AALBORG UNIVERSITET

Mapping Urban Readiness of Cycling Infrastructure with Open Data: A Spatial Framework

Andrea Niccolò Mantegna

SPLM - 10th Semester
February 2026

ALBORG UNIVERSITE

Abstract

This thesis develops and applies a spatial diagnostic framework to assess the structural readiness of urban cycling infrastructure to support different cycling vehicle profiles, with a particular focus on the physical feasibility of cargo-bike use. Rather than modelling cycling demand, route choice, or logistics performance, the framework evaluates whether existing cycling infrastructure provides the minimum physical and geometric conditions required for different types of bicycles to operate reliably. In this context, cargo bikes are treated as a stricter feasibility case, reflecting their higher requirements in terms of width, surface quality, continuity, and terrain.

Building on established GIS-based bikeability methodologies, the proposed Cycling Readiness framework evaluates standard bicycles and cargo bikes in parallel on a shared cycling infrastructure network using a common set of infrastructure and terrain indicators derived from open data sources. Profile differentiation is implemented exclusively through stricter feasibility thresholds applied to the cargo-bike profile, while indicators, weights, spatial units, and aggregation logic remain identical across profiles. Differences between commuter and cargo-bike readiness are therefore interpreted as indicators of structural robustness and fragility within existing cycling networks, rather than as differences in user preference or behavioural tolerance.

The methodology relies exclusively on open and transferable datasets and applies conservative, median-based spatial aggregation to a regular 50 m hexagonal grid to support city-scale interpretation while avoiding inflation effects associated with dense but fragmented infrastructure. Multiple European cities are analysed as comparative case studies to examine how cycling infrastructure readiness patterns change under stricter feasibility requirements, independent of routing assumptions or demand modelling.

Results are presented as spatial readiness maps and cross-city comparative patterns, highlighting locations where cycling networks that appear adequate for standard commuter use become structurally constrained under cargo-bike requirements. The framework is intended as an early-stage planning and benchmarking tool to support diagnostic assessment and strategic prioritisation of cycling infrastructure, rather than as a predictive model of cycling uptake or urban freight activity.

1. Introduction

1.1 Motivation of the Study

Urban freight and everyday mobility are increasingly central to the transition toward low-carbon cities. A significant share of urban freight activity consists of short-distance deliveries that are technically suitable for cargo bikes and other light electric vehicles, with well-documented benefits in terms of emissions reduction, congestion mitigation, and urban liveability (Gruber et al., 2014; Schliwa et al., 2015; C40 Cities, 2023). As a result, cargo bikes are moving from niche applications toward a more prominent role in urban transport systems.

At the same time, cycling infrastructure in most cities has developed incrementally and primarily to support standard commuter cycling. While this infrastructure has enabled growth in everyday bicycle use, it has rarely been assessed in relation to the physical and operational demands associated with freight-oriented cycling. The increasing diversity of cycling vehicles therefore raises questions about whether existing networks are capable of supporting new uses without substantial structural adaptation. These questions are particularly relevant in cities with limited technical capacity and constrained data environments.

Many municipalities rely heavily on open data and require assessment tools that are transparent, transferable, and feasible to apply without extensive local calibration. In such contexts, methods that depend on proprietary datasets, detailed behavioural modelling, or complex assumptions are difficult to operationalise and risk remaining disconnected from planning practice.

Against this background, there is a growing need for spatial approaches that can help cities understand how well their existing cycling infrastructure aligns with emerging mobility demands. Assessing the structural readiness of cycling networks provides a basis for informed discussion about prioritisation, robustness, and long-term adaptability within constrained urban environments.

1.2 Problem Statement

Despite the growing relevance of cargo bikes and cycle logistics in sustainable mobility strategies, most spatial assessment tools remain calibrated to standard commuter cycling. These tools typically evaluate cycling environments through comfort, stress, or perceived safety indicators and therefore provide limited insight into whether existing infrastructure is physically capable of supporting more demanding cycling vehicles.

As a result, cycling networks that appear adequate under conventional bikeability assessments may still exhibi geometric, surface, or continuity constraints that limit or prevent cargo-bike operation. The absence of explicit feasibility-oriented evaluation makes it difficult to distinguish between infrastructure that is acceptable for commuter use and infrastructure that remains structurally robust under increased physical requirements.

Existing cycle-logistics frameworks and benchmarking tools largely operate at a qualitative or descriptive level. While valuable for policy comparison and advocacy, they lack a network-based spatial methodology, explicit data requirements, and systematic links to street-level infrastructural conditions. Consequently, they offer limited support for identifying where cargo bikes can realistically operate within existing cycling networks or where infrastructural limitations constitute hard constraints.

This situation leaves planners without a reproducible, spatially explicit, and data-driven method to assess cargo-bike feasibility using widely available datasets. Without such a method, decisions about infrastructure prioritisation and adaptation risk being based on incomplete or commuter-biased representations of cycling readiness.

1.3 Research Objectives

O1. Conceptual and methodological contribution
To define and operationalise the physical, geometric, and terrain-related conditions that distinguish cycling infrastructure suitable for standard bicycle use from infrastructure that remains feasible under cargo-bike requirements, using a reproducible, network-based spatial framework based exclusively on open data.

O2. Empirical and analytical objective
To apply the framework across multiple urban contexts in order to test its transferability, identify spatial mismatches between standard bicycle readiness and cargo-bike readiness, and demonstrate how these mismatches can support early-stage planning prioritisation for everyday cycling and cycle logistics.

1.4 Research Questions

"How can open data be used to assess the structural feasibility and robustness of urban cycling infrastructure, distinguishing between networks that remain usable under increased physical requirements and those suited only to standard bicycle use?" (Answered in Chapter 6.1)

RQ1. Which infrastructural, network, and terrain characteristics determine whether cycling infrastructure remains structurally robust under stricter cargo-bike requirements, and how can these be operationalised as spatial indicatorsusing open data? (Answered in Chapter 6.2)

RQ2. Which aspects of cargo-bike feasibility and robustness can be reliably assessed using OpenStreetMap and other open datasets, and where do data limitations impose hard analytical constraints? (Answered in Chapter 6.3)

RQ3. How do feasibility limits and robustness losses manifest spatially across cycling networks when stricter requirements are applied, and how can these patterns support early-stage planning diagnosis for everyday cycling and cycle logistics? (Answered in Chapter 6.4)

1.5 Contribution and Positioning

This thesis contributes to cycling infrastructure assessment by shifting the focus from perceived cycling quality toward structural feasibility. While most GIS-based bikeability studies evaluate cycling environments primarily for standard commuter bicycles, they rarely examine whether existing infrastructure remains operable under stricter physical and geometric requirements associated with cargo bikes and other heavy or wide cycling vehicles.

The proposed framework addresses this gap by evaluating standard bicycles and cargo bikes in parallel on the same cycling infrastructure network, using identical indicators, weights, and spatial aggregation logic. Differences between the two profiles arise exclusively from stricter feasibility thresholds applied to the cargo-bike profile. In this way, cargo bikes function as a structural stress test, revealing robustness margins and latent infrastructural constraints that remain invisible in commuter-oriented assessments.

Rather than introducing new behavioural models, demand forecasts, or operational assumptions, the contribution of this study lies in the methodological recombination and constraint of established spatial assessment techniques. By relying on open data, conservative scoring rules, and diagnostic interpretation, the framework prioritises transparency, transferability, and cross-city comparability. The resulting outputs are intended to support early-stage planning diagnosis and prioritisation, not to predict cycling uptake or optimise logistics operations.

1.6 Scope and Analytical Limits

This study evaluates the structural and spatial readiness of urban cycling infrastructure to support multiple cycling vehicle profiles using a GIS-based, open-data framework. The analysis focuses on whether existing infrastructure meets the minimum physical and geometric conditions required for cycling under different vehicle demands, rather than on how cycling is currently used or perceived.

The framework operationalises readiness through a constrained set of infrastructure and terrain indicators derived from open and transferable datasets. These include infrastructure type, effective rideable width, surface characteristics, longitudinal slope. Indicators are computed at the network-edge level and aggregated spatially to support urban-scale interpretation.

Indicator selection is intentionally limited to variables that can be derived consistently across cities using open data. This choice prioritises reproducibility, transparency, and cross-city comparability over exhaustive representation of cycling conditions. As a result, qualitative factors such as perceived safety, comfort, enforcement, local design standards, and behavioural adaptation fall outside the analytical scope.

The study does not address cycling demand, route choice, traffic interactions, freight operations, infrastructure costs, policy effectiveness, or implementation feasibility. Results are presented as spatial readiness patterns and comparative robustness margins between standard bicycle and cargo-bike profiles. The framework is intended as an early-stage diagnostic and screening tool to support strategic planning and prioritisation, not as a basis for detailed infrastructure design, operational optimisation, or behavioural forecasting.

1.7 Structure of the Document

This thesis is structured as follows. Chapter 1 introduces the research context, motivation, problem statement, objectives, scope and limitations. Chapter 2 reviews relevant literature on cycling assessment, focusing on methodological approaches to bikeability, infrastructure persistence, spatial analysis, vehicle heterogeneity, and opendata-based diagnostics. Chapter 3 presents the conceptual framework supporting the proposed cycling readinessframework. Chapter 4 details the technical methodology and analytical workflow referencing other methods listed in the literature review. Chapter 5 presents the empirical results. Chapter 6 discusses the findings, limitations, and planning implications. Chapter 7 concludes with a summary of contributions and directions for future research.

The diagram illustrates how each chapter of the thesis is connected to each other. Within each dashed hox, representing the main chapter of the thesis, the main elements of each

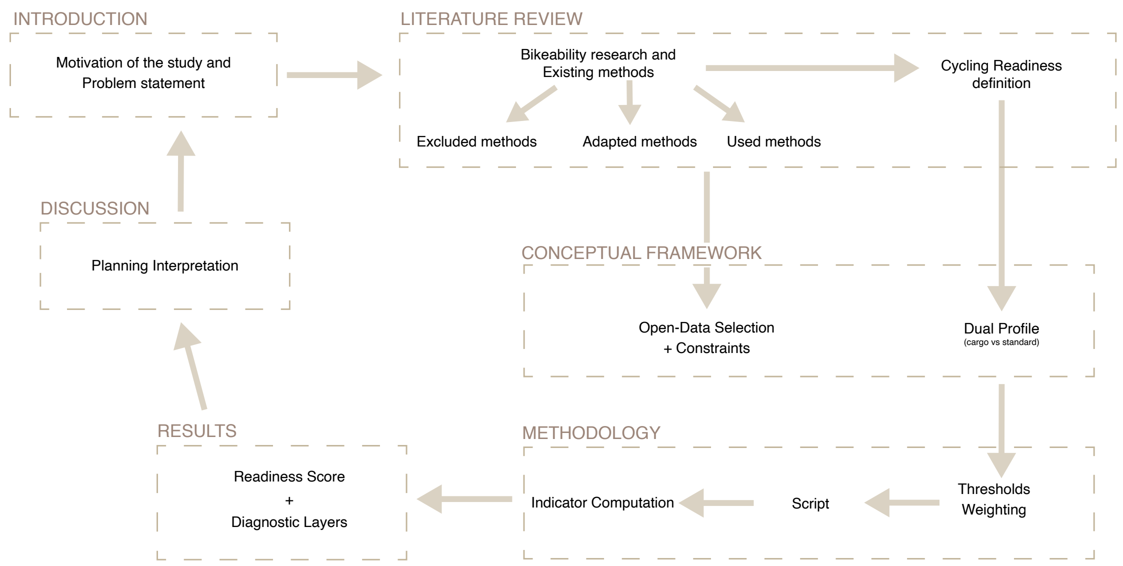


Figure 1: Diagram representing the overall structure of the research project.
Source: Author's own work.

2. Literature Review

The following chapter situates the thesis within existing research on cycling infrastructure with the aim of identifying conceptual and methodological gaps relevant to the assessment of cycling cycling infrastructure readiness. Rather than providing an exhaustive overview of cycling research, the chapter focuses on those strands of literature that directly inform spatial, network-based evaluation of infrastructural feasibility. Section 2.1 introduces the evolution of bikeability concepts and outlines their underlying assumptions, highlighting the limitations of perception- and comfort-oriented frameworks for assessing structural readiness. Section 2.2 discusses infrastructure persistence and path dependency, explaining how inherited street geometries constrain the accommodation of evolving cycling modes and motivate feasibility-oriented analysis. Section 2.3 examines the role of spatial units and analytical scales in cycling assessment, distinguishing between segment-, route-, and network-based approaches and situating the methodological choices adopted in this thesis. Section 2.4 reviews physical and geometric constraints commonly used as indicators in cycling assessment, establishing their relevance as first-order feasibility conditions. Section 2.5 addresses vehicle heterogeneity and introduces cargo bikes as a robustness test for existing cycling infrastructure. Section 2.6 focuses on spatial aggregation and diagnostic mapping approaches, clarifying how edge-level indicators can be synthesised to support urban-scale interpretation without reliance on routing or demand modelling. Section 2.7 discusses the opportunities and limitations of open-data-based cycling assessment, with particular attention to transferability and reproducibility. The chapter concludes with Section 2.8, which situates cycling indices within planning practice and clarifies the diagnostic role of the proposed framework, followed by a synthesis that positions the methodological contribution of the thesis within the reviewed literature.

2.1 From Bikeability to Cycling Readiness

Early research on cycling conditions emerged primarily from concerns about road safety, perceived comfort, and stress in environments dominated by motorised traffic. Within this tradition, bikeability was commonly defined as the extent to which the built environment supports cycling by providing safe, comfortable, and convenient conditions (Winters et al., 2013). Similar formulations emphasised perceived safety, interaction with traffic, and subjective comfort, reflecting the strong influence of transport psychology and safety engineering on early cycling research (Sorton & Walsh, 1994; Landis et al., 1997; Kang et al., 2019). These approaches proved effective for identifying spatial barriers to cycling uptake and informing design assessment at the level of individual road segments.

As bikeability research evolved, a growing body of research tried to operationalise cycling conditions through objective built-environment determinants. Infrastructure type, lane width, traffic volumes, speed differentials, intersection design, and terrain were increasingly incorporated into quantitative assessment tools such as the Bicycle Compatibility Index, Bicycle Level of Service, and related segment-based models (Dixon, 1996; Harkey et al., 1998; Landis et al., 2001; Jensen, 2007). Composite bikeability indices later combined these variables within geospatial frameworks to enable broader spatial comparison across urban areas (Arellana et al., 2020; Castañon & Ribeiro, 2021; Valenzuela et al., 2021).

Despite this methodological progression, most bikeability frameworks still had two limitations. First, **early bikeability indices remained largely segment-centric, assessing cycling conditions as collections of isolated links rather than as interconnected networks** (Dixon, 1996; Landis et al., 2001; Jensen, 2007). Second, **their calibration implicitly reflected the physical characteristics and tolerance thresholds of standard commuter bicycles. Even when objective indicators were used, feasibility was typically interpreted through proxies of comfort, stress, or acceptability rather than through explicit physical constraints** (Sorton & Walsh, 1994; Winters et al., 2013; Dill & McNeil, 2016; Arellana et al., 2020).As a result, infrastructure could be classified as "bikeable" while still exhibiting geometric or surface conditions that limit its usability for more demanding cycling profiles.

These limitations motivated a shift toward more structural and network-oriented approaches. Frameworks such as Levels of Traffic Stress introduced network-wide classification schemes that moved beyond purely perceptual measures, enabling city-scale representations of cycling conditions (Dill & McNeil, 2016). Related research further demonstrated the importance of cumulative and network-level effects, such as continuity, detours, and terrain, over isolated segment quality (Lowry et al., 2012; Winters et al., 2011). However, even these approaches largely framed cycling suitability in terms of user stress or comfort, rather than explicitly addressing the physical feasibility of infrastructure under varying operational demands.

In response to these conceptual and methodological gaps, this thesis adopts the **concept of cycling readiness**. Cycling readiness is defined here as a structural property of the built environment: the extent to which existing cycling infrastructure meets the minimum physical and geometric conditions required to support cycling as a functional transport mode. Unlike conventional bikeability measures, readiness is not concerned with perceived quality, behavioural preferences, or demand prediction. Instead, **it focuses on infrastructural feasibility, assessed through measurable spatial indicators and evaluated at the network scale**. This reframing provides the conceptual foundation for the feasibility-oriented, GIS-based methodology developed in the following sections.

Table 1 - Types of bikeability indices and their respective roles in the research.
Source: Author's own work.

Concept	Key Aythors	Disciplinary Roots	Research Question	Scale	Unit of Analysis	Indicators	Strenght	Limitations
Bicycle Suitability	Landis et al. (1997, 2001)	Transport psychology, safety engineering	How comfortable/safe is this specific segment?	Micro	Single road segment	Lane presence, surface quality, traffic speed, lateral clearance	High sensitivity to rider experience; useful for design audits	Fragmented view; ignores network continuity and routing logic
Early Bikeability (Perceptual)	Winters et al. (2013); Kang et al. (2019)	Environmental psychology	How safe/pleasant does cycling feel here?	Micro → Local	Segment or short corridor	Perceived risk, stress, comfort, interaction with traffic	Captures subjective barriers to cycling uptake	Low reproducibility; limited policy transferability
Segment-Based LOS Tools (BLOS, BCI, BSIR)	HCM (TRB); Sorton & Walsh (1994)	Traffic engineering	How well does this road perform for cycling?	Micro	Road segment	Traffic volume, speed, lane width, parking friction	Standardised, comparable, operational, standardised, comparable, operational	Treats cycling as isolated links; ignores route composition
Levels of Traffic Stress (LTS)	Mekuria, Furth & Nixon (2012)	Transport planning	Who can cycle here without stress?	Micro → Network	Road segment (classified)	Separation, speed, lane type, intersection exposure	Bridge between perception and structure; scalable	Still segment-centric; binary thresholds oversimplify logistics needs
Route-Based Bikeability	Lowry et al. (2012); Winters et al. (2011)	GIS & network analysis	How cyclable is a complete trip?	Meso	Origin–destination route	Cumulative stress, detours, slope, intersections	Accounts for real cycling experience	Sensitive to routing assumptions
Network-Based Bikeability	Dill (2004); Xing et al. (2018)	Graph theory, spatial analysis	How supportive is the cycling network as a system?	City-wide	Network graph	Connectivity, density, redundancy, directness	Reveals systemic barriers and gaps	Less intuitive for non-technical stakeholders
Cycling Readiness	Zayed (2016, 2017); Silva et al. (2021)	Urban planning, infrastructure policy	Is the city structurally capable of supporting cycling?	City / District	Network + terrain + policy proxies	Infrastructure completeness, slope distribution, barrier effects	Diagnostic, policy-relevant, future-proof	Does not predict demand or uptake
Bicycle Friendliness	Copenhagenize Index; ECF	Governance, policy studies	How supportive is the city as a whole?	City / Region	Institutional environment	Policies, funding, culture, education	Holistic framing	Weak spatial precision; difficult to operationalise

2.2 Infrastructure Persistence and the Limits of Retrofitting

Urban transport systems evolve through successive changes in needs, regulations, and designs, while the underlying street geometry tends to persist over long time periods. Streets are rarely rebuilt from scratch; instead, new transport modes, such as cargo bikes and light electric vehicles, are accommodated through incremental adaptations of inherited street section. This persistence creates a structural mismatch between rapidly evolving mobility technologies and slowly changing physical infrastructure, a dynamic widely discussed in the literature on path dependency and infrastructure lock-in (Bertolini, 2007; Marshall, 2004; Levinson & King, 2019).

Within this context, cycling infrastructures are often retrofitted into street environments originally designed to prioritise motor vehicle systems. While such adaptations can support basic commuter cycling, they frequently rely on minimum geometries, narrow widths, discontinuous path, or shared-space solutions. These conditions may satisfy conventional bikeability criteria focused on comfort or perceived safety, yet they expose the limits of inherited street design when cycling is required to operate as a functional and scalable transport mode essential for a more sustainable freight system.

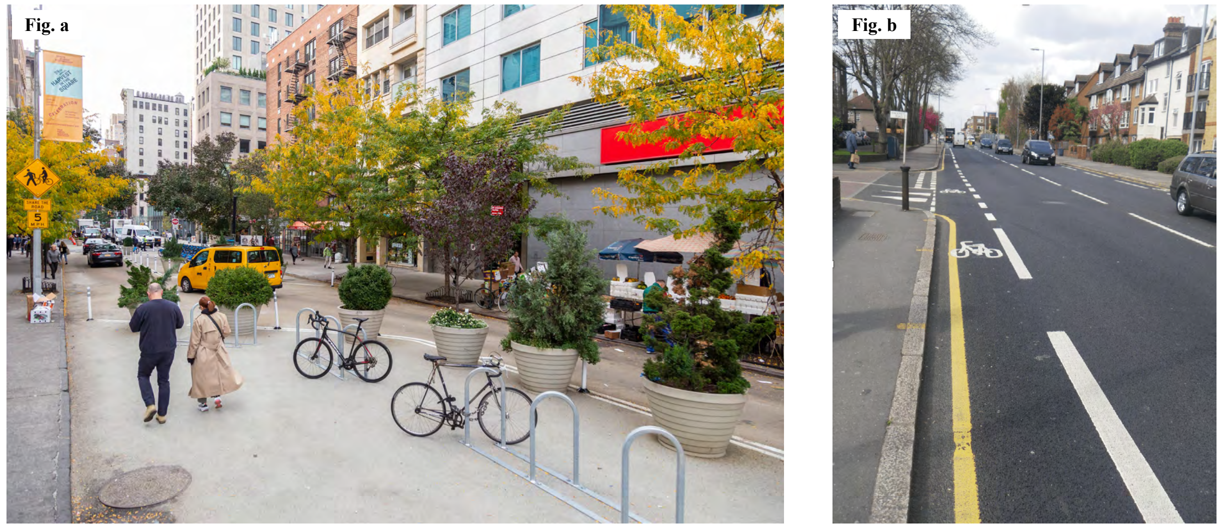


Figure 2: Contrasting approaches to bicycle lane implementation.
(a) Street cross-section reallocated to accommodate multiple transport modes.
(b) Painted bicycle lane inserted into a car-dominated street section.
Source (a): NYC Street Design Manual. Source (b): Reading Cycling Campaign, "Narrow Cycle Lanes", 2020.

The persistence of street geometry becomes particularly important when stricter operational requirements are introduced. Vehicles with larger spatial envelopes, higher loads, or lower manoeuvrability tolerance, such as cargo bikes, are influenced more strongly with geometric constraints related to width, surface quality, slope, and continuity. In this sense, **cargo bikes act as a stress test of existing cycling infrastructure, revealing latent structural limitations that remain obscured when assessment frameworks are calibrated exclusively to standard bicycles**.

This perspective reinforces the need to evaluate cycling infrastructure not only in terms of perceived quality, but in terms of its **structural capacity to accommodate different use profiles within fixed spatial constraints**. By treating street geometry as a persistent boundary condition, cycling readiness assessments can identify where retrofitted networks approach hard feasibility limits and where infrastructural upgrades would require more fundamental spatial reallocation. This framing supports a diagnostic, feasibility-oriented approach to spatial analysis, aligned with early-stage planning and prioritisation rather than detailed design prescription.

2.3 Spatial Units and Analytical Scales in Cycling Assessment

The way cycling conditions are assessed depends fundamentally on the spatial unit and analytical scale at which evaluation is performed. Early cycling assessment tools typically operate at the level of individual road segments, assigning scores based on local attributes such as traffic volume, lane width, or separation from motor vehicles. Segment-based approaches, including *Bicycle Level of Service* and related indices, offer clear and standardised metrics for evaluating isolated links but provide limited insight into how cycling infrastructure functions as a connected system (Dixon, 1996; Landis et al., 2001; Jensen, 2007). From a GIS perspective, these approaches rely on edge-level attribute evaluation but remain analytically local, with limited capacity to capture network-wide structure.

To address these limitations, subsequent research expanded the analytical focus from individual segments to routes and paths. Route-based bikeability studies aggregate conditions along origin–destination paths, accounting for cumulative exposure to stress, detours, intersections, and terrain (Lowry et al., 2012; Winters et al., 2011). In GIS terms, this shift introduces network impedance models and shortest-path algorithms, transforming segment-level scores into route-level costs. While such approaches better reflect experienced cycling conditions, they depend on explicit routing assumptions, origin–destination definitions, and behavioural parameters. As a result, route-based methods embed implicit demand and choice hypotheses, making them sensitive to modelling decisions and less suitable for diagnostic assessments that aim to characterise infrastructure conditions independently of travel behaviour.

More recent GIS-based frameworks adopt a network-oriented perspective, treating cycling infrastructure as an interconnected system rather than as a collection of isolated links or predefined routes. These approaches evaluate properties such as connectivity, continuity, density, and fragmentation across the entire cycling network, enabling city-scale structural diagnostics and cross-city comparison (Dill, 2004; Xing et al., 2018). Network-level analyses often retain edge-based computation but interpret results through spatial aggregation or coverage metrics rather than through routing. The *Levels of Traffic Stress framework* represents a key step in this direction by classifying network segments according to stress thresholds and mapping their spatial distribution across urban areas (Dill & McNeil, 2016). Importantly, LTS operationalises network suitability without requiring explicit origin–destination modelling, making it compatible with diagnostic and planning-oriented GIS workflows.

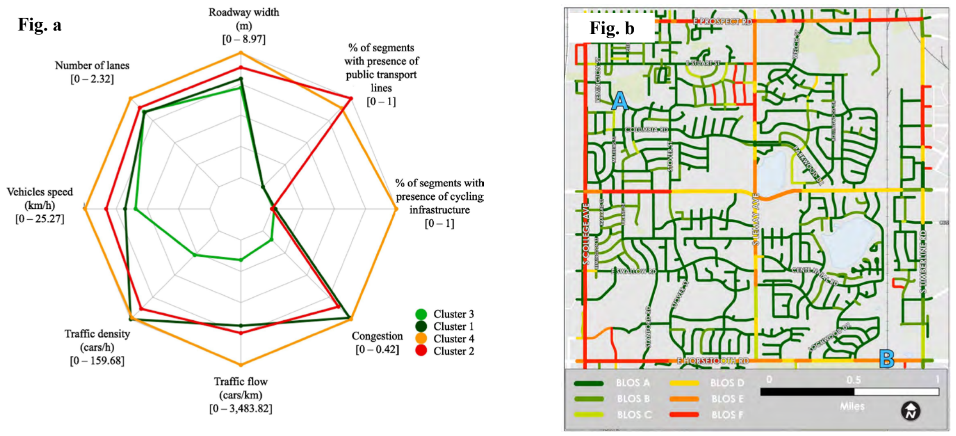


Figure 3: Bicycle Level of Service (BLOS) representations.
(a) Illustrative map showing edge-level results of a BLOS analysis.
(b) Radar plot representing network-level performance across selected criteria.
Source (a): National Institute for Transport and Communities. Source (b): Huertas (2020), "Level of Traffic Stress–Based Classification: A Clustering Approach for Bogotá, Colombia".

Parallel to stress-based classification, several recent bikeability indices explicitly combine edge-level scoring with spatial aggregation into grids or zones to produce interpretable maps of cycling conditions. These GIS-based approaches typically compute standardised scores for each network edge using open data, often derived from OpenStreetMap and terrain models, and then aggregate results using buffers, regular grids, or hexagonal tessellations to reveal spatial patterns (Hardinghaus et al., 2021; Weikl & Mayer, 2023). Aggregation operators such as mean or median values are used to translate network-level information into area-based diagnostics, balancing spatial interpretability with computational robustness.

This thesis builds on the network-based GIS tradition while deliberately avoiding route optimisation and behavioural modelling. Cycling readiness is assessed at the level of network edges, where physical and geometric attributes can be directly observed and measured using open spatial data. Evaluating feasibility at the edge level allows infrastructural constraints to be identified without assuming specific origins, destinations, or routing behaviour. Network-wide patterns are then interpreted through spatial aggregation rather than through route simulation, ensuring that the analysis remains diagnostic rather than predictive.

By distinguishing clearly between segment-based, route-based, and network-based analytical scales, this approach positions cycling readiness as a structural property of the infrastructure network itself. This distinction is particularly important for comparative and transferable GIS-based assessments, where the objective is to identify structural limitations and robustness margins under fixed spatial conditions, rather than to model how cyclists might navigate around those constraints.

2.4 Physical and Geometric Constraints as Cycling Feasibility Indicators

Assessing cycling readiness as a structural property of the built environment requires indicators that describe the physical and geometric conditions under which cycling infrastructure operates. Across the bikeability literature, a broad consensus exists that infrastructure type, effective width, surface characteristics, and terrain exert first-order influence on cycling feasibility, shaping both the usability and functional limits of cycling networks (Dixon, 1996; Landis et al., 2001; Reggiani, 2021).

Infrastructure type is commonly used as a proxy for design intent and its relation with motorised traffic. Segregated cycle tracks, on-street lanes, shared streets, and mixed-traffic roads have different assumptions about user safety, capacity, and operational tolerance. While many bikeability indices treat infrastructure type primarily as a comfort or stress modifier, it also include structural constraints related to available space, continuity, and potential conflicts, making it a fundamental variable for feasibility-oriented assessment (Harkey et al., 1998; Arellana et al., 2020).

Effective rideable width represents a critical geometric constraint that directly limits vehicle stability, manoeuvrability, and passing behaviour. Previous studies have shown that narrow cycling facilities can remain acceptable for standard bicycles while becoming functionally restrictive for wider or longer vehicles (Landis et al., 1997; Jensen, 2007). Despite its importance, width is often treated simplistically or not included entirely in composite indices due to data limitations. When available, however, width provides a direct and measurable indicator of physical feasibility rather than a value of perceived quality.

Surface characteristics further influence cycling feasibility by affecting rolling resistance, comfort, safety, and vehicle control. Informal or low quality surfaces disproportionately affect heavier and less agile vehicles, increasing vibration exposure and reducing operational reliability. Although surface quality is frequently incorporated into bikeability assessments as a comfort factor, its role as a structural constraint becomes more pronounced when cycling is expected to support utilitarian or freight-oriented functions (Castañon & Ribeiro, 2021; Reggiani, 2021).

Terrain and slope, introduces additional physical constraints related to effort, stability, and braking performance. Numerous studies have demonstrated that slope influences route choice and cycling accessibility, especially in hilly environments (Winters et al., 2011; Lowry et al., 2012). From a feasibility perspective, slope acts as a hard constraint when combined with vehicle mass and load, amplifying the importance of gradients for assessing the robustness of cycling infrastructure under different use profiles.

Together, these indicators describe conditions that are directly observable in the physical environment and can be derived consistently from open spatial datasets. By focusing on infrastructure type, width, surface, and slope, the framework prioritises variables that capture minimum operational requirements rather than subjective perceptions from users. This indicator selection supports a feasibility-oriented assessment of cycling readiness, providing a transparent link between measurable spatial attributes and the physical limits of cycling infrastructure at the network scale.

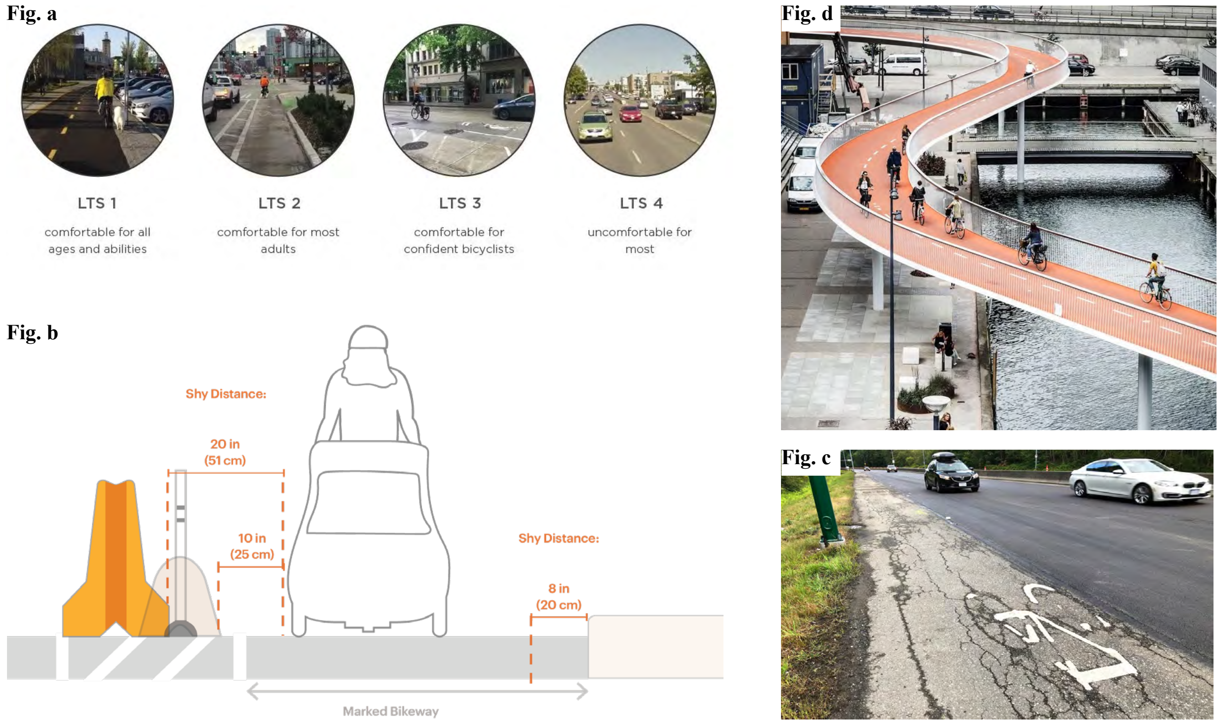


Figure 4: Examples of physical and geometrical constraints affecting cycling infrastructure.
(a) Levels of Traffic Stress (LTS) illustrating cycling infrastructure types based on separation from motorised traffic.
(b) Design guidance indicating recommended rideable width for cargo bikes.
(c) Difference in surface maintenance quality between motor vehicle lanes and bicycle lanes.
(d) Example of slope mitigation through graded cycling infrastructure.
Source (a): Alta (2017), "Level of Traffic Stress—What It Means for Building Better Bike Networks".
Source (b): NACTO, Urban Bikeway Design Guide.
Source (c): Vancouver Is Awesome, 2019.
Source (d): Snake Bridge, Copenhagen (Reddit), 2016.

2.5 Vehicle Heterogeneity and Cargo Bikes as a Robustness Test

Most cycling assessment frameworks implicitly assume a homogeneous user profile, typically calibrated to the physical characteristics and operating conditions of standard commuter bicycles. This assumption simplifies indicator construction and interpretation, but it obscures important differences in vehicle dimensions, weight, manoeuvrability, and tolerance to infrastructural constraints. As a result, infrastructure that performs adequately under commuter-oriented assessments may approach or exceed feasibility limits when evaluated under more demanding cycling profiles.

Recent research on cycle logistics highlights how cargo bikes differ fundamentally from standard bicycles in terms of spatial envelope, load, and operational stability. Cargo bikes generally require greater effective width, smoother surfaces, gentler gradients, and higher continuity to operate safely and reliably, particularly when carrying loads or operating at low speeds. These requirements are not marginal refinements of commuter cycling conditions, but reflect distinct physical constraints that interact directly with street geometry and infrastructure design (Gruber et al., 2014; Schliwa et al., 2015; European Cycling Federation, 2023).

Despite this, most existing bikeability and cycling-readiness frameworks do not explicitly differentiate between cycling vehicle types. When freight cycling is addressed, it is often treated at the policy or strategic level, through qualitative inventories or best-practice guidelines, rather than through spatially explicit, network-based assessment. This mismatch limits the ability and knowledge of planners to identify where existing cycling networks can realistically support cargo-bike operations and where structural bottlenecks persist.

Within this context, cargo bikes can be interpreted not only as an emerging transport mode, but as a robustness test for cycling infrastructure. Applying stricter feasibility thresholds to the same underlying cycling network reveals whether infrastructure conditions remain usable when physical requirements increase. This comparative logic shifts the analytical focus from whether infrastructure is nominally “bikeable” to whether it retains functional capacity under more demanding use scenarios.

By evaluating multiple cycling profiles in parallel, the framework distinguishes between infrastructure that is structurally robust and infrastructure that is narrowly optimised for lightweight commuter use. The resulting differences between standard bicycle and cargo-bike readiness do not describe demand or adoption potential, but instead expose latent structural fragility within existing networks. This approach provides a methodologically consistent way to integrate vehicle heterogeneity into cycling assessment, while preserving a unified spatial framework and avoiding assumptions about logistics operations or user behaviour.

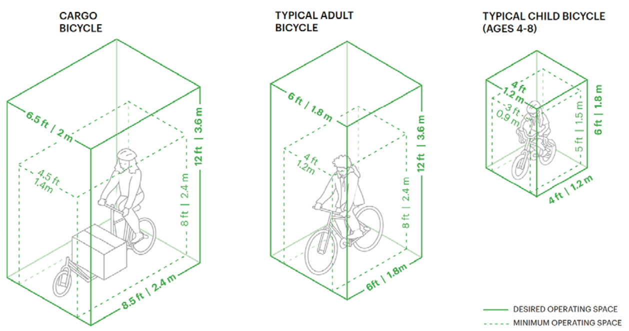


Figure 5: NACTO illustration of bicycle volume and dimensional differences.
(a) Comparative representation of spatial envelopes for different bicycle types and users.
Source: NACTO, Urban Bikeway Design Guide, Island Press, 2011.

2.6 Spatial Aggregation and Diagnostic Mapping Approaches

Network-based assessments of cycling readiness require a spatial strategy for interpreting large sets of edge-level indicators in a form that supports comparison and diagnosis at the urban scale. While feasibility is evaluated at the level of individual network segments, planning-relevant insights emerge only when these local conditions are synthesised spatially. In GIS-based bikeability research, **spatial aggregation functions as a translation layer between network-level computation and area-based interpretation**, allowing structural patterns to be observed and support evidence based planning interpretations.

A central methodological challenge in aggregating network indicators is avoiding bias toward areas with dense but fragmented infrastructure. Simple summation or unweighted averaging of segment scores can inflate apparent performance in locations where many short or discontinuous links are present, even if overall network usability remains limited. To mitigate this effect, several studies adopt regular grid-based aggregation schemes that summarise local infrastructure conditions within fixed spatial units, enabling consistent comparison across heterogeneous urban contexts and reducing sensitivity to network density artefacts (Papa & Bertolini, 2015; Vale et al., 2016; Hardinghaus et al., 2021).

Regular grid structures offer methodological advantages over administrative zones or irregular buffers. Because they are independent of political boundaries, grid-based maps reduce noise and facilitate cross-city comparison. They also integrate naturally with raster-based terrain analysis and spatial overlays commonly used in cycling assessment pipelines. Within this types of approaches, hexagonal grids are frequently preferred due to their uniform adjacency relationships and reduced directional bias, which improve spatial continuity and visual interpretability in comparative mapping (Birch et al., 2007; Čech et al., 2020). Recent GIS-based bikeability frameworks explicitly employ hexagonal tessellations to aggregate edge-level indicators into area-based diagnostics while preserving spatial coherence (Weikl & Mayer, 2023).

The choice of aggregation statistic further influences the interpretation of cycling readiness patterns. Mean-based aggregation can obscure feasibility constraints by averaging high- and low-quality segments within the same cell, while maximum values tend to overemphasise isolated high-performing infrastructure. Median-based aggregation provides a more conservative representation of typical conditions, preserving the presence of structural bottlenecks and reducing sensitivity to outliers. This approach has been recommended in spatial diagnostics where the objective is to identify limiting conditions rather than best-case performance, particularly when working with heterogeneous or partially incomplete open datasets (Hardinghaus et al., 2021; Weikl & Mayer, 2023).

Importantly, spatial aggregation in GIS-based cycling assessment is generally used as a diagnostic device rather than as a substitute for network analysis. Aggregated readiness values do not represent route quality, accessibility, or predicted movement, but instead summarise prevailing structural conditions within local areas. Network continuity, connectivity, and fragmentation are therefore often analysed separately as complementary diagnostics that support interpretation without being incorporated directly into composite readiness scores (Dill, 2004; Abad et al., 2018). This separation avoids conflating physical feasibility with topological structure and maintains transparency in how different analytical components contribute to final outputs.

By combining edge-level feasibility indicators with conservative, grid-based spatial aggregation, the framework produces diagnostic maps that highlight structural robustness and fragility across the urban fabric. These representations support early-stage planning by revealing where cycling infrastructure conditions systematically approach feasibility limits, while remaining independent of assumptions about demand, routing behaviour, or future network expansion.

2.7 Data Collection Strategies and Methodological Dependencies in Bikeability Assessment

Bikeability indices are not defined solely by the indicators they employ, but by the **data collection strategies** that make those indicators operational. Existing bikeability studies rely on markedly different data sources, ranging from locally calibrated traffic datasets and surveys to modelled accessibility measures and national statistical layers. These choices shape both the analytical scope of each index and its transferability across cities.

A large share of bikeability research combines network geometry with locally specific inputs such as motor traffic speed and volume, intersection control data, or stated-preference survey responses (e.g. Winters et al., 2013; Furth et al., 2012; Mekuria et al., 2012). While these approaches allow for detailed assessment of perceived safety, stress, or route attractiveness, they introduce strong data dependencies. Traffic counts, speed profiles, and behavioural surveys are often unavailable, inconsistently maintained, or methodologically incomparable across cities, limiting reproducibility beyond the original study context.

Accessibility-oriented bikeability approaches further expand data requirements by integrating land-use data, destination inventories, or calibrated routing models (e.g. Lowry et al., 2012). These methods are effective for analysing potential cycling access or route choice under assumed behavioural models, but they hinder infrastructural suitability with demand, exposure, and modelling assumptions, Therefore, they are difficult to apply consistently in data-scarce cities and unsuitable for isolating structural feasibility conditions of cycling infrastructure alone.

In contrast, many commonly cited physical infrastructure attributes are frequently omitted from bikeability indices, not because they are considered irrelevant, but because they are difficult to collect systematically using conventional data sources. Even when objective indicators are used, feasibility is often interpreted through comfort or level of stress binary value rather than through explicit physical thresholds, reflecting the constraints imposed by available data rather than conceptual intent.

Recent efforts to standardise cycling infrastructure data using OpenStreetMap demonstrate both the potential and the limits of open-data-based assessment. Initiatives such as the *European Cyclists' Federation Cycling Infrastructure Tracker* show that harmonised extraction of cycling infrastructure type, continuity, and selected physical attributes is possible at scale, while also revealing persistent gaps in attributes such as width, surface condition, and access constraints. These gaps are not incidental; they shape which methodological approaches can be realistically implemented across multiple cities.

Taken together, **the literature indicates that methodological differences between bikeability indices are driven as much by data availability and collection strategies as by conceptual framing**. This creates a structural bias toward indices that prioritise perceptual comfort, traffic interaction, or accessibility modelling, while limiting the ability to assess infrastructural feasibility in a transferable and reproducible manner. Addressing this gap requires a deliberate methodological process that aligns indicator selection with data that can be derived consistently across urban contexts, even at the cost of excluding behaviourally rich but data-intensive variables.

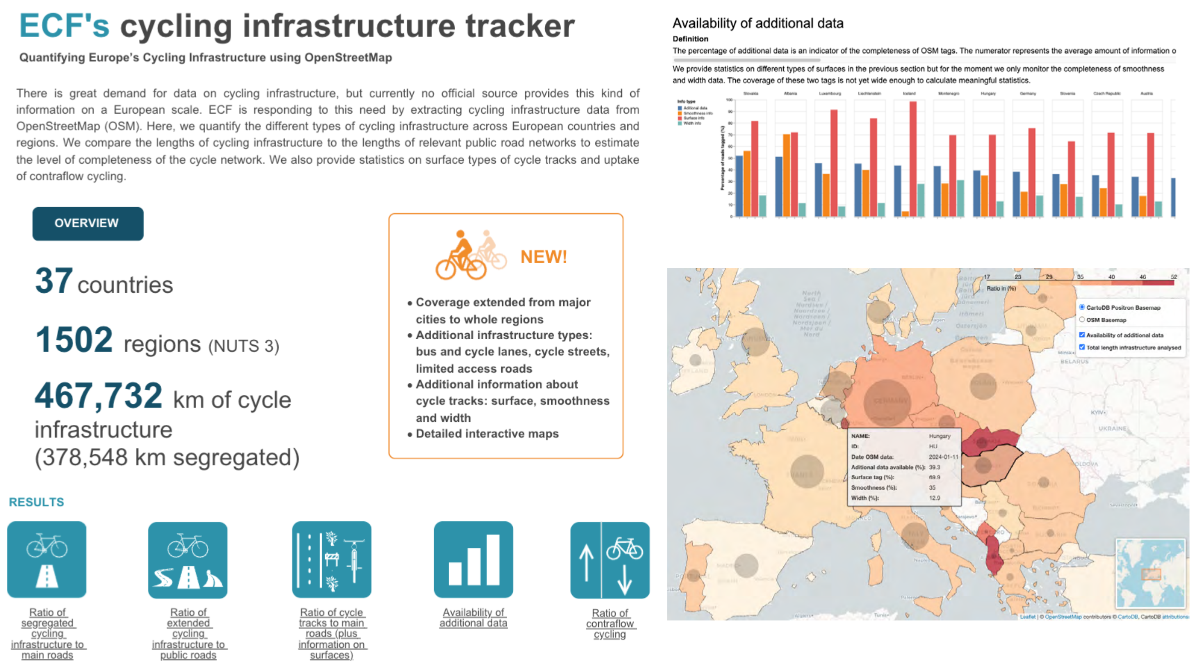


Figure 6: European Cyclists' Federation (ECF) Cycling Infrastructure Tracker interface.
The images show the ECF platform used to collect and visualise European cycling infrastructure data, including data availability, infrastructure typology, and segregation ratios.
Source: European Cyclists' Federation, Resources, 2025.

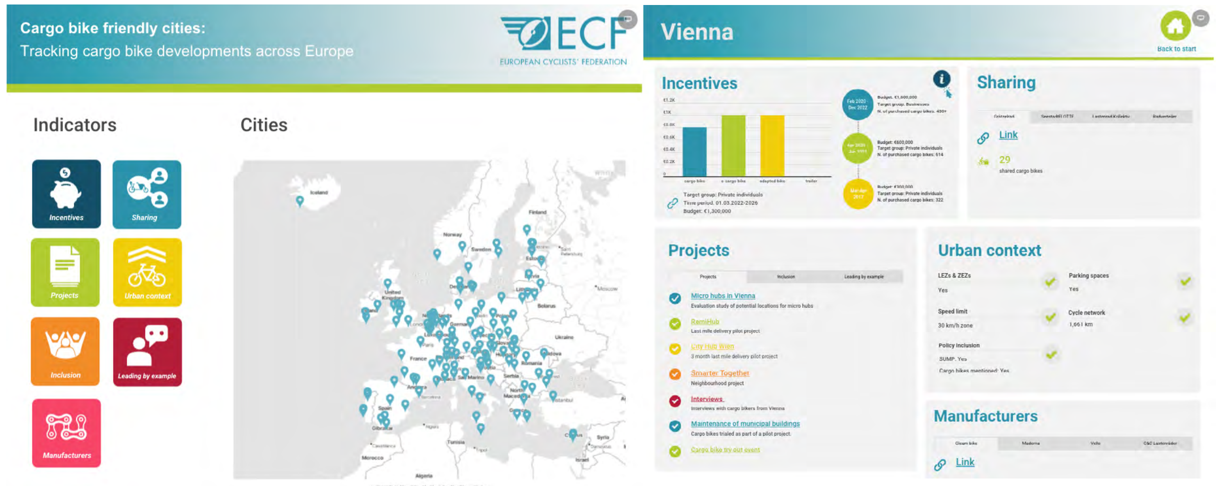


Figure 7 - ECF Cargo Bike Friendly Cities Tracker interface.
The tracker provides a qualitative and descriptive overview of projects, incentives, and contextual conditions related to cargo-bike adoption across cities.
Source: European Cyclists' Federation, Resources, 2025.

2.8 Open-Data-Based Cycling Assessment: Opportunities and Constraints

The feasibility and transferability of spatial cycling assessments are strongly shaped by data availability and institutional capacity. While some cities maintain detailed and standardised transport datasets, many planning contexts particularly outside Northern European settings operate with limited technical resources and uneven data collection process. As a result, methodologies that rely on proprietary datasets, extensive calibration procedures, or locally specific municipal inputs often remain difficult to replicate or apply consistently across cities, limiting their usefulness for comparative and exploratory analysis.

In this context, open spatial data sources, and OpenStreetMap (OSM) in particular, have become central to GIS-based cycling research. OSM provides globally available, continuously updated representations of street networks, cycling infrastructure, and selected surface and access attributes, enabling large-scale spatial analysis without reliance on municipal data access agreements (Haklay, 2010; Barrington-Leigh & Millard-Ball, 2017). Multiple studies have shown that, while OSM data quality varies geographically, it can reach levels comparable to official datasets in cities with active mapping communities, especially for linear transport infrastructure and cycling facilities (Girres & Touya, 2010; Hecht et al., 2013). Recent large-scale assessments further demonstrate that, in countries with mature open-data ecosystems such as Denmark, OSM bicycle network data achieve high completeness and positional accuracy, supporting national-scale network analysis and comparative evaluation (Viero et al., 2024).

The use of open data nevertheless introduces clear analytical constraints. Attribute completeness for variables such as effective lane width, surface condition, kerb treatment, or intersection design remains inconsistent, and tagging conventions may differ across regions. These limitations restrict the set of indicators that can be derived reliably and require smart treatment of missing values. Rather than treating these constraints as methodological weaknesses, recent planning and accessibility literature emphasises the importance of aligning analytical ambition with data realism, particularly when the objective is to support planning practice rather than to produce optimised or predictive models (Geurs & van Wee, 2004; Papa & Bertolini, 2015).

For GIS-based cycling readiness assessment, this implies prioritising indicators that are both physically meaningful and consistently observable within open datasets. By restricting the indicator set to variables that can be derived reproducibly across cities open-data-based frameworks favour transparency, comparability, and interpretability over exhaustive representation of all infrastructure features. This trade-off is widely adopted in transferable bikeability indices and supports early-stage diagnosis and benchmarking, where the objective is to identify structural constraints and relative robustness rather than to deliver design-ready prescriptions (Hardinghaus et al., 2021; Weikl & Mayer, 2023).

Importantly, reliance on open data does not preclude the use of richer local datasets where available. Instead, it establishes a minimum methodological baseline that can be applied uniformly across cities, while allowing optional enrichment with municipal or survey-based data for more detailed, context-specific analysis. Several GIS-based cycling studies explicitly adopt this layered strategy, using open data for core indicators and supplementing them selectively when higher-resolution inputs exist (Vale et al., 2016; Abad et al., 2018).

By explicitly acknowledging both the strengths and limits of open spatial data, the framework positions cycling readiness assessment as a pragmatic and scalable tool. Its outputs are intended to inform strategic discussion, screening, and prioritisation, not to replace detailed engineering surveys or local design expertise. This clarity of scope is essential to ensuring that spatial readiness maps are interpreted as diagnostic evidence of structural conditions, rather than as definitive evaluations of cycling performance.

2.9 How Cycling Indices Are Used in Planning

Cycling indices are commonly employed in planning practice as screening and diagnostic tools rather than as predictive or decision-making instruments. Their primary function is to summarise complex spatial conditions into interpretable representations that help planners identify gaps, compare areas, and prioritise further investigation. In this role, indices are rarely used to justify specific design solutions; instead, they support agenda-setting, problem framing, and strategic discussion (Geurs & van Wee, 2004).

A recurring challenge in the application of composite indices lies in the gap between methodological sophistication and institutional usability. Highly detailed or data-intensive indices may offer theoretical precision but often exceed the technical capacity, data availability, or time constraints of planning departments. As a result, many indices remain confined to academic contexts, with limited uptake in practice. Literature on planning support systems consistently emphasises that interpretability, transparency, and reproducibility are critical conditions for real-world use, often more so than analytical completeness (Papa & Bertolini, 2015).

Within this context, a distinction can be made between descriptive, diagnostic, and predictive indices. Descriptive indices summarise existing conditions, diagnostic indices identify structural constraints and relative weaknesses, and predictive indices attempt to model future behaviour or outcomes. Cycling readiness frameworks are most appropriately situated within the diagnostic category: they do not estimate cycling demand, uptake, or mode shift, but instead assess whether infrastructural conditions are physically capable of supporting cycling under specified requirements.

This thesis adopts a diagnostic interpretation of cycling indices. The proposed framework is intended to support early-stage planning by revealing where existing cycling infrastructure approaches feasibility limits and where robustness differs across use profiles. Its outputs are designed to inform prioritisation, comparison, and further inquiry, rather than to prescribe interventions or forecast impacts. By clarifying this role explicitly, the framework avoids over-interpretation and aligns with how spatial indices are typically and effectively used in planning practice.

2.10 Synthesis: Methodological Gaps and Positioning

The literature reviewed in this chapter shows a clear progression in the assessment of cycling conditions, from early perceptual and segment-based approaches toward more spatially explicit and network oriented frameworks. This evolution has improved the representation of cycling environments at larger scales and consolidate the role of GIS-based analysis in cycling research. However, several conceptual and methodological gaps remain relevant when assessing the structural readiness of cycling infrastructure.

First, **much of the bikeability literature continues to frame cycling suitability primarily in terms of comfort, stress, or perceived safety, even when objective indicators are employed**. While these perspectives provide valuable insight into user experience, they are limited in their ability to assess whether infrastructure meets minimum physical and geometric requirements. As a result, infrastructure that performs well under commuter-oriented assessments may still exhibit structural constraints that limit its usability under more demanding cycling conditions.

Second, although network based and route based approaches have advanced the spatial representation of cycling systems, many rely on routing assumptions, origin–destination modelling, or behavioural hypotheses. These approaches are less suited to diagnostic analyses that aim to characterise infrastructural conditions independently of demand, route choice, or future scenarios. This limits their applicability in early-stage planning contexts where transparent and reproducible assessments of existing conditions are required.

Third, existing frameworks rarely account explicitly for vehicle heterogeneity within cycling assessment. Differences in vehicle dimensions, load, and operational tolerance are typically overlooked, leading to implicit calibration around standard commuter bicycles. This hides variations in infrastructural robustness and reduces the capacity of spatial assessments to inform emerging forms of cycle logistic.

Finally, the practical use of cycling indices in planning is constrained by data availability and institutional capacity. Methods that depend on detailed local datasets or complex calibration procedures often struggle to achieve consistent application across cities. Open-data-based approaches offer opportunities for comparability and scalability, but require deliberate methodological restraint and clear articulation of analytical limits.

Taken together, the literature does not converge on a single optimal methodology for assessing cycling cycling infrastructure readiness. Instead, it reveals recurring trade-offs between analytical precision, behavioural interpretation, data availability, and transferability. These unresolved tensions motivate the need for a feasibility-oriented, network-based approach that can diagnose structural conditions using methods and data that remain applicable across diverse urban contexts.

2.11 Methodological Positioning and Design Implications

Building on the bikeability methods reviewed in Sections 2.1–2.9 (e.g. Landis et al., 1997; Winters et al., 2013; Arellana et al., 2020), this section positions the methodological choices adopted in the thesis. The gaps identified in the Chapter 2.10 indicates those which this thesis is going to fill in order to answer the research questions. Rather than proposing an entirely new assessment paradigm, this thesis positions itself through a selective and deliberate use of established bikeability methods, choosing those that are essential for spatial feasibility assessment, adapting others, and excluding those that conflict with a diagnostic, open-data-based objective.

At the core of any bikeability framework and cycling infrastructure assesment framework lies a **GIS-based approach, network-level analysis using objective physical and the use geometric indicators**. Their use reflects a well established use in the literature of infrastructure type, surface characteristics, slope, and related geometric properties representing the main constraints on cycling feasibility. Using these methods ensures continuity with existing research while anchoring the analysis in measurable, reproducible attributes of the built environment.

Composite index construction is also adopted as a standard mechanism. However, in this thesis its construction is deliberately focused to feasibility-oriented indicators (for example type, width, slope), avoiding the inclusion of behavioural, perceptual, or service related variables that dominate many bikeability indices. This approach reflects the conceptual shift from assessing cycling attractiveness toward diagnosing whether infrastructure remains physically operable under different vehicle requirements.

Several other methods have been adopted but adapted in relation to the project scope and objectives.

Spatial aggregation to a regular grid is used to support pattern interpretation, spatial continuity in visual outputs and cross-city comparison. Within this aggregation step, **median-based rather than mean-based or sum aggregation is used**. This choice responds directly to inflation effects observed in dense but fragmented cycling networks, where short, high-quality segments can disproportionately influence aggregated scores despite limited structural continuity.

The **dual-profile logic** is conceptually inspired by Level of Traffic Stress (LTS) frameworks, which differentiate cycling suitability according to varying user tolerance and experience levels. Rather than modelling perceived stress or comfort, the thesis's framework extends this differentiation to vehicle profiles, translating user heterogeneity into explicit physical and geometric feasibility thresholds. Differences between profiles arise from stricter feasibility thresholds applied to the cargo-bike profile, rather than from changes in indicators, weights, or aggregation logic. In this thesis cargo bikes function as a structural stress test, revealing robustness margins and constraints that remain hidden in commuter oriented assessments.

Most of the current indices have a bikeability score as final outputs, creating a gap for understanding the phenomena. In this framework, additional analytical components are incorporated as **diagnostic layers**. Bottleneck attributions, hard infeasibility conditions, and robustness differentials are computed to support interpretation but are kept separate from the composite readiness score.

Several methods commonly found in the bikeability literature are **explicitly excluded in this framework**. Route-based assessments, behavioural and perceptual surveys, demand modelling, and policy or governance indicators are omitted because they introduce assumptions about user behaviour, route choice, or institutional context that are incompatible with an open-data, feasibility-oriented and reproducible framework. While these approaches are valuable for other research questions, their inclusion would reduce transferability and blur the distinction between structural conditions and observed or predicted cycling outcomes.

A final and critical design constraint concerns **data availability and analytical scale**. Unlike many bikeability studies that rely on detailed municipal datasets and are calibrated to single-city contexts, this thesis operates exclusively on open and transferable datasets, primarily OpenStreetMap and pan-European elevation models. This choice enables multi-city comparison at a European scale but necessitates methodological trade-offs. Indicator selection, aggregation logic, and exclusion of certain methods are therefore direct consequences of data consistency requirements rather than analytical preference.

Taken together, these methodological choices position the proposed framework as a **feasibility-oriented, network-based diagnostic tool that complements existing bikeability research**. By selectively recombining established methods under explicit data and scale constraints, the framework provides a transparent and reproducible means of identifying structural robustness and fragility in urban cycling networks, forming a clear bridge to the technical methodology presented in the following chapter.

Table 2.1 summarises the principal methods encountered in the bikeability literature, their typical application, and their application within this thesis. Methods are grouped into four tiers: **core methods that are kept as essential, methods that are adopted but deliberately adapted, diagnostic methods used outside the composite index, and methods that are explicitly excluded**. This structure clarifies both methodological continuity with existing research and the points at which the framework diverges in response to the conceptual gaps identified in Section 2.10.

Table 2 - Relationship between existing bikeability research methods and their application within this thesis.
Source: Author's own work.

Tier	Methods	Representitive study	Status in the thesis	Justification	Implication for method design
1	GIS-based networklevel analysis	Winters et al. (2013); Arellana et al. (2020); Dill & McNeil (2016) and others	Used	Established standard for objective bikeability assessment	Enables edge-level and hex level feasibility evaluation
1	Physical & geometric indicators (type, surface, slope)	Landis et al. (1997); Jensen (2007); Winters et al. (2013) and others	Used	Represent first-order feasibility constraints	Limits analysis to structural conditions
1	Composite index construction	Winters et al. (2013); Harding-haus et al. (2021) and others	Used	Standard synthesis approach in bikeability indices	Requires indicator normalisation
2	Spatial aggregation to regular grid	Winters et al. (2013); Arellana et al. (2020) and others	Adapted	Supports comparability and spatial interpretation	Grid used for aggregation, not routing
2	Hexagonal grid tessellation	Arellana et al. (2020)	Adapted	Reduces bias and supports continuity	Facilitates visual, analytical consis-tency and relation with other urban phenomena
2	Median aggregation (vs mean/sum)	Rarely explicit in literature	Adapted	Avoids inflation from dense fragmented infrastructure	Produces conservative readiness estimates
2	Dual-profile evaluation (com-muter vs cargo)	Implicit in feasibility discus-sions (Schliwa et al., 2015)	Adapted	Shows structural robustness testing	Cargo profile acts as stress test
3	Bottlekeck diagnostics	Not standard in bikeability indices	Used (diagnostic)	Recognised importance, but not index-driving	Inform main limitation for each cell
3	Hard infeasibility layers	Limited direct precedents	Used (diagnostic)	Makes feasibility limits explicit	Prevents false-positive readiness
3	Δ Readinesscomparison	Not standard in bikeability indices	Used (diagnostic)	Reveals tolerance margins	Supports comparative interpretation
4	Route-based bikeability	Lowry et al. (2012)	Excluded	Requires routing and behavioural assumptions	Avoids OD focus
4	Behavioural / perceptual surveys	Landis et al. (1997); Harding-haus et al. (2021)	Excluded	Incompatible with open-data transferability	Focus remains structural
4	Demand modelling	Transport modelling literature	Excluded	Outside feasibility oriented scope	Prevents predictive claims
4	Policy / governance indicators	Copenhagenize Index; ECF trackers	Excluded	Descriptive, not spatial-ly diagnostic	Treated as contextual only

3. Conceptual Framework

The diagram synthesises the **Conceptual and Research Logic** of proposed cycling readiness framework. It situates the study at the intersection of emerging urban mobility challenges and limitations identified in existing bikeability literature, and shows how these gaps motivate a shift toward infrstructural feasibility assessment. The diagram illustrates how dual-profile evaluation and cycling readiness concepts are derived from these gaps and translated into a diagnostic tool with a clearly defined role in planning.

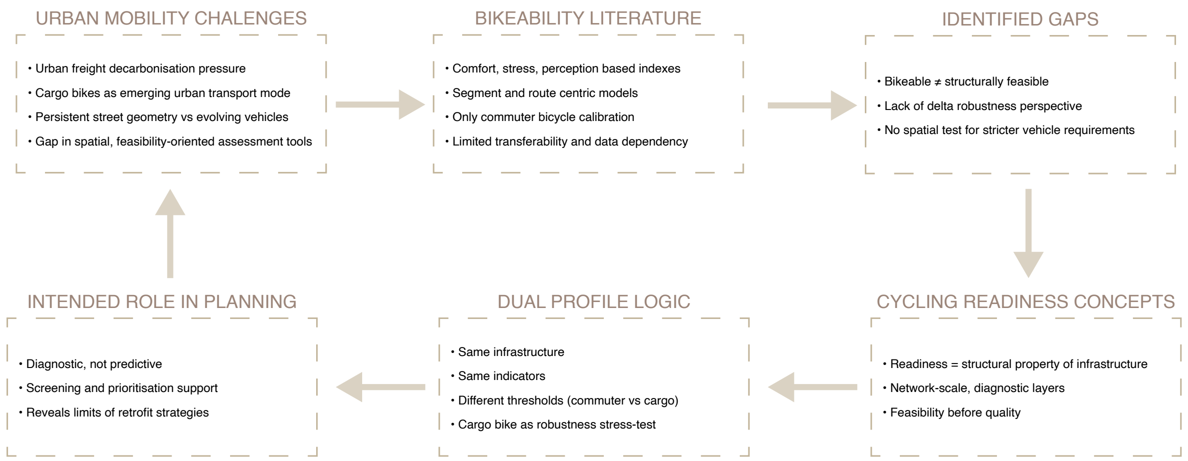


Figure 8: Conceptual and research logic diagram.
Source: Author's own work.

3.1 Defining Cycling Readiness and Its Conceptual Domain

Cycling infrastructure readiness builds on the premise that different cycling vehicle types operate on the same physical network while placing unequal physical demands on it. Conventional bikeability frameworks are largely calibrated to standard commuter bicycles and typically evaluate cycling environments in terms of comfort, stress, or perceived safety. In contrast, the readiness perspective focuses on whether existing infrastructure remains structurally usable when stricter physical requirements are applied. Cargo bikes are therefore used as a robustness test: by imposing higher demands on width, surface quality, slope, and infrastructure form, the framework reveals latent physical constraints that may remain invisible under commuter-oriented bikeability assessments.

Empirical and academic evidence reviewed in Chapter 2 shows that cargo-bike use is particularly sensitive to infrastructural characteristics such as effective width, infrastructure type, surface continuity, obstacles, slope, manoeuvring space, and access conditions at origins and destinations. These factors are not exclusive to cargo bikes; rather, they become more influencial as vehicle dimensions, weight, and stability requirements increase. As a result, cargo bikes tend to expose infrastructural weaknesses that may remain tolerable for standard commuter cycling.

In this framework, cargo bikes are not treated as a separate transport system, nor is logistics performance modelled explicitly. Instead, cargo bike use is conceptualised as a stress test of existing cycling infrastructure. Robustness is defined here as the capacity of infrastructure to remain physically usable when stricter vehicle requirements are applied to the same network. By evaluating whether infrastructure continues to meet minimum feasibility thresholds under increased demands, cycling readiness is reframed as a question of structural robustness rather than user comfort alone.

Based on the literature, **determinants of cycling readiness can be grouped into five conceptual domains: (1) infrastructure quality, (2) terrain and slope, (3) urban form and accessibility, (4) traffic environment, and (5) access and geometric constraints.** Together, these domains describe the spatial conditions that influence the feasibility and functional performance of cycling as a transport mode. The domains serve as a conceptual classification to organise requirements identified in the literature; they do not imply that all dimensions are operationalised in the current analysis.

In this thesis, only infrastructure quality and terrain are operationalised computationally. These domains capture physical characteristics that can be derived with reasonable consistency from open spatial network data and elevation datasets and are directly linked to the feasibility of both commuter and cargo bike use. Urban form variables, such as land-use mix, destination density, or demographic patterns, are excluded from the index because they primarily describe latent demand or cycling potential rather than infrastructural readiness, though they may support interpretation when used as contextual layers. Similarly, traffic-environment indicators and detailed access constraints are not included due to inconsistent data availability and limited cross-city comparability.

By explicitly separating conceptual scope from operational scope, the framework establishes a clear boundary between what cycling readiness means and what can be measured reliably within an open-data, comparative methodology. This distinction underpins all subsequent design choices in the framework and ensures that readiness is interpreted as a structural property of the built environment rather than as a proxy for cycling uptake or performance .

3.2 Expected Indicator Behaviour Across Cycling Profiles

Each indicator included in the Cycling Readiness framework is expected to influence readiness in a consistent and theoretically grounded direction, based on established bikeability research and emerging evidence from cycle logistics studies. While the same physical indicators apply to all cycling modes, their effect on feasibility differs systematically across cycling profiles due to differences in vehicle dimensions, load, stability, and operating tolerance.

Indicators related to infrastructure quality (infrastructure type, effective width, surface condition, and continuity) are expected to increase readiness for both commuter and cargo bike use. However, their influence is structurally stronger for cargo bikes, which are more sensitive to spatial constraints, surface irregularities, and interruptions in network continuity. Conditions that remain marginally acceptable for standard bicycles may therefore approach or exceed feasibility limits when evaluated under cargo-bike requirements.

Terrain indicators, represented primarily through slope, are expected to have a consistently negative effect on readiness as gradients increase. This effect is asymmetric across cycling profiles: steeper slopes impose disproportionately higher penalties on cargo bikes due to increased vehicle mass, reduced manoeuvrability, and higher energy demands under load. As a result, terrain acts as a compounding constraint when combined with other infrastructural limitations.

The framework applies all indicators to a shared representation of the cycling network while distinguishing between cycling profiles through **differentiated thresholds and penalty functions**. Rather than constructing separate indices for different vehicle types, readiness is evaluated using the same indicators, spatial units, and aggregation logic. Differences between commuter and cargo-bike readiness therefore reflect stricter feasibility requirements rather than changes in data inputs or analytical structure, ensuring internal consistency and comparability.

Urban form characteristics, traffic-environment variables, and access constraints are recognised as important contextual factors influencing cycling performance and use, and are often incorporated in bikeability research through hexagon-based aggregation as interpretive context rather than direct feasibility inputs (Kraft et al., 2021). However, they are excluded from the computational framework because they primarily describe demand, exposure, or operational conditions rather than structural feasibility, and because their reliable derivation would require locally specific datasets and case-by-case calibration. These factors are retained as interpretative layers anche could support contextual reading of results without being embedded in the readiness score itself.

By defining expected indicator behaviour explicitly and applying differentiated feasibility logic across cycling profiles, the framework ensures that observed readiness differences can be interpreted as structural robustness margins within the same infrastructure network. This conceptual clarity provides the foundation for the computational implementation described in the following sections.

3.3 Data Sources and Characteristics

Cities operate within highly uneven data ecosystems, and these differences directly affect the granularity, reliability, and comparability of cycling-readiness assessments. While some cities maintain detailed and well-curated municipal datasets, many planning contexts rely primarily on open data, resulting in variability in attribute completeness and spatial accuracy. These conditions place practical constraints on what can be assessed consistently across cities and therefore shape the operational scope of transferable spatial frameworks.

The minimum-tier implementation of the Cycling Readiness framework relies on open, globally available datasets, primarily OpenStreetMap (OSM) cycling networks combined with digital elevation models. OSM provides standardised geometries and tagging conventions that enable the reproducible extraction of infrastructure type, network continuity, surface proxies, and selected accessibility features across a wide range of urban contexts. The *European Cyclists' Federation Cycling Infrastructure Tracker (add reference)* illustrates how OSM-based data can be systematically processed to generate comparable cycling-infrastructure metrics at scale, while also highlighting persistent gaps in attributes such as effective width, surface condition, and detailed barrier inventories.

Where available, municipal datasets can substantially improve analytical precision by offering richer attribute schemas, more accurate geometric measurements, and information directly relevant to cargo-bike accessibility (kerbs). However, such datasets are often heterogeneous, unevenly maintained, and difficult to integrate consistently across cities. These characteristics limit their suitability for a reproducible, cross-city methodology and complicate automated analytical pipelines. For this reason, the Cycling Readiness framework is deliberately developed using open datasets only, treating municipal data as a potential extension rather than as a prerequisite.

Within the framework, data availability influences two distinct aspects of the analysis. First, it defines **feasibility**: what indicators can be computed reliably using open data, thereby establishing the operational boundary of the index. Second, it affects **precision**: how accurately infrastructural conditions can be represented, particularly in the presence of missing or partially tagged attributes. To address this, the framework adopts conservative assumptions and transparent handling of incomplete data, prioritising robustness of interpretation over local optimisation.

By grounding the framework in harmonised open data, the methodology remains stable when interpreting current cycling readiness while remaining adaptable to future improvements in data coverage and quality. This approach balances methodological restraint with analytical usefulness, ensuring that observed readiness patterns reflect structural properties of cycling infrastructure rather than artefacts of uneven data availability.

3.4 Methodological Contribution and Positioning

This thesis contributes to the literature on cycling assessment by reframing cycling readiness as a question of structural robustness rather than user comfort or perceived suitability alone. While conventional bikeability indices evaluate whether infrastructure supports everyday commuter cycling, they implicitly assume vehicle characteristics and operational tolerances that do not generalise to heavier, wider, or load-bearing cycling modes. As a result, cycling networks that perform well under standard bikeability assessments may still be structurally unsuitable for cargo-bike operations.

The proposed Cycling Readiness framework extends established bikeability methodologies by applying stricter feasibility criteria to the same underlying indicators, datasets, and spatial units. Instead of introducing new data sources or modelling cargo bike use as a separate transport system, the framework reinterprets core physical indicators through differentiated thresholds and penalty logic that reflect increased operational demands. This approach preserves comparability with existing bikeability indices while exposing latent infrastructural constraints that remain invisible under commuter-oriented assumptions.
By assessing commuter and cargo-bike readiness in parallel on a shared cycling network, the framework demonstrates that differences between cycling profiles are not categorical but incremental. Readiness losses observed

under cargo-bike requirements can therefore be interpreted as robustness margins within the same infrastructure, rather than as binary exclusions. This comparative logic enables the identification of infrastructure that is narrowly optimised for standard bicycles versus infrastructure that remains functional under more demanding conditions.

A further methodological contribution lies in how cycling readiness is operationalised under data and institutional constraints. The framework is deliberately designed to function with harmonised open datasets and to remain interpretable at each analytical step. By retaining shared indicators and spatial units across profiles, and by separating composite readiness scores from diagnostic layers that highlight infeasibility and limiting factors, the framework avoids over-aggregation and preserves traceability between spatial patterns and underlying infrastructure characteristics. This design responds directly to documented implementation gaps in planning-support tools, where increasing analytical sophistication often undermines transparency and practical uptake.

Positioned in this way, the Cycling Readiness framework complements existing bikeability and policy-oriented approaches. It does not seek to predict cycling demand, model logistics performance, or prescribe design solutions, but instead provides a spatially explicit diagnostic tool to support early-stage planning, comparison, and prioritisation for both everyday cycling and urban freight.

3.5 Conceptual Workflow and Analytical Logic

The Cycling Readiness framework is operationalised through a unified analytical logic that evaluates multiple cycling profiles on a shared representation of the cycling network. The core principle underpinning the workflow is that differences in readiness should arise exclusively from differentiated feasibility requirements, not from differences in data sources, indicators, or spatial units. This ensures that observed contrasts between commuter and cargo-bike readiness reflect structural robustness rather than analytical artefacts.

The workflow begins with the definition of two cycling profiles—standard commuter cycling and cargo bike use—conceptualised as distinct use cases operating on the same physical infrastructure. Cargo bike use is treated as a stricter feasibility case, reflecting higher requirements for effective width, surface quality, continuity, and slope tolerance. These profiles are not associated with behavioural assumptions or operational modelling, but serve to define different physical thresholds applied to the same set of infrastructural conditions.

Indicator scoping follows directly from this logic. Only physical infrastructure and terrain indicators are included in the computational framework, as these describe structural properties of the built environment that can be derived consistently from open spatial data. Urban form characteristics, traffic environment variables, and detailed access constraints are excluded from the readiness computation and retained solely for interpretative purposes. This separation prevents conflation between infrastructural feasibility and contextual or demand-related influences.

All indicators are derived within a deliberately constrained open-data boundary, relying on harmonised cycling network data and elevation models. This boundary defines both the analytical scope of the framework and its transferability across cities with varying data capacities. Readiness is first evaluated at the network-edge level, where physical constraints can be directly associated with specific infrastructure segments. Network-level patterns are then interpreted through spatial aggregation, allowing local feasibility conditions to be synthesised into area-based diagnostics without introducing routing assumptions or optimisation.

The final step of the conceptual workflow is the parallel evaluation of readiness under both cycling profiles. By applying profile-specific feasibility thresholds to the same underlying indicators, the framework produces two readiness surfaces and an explicit difference representation. This difference does not measure performance or demand, but functions as a diagnostic of robustness loss, highlighting where infrastructure that supports standard bicycles approaches or exceeds feasibility limits under cargo-bike requirements.

This conceptual workflow establishes a transparent link between theoretical framing and computational implementation. It defines the analytical logic that guides indicator selection, data handling, and spatial aggregation, and prepares the ground for the technical methodology described in the following chapte.

3.6 Summary and Transition to Technical Methodology

This chapter has established a conceptual framework for assessing cycling readiness as a structural property of the built environment. Cycling readiness is defined as the extent to which existing cycling infrastructure can physically support different cycling profiles operating on the same network, with cargo bikes conceptualised as a stricter feasibility case that exposes robustness limits within infrastructure designed primarily for standard commuter cycling.

The framework distinguishes clearly between conceptual scope and operational scope. While multiple domains influence cycling feasibility in principle, only infrastructure quality and terrain are operationalised computationally, reflecting both their direct relevance to physical feasibility and their consistent derivability from open spatial data. Other factors—such as urban form, traffic environment, and detailed access conditions—are explicitly excluded from the readiness index and retained for interpretative use only. This separation ensures methodological clarity and avoids conflating infrastructural readiness with demand, exposure, or behavioural dynamics.

A central methodological choice of the framework is the dual-profile logic, whereby commuter and cargo-bike readiness are evaluated in parallel on a shared cycling network using the same indicators, spatial units, and aggregation logic. Differences between profiles therefore reflect increased feasibility requirements rather than changes in data inputs or analytical structure. The resulting readiness and difference representations function as diagnostic tools, highlighting where existing cycling infrastructure remains structurally robust and where it approaches or exceeds feasibility limits under more demanding use conditions.

Finally, the chapter has outlined the conceptual workflow underpinning the framework, from profile definition and indicator scoping to open-data boundaries and diagnostic interpretation. This workflow provides the analytical logic that guides the computational implementation of the Cycling Readiness framework.

Chapter 4 translates this conceptual framework into a technical methodology, detailing the data processing steps, indicator computation, spatial aggregation procedures, and diagnostic outputs used to operationalise cycling readiness across the selected case study cities.

4. Methodology

The diagram synthesises the **Conceptual and Research Logic** of proposed cycling readiness framework. It situates the study at the intersection of emerging urban mobility challenges and limitations identified in existing bikeability literature, and shows how these gaps motivate a shift toward infrstructural feasibility assessment. The diagram illustrates how dual-profile evaluation and cycling readiness concepts are derived from these gaps and translated into a diagnostic tool with a clearly defined role in planning.

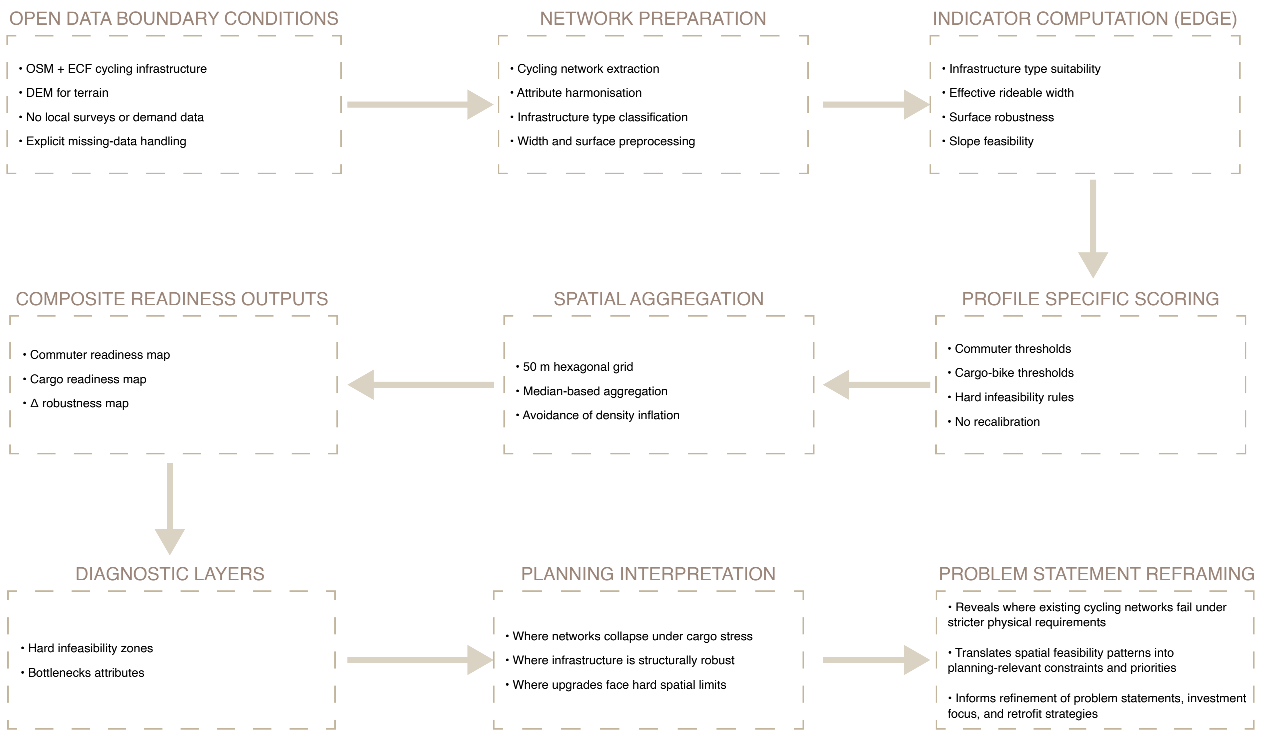


Figure 9: Methodological workflow diagram.
Source: Author's own work.

4.1 Methodology Bridging Paragraph

This chapter translates the conceptual framework developed in Chapter 3 into a reproducible spatial analysis methodology. The methodological design follows directly from the definition of cycling readiness as a structural property of the built environment and from the dual-profile logic distinguishing standard commuter cycling from cargo-bike cycling as a stricter feasibility case. All analytical choices in this chapter includes indicator selection, data insights, profile differentiation, aggregation logic, and diagnostic outputs, which are grounded in the conceptual scope and limitations established in Sections 3.1 to 3.6. Building on the review of GIS-based bikeability methodologies presented in Chapter 2, the methodological logic adopts a set of analytical methods that recur across network-oriented cycling assessments. These include edge-level computation of infrastructure indicators, network-wide interpretation through spatial aggregation, and reliance on open spatial data to support cross-city transferability. Rather than introducing a new analytical methods, the framework combines these established GIS practices under a feasibility-oriented objective, responding directly to the methodological patterns and constraints identified in Sections 2.3, 2.6, and 2.8.

Consistent with the framework, the methodology adopts a deliberately open-data implementation. Only physical infrastructure and terrain indicators are operationalised, using harmonised cycling-network data and elevation raster maps, while other contextual factors are retained for interpretation only. Commuter and cargo-bike readiness are evaluated in parallel on a shared network representation, with differences arising exclusively from profile-specific feasibility thresholds rather than from separate data sources or indicators. The methodological workflow is therefore designed to reveal infrastructural robustness margins within existing cycling infrastructure, rather than to model cycling demand, logistics operations, or behavioural outcomes.

The following sections detail the analytical workflow, data preprocessing steps, indicator computation, profile differentiation, spatial aggregation, and diagnostic analyses used to operationalise the Cycling Readiness framework across the selected case study cities.

4.2 Methodological Overview and Design Logic

This chapter operationalises the conceptual framework developed in Chapter 3 into a reproducible spatial methodology for assessing cycling readiness with a dual profile approach. In doing so, it relys explicitly on the GIS-based bikeability assessment approaches reviewed in Chapter 2, adopting their core analytical structure while modifying indicator selection, scoring logic, and aggregation to support the scope of the project. The methodological design follows directly from the definition of cycling readiness as a structural property of the built environment and from the dual-profile logic that distinguishes standard commuter cycling from cargo-bike cycling as a stricter feasibility case.

The framework adopts a diagnostic and planning-oriented approach. It does not aim to predict cycling uptake, model logistics operations, or optimise route choice. Instead, it evaluates whether existing cycling infrastructure provides the minimum physical conditions required for different cycling vehicle profiles to operate safely and continuously. Despite others indicators, such kerbs type, intersection geometry and barriers, are also highly important, their consistency and interpretability is out of the project scope. Readiness is therefore interpreted independently of observed demand, routing preferences, or operational performance; aspects directly connected to cycle logistic and ubran freight.

Methodologically, the approach is based on three core principles. **First, all analyses are conducted on a shared representation of the cycling infrastructure network**. Standard bicycles and cargo bikes are evaluated on the same physical network using the same indicators and spatial units. Differences between profiles arise exclusively from stricter feasibility thresholds applied to the cargo-bike profile, reflecting higher requirements for width, surface quality, continuity, and slope tolerance.

Second, the methodology is deliberately constrained to physical infrastructure and terrain indicators that can be derived consistently from open spatial data. This open-data boundary ensures reproducibility and cross-city comparability, particularly in contexts where municipal datasets are unavailable or uneven in quality. Other determinants of cycling performance, such as urban form, traffic environment, and detailed access conditions, are explicitly excluded from computation and retained for interpretation only.

Third, the analytical workflow is structured as a sequential pipeline. Spatial data are first assembled and preprocessed to define a consistent study area and an edge-based cycling network. Physical and terrain indicators are then computed at the network-edge level and transformed into profile-specific suitability scores. These scores are combined into composite readiness values and aggregated to a common spatial unit to support spatial interpretation and cross-city comparison. In addition to composite readiness outputs, a set of post-index diagnostic layers is produced to reveal robustness gaps, hard feasibility limits, and aggregation artefacts that are not visible in readiness values alone.

Together, these design choices ensure that the methodology directly reflects the conceptual framework, maintains transparency at each analytical step, and supports interpretation of cycling readiness as a structural capacity of the built environment rather than as a proxy for cycling demand or performance.

4.3 Data Scope and Preprocessing

This section defines the spatial data inputs and preprocessing steps used to construct the cycling-infrastructure network that serves as the common input for all subsequent analyses. The purpose of preprocessing is preparatory: it establishes a consistent spatial reference, harmonised datasets, and an edge-based network enriched with the attributes required for indicator computation. No readiness scoring, profile differentiation, or diagnostic interpretation is performed at this stage.

4.3.1 Data sources and study area definition

Cycling infrastructure data are derived from OpenStreetMap using curated extracts provided by the *European Cyclists' Federation Cycling Infrastructure Tracker (QECIO 2.0)* (ECF, 2025) which can be found in a GitHub Repository (GitHub, 2025). These extracts apply a consistent interpretation of cycling-related OpenStreetMap tags and geometry rules and are used directly, without additional feature selection or custom querying. This choice reflects the open-data boundary established in Section 3.3 and responds to the data availability and transferability constraints discussed in Section 2.8. By relying on a harmonised, externally maintained extraction process and trusted sources, the methodology ensures consistent representation of cycling infrastructure across all case study cities.

Administrative boundaries are obtained from OpenStreetMap and are used to define the spatial boundary of analysis for each city. All spatial inputs are clipped to these boundaries to ensure consistent spatial coverage and to avoid the inclusion of extraneous network segments outside the planning-relevant urban area. Differences between the extent of the network and the administrative boundary exist, but because of the clipping process, standardization and coherence ensure consistency in the results. Administrative boundaries are not treated as analytical units, yet they provide a pragmatic and reproducible means of defining the study area in comparative GIS-based assessments.

Topographic information is derived from a Digital Elevation Model (DEM + add reference) providing continuous elevation of 25 m per cell coverage across all case study areas in Europe. The elevation data are used exclusively to support terrain-related indicator computation at the network-edge level. No additional land-use, traffic, or demand-related datasets are incorporated at this stage, in line with the deliberately constrained data strategy outlined in Section 2.8.

The exclusive use of open and globally available datasets constitutes a deliberate methodological choice. As discussed in Chapter 2, reliance on proprietary or municipal datasets can improve local precision but substantially reduces reproducibility and cross-city comparability. The adopted data scope therefore prioritises transparency, scalability, and methodological consistency over exhaustive representation of local infrastructure detail.

4.3.2 Network preparation and attribute selection

Following data acquisition, the cycling infrastructure is prepared as an edge-based line network that forms the analytical backbone of the framework. This representation aligns with the network-oriented analytical spatial scale discussed in Section 2.3, where cycling readiness is conceptualised as a structural property of the infrastructure network rather than as a function of individual routes or travel behaviour.

All spatial layers are reprojected to a common coordinate reference system and clipped to the study area. Network geometry is cleaned to ensure topological coherence and suitability for edge-level analysis, including the removal of invalid geometries and the enforcement of consistent line segmentation. These operations are strictly preparatory and do not modify or infer infrastructural quality.

For each network edge, basic geometric attributes such as segment length are computed. Elevation values are sampled at edge endpoints from the digital elevation model to support the future slope calculation. Relevant OpenStreetMap attributes required for indicator computation (infrastructure type, surface material, and effective width where available) are retained, when avaialable, in the network schema without transformation. No assumptions are introduced regarding missing or ambiguous attributes at this stage.

Importantly, no indicator values are scored, normalised, or aggregated during network preparation. The output of this step is an preparatory, attribute focused cycling network that documents the physical conditions present in the input data. This network constitutes the sole input to the indicator computation stage described in Section 4.3, ensuring **a clear separation between data preparation and analytical evaluation**, consistent with the staged GIS workflows reviewed in Chapter 2.

4.4 Indicator Computation

This section describes how cycling readiness indicators are computed at the network-edge level. The indicator computation phase translates the prepared cycling infrastructure network derived directly from the ECF repository into a small set of measurable variables that describe the physical and terrain-related conditions shaping cycling feasibility. These indicators form the only quantitative inputs to the Cycling Readiness framework.

All indicators are computed for individual network edges and expressed on bounded, normalised scales. This enables consistent profile-specific scoring, weighting, and spatial aggregation in later steps, while preserving the ability to inspect conditions at the level of individual infrastructure segments. The same indicator set is applied to both the commuter bicycle and cargo-bike profiles. Differences between profiles are introduced exclusively through profile-specific scoring thresholds, not through different variables. This ensures that contrasts between profiles reflect differences in vehicle requirements rather than differences in data or model structure, in line with the conceptual framework introduced in Chapter 3.

At this stage, indicator computation is strictly descriptive. No interpretation, aggregation, or diagnostic logic is applied. Indicators represent measured infrastructural conditions only, without embedding assumptions about behaviour, demand, routing, or policy intent.

4.4.1 Indicator domains and scope

The Cycling Readiness Index is driven by four indicator domains:

- **Infrastructure type** describing the design intent and spatial form of cycling facilities
- **Surface quality** capturing the material type of the riding surface
- **Effective infrastructure width** representing usable lateral space available for cycling movement
- **Slope** representing terrain-related elevation constraints

These indicators are selected deliberately and conservatively. They are included because they meet three criteria that define the scope of the framework.

First, they represent first-order physical constraints on cycling feasibility. Each indicator describes a condition that can directly prevent cycling or significantly limit its operability, independent of user preference or behavioural tolerance. For example, insufficient width, unsuitable surface material, or excessive slope can make infrastructure unusable for certain bicycle types regardless of perceived comfort or safety.

Second, these indicators describe structurally persistent properties of the built environment. Infrastructure type, width, surface, and slope tend to change slowly over time and reflect long-term spatial allocation decisions rather than short-term operational conditions. This aligns with the framework's focus on assessing inherited infrastructural constraints rather than transient traffic states or behavioural responses.

Third, all four indicators can be operationalised consistently using open and transferable data sources, primarily harmonised OpenStreetMap attributes and digital elevation models. Indicator selection is intentionally limited to variables that can be derived with comparable reliability across cities, ensuring that observed spatial patterns reflect infrastructural conditions rather than data availability or local modelling choices.

Other commonly used bikeability variables, such as traffic volumes, speed limits, intersection complexity, perceived safety, or policy measures, are deliberately excluded. While relevant for understanding cycling experience or predicting uptake, these factors either depend on behavioural assumptions, require context-specific calibration, or rely on data that are inconsistently available across cities. Including them would shift the framework away from a feasibility-oriented assessment toward demand modelling or perception-based evaluation, which lies outside the scope of this study.

Together, the four selected indicator domains define the **minimum sufficient set of physical constraints needed to assess whether existing cycling infrastructure is structurally capable of supporting both standard bicycle use and more demanding cargo-bike operations.** Subsequent analysis builds on this constrained indicator base to examine profile-specific readiness, robustness under increased requirements, and the spatial distribution of hard infeasibility.

4.4.2 Infrastructure type

Infrastructure type represents the design intent of cycling facilities and constitutes the primary indicator within the infrastructure domain. The indicator is derived from the *infra_type* attribute of the QECIO dataset (reference?). The infrastructure classes are reclassified into a simplified typology category reflecting functional differences relevant to cycling feasibility. Each category is assigned a categorical suitability score on a bounded 0–1 scale, where higher values correspond to facilities explicitly designed for cycling and lower values represent environments where cycling is permitted but not prioritised. (FROM WHICH METHODOLOGY WE TOOK THIS FROM?) Physical separation from motor traffic is not treated as a separate indicator, as it is already embedded within the infrastructure type classification. Scores represent structural suitability rather than perceived comfort and are applied uniformly across cycling profiles prior to profile-specific feasibility scoring.

Infrastructure type	**Score**
Cycle track	1.00
Cycle lane	0.80
Cycle and pedestrian track	0.60
Bus–cycle lane	0.60
Cycle street	0.50
Pedestrian track with cycling allowed	0.30
Limited-access road	0.20

4.4.3 Surface quality

Surface quality captures the material type of the riding surface and is computed at the edge level using OpenStreetMap surface tags provided by the QECIO dataset. It is important to distinguish between surface type and surface condition. While surface type refers to the material composition of the riding surface, surface condition describes its state of maintenance and wear, which is often not mapped due to its temporal variability.

The QECIO composite surface-quality field is not used due to limited and inconsistent coverage. Instead, raw surface material tags are reclassified into ordered material categories reflecting increasing levels of structural suitability for cycling. Where multiple surface descriptors are present for a given edge, the lowest associated suitability score is applied, reflecting the weakest surface condition encountered. Surface suitability scores are bounded between 0 and 1, as shown in Table X. Surface scores represent structural feasibility and durability rather than ride comfort and are evaluated identically for both cycling profiles prior to profile differentiation.

Surface material	**Score**
Asphalt, concrete, metal, chipseal	1.00
Paved, paving stones, bricks, wood	0.75
Cobblestone, sett, compacted, fine gravel	0.50
Unpaved, ground, gravel, dirt, sand, mud	0.25

4.4.4 Effective width

Effective width represents the usable lateral space available for cycling and constitutes a key structural feasibility constraint, particularly for cargo bikes. Width values are derived from the width attribute provided by the QECIO dataset where available. Raw width values are transformed into bounded suitability scores using **profile-specific threshold tables**. Scores represent feasibility rather than comfort, and widths below minimum feasible thresholds are assigned a score of zero. Thresholds differ between the standard bicycle and cargo-bike profiles to reflect increased spatial requirements for wider and heavier vehicles.

Effective width (m)	Standard bicycle	Cargo bike
< 1.20	0.00	0.00
1.20 – < 1.50	0.50	0.00
1.50 – < 1.80	0.75	0.40
1.80 – < 2.20	1.00	0.70
≥ 2.20	1.00	1.00

Treatment of missing width values

Width data are often incomplete, and their missingness is systematic rather than random, reflecting known limitations of open spatial datasets for cycling infrastructure attributes (Hardinghaus et al., 2021). To preserve cross-city comparability without implicitly assuming completeness, missing width values are handled through a hierarchical treatment strategy rather than exclusion.

Previous open-data bikeability studies typically address missing attributes by excluding indicators that cannot be reliably evaluated and reporting the resulting gaps as data limitations (Weikl & Mayer, 2020; Hardinghaus et al., 2021). In contrast, this framework retains width as a core feasibility constraint and differentiates between situations where width can be meaningfully inferred and those where it cannot.

Where width observations are available from the ECF main source, measured values are used directly. Where width is missing but the infrastructure type is suitable for inference, imputation is applied conservatively: city-specific median values are used where sufficient local observations exist, and cross-city reference medians are applied only when city-level evidence is insufficient. This preserves internal consistency while avoiding overfitting to sparse local data.

Where width is missing and the infrastructure type does not allow reliable imputation, no value is assigned. Instead, the segment is treated as infeasible under strict cargo-bike criteria. This results in a distinct category of data-driven infeasibility, separating physical constraints from limitations introduced by data availability.

As a result, three analytically distinct situations emerge: segments that are infeasible due to observed geometric constraints, segments that are infeasible due to missing or ambiguous width information, and segments that remain feasible under the applied criteria. Width completeness is therefore assessed separately through a dedicated diagnostic layer retained for interpretative purposes, ensuring that data limitations are made explicit without conflating data quality with infrastructural feasibility.

4.4.5 Slope

Slope represents terrain related feasibility constraints and is computed for each network edge using elevation differences between its endpoints derived from the DEM. Slope is expressed as percent grade using absolute values, treating uphill and downhill segments symmetrically.

To calibrate the indicator and limit artefacts related to DEM resolution, slope values are capped at 20 percent prior to scoring. Slope is transformed into bounded suitability scores using fixed threshold bins and profile-specific penalty functions. Scores represent progressive loss of structural feasibility rather than comfort. Gradients at or above 10 percent are treated as infeasible for both cycling profiles.

Slope (%)	Standard bicycle	Cargo bike
≤ 2	1.00	1.00
2 – < 4	0.90	0.70
4 – < 6	0.75	0.45
6 – < 8	0.55	0.20
8 – < 10	0.30	0.05
≥ 10	0.00	0.00

4.4.6 Edge-level readiness scores

For each network edge, indicator scores are combined into a composite readiness score using a weighted aggregation scheme. Separate readiness scores are computed for the standard bicycle and cargo-bike profiles by applying different feasibility thresholds to the same indicator set. Where indicator values are missing, aggregation is performed over available components and weights are renormalised accordingly. The resulting edge-level readiness scores represent the final output of the indicator computation stage and constitute the only input to subsequent spatial aggregation and post-index diagnostic analyses.

4.5 Profile Differentiation and Indicator Weighting

This section describes how the Cycling Readiness framework differentiates between standard bicycle and cargo-bike profiles using a shared indicator base. The adopted approach builds on a well-established pattern in GIS-based bikeability assessment, in which different user groups are evaluated on the same network representation using differentiated scoring thresholds rather than separate indicators or datasets. This logic is commonly applied in cyclist-typology and stress-based frameworks, including bikeability models distinguishing confident and less confident cyclists (e.g. Winters et al., 2011; Winters et al., 2013) and the Levels of Traffic Stress (LTS) framework (Furth et al., 2012; Dill & McNeil, 2016), as reviewed in Chapter 2. In the present framework, profile differentiation is implemented through **profile-specific feasibility thresholds** applied to the same indicators, spatial units, and aggregation logic.

4.5.1 Profile-specific scoring

Both cycling profiles are evaluated on the same edge-based indicator set described in Section 4.3. Raw indicator values are computed one time only and expressed on bounded scales [0,1]. Differences between profiles arise ony from the application of stricter feasibility thresholds for the cargo-bike profile, particularly for effective width and slope, reflecting higher spatial, stability, and terrain-related requirements associated with larger and heavier vehicles.
This differentiation logic is structurally aligned with cyclist-typology and stress-based bikeability frameworks,

which apply varying tolerance thresholds to identical network conditions. However, **the conceptual interpretation differs fundamentally**. In studies such as Winters et al., profile differentiation reflects differences in perceived safety, comfort, or tolerance to traffic stress, often grounded in behavioural surveys or stated preferences. Similarly, the LTS framework classifies infrastructure according to stress levels that are interpreted relative to user confidence rather than physical operability.

In contrast, the **Cycling Readiness framework reinterprets threshold differentiation in terms of vehicle-related physical feasibility rather than user perception**. Standard bicycles and cargo bikes are treated as distinct vehicle profiles with different spatial and terrain requirements, evaluated on the same infrastructure network using identical indicators and weights. Observed differences in readiness therefore arise from infrastructural constraints that physically limit vehicle operation, such as insufficient width or excessive slope, rather than from behavioural tolerance or subjective comfort.

By avoiding profile-specific indicators, behavioural modifiers, or separate network representations, the framework preserves internal consistency and enables direct spatial comparison between commuter and cargo-bike readiness. Profile differentiation is thus limited strictly to physical feasibility assessment and does not imply differences in user preferences, route choice, or operational performance.

4.5.2 Indicator weights

Indicator weights are used to express the relative contribution of each physical constraint to overall cycling readiness once minimum feasibility has been established through profile-specific scoring. Weights are applied at the network-edge level after indicator scoring and prior to spatial aggregation, consistent with composite, edge-based bikeability and network assessment approaches reviewed in Chapter 2.

Weighting strategies in the bikeability literature vary widely and reflect fundamentally different analytical goals. Many comfort or behaviour focused indices derive weights from informed preference data from users, expert surveys, or multi-criteria decision analysis techniques such as Analytic Hierarchy Process (e.g. Winters et al., 2011; Winters et al., 2013; Arellana et al., 2020). While suitable for locally calibrated or demand-oriented applications, these approaches rely on context-specific behavioural inputs and are difficult to reproduce or transfer consistently across cities. In contrast, this Cycling Readiness framework adopts a fixed and transparent weighting scheme aligned with transferable GIS-based bikeability approaches that prioritise structural assessment and rule-based feasibility logic over behavioural calibration (e.g. Dill & McNeil, 2016; Hardinghaus et al., 2021). No behavioural calibration, preference modelling, or expert insights is used. This choice reflects the diagnostic intent of the framework and avoids mismatch between physical feasibility and user perception or institutional capacity.

The relative weights assigned to indicators derive from methods in bikeability research and cycling infrastructure assessment rather than by a single reference research. Infrastructure type receives the highest weight, reflecting its dominant role in shaping separation from motor traffic, functional design intent, and baseline cycling feasibility across most bikeability and stress-based frameworks (Landis et al., 2001; Mekuria et al., 2012; Dill & McNeil, 2016). Effective width and slope are weighted equally, reflecting their role as primary geometric constraints that directly limit vehicle stability, manoeuvrability, and load tolerance, particularly under cargo-bike requirements (Jensen, 2007; Arellana et al., 2020; Monteiro et al., 2023). Surface quality is assigned a lower, yet non-negligible weight, acknowledging its influence on rolling resistance, comfort, and maintenance suitability without treating it as a dominant feasibility determinant (Winters et al., 2013; Hardinghaus et al., 2021).

Indicator	**Weight**
Infrastructure type	0.35
Effective width	0.25
Surface quality	0.15
Slope	0.25
Total	1.00

These weights are not intended to reflect user preferences or behavioural sensitivity. They are conservative structural influence factors that indicate how strongly each physical constraint contributes to cycling readiness once basic feasibility conditions are satisfied. The weighting scheme is meant to be simple and fixed to ensure transparency, reproducibility, and comparability across cities.

The same weights are applied to both standard bicycle and cargo-bike profiles to isolate the effect of stricter feasibility thresholds. As a result, differences in readiness between profiles reflect differences in physical requirements alone, not changes in indicator importance or analytical focus.

The selected weights and scoring thresholds should therefore be understood as feasibility-oriented bins informed by design guidance, engineering research, and common bikeability study intentions rather than as optimal calibrated values. Sensitivity testing and empirical calibration are left as directions for future research, particularly where richer local data and planning capacity are available.

4.6 Spatial Aggregation and Composite Outputs

Consistent with GIS-based bikeability and network assessment approaches, edge-level readiness scores are aggregated to an area-based representation to support spatial interpretation and cross-city comparison (Winters et al., 2011; Dill & McNeil, 2016). While cycling readiness is computed at the level of individual network edges, aggregation serves to translate local feasibility conditions into interpretable spatial patterns without introducing routing assumptions, demand modelling, or behavioural hypotheses. Aggregation therefore functions as a diagnostic translation step rather than as an additional analytical operation.

All edge-level readiness values are aggregated to a regular hexagonal grid, which serves as the common spatial unit for mapping and comparative analysis. The use of a regular grid avoids dependence on administrative boundaries or irregular buffer geometries and aligns with transferable, open-data-based bikeability frameworks (Hardinghaus et al., 2021). A hexagonal tessellation is selected to ensure uniform spatial coverage and to reduce directional bias when aggregating linear infrastructure elements. A grid resolution of 50 m is adopted as a compromise between spatial detail and city-scale interpretability.

Edges are spatially intersected with hexagonal cells, and all edge segments intersecting a given cell are associated with that cell. Within each hexagon, the median of the intersecting edge-level readiness values is computed. Cells containing no intersecting cycling infrastructure are treated as invalid and excluded from readiness surfaces. Median-based aggregation provides a conservative representation of typical structural conditions by reducing sensitivity to fragmented infrastructure, short anomalous segments, or locally extreme values, as commonly recommended in network-based cycling assessments (Winters et al., 2011). This approach is particularly suited to feasibility-oriented analysis, where the objective is to identify limiting conditions and robustness margins rather than best-case performance.

Aggregation is performed independently for the standard bicycle and cargo-bike readiness scores, preserving profile-specific differences introduced during indicator scoring. This process yields two composite readiness surfaces per city: one representing readiness for standard bicycles and one representing readiness for cargo bikes, ensuring that observed differences are driven solely by the physical requirements associated with each cycling profile.

To make these differences explicit, a readiness-difference layer is computed as the hex-level difference between cargo-bike readiness and standard-bicycle readiness (Cargo − Standard). This derived layer functions as a comparative diagnostic that highlights locations where infrastructure conditions suitable for standard cycling become limiting under cargo-bike requirements. The difference layer does not constitute a separate index and should be interpreted exclusively as an indicator of structural robustness loss under stricter feasibility constraints.

4.7 Post-Index Diagnostic Analyses

While most bikeability indices terminate at composite mapping, this framework extends the analytical workflow with post-index diagnostics to support interpretation and avoid misreading aggregated values. After index construction and spatial aggregation, a set of post-index diagnostic analyses is performed on the readiness outputs. These diagnostics have a interpretative nature and do not modify indicator values, weights, aggregation logic, or composite readiness scores. Their purpose is to support interpretation of aggregated readiness patterns, identify structural constraints, and expose robustness limits that may be obscured by composite values alone.

Many existing bikeability indices rely primarily on aggregated composite outputs, often prioritising compact representation over diagnostic transparency. As discussed in Chapter 2, such aggregation can hide bottlenecks and feasibility thresholds that are critical for understanding how a cycling network performs. In response, this framework retains a limited set of post-index diagnostics to make explicit what the aggregation process necessarily compresses.

By separating index construction from diagnostic interpretation, the framework preserves methodological transparency and avoids conflating feasibility assessment with explanatory or evaluative judgement. All diagnostics are derived exclusively from the ultimate readiness outputs described in Sections 4.3 to 4.5 and are used only to support interpretation and offer planning insights.

4.7.1 Robustness under cargo-bike requirements (Δ Readiness)

Structural robustness is assessed through a strict difference analysis between cargo-bike and standard-bicycle readiness. For each hex cell, the difference is computed as cargo-bike readiness minus standard-bicycle readiness. This difference layer isolates sensitivity to stricter cargo-bike feasibility requirements. **Negative values indicate locations where infrastructure that supports standard commuter cycling becomes fragile or unsuitable under cargo-bike constraints.** The difference layer does not represent quality, performance, or demand. It functions solely as a diagnostic of robustness loss within the existing cycling network.

4.7.2 Hard feasibility constraints

Binary feasibility diagnostics are used to distinguish low readiness from hard infeasibility. **Hex cells are classified as infeasible for cargo bike use when all contributing network edges violate minimum feasibility thresholds,** such as insufficient effective width or excessive slope. These diagnostics define hard structural limits under current infrastructure conditions and prevent low readiness values from being misinterpreted as marginal or improvable conditions in locations where cargo bike use cannot physically occur. Hard infeasibility is therefore treated separately from relative readiness variation.

4.7.3 Bottleneck attribution

Where cargo bike use remains feasible but readiness values are low, bottleneck attribution is used to identify the dominant limiting factor within each hex cell. **The bottleneck corresponds to the indicator component with the lowest median suitability score**, such as effective width, slope, surface quality, or infrastructure type. Bottleneck attribution is descriptive and categorical. It does not affect readiness scores, imply prioritisation, or prescribe design interventions. Its function is to support interpretative reading of readiness patterns by linking low values to specific structural constraints.

4.8 Validation, Robustness, and Reproducibility

Validation in this study is understood as **internal and methodological validation** rather than empirical validation against observed cycling or logistics behaviour, due to methodological focus and lack of external resources. The purpose of validation is to confirm that the Cycling Readiness framework behaves in a logically consistent and interpretable way given its conceptual design and scope, rather than to predict real-world cycling uptake or delivery performance. Here, robustness refers to the internal consistency of the framework rather than to infrastructural robustness assessed through Δ readiness.

4.8.1 Internal consistency and robustness checks

The methodology's internal consistency is assessed by ensuring the directional behaviour of the readiness outputs. Improvements in physical infrastructure characteristics are expected to increase the readiness values. On the other hand, constraining conditions should systematically reduce readiness score.

Profile differentiation is verified by ensuring that, under identical spatial conditions, cargo-bike readiness values are consistently equal to or lower than standard-bicycle readiness values. This confirms that stricter feasibility thresholds for cargo bikes operate as intended and that differences between profiles arise from differential tolerance to the same physical constraints rather than from inconsistencies in data processing or aggregation.

Aligning to the scope of the project, no formal sensitivity analysis is conducted. The framework prioritises transparency, interpretability, and diagnostic clarity over optimisation. Exploration of alternative weighting schemes, threshold values, or aggregation strategies is identified as a potential direction for future research rather than a requirement for the present analysis.

4.8.2 Limitations and modelling judgement

The framework explicitly presents choices regarding indicator selection, scoring thresholds, and indicator weights. These choices are informed by the literature review and by planning practices but are not universally optimal and can be adapted to every context. Alternative parameterisations may be appropriate in different urban contexts or for different planning objectives.

Readiness outputs are sensitive dependent to the quality and completeness of the spatial data selected. Although the use of harmonised OpenStreetMap data via the QECIO framework from ECF supports comparability across cities, many attributes remain unevenly mapped. The methodology addresses this through conservative scoring rules and explicit handling of missing values, but residual uncertainty remains, particularly in data-sparse contexts.

Spatial aggregation to a 50 m hexagonal grid generalises local conditions. This supports interpretable city-scale analysis and comparison but may smooth fine grained constraints such as short discontinuities, intersection geometry. The framework is therefore intended for strategic diagnosis rather than detailed infrastructure design or operational routing. However, all readiness scores and diagnostic outputs can also be examined at the edge level to highlight those fine grained phenomena.

4.8.3 Reproducibility and procedural protocol

Reproducibility is ensured through the exclusive use of open datasets, standard indicator definitions, and a documented processing workflow covering data preparation, indicator computation, profile differentiation, weighting, spatial aggregation, and diagnostic analysis, as well as the script. All analytical steps were implemented through a scripted process to ensure reproducibility and to minimise manual intervention (See Appendex) . The analytical pipeline is implemented using scripted geospatial processing to minimise manual intervention and support repeatability.

All results presented in Chapter 5 are generated using a frozen version of the analytical pipeline. After finalising the methodology, the computational workflow, scoring parameters, and execution order are locked, and no further changes affecting numerical outputs are made. Diagnostic layers are derived exclusively from outputs and do not modify readiness values.

4.9 Use of AI-assisted tools

During the development of this thesis, AI-assisted tools were used in a limited and pragmatic way to support technical work and manuscript preparation. Their use focused on practical tasks such as debugging Python code, clarifying code logic during development, and generating or inspecting exploratory charts and tables within the VSCode environment. These tools were used to assist the implementation of methods designed by the author, not to define or automate analytical procedures.

AI-assisted tools were also used to help maintain internal consistency across the document, including checking terminology, polishing sentences, assessing structure, and bibliographic formatting. In addition, they were occasionally used as a reading aid when engaging with technically dense literature, for example to clarify how indicators or thresholds were described in previous studies. In all such cases, AI outputs were treated as supportive explanations and were always evaluated critically against the original sources.

AI-assisted tools did not play any role in defining the research questions, selecting indicators, setting thresholds, designing the methodology, or interpreting the results. All analytical decisions, methodological choices, and conclusions presented in this thesis were made by the author. The use of AI tools was therefore comparable to other forms of technical assistance commonly used in research, such as programming documentation, reference management software, or code debugging utilities. Full responsibility for the content and conclusions of this thesis rests with the author.

List of the indicators included in the project’s index

Infrastructure type	Score
Cycle track	1.00
Cycle lane	0.80
Cycle and pedestrian track	0.60
Bus–cycle lane	0.60
Cycle street	0.50
Pedestrian track with cycling allowed	0.30
Limited-access road	0.20

Surface material	Score
Asphalt, concrete, metal, chipseal	1.00
Paved, paving stones, bricks, wood	0.75
Cobblestone, sett, compacted, fine gravel	0.50
Unpaved, ground, gravel, dirt, sand, mud	0.25

Effective width (m)	Standard bicycle	Cargo bike
< 1.20	0.00	0.00
1.20 – < 1.50	0.50	0.00
1.50 – < 1.80	0.75	0.40
1.80 – < 2.20	1.00	0.70
≥ 2.20	1.00	1.00

Slope (%)	Standard bicycle	Cargo bike
≤ 2	1.00	1.00
2 – < 4	0.90	0.70
4 – < 6	0.75	0.45
6 – < 8	0.55	0.20
8 – < 10	0.30	0.05
≥ 10	0.00	0.00

Indicator	Weight
Infrastructure type	0.35
Effective width	0.25
Surface quality	0.15
Slope	0.25
Total	1.00

5. Results

5.1 Overview of Results and Reading Guide

This chapter presents the spatial results of the Cycling Readiness framework. The results consist of two composite readiness indices (Core Readiness and Robustness) and a set of diagnostic layers (Hard Feasibility and Bottleneck Attribution) used to support their interpretation. The composite indices summarise overall cycling feasibility, while the diagnostic layers explain why readiness is high, low, or fragile in specific areas. All results are based on the same cycling infrastructure network and are aggregated using a consistent hexagonal grid. Differences between outputs therefore reflect changes in feasibility conditions rather than differences in data coverage or network extent.

Four diagnostic layers are used.

Core Cycling Readiness scores represent the baseline structural feasibility of the cycling network for each vehicle profile. Separate readiness scores are computed for standard bicycles and cargo bikes, reflecting whether existing infrastructure meets minimum physical requirements under each set of assumptions. These scores provide an overall picture of where cycling infrastructure is structurally usable, without indicating robustness margins or causes of limitation.

Robustness Loss (Δ Readiness) shows the difference between cargo-bike readiness and standard bicycle readiness for the same infrastructure and functions as a stress test. Large negative values indicate locations where infrastructure that supports commuter cycling becomes unsuitable for cargo bikes once stricter physical requirements are applied.

Hard Feasibility constraints identify absolute limits to cargo-bike use. These binary layers indicate whether at least one network segment within a hexagon is strictly infeasible due to insufficient width or excessive slope. They distinguish locations where cargo-bike use is impossible without physical change from locations where readiness is low due to cumulative but potentially improvable conditions.

Bottleneck Attribution identifies the dominant factor limiting cargo-bike readiness in each hexagon. Each area is classified by the single most influential constraint—such as width, slope, surface condition, or infrastructure type. This layer does not measure severity; its purpose is to clarify which type of intervention would be most relevant if readiness were to be improved.

Together, these diagnostic layers support interpretation of the composite readiness maps. Constraint-focused layers explain what limits cargo-bike feasibility, while network-structure layers explain how robustness or fragility is distributed spatially. Brief explanatory notes for graphs and data coverage are provided where necessary, with detailed discussion deferred to Chapter 6.

5.2 Core Cycling Readiness Across Profiles

5.2.1 Case selection and reading logic

To present the Core Cycling Readiness results in a clear and comparable way, two case study cities are selected for detailed visualisation based on the Table 3 (Cross-City Overview Table of Results). The selection is not intended to rank cities or highlight best and worst performers, but to illustrate contrasting readiness patterns that happen across the full set of analysed cities.

Copenhagen is selected as a control case, as it exhibits consistently high readiness values for both standard bicycle and cargo-bike profiles (Commuter Median = 0.925 and Cargo Median = 0.925), with limited divergence between the two. This stability makes it a useful reference for interpreting what structurally robust cycling readiness looks like when stricter physical requirements are applied.

Paris is selected as a contrast case. While it shows relatively high readiness for standard bicycle use (Commuter Median = 0.83), its cargo-bike readiness is substantially lower (Cargo Median = 0.713), indicating a pronounced loss of feasibility under increased physical constraints. This divergence makes Paris representative of cities where cycling networks support commuter use but remain structurally fragile for cargo-bike operation.

The paired maps presented in the following sections illustrate these two cases using identical visual settings to support direct comparison between profiles. Although only two cities are shown in detail, the same analytical procedure and outputs are generated for all study cities, and the patterns illustrated here are reproducible across the full dataset.

The **Cross-City Summary Table** provides a compact overview of the core readiness results for all study cities. Each row represents a city, while the columns report a fixed set of metrics derived directly from the final hex-level outputs, including standard bicycle readiness, cargo-bike readiness, robustness loss (Δ Readiness), and selected feasibility and structure diagnostics. The table is not intended as a ranking or performance evaluation; the Cross-city comparison is instead used to test methodological behaviour. Its role is to support comparison and case selection by highlighting differences in overall readiness levels, profile divergence, and structural robustness across cities. In this chapter, the table is used to identify representative cases for detailed mapping, while the full set of city-level results remains available and reproducible using the same analytical pipeline.

Table 3 - Cross-city summary table of readiness and robustness indicators.
Source: Author's own work.

City	Hex total	Valid Delta Share	Commuter median	Cargo Median	Delta Median	Delta Negative Share	Delta Q25	Infeasible Any	Infeasible Width	Infeasible Slope
Barcelona	45551	16.4%	0.925	0.813	-0.075	79.4%	-0.07	37.5%	34.5%	10.5%
Bratislava	61362	5.5%	0.855	0.785	-0.075	71.0%	-0.075	14.8%	12.0%	3.9%
Copenhagen	122832	12.5%	0.925	0.925	0.000	30.2%	-0.050	0.0%	0.0%	0.0%
Hofuborgarsvi	463441	3.1%	0.835	0.785	0.000	44.9%	-0.050	11.6%	1.1%	10.5%
Lisbon	40107	13.6%	0.755	0.705	-0.075	67.7%	-0.088	9.7%	9.7%	11.2%
Luxembourg	2043696	2.4%	0.555	0.47	-0.075	72.1%	-0.087	48.3%	46.2%	4.2%
Madrid	279308	4.6%	0.855	0.775	-0.075	92.0%	-0.100	10.5%	7.9%	2.7%
Milan	84022	11.5%	0.855	0.775	-0.075	91.1%	-0.075	16.2%	12.5%	4.0%
Padova	989814	3.6%	0.8413	0.823	0.000	23.3%	0.000	28.8%	27.5%	8.7%
Paris	48688	29.8%	0.83	0.713	-0.075	88.1%	-0.100	18.6%	14.8%	4.6%

5.2.2 Structural readiness patterns across profiles

The maps below show the spatial distribution of cycling readiness for standard bicycles and cargo bikes for the selected case study cities. Readiness values represent median structural feasibility within each hexagon and reflect current infrastructure conditions rather than demand, behaviour, or future scenarios. Differences between maps therefore indicate changes in feasibility under stricter physical requirements, not changes in network coverage.

Across both cities, standard bicycle readiness exhibits broader spatial coverage and higher continuity than cargo-bike readiness. When cargo-bike requirements are applied, readiness patterns become more fragmented, with feasibility retained only in parts of the network that meet stricter width, surface, and slope constraints. The extent and spatial expression of this phenomena is different between cities, revealing differences in how cycling infrastructure responds to increased operational demands.

The paired maps are presented using identical visual settings (scale and orientation, legend values and symbology) to support direct comparison between profiles. The scale of the map is intentionally not representing the whole area of interestes to focus on the small scale of the phenomena. Although only two cities are shown here, the same readiness metrics and mapping procedures are applied consistently across all study cities, and the patterns illustrated are representative of behaviours observed across the full dataset. While these maps describe baseline cycling readiness across profiles, they do not explain where or why feasibility is lost under stricter requirements, which is examined explicitly in the following section through Robustness loss (Δ Readiness).

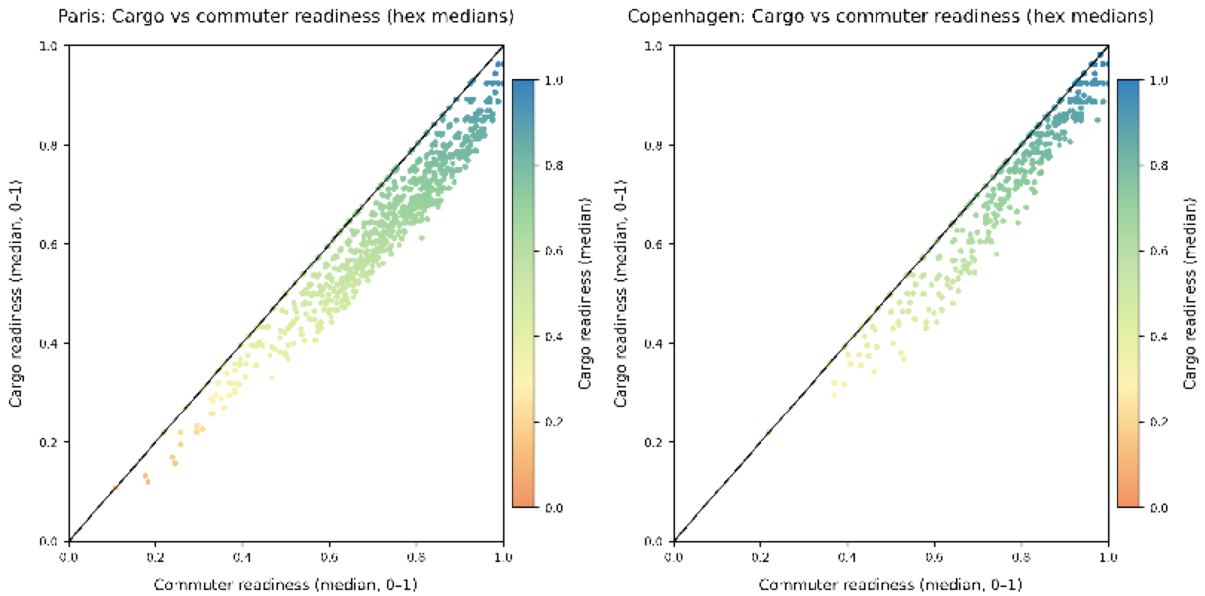
Graphs and Plots. The distribution plots and commuter–cargo scatter diagrams provide a complementary, non-spatial view of how cycling readiness responds to stricter cargo-bike requirements, reaviling if losses are proportional, systematic, or indicative of structural breaks. Taken together, these graphs distinguish robustness from fragility at the network scale. By abstracting from spatial location, these diagnostics clarify whether cargo-bike penalties reflect isolated changes or deeper structural limits, providing a necessary complement add to the spatial analyses presented elsewhere in the chapter.

In Copenhagen, the readiness distributions for commuter and cargo profiles largely overlap, with only minor leftward shifts under the cargo-bike profile. The scatter plot shows a strong alignment along the 1:1 line, indicating that reductions in readiness are generally proportional and limited in magnitude. Deviations from the diagonal are small and evenly distributed, suggesting that stricter requirements do not introduce widespread structural penalties.

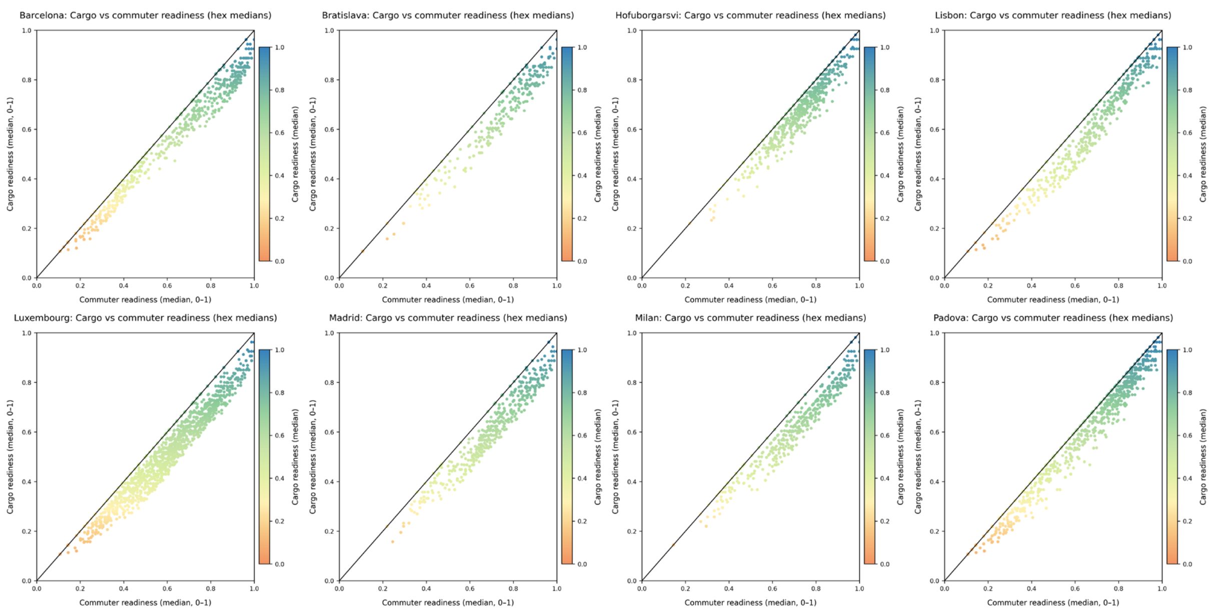
In Paris, the distributions diverge more clearly. The cargo readiness distribution shifts downward and broadens, indicating uneven losses. The scatter plot reveals a systematic departure below the 1:1 line, with increasing dispersion at mid-to-high commuter readiness levels. This pattern suggests that high commuter performance does not reliably translate into cargo-bike suitability and that stricter requirements expose latent structural weaknesses rather than producing uniform degradation.

Map 1 - Cycling infrastructure readiness maps for Copenhagen and Paris under commuter bicycle and cargo-bike profiles.
Source: Author's own work.

These plots compare median commuter and cargo readiness values within each hex cell, using a common spatial aggregation. Points close to the diagonal indicate locations where cycling infrastructure remains structurally robust under stricter cargo-bike requirements, while downward deviations indicate feasibility loss when physical constraints are applied. The distributions therefore describe changes in structural usability, not differences in network extent or cycling coverage.

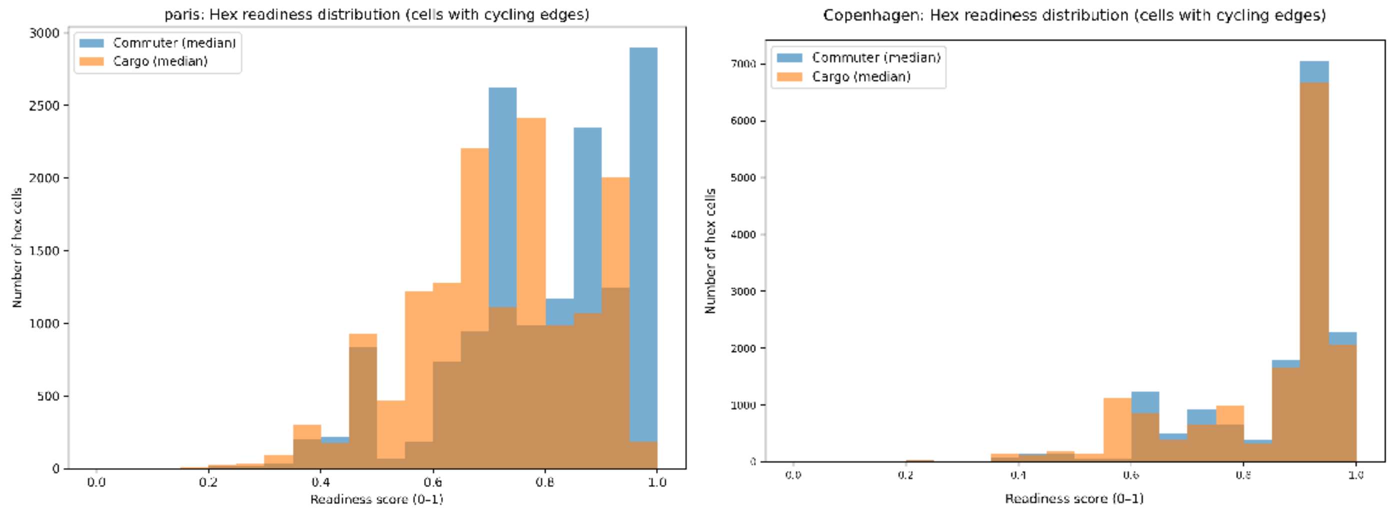


Equivalent scatter plots are provided for all case-study cities. Together, they allow cross-city comparison of readiness patterns and robustness phenomena.

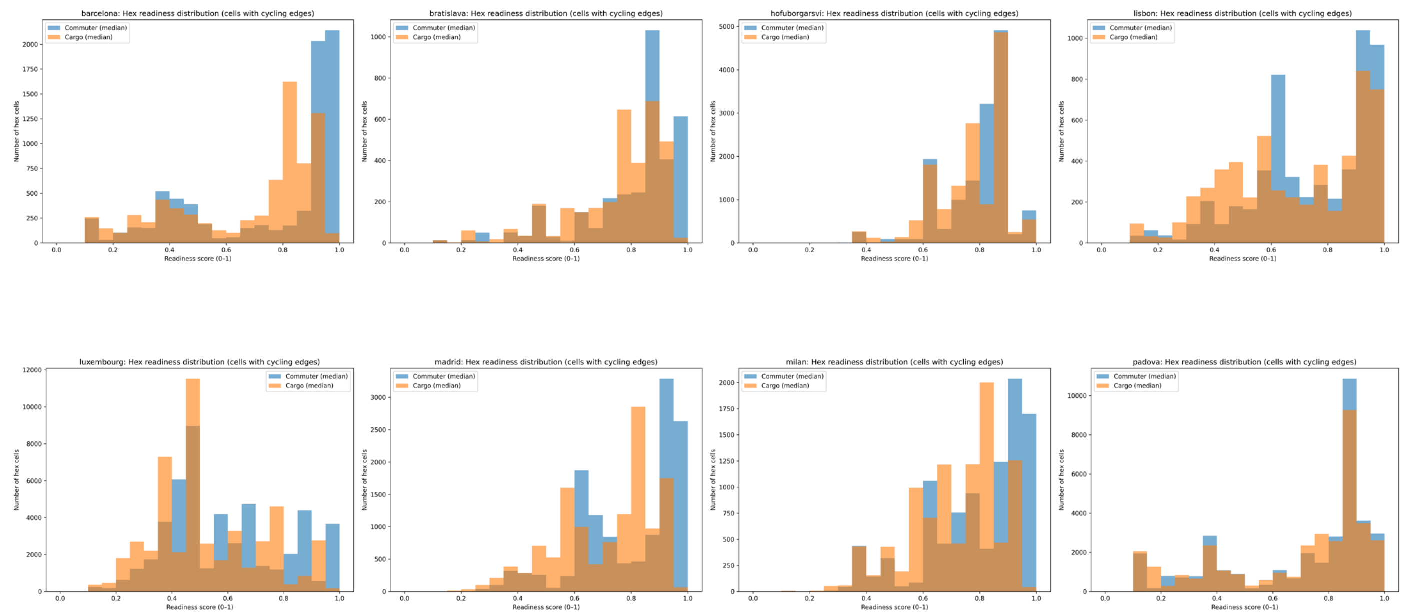


Figures 10 - Scatter plots and histograms illustrating readiness score distributions.
Source: Author's own work.

The histograms show how readiness values are distributed across the network for commuter and cargo profiles. Comparing the two reveals how many areas remain feasible when stricter cargo-bike requirements are applied. Changes in the distribution reflect losses in structural feasibility, not changes in network coverage.



Equivalent histogram are provided for all case-study cities.



Figures 11 - Scatter plot and Histogram for Readiness Maps
Source: Author's own work.

5.3 Robustness loss under increased physical requirements (Δ Readiness)

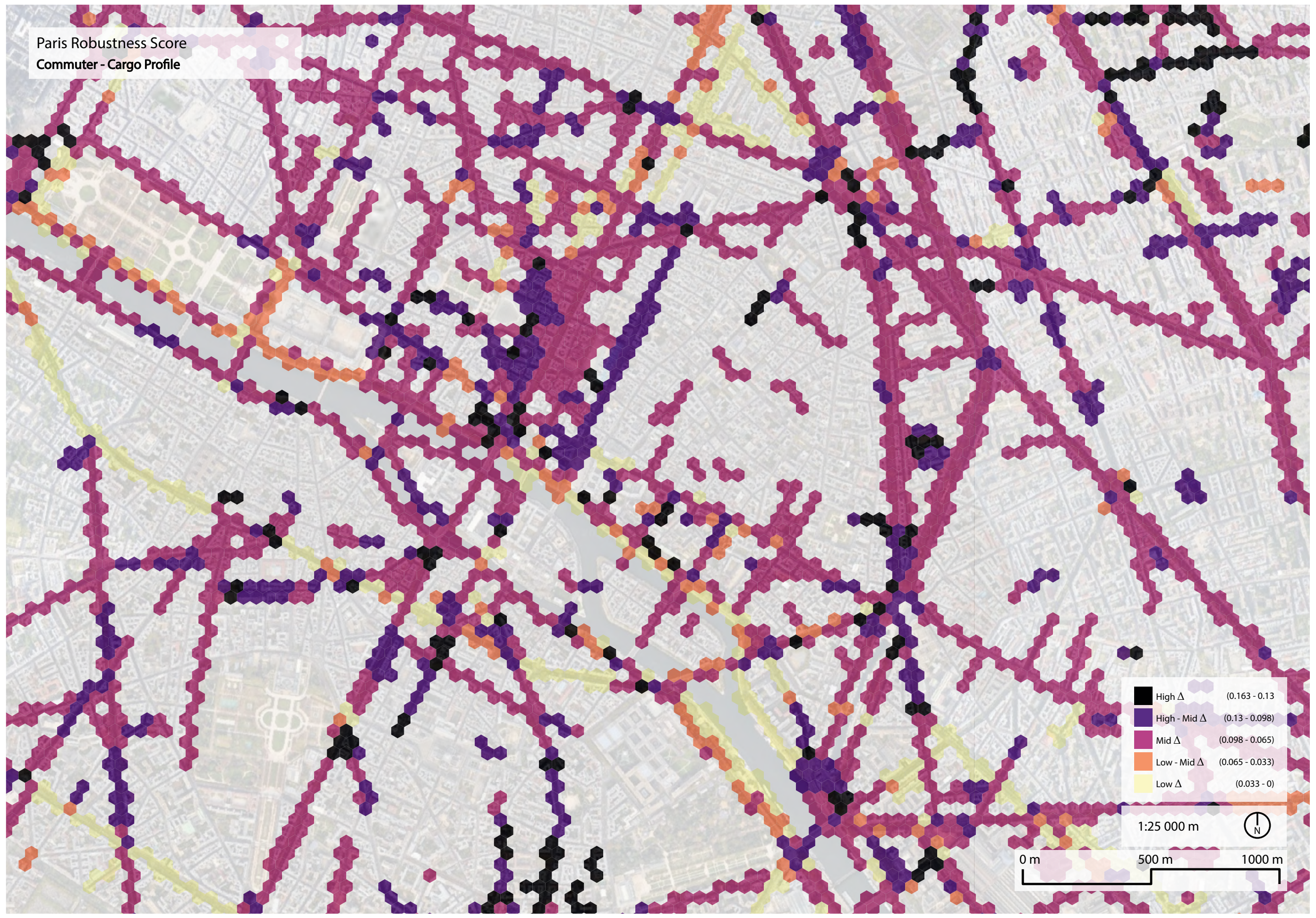
This section directly answers **Research Question 3: How do feasibility limits and robustness losses manifest spatially across cycling networks when stricter requirements are applied?** It examines robustness loss using Δ Readiness, defined as the difference between cargo-bike readiness and standard bicycle readiness for the same underlying cycling infrastructure.

Δ Readiness functions as a stress test of cycling infrastructure by measuring the change in feasibility when cargo-bike requirements are applied to the same underlying network. It is computed as cargo-bike readiness minus standard bicycle readiness and is therefore bounded above by zero. Values close to zero indicate limited or no robustness loss, meaning that infrastructure remains usable under cargo-bike requirements, while increasingly negative values indicate greater loss of feasibility under stricter physical constraints. Differences in Δ thus reflect structural robustness rather than changes in network coverage or data availability.

In Copenhagen, robustness loss is generally limited and spatially localised. The Δ maps show large contiguous areas with values close to zero, indicating that much of the cycling infrastructure suitable for standard bicycle use remains feasible for cargo bikes. This pattern is reinforced by the distribution, which is strongly concentrated near zero with a narrow range and relatively few negative outliers. Together, these results indicate a structurally robust network in which feasibility loss under cargo-bike requirements is confined to a small number of locations.

In contrast, Paris exhibits widespread and clustered robustness loss. The Δ maps reveal extensive areas with moderate to severe negative values, indicating that cargo-bike feasibility declines sharply relative to standard bicycle use across large parts of the network. This spatial pattern is mirrored in the distribution graph, which is shifted toward more negative values and displays a wider spread and heavier area. These combined results show that robustness loss in Paris is not driven by isolated segments, but reflects a pervasive and spatially fragmented reduction in cargo-bike feasibility.

While Δ Readiness identifies where and to what extent cycling infrastructure loses feasibility under stricter requirements, it does not explain which infrastructural constraints are responsible for these losses. The specific physical limits underlying robustness loss are examined in the following section through **hard feasibility and bottleneck attribution diagnostics.**



Maps 2 -Robustness maps for Copenhagen and Paris.
Source: Author's own work.

The figure shows the distribution of Δ Readiness (cargo minus commuter) across hexes: the violin shape reflects how values are concentrated, while the box plot highlights the median and spread. Values closer to zero mean cargo readiness is similar to commuter readiness; more negative values indicate a larger gap where cargo bike use is structurally less feasible.

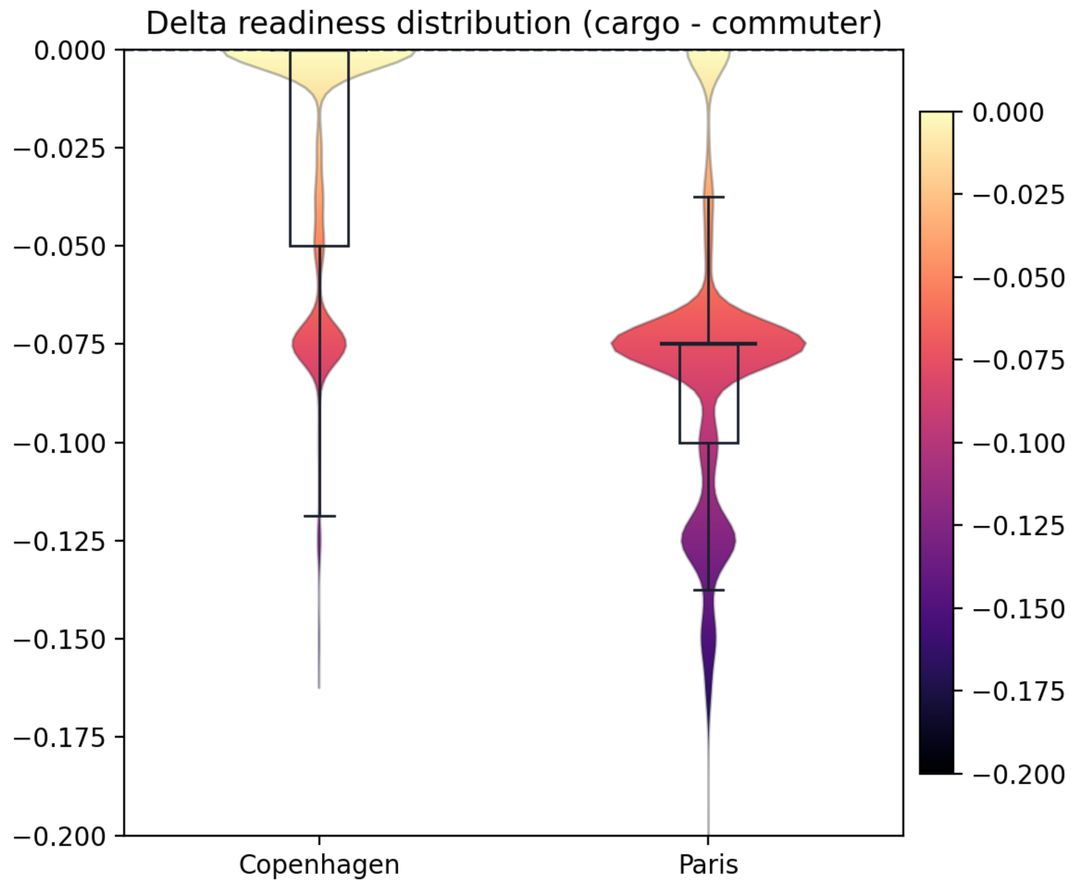


Figure 12 - Violin plots representing robustness score distributions for Copenhagen and Paris.
Source: Author's own work.

The framework generated the same distribution plot for the remaining eight cities to enable consistent visual comparison across the full study set.

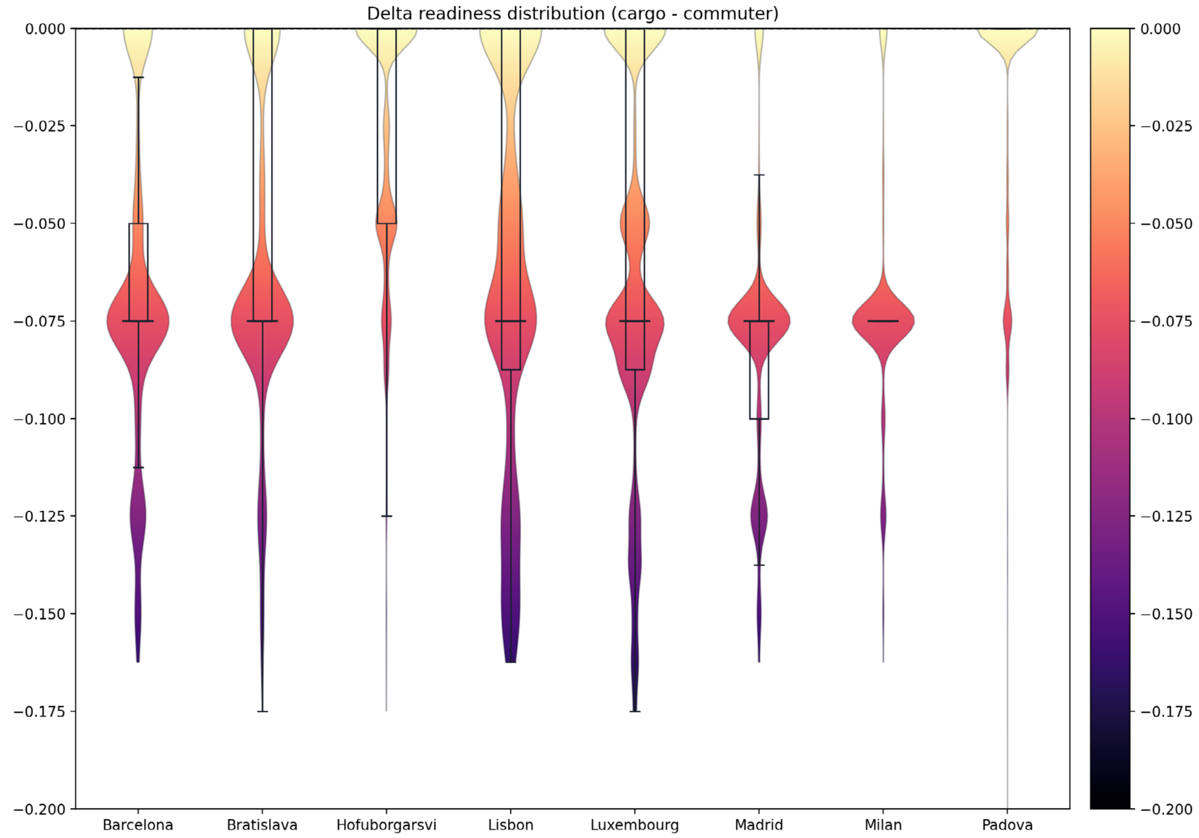


Figure 13 -Violin plots representing robustness score distributions for Barcelona, Bratislava, Höfuðborgarsvæðið, Lisbon, Luxembourg, Madrid, Milan, and Padova.
Source: Author's own work.

5.4 Identifying hard feasibility constraints

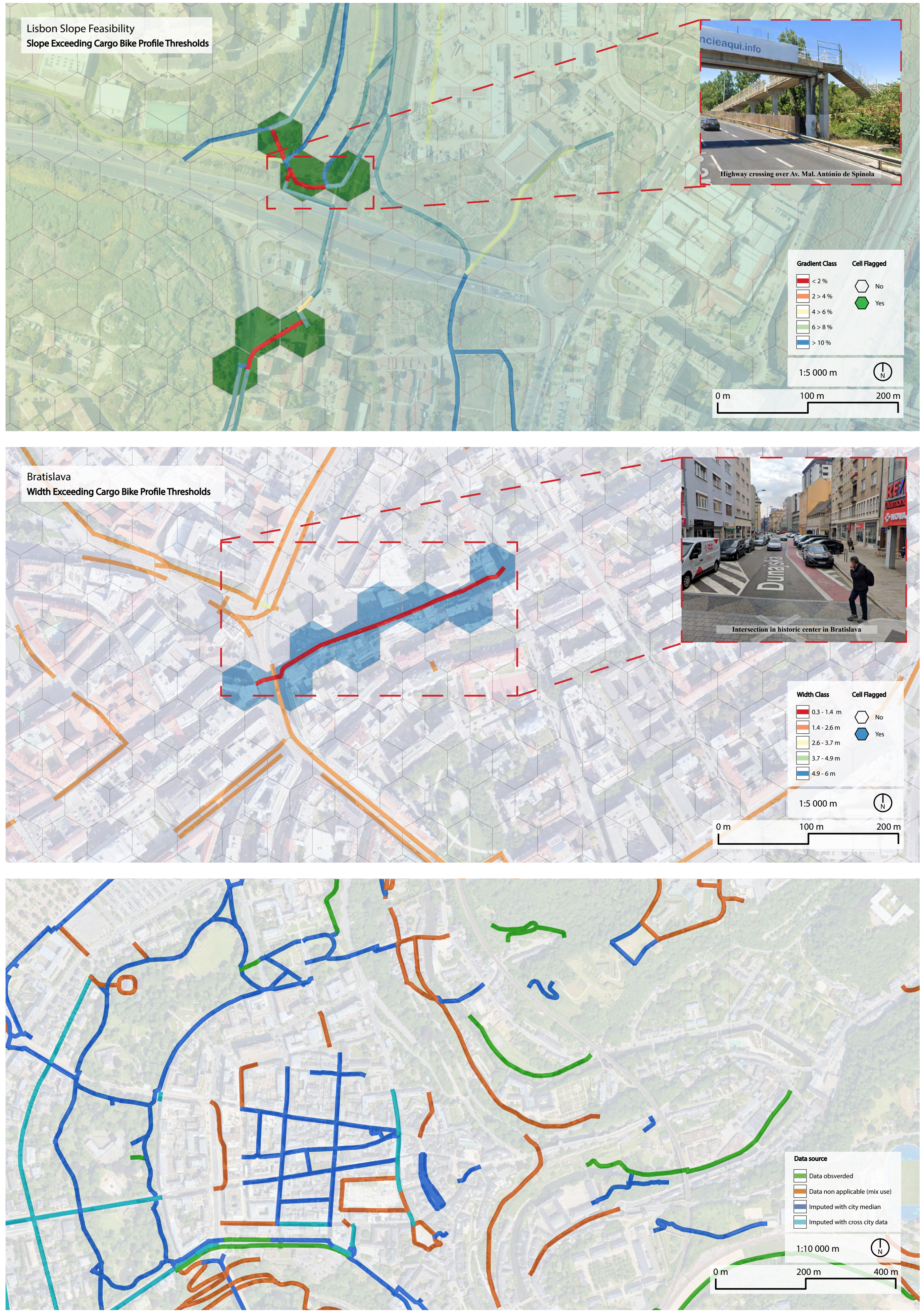
While the previous section examined how cycling readiness changes under stricter physical requirements, this section shifts the focus **from relative performance to hard feasibility**. The purpose of the hard feasibility diagnostics is to identify locations where cargo bike use cannot theoretically assumed feasible due to inadequate physical or structural constraints, regardless of how the network performs under standard bicycle conditions.

Hard feasibility therefore functions as a categorical boundary rather than a graded measure. Where hard infeasibility is flagged, readiness values should not be interpreted as indicators of relative performance; the primary issue is whether the minimum physical conditions required for cargo-bike operation are satisfied under the evaluated criteria. Within the framework, infeasibility functions as an analytical screening step, not as a screening of observed cycling behaviour, where riders may still operate under informal or constrained conditions.

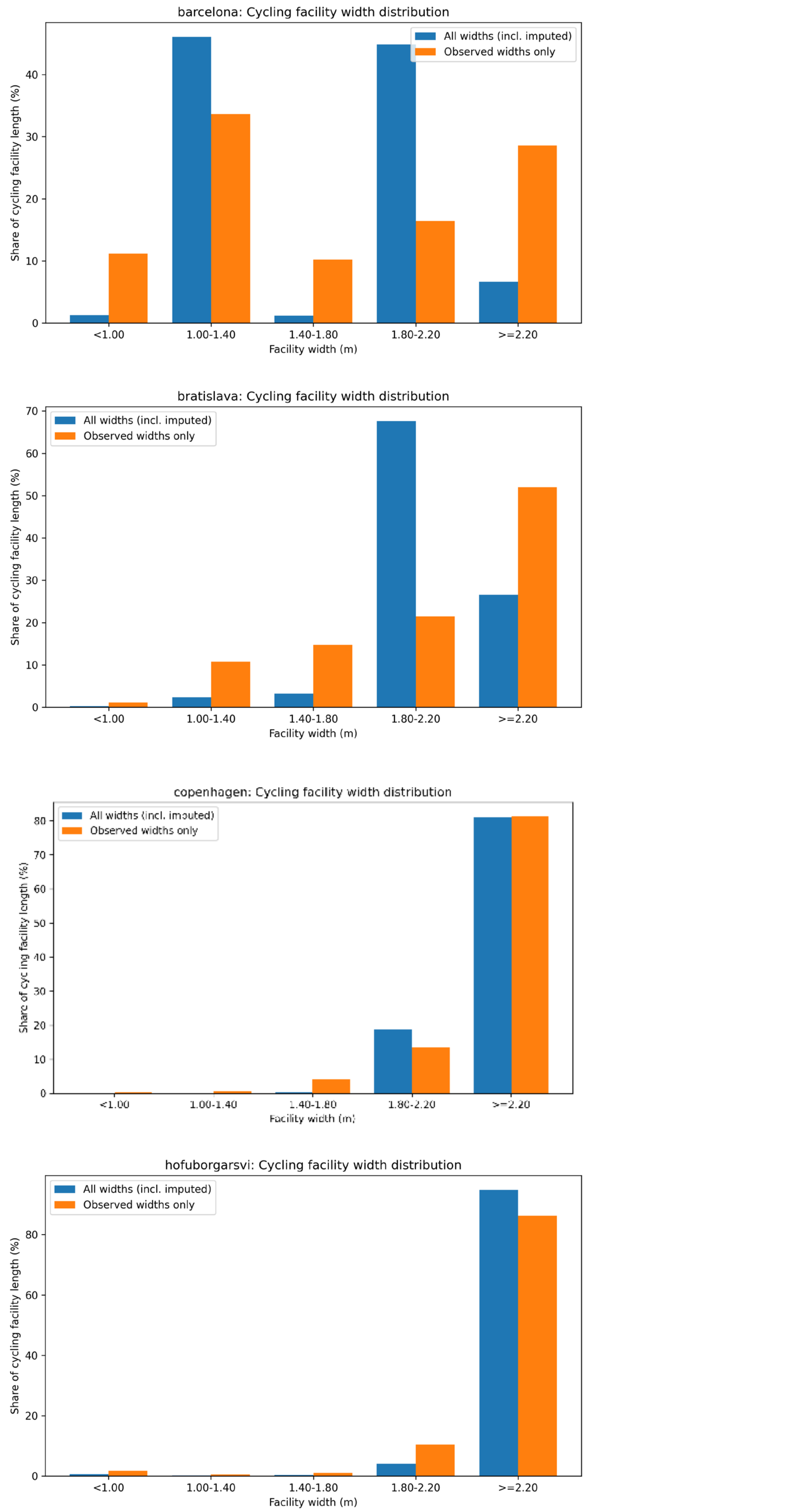
This distinction is necessary to interpret readiness results correctly. Aggregated readiness scores can mask localised segments that are physically impassable for cargo bikes, leading to over-interpretation of feasibility.Without explicitly identifying such limits, readiness values risk being interpreted beyond their valid scope.

Hard feasibility constraint types: width and slope. Within the framework, feasibility constraints are evaluated through two primary physical dimensions: effective width and slope; together with an explicit treatment of data availability. These components are assessed separately in the script and combined to produce a set of infeasibility diagnostics that distinguish between structural limits, terrain-driven limits, and data-driven constraints. **Width infeasibility** captures constraints of cycling infrastructure related to available rideable space. A network segment is flagged as width-infeasible in two situations: first, where the effective rideable width falls below the minimum threshold required for cargo-bike use; and second, where effective width cannot be reliably determined from the available data. In the latter case, infeasibility is assigned conservatively following the missing-data treatment defined in Section 4.3.4. **Observed widths** are directly provided in the source data from ECF. Where width is missing but the infrastructure type is imputable, values may be chose using either a **city-level median** (when sufficient local observations are available) or a **cross-city reference median** (when local data are insufficient). The last group is for infrastructure types that are **not eligible for width imputation**, such as cycle streets, limited-access roads, or unclassified facilities, width is treated as not applicable and is not inferred. These cases are explicitly mapped as data-driven infeasibility rather than assumed to be compliant. **Slope infeasibility** reflects terrain conditions that impose a theoretical limit on cargo-bike use independent of infrastructure design or data completeness. Where slope thresholds are exceeded, cargo-bike use is treated as infeasible regardless of available width or facility type. This constraint captures terrain-driven limits that cannot be resolved through design adjustments alone.

Graphs and Plots. The width distribution graphs provide context for interpreting the width infeasibility results. They show the distribution of different widths across the cycling facilities and highlight the gap between **observed width data** and all the set including **imputed width data**. By comparing these two sets, the graphs make help to understand where infeasibility reflects confirmed narrow infrastructure (observed) and where it is driven by data uncertainty (imputed). They support cautious interpretation of width-based infeasibility as a conservative screening result, not as a complete inventory of narrow infrastructure.



Maps 4 - Hard feasibility and Missing Width Data maps for Lisbon, Bratislava and Luxembourg.
Source: Author’s own work.



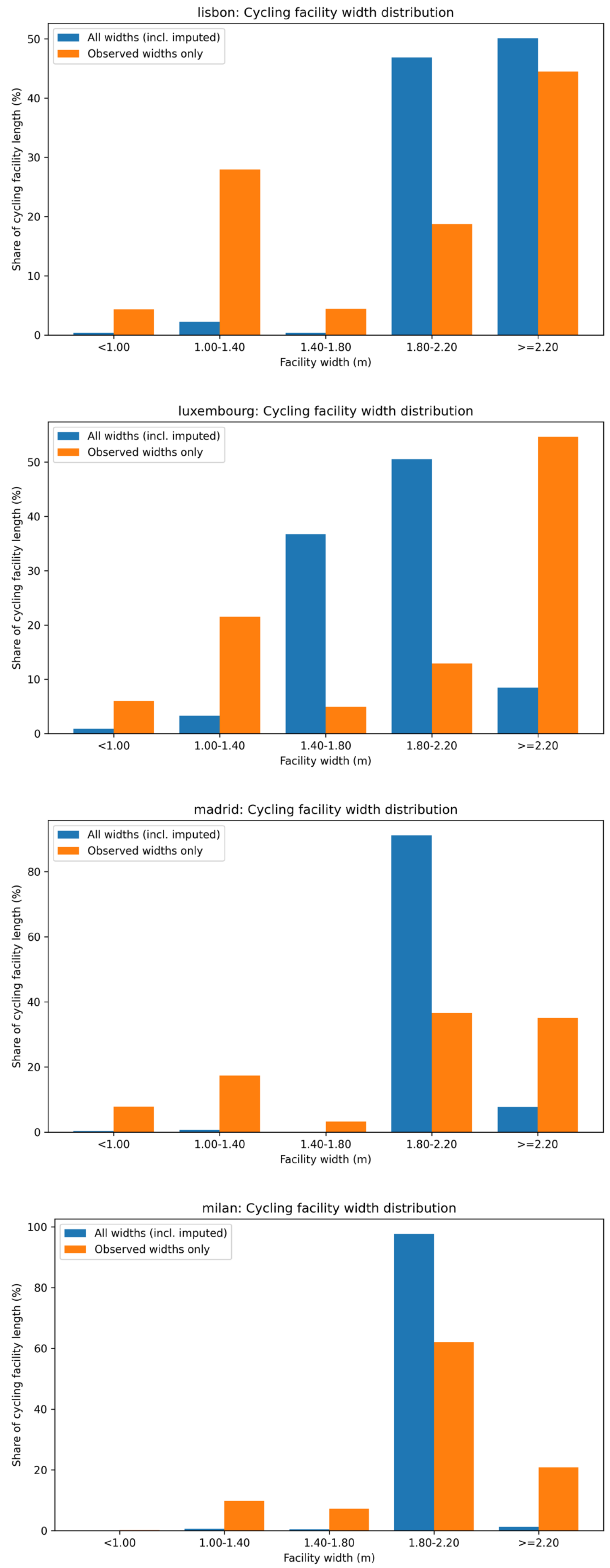


Figure 14 - Histograms showing the distribution of cycle lane widths across all study cases.
Source: Author's own work.

5.5 Bottleneck attribution

While hard feasibility diagnostics identify locations where cargo bike use cannot be assumed possible, **bottleneck attribution examines the dominant constraint factor among width, slope, surface quality, and infrastructure type in each hexagon where cycling infrastructure exists**. Bottlenecks describe what mainly limits cargo-bike readiness in each hex cell, rather than whether operation is possible at all. Bottlenecks is computed for every hex cell and where multiple indicators share the same minimum value, ties are resolved deterministically using a fixed priority order: width, slope, surface, and infrastructure type.

Two cities are selected to illustrate contrasting bottleneck structures based on their city-level bottleneck compositions. Barcelona represents a case where cargo-bike readiness is predominantly constrained by width-related limitations, reflecting cross-sectional restrictions within the cycling network. In contrast, Milan shows a weaker cycling network where the two major bottleneck are surface and width features. These cases are selected to highlight how similar readiness outcomes show different constraints. The **radar plots** summarise the relative contribution of each bottleneck category at the city scale and support interpretation of the spatial patterns observed in the maps.

Just like the other layers, bottlenecks are primarlyv interpreted as diagnostic signals rather than as prioritisation strategies. They indicate whether constraints are primarily geometric, terrain-related, surface-related, or typological. When read along other results or contextual layers their meaning becomes relevant in terms of which planning strategy to use, for example focusing on width or surfaces. Together with robustness loss and infeasibility layers, bottleneck attribution completes the results chapter by translating abstract readiness scores into interpretable constraint patterns that can be examined further in the discussion.

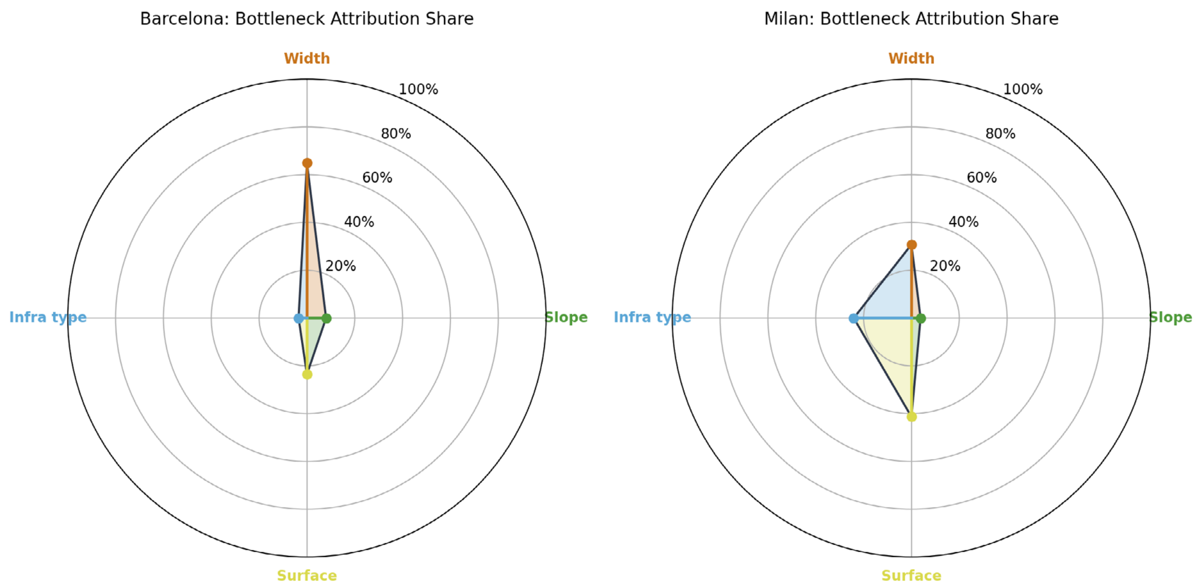
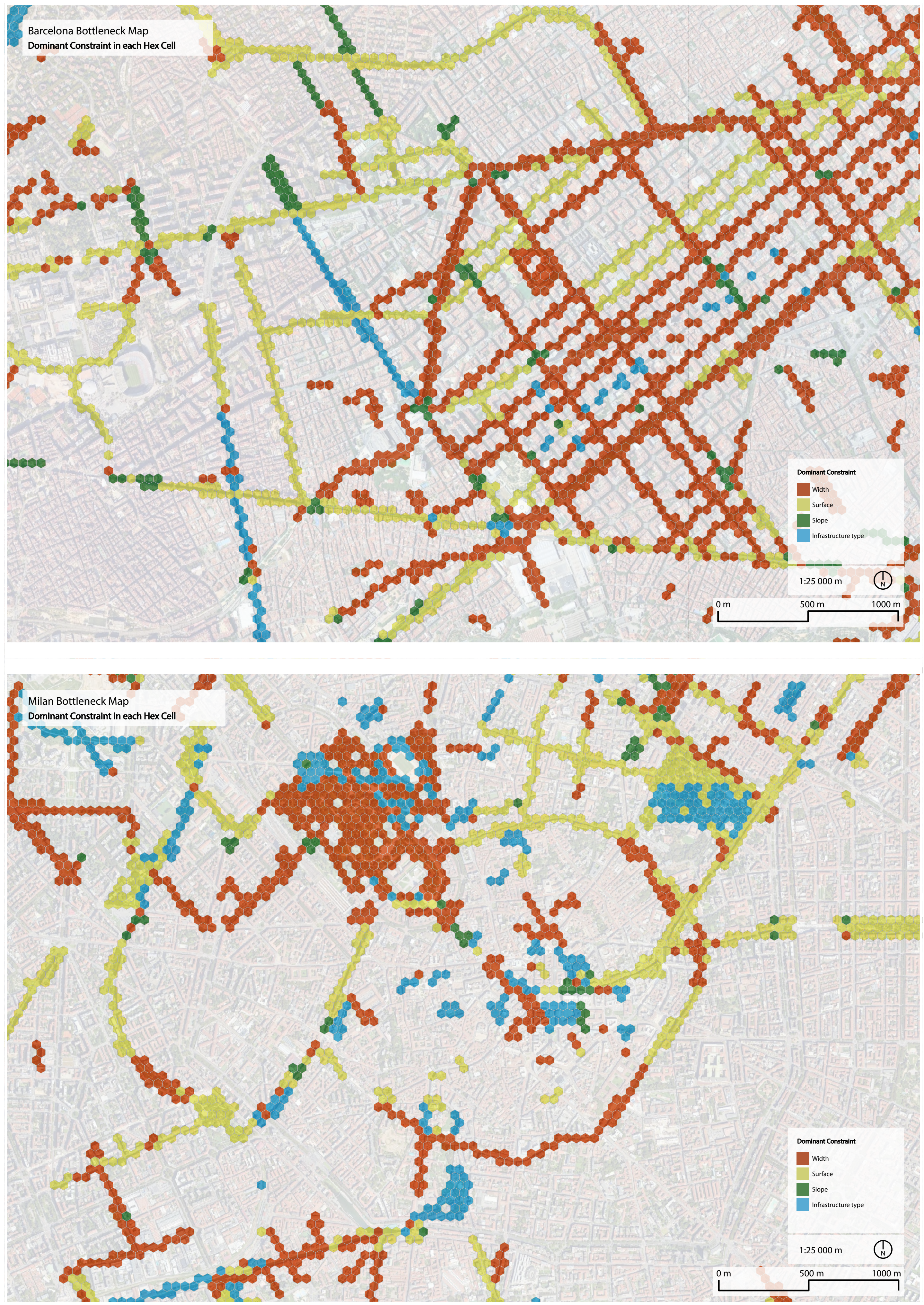
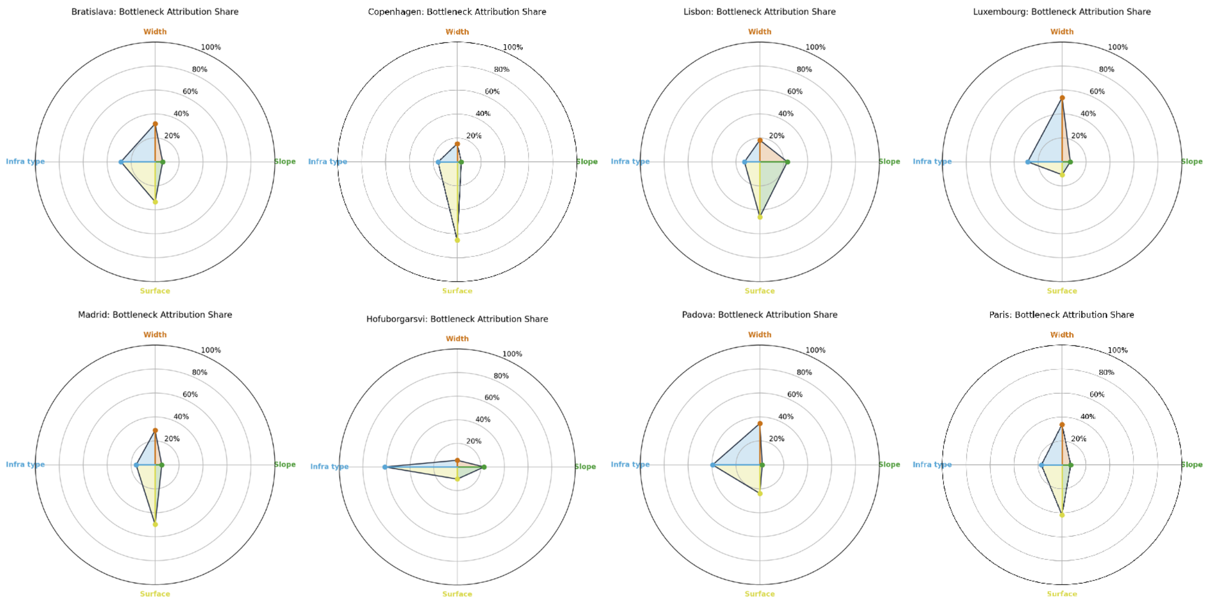


Figure 15 - Radar plots graphs representing the bottleneck attribution distribution in Barcelona and Milan
Source: Author's own work.



Maps 4 - Hard feasibility maps for Barcelona and Milan.
Source: Author's own work.

These radar plots illustrate th dominant limitations for the cargo bike profile for each city.



Figures 16 - Radar plots illustrating bottleneck attribution for each study city.
Source: Author's own work.

5.6 Synthesis of Results

This chapter has presented a set of complementary spatial diagnostic maps and graphs that characterise cycling infrastructure networks with a focus on their structural limits under increased physical requirements. Taken together, these results directly address the Research Questions by demonstrating how feasibility constraints and losses of readiness can be visualised spatially when cycling infrastructure is evaluated beyond standard commuter-oriented assumptions.

The Core Readiness Maps establish where cycling infrastructure remains structurally usable under each profile, while Δ Readiness reveals where this usability declines when stricter cargo-bike requirements are applied. Hard Infeasibility diagnostics then delineate segments where cargo-bike use cannot be assumed under current infrastructural conditions. Bottleneck Attribution further clarifies which specific physical constraints dominate the observed loss of readiness.

Read together, these outputs show that cycling infrastructure readiness for cargo-bike use is neither uniform nor incidental. Instead, losses of readiness follow distinct spatial patterns driven by geometric constraints, terrain, infrastructure typology, and network concentration. Networks that perform well for commuter cycling may remain structurally robust under increased demands, or may exhibit sharp and spatially clustered weakening that remains hidden in commuter-only assessments. The results presented in this chapter are descriptive and diagnostic in nature. The following chapter builds on these findings to interpret their implications for planning practice, methodological positioning, and the limits of commuter-oriented cycling assessment frameworks.

6. Discussion

6.1 Reframing cycling assessment through future-oriented readiness

This section addresses the main research question of this thesis:
How can open data be used to assess the structural robustness and feasibility of urban cycling infrastructure, distinguishing between networks that remain usable under increased physical requirements and those suited only to standard bicycle use?

The framework answers this question by using open and transferable spatial data to evaluate cycling infrastructure as a system of physical feasibility constraints, rather than as a proxy for comfort, perceived safety, or cycling uptake. Open data are used to derive edge-level infrastructural attributes, such as width, surface condition, slope, and infrastructure type, which are then assessed through vehicle-specific feasibility thresholds applied consistently across the same cycling network. This allows infrastructure to be evaluated according to whether it remains physically operable under increased requirements, rather than how it is experienced by current users.

This approach differs from established bikeability frameworks such as the “Bicycle Compatibility Index” and “Bicycle Level of Service”, where similar infrastructural attributes are interpreted primarily in terms of comfort or perceived safety for standard cyclists. It also departs from uptake-oriented studies such as “Mapping Bikeability” (Winters, 2013), where composite bikeability scores are linked to observed or potential cycling behaviour. In contrast, the present framework does not seek to explain or predict use. Instead, it applies stricter feasibility criteria to test how much physical tolerance is embedded in existing infrastructure.

By comparing commuter and cargo-bike feasibility on the same network, differences in readiness are interpreted as measures of **structural robustness**. The resulting Δ Readiness (Robustness Map) highlight where cycling networks operate close to their physical limits, producing diagnostic spatial patterns that reveal latent infrastructural constraints without using behavioural data or demand modelling.

In contrast, this framework treats the same indicators as feasibility constraints, explicitly distinguishing between infrastructure that are operable under stricter requirements and infrastructure that functions only within narrow physical margins. This methodological shift does not represent a critique of bikeability research, but a response to a different analytical question: not how cycling infrastructure is experienced today, but how structurally capable it is of accommodating future demands within largely fixed street geometries.

Methodologically, the framework is inspired by the approach proposed by Mekuria et al. (2012) in the ”Level of Traffic Stress” model, in that edge-level infrastructural attributes are evaluated through threshold-based classification. However, while LTS differentiates stress tolerance by user groups, this framework differentiates feasibility by vehicle type, applying stricter physical requirements to cargo bikes rather than varying cyclist experience. Cargo bikes are used here as an analytical stress test rather than as a normative policy objective. Their larger spatial volume and lower tolerance to geometric and surface constraints make latent infrastructural limits visible.

Structural robustness is reflected in how readiness changes under stricter thresholds: gradual decline indicates limited but extendable tolerance, while abrupt collapse signals hard physical constraints related to width, configuration, or terrain. Read together, these responses show how open-data-based feasibility assessment can distinguish between cycling networks that remain operable under increased physical requirements and those that are usable only for standard bicycle use. In this way, the observed patterns are interpreted as properties of the built environment shaped by past design choices, rather than as judgments of infrastructure quality or performance.

The discussion elaborates this answer by addressing the following research questions. Section 6.2 examines which infrastructural and terrain characteristics drive robustness loss under stricter requirements. Section 6.3 discusses which aspects of feasibility can be reliably assessed using open data and where data limitations impose hard analytical constraints. Section 6.4 interprets how these feasibility limits manifest spatially and how resulting patterns can support early-stage planning diagnosis. Subsequent sections clarify interpretive use, methodological boundaries, and the positioning of cycling readiness within existing cycling research and planning practice.

6.2 Structural determinants of cycling readiness under stricter physical requirements

This section addresses RQ1:
Which infrastructural, network, and terrain characteristics determine whether cycling infrastructure remains structurally robust under stricter cargo-bike requirements, and how can these be operationalised as spatial indicators using open data?

Drawing on the bikeability and cycling-infrastructure literature reviewed in Chapter 2, the analysis focuses on a limited set of infrastructural and terrain characteristics that the literature consistently identifies as physically constraining for bicycle operation, and that become decisive feasibility limits for larger and heavier vehicles such as cargo bikes. These characteristics: **effective rideable width, surface condition, longitudinal slope, infrastructure type, and the clarity of spatial allocation for cycling**, are selected because they directly define the existence and stability of a usable riding facilities, rather than modifying comfort, perceived safety, or behavioural response as in many bikeability indices. In this framework, they are operationalised as edge-level spatial indicators derived from open data and evaluated through stricter, vehicle-specific feasibility thresholds across the same cycling network.

From the results such the Δ Readiness it is clear that these indicators determine if the infrastructure shows a gradual loss of structural tolerance or reaches hard physical limits when cargo-bike requirements are applied. Where Readiness declines gradually as thresholds are applied, usually means that the infrastructure satisfies minimum geometric and surface conditions for both standard cycles and cargo bikes. Such segments can support everyday cycling but offer little capacity to accommodate additional physical demands, indicating contexts where improvments may be possible through incremental adjustments rather than fundamental spatial reallocation.

By contrast, when the Δ Readiness shows a greater value that is a clear sign of insufficient width, excessive gradients, degraded surfaces, incompatible infrastructure type or shared configurations that generates low or impossible conditions for cargo bikes feasibility. In these cases, infeasibility reflects structural constraints present in the built environment, rather than small differences in quality, suggesting planners to reconfigure the space allocation of that area. These results distiguish between infrastructure that operates close close to its physical limits and infrastructure that lacks the spatial capacity to support more demanding cycling vehicles under current conditions, which is what the problem statement suggest to happen.

Methodologically, this process reflects a shift from how similar indicators are treated in much of the bikeability literature reviewed in Chapter 2. Segment based level-of-service models and early bikeability indices typically interpret width, slope, and surface quality as continuous modifiers of comfort, stress, or perceived safety (Bicycle Level of Service and related approaches) limiting the interpretation of the cycling network to an hidden binary score. While network-oriented frameworks such as Levels of Traffic Stress apply threshold logic, they primarily classify stress exposure for standard cyclists rather than to test physical operability under stricter vehicle requirements. In contrast, the novelty of this framework is to reinterpretate these same indicators as in: below certain thresholds, infrastructure is considered structurally inoperable for cargo-bike use rather than merely less comfortable. One result that directly illustrate this is the Hard Infeasibility map in relation to the width (See Map 4) where explicit cells are flagged as impossible to ride for cargo bikes users. By distinguishing between infrastructure that operates close to its physical limits and infrastructure that lacks the spatial capacity to support more demanding cycling vehicles under current conditions, the analysis directly addresses the gap identified in the problem statement, where commuter-oriented bikeability assessments fail to reveal whether existing cycling networks remain structurally feasible under increased physical requirements.

Importantly, observed robustness collapse is only not interpreted as evidence of poor planning or infrastructural failure. As discussed in the literature on infrastructure inertia and path dependency (Chapter 2.2 Infrastructure Persistence and the Limits of Retrofitting), cycling networks are largely shaped by inherited street geometries, historical design standards, and incremental retrofits implemented under spatial, political, and temporal constraints. Narrow or discontinuous solutions therefore often reflect pragmatic compromises within fixed urban environments rather than deficient planning intent. By focusing on structural response instead of performance ranking, the framework aligns with how planning indices are typically used in practice: as diagnostic tools to frame problems and support early-stage reasoning, rather than as instruments that prescribe solutions or assign blame.

At the same time, assessing the physical environment alone is an intentional limitation. Cycling readiness does not capture demand, policy priorities, or local socio-economic context, and therefore cannot determine where intervention is most urgent or desirable. This constraint, however, is also what allows the framework to remain transferable and usable across cities with very different data availability and technical capacity. By isolating the structural conditions of the built environment, the tool provides a common diagnostic baseline that can support planners regardless of local resources, while leaving room for future work that integrates contextual and policy layers where data and capacity permit.

6.3 Open data as a diagnostic boundary, not a weakness

This section addresses RQ2:
Which aspects of cargo-bike feasibility and robustness can be reliably assessed using OpenStreetMap and other open datasets, and where do data limitations impose hard analytical constraints?

As with any empirical spatial assessment, the analytical scope and certainty of the framework are inherently shaped by the availability, quality, and structure of the underlying data, a limitation that has been explicitly discussed in open-data-based bikeability research (Hardinghaus et al., 2021). The results produced by this framework are inseparable from the QECIO 2.0 dataset repository from ECF in which they are generated (European Cyclists' Federation, 2025; QECIO data repository). As outlined in the motivation and problem statement, many cities rely primarily on open spatial data when assessing cycling infrastructure, while the literature reviewed in Chapter 2 shows that many bikeability frameworks depend on locally calibrated datasets or implicitly smooth over data gaps to produce complete scores. This creates a gap between analytically refined methods and tools that are transferable across diverse urban contexts.

Rather than treating limitations in open data as errors to be minimised or hidden, this study treats them as part of the diagnostic outcome, offering visuals about the data completness of certain study case. Cycling readiness therefore reveals not only where cycling infrastructure becomes structurally constraining under stricter physical requirements, but also where the available data supports confident interpretation and where it does not. By making analytical boundaries explicit and focusing on the physical environment alone, the framework prioritises transparency and transferability over completeness. While this limits explanatory scope and motivates further research integrating contextual layers, it also enables the framework to function as a common diagnostic baseline applicable to cities with very different data availability and technical capacity.

While most bikeability indices rely on administrative data, surveys, or calibrated local datasets , this thesis relies on open data plays which play a central role in this approach. Using OpenStreetMap and other open datasets, the framework assesses feasibility with respect to a limited but critical set of infrastructural and terrain attributes, infrastructure type, effective rideable width where available, surface condition, and longitudinal slope, that directly condition the physical operability of cargo bikes and can be derived consistently across cities. This deliberate restriction reflects the project's aim to develop a reproducible and transferable diagnostic framework under constrained data conditions, as identified in the problem statement. As a consequence, aspects of cycling feasibility that require fine-grained local knowledge, such as detailed design intent, enforcement practices, interaction dynamics, or behavioural adaptation, fall outside the reliable reach of open data and are therefore explicitly excluded from the analytical scope and becoming useful materials for further research.

As explained in Chapter 4.3 Data Scope and Preprocessing and 4.4.4 Effective Width for the treatment of missing data, which derive from the constraints explained above, the framework distinguishes between three analytically meaningful scenario. Hard infeasibility occurs where observable attributes such as width, surface quality, or slope clearly violate minimum feasibility thresholds. Data-driven infeasibility arises where required attributes are missing, ambiguous, or inconsistently mapped and are therefore treated as constraining by design. Finally, non-evaluable areas refer to locations where neither feasibility nor infeasibility can be inferred with sufficient confidence. These categories are not artefacts of poor data quality; they are explicit outputs of the assessment and are visualised directly in the infeasibility maps.

Missing or uncertain attributes are handled conservatively. Where key variables such as effective width or surface condition cannot be reliably derived, segments are treated as infeasible rather than assumed to be acceptable. This reflects a planning-oriented preference for avoiding false positives, where infrastructure appears structurally usable despite unresolved constraints and highlight a gap in the data completness, attributes that most of the bikeability indeces do not show. As a result, cycling readiness should be interpreted as a lower-bound estimate of structural feasibility under the specified requirements, not as a complete description of cycling conditions.

This approach differs from many bikeability and cycling index methodologies reviewed in Chapter 2, which often rely on imputation, smoothing, or aggregation strategies that reduce the visibility of data gaps in order to produce complete composite scores. While such strategies can be appropriate for comfort-oriented or specific study cases, they risk obscuring the distinction between physically constrained infrastructure and analytically uncertain conditions deriving from systemic data completness.

Making data limitations visible also highlights data completeness as a planning issue in its own right. Areas where readiness is limited primarily by missing information indicate not only uncertainty about infrastructure conditions, but also weaknesses in the underlying data ecosystem that restrict spatial diagnosis. In contexts where open data forms the primary analytical resource, exposing these limits supports more informed interpretation and helps clarify where further data collection or local investigation would be required before stronger conclusions can be drawn. Cycling readiness therefore remains an early-stage diagnostic tool: it identifies where structural feasibility can be assessed with confidence, where it cannot, and why. This explicit treatment of analytical boundaries is not a limitation of the approach, but a condition of its transparency and transferability.

6.4 From spatial patterns to planning diagnosis

This section addresses RQ3:
How do feasibility limits and robustness losses manifest spatially across cycling networks when stricter requirements are applied, and how can these patterns support early-stage planning diagnosis for everyday cycling and cycle logistics?

Addressing RQ3, the contrast between commuter and cargo-bike readiness reveals how feasibility limits manifest spatially across cycling networks when stricter requirements are applied. Robustness loss appears not as isolated spot, but as spatially structured patterns. These manifestations indicate where cycling infrastructure operates close to their physical limits. By making these limits visible through Infeasibility Maps and Robustness (Δ) patterns rather than composite scores alone, the framework supports early-stage planning diagnosis by identifying where structural constraints are likely to shape future cycling and cycle-logistics opportunities. Importantly, these patterns are not interpreted as measures of performance, urgency, or failure. By distinguishing between areas where feasibility degrades gradually and areas where it collapses greatly, the framework helps differentiate conditions and context that may be adaptable through incremental adjustment from those that would require more fundamental spatial reallocation should future demands justify it.

From a planning perspective and from an user prespective, this distinction supports an early-stage diagnostic logic. Readiness patterns function as a screening tool that helps vary stakeholders identify where structural constraints are more intense and therefore hinder or support cycle logistic for example. In other words, this framework reveals the areas within later planning choices must operate. Consistent with several spatial cycling assessment methods discussed in the literature review, especially Kraft in "Mapping urban bikeability using OSM and open spatial indicators", readiness indicators are aggregated to a regular hexagonal grid to support city-scale interpretation and comparison. As shown in previous bikeability studies, hex-based aggregation provides a neutral spatial interface through which infrastructural conditions can be read alongside broader contextual information. For example, the grid allows cycling readiness patterns to be interpreted in relation to commonly used planning layers such as population density, land-use intensity, or freight-relevant activity. While socio-demographic factors such as household composition, income levels, or car ownership are known from the literature to influence cycling uptake and mode choice, they fall outside the scope of a structurally focused feasibility assessment. By limiting the analysis to the physical properties of the built environment, the framework isolates infrastructural constraints that apply regardless of local demand conditions, while leaving room for future research to combine readiness outputs with contextual and socio-economic layers when assessing cargo-bike adoption or broader mobility impacts and their relations within broader urban conditions. By separating spatial diagnosis from contextual interpretation, the framework maintains analytical clarity while remaining usable within planning workflows.

6.5 Contextual and policy overlays as interpretive interfaces

Cycling readiness maps are intentionally limited to diagnosing the structural feasibility of the cycling network and do not, on their own, indicate where cycling demand is highest, where intervention is most urgent, or where political attention is currently focused. This limitation is deliberate. As outlined in the problem statement and scope, the framework is designed as an infrastructural diagnostic rather than as a comprehensive planning or prioritisation tool. Its purpose is to identify where physical constraints shape what is possible, not to determine where action should occur or which objectives should take precedence.

Policy benchmarking tools operate in a complementary but distinct way. Instruments such as the European Cyclists' Federation Cargo Bike-Friendly City Tracker and Cycling Infrastructure Tracker capture institutional support, regulatory frameworks, and strategic ambition related to cycling and cycle logistics. Their strength lies in documenting governance conditions and policy intent, but they do not provide spatially explicit information on where supportive or constraining infrastructural conditions are within cities. Cycling readiness adds this spatial dimension by indicating where existing infrastructure can, or cannot, accommodate cargo-bike use under current physical constraints.

When read together, policy benchmarks and spatial readiness maps open up different scenarios for interpretations. Areas where strong policy ambition matches with high structural readiness suggest favourable conditions for cycling uptake and could spark stakeholders interest. Locations where policy goals exceed infrastructural feasibility point to potential challenges that would need to be addressed. On the other hand, areas with high readiness but limited policy engagement may indicate latent infrastructural capacity that is not yet reflected in strategic priorities.

Ultimately, the relationship between cycling readiness and contextual or policy data is complementary yet immature. The separation ensures analytical clarity but also limites the framework's ability to directly assess demand, prioritisation and policy effectiveness. This gap points to possibilities for future research where these readiness outputs could be combined with socio-demographic, land-use, or policy datasets to support more integrated planning analyses, without compromising the structural diagnostic role of the framework.

6.6 Positioning cycling readiness within cycling research and planning

Having clarified how structural readiness outputs should be interpreted and where their analytical boundaries lie, this section positions cycling readiness within the broader landscape of cycling research and planning tools. This framework should be understood neither as a replacement for established bikeability frameworks nor as an extension of demand or behaviour oriented models. Instead, it represents a complementary analytical angle that addresses a question that has remained under-examined in much of the literature: whether existing cycling infrastructure is structurally capable of accommodating more demanding forms of cycling within largely fixed street geometries.

Most bikeability research has focused on explaining cycling uptake, route choice, or perceived comfort and safety. These approaches have produced valuable insights into how cyclists experience infrastructure and how built-environment characteristics influence behaviour. Composite bikeability indices, level-of-service models, and stress-based classifications translate these insights into spatial representations that support planning strategies and policy evaluation. Their calibration, however, is implicitly anchored in the physical characteristics and tolerance thresholds of standard commuter bicycles. Even when objective indicators such as width, surface quality, or slope are used, these attributes are typically interpreted through proxies of comfort, stress, or acceptability rather than through explicit feasibility constraints.

This framework shift from this tradition by moving the analytical focus from experience to feasibility. It asks not how cycling infrastructure is perceived or used today, but how much physical tolerance is embedded in the existing network. By applying stricter physical requirements to the same underlying infrastructure, the framework exposes where cycling provision relies on minimal geometries, sufficient surfaces, or tight spatial compromises that function adequately for commuter use but offer little capacity for adaptation. In this sense, the thesis reframes cycling infrastructure as a system with varying degrees of robustness rather than as a static measure of quality or performance. Within this framing, cargo bikes serve as an analytical device rather than a normative policy objective. Their larger dimensions, higher loads, and lower tolerance for discontinuity make them particularly sensitive to geometric and surface constraints. When used as a stress-test vehicle, cargo bikes reveal where existing cycling infrastructure approaches hard physical limits. Where networks remain feasible under these stricter conditions, they can be interpreted as structurally robust; where readiness collapses, the results indicate closeness to spatial boundaries that constrain not only freight-oriented cycling but also future diversification of cycling modes. This logic allows the framework to adopt a future-oriented perspective without relying on behavioural prediction, demand forecasting, or prescriptive assumptions about modal shift.

This thesis also aligns with a growing body of research advocating for open, transferable, and transparent spatial assessment methods. By using harmonised open datasets and conservative assumptions, the framework prioritises reproducibility and cross-city comparability. Differences between cities or neighbourhoods are interpreted as manifestations of infrastructural structure and data environments rather than as direct indicators of planning success or failure. This distinction is important: cycling readiness does not rank cities by performance, nor does it evaluate policy effectiveness. Instead, it provides a consistent diagnostic lens through which structural conditions can be compared and discussed. In relation to existing planning tools, cycling readiness occupies an early position in the analytical workflow. Policy benchmarks and governance-focused indices, such as bicycle-friendliness rankings (such as the Copenhagenise Index) or cargo-bike policy trackers (from ECF), capture institutional commitment, regulatory support, and strategic ambition. These instruments are valuable for understanding a city intent but offer limited insight into where physical constraints enable or hinder implementations. This project complements these tools by translating abstract policy goals into spatially explicit questions about feasibility within the street network. Where policy ambition aligns with high readiness, conditions are favourable for implementation; where ambition exceeds readiness, structural constraints become visible as challenges that must be addressed or acknowledged.

Looping back to the problem statement, this discussion demonstrates how this new angle addresses a key gap in existing cycling assessment approaches: the absence of spatial methods that explicitly evaluate whether current cycling infrastructure can support evolving operational demands under constrained urban conditions or new transport modes. By distinguishing feasibility from comfort and robustness from performance, the framework contributes with a diagnostic layer to cycling research and planning. Its value lies not in defining solutions or predicting outcomes, but in clarifying the physical boundaries within which future cycling and cycle-logistics strategies must operate.

7. Conclusion

This thesis explored whether existing urban cycling infrastructure is structurally able to support emerging cycling uses, with a particular focus on cargo bikes, using open and transferable data. As cargo bikes become more relevant for urban mobility and freight, the key issue for planners is no longer simply where cycling infrastructure exists, but whether it remains physically usable once vehicle requirements increase. This question is especially pressing in planning contexts that rely on open data and limited analytical resources.

To address this, the study developed a feasibility oriented spatial framework that distinguishes between infrastructure suitable for standard commuter bicycles and infrastructure that remains operable under cargo-bike requirements. Structural readiness was evaluated through a limited set of physical, geometric, and terrain-related indicators derived entirely from open data. By assessing commuter and cargo-bike profiles in parallel on the same network, using identical indicators, weights, and aggregation logic, differences in readiness can be interpreted directly as losses of robustness.

When applied across multiple cities, the framework revealed consistent spatial mismatches between commuter cycling readiness and cargo-bike readiness. Cycling networks that appear adequate from a standard users often break down once constraints related to width, slope, surface and typology are applied. These feasibility losses are not evenly distributed but tend to cluster around specific structural conditions, exposing weaknesses that conventional bikeability assessments typically hide.

The analysis also highlights both the strengths and limits of open data for evaluating cargo-bike feasibility. Key physical constraints can be assessed consistently across cities using datasets such as OpenStreetMap, while other aspects remain limited by missing or ambiguous information. Rather than avoiding these limitations, the framework treats them explicitly through conservative imputing, allowing data uncertainty itself to become part of the diagnostic output.

From a planning prespective, the framework is intended as an early-stage diagnostic and prioritisation tool. It does not attempt to predict cycling uptake, optimise routes, or design infrastructure in detail. Instead, it helps identify where cycling networks are already structurally robust, where they become fragile under increased demands. In this sense, cargo bikes act less as a goal mode and more as a practical stress test for the adaptability of existing infrastructure.

The study remains limited by the quality and completeness of open data and by its deliberate exclusion of traffic interactions, behavioural factors, and freigh-logistic aspects. These constraints reflect conscious scope choices aligned with early-stage planning analysis. Future work could build on this foundation by integrating municipal datasets, refining feasibility thresholds, or linking readiness diagnostics to investment and design strategies.

Overall, the thesis shows that looking at cycling infrastructure through the lens of structural feasibility and robustness leads to more planning relevant insights than traditional bikeability approaches. As cities seek to accommodate a wider range of slow mobility modes within inherited street environments, feasibility based, open-data diagnostics can help support more realistic and transparent decisions about how cycling networks evolve.

Bibliography

Abad, J., Borrero, J. M., & Cea, L. (2018). Assessing bicycle network connectivity using open data. Information, 9(11), 287. https://doi.org/10.3390/info9110287

Arellana, J., Saltarín, M., Larrañaga, A. M., González, V. I., & Henao, C. A. (2020). Developing an urban bikeability index for different types of cyclists as a tool to prioritise bicycle infrastructure investments. Transportation Research Part A: Policy and Practice, 139, 310–334. https://doi.org/10.1016/j.tra.2020.07.010

Barrington-Leigh, C., & Millard-Ball, A. (2017). The world's user-generated road map is more than 80% complete. PLOS ONE, 12(8), e0180698. https://doi.org/10.1371/journal.pone.0180698

Bertolini, L. (2007). Evolutionary urban transportation planning: An exploration. Environment and Planning A, 39(8), 1998–2019. https://doi.org/10.1068/a38345

Birch, C. P. D., Oom, S. P., & Beecham, J. A. (2007). Rectangular and hexagonal grids used for observation, experiment and simulation in ecology. Ecological Modelling, 206(3–4), 347–359. https://doi.org/10.1016/j.ecolmodel.2007.03.041

Castañon, U. N., & Ribeiro, P. J. G. (2021). Bikeability and emerging phenomena in cycling: Exploratory analysis and review. Sustainability, 13(4), 2394. https://doi.org/10.3390/su13042394

Čech, V., Křivánková, Z., & Kuda, F. (2020). Hexagonal grids in spatial analysis: Advantages for continuous phenomena representation. ISPRS International Journal of Geo-Information, 9(6), 373. https://doi.org/10.3390/ijgi9060373

Dill, J. (2004). Measuring network connectivity for bicycling and walking. Transportation Research Record, 1878, 24–32. https://doi.org/10.3141/1878-04

Dill, J., & McNeil, N. (2016). Revisiting the four types of cyclists: Findings from a national survey. Transportation Research Record, 2587, 90–99. https://doi.org/10.3141/2587-11

Dixon, L. B. (1996). Bicycle and pedestrian level-of-service performance measures and standards for congestion management systems. Transportation Research Record, 1538, 1–9.

Furth, P. G., Mekuria, M. C., & Nixon, H. (2016). Network connectivity for low-stress bicycling. Transportation Research Record: Journal of the Transportation Research Board, 2587(1), 41–49. https://doi.org/10.3141/2587-06

Geurs, K. T., & van Wee, B. (2004). Accessibility evaluation of land-use and transport strategies: Review and research directions. Journal of Transport Geography, 12(2), 127–140. https://doi.org/10.1016/j.jtrangeo.2003.10.005

Girres, J.-F., & Touya, G. (2010). Quality assessment of the French OpenStreetMap dataset. Transactions in GIS, 14(4), 435–459. https://doi.org/10.1111/j.1467-9671.2010.01203.x

Haklay, M. (2010). How good is volunteered geographical information? A comparative study of OpenStreetMap and Ordnance Survey datasets. Environment and Planning B: Planning and Design, 37(4), 682–703. https://doi.org/10.1068/b35097

Hardinghaus, M., Nieland, S., Lehne, M., & Weschke, J. (2021). More than bike lanes—A multifactorial index of urban bikeability. Sustainability, 13(21), 11584. https://doi.org/10.3390/su132111584

Harkey, D. L., Reinfurt, D. W., & Knuiman, M. (1998). Development of the Bicycle Compatibility Index. Transportation Research Record, 1636, 13–20.

Jensen, S. U. (2007). Bicycle tracks and lanes: A before–after study. Transportation Research Record, 2031, 1–8.

Kang, H., Kim, D. H., & Yoo, S. (2019). Attributes of perceived bikeability in a compact urban neighborhood based on qualitative multi-methods. International Journal of Environmental Research and Public Health, 16(19), 3738. https://doi.org/10.3390/ijerph16193738

Kraft, M., Stein, A., Pebesma, E., & Hecht, R. (2021). Mapping urban bikeability using OpenStreetMap and open spatial indicators. ISPRS International Journal of Geo-Information, 10(2), 81. https://doi.org/10.3390/ijgi10020081

Landis, B. W., Vattikuti, V. R., & Brannick, M. T. (1997). Real-time human perceptions: Toward a bicycle level of service. Transportation Research Record: Journal of the Transportation Research Board, 1578(1), 119–126. https://doi.org/10.3141/1578-15

Landis, B. W., Vattikuti, V. R., Ottenberg, R. M., McLeod, D. S., & Guttenplan, M. (2001). Modeling the roadside walking environment: Bicycle level of service. Transportation Research Record, 1773, 82–88.

Levinson, D., & King, D. (2019). A political economy of access. University of Chicago Press.

Lowry, M. B., Furth, P. G., & Hadden-Loh, T. (2012). Prioritizing new bicycle facilities to improve low-stress network connectivity. Transportation Research Record, 2314, 25–31.

Marshall, S. (2004). Streets and patterns. Spon Press.

Monteiro, J. (2023). The potential impact of cycling on urban transport energy and modal share: A GIS-based methodology. Sustainability, 15(3), 2147. https://doi.org/10.3390/su15032147

Papa, E., & Bertolini, L. (2015). Accessibility and transit-oriented development in European metropolitan areas. Journal of Transport Geography, 47, 70–83. https://doi.org/10.1016/j.jtrangeo.2015.07.003

Reggiani, G., van Oijen, T., Hamedmoghadam, H., et al. (2022). Understanding bikeability: A methodology to assess urban networks. Transportation, 49, 897–925. https://doi.org/10.1007/s11116-021-10198-0

Silva, C., Marques, J. S., Lopes, M., & Dias, A. M. (2021). The gross potential for cycling. Transportation Research Procedia, 52, 104–117. https://doi.org/10.1016/j.trpro.2021.01.014

Sorton, A., & Walsh, T. (1994). Bicycle stress level as a tool to evaluate urban and suburban bicycle compatibility. Transportation Research Record, 1438, 17–24.

Valenzuela, A. L. E. M., Lopes, A. A. S., Araújo, P. A. B., Justina, M. D., Arins, G. C. B., & Rech, C. R. (2021). Geospatial indicators of bikeability index as cycle-friendly city design: A systematic review. Revista Brasileira de Atividade Física & Saúde, 27, e0255. https://doi.org/10.12820/rbafs.27e0255

Weikl, S., & Mayer, T. (2023). A data-driven quality assessment of cycling networks. Frontiers in Future Transportation, 4, 1127742. https://doi.org/10.3389/ffutr.2023.1127742

Winters, M., Brauer, M., Setton, E. M., & Teschke, K. (2013). Mapping bikeability: A spatial tool to support sustainable travel. Environment and Planning B: Planning and Design, 40(5), 865–883. https://doi.org/10.1068/b38185

Zayed, M. A. (2017). Towards an index of city readiness for cycling. International Journal of Transportation Science and Technology, 5(4), 210–225. https://doi.org/10.1016/j.ijtst.2017.01.002

Alta Planning + Design. (2017). Level of traffic stress: What it means for building better bike networks. altago.com (Accessed 23 January 2026)

C40 Cities. (2023). How-to guide: Enabling e-cargo bike deliveries as part of zero-emission freight plans. C40 Knowledge Hub. www.c40knowledgehub.org
(Accessed 23 January 2026)

European Commission. (2024). European declaration on cycling. transport.ec.europa.eu (Accessed 23 January 2026)

European Cyclists' Federation. (2023). Cargo Bike Friendly Cities dashboard. www.ecf.com
(Accessed 23 January 2026)

European Cyclists' Federation. (2025). Cycling Infrastructure Tracker (QECIO 2.0). www.ecf.com/resources/cycling-infrastructure-tracker
(Accessed 23 January 2026)

European Cyclists' Federation. (2025). QECIO data repository (GitHub). github.com/European-Cyclists-Federation/European-Cyclists-Federation.github.io (Accessed 23 January 2026)

International Road Assessment Programme. (2020). CycleRAP methodology and tools. www.irap.org
(Accessed 23 January 2026)

National Association of City Transportation Officials. (2020). Urban bikeway design guide. nacto.org/publication/urban-bikeway-design-guide/ (Accessed 23 January 2026)

Appendix

WWAppendix A — List of Figures

Appendix B — List of Maps

Appendix C — List of Tables

Appendix D — Extra

The image belowe shows the VSCode interface used by the author to run the script. The full package containing the Conda Environment, the Phyton project and the Data source will be attached in the thesis upload.

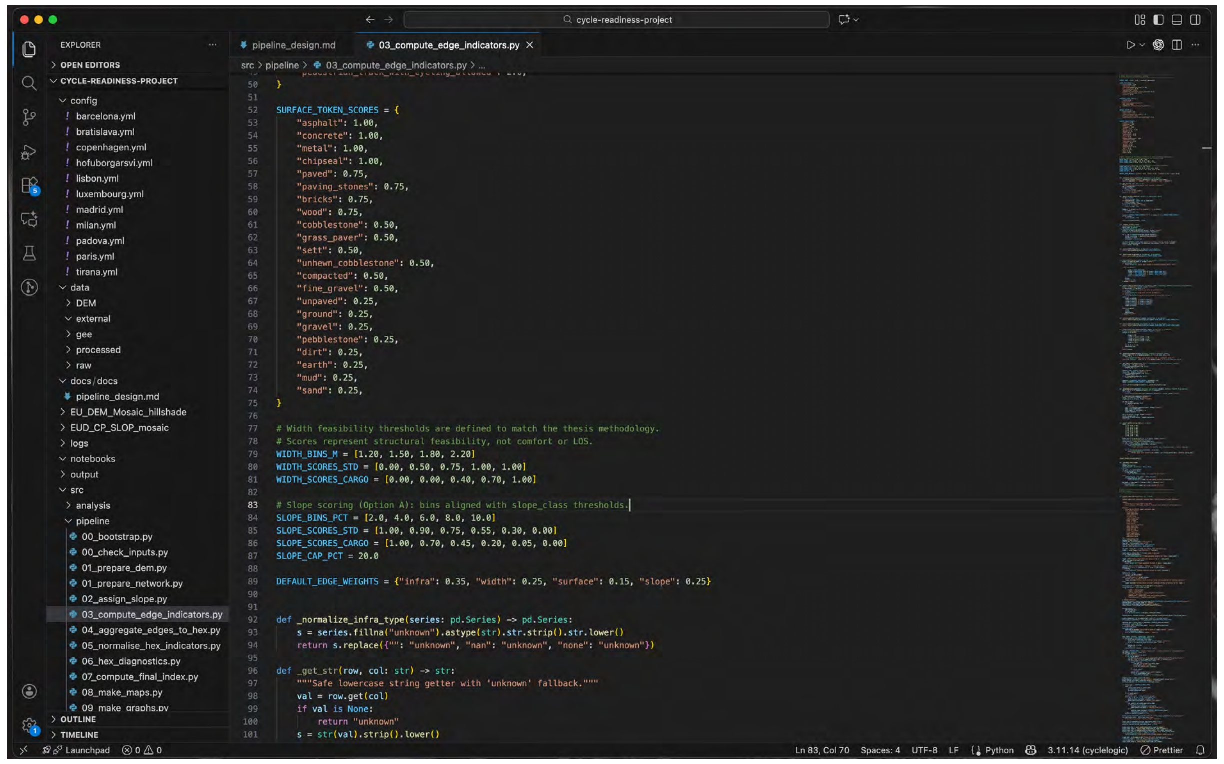


Figure 17 - VSCode inferface for coding
Source: Author's own work.