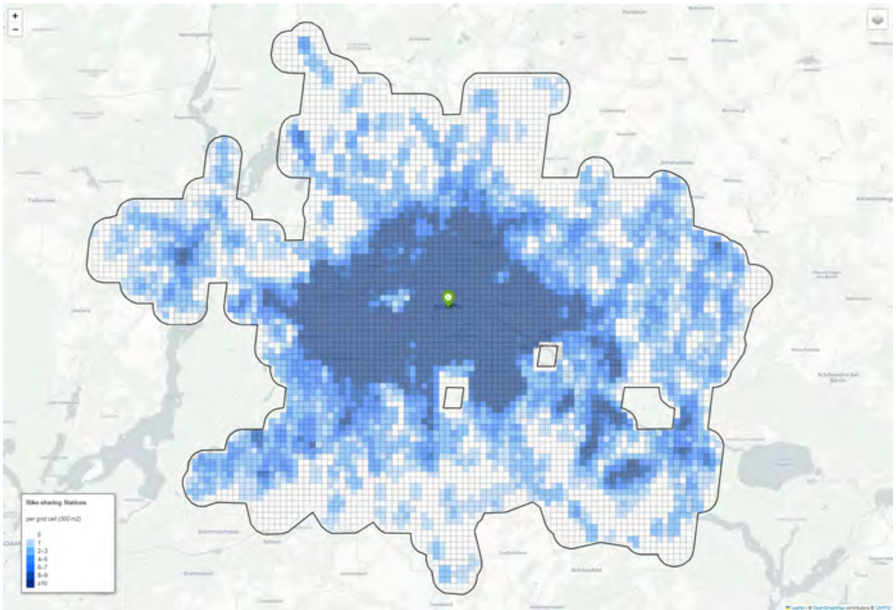

Figure 86: Berlin – Indicator 2B

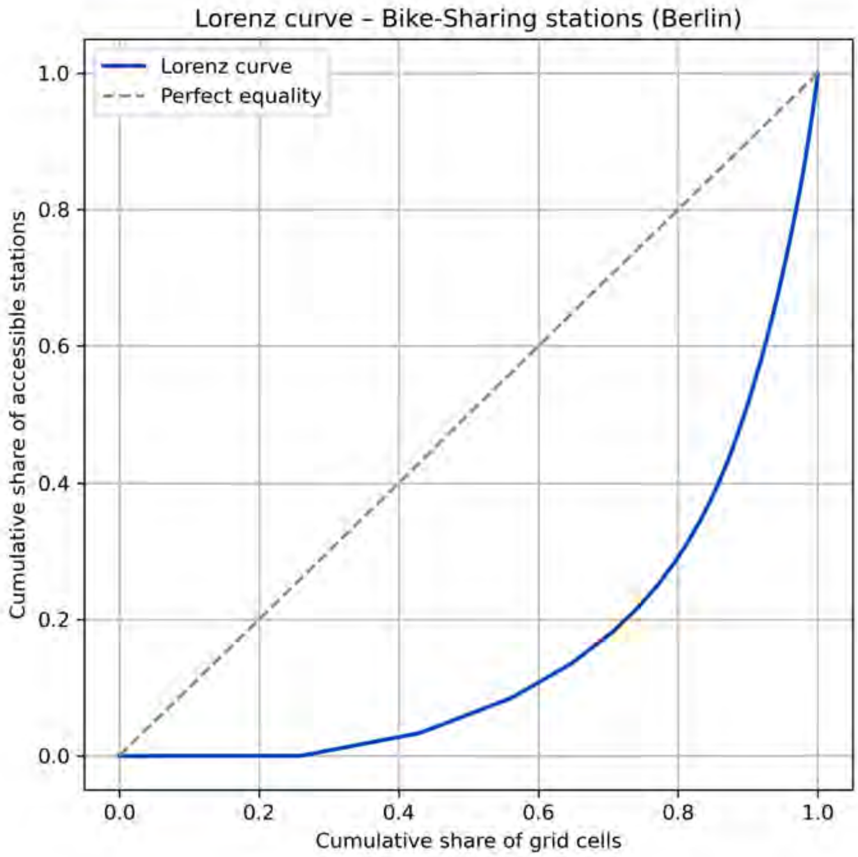

Figure 87: Berlin – Indicator 2B

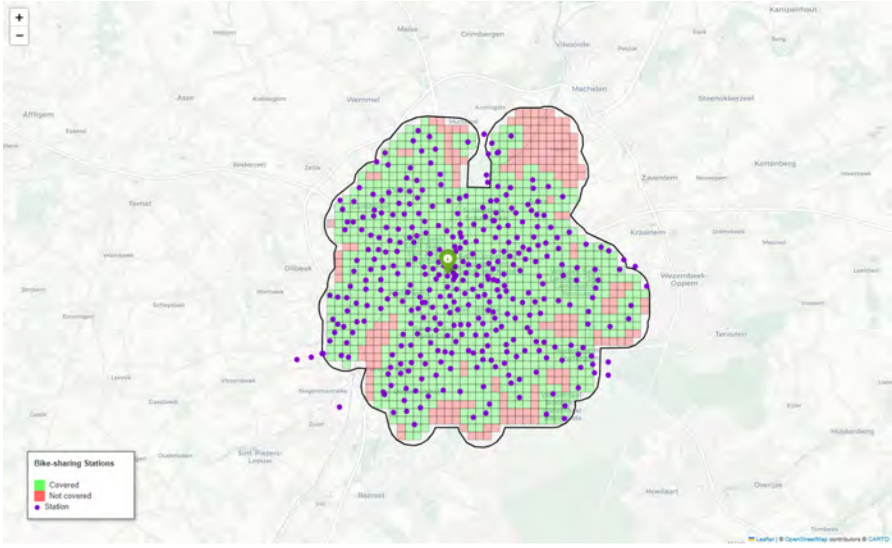

Figure 88: Brussels – Indicator 2B

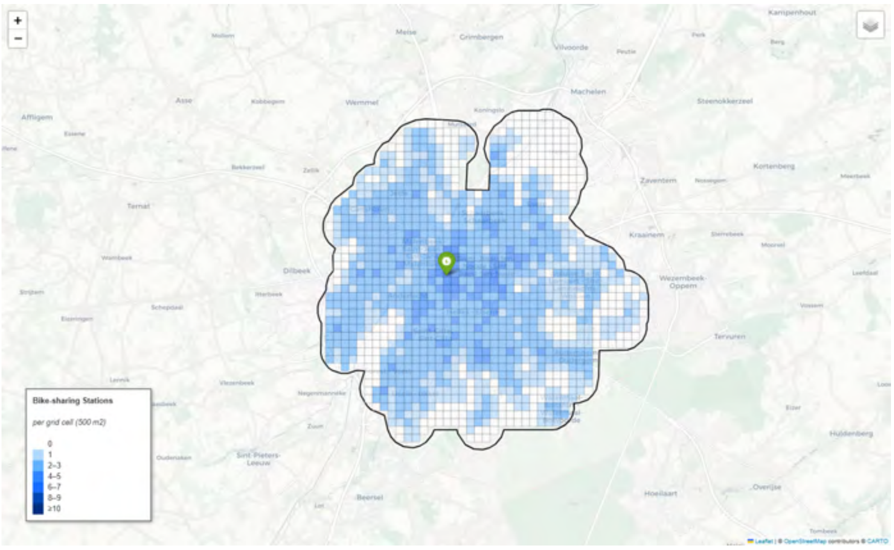

Figure 89: Brussels – Indicator 2B

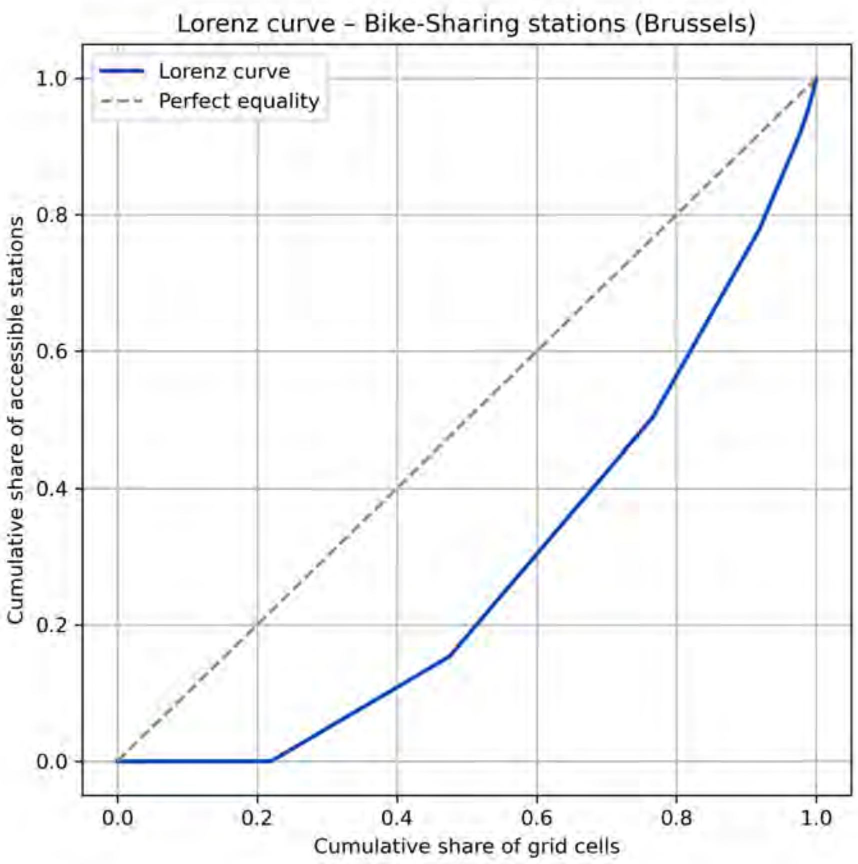

Figure 90: Brussels – Indicator 2B

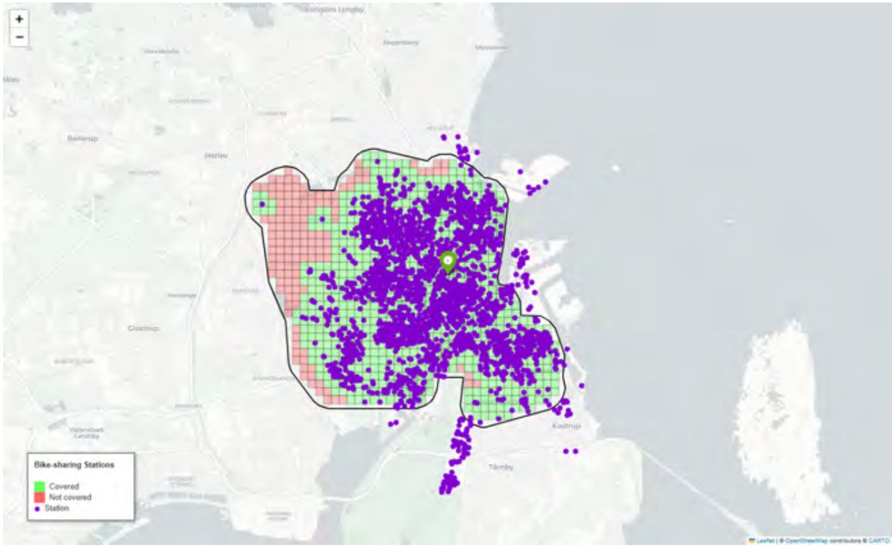

Figure 91: Copenhague – Indicator 2B

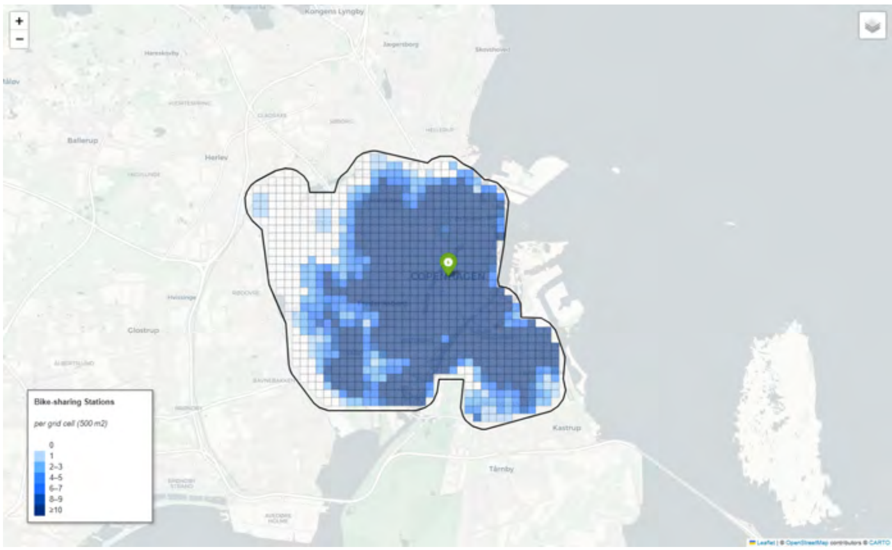

Figure 92: Copenhague – Indicator 2B

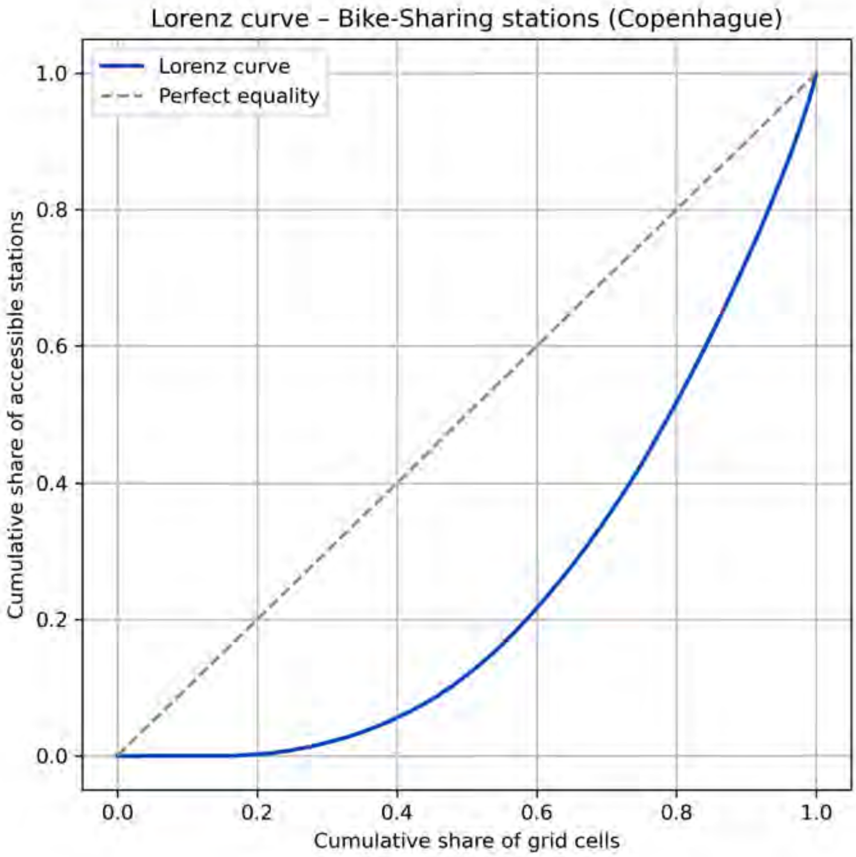

Figure 93: Copenhague – Indicator 2B

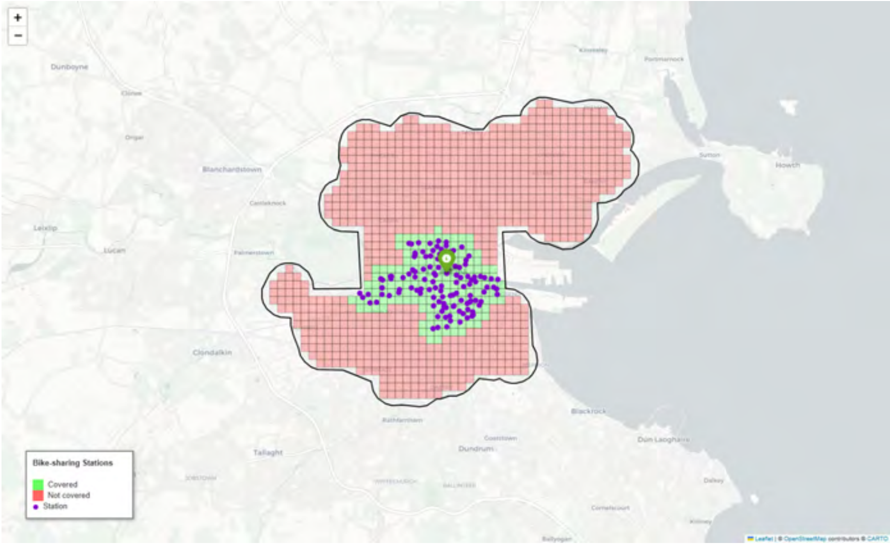

Figure 94: Dublin – Indicator 2B

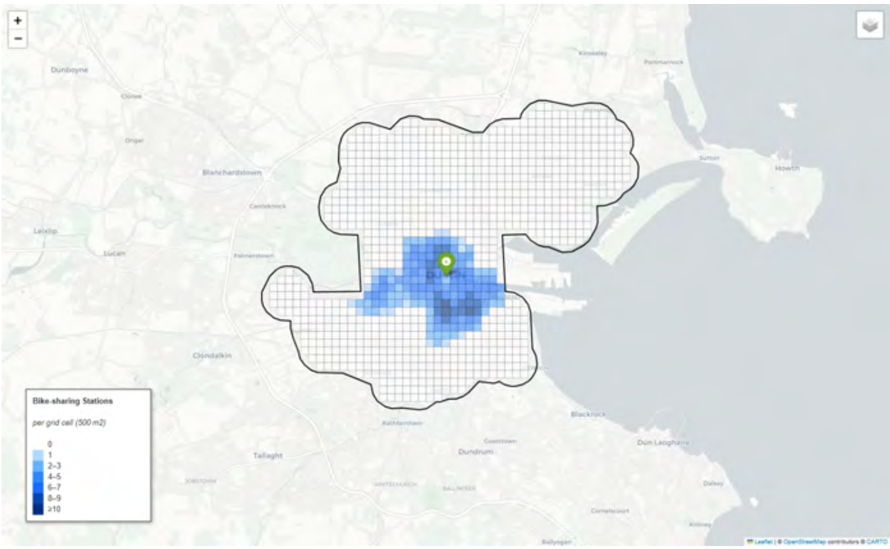

Figure 95: Dublin – Indicator 2B

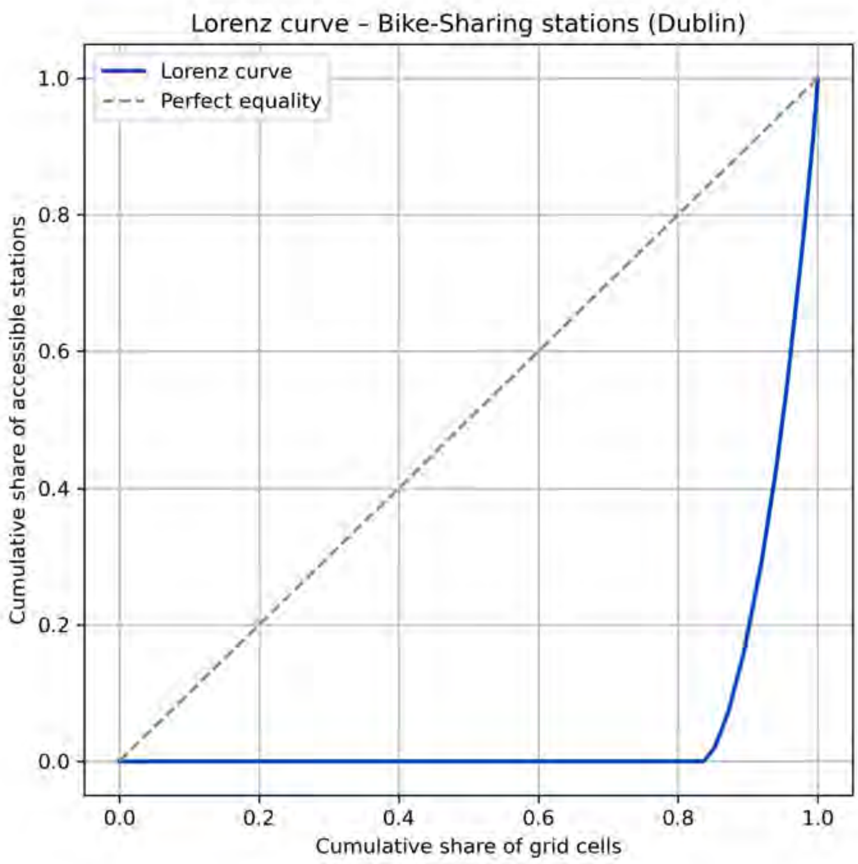

Figure 96: Dublin – Indicator 2B

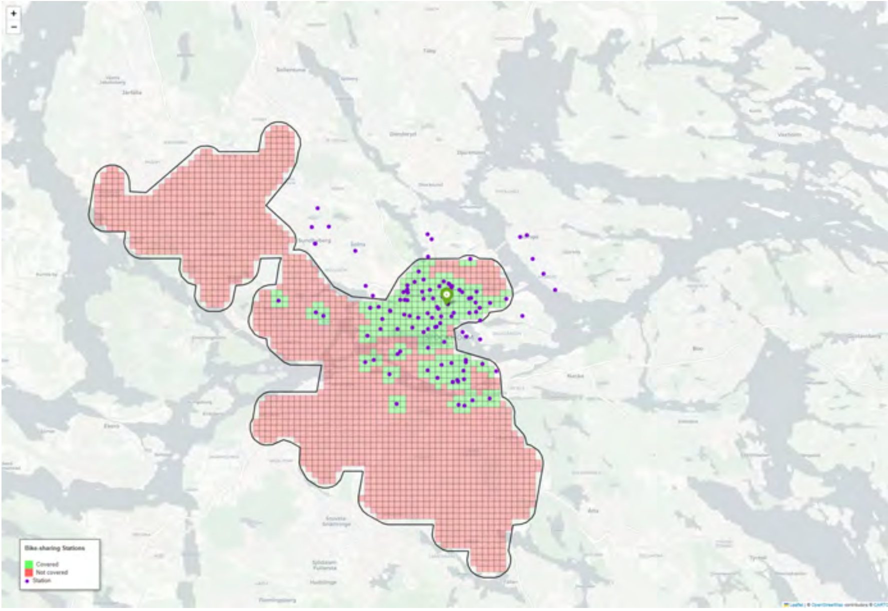

Figure 97: Estocolmo – Indicator 2B

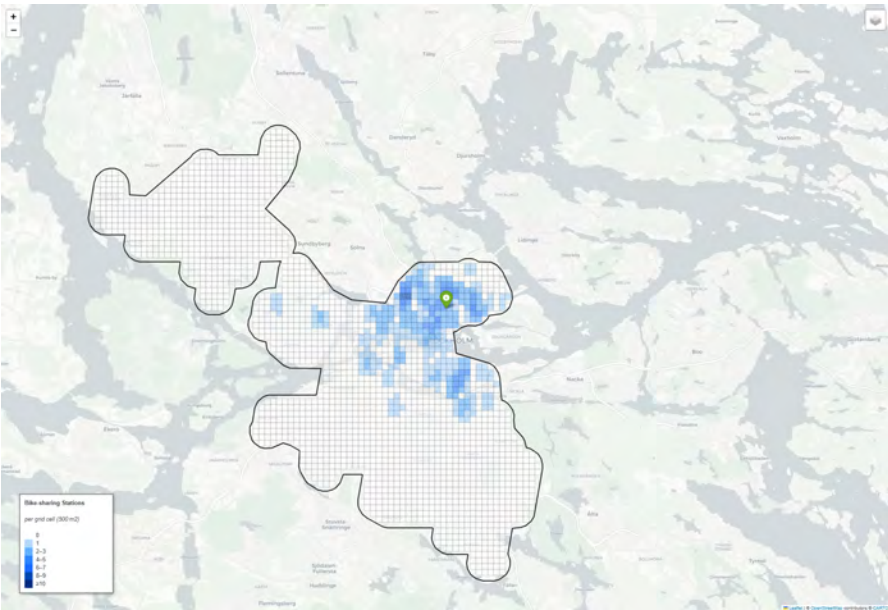

Figure 98: Estocolmo – Indicator 2B

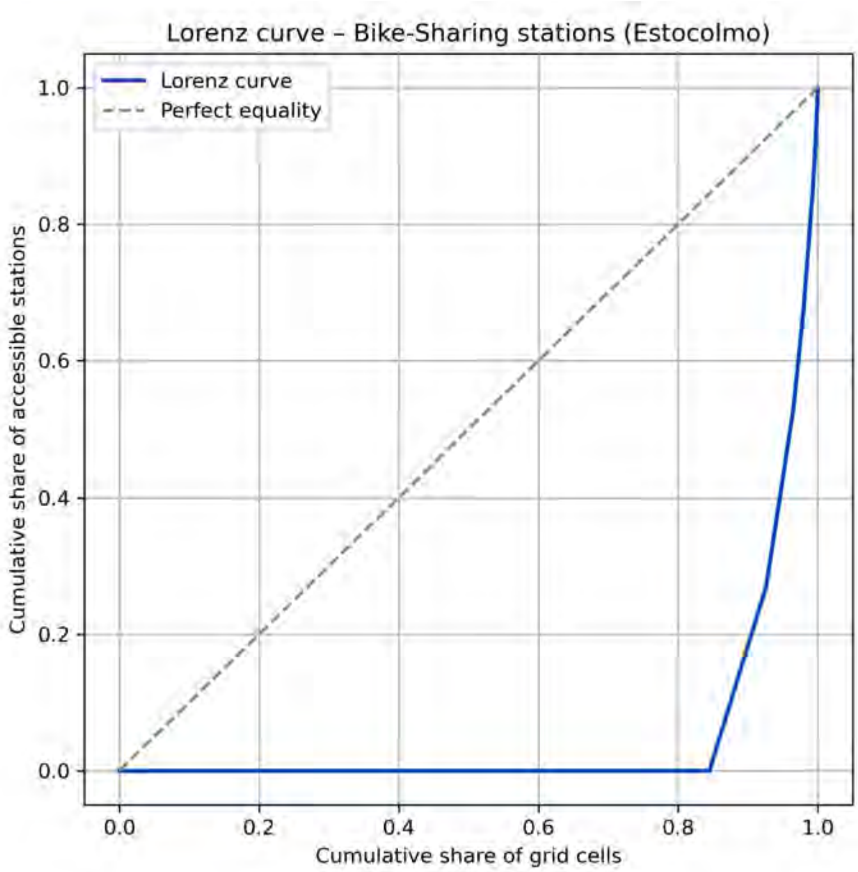

Figure 99: Estocolmo – Indicator 2B

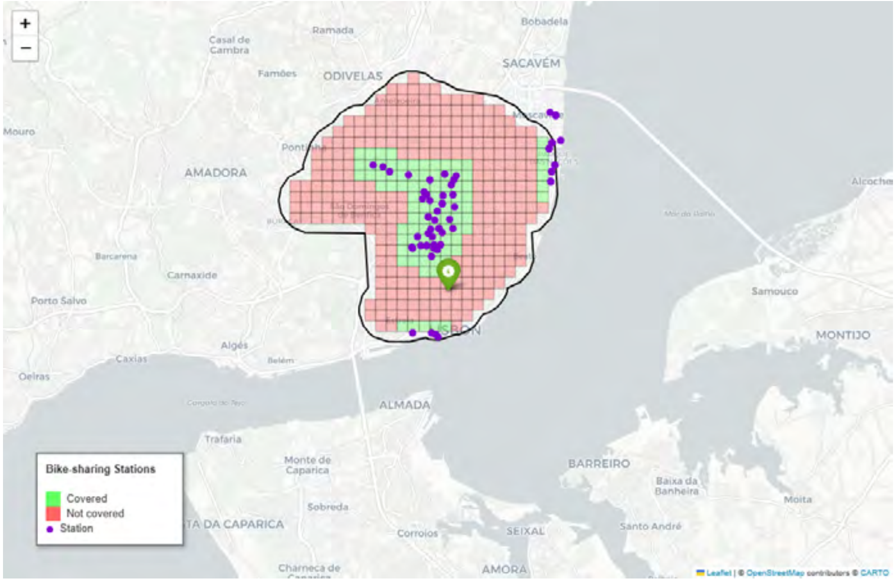

Figure 100: Lisbon – Indicator 2B

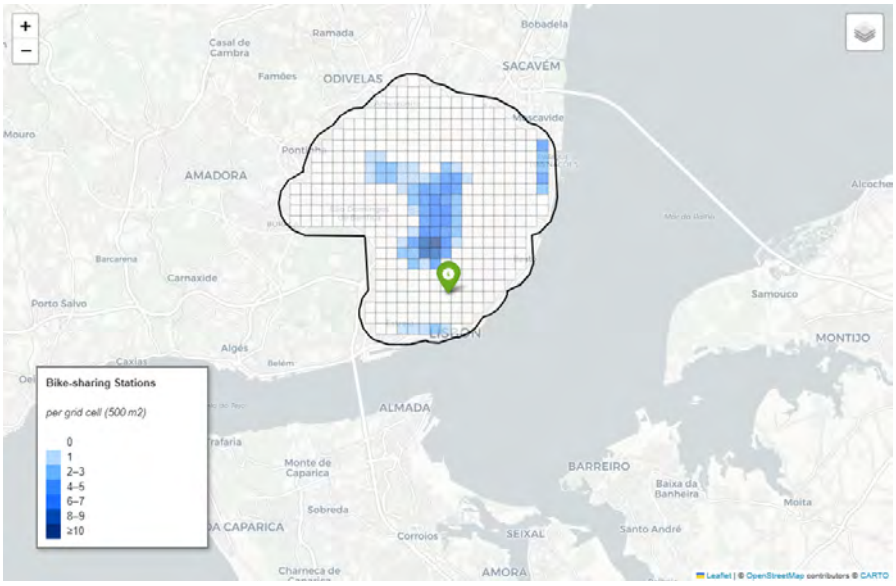

Figure 101: Lisbon – Indicator 2B

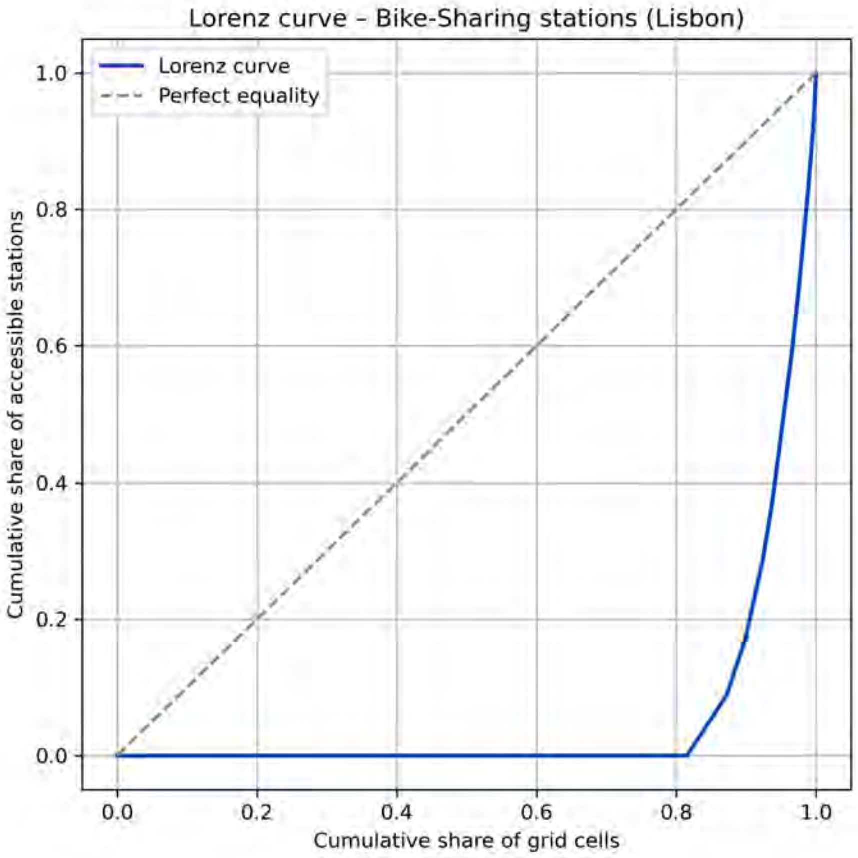

Figure 102: Lisbon – Indicator 2B

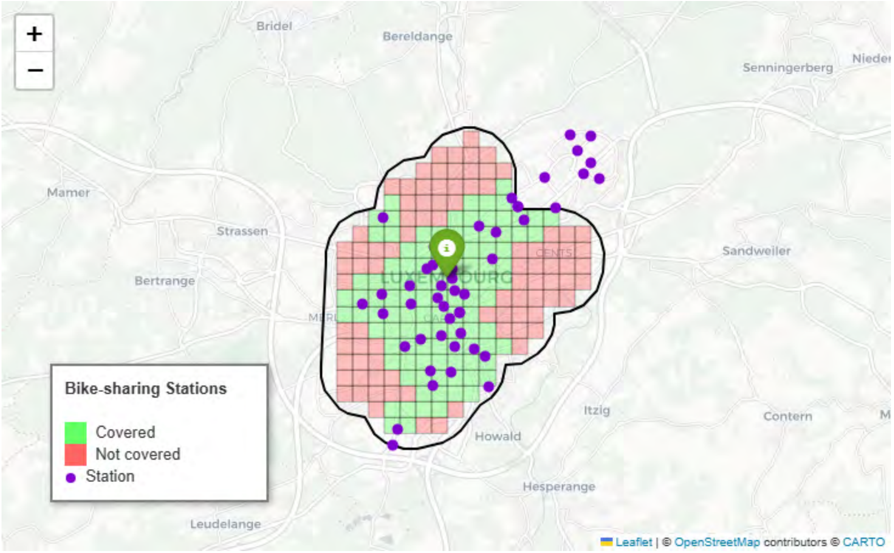

Figure 103: Luxemburgo – Indicator 2B

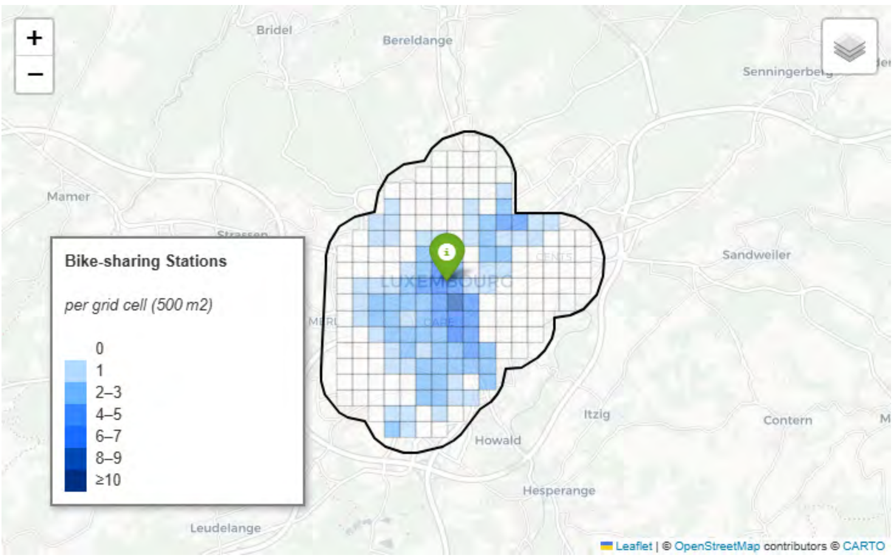

Figure 104: Luxemburgo – Indicator 2B

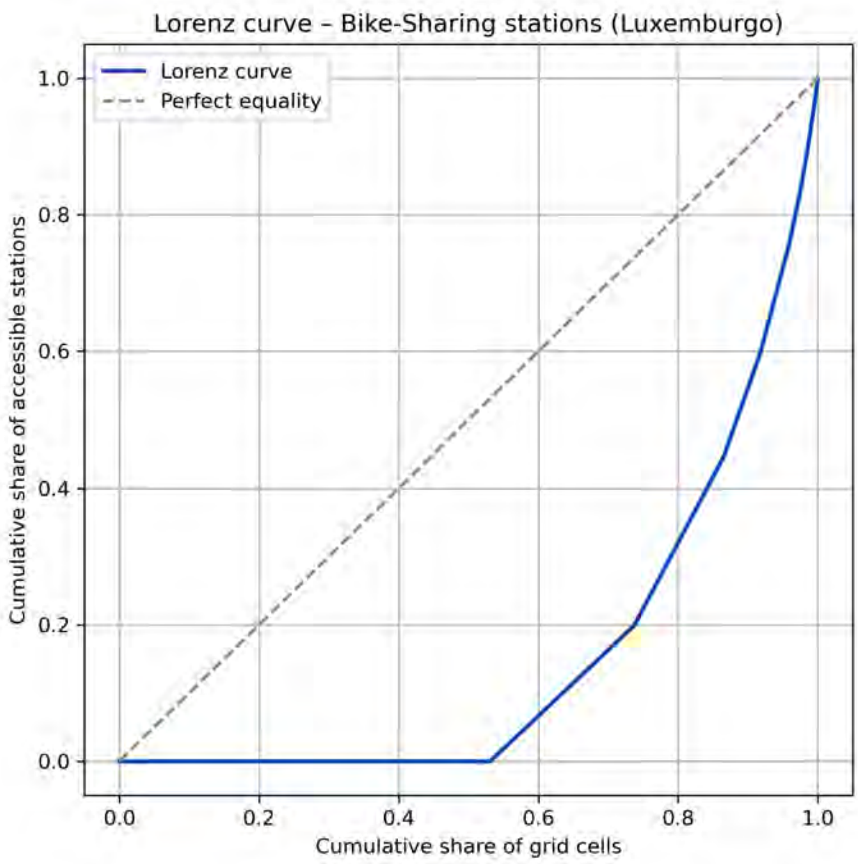

Figure 105: Luxemburgo – Indicator 2B

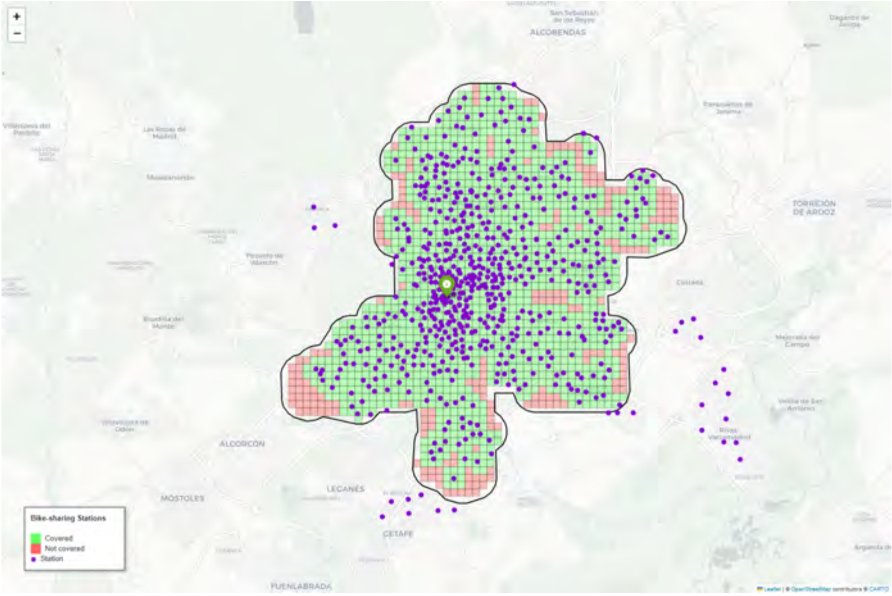

Figure 106: Madrid – Indicator 2B

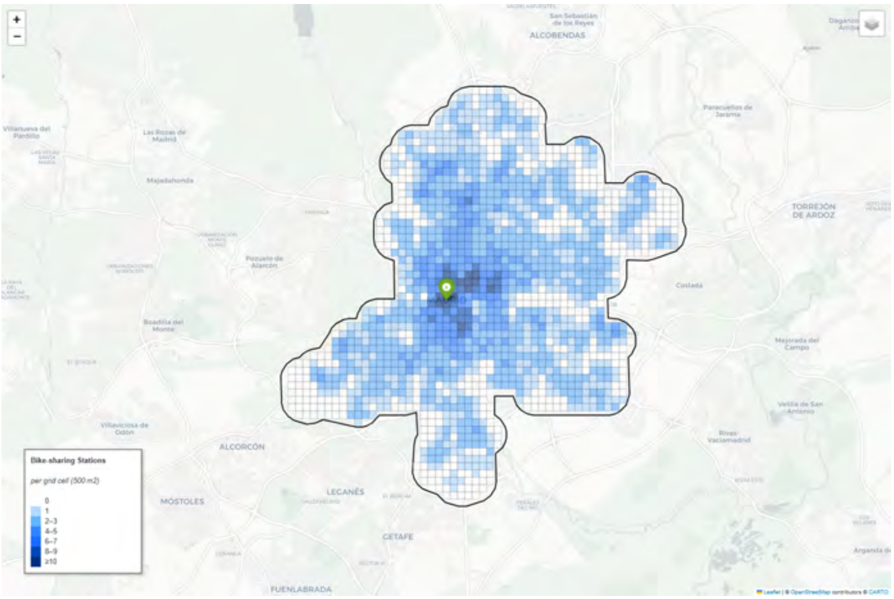

Figure 107: Madrid – Indicator 2B

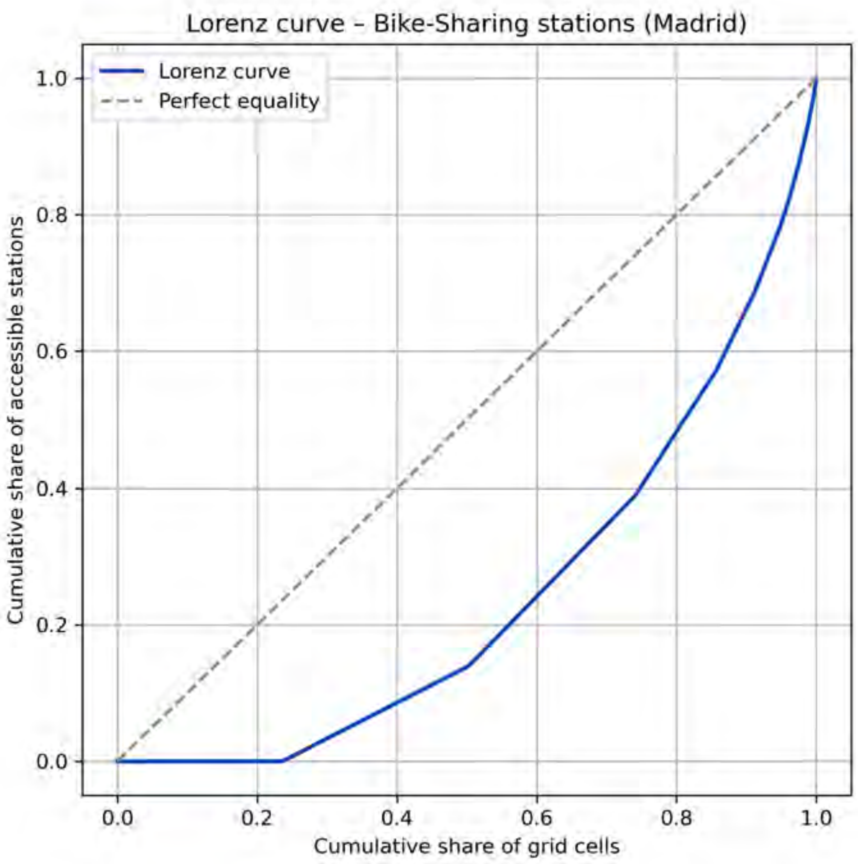

Figure 108: Madrid – Indicator 2B

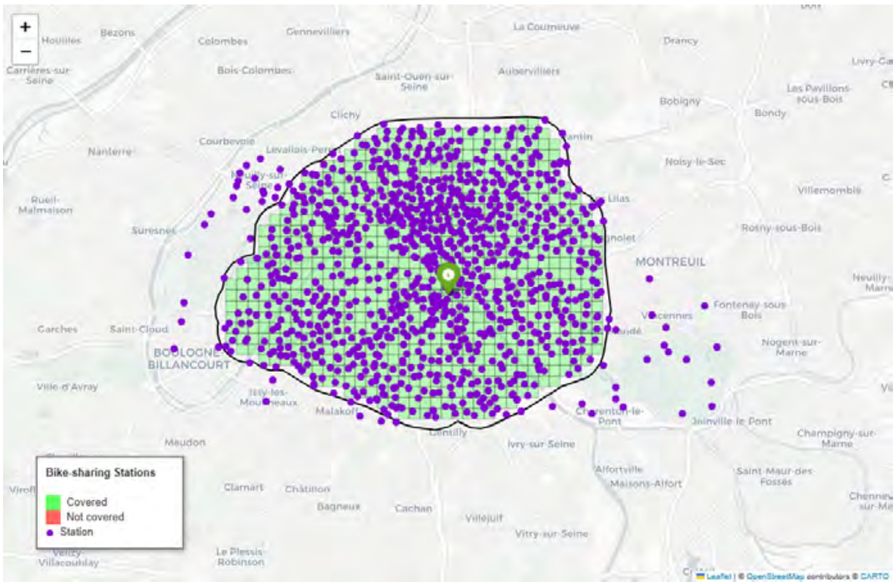

Figure 109: Paris – Indicator 2B

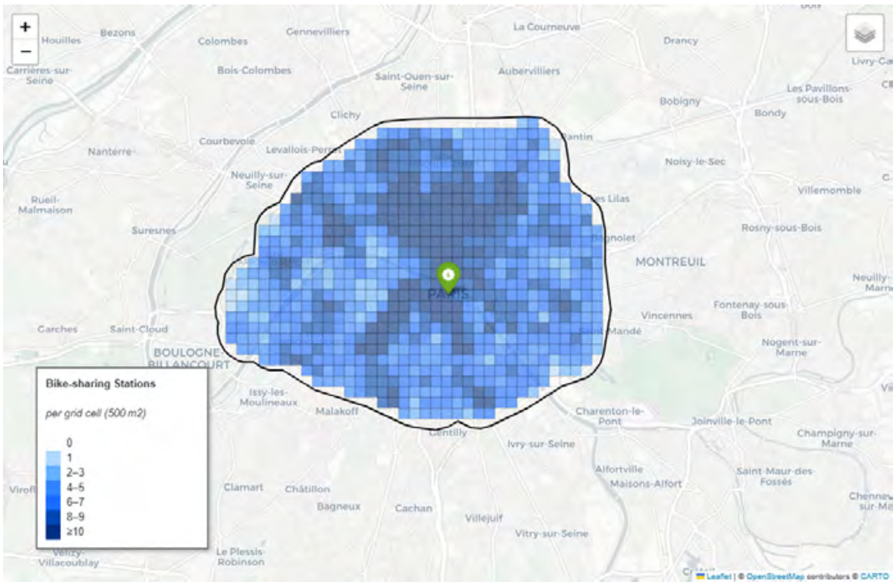

Figure 110: Paris – Indicator 2B

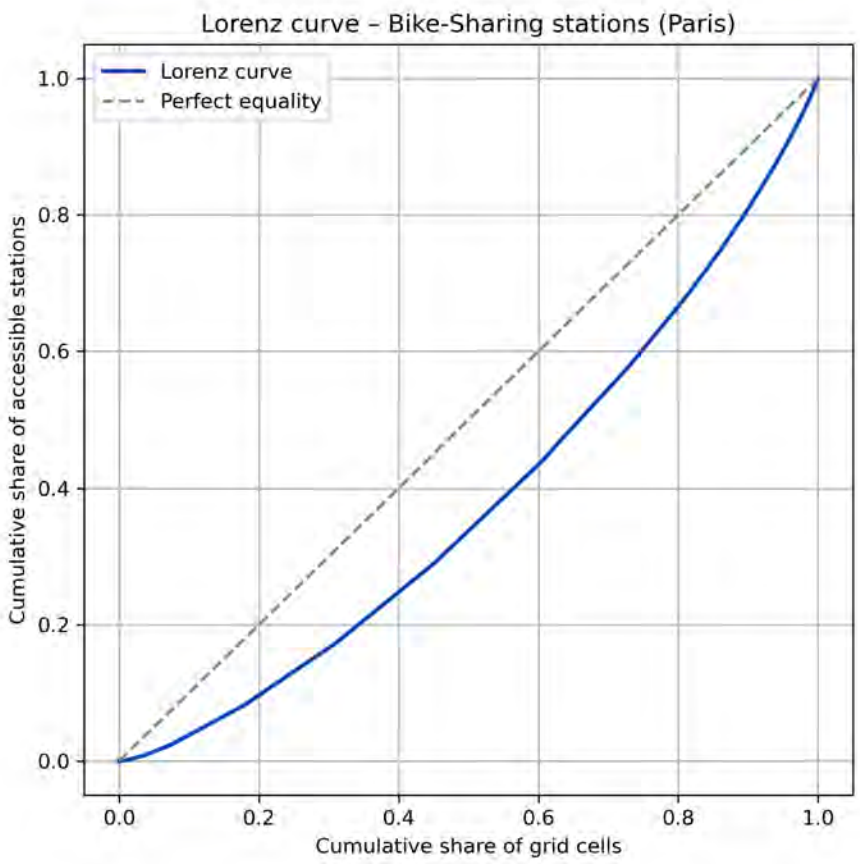

Figure 111: Paris – Indicator 2B

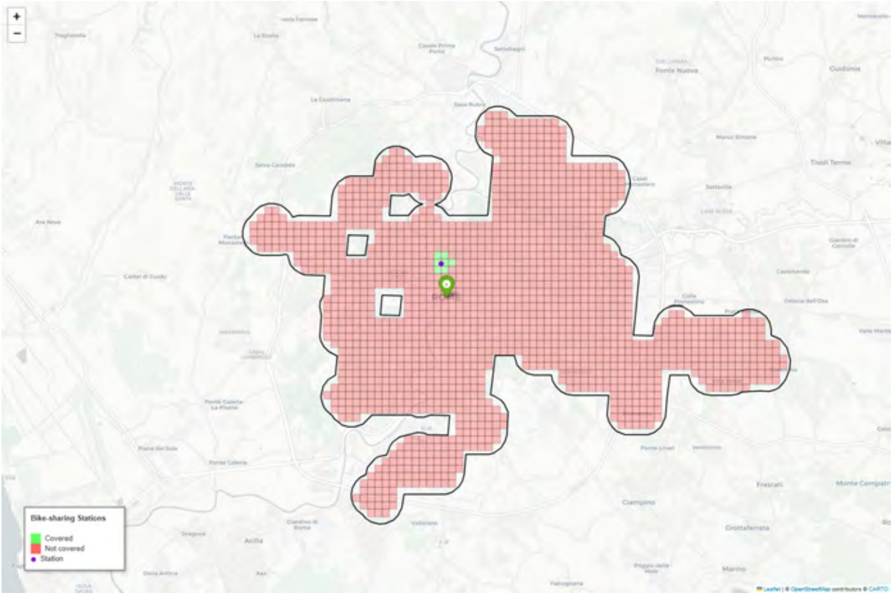

Figure 112: Rome – Indicator 2B

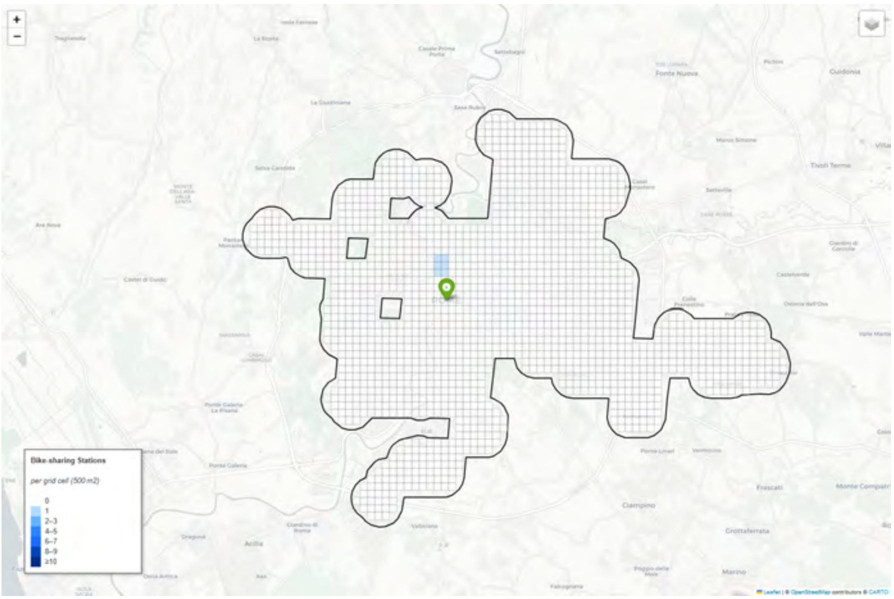

Figure 113: Rome – Indicator 2B

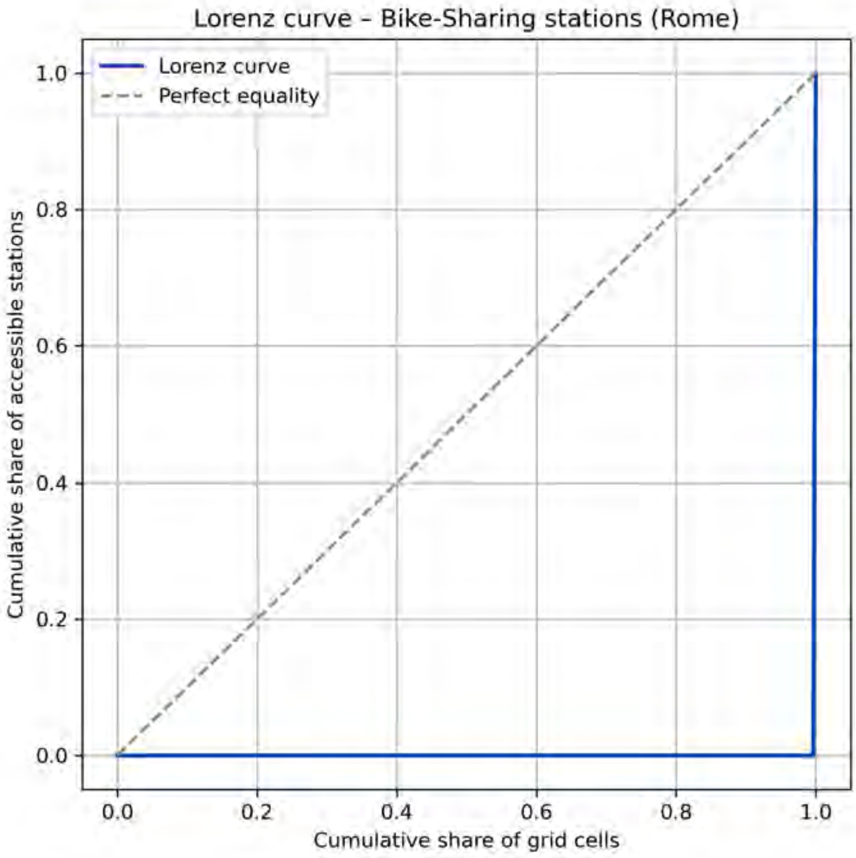

Figure 114: Rome – Indicator 2B

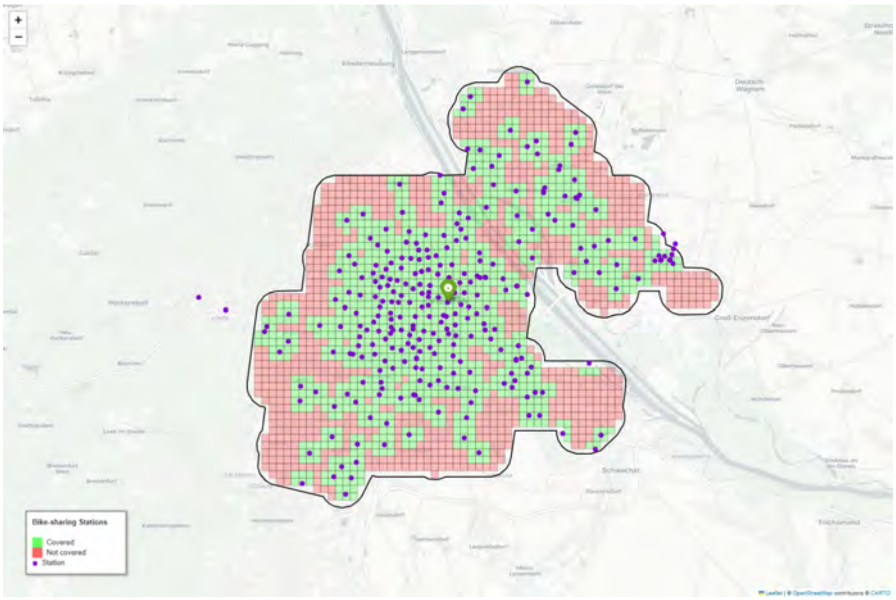

Figure 115: Viena – Indicator 2B

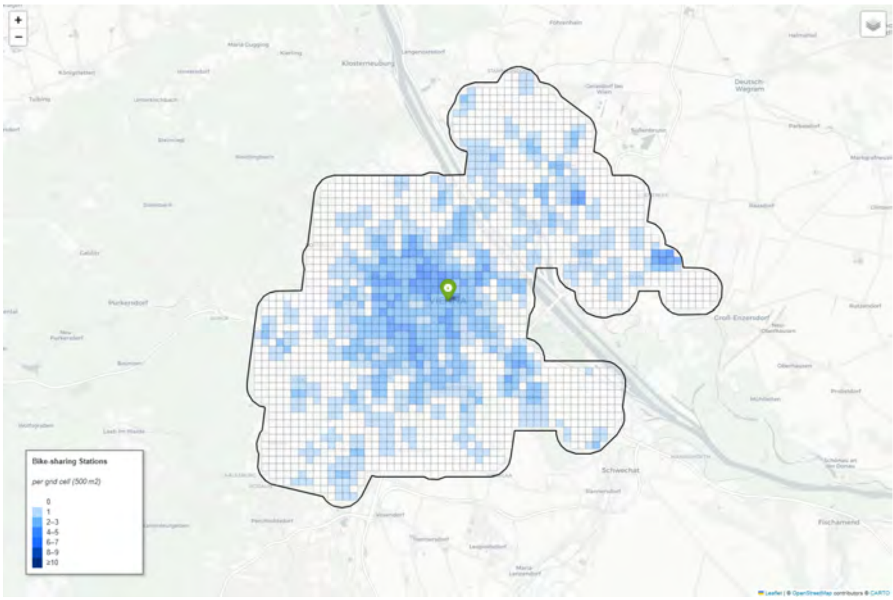

Figure 116: Viena – Indicator 2B

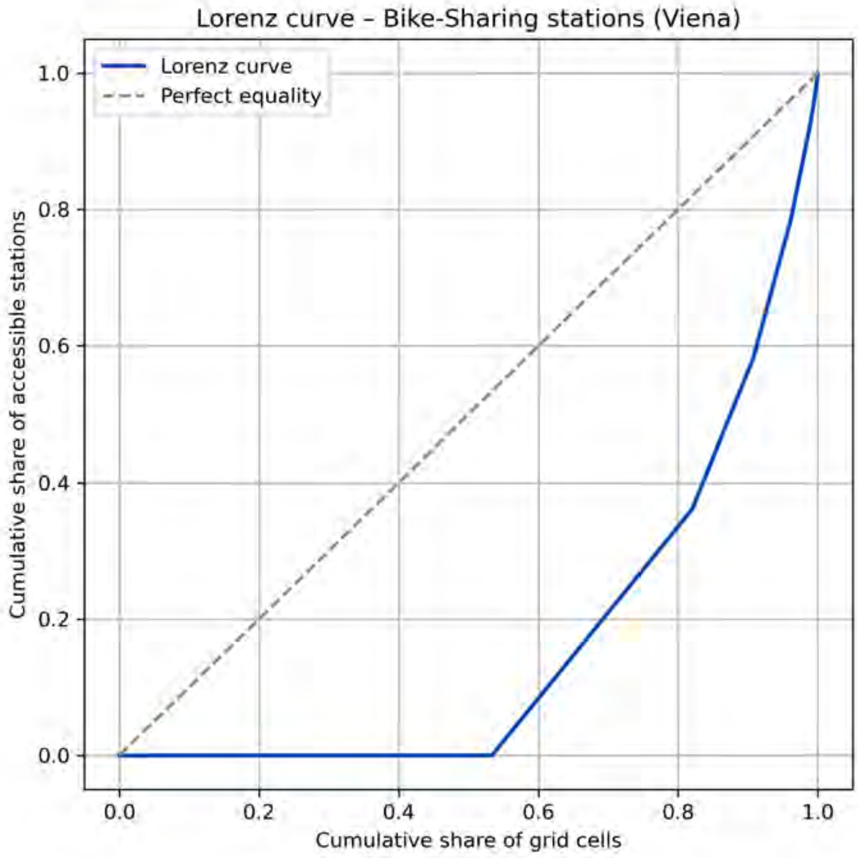

Figure 117: Viena – Indicator 2B

Indicator 3a

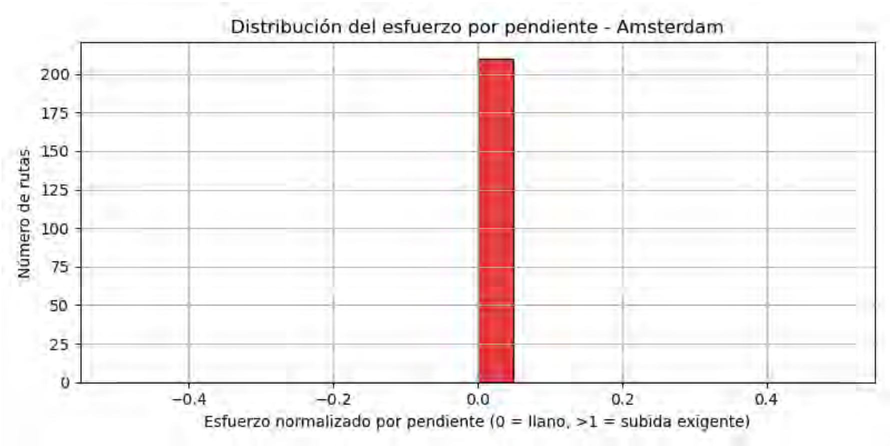

Figure 118: Amsterdam – Indicator 3A

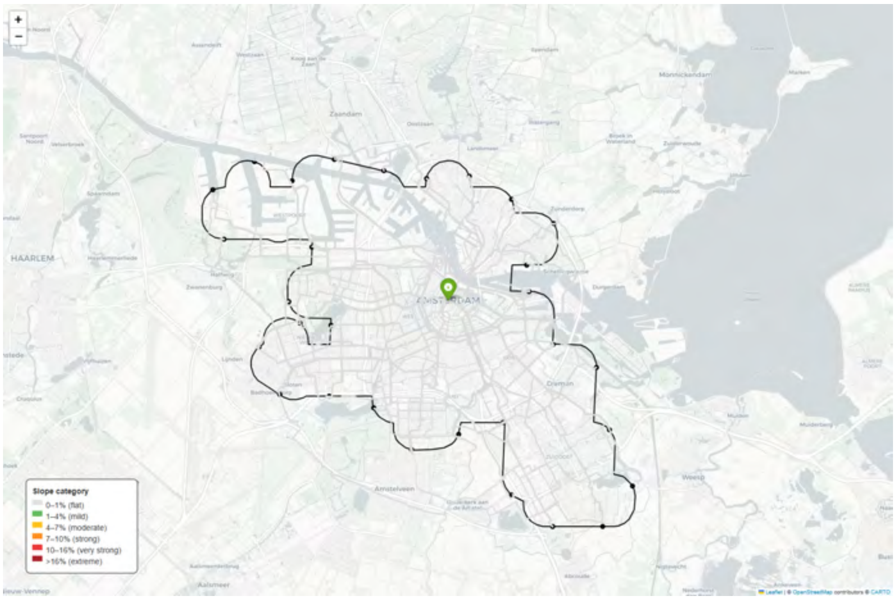

Figure 119: Amsterdam – Indicator 3A

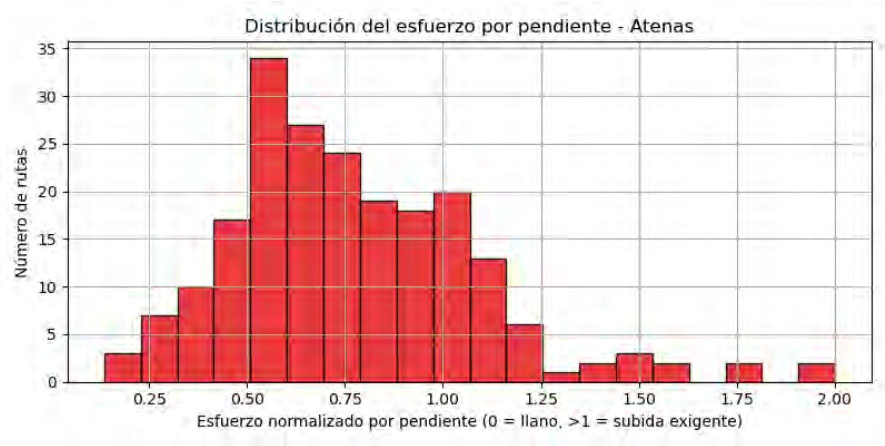

Figure 120: Atenas – Indicator 3A

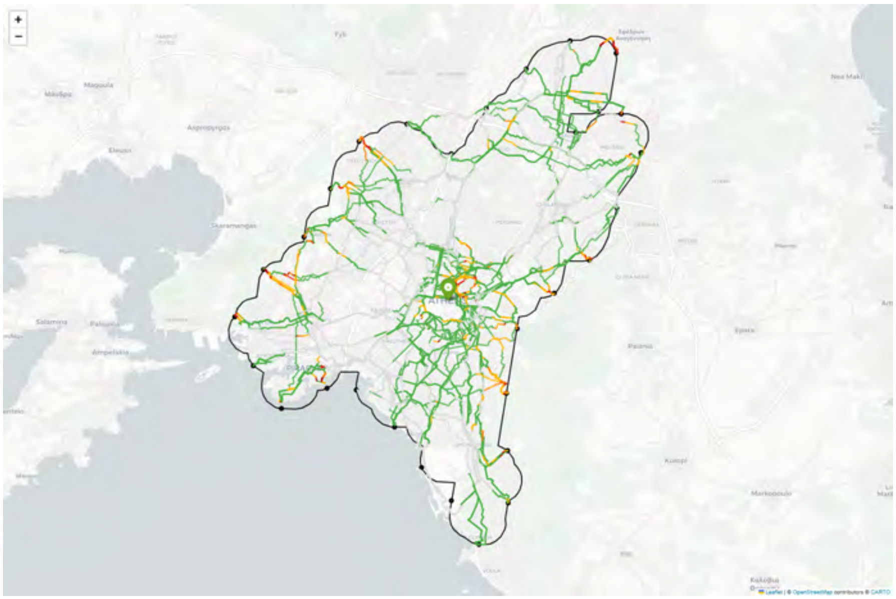

Figure 121: Atenas – Indicator 3A

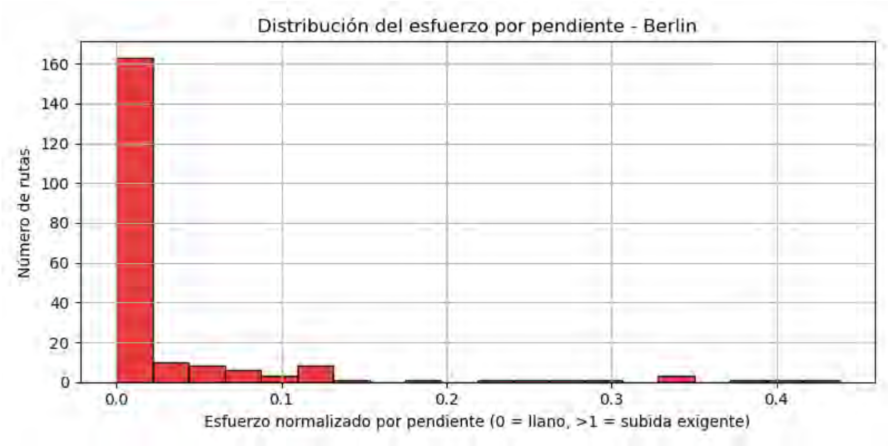

Figure 122: Berlin – Indicator 3A

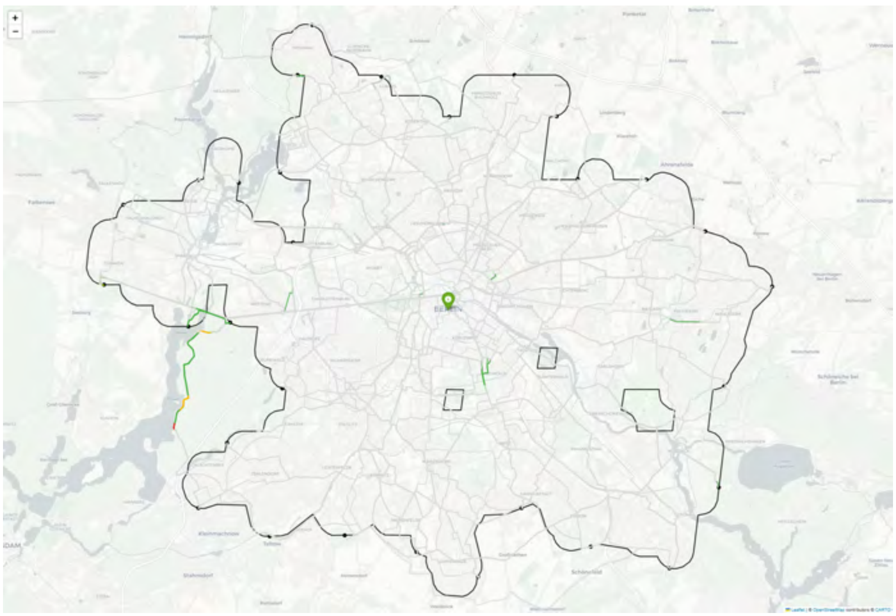

Figure 123: Berlin – Indicator 3A

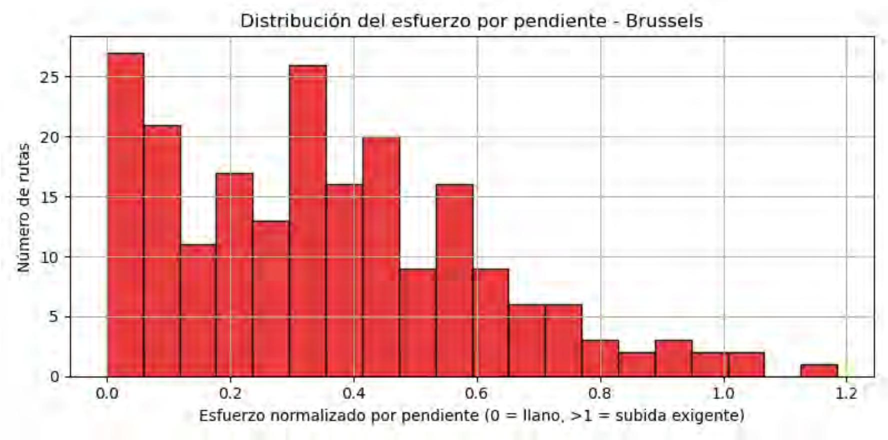

Figure 124: Brussels – Indicator 3A

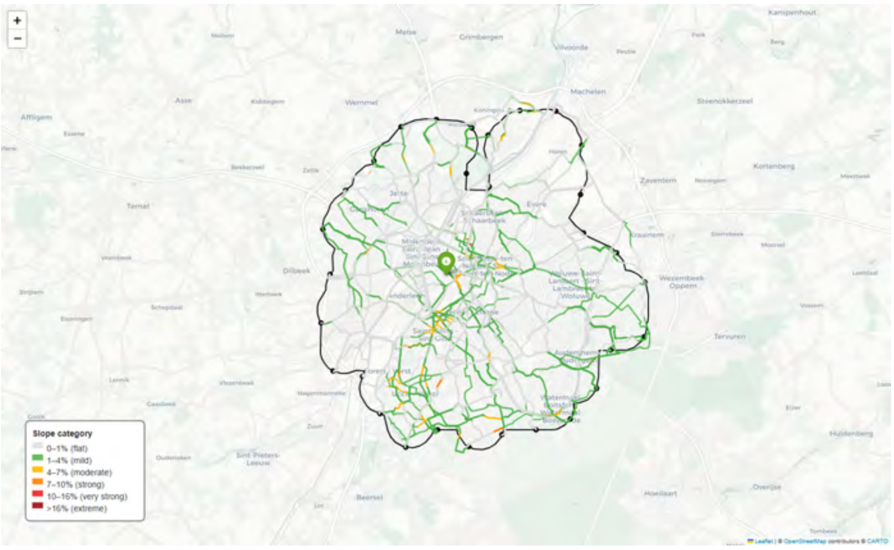

Figure 125: Brussels – Indicator 3A

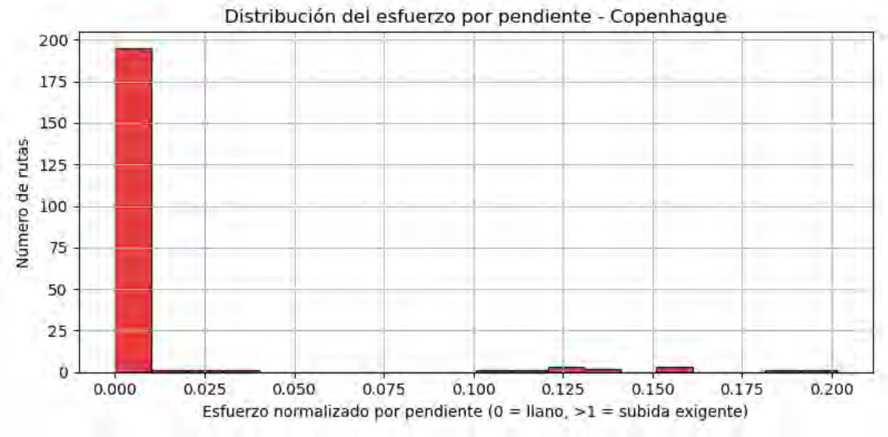

Figure 126: Copenhague – Indicator 3A

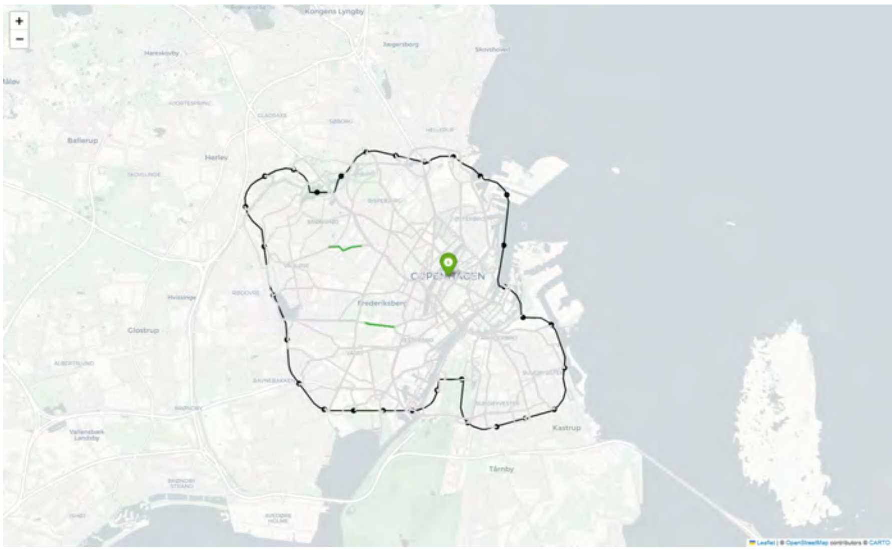

Figure 127: Copenhague – Indicator 3A

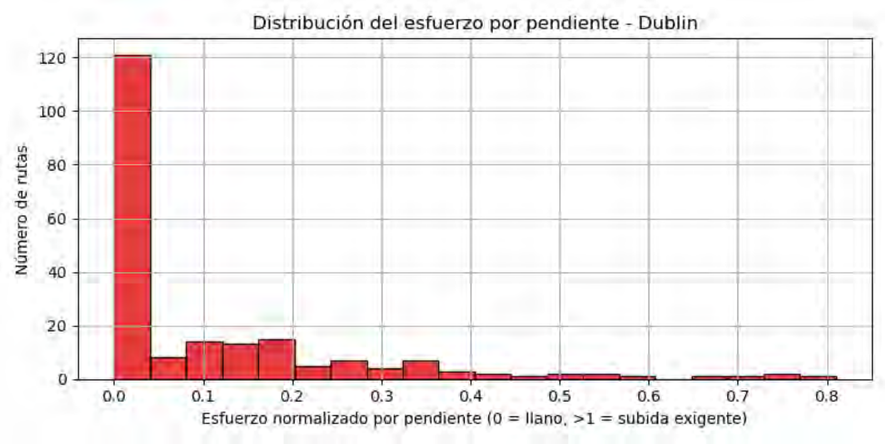

Figure 128: Dublin – Indicator 3A

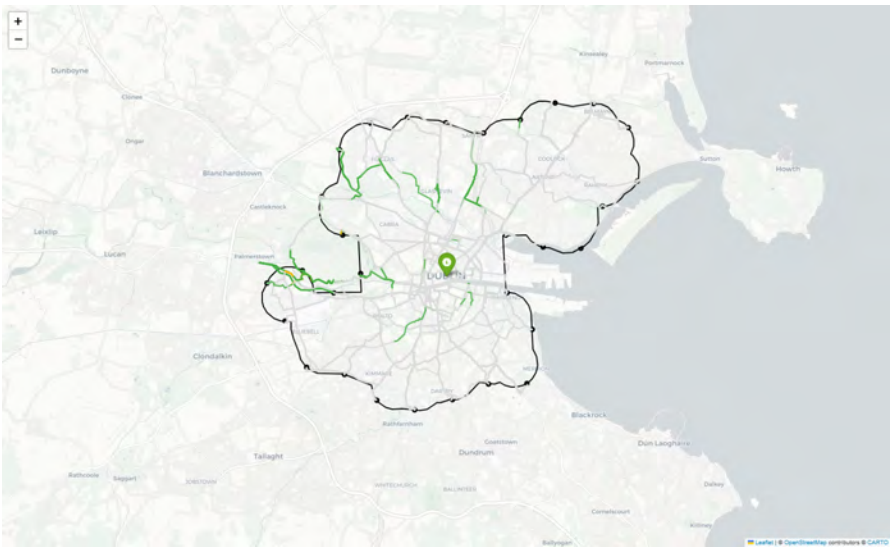

Figure 129: Dublin – Indicator 3A

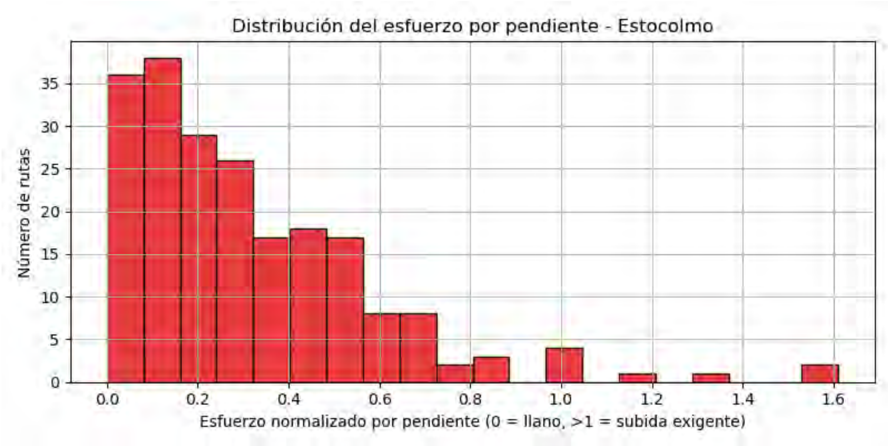

Figure 130: Estocolmo – Indicator 3A

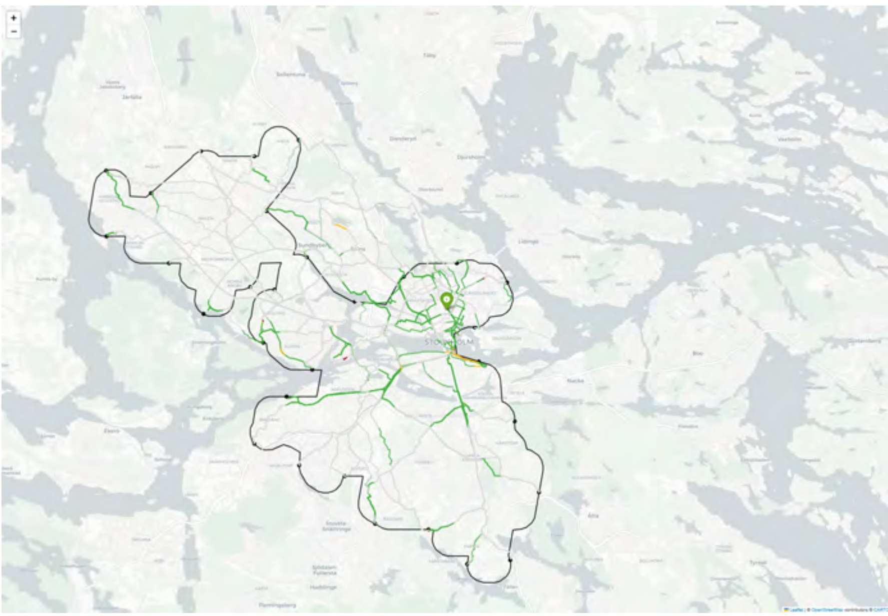

Figure 131: Estocolmo – Indicator 3A

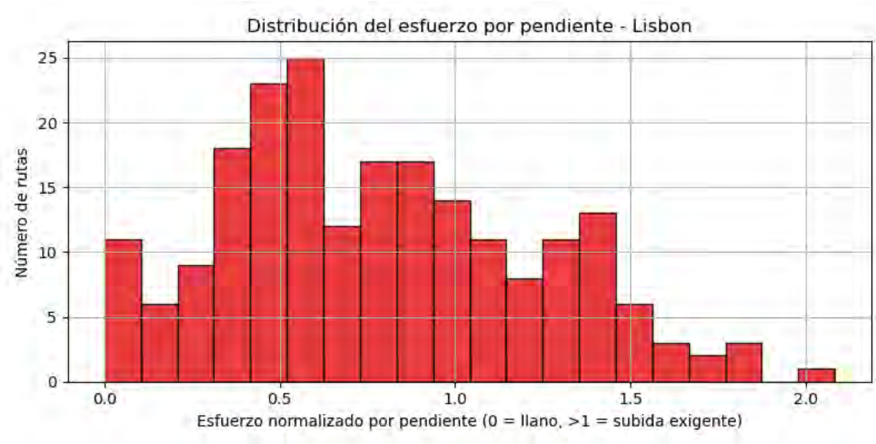

Figure 132: Lisbon – Indicator 3A

Figure 133: Lisbon – Indicator 3A

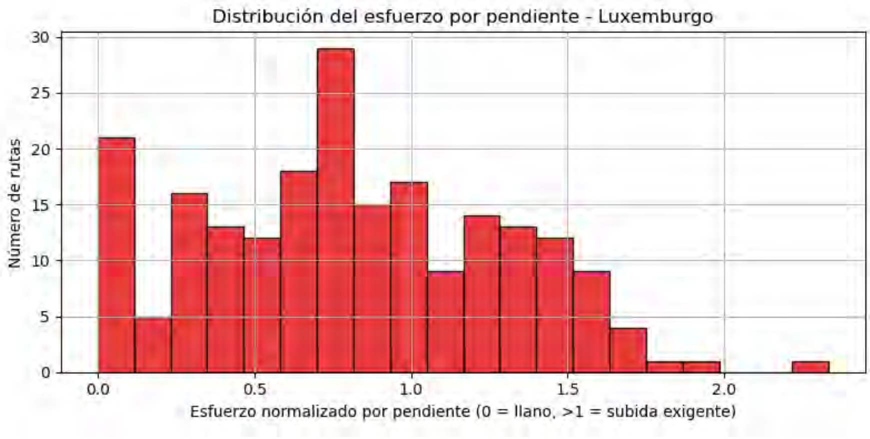

Figure 134: Luxemburgo – Indicator 3A

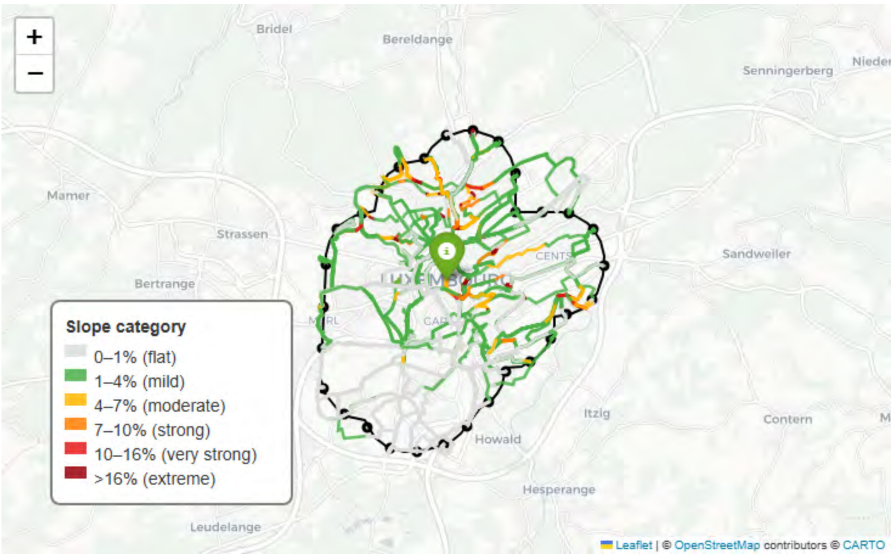

Figure 135: Luxemburgo – Indicator 3A

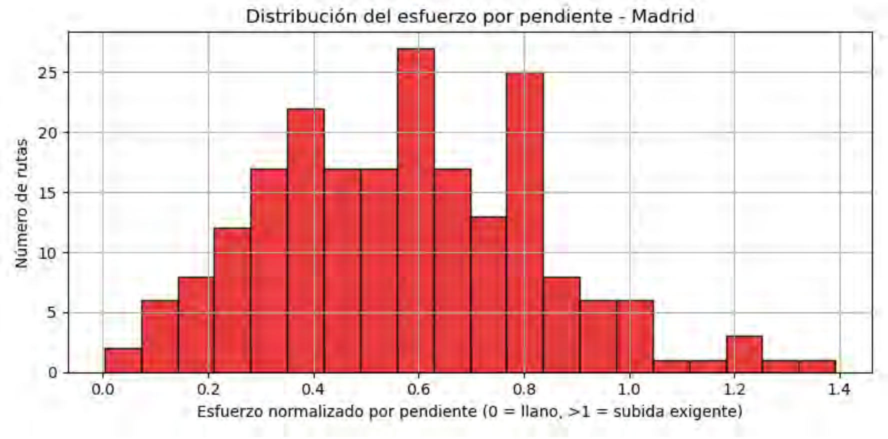

Figure 136: Madrid – Indicator 3A

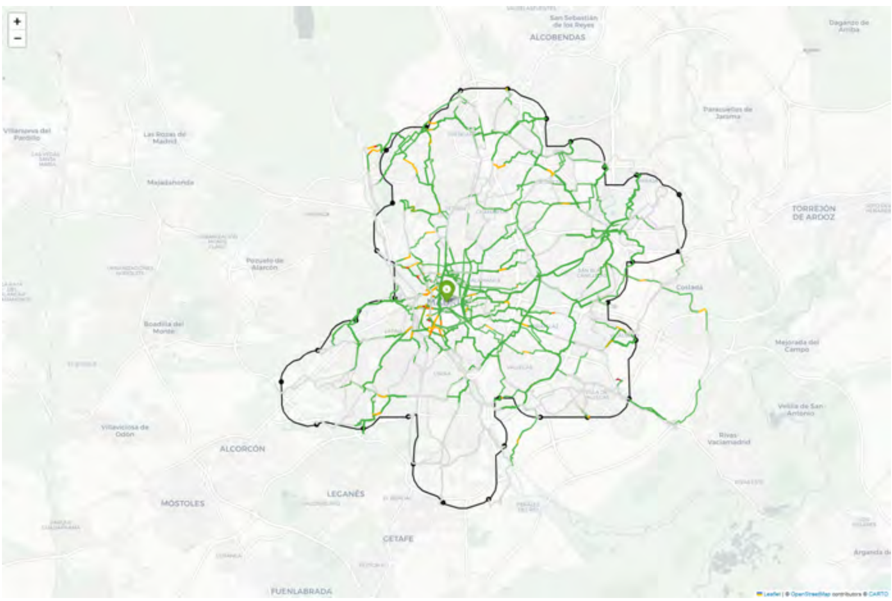

Figure 137: Madrid – Indicator 3A

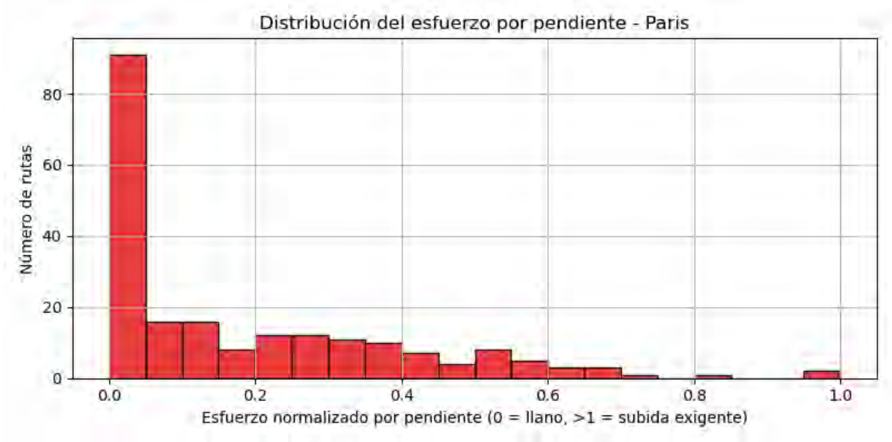

Figure 138: Paris – Indicator 3A

Figure 139: Paris – Indicator 3A

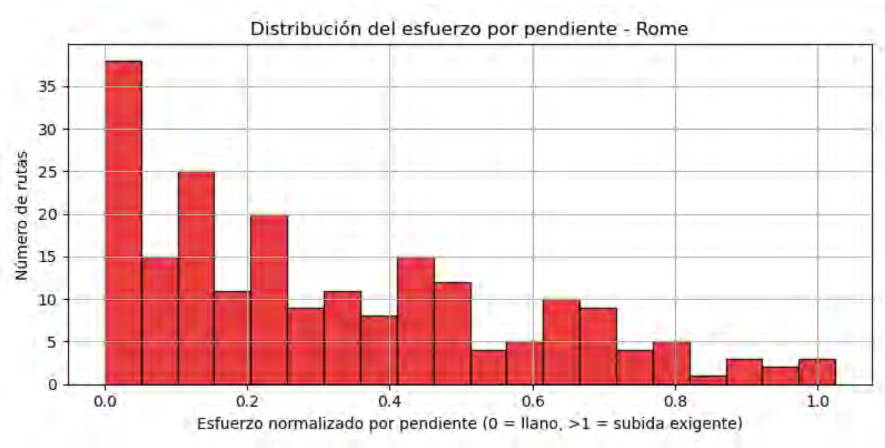

Figure 140: Rome – Indicator 3A

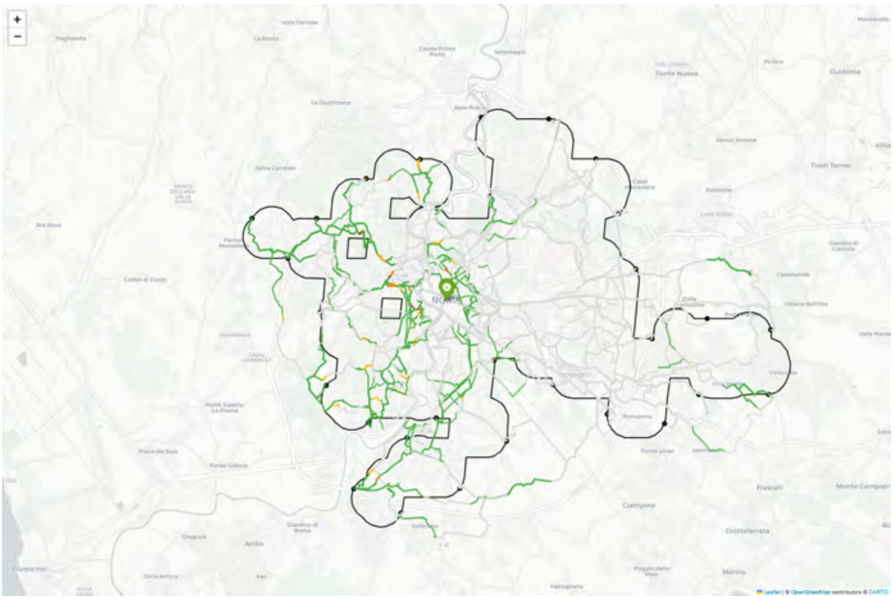

Figure 141: Rome – Indicator 3A

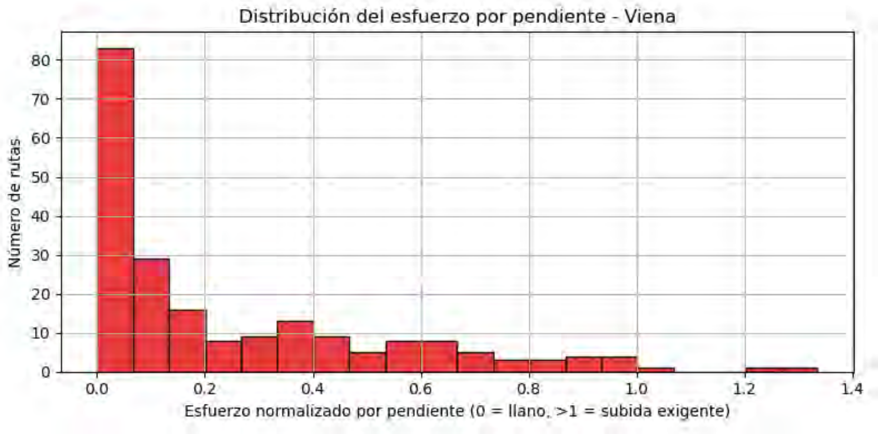

Figure 142: Viena – Indicator 3A

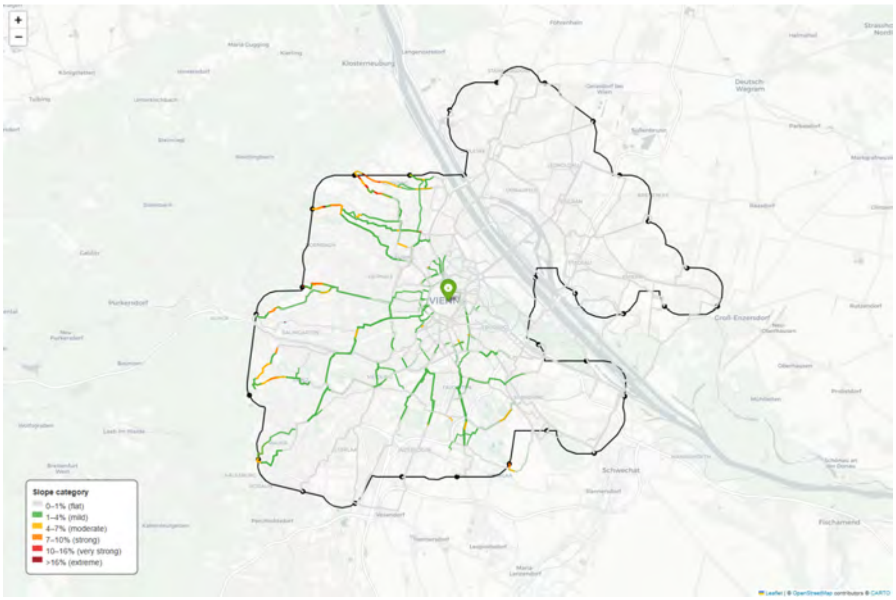

Figure 143: Viena – Indicator 3A

Indicator 3b

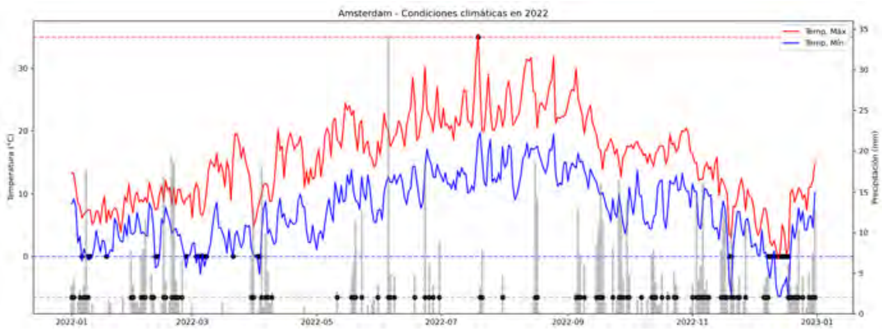

Figure 144: Amsterdam – Indicator 3B

Figure 145: Atenas – Indicator 3B

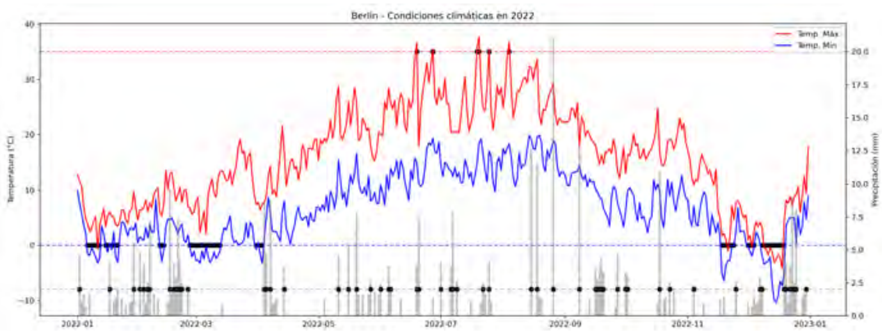

Figure 146: Berlin – Indicator 3B

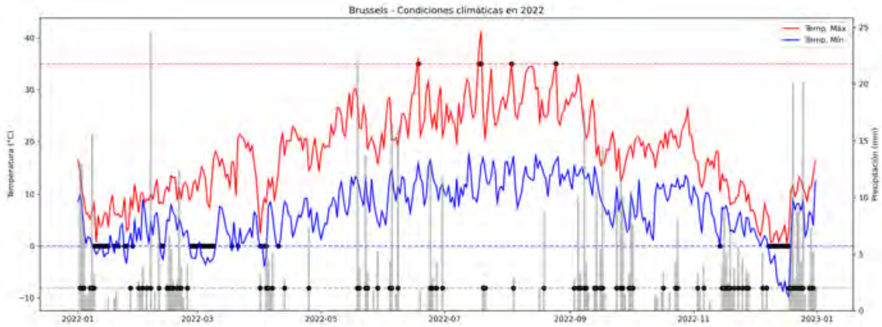

Figure 147: Brussels – Indicator 3B

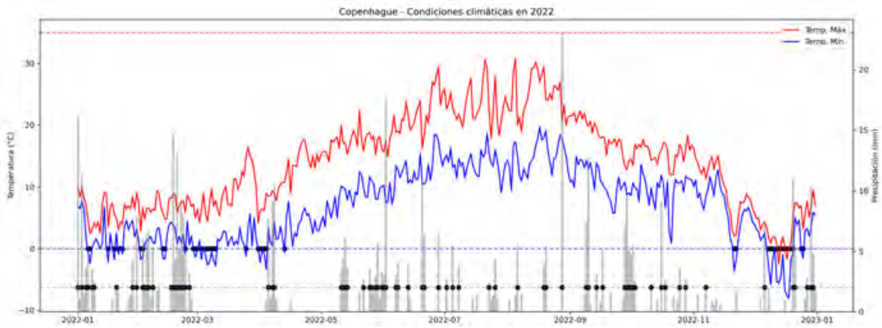

Figure 148: Copenhague – Indicator 3B

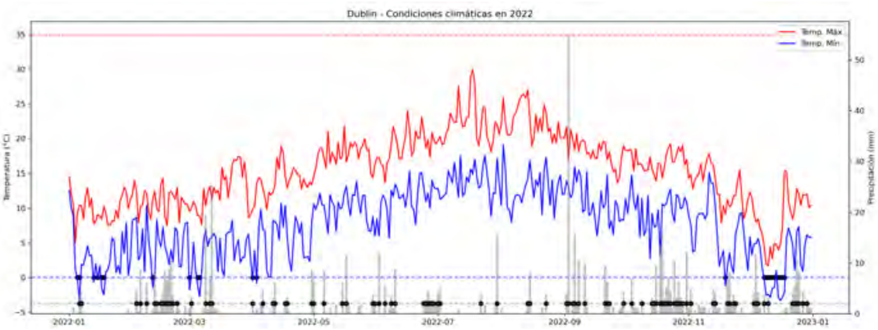

Figure 149: Dublin – Indicator 3B

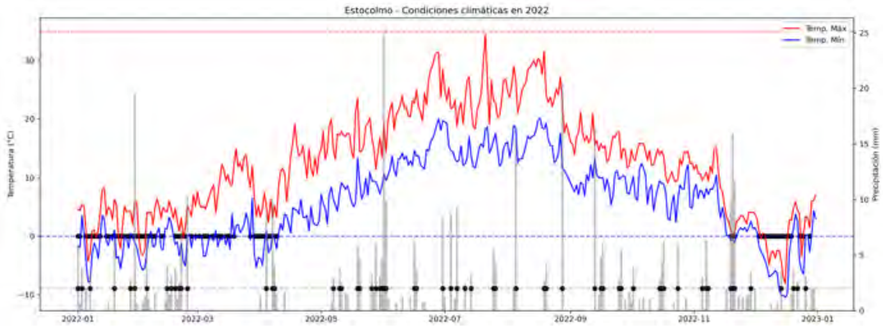

Figure 150: Estocolmo – Indicator 3B

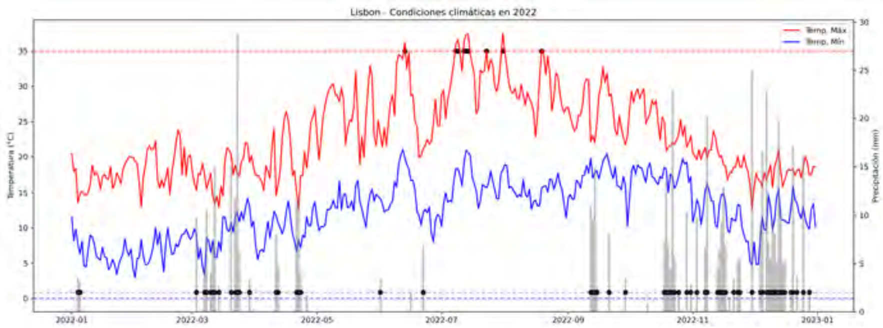

Figure 151: Lisbon – Indicator 3B

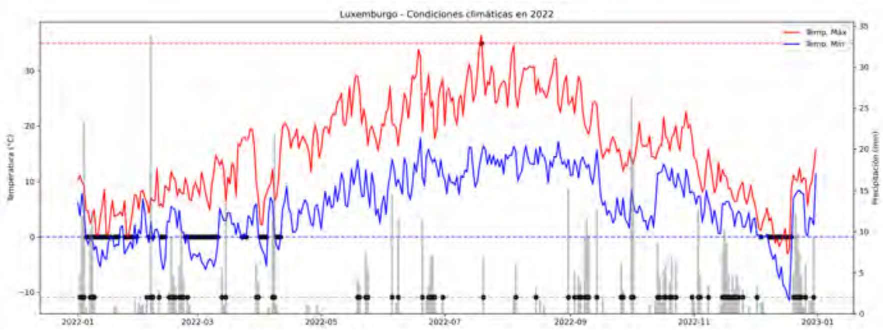

Figure 152: Luxemburgo – Indicator 3B

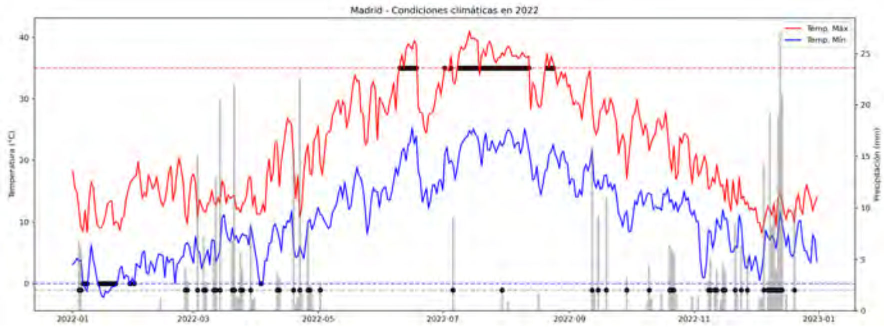

Figure 153: Madrid – Indicator 3B

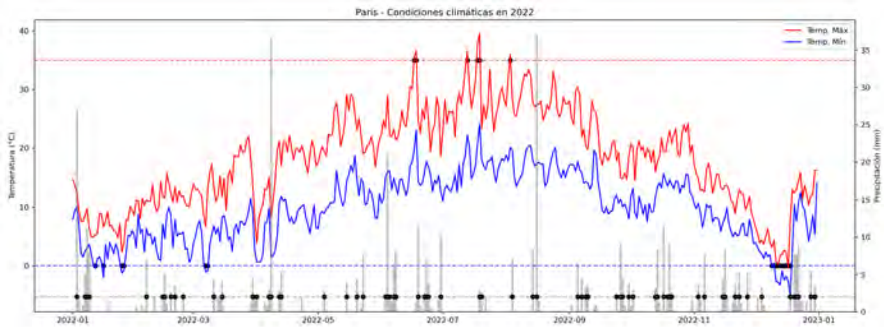

Figure 154: Paris – Indicator 3B

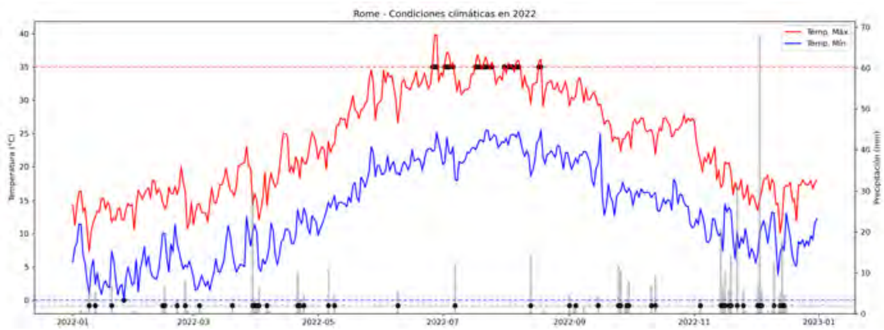

Figure 155: Rome – Indicator 3B

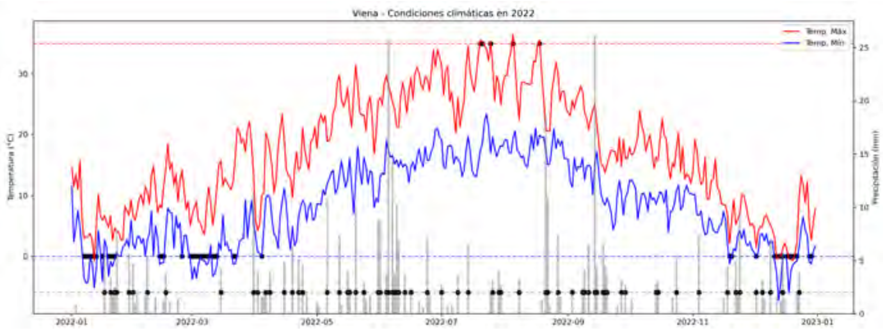

Figure 156: Viena – Indicator 3B

Indicator 4b

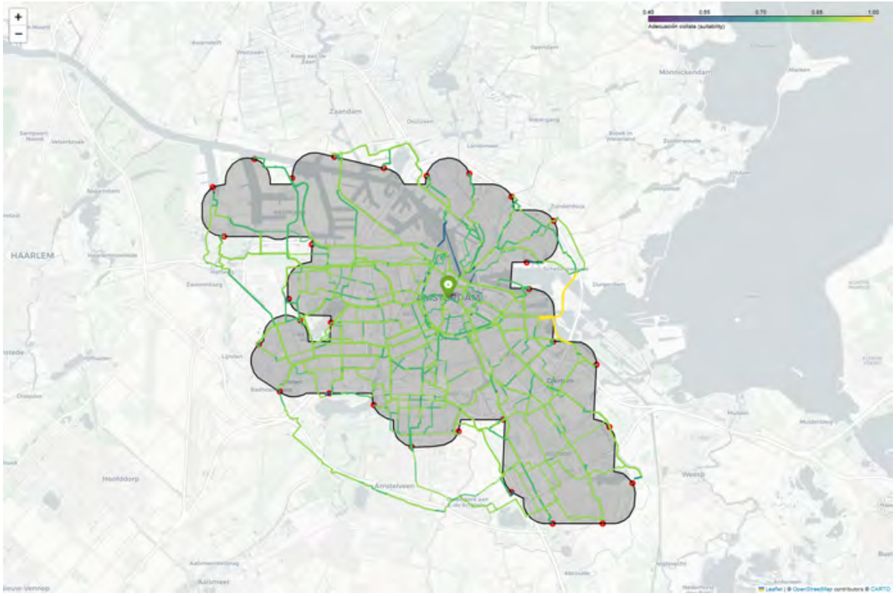

Figure 157: Amsterdam – Indicator 4B

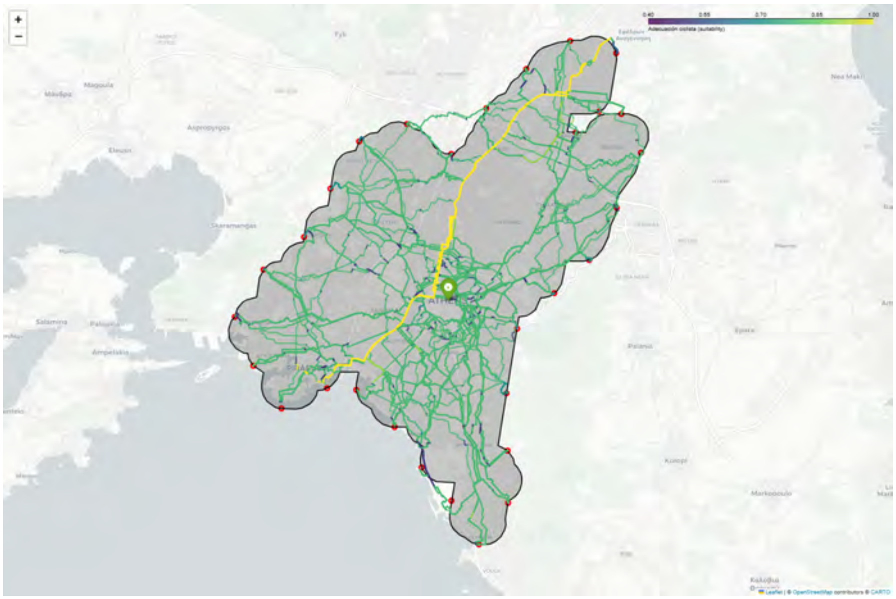

Figure 158: Atenas – Indicator 4B

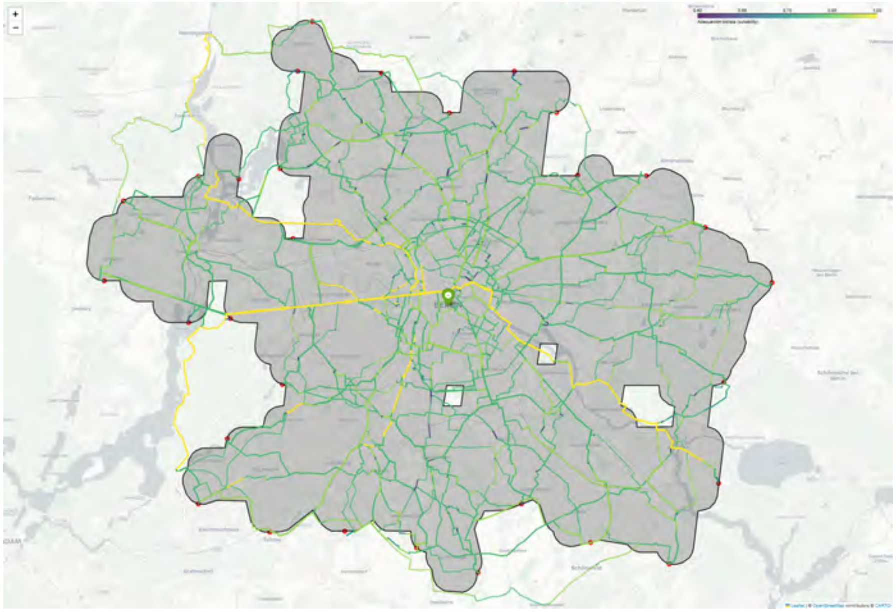

Figure 159: Berlin – Indicator 4B

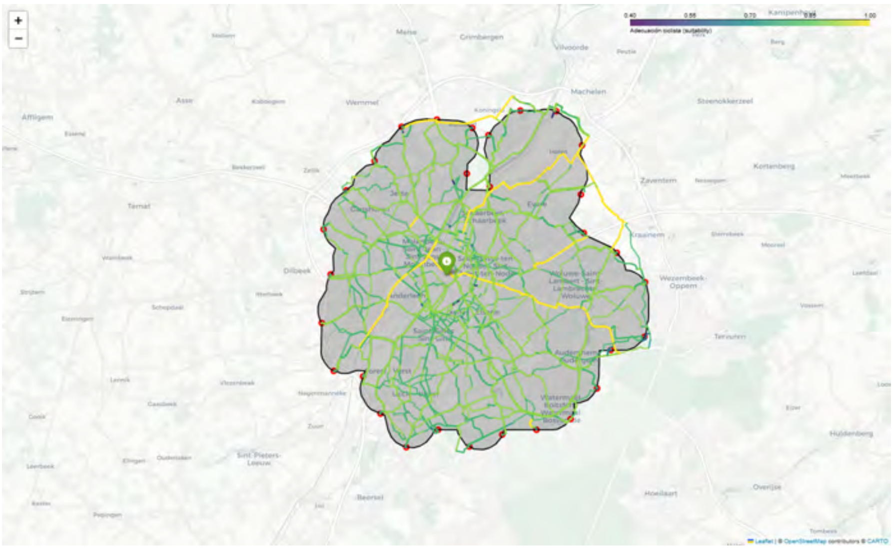

Figure 160: Brussels – Indicator 4B

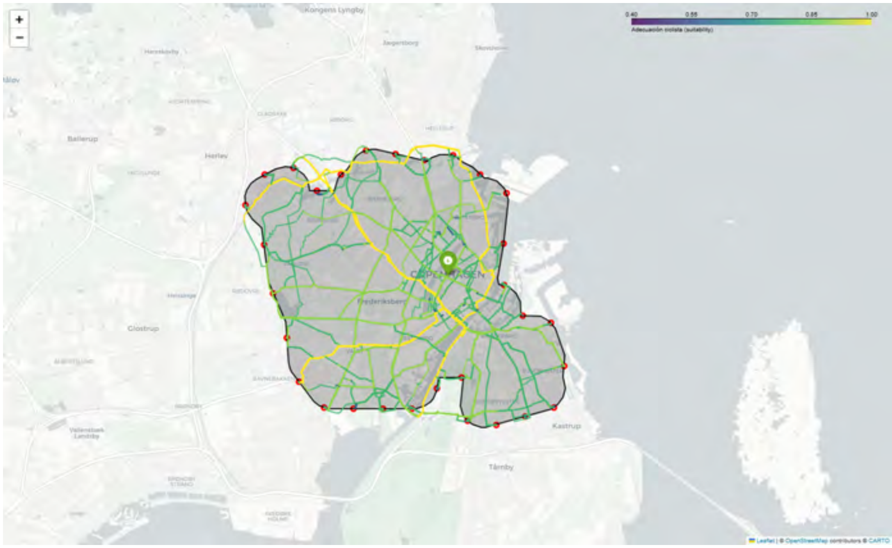

Figure 161: Copenhague – Indicator 4B

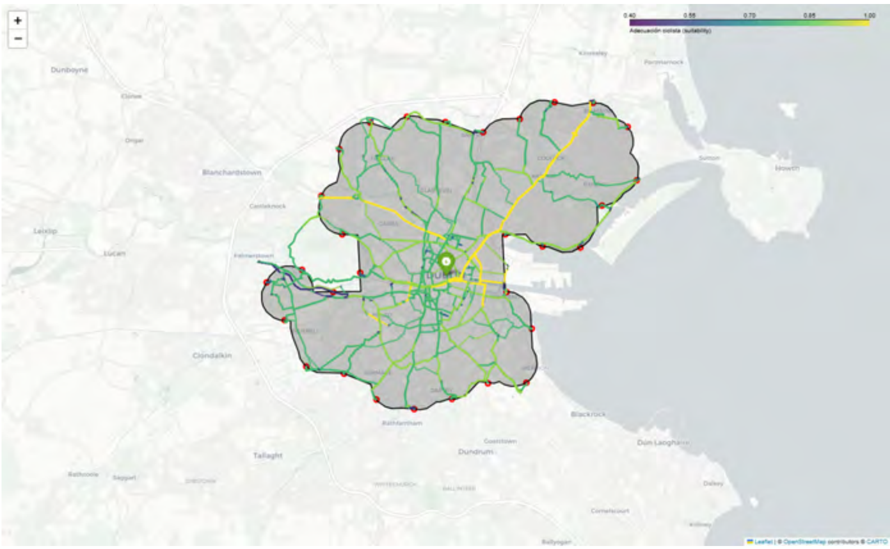

Figure 162: Dublin – Indicator 4B

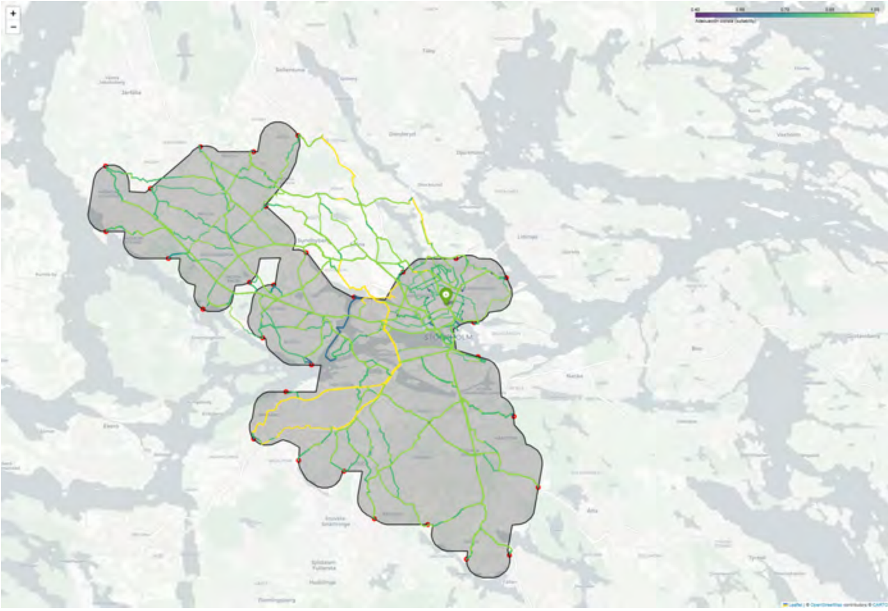

Figure 163: Estocolmo – Indicator 4B

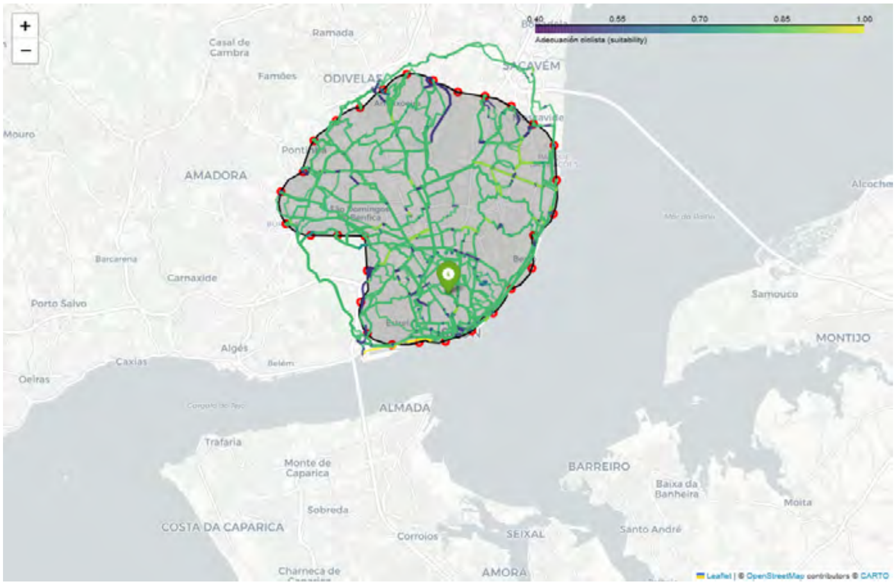

Figure 164: Lisbon – Indicator 4B

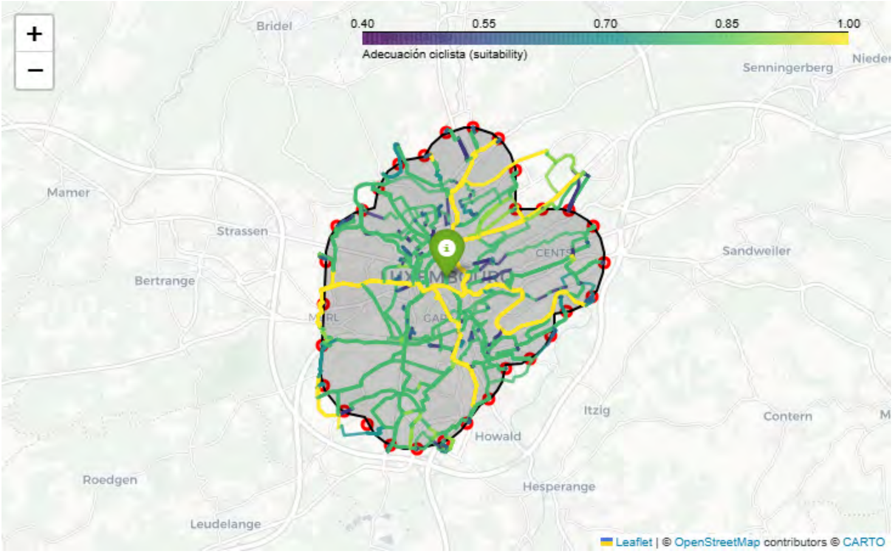

Figure 165: Luxemburgo – Indicator 4B

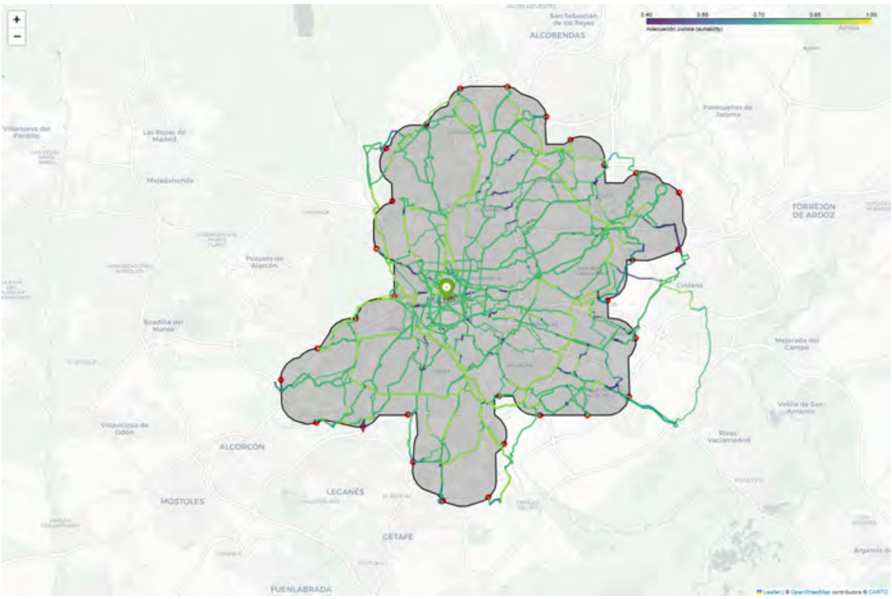

Figure 166: Madrid – Indicator 4B

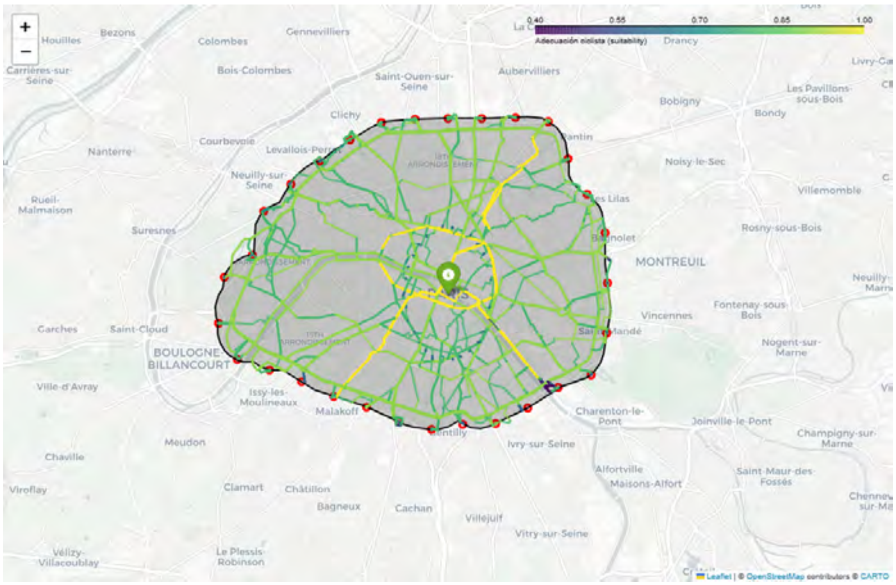

Figure 167: Paris – Indicator 4B

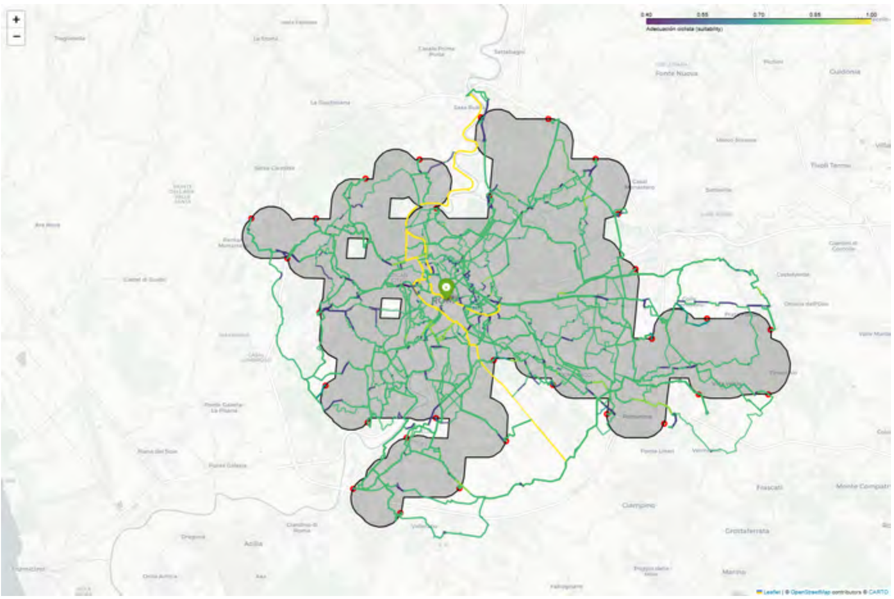

Figure 168: Rome – Indicator 4B

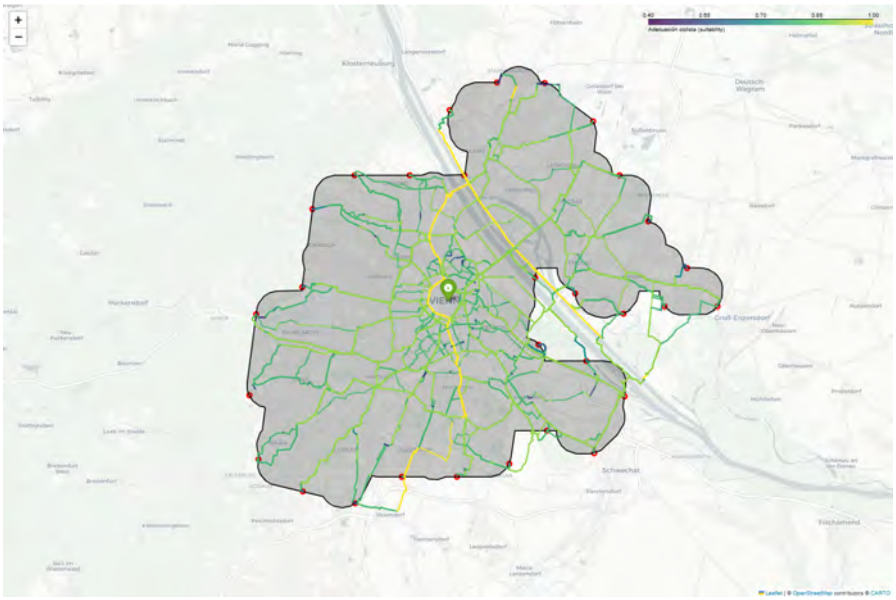

Figure 169: Viena – Indicator 4B

Appendix A

Source Code for the BIKE Index

This appendix includes the main code used to implement the BIKE Index indicators. Each section corresponds to a different block or indicator.

A.1 General setup and folder structure

The following listing shows how the city perimeter and folders are loaded and created.

```
import os, json, folium
from shapely.geometry import Polygon, MultiPolygon

ciudad = "brussels" # Change this depending on the city to analyze
folder_ciudad =
   ↪ os.path.join("C:/4GITIADE/tfg_bike_index/Procesamiento de
   ↪ datos/inputs/A. Informacion ciudades", ciudad.capitalize())

with open(os.path.join(folder_ciudad,
   ↪ f"centro_perimetro_{ciudad}.json"), "r") as f:
    config = json.load(f)

city_center = tuple(config["center"])
raw_coords = config["raw_coords"]

output_base = os.path.join("outputs", ciudad.lower())
estructura_indice = {
    "1_infraestructura": [
        "1a_cobertura_carril_bici",
        "1b_conectividad_red",
        "1c_eficiencia_rutas"
    ],
    "2_servicios": [
        "2a_acceso_talleres",
        "2b_bici_compartida"
    ],
```

```
    "3_factores_ambientales": [
        "3a_pendiente",
        "3b_dias_clima_desfavorable"
    ],
    "4_seguridad_vial": [
        "4a_tasa_accidentes",
        "4b_zonas_calmadas"
    ]
}

for dimension, indicadores in estructura_indice.items():
    for indicador in indicadores:
        os.makedirs(os.path.join(output_base, dimension,
            ↪ indicador), exist_ok=True)

base_misc_folder = os.path.join(output_base, "0_base")
for sub in ["0a_perimetros", "0b_rutas", "0c_grid"]:
    os.makedirs(os.path.join(base_misc_folder, sub),
        ↪ exist_ok=True)

def construir_poligono(coords):
    if isinstance(coords[0][0], (float, int)):
        return Polygon(coords)
    elif isinstance(coords[0][0], list):
        return MultiPolygon([Polygon(part) for part in coords])
    else:
        raise ValueError("Formato no valido para raw_coords")

poly = construir_poligono(raw_coords)
m = folium.Map(location=city_center, zoom_start=12)
folium.GeoJson(poly, style_function=lambda _: {
    "color": "blue", "weight": 2.5, "fillColor": "blue",
        ↪ "fillOpacity": 0.15
}, tooltip="Perimetro raw").add_to(m)
folium.Marker(location=city_center,
    ↪ icon=folium.Icon(color="green"), popup="Centro").add_to(m)
m
```

Listing A.1: Initial setup and folder structure for the city

A.2 Base layer 0a: Clean urban perimeter generation

```
import os, json, folium, numpy as np
import rasterio
from rasterio.features import shapes
import geopandas as gpd
from shapely.geometry import shape, Polygon, MultiPolygon, mapping
```

```
from shapely.ops import unary_union

folder = os.path.join(output_base, "0_base", "0a_perimetros")
os.makedirs(folder, exist_ok=True)
tif_path = os.path.join(folder_ciudad, f"density_{ciudad}.tif")

with rasterio.open(tif_path) as src:
    image = src.read(1).astype("float32")
    mask = image > 0
    results = ({"properties": {"density": v}, "geometry": s} for
       ↪ s, v in shapes(image, mask=mask,
       ↪ transform=src.transform))

geoms = list(results)
gdf = gpd.GeoDataFrame.from_features(geoms,
   ↪ crs=src.crs).to_crs(epsg=4326)
gdf = gdf[gdf["density"] > 1000]

recorte_poly = Polygon(raw_coords)
gdf = gpd.overlay(gdf, gpd.GeoDataFrame(geometry=[recorte_poly],
   ↪ crs="EPSG:4326"), how='intersection')

unido = unary_union(gdf.geometry)
if unido.geom_type == "Polygon":
    final_poly = Polygon(unido.exterior)
elif unido.geom_type == "MultiPolygon":
    polys = [p for p in unido.geoms if p.area > 1e-5]
    final_poly = sorted(polys, key=lambda p: p.area,
       ↪ reverse=True)[0]
else:
    raise ValueError("Unexpected geometry")

gdf_m = gpd.GeoDataFrame(geometry=[final_poly],
   ↪ crs="EPSG:4326").to_crs(epsg=3857)
gdf_m["geometry"] = gdf_m.buffer(-1500).buffer(1500)
gdf_clean = gdf_m.to_crs(epsg=4326)

geom = gdf_clean.geometry.values[0]
if geom.geom_type == "MultiPolygon":
    polys = [p for p in geom.geoms if p.area > 1e-5]
    final_poly_clean = sorted(polys, key=lambda p: p.area,
       ↪ reverse=True)[0]
elif geom.geom_type == "Polygon":
    final_poly_clean = geom
else:
    raise ValueError("Invalid geometry")

gdf_out = gpd.GeoDataFrame(geometry=[final_poly_clean],
   ↪ crs="EPSG:4326")
```

```
gdf_out["id"] = 0
gdf_out.to_file(f"{folder}/{ciudad}_clean_perimeter.geojson",
   ↪ driver="GeoJSON")

coords = np.array(final_poly_clean.exterior.coords[:-1])
distances = np.cumsum(np.linalg.norm(np.diff(coords, axis=0),
   ↪ axis=1))
distances = np.insert(distances, 0, 0)
target_distances = np.linspace(0, distances[-1], num_points + 1)

lon_interp = np.interp(target_distances, distances, coords[:, 0])
lat_interp = np.interp(target_distances, distances, coords[:, 1])
simplified_coords = list(zip(lon_interp, lat_interp))[:-1]

with open(f"{folder}/{ciudad}_clean_points.json", "w") as f:
    json.dump(simplified_coords, f, indent=4)

m = folium.Map(location=city_center, zoom_start=12)
folium.PolyLine(locations=[(lat, lon) for lon, lat in
   ↪ raw_coords], color='black', weight=1.5).add_to(m)
for p in simplified_coords:
    folium.CircleMarker(location=(p[1], p[0]), radius=4,
       ↪ color='red', fill=True).add_to(m)
folium.GeoJson(final_poly, style_function=lambda _: {
    "color": "orange", "weight": 2, "fillColor": "orange",
       ↪ "fillOpacity": 0.1
}).add_to(m)
folium.GeoJson(final_poly_clean, style_function=lambda _: {
    "color": "darkgreen", "weight": 2, "fillColor": "green",
       ↪ "fillOpacity": 0.3
}).add_to(m)
folium.Marker(location=city_center,
   ↪ icon=folium.Icon(color='green'), popup='Centro').add_to(m)
m.save(f"{folder}/{ciudad}_clean_map.html")

area_km2 = gdf_out.to_crs(epsg=3857).geometry.area.values[0] / 1e6
length_km = gdf_out.to_crs(epsg=3857).geometry.length.values[0] /
   ↪ 1000

info_perimetro = {
    "ciudad": ciudad,
    "area_km2": round(area_km2, 2),
    "longitud_km": round(length_km, 2),
    "n_puntos_discretizados": len(simplified_coords),
    "bounding_box": final_poly_clean.bounds,
    "geometry": mapping(final_poly_clean)
}
```

```
with open(f"{folder}/{ciudad}_clean_perimeter_info.json", "w",
    ↪ encoding="utf-8") as f:
    json.dump(info_perimetro, f, indent=2, ensure_ascii=False)
```

Listing A.2: Perimeter cleaning from population density raster

A.3 Base layer 0b: Radial route generation (inner circle + cardinal routes)

```
import os, json, time, requests, folium
import numpy as np
from geopy.distance import geodesic

folder_rutas = os.path.join(output_base, "0_base", "0b_rutas")
os.makedirs(folder_rutas, exist_ok=True)

points_path = os.path.join(output_base, "0_base",
    ↪ "0a_perimetros", f"{ciudad}_clean_points.json")
perimeter_path = os.path.join(output_base, "0_base",
    ↪ "0a_perimetros", f"{ciudad}_clean_perimeter.geojson")

with open(points_path, "r") as f:
    puntos_exterior = json.load(f)

num_puntos = len(puntos_exterior)
center_lat, center_lon = city_center[0], city_center[1]

min_dist = min(geodesic((p[1], p[0]), (center_lat,
    ↪ center_lon)).meters for p in puntos_exterior)
radio_interior = max(0.5 * min_dist, 1500)

angles = np.linspace(0, 2 * np.pi, num_puntos, endpoint=False)
puntos_interior = [
    [
        center_lon + (radio_interior / 111320) * np.cos(a),
        center_lat + (radio_interior / 110540) * np.sin(a)
    ]
    for a in angles
]

m = folium.Map(location=(center_lat, center_lon), zoom_start=13)
for p in puntos_exterior:
    folium.CircleMarker(location=(p[1], p[0]), radius=4,
        ↪ color="red", fill=True).add_to(m)
for p in puntos_interior:
```

```
    folium.CircleMarker(location=(p[1], p[0]), radius=4,
       ↪ color="green", fill=True).add_to(m)
folium.PolyLine(locations=[(p[1], p[0]) for p in puntos_interior]
   ↪ + [(puntos_interior[0][1], puntos_interior[0][0])],
                color="green", weight=1.5, opacity=0.8).add_to(m)
folium.Marker(location=(center_lat, center_lon),
   ↪ icon=folium.Icon(color="blue"), popup="Centro").add_to(m)
folium.GeoJson(perimeter_path, style_function=lambda _: {
    "color": "black", "weight": 2, "fillOpacity": 0.0
}).add_to(m)
m.save(os.path.join(folder_rutas,
   ↪ f"{ciudad}_debug_puntos_interior.html"))

info_interior = {
    "ciudad": ciudad,
    "num_puntos": num_puntos,
    "radio_interior_m": round(radio_interior, 2),
    "distancia_min_al_centro_m": round(min_dist, 2),
    "centroide": {"lat": center_lat, "lon": center_lon}
}
with open(os.path.join(folder_rutas,
   ↪ f"{ciudad}_circunferencia_info.json"), "w",
   ↪ encoding="utf-8") as f:
    json.dump(info_interior, f, indent=2, ensure_ascii=False)

# ORS API CALL
ORS_API_KEY = "YOUR_API_KEY_HERE"

def get_route(start, end):
    url =
       ↪ "https://api.openrouteservice.org/v2/directions/cycling-regular/geoj
    headers = {"Authorization": ORS_API_KEY, "Content-Type":
       ↪ "application/json"}
    payload = {
        "coordinates": [start, end],
        "elevation": "true",
        "extra_info": ["steepness", "waycategory", "waytype",
           ↪ "surface", "suitability"],
        "preference": "recommended",
        "radiuses": [-1, -1]
    }
    time.sleep(1.5)
    r = requests.post(url, json=payload, headers=headers)
    if r.status_code == 200:
        data = r.json()
        props = data["features"][0]["properties"].get("extras",
           ↪ {})
        coords = [(c[1], c[0]) for c in
           ↪ data["features"][0]["geometry"]["coordinates"]]
```

```
        return {
            "route": coords,
            "steepness": props.get("steepness", {}).get("values",
              ↪ []),
            "way_types": props.get("waytype", {}).get("values",
              ↪ []),
            "way_category": props.get("waycategory",
              ↪ {}).get("values", []),
            "surface": props.get("surface", {}).get("values", []),
            "suitability": props.get("suitability",
              ↪ {}).get("values", [])
        }
    elif r.status_code == 429:
        time.sleep(20)
        return get_route(start, end)
    else:
        return None

offsets_exterior = [num_puntos // 4, num_puntos // 2, 3 *
   ↪ num_puntos // 4]
offsets_interior = [0, num_puntos // 4, num_puntos // 2, 3 *
   ↪ num_puntos // 4]
all_routes_data = []

for i, origen in enumerate(puntos_exterior):
    destinos_exterior = [puntos_exterior[(i + o) % num_puntos]
       ↪ for o in offsets_exterior]
    for destino in destinos_exterior:
        route_data = get_route(origen, destino)
        if route_data:
            route_data["start"] = origen
            route_data["end"] = destino
            all_routes_data.append(route_data)
    destinos_interior = [puntos_interior[(i + o) % num_puntos]
       ↪ for o in offsets_interior]
    for destino in destinos_interior:
        route_data = get_route(origen, destino)
        if route_data:
            route_data["start"] = origen
            route_data["end"] = destino
            all_routes_data.append(route_data)

output_json = os.path.join(folder_rutas, f"{ciudad}_rutas.json")
with open(output_json, "w") as f:
    json.dump(all_routes_data, f, indent=4)

m = folium.Map(location=city_center, zoom_start=12)
for ruta in all_routes_data:
```

```
    folium.PolyLine(locations=ruta["route"], color="blue",
       ↪ weight=2.5, opacity=0.8).add_to(m)
for p in puntos_exterior:
    folium.CircleMarker(location=(p[1], p[0]), radius=4,
       ↪ color="red", fill=True).add_to(m)
for p in puntos_interior:
    folium.CircleMarker(location=(p[1], p[0]), radius=3,
       ↪ color="green", fill=True).add_to(m)
folium.Marker(location=city_center,
   ↪ icon=folium.Icon(color="green"), popup="Centro").add_to(m)
folium.GeoJson(perimeter_path, style_function=lambda _: {
    "color": "black", "weight": 2, "fillOpacity": 0.0
}).add_to(m)
m.save(os.path.join(folder_rutas,
   ↪ f"{ciudad}_mapa_rutas_cardinales_expandido.html"))

info_rutas = {
    "ciudad": ciudad,
    "num_puntos": num_puntos,
    "num_rutas_total": len(all_routes_data),
    "num_rutas_exterior_exterior": num_puntos *
       ↪ len(offsets_exterior),
    "num_rutas_exterior_interior": num_puntos *
       ↪ len(offsets_interior),
    "offsets_exterior": offsets_exterior,
    "offsets_interior": offsets_interior,
    "comentario": "Each outer point generates 3 exterior and 4
       ↪ interior routes (7 total)."
}
with open(os.path.join(folder_rutas,
   ↪ f"{ciudad}_info_rutas_cardinales.json"), "w",
   ↪ encoding="utf-8") as f:
    json.dump(info_rutas, f, indent=2, ensure_ascii=False)
```

Listing A.3: Internal circle generation and route computation from perimeter points

A.4 Base layer 0c: 500 m grid generation over the clean perimeter

```
import geopandas as gpd
from shapely.geometry import box, shape
import numpy as np, json, os, folium

folder_grid = os.path.join(output_base, "0_base", "0c_grid")
os.makedirs(folder_grid, exist_ok=True)
```

```
perimeter_path = os.path.join(output_base, "0_base",
    ↪ "0a_perimetros", f"{ciudad}_clean_perimeter.geojson")
with open(perimeter_path, "r") as f:
    geom = shape(json.load(f)["features"][0]["geometry"])

gdf_perimetro = gpd.GeoDataFrame(geometry=[geom],
    ↪ crs="EPSG:4326").to_crs(3857)
perimetro_geom = gdf_perimetro.geometry.values[0]

cell_size = 500
minx, miny, maxx, maxy = perimetro_geom.bounds
cols, rows = np.arange(minx, maxx, cell_size), np.arange(miny,
    ↪ maxy, cell_size)

polygons = [
    box(x, y, x + cell_size, y + cell_size)
    for x in cols for y in rows
    if box(x, y, x + cell_size, y +
        ↪ cell_size).within(perimetro_geom)
]
gdf_grid = gpd.GeoDataFrame(geometry=polygons,
    ↪ crs="EPSG:3857").to_crs(4326)

output_geojson = os.path.join(folder_grid,
    ↪ f"{ciudad}_grid_500m.geojson")
gdf_grid.to_file(output_geojson, driver="GeoJSON")

m = folium.Map(location=city_center, zoom_start=12)
for _, row in gdf_grid.iterrows():
    folium.GeoJson(row["geometry"], style_function=lambda x: {
        "fillColor": "#66aaff", "color": "#004488", "weight":
            ↪ 0.4, "fillOpacity": 0.00001
    }).add_to(m)

folium.GeoJson(perimeter_path, style_function=lambda _: {
    "color": "black", "weight": 2, "fillOpacity": 0
}, tooltip="Clean urban perimeter").add_to(m)

folium.Marker(location=city_center,
    ↪ icon=folium.Icon(color="green"), popup="Centro").add_to(m)

output_map = os.path.join(folder_grid,
    ↪ f"{ciudad}_mapa_grid_500m.html")
m.save(output_map)

grid_summary = {
    "city": ciudad,
    "cell_count": len(gdf_grid),
    "cell_size_m": cell_size,
```

```
    "area_km2": round(gdf_grid.to_crs(3857).geometry.area.sum() /
        ↪ 1e6, 2),
    "crs": str(gdf_grid.crs),
    "output_geojson": os.path.basename(output_geojson),
    "output_map": os.path.basename(output_map)
}

output_summary_json = os.path.join(folder_grid,
   ↪ f"{ciudad}_grid_500m_summary.json")
with open(output_summary_json, "w", encoding="utf-8") as f:
    json.dump(grid_summary, f, indent=2)
```

Listing A.4: Generation of 500 m analysis grid and interactive map

A.5 Indicator 1a: Bike lane coverage

```
import os, json, folium
from datetime import datetime
from branca.element import Template, MacroElement
import pandas as pd

indicador = "1a_cobertura_carril_bici"
folder_fase3 = os.path.join(output_base, "1_infraestructura",
   ↪ indicador)
os.makedirs(folder_fase3, exist_ok=True)

ruta_json = os.path.join(output_base, "0_base", "0b_rutas",
   ↪ f"{ciudad}_rutas.json")
with open(ruta_json, "r") as f:
    all_routes_data = json.load(f)

points_path = os.path.join(output_base, "0_base",
   ↪ "0a_perimetros", f"{ciudad}_clean_points.json")
with open(points_path, "r") as f:
    puntos = json.load(f)

perimeter_path = os.path.join(output_base, "0_base",
   ↪ "0a_perimetros", f"{ciudad}_clean_perimeter.geojson")

waytype_labels = {
    0: "Unknown", 1: "State Road", 2: "Road", 3: "Street", 4:
        ↪ "Path",
    5: "Track", 6: "Cycleway", 7: "Footway", 8: "Steps", 9:
        ↪ "Ferry", 10: "Construction"
}
friendly_waytypes = {4, 5, 6, 7}
```

```
m = folium.Map(location=city_center, zoom_start=12,
    ↪ tiles="cartodbpositron")
total_distance = 0
bike_lane_distance = 0
bike_friendly_distance = 0
waytype_distances = {}

for p in puntos:
    folium.CircleMarker(location=(p[1], p[0]), radius=4,
        ↪ color="red", fill=True).add_to(m)

folium.Marker(location=city_center,
    ↪ icon=folium.Icon(color="green"), popup="Centro").add_to(m)
folium.GeoJson(data=perimeter_path, style_function=lambda _:
    ↪ {"color": "black", "weight": 2, "fillOpacity":
    ↪ 0.0}).add_to(m)

for route_data in all_routes_data:
    coords = route_data["route"]
    way_types = route_data.get("way_types", [])

    for segment in way_types:
        start_idx, end_idx, way_type = segment
        if end_idx <= start_idx or end_idx >= len(coords):
            continue

        segment_coords = coords[start_idx:end_idx+1]
        segment_distance = end_idx - start_idx

        total_distance += segment_distance
        waytype_distances[way_type] =
            ↪ waytype_distances.get(way_type, 0) +
            ↪ segment_distance
        if way_type == 6:
            bike_lane_distance += segment_distance
        if way_type in friendly_waytypes:
            bike_friendly_distance += segment_distance

        if way_type == 6:
            color, tooltip = "purple", "Bike lane"
        elif way_type in {4, 5, 7}:
            color, tooltip = "orange", "Friendly infrastructure"
        else:
            color, tooltip = "gray", "Other"

        folium.PolyLine(locations=segment_coords, color=color,
            ↪ weight=2.5, opacity=0.8, tooltip=tooltip).add_to(m)
```

```
bike_lane_pct = (bike_lane_distance / total_distance) * 100 if
    ↪ total_distance else 0
bike_friendly_pct = (bike_friendly_distance / total_distance) *
    ↪ 100 if total_distance else 0

waytype_pct = {
    waytype_labels.get(k, str(k)): round((v / total_distance) *
        ↪ 100, 2)
    for k, v in waytype_distances.items()
}

resultado = {
    "ciudad": ciudad,
    "indicador": indicador,
    "unidad": "porcentaje (%)",
    "indicadores": {
        "porcentaje_carril_bici": round(bike_lane_pct, 2),
        "porcentaje_vias_ciclables_amigables":
            ↪ round(bike_friendly_pct, 2)
    },
    "distancias": {
        "total": total_distance,
        "carril_bici": bike_lane_distance,
        "vias_ciclables_amigables": bike_friendly_distance,
        "por_waytype": waytype_distances
    },
    "porcentaje_por_waytype": waytype_pct,
    "num_rutas": len(all_routes_data),
    "timestamp": datetime.now().isoformat()
}

output_json = os.path.join(folder_fase3,
    ↪ f"{ciudad}_indicador_{indicador}.json")
with open(output_json, "w") as f:
    json.dump(resultado, f, indent=4)

legend_html = """
{% macro html(this, kwargs) %}
<div style="position: fixed; bottom: 50px; left: 50px; width:
    ↪ 180px;
background-color: white; border: 2px solid grey; z-index: 9999;
font-size: 14px; padding: 10px;">
<b>Way Types</b><br>
<span style='color:purple;'>   </span> Bike Lanes<br>
<span style='color:orange;'>   </span> Paths and Footways<br>
<span style='color:gray;'>   </span> Other
</div>
{% endmacro %}
"""
```

```
legend = MacroElement()
legend._template = Template(legend_html)
m.get_root().add_child(legend)

output_map = os.path.join(folder_fase3,
   ↪ f"{ciudad}_mapa_{indicador}.html")
m.save(output_map)

orden_personalizado = ["Cycleway", "Footway", "Path", "Street",
   ↪ "Road", "State Road"]
otros = sorted([k for k in waytype_pct if k not in
   ↪ orden_personalizado])
columnas_ordenadas = orden_personalizado + otros

row = {
    "ciudad": ciudad,
    "% carril bici": round(bike_lane_pct, 2),
    "% v as amigables": round(bike_friendly_pct, 2),
    "diferencia (%)": round(bike_friendly_pct - bike_lane_pct, 2),
}
for k in columnas_ordenadas:
    row[f"% {k}"] = waytype_pct.get(k, 0)

df = pd.DataFrame([row])
df.to_excel(os.path.join(folder_fase3,
   ↪ f"{ciudad}_indicador_{indicador}.xlsx"), index=False)
```

Listing A.5: Calculation of bike lane and friendly infrastructure coverage

A.6 Indicator 1b: Network connectivity and coverage

```
import os, json, osmnx as ox, geopandas as gpd, numpy as np,
   ↪ networkx as nx, folium
from shapely.geometry import shape
from datetime import datetime

indicador = "1b_conectividad_red"
folder = os.path.join(output_base, "1_infraestructura", indicador)
os.makedirs(folder, exist_ok=True)

with open(os.path.join(output_base, "0_base", "0a_perimetros",
   ↪ f"{ciudad}_clean_perimeter.geojson")) as f:
    geom = shape(json.load(f)["features"][0]["geometry"])
gdf_perimetro = gpd.GeoDataFrame(geometry=[geom], crs=4326)

tags = {"highway": "cycleway"}
gdf_cycleways = ox.features_from_polygon(geom, tags=tags)
```

```
gdf_cycleways =
    ↪ gdf_cycleways[gdf_cycleways.geom_type.isin(["LineString",
    ↪ "MultiLineString"])]
gdf_cycleways = gpd.clip(gdf_cycleways,
    ↪ gdf_perimetro).to_crs(3857)
long_km = round(gdf_cycleways.length.sum() / 1000, 2)

with open(os.path.join(output_base, "0_base", "0c_grid",
    ↪ f"{ciudad}_grid_500m.geojson")) as f:
    raw_grid = json.load(f)
gdf_grid = gpd.GeoDataFrame(geometry=[shape(feat["geometry"]) for
    ↪ feat in raw_grid["features"]], crs=4326).to_crs(3857)

matches = gdf_grid.sindex.query(gdf_cycleways.geometry,
    ↪ predicate="intersects")
idx_cubiertas = np.unique(matches[1])
gdf_ciclistas =
    ↪ gdf_grid.iloc[idx_cubiertas].copy().reset_index(drop=True)

G = nx.Graph()
for i, c1 in enumerate(gdf_ciclistas.geometry):
    G.add_node(i)
    for j in range(i + 1, len(gdf_ciclistas)):
        if c1.touches(gdf_ciclistas.geometry[j]):
            G.add_edge(i, j)

comp = sorted(nx.connected_components(G), key=len, reverse=True)
tam = [len(c) for c in comp[:3]] + [0] * (3 - len(comp))
gdf_ciclistas["grupo"] = [1 if i in comp[0] else 2 if i in
    ↪ comp[1] else 3 if i in comp[2] else 0 for i in
    ↪ range(len(gdf_ciclistas))]

pct_con = round(100 * tam[0] / len(gdf_ciclistas), 2)
pct_cov = round(100 * len(gdf_ciclistas) / len(gdf_grid), 2)

json_path = os.path.join(folder,
    ↪ f"{ciudad}_indicador_{indicador}_clean.json")
with open(json_path, "w") as f:
    json.dump({
        "ciudad": ciudad,
        "indicador": indicador,
        "unidad": "porcentaje de celdas conectadas",
        "valor": pct_con,
        "num_celdas_con_infraestructura": len(gdf_ciclistas),
        "tamano_componente_principal": tam[0],
        "tamano_segundo_componente": tam[1],
        "tamano_tercer_componente": tam[2],
        "porcentaje_cobertura_grid": pct_cov,
        "longitud_total_km": long_km,
```

```
        "timestamp": datetime.now().isoformat()
    }, f, indent=4)

m1 = folium.Map(location=city_center, zoom_start=12,
   ↪ tiles="cartodbpositron")
colors = {1: "green", 2: "blue", 3: "orange", 0: "red"}
for _, row in gdf_ciclistas.to_crs(4326).iterrows():
    folium.GeoJson(row["geometry"], style_function=lambda x,
       ↪ c=colors[row["grupo"]]: {
        "fillColor": c, "color": c, "weight": 0.5, "fillOpacity":
           ↪ 0.5
    }).add_to(m1)
for _, row in gdf_cycleways.to_crs(4326).iterrows():
    folium.GeoJson(row["geometry"], style_function=lambda x:
       ↪ {"color": "magenta", "weight": 1.5, "opacity":
       ↪ 0.6}).add_to(m1)
folium.GeoJson(gdf_perimetro, style_function=lambda x: {"color":
   ↪ "black", "weight": 2, "fillOpacity": 0}).add_to(m1)
folium.Marker(location=city_center,
   ↪ icon=folium.Icon(color="green")).add_to(m1)
m1.save(os.path.join(folder,
   ↪ f"{ciudad}_mapa_conectividad_clean.html"))

gdf_grid["cubierta"] = gdf_grid.geometry.apply(lambda cell:
   ↪ any(cell.intersects(seg) for seg in gdf_cycleways.geometry))
m2 = folium.Map(location=city_center, zoom_start=12,
   ↪ tiles="cartodbpositron")
for _, row in gdf_grid.to_crs(4326).iterrows():
    color, opacidad = ("green", 0.3) if row["cubierta"] else
       ↪ ("red", 0.1)
    folium.GeoJson(row["geometry"], style_function=lambda x,
       ↪ c=color, o=opacidad: {
        "fillColor": c, "color": c, "weight": 0.1, "fillOpacity":
           ↪ o
    }).add_to(m2)
for _, row in gdf_cycleways.to_crs(4326).iterrows():
    folium.GeoJson(row["geometry"], style_function=lambda x:
       ↪ {"color": "magenta", "weight": 1.5, "opacity":
       ↪ 0.8}).add_to(m2)
folium.GeoJson(gdf_perimetro, style_function=lambda x: {"color":
   ↪ "black", "weight": 2, "fillOpacity": 0}).add_to(m2)
folium.Marker(location=city_center,
   ↪ icon=folium.Icon(color="green")).add_to(m2)
m2.save(os.path.join(folder,
   ↪ f"{ciudad}_mapa_cobertura_clean.html"))
```

Listing A.6: Computation of connected components and coverage of the cycleway network

A.7 Indicator 1c: Route Efficiency (Straight-line vs Actual Distance)

```
import os, json, numpy as np, matplotlib.pyplot as plt, folium,
    ↪ pandas as pd
from geopy.distance import geodesic
from datetime import datetime
from branca.colormap import linear

indicador = "1c_eficiencia_rutas"
folder = os.path.join(output_base, "1_infraestructura", indicador)
os.makedirs(folder, exist_ok=True)

with open(os.path.join(output_base, "0_base", "0b_rutas",
    ↪ f"{ciudad}_rutas.json")) as f:
    rutas = json.load(f)
with open(os.path.join(output_base, "0_base", "0a_perimetros",
    ↪ f"{ciudad}_clean_perimeter.geojson")) as f:
    perimeter_geojson = json.load(f)

eficiencias, dist_real, dist_recta = [], [], []
for r in rutas:
    coords, start, end = r["route"], r["start"], r["end"]
    d_recta = geodesic((start[1], start[0]), (end[1],
        ↪ end[0])).meters
    d_real = sum(geodesic((coords[i][1], coords[i][0]),
        ↪ (coords[i+1][1], coords[i+1][0])).meters for i in
        ↪ range(len(coords)-1))
    if d_real > 0:
        eficiencia = d_recta / d_real
        eficiencias.append(eficiencia)
        dist_real.append(d_real)
        dist_recta.append(d_recta)

media = round(np.mean(eficiencias), 3)
mediana = round(np.median(eficiencias), 3)
std = round(np.std(eficiencias), 3)
max_, min_ = round(np.max(eficiencias), 3),
    ↪ round(np.min(eficiencias), 3)

json_path = os.path.join(folder,
    ↪ f"{ciudad}_indicador_{indicador}_clean.json")
with open(json_path, "w") as f:
    json.dump({
        "ciudad": ciudad,
        "indicador": indicador,
        "unidad": "ratio (distancia_recta / distancia_real)",
```

```
        "valor_medio": media,
        "mediana": mediana,
        "desviacion_tipica": std,
        "maximo": max_,
        "minimo": min_,
        "num_rutas": len(eficiencias),
        "timestamp": datetime.now().isoformat(),
        "valores_individuales": [round(e, 3) for e in
           ↪ eficiencias],
        "distancias_reales": [round(d, 1) for d in dist_real],
        "distancias_rectas": [round(d, 1) for d in dist_recta]
    }, f, indent=4)

plt.figure(figsize=(10, 6))
plt.hist(eficiencias, bins=20, color='skyblue', edgecolor='black')
plt.axvline(media, color='red', linestyle='--', label=f"Mean =
   ↪ {media}")
plt.axvline(mediana, color='orange', linestyle='--',
   ↪ label=f"Median = {mediana}")
plt.axvline(1, color='green', linestyle='--', label="Optimal
   ↪ route (1.0)")
plt.title("Distribution of Cycling Route Efficiency")
plt.xlabel("Efficiency ratio")
plt.ylabel("Number of routes")
plt.legend()
plt.tight_layout()
plt.savefig(os.path.join(folder,
   ↪ f"{ciudad}_histograma_{indicador}_clean.png"))
plt.close()

m = folium.Map(location=city_center, zoom_start=12,
   ↪ tiles="cartodbpositron")
colormap = linear.YlGnBu_09.scale(min_, 1.0)
colormap.caption = "Route efficiency"
folium.Marker(location=city_center,
   ↪ icon=folium.Icon(color="green")).add_to(m)
folium.GeoJson(perimeter_geojson, style_function=lambda _:
   ↪ {"color": "black", "weight": 2}).add_to(m)
colormap.add_to(m)
for i, ruta in enumerate(rutas):
    if i >= len(eficiencias): continue
    color = colormap(eficiencias[i])
    folium.PolyLine([(lat, lon) for lat, lon in ruta["route"]],
                    color=color, weight=2.5, opacity=0.8,
                    tooltip=f"Efficiency:
                       ↪ {eficiencias[i]:.2f}").add_to(m)
    folium.CircleMarker((ruta["start"][1], ruta["start"][0]),
       ↪ radius=3,
                        color="black", fill=True).add_to(m)
```

```
m.save(os.path.join(folder,
    ↪ f"{ciudad}_mapa_{indicador}_clean.html"))

df = pd.DataFrame([{
    "ciudad": ciudad,
    "valor_medio": media,
    "mediana": mediana,
    "desviacion_tipica": std,
    "maximo": max_,
    "minimo": min_
}])
df.to_excel(os.path.join(folder,
    ↪ f"{ciudad}_indicador_{indicador}.xlsx"), index=False)
```

Listing A.7: Computation of route efficiency ratios and visualisation

A.8 Indicator 2b: Coverage of Bike-Sharing Stations

```
import pandas as pd, geopandas as gpd, json, os, folium
from shapely.geometry import shape
from datetime import datetime
from scipy.spatial import cKDTree
from pyproj import Geod
import numpy as np, matplotlib.pyplot as plt

# Load stations
df =
    ↪ pd.read_excel(os.path.join("C:/4GITIADE/tfg_bike_index/Procesamiento
    ↪ de datos/inputs/A. Informacion
    ↪ ciudades/Bike_coordinates_final", f"{ciudad.lower()}.xlsx"))
df = df[df["Tags"].apply(lambda x: "Bike sharing station" in
    ↪ str(x))]
gdf_estaciones = gpd.GeoDataFrame(df,
    ↪ geometry=gpd.points_from_xy(df["Spot_location_x"],
    ↪ df["Spot_location_y"]), crs="EPSG:4326").to_crs(3857)
gdf_buffers = gdf_estaciones.copy()
gdf_buffers["geometry"] = gdf_buffers.buffer(500)

# Load grid
with open(os.path.join(output_base, "0_base", "0c_grid",
    ↪ f"{ciudad}_grid_500m.geojson")) as f:
    grid_geoms = [shape(feat["geometry"]) for feat in
        ↪ json.load(f)["features"]]
gdf_grid = gpd.GeoDataFrame(geometry=grid_geoms,
    ↪ crs="EPSG:4326").to_crs(3857)
gdf_grid["cubierta"] =
    ↪ gdf_grid.intersects(gdf_buffers.unary_union)
```

```
# Calculate accessible stations using geographic distance
grid_centroids = gdf_grid.centroid.to_crs(4326)
station_coords = gdf_estaciones.to_crs(4326)
tree = cKDTree(np.vstack([station_coords.geometry.x,
    ↪ station_coords.geometry.y]).T)
geod = Geod(ellps="WGS84")

cuentas_estaciones = []
for i, centro in grid_centroids.items():
    indices = tree.query_ball_point([centro.x, centro.y], r=0.005)
    cuenta = sum(1 for j in indices if geod.inv(centro.x,
        ↪ centro.y, station_coords.iloc[j].geometry.x,
        ↪ station_coords.iloc[j].geometry.y)[2] <= 500)
    cuentas_estaciones.append(cuenta)
gdf_grid["estaciones_accesibles"] = cuentas_estaciones

def gini(array):
    array = np.sort(np.array(array))
    n = len(array)
    index = np.arange(1, n + 1)
    return (np.sum((2 * index - n - 1) * array)) / (n *
        ↪ np.sum(array)) if np.sum(array) != 0 else 0

# Summary values
celdas_total = len(gdf_grid)
celdas_cubiertas = gdf_grid["cubierta"].sum()
porcentaje_cubierto = 100 * celdas_cubiertas / celdas_total
gini_estaciones = round(gini(cuentas_estaciones), 4)

# Export outputs
output_folder = os.path.join(output_base, "2_servicios",
    ↪ "2b_bici_compartida")
gdf_grid.to_crs(4326).to_file(os.path.join(output_folder,
    ↪ "celdas_cobertura_bikesharing.geojson"), driver="GeoJSON")
with open(os.path.join(output_folder, "resultado.json"), "w") as
    ↪ f:
    json.dump({
        "indicador": "2b_cobertura_bici_compartida",
        "ciudad": ciudad,
        "valor_indicador": round(porcentaje_cubierto, 2),
        "indice_gini": {"estaciones": gini_estaciones},
        "celdas_totales": celdas_total,
        "celdas_cubiertas": celdas_cubiertas,
        "num_estaciones": len(gdf_estaciones),
        "fecha_calculo": datetime.now().strftime("%Y-%m-%d
            ↪ %H:%M:%S")
    }, f, indent=2)
```

```
pd.DataFrame([{
    "City": ciudad.capitalize(),
    "Indicator 2b (%)": round(porcentaje_cubierto, 2),
    "Gini     Stations": gini_estaciones,
    "Total Stations": int(len(gdf_estaciones)),
    "Grid Cells Total": int(celdas_total),
    "Grid Cells Covered": int(celdas_cubiertas),
    "Date": datetime.now().strftime("%Y-%m-%d")
}]).to_excel(os.path.join(output_folder,
   ↪ "resumen_resultado_2b.xlsx"), index=False)
```

Listing A.8: Calculation of urban bike-sharing coverage and inequality

A.9 Indicator 3a: Slope Effort Along Bicycle Routes

```
import os, json, folium, statistics
import matplotlib.pyplot as plt
from shapely.geometry import LineString
from geopy.distance import geodesic
from datetime import datetime
from branca.element import Template, MacroElement
import pandas as pd

indicador = "3a_pendiente"
folder = os.path.join(output_base, "3_factores_ambientales",
   ↪ indicador)
os.makedirs(folder, exist_ok=True)

ruta_json = os.path.join(output_base, "0_base", "0b_rutas",
   ↪ f"{ciudad}_rutas.json")
with open(ruta_json, "r") as f: rutas = json.load(f)

points_path = os.path.join(output_base, "0_base",
   ↪ "0a_perimetros", f"{ciudad}_clean_points.json")
with open(points_path, "r") as f: puntos = json.load(f)

perimeter_path = os.path.join(output_base, "0_base",
   ↪ "0a_perimetros", f"{ciudad}_clean_perimeter.geojson")

colores = {0:"#dddddd", 1:"#4daf4a", 2:"#ffb700", 3:"#ff7f00",
   ↪ 4:"#e31a1c", 5:"#99000d"}
labels = {0:"0-1% (llano)", 1:"1-4% (leve)", 2:"4-7% (moderada)",
          3:"7-10% (fuerte)", 4:"10-16% (muy fuerte)", 5:">16%
             ↪ (extrema)"}
```

```
m = folium.Map(location=city_center, zoom_start=12,
   ↪ tiles="cartodbpositron")
for p in puntos:
    folium.CircleMarker(location=(p[1], p[0]), radius=3,
        ↪ color="black", fill=True).add_to(m)
folium.Marker(location=city_center,
   ↪ icon=folium.Icon(color="green"), popup="Centro").add_to(m)
folium.GeoJson(perimeter_path, style_function=lambda _: {"color":
   ↪ "black", "weight": 2, "fillOpacity": 0}).add_to(m)

dist_pendiente, total_dist, esfuerzos = {}, 0, []

for ruta in rutas:
    coords = ruta["route"]
    steepness = ruta.get("steepness", [])
    esf_total, long_total = 0, 0
    for start, end, cat in steepness:
        if end <= start or end >= len(coords): continue
        l = geodesic(coords[start], coords[end]).meters
        seg = coords[start:end+1]
        cat_abs = abs(cat)
        if cat_abs > 5: continue
        folium.PolyLine(seg, color=colores[cat_abs], weight=2.5,
            ↪ opacity=0.85,
                        tooltip=f"Categor a {cat_abs}:
                            ↪ {labels[cat_abs]}").add_to(m)
        dist_pendiente[cat_abs] = dist_pendiente.get(cat_abs, 0)
            ↪ + l
        total_dist += l
        esf_total += l * cat_abs
        long_total += l
    if long_total > 0:
        esfuerzos.append(esf_total / long_total)

porcentajes = {labels[k]: round((v / total_dist) * 100, 2) for k,
   ↪ v in dist_pendiente.items()}
stats = {
    "media": round(statistics.mean(esfuerzos), 4),
    "mediana": round(statistics.median(esfuerzos), 4),
    "max": round(max(esfuerzos), 4),
    "min": round(min(esfuerzos), 4),
    "std": round(statistics.stdev(esfuerzos), 4) if
        ↪ len(esfuerzos) > 1 else 0,
    "num_rutas": len(esfuerzos)
}

# Export JSON result
output_data = {
    "valor_indicador": stats["media"],
```

```
    "ciudad": ciudad,
    "tipo_perimetro": "clean",
    "indicador": indicador,
    "unidad": "media del esfuerzo normalizado por ruta",
    "estadisticas": stats,
    "porcentaje_por_pendiente": porcentajes,
    "distancias_raw": dist_pendiente,
    "total_distancia_evaluada": total_dist,
    "timestamp": datetime.now().isoformat()
}
json_path = os.path.join(folder, f"{ciudad}_indicador_{indicador}_clean.json")
with open(json_path, "w") as f:
    json.dump(output_data, f, indent=4)

# Histogram
plt.figure(figsize=(8, 4))
plt.hist(esfuerzos, bins=20, color="#e31a1c", edgecolor="black", alpha=0.85)
plt.xlabel("Esfuerzo normalizado por pendiente (0 = llano, >1 = subida exigente)")
plt.ylabel("N mero de rutas")
plt.title(f"Distribuci n del esfuerzo por pendiente - {ciudad.capitalize()}")
plt.grid(True)
plt.tight_layout()
plt_path = os.path.join(folder, "histograma_esfuerzo.png")
plt.savefig(plt_path)

# Add slope legend to map
legend_html = """{% macro html(this, kwargs) %}
<div style="position: fixed; bottom: 40px; left: 40px; width: 200px;
background-color: white; border:2px solid grey; z-index:9999;
font-size:14px; padding: 10px; border-radius: 8px;">
<b>Slope category</b><br><div style='margin-top: 5px'>
<i style="background: #dddddd; width: 18px; height: 10px; float: left;
margin-right: 6px; opacity: 0.85"></i> 0 1 % (flat)<br>
<i style="background: #4daf4a; width: 18px; height: 10px; float: left;
margin-right: 6px; opacity: 0.85"></i> 1 4 % (mild)<br>
<i style="background: #ffb700; width: 18px; height: 10px; float: left;
margin-right: 6px; opacity: 0.85"></i> 4 7 % (moderate)<br>
<i style="background: #ff7f00; width: 18px; height: 10px; float: left;
margin-right: 6px; opacity: 0.85"></i> 7 10 % (strong)<br>
```

```
<i style="background: #e31a1c; width: 18px; height: 10px; float:
    ↪ left;
margin-right: 6px; opacity: 0.85"></i> 10  16  % (very strong)<br>
<i style="background: #99000d; width: 18px; height: 10px; float:
    ↪ left;
margin-right: 6px; opacity: 0.85"></i> >16%
    ↪ (extreme)</div></div>{% endmacro %}"""

macro = MacroElement()
macro._template = Template(legend_html)
m.get_root().add_child(macro)

# Save map
map_path = os.path.join(folder,
    ↪ f"{ciudad}_mapa_{indicador}_clean.html")
m.save(map_path)

# Export table
orden = ["0-1% (llano)", "1-4% (leve)", "4-7% (moderada)", "7-10%
    ↪ (fuerte)",
         "10-16% (muy fuerte)", ">16% (extrema)"]
row = {
    "ciudad": ciudad,
    "valor_indicador": stats["media"],
    "mediana": stats["mediana"],
    "desviacion_tipica": stats["std"],
    "minimo": stats["min"],
    "maximo": stats["max"]
}
for label in orden:
    row[f"% {label}"] = porcentajes.get(label, 0)
df = pd.DataFrame([row])
df.to_excel(os.path.join(folder,
    ↪ f"{ciudad}_indicador_{indicador}.xlsx"), index=False)
```

Listing A.9: Calculation of slope effort indicator using steepness categories and route geometry

A.10 Indicator 3b: Visualisation of Yearly Weather Conditions

```
year = 2022
if year in resumen.index:
    df = data[data['year'] == year]
    fig, ax1 = plt.subplots(figsize=(16,6))
```

```
    # Main time series
    l1 = ax1.plot(df.index, df['tmax'], color='red', label='Max.
        ↪ temperature')
    l2 = ax1.plot(df.index, df['tmin'], color='blue', label='Min.
        ↪ temperature')
    ax2 = ax1.twinx()
    l3 = ax2.bar(df.index, df['prcp'], color='gray', width=1.0,
        ↪ alpha=0.5, label='Precipitation')

    # Threshold lines
    l4 = ax1.axhline(0, color='blue', linestyle='--', alpha=0.6,
        ↪ label='Cold threshold (0   C   )')
    l5 = ax1.axhline(35, color='red', linestyle='--', alpha=0.6,
        ↪ label='Heat threshold (35   C   )')
    l6 = ax2.axhline(2, color='gray', linestyle='--', alpha=0.6,
        ↪ label='Rain threshold (2 mm)')

    # Mark extreme days
    l7 = ax1.scatter(df.index[df['frio']], [0]*df['frio'].sum(),
        ↪ color='black', s=30, label='Cold day (<    0C    )')
    l8 = ax1.scatter(df.index[df['calor']],
        ↪ [35]*df['calor'].sum(), color='black', s=30, label='Hot
        ↪ day (>    35C    )')
    l9 = ax2.scatter(df.index[df['lluvia']],
        ↪ [2]*df['lluvia'].sum(), color='black', s=30,
        ↪ label='Rainy day (> 2   mm)')

    ax1.set_ylabel("Temperature ( C )")
    ax2.set_ylabel("Precipitation (mm)")
    ax1.set_title(f"{ciudad.capitalize()} - Weather conditions in
        ↪ {year}")
    fig.tight_layout()

    # Ordered legend
    handles = [
        l1[0], l2[0], l3, l4, l5, l6, l7, l8, l9
    ]
    labels = [h.get_label() for h in handles]
    ax1.legend(handles, labels, loc='upper left')

    plt.savefig(os.path.join(graficos_folder,
        ↪ f"{ciudad}_climate_{year}.png"), dpi=300)
    plt.close(); print(f"          Graph saved:
        ↪ {ciudad}_climate_{year}.png")
else:
    print(f"       Year {year} does not have valid data.")
```

Listing A.10: Visualisation of cold, hot and rainy days for a specific year

A.11 Indicator 4b: Cycling Suitability Index Along Urban Routes

```
import os, json, folium
from datetime import datetime
from branca.colormap import LinearColormap
import pandas as pd

indicador = "4b_zonas_calmadas"
folder_out = os.path.join(output_base, "4_seguridad_vial",
    ↪ indicador)
os.makedirs(folder_out, exist_ok=True)

with open(os.path.join(output_base, "0_base", "0b_rutas",
    ↪ f"{ciudad}_rutas.json")) as f:
    rutas = json.load(f)
with open(os.path.join(output_base, "0_base", "0a_perimetros",
    ↪ f"{ciudad}_clean_points.json")) as f:
    puntos = json.load(f)
perimetro_path = os.path.join(output_base, "0_base",
    ↪ "0a_perimetros", f"{ciudad}_clean_perimeter.geojson")

m = folium.Map(location=city_center, zoom_start=12,
    ↪ tiles="cartodbpositron")
for p in puntos:
    folium.CircleMarker(location=(p[1], p[0]), radius=4,
        ↪ color="red", fill=True).add_to(m)
folium.Marker(location=city_center,
    ↪ icon=folium.Icon(color="green"), popup="Centro").add_to(m)
folium.GeoJson(perimetro_path, style_function=lambda _: {"color":
    ↪ "black", "weight": 2}).add_to(m)

colormap = LinearColormap(
    colors=['#440154', '#3b528b', '#21918c', '#5ec962',
        ↪ '#fde725'],
    vmin=0.4, vmax=1.0,
    caption="Adequacy for cycling (suitability)"
)
colormap.add_to(m)

peso_total, suma_ponderada, n_segmentos = 0, 0, 0
rangos = {f"[{i/10:.1f}-{(i+1)/10:.1f})": 0 for i in range(0, 10)}

for r in rutas:
    coords = r["route"]
    for i0, i1, raw in r.get("suitability", []):
        if i1 <= i0 or i1 >= len(coords): continue
```

```
        score = raw / 10
        seg_len = i1 - i0
        peso_total += seg_len
        suma_ponderada += score * seg_len
        n_segmentos += 1
        folium.PolyLine(coords[i0:i1+1], color=colormap(score), weight=2.5, opacity=0.8,
                        tooltip=f"{score:.2f}").add_to(m)

        bin_idx = int(score * 10)
        key = f"[{bin_idx/10:.1f}-{(bin_idx+1)/10:.1f})" if bin_idx < 10 else "[1.0]"
        rangos.setdefault(key, 0)
        rangos[key] += seg_len

res = {
    "ciudad": ciudad,
    "indicador": indicador,
    "unidad": "valor entre 0 y 1",
    "descripcion": " ndice  medio de adecuaci n ciclista (media ponderada del suitability en rutas urbanas).",
    "valor_indicador": round(suma_ponderada / peso_total, 4) if peso_total else 0,
    "total_segmentos": n_segmentos,
    "peso_total": peso_total,
    "desglose_por_rango": {k: round(v, 2) for k, v in sorted(rangos.items())},
    "timestamp": datetime.now().isoformat()
}

with open(os.path.join(folder_out, f"{ciudad}_indicador_{indicador}.json"), "w") as f:
    json.dump(res, f, indent=4)

m.save(os.path.join(folder_out, f"{ciudad}_mapa_{indicador}.html"))

print(f"    Indicador 4b completado para {ciudad}     Valor: {res['valor_indicador']:.4f}")

# Export to Excel
row = {
    "ciudad": ciudad,
    "valor_indicador": res["valor_indicador"],
    "segmentos_analizados": peso_total
}
for k in sorted(res["desglose_por_rango"].keys(), reverse=True):
    v = res["desglose_por_rango"][k]
    row[k] = round((v / peso_total) * 100, 2) if peso_total else 0
```

```
df = pd.DataFrame([row])
df.to_excel(os.path.join(folder_out,
    ↪ f"{ciudad}_indicador_{indicador}.xlsx"), index=False)
```

Listing A.11: Calculation of cycling suitability index and fine-grained segment breakdown

Bibliography

[1] European Commission. *Urban Mobility and Accessibility*. https://commission.europa.eu/eu-regional-and-urban-development/topics/cities-and-urban-development/priority-themes-eu-cities/urban-mobility-and-accessibility_ro. Accessed on June 28, 2025. 2025.

[2] European Environment Agency. *Sustainability of Europe's Mobility Systems*. https://www.eea.europa.eu/en/analysis/publications/sustainability-of-europes-mobility-systems. Accessed on June 28, 2025. 2023.

[3] EU Urban Mobility Observatory. *Cycling to work on the rise in the Netherlands: 57% increase in one year*. https://urban-mobility-observatory.transport.ec.europa.eu/news-events/news/cycling-work-rise-netherlands-57-increase-one-year-2025-06-02_en. Accessed on June 28, 2025. 2025.

[4] European Cyclists' Federation. *European cities are improving cycling for citizens*. https://www.ecf.com/en/news/european-cities-are-improving-cycling-for-citizens/. Accessed on June 28, 2025. 2025.

[5] Cycling Industry News. *Netherlands further builds on cycling's modal share, hitting 51% in Utrecht*. Accessed: 2025-07-06. 2024. URL: https://cyclingindustry.news/netherlands-further-builds-on-cyclings-modal-share-hitting-51-in-utrecht/.

[6] João Monteiro et al. "The Potential Impact of Cycling on Urban Transport Energy and Modal Share: A GIS-Based Methodology". In: *ISPRS International Journal of Geo-Information* 12 (Feb. 2023). DOI: 10.3390/ijgi12020048.

[7] Copenhagenize Design Co. *Our Methodology*. https://copenhagenizeindex.eu/about/methodology/. Accedido el 28 de junio de 2025. 2025.

[8] European Commission. *Sustainable Transport*. https://transport.ec.europa.eu/transport-themes/sustainable-transport_en. Accessed on June 28, 2025. 2025.

[9] European Commission. *Transport and the Green Deal.* https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal/transport-and-green-deal_en. Accessed on June 28, 2025. 2025.

[10] European Environment Agency. *Availability of bike sharing systems in European cities – intensity of use.* https://www.eea.europa.eu/en/circularity/sectoral-modules/product-lifespans/availability-of-bike-sharing-systems-in-european-cities-intensity-of-use. Accessed on June 28, 2025. 2025.

[11] ISINNOVA and Vèlo Mondial. *The Wheels of Change: Riding Europe's Commitment to Cycling for Sustainable Change with an International Cycling Community of Practice.* PDF report. Accessed on June 28, 2025. 2023.

[12] PeopleForBikes. *There's Already Record Funding for Bikes in 2023.* https://www.peopleforbikes.org/news/theres-already-record-funding-for-bikes-in-2023. Accessed on June 28, 2025. 2023.

[13] Urban Land Institute. *Trends in Transportation and Real Estate.* https://urbanland.uli.org/infrastructure-transit/trends-transportation-real-estate. Accessed on June 28, 2025. 2025.

[14] German Federal Ministry for the Environment. *Transport and Climate Change: Global Status Report 2018.* https://www.changing-transport.org/wp-content/uploads/2018_TCC_GSR.pdf. Accessed on June 28, 2025. 2018.

[15] PeopleForBikes. *About the City Ratings Methodology.* https://cityratings.peopleforbikes.org/about/methodology. Accedido el 28 de junio de 2025. 2025.

[16] EU Urban Mobility Observatory. *Utrecht named most bike-friendly city 2022.* https://urban-mobility-observatory.transport.ec.europa.eu/news-events/news/utrecht-named-most-bike-friendly-city-2022-2022-09-12_en. Accedido el 28 de junio de 2025. 2022.

[17] Getsafe. *Getsafe acquires Luko portfolio.* https://www.hellogetsafe.com/en-de/posts/getsafe-acquires-luko-portfolio. Accedido el 28 de junio de 2025. 2025.

[18] Meghan Winters et al. "Mapping bikeability: A spatial tool to support sustainable travel". In: *Environment and Planning B Planning and Design* 40 (Sept. 2013), pp. 865–883. DOI: 10.1068/b38185.

[19] Michael Hardinghaus. "Exploring Bikeability - Urban Infrastructure and Bicycle Transport". PhD thesis. Jan. 2021.

[20] Simone Weikl and Patricia Mayer. "Data-driven quality assessment of cycling networks". In: *Frontiers in Future Transportation* 4 (Mar. 2023). DOI: 10.3389/ffutr.2023.1127742.

[21] Julia Griswold et al. "A behavioral modeling approach to bicycle level of service". In: *Transportation Research Part A: Policy and Practice* 116 (Oct. 2018), pp. 166–177. DOI: 10.1016/j.tra.2018.06.006.

[22] Debra Kellstedt et al. "A Scoping Review of Bikeability Assessment Methods". In: *Journal of Community Health* 46 (Feb. 2021). DOI: 10.1007/s10900-020-00846-4.

[23] OpenRouteService. *OpenRouteService Directions API - Documentation*. Available at https://openrouteservice.org/dev/#/api-docs. Accessed June 2025. 2024.

[24] OECD, European Union, and European Commission Joint Research Centre. *Handbook on Constructing Composite Indicators: Methodology and User Guide*. Paris: OECD Publishing, 2008. DOI: 10.1787/9789264043466-en. URL: https://doi.org/10.1787/9789264043466-en.

[25] Kurniawan Hartanto et al. "Developing a bikeability index in the context of transit-oriented development (TOD)." In: July 2017.

[26] Tufail Ahmed et al. "Micro-Level Bicycle Infrastructure Design Elements: A Framework for Developing a Bikeability Index for Urban Areas". In: *Smart Cities* 8 (Mar. 2025), p. 46. DOI: 10.3390/smartcities8020046.

[27] Jessica Schoner and David Levinson. "The missing link: bicycle infrastructure networks and ridership in 74 US cities". In: *Transportation* 41 (Nov. 2014), pp. 1187–1204. DOI: 10.1007/s11116-014-9538-1.

[28] BWB Consulting. *The Truth About Cycle Lanes: Investment, Impact and Public Perception*. https://www.bwbconsulting.com/insights/the-truth-about-cycle-lanes-investment-impact-and-public-perception/. Accessed on June 28, 2025. 2023.

[29] Tufail Ahmed et al. "Bicycle Infrastructure Design Principles in Urban Bikeability Indices: A Systematic Review". In: *Sustainability* 16.6 (2024). ISSN: 2071-1050. DOI: 10.3390/su16062545. URL: https://www.mdpi.com/2071-1050/16/6/2545.

[30] Valerian Kwigizile, Jun-Seok Oh, and Sia M. Lyimo. *Investigating and Prioritizing Factors for Quantifying Bikeability*. Technical Report TRCLC 2018-02. United States Department of Transportation. University Transportation Centers Program, Published: 2019-08-31. Western Michigan University. Transportation Research Center for Livable Communities, 2019. URL: https://rosap.ntl.bts.gov/view/dot/62328.

[31] Abdallah Al-Hamdan et al. "Weighting Variables for Transportation Assets Condition Indices Using Subjective Data Framework". In: *CivilEng* 5 (Oct. 2024), pp. 949–970. DOI: 10.3390/civileng5040048.

[32] Transport Scotland. *Literature Review: Best Practice in Active Travel and its Associated Benefits*. https://www.transport.gov.scot/publication/literature-review-best-practice-in-active-travel-and-its-associated-benefits/. Accessed on June 28, 2025. 2020.

[33] Hong Yan, Kees Maat, and Bert van Wee. "Cycling Speed and Weather: Roles of Cyclist Weather-Sensitivity, Spatial and Infrastructural Conditions". In: *SSRN Electronic Journal* (2024). Accessed on June 28, 2025. DOI: 10.2139/ssrn.5052377. URL: https://ssrn.com/abstract=5052377.

[34] Meghan Winters et al. "Safe Cycling: How Do Risk Perceptions Compare With Observed Risk?" In: *Canadian journal of public health. Revue canadienne de santé publique* 103 (Dec. 2012), S42–S47. DOI: 10.1007/BF03403834.

[35] Alberto Castro, Sonja Kahlmeier, and Thomas Gotschi. *Exposure-Adjusted Road Fatality Rates for Cycling and Walking in European Countries*. International Transport Forum Discussion Papers 2018/05. Paris: OECD Publishing, 2018. DOI: 10.1787/fd022267-en. URL: https://doi.org/10.1787/fd022267-en.

[36] Stefan Fuest et al. "I bet you feel safe! assessing cyclists' subjective safety by objective scores". In: *Journal of Urban Mobility* 4 (Dec. 2023), p. 100066. DOI: 10.1016/j.urbmob.2023.100066.

[37] IBM. *Modified z score*. https://www.ibm.com/docs/en/cognos-analytics/12.0.0?topic=terms-modified-z-score. Accessed on June 28, 2025. 2025.

[38] Copernicus. *Copernicus Data Visualization Tool*. Available at https://land.copernicus.eu/en/map-viewer. Accessed June 2025. 2022.

[39] Eurostat. *Methodological Manual on Territorial Typologies*. Available at https://ec.europa.eu/eurostat/web/gisco/geodata/statistical-units/local-administrative-units. 2023.

[40] Copernicus. *Global Human Settlement Layer (GHSL) - Population Grid Download Portal*. Available at https://human-settlement.emergency.copernicus.eu/download.php. Accessed June 2025. 2024.

[41] Martino Pesaresi et al. "Advances on the Global Human Settlement Layer by joint assessment of Earth Observation and population survey data". In: *International Journal of Digital Earth* 17.1 (2024), p. 2390454. DOI: 10.1080/17538947.2024.2390454. eprint: https://doi.org/10.1080/17538947.2024.2390454. URL: https://doi.org/10.1080/17538947.2024.2390454.

[42] Sergio Freire et al. "Development of new open and free multi-temporal global population grids at 250 m resolution". In: June 2016.

[43] Lewis Dijkstra, Hugo Poelman, and Paolo Veneri. *The EU-OECD definition of a functional urban area.* OECD Regional Development Working Papers 2019/11. Accessed June 2025. Paris: OECD Publishing, 2019. DOI: 10.1787/d58cb34d-en. URL: https://doi.org/10.1787/d58cb34d-en.

[44] Eurostat. *Territorial typologies manual.* Available at https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Territorial_typologies_manual. 2023.

[45] Shlomo Angel et al. "The Dynamics of Global Urban Expansion". In: (Jan. 2005).

[46] Pengjun Zhao, Dandan Yuan, and Yixue Zhang. "The Public Bicycle as a Feeder Mode for Metro Commuters in the Megacity Beijing: Travel Behavior, Route Environment, and Socioeconomic Factors". In: *Journal of Urban Planning and Development* 148.1 (2022), p. 04021064. DOI: 10.1061/(ASCE)UP.1943-5444.0000785. eprint: https://ascelibrary.org/doi/pdf/10.1061/%28ASCE%29UP.1943-5444.0000785. URL: https://ascelibrary.org/doi/abs/10.1061/%28ASCE%29UP.1943-5444.0000785.

[47] David Boyce. "Urban Transit: Operations, Planning, and Economics, edited by Vukan R. Vuchic". In: *Journal of Regional Science - J REG SCI* 46 (Aug. 2006), pp. 566–568. DOI: 10.1111/j.1467-9787.2006.00453_2.x.

[48] OpenRouteService. *OpenRouteService – Directions Tool.* Available at: https://classic-maps.openrouteservice.org/directions. Accessed June 2025. 2024.

[49] Muki Haklay. "How good is OpenStreetMap information? A comparative study of OpenStreetMap and Ordnance Survey datasets for London and the rest of England". In: *Environment and Planning B: Planning and Design* 37 (July 2010), pp. 682–703. DOI: 10.1068/b35097.

[50] Lawrence Frank et al. "Linking Objectively Measured Physical Activity with Objectively Measured Urban Form. Findings from SMARTRAQ". In: *American journal of preventive medicine* 28 (Feb. 2005), pp. 117–25. DOI: 10.1016/j.amepre.2004.11.001.

[51] Jan Gehl. *Life Between Buildings: Using Public Space.* 6th ed. Washington, D.C.: Island Press, 2011. ISBN: 9781597268271.

[52] John Parkin. "Infrastructure and cycling". In: *Encyclopedia of Sustainable Technologies* 4 (2018), pp. 319–326.

[53] Caroline Mulvaney et al. "Cycling infrastructure for reducing cycling injuries in cyclists". In: *Cochrane database of systematic reviews (Online)* 2015 (Dec. 2015). DOI: `10.1002/14651858.CD010415.pub2`.

[54] OpenRouteService. *Way Types — Extra Info | OpenRouteService API Reference*. `https://giscience.github.io/openrouteservice/api-reference/endpoints/directions/extra-info/waytype`. Accessed June 2025. 2024.

[55] OpenStreetMap Wiki. *Key:cycleway — OpenStreetMap Wiki*. [Online; accessed 13-June-2025]. 2025. URL: `%5Curl%7Bhttps://wiki.openstreetmap.org/w/index.php?title=Key:cycleway%5C&oldid=2846922%7D`.

[56] OpenStreetMap Wiki. *Path examples — OpenStreetMap Wiki*. [Online; accessed 13-June-2025]. 2024. URL: `%5Curl%7Bhttps://wiki.openstreetmap.org/w/index.php?title=Path_examples%5C&oldid=2731097%7D`.

[57] OpenStreetMap Wiki. *Tag:highway=footway — OpenStreetMap Wiki*. [Online; accessed 13-June-2025]. 2025. URL: `%5Curl%7Bhttps://wiki.openstreetmap.org/w/index.php?title=Tag:highway%3Dfootway%5C&oldid=2848736%7D`.

[58] OpenStreetMap Wiki. *Tag:highway=cycleway — OpenStreetMap Wiki*. [Online; accessed 13-June-2025]. 2025. URL: `%5Curl%7Bhttps://wiki.openstreetmap.org/w/index.php?title=Tag:highway%3Dcycleway%5C&oldid=2827949%7D`.

[59] John Pucher and Ralph Buehler. "Safer Cycling Through Improved Infrastructure". In: *American Journal of Public Health* 106 (Dec. 2016), pp. 2089–2091. DOI: `10.2105/AJPH.2016.303507`.

[60] Meghan Winters et al. "Motivators and deterrents of bicycling: Comparing influences on decisions to ride". In: *Transportation* 38 (Nov. 2010), pp. 153–168. DOI: `10.1007/s11116-010-9284-y`.

[61] Kevin Krizek and Pamela Jo Johnson. "Proximity to Trails and Retail: Effects on Urban Cycling and Walking". In: *Journal of the American Planning Association* 72 (Mar. 2006), pp. 33–42. DOI: `10.1080/01944360608976722`.

[62] Otis Dudley Duncan and Beverly Duncan. "A Methodological Analysis of Segregation Indexes". In: *American Sociological Review* 20.2 (1955), pp. 210–217. DOI: `10.2307/2088328`. URL: `https://doi.org/10.2307/2088328`.

[63] Elliot Fishman. "Bikeshare: A Review of Recent Literature". In: *Transport Reviews* 36 (Apr. 2015). DOI: `10.1080/01441647.2015.1033036`.

[64] Susan Shaheen, Stacey Guzman, and Hua Zhang. "Bikesharing in Europe, the Americas, and Asia: Past, Present, and Future". In: *Institute of Transportation Studies, UC Davis, Institute of Transportation Studies, Working Paper Series* 2143 (Jan. 2010). DOI: `10.3141/2143-20`.

[65] Clink Hostels. *Cycling in Amsterdam: All You Need to Know*. Accessed: 2025-06-28. 2024. URL: `https://www.clinkhostels.com/city-tips/cycling-in-amsterdam/`.

[66] Alfredo Valenzuela et al. "Geospatial indicators of bikeability index as cycle-friendly city design: a systematic review". In: *Revista Brasileira de Atividade Física & Saúde* 27 (July 2022), p. 12. DOI: `10.12820/rbafs.27e0255`.

[67] Sylwia Pazdan. "The impact of weather on bicycle risk exposure". In: *Archives of Transport* 56 (Dec. 2020), pp. 89–105. DOI: `10.5604/01.3001.0014.5629`.

[68] Christopher Kane and Stefanos Kythreotis. "Relationships Between Weather and Cycling". In: *Liikenne-vuosikirja* 6 (Feb. 2024). DOI: `10.58956/liikenne.142999`.

[69] European Climate Assessment & Dataset (ECA&D). *E-OBS Gridded Dataset - Ensembles Download Page*. Accessed June 2025. 2024. URL: `https://www.ecad.eu/download/ensembles/download.php` (visited on 06/14/2025).

[70] OpenRouteService. *Extra Information: Suitability — OpenRouteService Directions API*. Accessed June 2025. 2024. URL: `https://giscience.github.io/openrouteservice/api-reference/endpoints/directions/extra-info/` (visited on 06/15/2025).

[71] GIScience Heidelberg. *OpenRouteService Documentation GitHub Repository*. `https://github.com/GIScience/openrouteservice-docs`. Accessed June 2025. 2024.

[72] OpenRouteService Forum. *Suitability parameter not explained*. Accessed: 2025-06-26. 2021. URL: `https://ask.openrouteservice.org/t/suitability-paramaeter-not-explained/1115`.

[73] OpenRouteService Forum. *Extra info for directions*. Accessed: 2025-06-26. 2022. URL: `https://ask.openrouteservice.org/t/extra-info-for-directions/1954`.

[74] Wikipedia contributors. *Cycling in Amsterdam — Wikipedia, The Free Encyclopedia*. [Online; accessed 3-July-2025]. 2025. URL: `https://en.wikipedia.org/w/index.php?title=Cycling_in_Amsterdam&oldid=1296352845`.

[75] I amsterdam. *Cycling Facts and Figures*. https://web.archive.org/web/20140512214416/http://www.iamsterdam.com/en-GB/Media-Centre/city-hall/dossier-cycling/Cycling-facts-and-figures. Accessed on June 28, 2025 (archived version). 2014.

[76] Juliette Gache. *Paris Is Becoming a Cycling City, for Better or Worse*. https://www.cntraveler.com/story/biking-cycling-in-paris-france. Accessed on June 28, 2025. 2024.