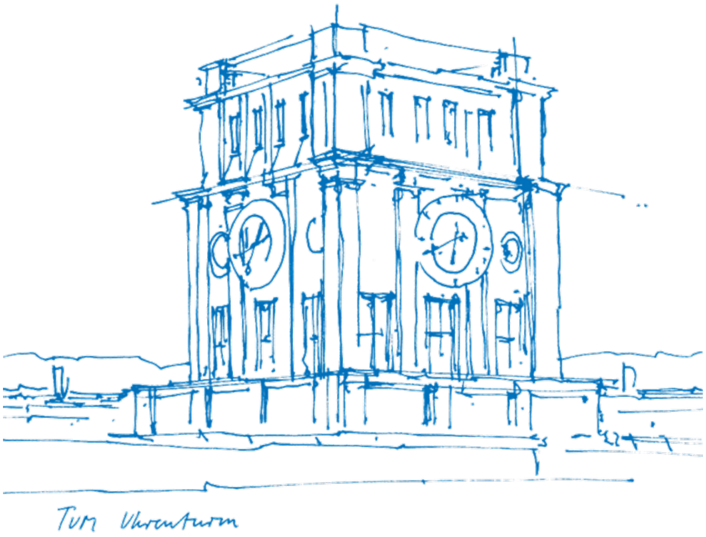
Chair of Urban Structure and Transport Planning
TUM School of Engineering and Design
Technical University of Munich

The Bike-and-Ride Network Design Problem

Optimizing Bicycle Networks in Peripheral Areas to Enhance Intermodal Cycling and Public Transport Regional Accessibility

Bartosz McCormick



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Optimizing Bicycle Networks in Peripheral Areas to Enhance Intermodal Cycling and Public Transport Regional Accessibility

Bartosz McCormick

Thesis for the attainment of the academic degree

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I hereby declare that this thesis is entirely the result of my own work except where otherwise indicated. I have only used the resources given in the list of references.

Munich, 30.04.2024 Bartosz McCormick

Abstract

What do you get when you combine bicycles, the most efficient private mode of transport, with trains, the most efficient mode of mass transport? Magic... or at least the next best thing: a compelling alternative to the car. The integration of these modes allows for their respective strengths to be leveraged, namely the speed and range of public transport and the flexibility of the bicycle. However, this synergy is inhibited by the pervasiveness of sparse, fragmented bicycle networks. To this end, an integrated analytical framework was developed to identify and realize latent regional accessibility (LRA), which is defined as the potential to increase regional accessibility through bicycle network improvements. LRA is determined through an accessibility analysis by considering bike-and-ride (B+R), a fundamental form of integration. It is then used to instantiate the demand in the Bike-and-Ride Network Design Problem (B+RNDP), synchronizing the regional and local scales of the analyses. Subsequently, the B+RNDP determines how a network can be upgraded to realize the LRA most efficiently. The thesis focused on peripheral, suburban areas, as their dispersed urban form heightens the importance of improving alternatives to the car and exacerbates the challenges associated with doing so. Therefore, the framework was demonstrated for the periphery of Munich. The results demonstrate the ability of the accessibility analysis to identify target stops for improvement at the regional scale and the ability of the B+RNDP to subsequently optimize the network within their catchment areas. The performance of the B+RNDP was evaluated by comparing its demand coverage for a given budget to a greedy, shortest-path-based heuristic. The results indicate the value of leveraging an optimization approach, with an improvement of up to 32 percentage points. The longest runtime in the evaluated scenarios was 47 minutes, indicating that B+RNDP is efficient enough for practical applications without needing a powerful computer. The framework is expressed using general forms and was developed for use with OpenStreetMap and GTFS feeds, enabling its adaptation to planning contexts worldwide.

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Acronyms

AP	Public Transport Access Point
B+R	Bike-and-Ride
B+RNDP	Bike-and-Ride Network Design Problem
BCI	Bicycle Compatibility Index
BLOS	Bicycle Level of Service
BNDP	Bicycle Network Design Problem
DC	Demand Coverage
GRASP	Greedy Randomized Adaptive Search Procedure
GTFS	General Transit Feed Specification
IoRA	Indicator of Regional Accessibility
LRA	Latent Regional Accessibility
LTS	Level of Traffic Stress
MILP	Mixed-Integer Linear Program
MVV	Münchner Verkehrs- und Tarifverbund
NDP	Network Design Problem
OD	Origin-Destination
OSM	OpenStreetMap
PuT	Public Transport
RDF	Realized Detour Factor
RNDP	Road Network Design Problem
TTM	Travel Time Matrix

1 Introduction

Since its introduction in the early 1900s, the prevailing model for urban and transport planning has overwhelmingly prioritized the car. Its speed and flexibility have enabled a sprawling, resource-intensive form of development that has become increasingly difficult, if not impossible, to sustain (Brueckner, 2000; Newman & Kenworthy, 1996). In the interest of a more sustainable and livable future, a transition away from this car-dominant paradigm is necessary (Banister, 2008; Montgomery, 2013).

Reorienting transportation planning to prioritize accessibility rather than mobility is a pathway for achieving this change. Doing so aligns planning with the purpose of transportation: enabling people to perform spatially distributed activities. Through its simultaneous consideration of land use and transport, accessibility planning represents a more holistic and flexible approach, one where the efficient flow of vehicles is treated as a means, not an end (Levine et al., 2019, p. 3).

For travel demand that cannot be mitigated or satisfied locally, public transport is the most climate-friendly mode (IEA, 2022). It is difficult, however, to operate a financially viable, attractive service that also has a broad coverage area in a low-density context. Meandering alignments and frequent stop spacing compromise a service's operational speed, resulting in a need to balance operational performance and spatial availability (Walker, 2012, pp. 47–58). This tension is the basis for public transport's "first/last mile problem", the challenge associated with access to, and egress from, the system.

The integration of cycling and public transport is a promising solution. Cycling is clean, inexpensive, and the most energy-efficient mode of transport (Pucher & Buehler, 2017; Woodcock et al., 2007). The efficiency of cycling allows for greater distances to be traversed compared to walking. This is indicative of the capability of cycling to increase the catchment area of public transport stops and to reduce reliance on feeder services for intermediate distances. Combining the efficiency of cycling at the local level with the speed and range of public transport unlocks a synergy between the modes that is greater than the sum of its parts. The integrated system increases the speed and flexibility of travel, allowing it to compete more closely with the car (Kager et al., 2016).

In many planning contexts, cycling is not treated a serious mode of transportation. As such, the infrastructure needed to enable its integration with public transport is usually lacking. In such contexts, there is often a focus on the design of individual routes, with little to no consideration of the network as a whole (McLeod et al., 2020). As to not inhibit motor vehicle traffic, these routes tend to be ones that are convenient to implement, not necessarily ones that enable important connections. As a result, bicycle networks are often sparse, disconnected, and misaligned with the needs and interests of cyclists (Parkin, 2022). As demonstrated by Natera Orozco et al. (2020) and Schoner and Levinson (2014), it is the norm for bicycle networks to have a fragmented form, even in bicycle-friendly cities such as Copenhagen.

1.1 Motivation and Study Design

On their own, public transport and cycling have difficulty competing with the car, especially in the peripheral, suburban context. The former cannot offer a high degree of spatial availability without compromising its speed, while the range of the latter is limited. The integration of the two holds a lot of potential to enhance accessibility and, in turn, serve as a compelling alternative to driving. This potential is inhibited, however, by the pervasiveness of sparse, fragmented bicycle networks. Resolving this bottleneck is the motivation for the thesis. Accordingly, the goal is to develop a methodology to (a) identify and (b) realize the potential of local bicycle network improvements to enhance regional accessibility by enabling the integration of cycling and public transport.

The thesis focuses on peripheral, suburban areas where it is inevitable for there to be travel demand that cannot be mitigated or satisfied locally. The scope is refined further by focusing on bike-and-ride (B+R), a fundamental form of integration that involves riding to a stop using a private bicycle, parking, and transferring to public transport. Within this scope, the thesis aims to answer the following research questions:

> **RQ1:** What are the requirements to enable the integration of cycling and public transport in peripheral areas?
>
> **RQ2:** What is the potential of cycling and public transport integration to enhance regional accessibility in peripheral areas?
>
> **RQ3:** How can the design of local bicycle networks be optimized to enhance regional accessibility?

RQ1 is answered through a literature review of cycling and public transport integration requirements that focuses on bicycle network design. RQ2 is answered by proposing an accessibility analysis methodology for calculating the latent regional accessibility (LRA), the potential to increase B+R regional accessibility through bicycle network improvements. RQ3 is concerned with realizing the LRA using a network optimization approach. The question is answered by proposing the Bike-and-Ride Network Design Problem (B+RNDP), which leverages the output of the accessibility analysis. Collectively, the two methods form a cohesive analytical framework that bridges the divide between local bicycle network design and regional accessibility planning.

1.2 Study Area

The periphery of Munich was chosen as the study area to demonstrate the methodology's effectiveness. The city is the capital of Bavaria and has a population of 1,590,877 (Landeshauptstadt München, 2024), making it the third largest city in Germany. The Munich Metropolitan Region has a primarily monocentric structure that is dominated by the city's high concentration of economic activity (Bentlage et al., 2021). This leads to significant travel demand oriented towards the city, which is partly reflected by the imbalance of commuter flows. As of 2023, 458,000 people subject to social insurance contributions commute into Munich, more than twice the amount commuting out (Statistik der Bundesagentur für Arbeit, 2023). Relative to the city, car use is much more prevalent in the surrounding counties. In 2017, the mode share was 58% compared to the city's 34% (Bundesministerium für Digitales und Verkehr, 2020). This reflects the present inability of the transportation system to provide a compelling alternative to the car.

The most prominent public transport service in these counties is the S-Bahn. The network comprises eight diametric lines that join along a central corridor to provide direct access throughout the city's core. Service is fast and frequent, with headways ranging from 10 to 20 minutes. These characteristics allow the S-Bahn to compete with the car. However, to achieve this level of operational performance, stop spacing needs to be relatively low. As a result, most people need to use a mode other than walking to access the service, degrading their overall travel time. Expanding rail service is expensive and, in many cases, infeasible. Therefore, maximizing the catchment area of the S-Bahn stops is of interest to make the most of the existing infrastructure.

To align with the focus of the thesis on peripheral areas, the case study targets stops with S-Bahn service that are at least 6 km away from Munich's administrative boundary. The study area was defined as the area within a 3 km network distance of the stops. As the focus of the thesis is regional accessibility, the target user group is working-age adults as they tend to have longer trip lengths due to commuting (Bundesministerium für Digitales und Verkehr, 2020, p. 39). As of the 2011 census, 279,000 working-age adults live within the study area (Statistische Ämter des Bundes und der Länder, 2018). Figure 1.1 shows the working-age population density in the region, highlighting the populated area within the study area.

1.3 Thesis Structure

The thesis begins with a literature review of cycling and public transport integration requirements and bicycle network design optimization (Chapter 2). Chapter 3 describes the methods. Chapter 4 presents the case study results, which are then discussed in Chapter 5. Finally, Chapter 6 summarizes the outcomes of the thesis and provides recommendations for future studies.

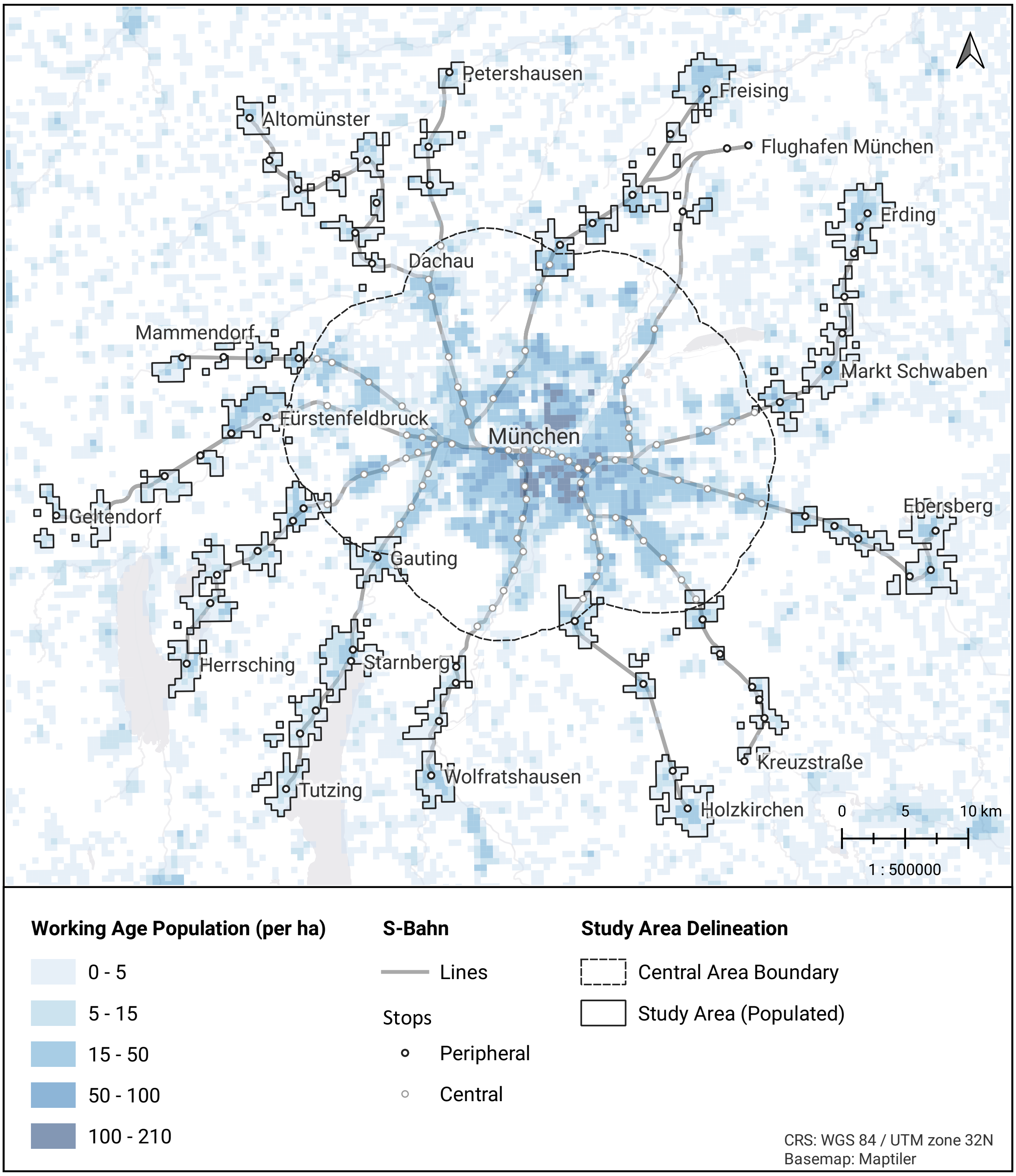


Figure 1.1 Working-age population density in Munich and its periphery. Populated area within the study area is highlighted.

2 Literature Review

This chapter begins with a literature review of cycling and public transport integration requirements. This is followed by a review of bicycle network design optimization.

2.1 Cycling and Public Transport Integration Requirements

A high-quality bicycle network is the principal requirement for integrating cycling and public transport (Oeschger et al., 2020) and is, therefore, the review's focus. The definition of "high quality" is developed by describing the five main requirements of network design and their connection to the characteristics of cycling. Focus is placed on the topology of the network rather than street-level design, as the former is more pertinent to the strategic planning context of the present work. It's noted that this is not meant to diminish the importance of street-level design. On the contrary, the design quality at this lower level ultimately determines how different cyclists perceive the network and thus its success (Mekuria et al., 2012). The section concludes with a brief overview of requirements specific to the different forms of integration.

2.1.1 Bicycle Network Design Requirements

Ranging from children to older adults, cyclists are a diverse user group covering the full spectrum of physical and cognitive abilities (Parkin & Koorey, 2012). Cyclists are inherently deeply engaged while traveling as they propel the vehicle using their own energy and are directly exposed to the environment due to the minimalist form of bicycles. This is unlike driving a car, which affords a degree of detachment while traveling. Drivers can regulate the speed and trajectory of the vehicle with minimal physical effort. Furthermore, they are physically shielded from potential collisions and are isolated from adverse environmental conditions such as noise, pollution, and poor weather. Unlike cars, bicycles accentuate users' characteristics. Accordingly, the requirements of bicycle infrastructure are highly dependent on the target user.

The Netherlands is renowned for the prominence of cycling as a mode of transport. In 2023, 28% of all trips were by bike, with high rates across all ages and genders (Haas & Kolkowski, 2023). These figures are a testament to the effectiveness of Dutch bicycle planning and design. As such, Dutch bicycle design guidelines are considered an authoritative reference for state-of-the-art practice. The guidelines, as described by the CROW (2016) Design Manual for Bicycle Traffic, specify the following five design requirements for bicycle infrastructure: cohesion, directness, safety, attractiveness, and comfort. The importance of these requirements is widely accepted and supported by academic studies (Gerike et al., 2022; Parkin & Koorey, 2012).

Cohesion and Directness

Cohesion refers to the continuity and interconnectedness of routes. It is what distinguishes between a collection of independent routes and a network, something greater than the sum of its parts. A network provides the degree of choice and flexibility necessary to make cycling viable for a variety of trip purposes.

Directness refers to a route's deviation from an optimal route in terms of distance or time. From a geometric perspective, a route becomes less attractive as it deviates from the shortest connection between two points. An indirect route can, however, be preferable if an increase in travel distance is compensated by a lower travel time. In essence, this is the organizing principle of street networks. In conventional, hierarchical networks, as one progresses from local streets to arterials, infrastructure is designed to enable higher travel speeds, leading to a lower overall travel time (Wang et al., 2018). While this organizing principle is viable for motorized vehicles, it is not as applicable to bicycles due to the heightened importance of distance-based directness (Parkin & Koorey, 2012). Conventional bicycles are powered by the user, meaning that a cyclist's speed is primarily constrained by their physical ability rather than the infrastructure. As a result, speeds are relatively uniform throughout the network, making it difficult to compensate detours with lower travel times. Furthermore, the total distance of a bicycle route is limited as it is directly proportional to the required level of physical exertion.

Temporal directness is also an important facet of directness, as while distance determines the physical viability of cycling, time determines if a connection matches a user's preferences. Temporal directness is based mainly on distance but allows for added sensitivity to delay. As congestion is rare in bicycle networks, traffic lights are the most prevalent source of delay. Accordingly, routes should be planned to avoid crossings where possible. Temporal directness can also be interpreted relative to other modes of transport, which opens up the potential for a multimodal perspective to planning. Relative temporal directness can be enhanced not only through "pull" measures, but also "push" measures that make other modes of transport slower or less attractive. At a network level, this can be implemented through modal filtering, resulting in more circuitous routes for motorists that don't compensate them with higher speeds.

To summarize, whereas cohesion makes cycling *a* choice, directness makes cycling a *compelling* choice. Routes need to be direct in terms of distance to be physically viable and direct in terms of time to meet users' preferences. The importance of directness drives the need for a high degree of cohesion in networks. Traffic cannot be channeled into primary corridors in the same way as motor vehicles, leading to the need for a dense, ubiquitous form. For reference, Dutch guidelines recommend a grid size of 300–500 m and 1000–1500 m for the main network in built-up and outlying areas, respectively (CROW, 2016).

Safety, Comfort and Attractiveness

Whereas the importance of directness and a high degree of cohesion stemmed primarily from bicycles being powered by the user, the importance of safety, comfort, and attractiveness are mainly a consequence of the bicycle's minimalist form.

Regarding safety, cyclists are most vulnerable in mixed traffic, especially when they have a high speed differential with other road users (Parkin & Koorey, 2012). In mixed traffic, a speed limit of 30 kph is often recommended as the risk of injury and fatality increases significantly beyond this threshold (Johansson, 2009; Kim et al., 2007). Crashes tend to be concentrated at intersections as this is where road users' trajectories conflict (Gerike et al., 2022).

As previously discussed, intersections are the primary source of delay for cyclists. This has a significant influence on their comfort. Relative to motorists, delays have a heightened impact as they not only increase cyclists' travel time but also their exposure to adverse weather, pollution, and noise (CROW, 2016). Many street-level design elements influence comfort. Examples include the continuity of a smooth riding surface and turn radii suited for a sufficiently high design speed (CROW, 2016; Parkin & Koorey, 2012). Attractiveness is a requirement closely related to comfort. As cyclists travel at relatively low speeds while exposed to the environment, they value an aesthetically pleasing, engaging environment (Gerike et al., 2022).

While safety, comfort, and attractiveness are largely determined by street-level design, some aspects can be influenced at the network level. For instance, the risk of crashes and discomfort caused by intersections can be mitigated by planning routes that avoid intersections. Attractiveness can be enhanced at the network level by planning routes that pass through engaging environments such as lively, mixed-use corridors and green spaces (Gerike et al., 2022).

2.1.2 Form-dependent Requirements

While a high-quality network is the primary requirement for all forms of integration, each also has its unique requirements. For instance, safe, convenient, and affordable parking is essential for home-based B+R as private bicycles are predominantly used for this purpose (Heinen & Buehler, 2019). Bike-on-board integration allows for a private bicycle to be transported by public transport. Therefore, its viability is dependent on the vehicle's capacity. Services with high ridership generally lack space to accommodate bicycles. For this reason, bringing a bicycle onto a train is typically prohibited during peak hours (Parkin & Koorey, 2012; Pucher & Buehler, 2009). As for bike-sharing, its viability is contingent on the operating area and availability of vehicles being well-aligned with travel demand. The vehicles need to be well maintained and have affordable rates. Furthermore, due to the dynamic nature of the system, real-time information is necessary to enable reliable trip planning (Oeschger et al., 2020).

2.2 Bicycle Network Design Optimization

Conventional approaches to network design, as understood based on a review of international bicycle network planning guidelines by Gerike et al. (2022), typically follow a similar sequence of steps. The main ones are analysis and route creation. The analysis step involves evaluating the planning context to identify OD pairs that are to be connected through the network. Conventional approaches tend to be supply-based. Therefore, demand is usually only indirectly considered through OD pair selection. For instance, a large residential area and a train station may be chosen as an OD pair due to the importance of the connection. While this choice may be based on the potential ridership, the precise magnitude is not typically considered. The analysis step is followed by route creation, which involves converting desire lines between OD pairs into routes.

An alternative to conventional network design approaches is mathematical optimization. In a general sense, optimization refers to the process of finding the best solution from a set of possible solutions. Mathematical optimization involves modeling a problem using an objective that expresses the goal of optimization in a quantifiable way, variables that can be manipulated to influence the objective, and constraints that specify the requirements for a feasible solution (Nocedal & Wright, 2006, p. 2).

The Network Design Problem (NDP) is relevant to the present work, which involves designing a network that enables the flow of commodities while satisfying demand characteristics (Costa, 2005). NDPs are formulated using a graph comprised of nodes and edges. Edges have a capacity and a cost associated with their use. Edges with zero capacity represent candidate edges not currently part of the network. As such, increasing the capacity of the edge from zero represents "upgrading" or "constructing" it (Wong, 1976). The Road Network Design Problem (RNDP) is an umbrella term for NDP variants that model street networks and the flow of vehicles (Farahani et al., 2013). The Bicycle Network Design Problem (BNDP), the focus of the present work, is a form of the RNDP distinguished by its incorporation of aspects unique to bicycle network design.

BNDPs were reviewed by first identifying 12 prior studies using Google Scholar and snowball search techniques. Afterward, the studies were interrogated for the following aspects:

- Type of Optimization Problem
- Objective
- Demand (Form and Coverage)
- Route Suitability Constraints (Cost and Continuity)
- Construction Cost
- Budget Constraint
- Largest Problem Instance
- Solution Approach

To the author's knowledge, this represents the most extensive review of this particular network design problem. The remainder of this section describes the results. First, the general characteristics of BNDPs that distinguish them from typical motor vehicle RNDPs are described. Next, the diversity of the reviewed

BNDPs is described by comparing their formulations. This is followed by a section explaining how the BNDPs align with the five network design requirements identified in Section 2.1.1. The review concludes by describing solution approaches.

2.2.1 General Characteristics of Bicycle Network Design Problems

In comparison to the motor vehicle RNDPs, which have literature dating back to the 1970s (Farahani et al., 2013), the BNDP is not as well studied. The earliest approaches date back to the early 2010s (Lin & Yu, 2013; Mesbah et al., 2012; Smith, 2011).The BNDP is primarily distinguished from motor vehicle RNDPs by the negligible influence of congestion. Modeling congestion is central to motor vehicle RNDPs as it is a key determinant of travel time and, thus, route choice. As the relationship between network design decisions (e.g., constructing an edge) and flow cannot be explicitly expressed, the problem is typically formulated using a bi-level structure. The upper and lower levels represent the perspective of the planning authority and road users. Route choice is generally modeled based on Wardrop's first principle, leading to a non-cooperative (user) equilibrium. The value of the bi-level structure is that it allows the design to be sensitive to users' travel behavior (Farahani et al., 2013). In all of the reviewed BNDP studies, congestion was considered negligible for cyclists, meaning criteria for route assignment were independent of network flow. In this sense, the BNDP is a simpler problem.

As discussed in Section 2.1.1, cohesion, directness, safety, comfort, and attractiveness are crucial in bicycle networks due to the characteristics of the mode. The incorporation of these characteristics further distinguishes the BNDP. For example, the heightened importance of perceived safety and comfort motivates its inclusion in BNDP formulations, whereas such aspects are not typically modeled for motorists (S. Liu et al., 2021).

2.2.2 Aspects of Bicycle Network Design Problem Formulations

The review revealed a wide variety of BNDPs. In this section, they are compared and contrasted based on aspects pertaining to problem formulation, instantiation, and solution approach. The formulations are summarized in Table 2.1.

Table 2.1: Overview of BNDP formulations identified in the literature review.

Reference	Problem Type	Objective	Demand		Route Suitability		Construction / Upgrade	
			Form	(C) Coverage	(C) Cost	(C) Continuity	Edge Cost	(C) Budget
Zhu and Zhu (2020)	multi-objective MILP	(1) min inaccessible activity locations (2) min intersections (3) min BLOS (4) min construction cost	origin-activity	partial	travel time budget	full	length	yes
Lin and Yu (2013)	multi-objective MILP (grey)	(1) min risk (2) max comfort (3) max demand coverage (4) min traffic impact	OD, fixed volume	partial	none	full	monetary	yes
Caggiani et al. (2019)	nonlinear	min difference in bicycle inf. accessibility between advantaged and disadvantaged groups	OD, fixed volume	full	shortest path × factor	none	length	yes
Mesbah et al. (2012)	nonlinear	(1) max proportion of bicycle travel on bicycle inf. and min total travel time by car (weighted) (2) traffic assignment	OD, fixed volume	full	bicycle: shortest path car: none	none but network has to be connected	monetary	yes
Smith (2011)	MILP	min travel cost and min BLOS (weighted)	OD, fixed volume	full	none	full (≥ target BLOS)	monetary	yes
Akbarzadeh et al. (2018)	MILP	min travel cost and min construction cost (weighted)	OD, fixed volume	full	none	full	length	no
Paulsen and Rich (2023)	MILP (multi-stage)	max net present value	OD, fixed volume	full	shortest path	none	monetary	yes
Ospina et al. (2022)	MILP (multi-stage)	(1) max demand coverage (2) min construction cost	OD, fixed volume	(1) partial (2) full	f(user characteristics, built environment)	full	monetary	yes

Continued on next page

Table 2.1: Overview of BNDP formulations identified in the literature review. (Continued)

Reference	Problem Type	Objective	Demand		Route Suitability		Construction / Upgrade	
			Form	(C) Coverage	(C) Cost	(C) Continuity	Edge Cost	(C) Budget
Lim et al. (2022)	MILP	min deviation from shortest paths alt: max demand coverage	OD, fixed volume	partial	shortest path × factor	full	length	yes
Duthie and Unnikrishnan (2014)	MILP	min construction cost	OD	full	shortest path × factor	full (≥ target BCI)	f(length, ΔBCI) (& intersections)	no
H. Liu et al. (2019)	MILP	max route utilities utility = f(route length, turn frequency, slope, presence of bicycle inf.)	OD, fixed volume	full	none	none	length	yes
Mauttone et al. (2017)	MILP	min travel cost travel cost = length × factor for links w.o inf.	OD, fixed volume	full	none	none but min discontinuities during GRASP	length	yes

Key: constraint [(C)]

Type of Optimization Problem

Ten of the BNDPs were modeled as mixed-integer linear programs (MILPs), meaning their objectives and constraints were expressed using linear combinations of continuous, integer, and binary variables. Caggiani et al. (2019) and Mesbah et al. (2012) formulated non-linear BNDPs. While formulating a BNDP as a MILP limits the types of relationships that can be modeled, their advantage is that they are significantly easier to solve for a global optimum.

Objective

Nine of the BNDPs optimized a single objective function. H. Liu et al. (2019) and Mauttone et al. (2017) optimized user benefits throughout the network by minimizing total travel cost and maximizing route utilities, respectively. Mauttone et al. (2017) represented travel cost by the route length, with a penalty factor applied to edges without bicycle infrastructure. In addition to route length and the presence of bike infrastructure, H. Liu et al. (2019) also incorporated turn frequency and slope, making their approach one of the most comprehensive in terms of modeling aspects of route choice. In contrast to these two approaches, Duthie and Unnikrishnan (2014) formulated an objective function that minimized construction cost, incorporating the user perspective into the model with constraints instead.

Four studies modeled multiple objectives using a single objective function by optimizing an aggregate of the individual objectives. Akbarzadeh et al. (2018) minimized the weighted sum of route length (user cost) and network length (operator cost), demonstrating a hybrid of the aforementioned approaches that optimized the network from one perspective or the other. Similarly, Smith (2011) minimized the weighted sum of route length and the Bicycle Level of Service (BLOS). The model proposed by Mesbah et al. (2012) is distinguished from the others as it balances bicycle network expansion with its impact on motorists. The model has a bi-level structure, with the first level maximizing the proportion of bike travel along cycleways minus the weighted total car travel time. The second level is responsible for traffic assignment, in which bicycle demand is assigned to the shortest path in the network, and car traffic is assigned based on user equilibrium. Like Mesbah et al. (2012), Caggiani et al. (2019) optimizes the amount of bicycle travel along cycleways. Their approach differs in that they aim to design a network equitably by minimizing the difference in cycleway accessibility between advantaged and disadvantaged groups.

Lim et al. (2022) and Ospina et al. (2022) formulated problems that maximize demand coverage. Lim et al. (2022) accomplished this using an objective that minimizes the difference in length between a route and the shortest path in the network. The problem is formulated so an "outside option" can be chosen for a given OD pair, allowing for partial demand coverage. They also specify an alternative formulation that purely maximizes coverage. Ospina et al. (2022) uses a two-stage problem structure. In the first stage, demand coverage is maximized for a given budget. In the second stage, the OD pairs connected in the first stage are fixed, and the problem is solved again to minimize construction cost. A multi-stage approach was also used by Paulsen and Rich (2023) to maximize the net present value of a sequence of network upgrades.

Two of the studies formulated multi-objective optimization problems. Unlike the approaches that aggregated objectives into a single objective function, these approaches allowed them to be negotiated freely. Of the reviewed studies, Lin and Yu (2013) had the broadest coverage of aspects pertinent to bicycle network design. Their problem involved maximizing demand coverage and comfort while minimizing risk and impacts to motorized traffic. Risk, comfort, and traffic impacts were represented by linear combinations of variables representing aspects of each objective. Risk was represented by the number of intersections, turns, traffic accidents, and the functional classification of roadways. Comfort was represented by the type of bicycle infrastructure and wooded area along the route. Traffic impacts were represented by the reallocation of space from roadways and parking for bicycle infrastructure, granted without modeling their influence on congestion as per Mesbah et al. (2012). Zhu and Zhu (2020) were the second ones to propose a multi-objective formulation. Their unique approach aimed to improve accessibility by minimizing the number of inaccessible activity locations subject to a travel time budget. Concurrently, intersections along routes, BLOS, and construction costs were minimized.

Demand

With the exception of Zhu and Zhu (2020), who used origin-activity pairs, all studies represented demand using OD pairs. None of the reviewed studies modeled elastic demand, meaning demand was independent of network conditions. Ten of the studies modeled variable amounts of demand for each connection, while Duthie and Unnikrishnan (2014) and Zhu and Zhu (2020) treated all equally - inline with supply-side, conventional approaches to network design (Gerike et al., 2022). All studies except for Lim et al. (2022), Lin and Yu (2013), Ospina et al. (2022), and Zhu and Zhu (2020) required the solution to fully cover the demand.

Route Suitability Constraints

Requirements specifying the suitability of a route connecting an origin and destination can be implemented using cost and continuity constraints. Route cost constraints specify a maximum distance or time, while route continuity constraints specify the need for continuous cycling infrastructure along the route. BNDPs without a route continuity constraint effectively allow connections using the underlying street network.

Route cost constraints were included in seven of the studies. Mesbah et al. (2012) and Paulsen and Rich (2023) required connections using the shortest path, while Caggiani et al. (2019), Duthie and Unnikrishnan (2014), Lim et al. (2022), and Ospina et al. (2022) required connections that were less than or equal to the product of the shortest path and a detour factor. Ospina et al. (2022) had the most sophisticated implementation, where the detour factor was dependent on cyclists' socioeconomic characteristics and the built environment at the origin, destination, and along the route. Zhu and Zhu (2020) implemented a constraint on the total travel time budget, achieving a similar effect. Seven studies had route continuity constraints, four of which also had route cost constraints (Duthie & Unnikrishnan, 2014; Lim et al., 2022; Ospina et al., 2022; Zhu & Zhu, 2020). H. Liu et al. (2019) and Mauttone et al. (2017) included neither constraint.

Construction Cost

The construction cost of an edge was based on its length in all of the reviewed studies. Five studies converted the length into a monetary value by assuming an average cost per unit of length. Of these, Lin and Yu (2013) had the most detailed approach as they also included the maintenance cost. Duthie and Unnikrishnan (2014) represented the cost as an abstract unit that accounted for the difference between the existing and target Bicycle Compatibility Index (BCI). Additionally, they were the only study to include the construction cost of intersections in their model.

Ten studies included a budget constraint in their formulation, with the remainder including the construction cost exclusively in their objective function (Akbarzadeh et al., 2018; Duthie & Unnikrishnan, 2014). Lin and Yu (2013) and Ospina et al. (2022) included construction cost as one of their objectives while also incorporating a constraint.

Maximum Instance Size and Solution Approach

Table 2.2 shows the largest problem instance solved in each study and the corresponding solution approach. The relatively small graphs of the multi-objective and nonlinear optimization problems indicate their high computational complexity. The computational complexity of multi-objective BNDPs (Lin & Yu, 2013; Zhu & Zhu, 2020) is attributed to the challenge of finding Pareto optimal solutions, ones where a given objective can't be improved any further without degrading at least one of the others. As for the non-linear BNDPs (Caggiani et al., 2019; Mesbah et al., 2012), it is not feasible to solve them using an exact method. Therefore, genetic algorithms were used to determine high-quality but not strictly optimal solutions.

Even single-objective BNDPs modeled as MILPs can become computationally intractable when the problem contains many nodes, edges, and OD pairs (Lim et al., 2022). One of the identified approaches to mitigate this was to reduce the search space. For example, Caggiani et al. (2019), H. Liu et al. (2019), and Paulsen and Rich (2023) approached the BNDP from a higher-level by considering a predefined set of routes rather than creating them from individual edges. While this categorically reduces the model's flexibility, it enables more complex relationships or networks to be modeled. For instance, Paulsen and Rich (2023) explored network extensions for the Greater Copenhagen region, a problem comprised of 471,226 edges and 52,742 OD pairs, by narrowing the search space to 55 possible network extensions.

Another approach to improve computational performance is to leverage more efficient solution approaches. H. Liu et al. (2019) and Mauttone et al. (2017) proposed metaheuristic approaches to solve large problem instances. While this sacrifices solution quality, i.e., the guarantee of global optimality, it greatly reduces the computational cost. Mauttone et al. (2017) demonstrated this by using a "Greedy Randomized Adaptive Search Procedure" (GRASP) that was validated on a problem with 416 nodes, 1,266 directed edges, and 1,406 OD pairs to solve a problem with 12,759 nodes, 26,165 directed edges, and 81 OD pairs. Lim et al. (2022) used an alternative approach to improve performance for large problem instances while still guaranteeing a globally optimal solution. They used Benders decomposition to split their problem into a master problem that was responsible for designing the network and many subproblems that were responsible for routing each OD pair. The solution process was iterative, with each iteration producing additional constraints to the master problem. This acts as the synchronizing mechanism between the otherwise independent subproblems, guiding the master problem towards an optimal solution. Computational performance was significantly improved since the individual problems were much smaller and could be solved independently at each step. They demonstrated the effectiveness of this approach by finding the exact solution to a problem with 5,815 nodes, 11,329 directed edges, and 1,039 OD pairs.

Table 2.2: Maximum instance size and solution approach of the BNDPs identified in the literature review.

Reference	Problem Type	Nodes	Edges	Demand	Predefined Route Set	Solution Approach
Paulsen and Rich (2023)	MILP (multi-stage)	?	471,226 "links"	52,742 OD pairs	55	exact
Mauttone et al. (2017)	MILP	12,759	26,165 (D)	81 OD pairs		metaheuristic (GRASP)
Lim et al. (2022)	MILP	5,815	11,329 (D)	1,039 OD pairs		exact (Benders decomposition)
H. Liu et al. (2019)	MILP	416	1,828 (D)	10 OD pairs	60	hybrid ("matheuristic")
Mauttone et al. (2017)	MILP	416	1,266 (D)	1,406 OD pairs		exact
Ospina et al. (2022)	MILP (multi-stage)	528	896 (UD)	149 OD pairs		exact
Smith (2011)	MILP	140	308 (D)	8 OD pairs		exact
Duthie and Unnikrishnan (2014)	MILP	75	185 (D)	5,625 OD pairs		exact
Mesbah et al. (2012)	nonlinear	42	142 (D)	30 OD pairs		metaheuristic (genetic algorithm)
Lin and Yu (2013)	multi-objective MILP (grey)	75	115 (UD)	66 OD pairs		exact
Zhu and Zhu (2020)	multi-objective MILP	32	47 (UD)	5 origins, 5 activity locations		exact

Continued on next page

Table 2.2: Maximum instance size and solution approach of the BNDPs identified in the literature review. (Continued)

Reference	Problem Type	Nodes	Edges	Demand	Predefined Route Set	Solution Approach
Caggiani et al. (2019)	nonlinear	20	44 (UD)	190 OD pairs	48	metaheuristic (genetic algorithm)
Akbarzadeh et al. (2018)	MILP	18	38 (D)	? OD pairs (6 demand nodes)		exact

Key: directed [(D)], undirected [(UD)]

2.2.3 Alignment of Bicycle Network Design Problems with Design Requirements

The alignment of the reviewed studies' BNDP formulations with the five network design requirements identified in Section 2.1.1 (cohesion, directness, safety, comfort, and attractiveness) was assessed by considering the combined effect of their objectives, constraints, and other pertinent aspects of the formulation. An overview is provided in Table 2.3.

Table 2.3: Alignment of BNDP formulations with the requirements of bicycle network design.

Reference	Cohesion	Directness	Safety	Comfort	Attractiveness
Zhu and Zhu (2020)	++	++	++	++	○
Lin and Yu (2013)	++	○	++	++	++
Duthie and Unnikrishnan (2014)	++	++	+	+	○
Smith (2011)	++	+	+	+	○
H. Liu et al. (2019)	○	+	++	++	○
Ospina et al. (2022)	++	++	○	○	○
Lim et al. (2022)	++	++	○	○	○
Akbarzadeh et al. (2018)	++	+	○	○	○
Mesbah et al. (2012)	+	++	○	○	○
Mauttone et al. (2017)	+	+	○	○	○
Caggiani et al. (2019)	○	++	○	○	○
Paulsen and Rich (2023)	○	++	○	○	○

Key: none / weakly implemented [○], implemented [+], strongly implemented [++]

Cohesion

At a minimum, the reviewed studies incorporated cohesion through the selection of OD, or origin-activity in the case of Zhu and Zhu (2020), pairs during the instantiation of the problem. As BNDPs aim to serve this demand, the resulting network tends to have a cohesive form, albeit to a varying degree, depending on the exact formulation of the problem. Problems that incorporated cohesion solely through the instantiation of demand (Caggiani et al., 2019; H. Liu et al., 2019; Paulsen & Rich, 2023) were considered weak implementations due to the implicit nature through which said cohesion arises. Mauttone et al. (2017) strengthened their incorporation of cohesion by maximizing the proportion of bicycle travel on bike infrastructure while minimizing network discontinuities. Mesbah et al. (2012) went a step further by adding a constraint to ensure the network was connected. The remaining seven studies were considered to have strong implementations based on their inclusion of route continuity constraints. In these studies, the instantiation of demand promoted interconnectivity while the constraints guaranteed continuous bicycle infrastructure along each route.

Directness

Of the reviewed studies, Lin and Yu (2013) was the only one that didn't explicitly incorporate directness in their formulation. Four of the studies incorporated directness through an objective that aimed to minimize travel cost throughout the network (Akbarzadeh et al., 2018; H. Liu et al., 2019; Mauttone et al., 2017; Smith, 2011). This was not considered as strong of an implementation as BNDPs with route cost constraints (Section 2.2.2). While minimizing travel costs leads to a network design that is, on average, direct, it does not guarantee the directness of individual routes. Consequently, it does not guarantee that individual routes are compelling to cyclists. Zhu and Zhu (2020) is a special case as they don't constrain the cost of individual routes but rather a total travel time budget. Despite this, their study is still considered to strongly incorporate directness due to the synergy with their objective of maximizing accessibility to activity locations. It's noted that the inclusion of route cost constraints does not necessarily make a model more useful. For instance, Mesbah et al. (2012) and Paulsen and Rich (2023) require connections by the shortest path in the network, which severely limits the possibility of bundling routes along common corridors.

Safety, Comfort, and Attractiveness

As discussed in Section 2.1.1, street-level design largely determines safety, comfort, and attractiveness. Three studies included quality of service indicators in their formulation, allowing a degree of sensitivity to such lower-level design aspects. This acts as a link between network- and street-level design. Instantiating a network with a quality of service indicator allows for the current condition of a network to be modeled with more detail. Furthermore, including the quality of service in the problem allows the solution to be translated into street-level design requirements. Smith (2011) and Zhu and Zhu (2020) minimized the Bicycle Level of Service (BLOS) as part of their objective function, with Smith (2011) also specifying a minimum quality threshold as part of their route continuity constraint. Duthie and Unnikrishnan (2014) didn't include the quality of service indicator in their objective but also specified a threshold in their route continuity constraint based on the BCI. It's worth noting that including quality of service thresholds in a BNDP's route continuity constraint does not significantly alter the problem formulation. All seven studies with route continuity constraints have nearly equivalent implementations but differ in how they define an edge suitable for cycling. Therefore, in the case of Duthie and Unnikrishnan (2014) and Smith (2011), the incorporation of safety and comfort is largely attributed to the instantiation of the problem rather than its formulation.

Lin and Yu (2013), S. Liu et al. (2021), and Zhu and Zhu (2020) minimized turns and/or intersections in their objectives, a valuable inclusion given that intersections significantly impact safety and comfort. Lin and Yu (2013) also minimized the use of crash-prone edges, while H. Liu et al. (2019) considered the influence of slope, further enhancing their incorporation of safety and comfort requirements, respectively. Lin and Yu (2013) was the only study that incorporated attractiveness, doing so through an objective that maximized routes along wooded areas.

3 Methodology

This chapter describes the candidate network preparation, travel time calculations, regional accessibility analysis, and B+RNDP formulation. The methods were developed for use with open datasets, namely OpenStreetMap (OSM) and GTFS feeds. As a result, with some minor changes, they can be applied to study areas worldwide. The accessibility analysis and B+RNDP are introduced in a general form, allowing them to be easily adapted. Figure 3.1 provides an overview of the methodology.

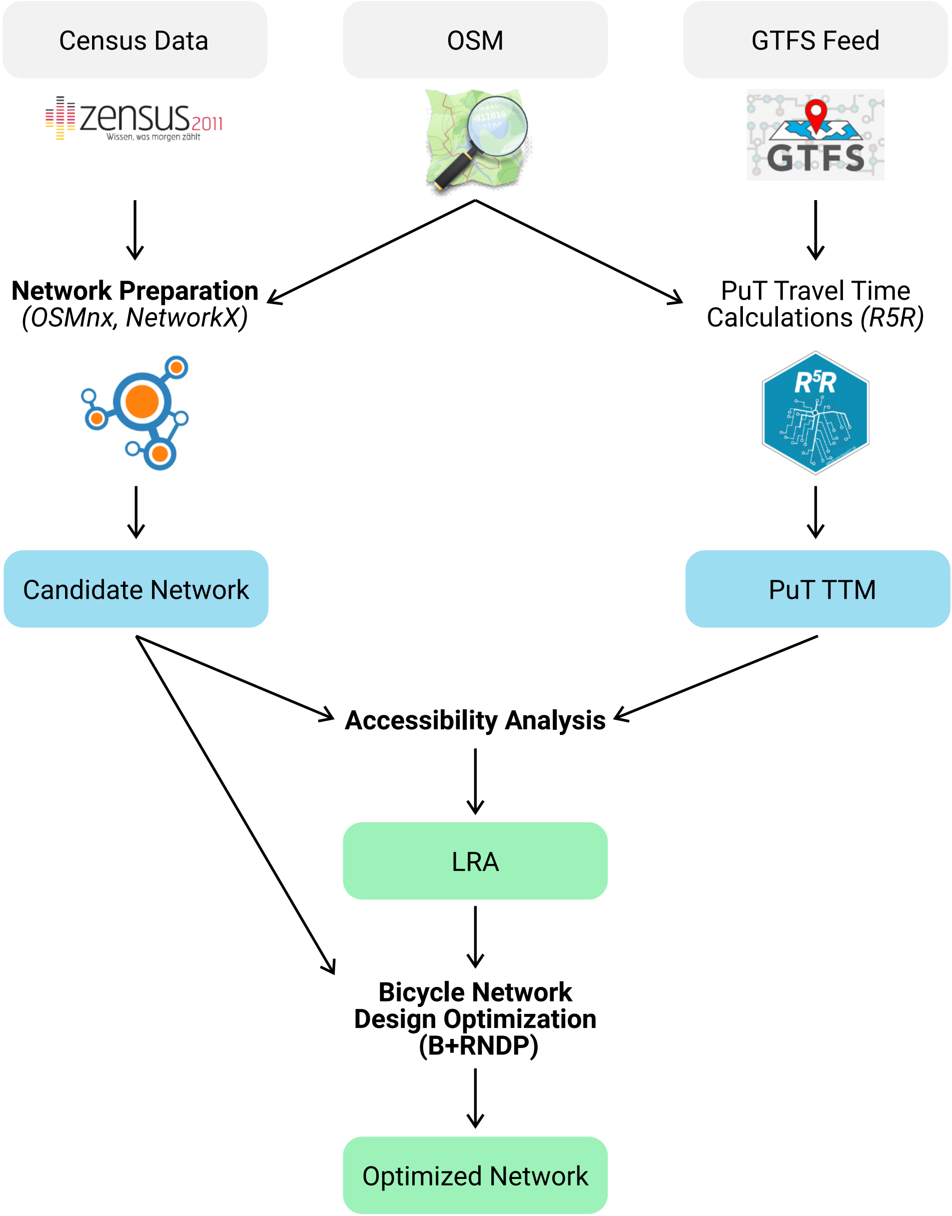


Figure 3.1 Methodology overview.

3.1 Candidate Network Preparation

The street network was modeled as a graph of nodes and directed edges. As the present work is concerned with the current state of the network and its potential for future upgrades, the goal was to prepare a "candidate" network comprising edges that are, at minimum, feasible to upgrade to a suitable quality for cycling. To this end, edges were enriched with a classification of the Level of Traffic Stress (LTS), a quality of service measure used to assess infrastructure suitability for a target user group.

Representing the network at a high level of detail was essential. Unlike motorized transport, the travel speed of active modes is largely independent of the infrastructure, meaning the omission of "minor" roads and paths can significantly misrepresent the network's performance. At the same time, it was essential to limit the size of the graph in terms of the number of nodes and edges so that the accessibility analysis and network design problem could be based on the same underlying data. While routing algorithms, the foundation of network-based accessibility analyses, can handle very large graphs, the same is not true for network design problems, as their computational complexity increases exponentially with graph size. Accordingly, a key part of the network preparation involved simplifying the graph while retaining its form and LTS characteristics.

3.1.1 Initializing the Street Network

The street network was prepared using OpenStreetMap (OSM) data. OSMnx (Boeing, 2017) was used to download and process the data. The network was initialized using a query for all OSM ways (linear features) with a *highway* key, excluding the key-value pairs listed in Table A.1.

The initial graph matched the form of OSM data, meaning that all ways were represented as directed edges with directional information stored as attributes. In other words, the orientation of an edge in the initial network was arbitrary unless it was tagged as one-way. This was considered throughout the network preparation to allow for the infrastructure and LTS to be classified in each node pair's forward and backward direction.

3.1.2 Level of Traffic Stress

The Level of Traffic Stress (LTS) is a normative quality of service indicator that estimates the suitability of street network elements for different profiles of cyclists (Mekuria et al., 2012). This allows the bicycle network to be defined dynamically based on a target user rather than an inventory of infrastructure and streets where cycling is legally permitted. This is favored over the latter, more conventional approach as it allows for sensitivity to different user groups and their needs. Consequently, aspects of safety and comfort that stem from street-level design are incorporated into the accessibility analysis and network design optimization.

The LTS method is connected to a typology of cyclists originally proposed by Roger Geller for the City of Portland (Dill & McNeil, 2016). Per the typology, it is estimated that 60% of adults are "Interested but Concerned," 7% are "Enthused and Confident," and less than 1% are "Strong and Fearless." The remaining 33% fall under the "No Way No How" classification, indicating that they are unable or entirely unwilling to cycle. The precise magnitude of these percentages is unimportant, as their purpose is just to express the notion that most of the population are cyclists or potential cyclists, of which relatively few are willing to cycle in high-intensity mixed traffic. The value of the typology is that it serves as a theoretical framework to facilitate planning for various types of cyclists and their needs. The "Interested but Concerned" category is of particular value, as it is a straightforward heuristic for developing cycling infrastructure suitable for a broad user base (McLeod et al., 2020).

The LTS methodology makes the connection to these profiles by assigning network elements an LTS ranging from 1 to 4 based on their adherence to state-of-the-art Dutch design standards. The general principle is that LTS increases with increasing speeds, an increasing number of lanes, and decreasing separation from motorized traffic. The Dutch standards are the basis for the LTS 2 classification, representing network elements suitable for the general adult population, i.e., the "Interested but Concerned." An overview of the LTS definitions by Furth (2023), one of the main developers of the method, is provided below:

> **LTS 1:** Strong separation from all except low speed, low volume traffic. Simple crossings. Suitable for children.
>
> **LTS 2:** Except in low speed / low volume traffic situations, cyclists have their own place to ride that keeps them from having to interact with traffic except at formal crossings. Physical separation from higher speed and multilane traffic. Crossings that are easy for an adult to negotiate. Corresponds to design criteria for Dutch bicycle route facilities. A level of traffic stress that most adults can tolerate, particularly those sometimes classified as “interested but concerned.”
>
> **LTS 3:** Involves interaction with moderate speed or multilane traffic, or close proximity to higher speed traffic. A level of traffic stress acceptable to those classified as “enthused and confident.”
>
> **LTS 4:** Involves interaction with higher speed traffic or close proximity to high speed traffic. A level of stress acceptable only to those classified as “strong and fearless.”

Level of Traffic Stress Criteria

The original criteria were adapted to classify edges in the initialized street network. Per the original LTS criteria, cycle paths are considered LTS 1, while cycle lanes and mixed-traffic edges can range from 1 to 4 depending on speed, the number lanes, presence of parking, and bike lane width. As this data is often unavailable in OSM, the LTS criteria were simplified to limit the number of necessary assumptions. The implemented criteria were based on infrastructure type, the number of lanes, and speed, which aligns with the OSM-based LTS implementation in R5 (Conway et al., 2017). Additionally, thresholds were modified to better suit the German context, as the original LTS criteria (Mekuria et al., 2012) were developed for use in the United States.

The implemented criteria classified cycle paths, play streets, traffic-calmed areas, and pedestrian streets where cycling is permitted as LTS 1. Criteria for bike lanes (Table 3.1) and mixed-traffic (Table 3.2) have more stringent lane and speed thresholds when compared to the original criteria. A 50 kph threshold is used as an upper limit for LTS 2 bike lanes, corresponding to a typical maximum speed limit for built-up areas in Germany. A 30 kph threshold was used as a maximum for mixed traffic due to its correspondence to "Tempo 30" zones and "Vision Zero" concepts (Johansson, 2009). In OSM, a single street can be represented by multiple ways. For instance, a two-way street with a median is typically mapped as two one-way ways. The criteria for one-way, mixed-traffic infrastructure was specified to be sensitive to this and, therefore, doesn’t exclusively correspond to one-way streets.

Table 3.1: Cycle lane LTS criteria.

lanes (one-way)	*maxspeed* (kph)			
	$\leq 10^{a}$	≤ 30	< 50	≥ 50
(1)	1	1	2	4
≤ 3 (2)	1	2	2	4
> 3 (2)	1	3	3	4

[a] includes play streets and traffic-calmed areas (*highway* = "living_street")

Table 3.2: Mixed-traffic LTS criteria.

lanes (one-way)	*maxspeed* (kph)			
	$\leq 10^{a}$	≤ 30	< 50	≥ 50
≤ 3 (2)	1	2	3	4
> 3 (2)	1	3	3	4

[a] includes play streets and traffic-calmed areas ($highway$ = "living_street")

Classification of the Street Network

To apply the LTS criteria, it was first necessary to identify the cycle paths and lanes in the network. This was accomplished using the criteria provided in Table A.2, an adaptation of a classification scheme proposed by Ferster et al. (2020). The direction of the infrastructure was assigned by considering the *oneway*, *oneway: bicycle*, *cycleway:left: oneway*, and *cycleway:right:oneway* keys.

Next, edges unsuitable for cycling were flagged as LTS 99 or LTS 999. LTS 99 edges included the backward direction of one-way streets where contraflow was unpermitted and OSM ways tagged as "paths" that did not specify use for cyclists. While unsuitable for cycling in their current state, these edges were still considered candidates for upgrades. Accordingly, the subset of the network with an LTS $\leq$ 99 is regarded as the "candidate" network. Edges unsuitable for cycling and infeasible for upgrade were flagged as LTS 999. This included mixed-traffic, high-speed roads, sidewalks, and pedestrian streets that don't permit cycling. An overview of the conditions for these flags is provided in Table A.3.

Finally, the LTS criteria were applied. In case of a missing speed limit (*maxspeed*), a conservative estimate based on a typical speed corresponding to the edge's *highway* value was assigned (Table A.4). If the edge was missing the number of lanes, it was assumed to be 2.

3.1.3 Network Simplification

After the LTS classification of each edge's forward and backward direction, the graph was restructured so that each direction was represented by its own edge. Before applying the simplification procedure, each edge (a, b) was assigned variables $l_{ab}^{LTS_{target}}$ representing how much of its length l_{ab} exceeded an LTS target threshold LTS_{target}. This was calculated using Equation 3.1 by comparing the LTS of the edge LTS_{ab} to LTS_{target} values of 1, 2, and 3.

$$l_{ab}^{LTS_{target}} = \begin{cases} l_{ab} & \text{if } LTS_{ab} > LTS_{target} \\ 0 & \text{otherwise} \end{cases} \qquad \forall LTS_{target} \in \{1, 2, 3\} \tag{3.1}$$

To reduce the size of the graph, the OSMnx (Boeing, 2017) simplification module was used. The following steps describe the simplification procedure:

1. Merge edges by removing nodes that aren't intersections or end points
2. Remove dead ends less than 100 m long
3. Merge edges by removing nodes that aren't intersections or end points
4. Consolidate nodes within 20 m of each other
5. For each node pair, keep a single edge per direction

Edges merged during steps 1 and 3 were assigned the maximum LTS; total length; and total length exceeding LTS 1, 2, and 3 of the original edges. Step 4 can result in a node pair having multiple edges in a single direction. In this case, the shortest edge with $LTS_{ab} \leq 2$ was kept if its length was within 120% of the shortest edge. Otherwise, the shortest edge was kept.

3.1.4 Demographic Data

After simplification, the graph was enriched with demographic data from the 2011 census (Statistische Ämter des Bundes und der Länder, 2018). The subset of the population between 18 and 64 were considered working-age adults. The data was aggregated to a 500 m spatial resolution (25 ha square cells) and was then snapped to the nearest node if it was within 500 m of the graph.

3.2 Travel Time Calculations

This section describes the calculation of cycling, walking, and public transport travel times. Cycling and walking times were determined using the candidate network prepared per the methodology in Section 3.1, while public transport times were derived from a separate model. The section concludes by describing how the travel times were synthesized into intermodal travel times.

3.2.1 Cycling and Walking

Cycling and walking travel times were calculated based on an OD pair's shortest path in the candidate network. An implementation of Dijkstra's algorithm in the NetworkX python package (Hagberg et al., 2008) was used to determine the shortest path. Network distances were converted into walking and cycling times by dividing them by 4 and 12 kph, respectively. The entire street network was considered suitable for walking, meaning the graph could be used without further processing. Consistent with the "weakest-link" principle of the LTS method (Mekuria et al., 2012), a cycling route was considered suitable for the target user only if all edges in the path had an LTS $\leq LTS_{target}$. As a result, the accessibility analysis is sensitive to the importance of cohesion. To enable this, the length of edges with an LTS $> LTS_{target}$ was artificially increased so that they could not be used.

3.2.2 Public Transport

Public transport travel times were calculated using R5R (Pereira et al., 2021), an R-based interface to the R5 routing engine (Conway et al., 2017). The input data consisted of public transport timetables in the General Transit Feed Specification (GTFS) format and an extract of raw OSM data. A GTFS feed was prepared by processing the DELFI (2022) Germany-wide GTFS feed using the R package, tidytransit (Poletti et al., 2023). The Germany-wide feed was trimmed to the extent of the Munich Metropolitan Region, and high-speed rail services were removed.

R5 uses OSM data to build a street network so that access to, transfers between, and egress from public transport stops is possible. While the underlying data of the R5 street network is the same as the street network that was prepared using the methodology in Section 3.1, it involves different processing and does not generalize the network to the same extent. While this is a potential source of error, R5 is only used to derive a stop-to-stop travel time matrix (TTM). Accordingly, the R5 street network was used exclusively to enable short transfers between public transport services. For this reason, it is maintained that any resulting discrepancies are negligible.

The model allows for the travel time to be calculated for any time of day. As the model maintains the full precision of the timetables in the GTFS feed, travel time is highly dependent on the departure time. The impact of this is heightened by the peripheral context of the present work, as the service frequency of PuT tends to be significantly lower than in the urban core. To account for this, the travel time between a pair of stops was represented as the 99th percentile of 60 departures evenly distributed in the hour selected for the analysis. Functionally, this is an approximation of the optimal travel time. This approach was chosen instead of considering random departure times, as it is assumed that the majority of travelers are "schedule-dependent," meaning they know the schedule of the public transport service and plan their departure time to minimize total trip time (Müller, 1981). Travel times were calculated between stops within 6 km of each target S-Bahn stop to all stops in the Munich Metropolitan Region. To allow for transfers, walking between public transport stops for up to 3 minutes at a speed of 4 kph (200 m) was permitted.

As with the street network, the stop-to-stop TTM was simplified in order to reduce its level of detail. This was accomplished by aggregating the stop-to-stop TTM in two steps: first at the stop cluster level and second at the node level. In a raw GTFS feed, a single stop is typically represented by numerous stop IDs. For example, a bus stop may be represented by two stop IDs, one on each side of the road. Using tidytransit, stops with the same name were assigned a common stop cluster if they (a) were within 300 m of each other or (b) had S-Bahn service. The stop-to-stop TTM was aggregated for each stop cluster origin and destination pair, where the lowest travel time was kept to represent the connection. Following this, each stop cluster was snapped to the street network by identifying the node nearest to the stop with the highest number of departures within the hour chosen for travel time calculations. After assigning the nearest node in the network, the aggregation was repeated.

3.2.3 Intermodal

Intermodal travel times were calculated by enriching the stop-to-stop PuT TTM with access and egress times. The times were calculated for a specified origin, maximum travel time, and access/egress constraints. The constraints specified the mode(s) that could be used, the stops that they could be used at, and the maximum travel time. The travel time calculation began by determining all stops accessible from the origin while adhering to the access constraints. Stops reached through the access leg of the trip were regarded as access points (APs) as they represent a traveler's entry point into the PuT network. For each AP, all stops accessible within the remaining travel time by PuT were determined using the stop-to-stop PuT TTM. For each accessible stop, all destination nodes within the remaining travel time and egress constraints were determined. As it was possible for numerous routes to connect an OD pair, the route with the lowest travel time was kept. If a destination could not be reached within the maximum travel time, a travel time of $+\infty$ was assigned.

3.3 Regional Accessibility Analysis

The goal of the accessibility analysis was to determine the LRA, the potential to increase regional B+R accessibility for a target user group through bicycle network improvements. The first part of this section provides general definitions for regional accessibility and four associated measures: OD access potential, the indicator of regional accessibility (IoRA), accessibility flow, and the AP-OD centrality. The second part specifies their implementation for the case study. The section concludes by describing how the LRA is determined and how it can be used to identify target stops for improvement.

3.3.1 Definition of Regional Accessibility Measures

Accessibility, as understood in contemporary urban and transportation planning, was first defined by Hansen (1959) as "the potential of opportunities for interaction." Hansen emphasizes that accessibility is a measure of "the intensity of the possibility of interaction," distinguishing it from mobility which instead focuses on "the ease of interaction." Accessibility has since been redefined many times in the literature. The present work adopts a definition proposed by Geurs and Van Wee (2004) as it makes a clear reference to the underlying land-use, transport, temporal, and individual aspects of accessibility: "the extent to which land-use and transport systems enable (groups of) individuals to reach activities or destinations by means of a (combination of) transport mode(s)."

OD Access Potential and the Indicator of Regional Accessibility

The present work focuses on regional B+R accessibility, with one of the corresponding measures being the indicator of regional accessibility (IoRA). The IoRA is a location-based measure of accessibility that is defined as the sum of destinations' contributions to the regional accessibility of a given origin. The OD access potential refers to the individual components of this summation, i.e. the contribution of a given destination to the regional accessibility of a given origin.

Mathematically, the OD access potential A'_{ij} is represented by Equation 3.2 where i and j represent the origin and destination, respectively. The OD access potential is calculated by taking the product of W_j, a weight representing the number of activities at the destination, and the impedance $f(t_{ij})$, where t_{ij} is the travel time. The IoRA A_i of a given origin is in turn represented by Equation 3.3 where D is a set of destinations.

$$A'_{ij} = W_j f(t_{ij}) \tag{3.2}$$

$$A_i = \sum_{j \in D} A'_{ij} \tag{3.3}$$

Accessibility Flow and the AP-OD Centrality

While the IoRA is useful in that it describes the spatial distribution of regional accessibility, it does not explicitly indicate how said accessibility is realized. To address this gap, a centrality indicator was leveraged to determine the amount of accessibility facilitated by public transport stops.

Centrality indicators measure the relative importance of an edge or node in a graph. As there is no universal definition of importance, many variants of centrality indicators exist to represent the different perspectives through which a network can be interpreted. One way to define centrality is in terms of the amount of flow passing through an edge or node (Rodrigues, 2019). A typical example is betweenness centrality, which measures the number of paths that use a node or edge while considering the shortest paths between all combinations of nodes. In their study, McDaniel et al. (2014) proposed an alternative, flow-based indicator, OD centrality. Unlike betweenness centrality, the OD centrality considers the shortest paths of a set of OD pairs rather than all combinations of nodes. OD centrality is further distinguished by scaling each path's contribution to centrality by the product of the origin and destination's weights. Moran et al. (2018) use a very similar approach, in which they scale the flow by the population at the origin and employment at the destination.

Enabling B+R through bicycle network upgrades is concerned with home-based trip legs. This provides the motivation for measuring the importance of PuT stops with respect to how much accessibility they facilitate when they function as access points (APs) to the public transport network. To this end, the AP-OD centrality is proposed. Like the OD centrality, the AP-OD centrality considers a set of OD pairs, origin and destination weights, and connections using the shortest paths in the network. The weighted flow is referred to as the accessibility flow. The main distinction of the AP-OD centrality is that the influence of the flow does not propagate through the whole network but rather is allocated entirely to the AP. The differences between the discussed centrality measures are depicted in Figure 3.2.

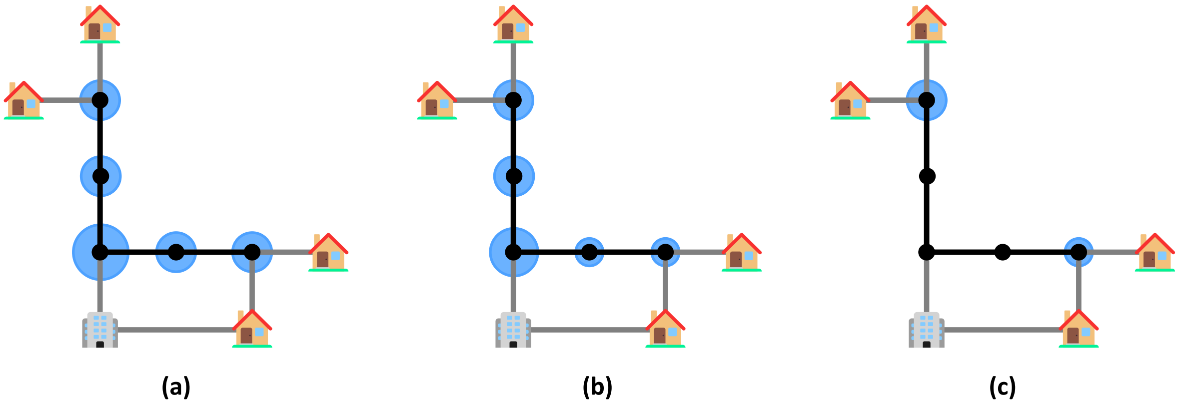


Figure 3.2 Comparison of (a) betweenness, (b) OD, and (c) AP-OD centrality indicators.

Mathematically, the accessibility flow F_{ij} is represented by Equation 3.4 which involves taking the product of the OD access potential A'_{ij} and the origin population P_i. The AP-OD centrality C_s of a public transport stop s is the sum of accessibility flow that uses that stop as an AP. The general form is specified by Equation 3.5. Given a set of OD pairs $(i, j) \in OD$, and s^*_{ij}, the AP used in the route, OD_s is defined as the subset of OD pairs using stop s as an AP ($OD_s = \{(i, j) \in OD \mid s^*_{ij} = s\}$).

$$F_{ij} = P_i A'_{ij} \tag{3.4}$$

$$C_s = \sum_{(i,j) \in OD_s} F_{ij} \tag{3.5}$$

Summary

To summarize, disaggregating the IoRA yields the OD access potential, a measure describing the contribution of a destination to an origin's regional accessibility. Weighting the OD access potential by the origin population can be interpreted as a flow through the network, and as such is referred to as the accessibility flow. Aggregating the accessibility flow at APs yields the AP-OD centrality, which represents the amount of accessibility that PuT stops facilitate when they function as APs. As all of these measures are derived from the OD access potential, they are aligned with a common definition of regional accessibility. Figure 3.3 provides a visual representation of the relationship between the measures.

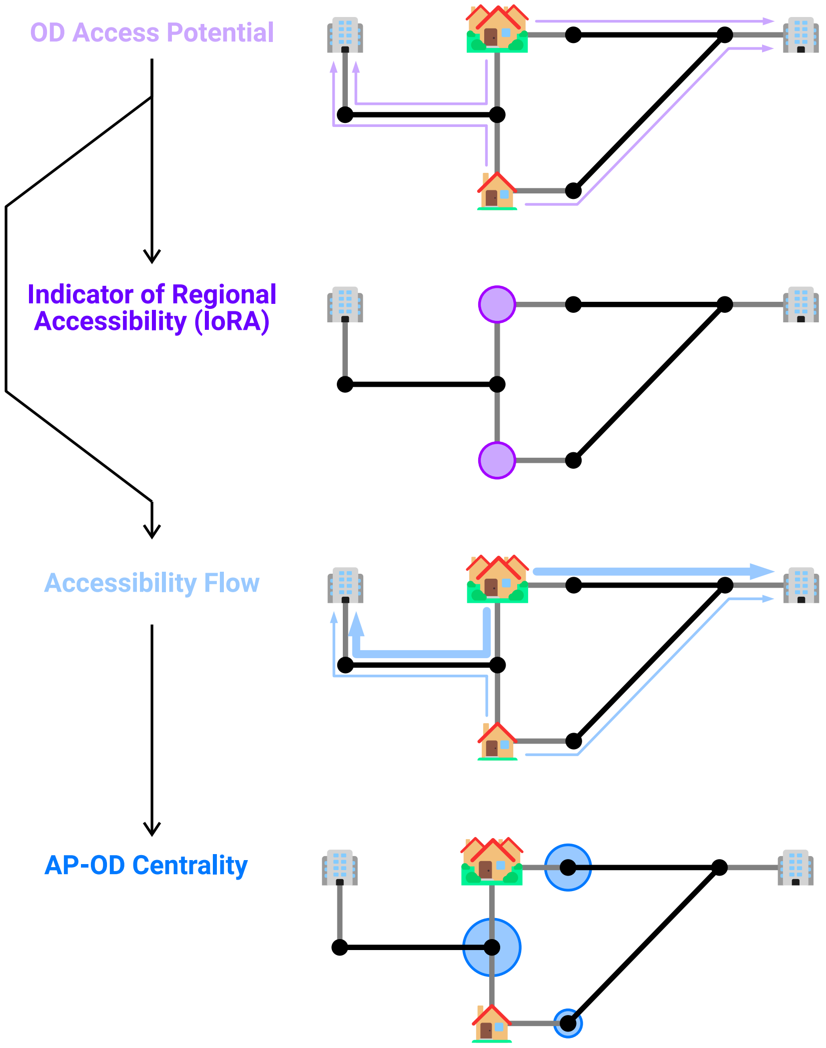


Figure 3.3 Relationship between the OD access potential, indicator of regional accessibility, accessibility flow, and AP-OD centrality.

3.3.2 Case Study Adaptation

This section describes the adaptation of the OD access potential, accessibility flow, IoRA, and AP-OD Centrality for the case study.

OD Access Potential

Equation 3.6 represents the modified form of the OD access potential. The OD access potential was calculated for origins in a set of working-age populated nodes ($i \in O$). Access to population was used as a proxy for access to activities, replacing the destination weight W_j with P_j, the population at the destination node. The underlying assumption was that amenities and services tend to be concentrated in populated areas. This was a pragmatic choice, given that the data was readily available at high spatial resolution. Furthermore, it is simpler to interpret than an aggregation of access to various amenities, as this introduces the need for categorization and weighting. Destinations within 3 km of an origin were considered local as this is a proximity where walking and cycling can be viable as the main modes of transport (Bundesministerium für Digitales und Verkehr, 2020, p. 88). Accordingly, a destination set D_i was associated with each origin, comprising populated nodes more than 3 km away from it.

The OD access potential was calculated separately for cycling and walking access modes, hence the inclusion of the index m. Travel times were calculated for departures on Tuesday, January 23, 2024, between 8:00 and 9:00. This represents peak morning demand and is consistent with the parameters used to calculate travel times in MVV's regional local public transport plan (MVV, 2019). The access and egress constraints in Table 3.3 were applied. Cycling was exclusively considered an access mode to model homed-based B+R. Furthermore, access by cycling was only considered to stops with S-Bahn service as B+R is most commonly used in combination with faster, higher-quality modes (Martens, 2004). The maximum cycling access time was set to 3 km, aligned with the findings of Moinse (2024), who reviewed studies pertaining to PuT system access by micromobility in Europe. A maximum detour factor of 1.2 was enforced to avoid circuitous bicycle routes, meaning the route had to be within 120% of the shortest path in the full candidate network. This value matches the German guidelines for the design of cycling facilities (FGSV, 2010, p. 10). Walking access and egress times were limited to 10 minutes, which is in line with the findings of Sarker et al. (2019), who studied willingness to walk to PuT stops in the city of Munich and its suburbs.

In the interest of maintaining the interpretability of the results, the impedance was calculated using a step function (Equation 3.7) that weighted access within a travel time of 60 minutes equally. Travel times exceeding 60 minutes would result in the destination having no contribution to the origin's regional accessibility. In the periphery of Munich, the median public transport travel time for trips $\leq$ 50 km is 40 minutes (Bundesministerium für Digitales und Verkehr, 2020). Therefore, the 60-minute threshold represents a relatively high but not unusual travel time. Overall, the implemented OD access potential incorporates all four aspects of accessibility:

- **Land-use:** implicitly through the consideration of access to population
- **Transport:** consideration of intermodal trips by public transport and walking or cycling
- **Temporal:** accessibility is sensitive to the departure time
- **Individual:** the target user's needs and preferences are incorporated through the LTS

$$A'^{m}_{ij} = P_j f\left(t^{m}_{ij}\right) \quad \forall j \in D_i, \forall i \in O, \forall m \in \{walk, bike\} \tag{3.6}$$

$$f(t) = \begin{cases} 1 & \text{if } t \leq 60 \\ 0 & \text{otherwise} \end{cases} \tag{3.7}$$

Table 3.3: Access and egress constraints for the accessibility analysis.

Mode	Trip Leg	Stops	Max Time (Distance)
Walking	Access/Egress	All	10 min (667 m)
Cycling	Access	S-Bahn	15 min (3 km), 120% of shortest route[a]

[a] shortest route in full candidate network

Accessibility Flow

For the case study, accessibility flow was calculated using Equation 3.8. The general form was modified using the working-age population at the origin $P_i^{'}$ to represent the target user group. Given the focus on B+R, the bicycle accessibility flow was of primary interest. As to not overestimate the use of cycling within walking distance of S-Bahn stops, the bicycle accessibility flow F_{ij}^{bike} was adjusted by subtracting the walking accessibility flow F_{ij}^{walk} (Equation 3.9). Since the impedance function implemented in the OD access potential (Equation 3.7) is a step function, this adjustment equates to excluding destinations that are accessible when walking is the access mode from contributing to the bicycle accessibility flow.

$$F_{ij}^{m} = P_i^{'} A_{ij}^{'m} \quad \forall j \in D_i, \forall i \in O, \forall m \in \{walk, bike\} \tag{3.8}$$

$$F_{ij}^{bike} -= F_{ij}^{walk} \quad \forall j \in D_i, \forall i \in O \tag{3.9}$$

Indicator of Regional Accessibility

As the OD access potential was calculated separately for cycling and walking access modes, the general form was consider the maximum of the two (Equation 3.10). Since the impedance function implemented in the OD access potential (Equation 3.7) is a step function, the IoRA is a measure of the cumulative, non-local population within a 60 minute travel time using public transport and (optionally) cycling as the access mode.

$$A_i = \sum_{j \in D_i} \max\left(A_{ij}^{'walk}, A_{ij}^{'bike}\right) \quad \forall i \in O \tag{3.10}$$

Bicycle AP-OD Centrality

The case study focused entirely on the bicycle AP-OD centrality C_s^{bike} which was calculated for all PuT stops $s \in S$ using Equation 3.11 where OD_s^{bike} is the subset of OD pairs using stop s as an AP when cycling is the access mode ($OD_s = \{(i, j) \in OD \mid s_{ij}^{*bike} = s\}$). As specified in the access constraints (Table 3.3) of the OD access potential calculation, cycling was only considered for access to stops with S-Bahn service. As such, the measure specifically represents the total accessibility flow passing through a given S-Bahn stop when it functions as an AP and when cycling is the access mode. In other words, the amount of B+R accessibility a given S-Bahn stop facilitates when it functions as an AP.

$$C_s^{bike} = \sum_{(i,j) \in OD_s^{bike}} F_{ij}^{bike} \quad \forall s \in S \tag{3.11}$$

3.3.3 Latent Regional Accessibility

The LRA was determined by calculating the accessibility measures for two network scenarios:

- **Target LTS Network:** edges with an LTS $\leq LTS_{target}$ are considered suitable for cycling. This represents the subset of the network that is considered to match the needs and preferences of the corresponding target user group.
- **Full Network:** all edges in the candidate network (LTS $\leq$ 99) are considered suitable for cycling.

The LTS_{target} network scenario represents an estimate of the existing regional B+R accessibility for the target user group, which in the case study was $LTS_{target} = 2$ to correspond to the working-age adult target user group. Meanwhile, the full network scenario represents a maximum level of accessibility that can be achieved given the existing structure of the network. Accordingly, the difference between the scenarios is considered representative of the LRA. The difference in the IoRA allows for the spatial distribution of the LRA to be analyzed. This is supplemented by the AP-OD centrality, where the difference highlights the increase in B+R accessibility a given S-Bahn stop facilitates when it functions as an AP. This is representative of the LRA that can be realized by improving bicycle routes to the stop, and is therefore used to select target stops for improvement.

3.4 Bike-and-Ride Network Design Problem Formulation

The goal of network optimization was to determine how a network can be upgraded to realize the LRA identified by the accessibility analysis. For this purpose, the bike-and-ride network design problem (B+RNDP) is proposed. The B+RNDP is a BNDP formulated as a two-stage MILP. The first stage maximizes demand coverage, and the second stage minimizes the total travel cost. Mathematically, the formulation is very similar to those proposed by Lim et al. (2022) and Ospina et al. (2022). The main distinction of the B+RNDP is that the demand is instantiated based on the results of a regional accessibility analysis. The demand is derived from the LRA and, as such, serves as a link between the local scale of the bicycle network design and the regional scale of accessibility. As in the accessibility analysis, the model incorporates the LTS, which allows for sensitivity to street-level design and the characteristics of the target user group.

3.4.1 Parameters

The street network is represented as a graph $G = (N, E)$ where N is a set of nodes and E is a set of directed edges. All edges $(a, b) \in E$ have a length l_{ab} and an LTS LTS_{ab}. The B+RNDP considers a target LTS (LTS_{target}) that represents the LTS that a given route has to achieve in order for the associated OD pair to be considered connected. Edges exceeding LTS_{target} are considered high-stress edges ($E^{high} = \{(a, b) \in E \mid LTS_{ab} > LTS_{target}\}$). All high-stress edges have an upgrade cost c_{ab} associated with them that represents the one-time cost to upgrade them to LTS_{target}.

Demand

To define the set of OD pairs $OD^{'}$ considered in the B+RNDP, B+R OD pairs k are first derived from the regional accessibility analysis OD pairs ($(i, j) \in OD$). Note that all variables corresponding to the accessibility analysis refer to the case where cycling is the access mode. Accordingly, $bike$ superscripts are omitted in the notation. B+R OD pairs have the same origin as their regional accessibility analysis counterparts ($o_k = i$). As for the destination, it is replaced by the AP that was used to connect the OD pair in the full candidate network scenario ($d_k = s_{ij}^{*full}$). A visual representation of this is provided in Figure 3.4. Accordingly, the B+R OD pairs represent cyclists' desire to access PuT stops to maximize their regional accessibility. Ultimately, only B+R OD pairs fully contained within the graph G are considered in the B+RNDP. As such, $OD^{'} = \{k | o_k \in N \text{ and } d_k \in N\}$.

Associated with each OD pair k is a demand n_k, which is derived from the difference in accessibility flow between the full candidate network and target LTS scenarios, F_{ij}^{full} and F_{ij}^{target}, respectively. Unlike for the calculation of the bicycle AP-OD centrality (Equation 3.11), the accessibility flow is aggregated for origin-AP pairs, rather than just the AP. The flow differential can be negative, which indicates that a stop is used less as an AP (in favor of a different AP) when the candidate network is fully upgraded. Accordingly, the flow differential is only modeled as a demand when it is positive. Accordingly, the n_k represents the maximum potential improvement in target users' accessibility associated with an improved connection between the corresponding origin-AP pair. In other words, the demand represents *how* the LRA can be realized, aligning the B+RNDP with the regional accessibility analysis. The calculation of n_k is specified by Equation 3.12, where OD_k represents the subset of regional accessibility OD pairs that have an origin o_k and use stop d_k as an AP ($OD_k = \{(i,j) \in OD \mid i = o_k \text{ and } s_{ij}^* = d_k\}$).

$$n_k = \max\left(0, \sum_{(i,j)\in OD_k} F_{ij}^{full} - \sum_{(i,j)\in OD_k} F_{ij}^{target}\right) \quad \forall k \in OD' \tag{3.12}$$

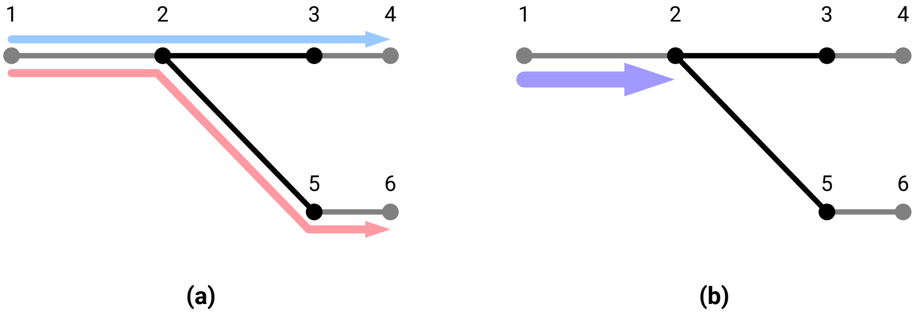


Figure 3.4 Comparison of (a) regional accessibility analysis OD pairs $\{(1,4),(1,6)\} \subseteq OD$ where $s_{14}^{*full} = s_{16}^{*full} = 2$. and (b) corresponding B+R OD pair $k = (1,2)$.

Maximum Path Length

Associated with each OD pair k is a maximum path length L_k which is included as a means of incorporating a route cost constraint in the model. In accordance with the cycling access constraints applied in the accessibility analysis (Section 3.3.2), L_k is calculated using Equation 3.13, where L_{min} is the shortest path between o_k and d_k in the full candidate network, DF is a detour factor ≥ 1, and L_{limit} is an absolute path length limit.

$$L_k = \min\left(L_{min}DF, L_{limit}\right) \quad \forall k \in OD' \tag{3.13}$$

Candidate Edges

Associated with each OD pair k is a set of candidate edges ($E_k' \subseteq E$) that is considered to create a route between o_k and d_k. A subset of E is considered because it improves the computational performance of the B+RNDP by reducing the size of the search space. This is an adaptation of an approach used by Ospina et al. (2022). However, rather than using an Euclidean buffer, the candidate edges are defined as those within a L_k network distance of the origin. This results in an even greater reduction of the search space while still ensuring the global optimum can be found. The nodes corresponding to E_k' are the candidate nodes, defined as: $N_k' = \{a \mid (a,b) \in E_k'\} \cup \{b \mid (a,b) \in E_k'\}$.

3.4.2 Decision Variables

The B+RNDP has three binary decision variables. For each OD pair, a variable z_k is included in the model to represent whether or not the origin o_k and destination d_k are connected. For each edge in an OD pair's candidate edges, a path flow variable x_{ab}^k is defined, where a value of 1 indicates that the edge is used in the path that connects the origin and destination. Finally, each high-stress edge ($(a, b) \in E^{high}$) has a variable y_{ab} associated with it that represents whether or not the edge has been upgraded.

3.4.3 First Stage

The objective of the first stage of the problem (Equation 3.14a) is to maximize the demand coverage of the network. This is subject to a budget constraint (Equation 3.14b) that ensures the total upgrade cost does not exceed B. Equation 3.14c defines the flow conservation constraints responsible for creating a continuous route between the origin and destination. If an OD pair is connected ($z_k = 1$), one unit of flow leaves the origin (source) node, and one unit of flow enters the destination (sink) node. For intermediate nodes, the flow in is equal to the flow out. If the OD pair is not connected ($z_k = 0$) there is no associated flow in the network. The model incorporates a route continuity constraint (Equation 3.14d), which specifies that high-stress edges E^{high} must be upgraded to be used to connect OD pairs. The model also incorporates a route cost constraint (Equation 3.14e), requiring the route connecting an OD pair k to have a length $\leq L_k$.

$$\begin{aligned}
\max \quad & \sum_{k \in OD'} n_k z_k && && \text{(3.14a)}\\
\text{s.t.} \quad & \sum_{(a,b) \in E^{high}} c_{ab} y_{ab} \leq B, && && \text{(3.14b)}\\
& \sum_{(a,b) \in E_k'} x_{ab}^k - \sum_{(b,a) \in E_k'} x_{ba}^k = \begin{cases} z_k & \text{if } i = o_k \\ -z_k & \text{if } i = d_k \\ 0 & \text{otherwise} \end{cases} && \forall i \in N_k', k \in OD', && \text{(3.14c)}\\
& x_{ab}^k \leq y_{ab} && \forall (a,b) \in E^{high}, k \in OD', && \text{(3.14d)}\\
& \sum_{(a,b) \in E_k'} x_{ab}^k l_{ab} \leq L_k && \forall k \in OD', && \text{(3.14e)}\\
& z_k \in \{0, 1\} && \forall k \in OD', && \text{(3.14f)}\\
& x_{ab}^k \in \{0, 1\} && \forall (a,b) \in E_k', k \in OD', && \text{(3.14g)}\\
& y_{ab} \in \{0, 1\} && \forall (a,b) \in E^{high} && \text{(3.14h)}
\end{aligned}$$

3.4.4 Second Stage

While optimizing demand coverage tends to favor low-cost and direct routes, it is not strictly guaranteed. Many solutions may exist that maximize demand for a given budget, especially when it is much higher than the cost needed to connect all OD pairs. This is addressed by the second stage of the B+RNDP, which minimizes the travel cost of the OD pairs connected during the first stage.

In the second stage, the z_k variables no longer need to be solved for. Instead, the optimal values z_k^* are obtained from the solution to the first stage of the problem. Based on this, the set of OD pairs considered in the second stage is defined: $OD'' = \{k \in OD' \mid z_k^* = 1\}$. The objective of the second stage (Equation 3.15a) minimizes the total length of routes weighted by the demand they connect. In the second stage, flow conservation constraints (Equation 3.15c) are reformulated. As all OD pairs $k \in OD''$ must be connected, the flow out of origins and into destinations is constrained to equal 1 and -1, respectively.

$$\begin{aligned}
\min \quad & \sum_{k \in OD''} \sum_{(a,b) \in E_k'} n_k x_{ab}^k l_{ab} && && (3.15a)\\
\text{s.t.} \quad & \sum_{(a,b) \in E^{high}} c_{ab} y_{ab} \leq B, && && (3.15b)\\
& \sum_{(a,b) \in E_k'} x_{ab}^k - \sum_{(b,a) \in E_k'} x_{ba}^k = \begin{cases} 1 & \text{if } i = o_k \\ -1 & \text{if } i = d_k \\ 0 & \text{otherwise} \end{cases} && \forall i \in N_k', k \in OD'', && (3.15c)\\
& x_{ab}^k \leq y_{ab} && \forall (a,b) \in E^{high}, k \in OD'', && (3.15d)\\
& \sum_{(a,b) \in E_k'} x_{ab}^k l_{ab} \leq L_k && \forall k \in OD'', && (3.15e)\\
& x_{ab}^k \in \{0,1\} && \forall (a,b) \in E_k', k \in OD'', && (3.15f)\\
& y_{ab} \in \{0,1\} && \forall (a,b) \in E^{high} && (3.15g)
\end{aligned}$$

4 Results

This chapter presents the results of the case study. The chapter begins by describing the candidate network. This is followed by the accessibility analysis, which estimates the LRA. The chapter concludes with an application of the B+RNDP that builds off of the results of the accessibility analysis.

4.1 Candidate Network Preparation

The unsimplified candidate network within the study area comprised 3,151,759 nodes and 5,904,732 edges, totaling 10,778 km in length. As shown in Figure 4.1, most (74.3%) of the candidate network consisted of mixed-traffic streets. Dedicated bicycle infrastructure made up 16.4% of the network, the vast majority of which were cycle paths. Cycle lanes were the least common infrastructure class, making up only 3% of dedicated infrastructure and 0.4% of the network. The remaining 9.3% was classified as "other." This consisted of paths unsuitable for cycling and pedestrian streets that permit cycling.

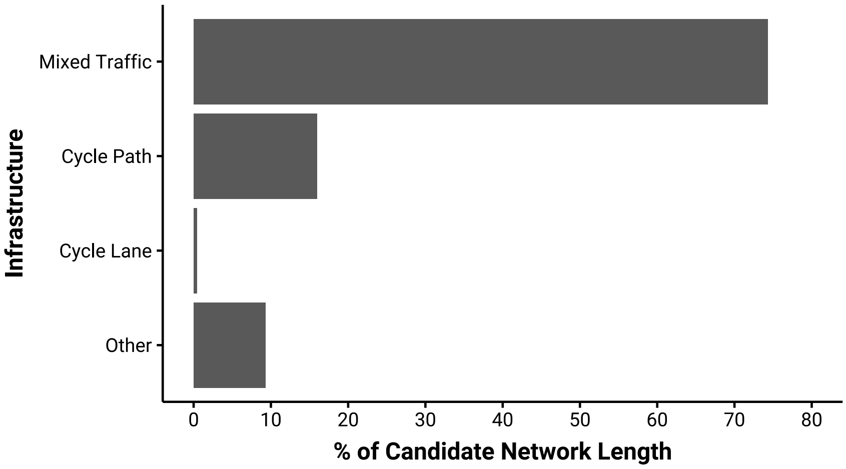


Figure 4.1 Candidate network infrastructure class distribution.

The LTS classification of cycle lanes and mixed-traffic infrastructure depended on the *lanes* and *maxspeed* keys in the OSM data. Due to missing data, 91% of these edges required at least one assumption. Many of the edges with missing data corresponded to minor streets (*highway* key: "residential", "service", or "living_street"). This reduces the uncertainty caused by the assumptions, as these typically have low speed limits. When minor streets are excluded, the rate of edges requiring assumptions is reduced to 16%. The uncertainty is reduced further by the relatively high availability of the *maxspeed* key, which is the more critical of the two. Excluding minor streets, assumptions for the speed were only needed for 6% of edges. Figure 4.2 shows the prevalence of missing data relative to the full candidate network.

The distribution of LTS for each infrastructure class and the candidate network is provided in Figure 4.3 and Figure 4.4, respectively. The corresponding values can be found in Table B.1. The total percentage of low-stress infrastructure in the network was 69% (50% LTS 2 and 19% LTS 1). Low-speed, mixed-traffic streets contributed greatly to this, making up over 99% of the LTS 2 and 14% of LTS 1 infrastructure. The remainder of the LTS 1 infrastructure was almost entirely cycle paths. Cycle lanes were essentially classified as either LTS 2 or 3. Of any class, cycle lanes had the highest share of LTS 3 infrastructure. However, this had a minimal contribution to the network total due to the low number of cycle lanes in the network. LTS 4 consisted nearly entirely of high-speed, mixed-traffic streets. Nearly all of the edges classified as "other" were paths that were unsuitable for cycling (LTS 99), making up 88% of the network total. The remaining 12% of LTS 99 edges corresponded to the contraflow direction of one-way, mixed-traffic streets. In total, 10.5% of the network was classified as LTS 99, which corresponds to the subset of the candidate network that is unsuitable for all cyclists in its present condition.

After enriching the OSM data with infrastructure and LTS classifications, the candidate network was simplified using the procedure described in Section 3.1.3. This reduced the number of nodes by 92%, the number of edges by 88%, and the length of the network by 18%. An example of the network preparation's output is shown in Figure 4.5, which depicts the LTS of the simplified network in the city of Freising.

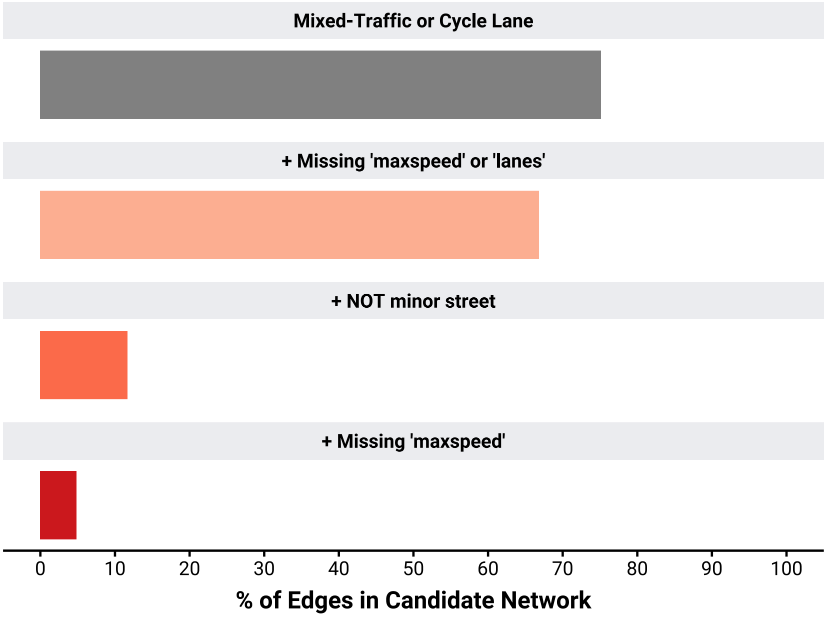


Figure 4.2 Candidate network edges requiring assumptions for the LTS classification.

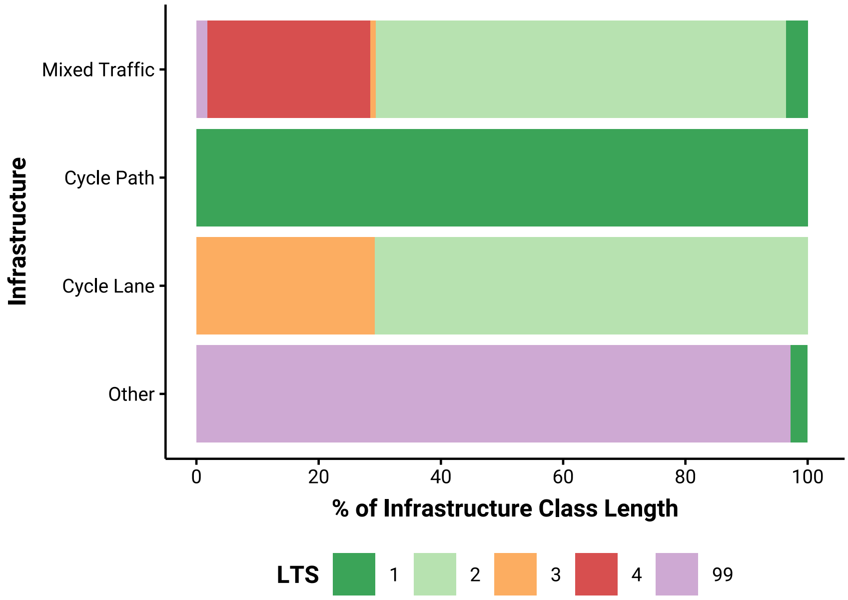


Figure 4.3 LTS distribution of each infrastructure class.

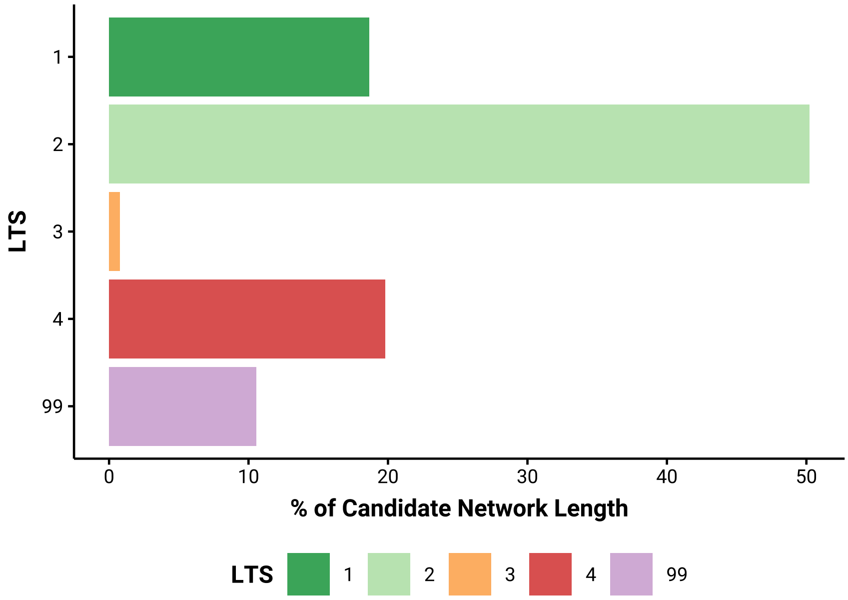


Figure 4.4 Candidate network LTS distribution.

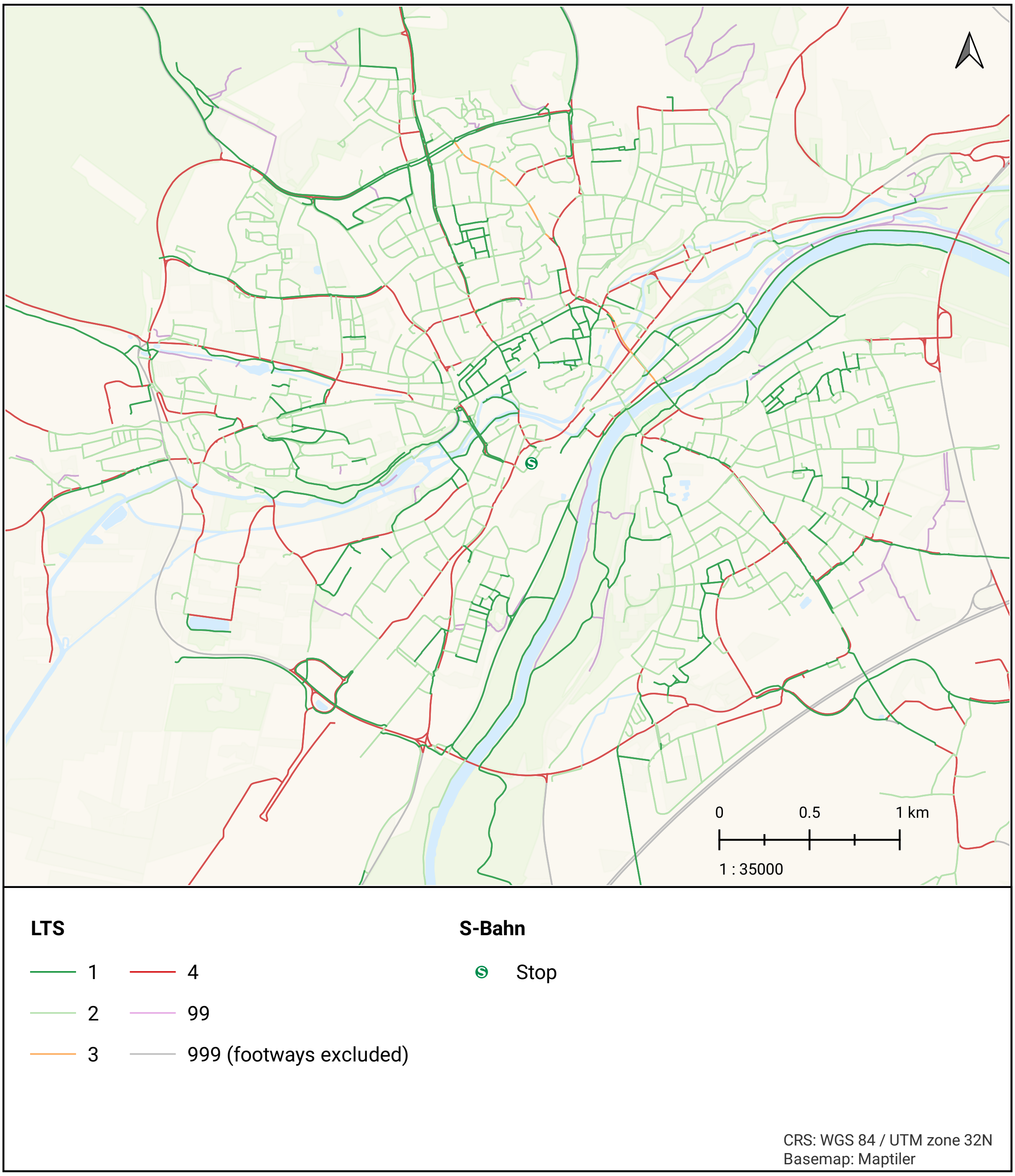
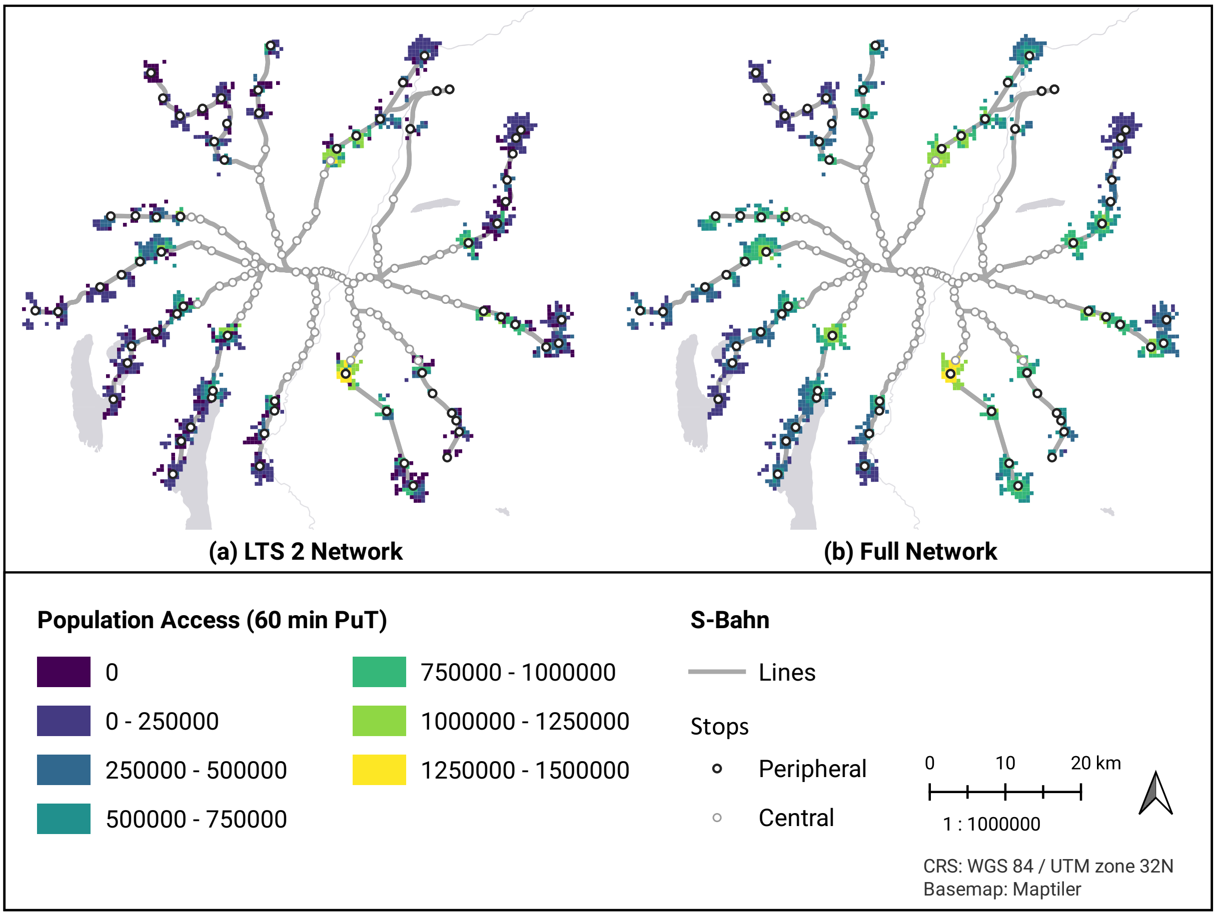


Figure 4.5 LTS of the simplified network in the city of Freising.

4.2 Regional Accessibility Analysis

To determine the LRA, LTS 2 and full candidate network scenarios (LTS 99) were considered. LTS 2 as the target user group is essentially the general adult population. Working-age-populated nodes within a 3 km network distance of target S-Bahn stops were used as origins.

Aggregating the access potential at the origins yielded the IoRA, serving as a measure of the cumulative population accessible within 60 minutes by public transport and, optionally, cycling as an access mode. The IoRA provides insight into the spatial distribution of regional accessibility throughout the study area for both network scenarios (Figure 4.6). The LTS 2 network IoRA is an estimate of the current level of accessibility for the working-age adult population. Meanwhile, the full candidate network IoRA is an upper bound of the accessibility that can be achieved through bicycle network upgrades.


(a) LTS 2 Network

(b) Full Network

Figure 4.6 Spatial distribution of regional accessibility (IoRA) for LTS 2 and full candidate network scenarios.

As shown in Figure 4.7, the accessibility distribution in the LTS 2 network scenario is skewed left as opposed to the more even distribution in the full candidate network scenario. In the full candidate network scenario, the working-age population-weighted mean value of the IoRA is 690,000, 225,000 higher than that of the LTS 2 scenario. This signifies a 48% increase in the number of people that can be reached within 60 minutes using B+R. In the LTS 2 scenario, 18,500 working-age adults live in areas with no B+R regional accessibility. This corresponds to approximately 7% of the working-age population within a 3 km network distance of an S-Bahn stop.

The difference between the IoRA of the two scenarios is highlighted in Figure 4.8, representing the spatial distribution of the potential for bicycle network improvements to increase B+R regional accessibility. In other words, the LRA. Areas with increased accessibility were either disconnected from an S-Bahn stop in the LTS 2 scenario or were connected by a sub-optimal route. In the latter case, the increase in accessibility is attributed to a travel time reduction during the access leg of the trip. Areas highlighted in pink have no

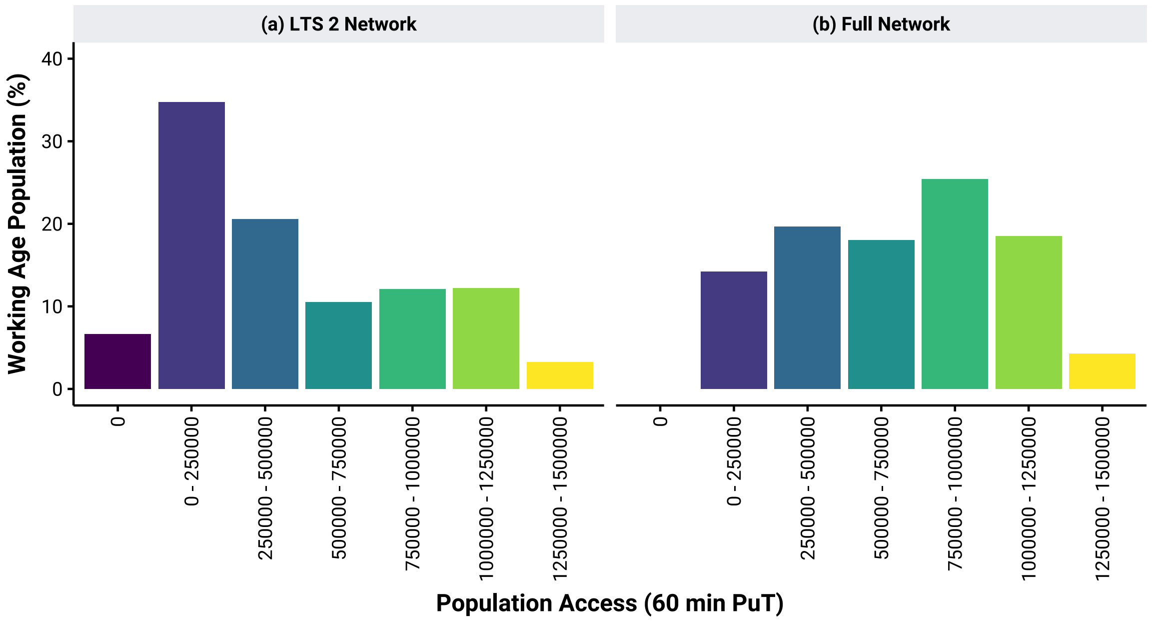


Figure 4.7 Working-age population distribution of regional accessibility (IoRA) for LTS 2 and full candidate network scenarios.

improvement, indicating that the shortest route connecting the origin to the S-Bahn is low-stress (LTS 2). Gauting, Holzkirchen, Markt Schwaben, Fürstenfeldbruck, and Freising stand out as municipalities with the largest concentrations of LRA.

The bicycle AP-OD centrality indicates the amount of accessibility facilitated by S-Bahn stops when they function as APs and cycling is the access mode. Accordingly, the difference in the bicycle AP-OD centrality between the scenarios Figure 4.9 indicates the extent to which improving connections to a given S-Bahn stop can realize the LRA. A boxplot of the difference and maps of the individual scenarios are provided in Figure C.2 and Figure C.1. To little surprise, the S-Bahn stops of the five aforementioned municipalities show the largest increase in bicycle AP-OD centrality. A difference between the IoRA and the bicycle AP-OD centrality is that the magnitude of the latter is sensitive to the population for whom accessibility is increased. Because of this, Freising had the highest AP-OD centrality despite the IoRA indicating a lower increase in regional accessibility compared to Holzkirchen and Markt Schwaben.

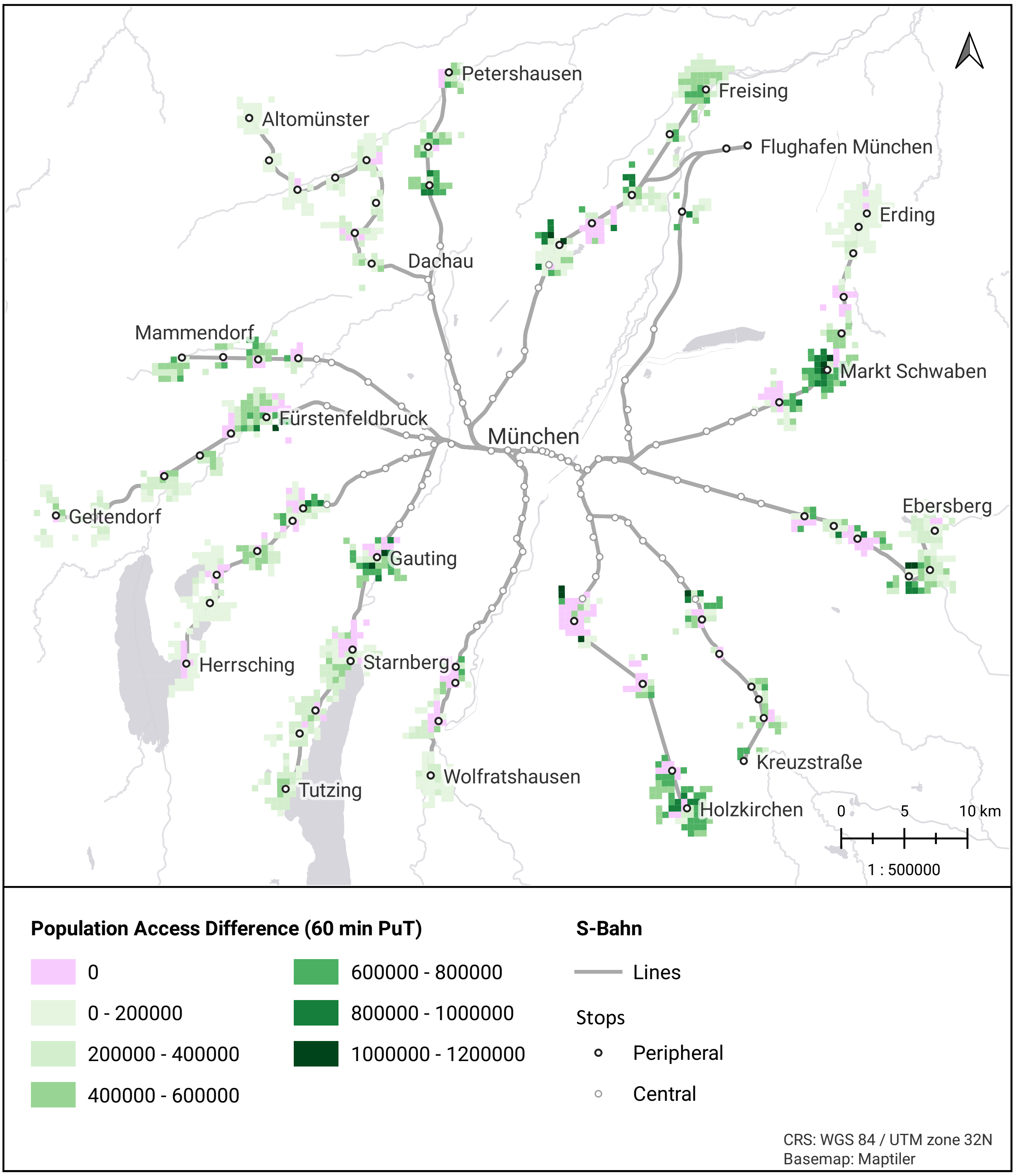


Figure 4.8 Change in regional accessibility (IoRA) between LTS 2 and full candidate network scenarios.

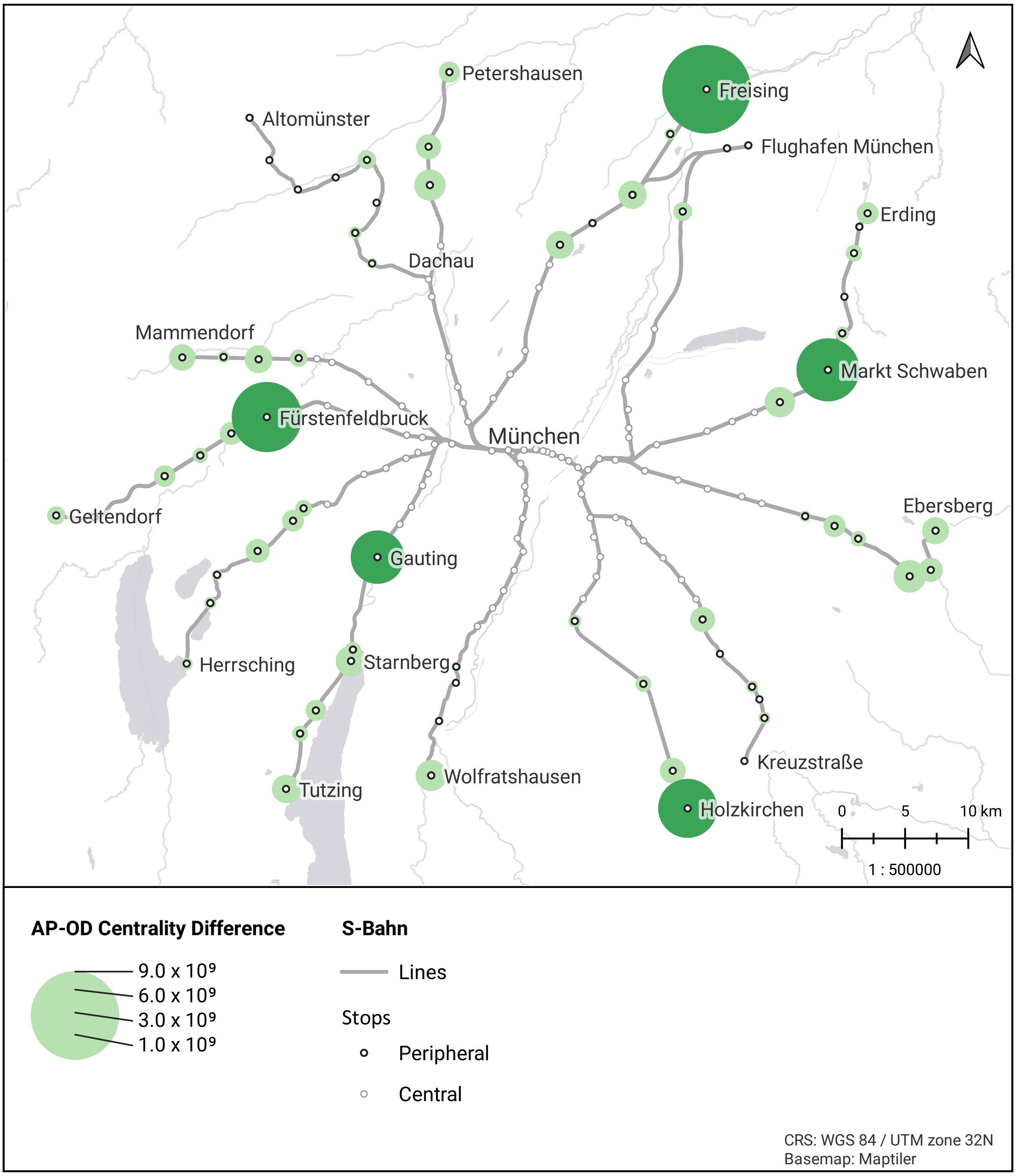


Figure 4.9 Change in bicycle AP-OD centrality between LTS 2 and full candidate network scenarios.

4.3 Bicycle Network Design Optimization

The accessibility analysis indicated that improving bicycle routes to the Freising S-Bahn stop had the highest potential to increase regional accessibility. Therefore, it was chosen as a case study to evaluate the performance of the B+RNDP. This section begins by describing the evaluated scenarios and then presents the results.

4.3.1 Evaluation Scenarios

The performance of the B+RNDP was evaluated by optimizing a subset of the candidate network within a 3 km distance of the S-Bahn stop, a graph comprising 1,248 nodes and 3,302 directed edges (Figure 4.10). The graph contained 52 populated nodes, representing 22,000 working-age adults. The performance of the BNDP was compared to a greedy, shortest-path heuristic that iteratively connected OD pairs based on the highest demand-to-upgrade-cost ratio. The influence of the target LTS (LTS_{target}) and detour factor (DF) were evaluated for a range of budgets by calculating the demand coverage (DC). Additionally, the realized detour factor (RDF), the demand-weighted mean detour factor of the routes in the network, was calculated to evaluate the directness.

Two LTS targets were evaluated. The first was LTS 2, which aligned directly with the accessibility analysis. As shown in Figure 4.10, much of the existing network was classified with a LTS ≤ 2 and, therefore, could be used without further upgrades. However, the LTS 2 network is fragmented, making the S-Bahn stop entirely disconnected from populated nodes. Due to this form, evaluation scenarios targeting LTS 2 were concerned with filling gaps in an otherwise extensive network. Accordingly, they are referred to as "network improvement" scenarios. The second target LTS was 0, which serves as a means of instantiating "network synthesis" scenarios. These scenarios involve designing a network from scratch as the suitability of all existing infrastructure is disregarded. For both LTS targets, the upgrade cost of high-stress edges was set to the length that exceeded the target LTS ($c_{ab} = l_{ab}^{LTS_{target}}$). As a result of the network simplification procedure (Section 3.1.3), it was possible for this to be less than the edge length when $LTS_{target} = 2$.

The demand was derived from the bicycle accessibility flow directed towards the S-Bahn stop. Defining the demand in this way prioritized the connection of nodes with a high potential increase in regional accessibility, serving as the bridge between the local scale of the B+RNDP and the broader goal of enhancing regional accessibility. The demand was the same for both LTS targets, as the S-Bahn stop is disconnected regardless of the LTS threshold. Accordingly, the demand is fully aligned with the accessibility analysis, representing the disaggregated components of the increase in the S-Bahn stop's bicycle AP-OD centrality. In total, 52 OD pairs were instantiated. The magnitude of the demand is mapped in Figure 4.10.

The influence of the detour factor DF was evaluated by considering values of 1, 1.05, and 1.2. An absolute maximum path length limit L_{limit} of 3 km was enforced in all cases. For each LTS_{target} and DF combination, the B+RNDP was solved for budgets ranging from 0.5 km up to the cost of connecting all OD pairs by their shortest paths (LTS 2: 15.75 km, LTS 0: 42.20 km).

4.3.2 Evaluation Results

The BNDP was solved using Gurobi, a commercial solver for mathematical programs. Gurobi version 10.0.3 and a laptop with an i7-1065G7 processor were used. A table summarizing the DC and RDF of all evaluated scenarios is provided in Table D.1. Unless specified otherwise, all of the DC improvements refer to the absolute increase in coverage, not the improvement relative to the heuristic method.

The DC for the evaluated budgets is plotted in Figure 4.11, with Table 4.1 highlighting the scenarios with the largest improvement over the heuristic. Maps of the optimized networks corresponding to the peak improvement are provided in the appendix for evaluation scenarios: $LTS_{target} = 2$, $B = 1$ km (Figure D.1) and $LTS_{target} = 0$, $B = 15$ km (Figure D.2).

The improvement of the demand coverage was relatively low when the B+RNDP was instantiated with $DF = 1$. The peak increase in demand coverage was approximately three percentage points and five percentage points for LTS 0 and LTS 2, respectively. Performance improved markedly when the detour

Table 4.1: B+RNDP evaluation scenarios with the largest improvement in demand coverage (ΔDC).

LTS	Budget (km)	Heuristic DC	ΔDC			ΔRDF	
			$DF = 1$	$DF = 1.05$	$DF = 1.20$	$DF = 1.05$	$DF = 1.20$
2	1.00	45.78	0	10.33	32.21*	0.01	0.06
2	5.00	76.74	4.16*	17.15*	22.84	0.01	0.04
0	2.50	25.46	0	4.00*	4.46	0.01	0.01
0	15.00	78.78	2.18*	3.80	6.96*	<0.01	0.06

* designates that this is the largest DC improvement for the given LTS_{target}, DF combination

factor was increased, especially for LTS 2. With $DF = 1.2$, the BNDP significantly outperformed the heuristic, achieving a peak increase in demand coverage of approximately 32 percentage points at a budget of 1 km. The improvement in demand coverage remained above 20 percentage points until a budget of 5 km, after which it fell sharply as the network had covered most of the demand at that point. The demand was fully covered by a budget of 7.5 km, less than half of the 15.75 km needed to connect all OD pairs by the shortest path. Figure 4.14 shows the solutions with full demand coverage for the heuristic and B+RNDPs with detour factors of 1.05 and 1.2. In the heuristic solution, a significant part of the budget was spent upgrading edges nearly parallel to low-stress edges. Allowing for minor detours mitigates this, significantly improving performance. This is demonstrated by the solution to the B+RNDP with $DF = 1.05$.

For LTS 0 and $DF = 1.2$, the B+RNDPs showed no improvement over the heuristic until a budget of 2.5 km, indicating that connections by the shortest path were optimal. From there, the improvement over the heuristic was relatively stable, hitting a peak increase in demand coverage of approximately seven percentage points at a budget of 15 km. Unlike in the LTS 2 scenarios, the performance of the heuristic was not influenced by LTS as the problem was instantiated with no existing low-stress edges. Figure 4.15 shows the solutions with full demand coverage for the heuristic and B+RNDP with $DF = 1.2$. The B+RNDP solution clearly demonstrates how introducing the detour factor allows routes to be bundled along common corridors. As a result, the entire demand is covered at a budget 17% (7.2 km) lower than needed to connect all OD pairs by the shortest path.

The realized detour factor (RDF) comes into play when the B+RNDP is instantiated with $DF > 1$. As shown in Figure 4.12, the RDF was consistently much lower than the constraint. For a $DF = 1.2$, the realized detour factor was typically around 1.06, meaning that, on average, the routes in the network were 6% longer than the shortest paths. As a result of the second stage of the problem formulation, the RDF returns to zero as the budget exceeds the cost to connect the OD pairs.

Figure 4.13 shows the runtimes for the evaluated scenarios. Runtimes of the heuristic were marginal, with solutions generated in less than a second. As for the B+RNDP, the runtime depended on the complexity of the solution space. Runtimes were significantly higher for LTS 0 as this involved building a network from scratch. The runtime increased alongside the detour factor as this increased the number of possible routes between OD pairs. The first stage of the B+RNDP was much more difficult to solve and was responsible for approximately 95% of the runtime. The maximum runtime for a target LTS of 2 was approximately 10 minutes, as opposed to 47 minutes for LTS 0.

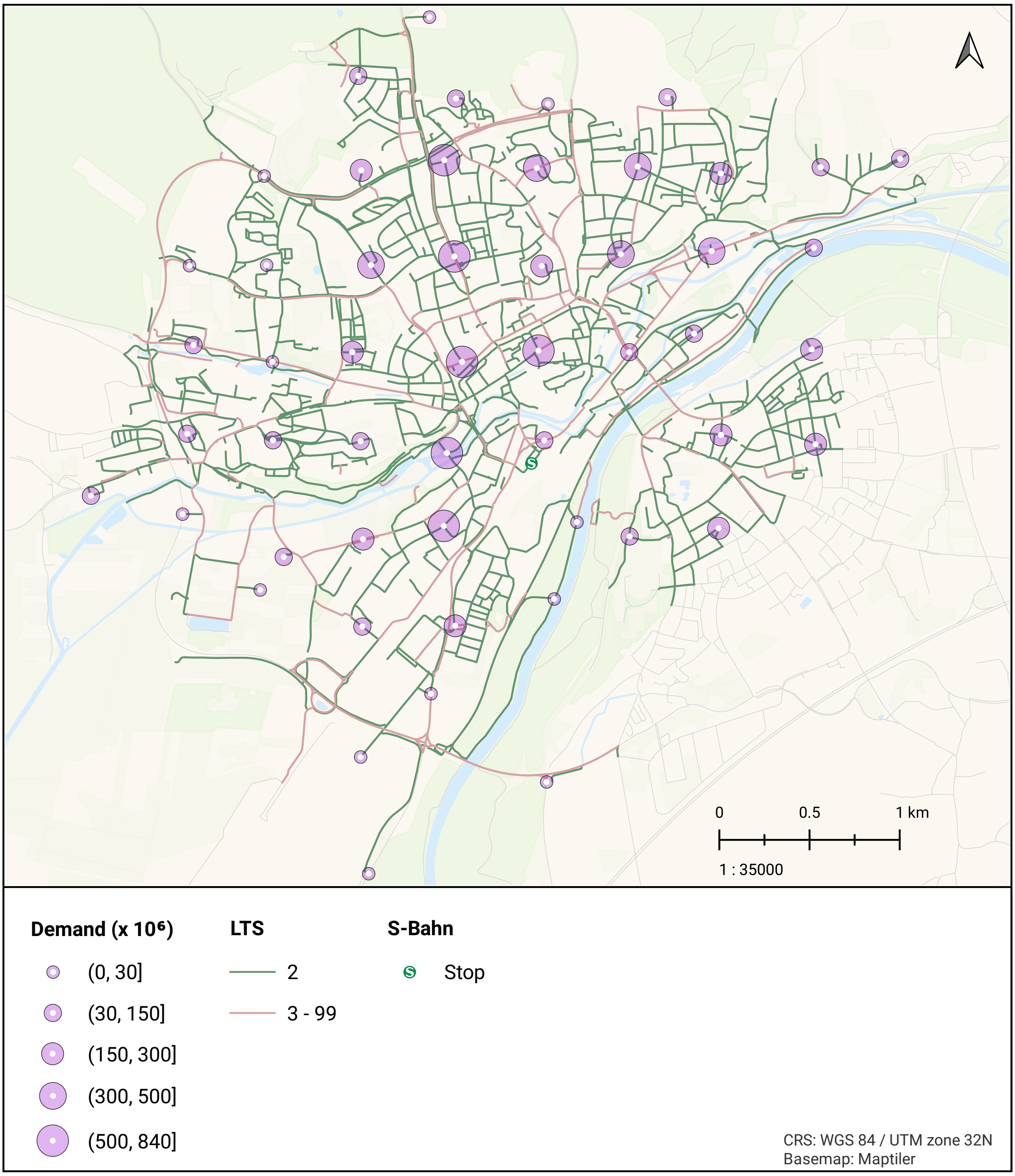


Figure 4.10 Candidate network and demand considered in the B+RNDP for optimizing the bicycle network within the catchment area of the Freising S-Bahn stop.

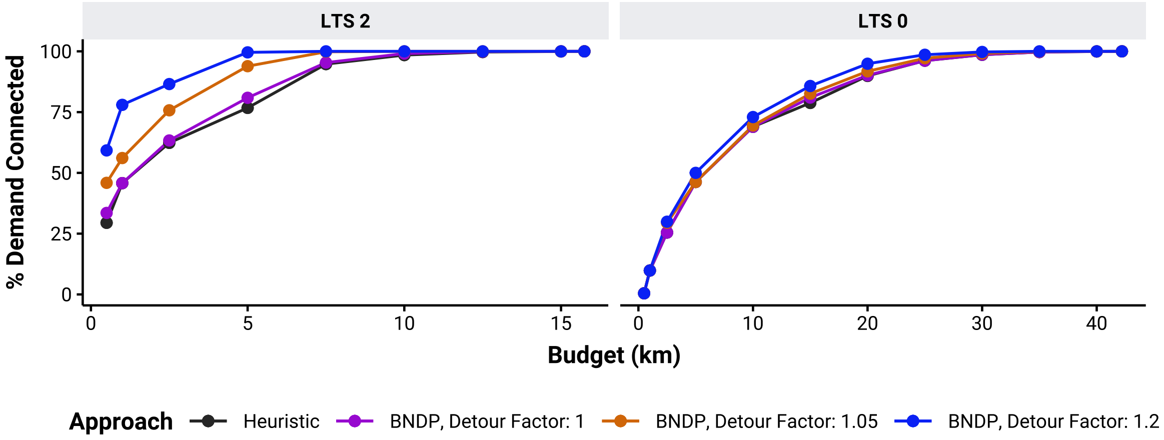


Figure 4.11 Demand coverage of B+RNDP evaluation scenarios.

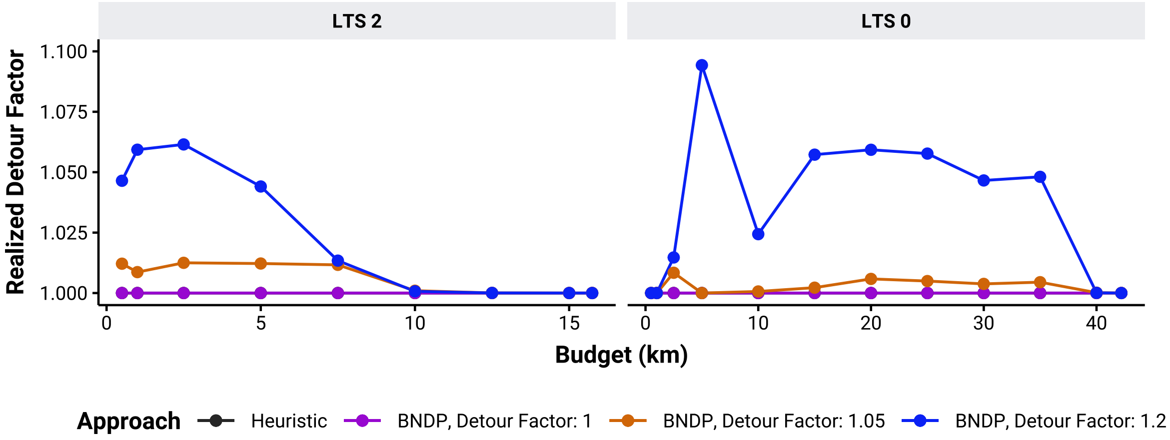


Figure 4.12 Realized detour factor of B+RNDP evaluation scenarios.

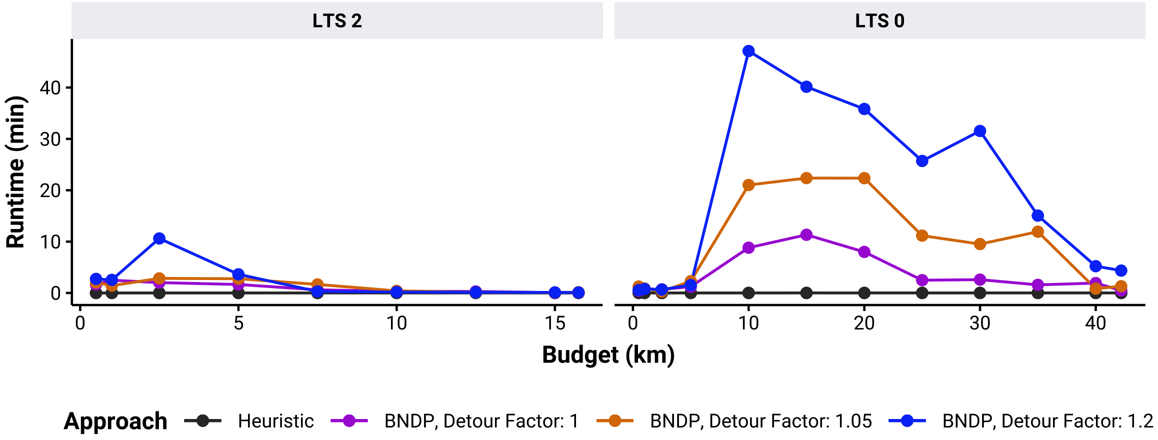
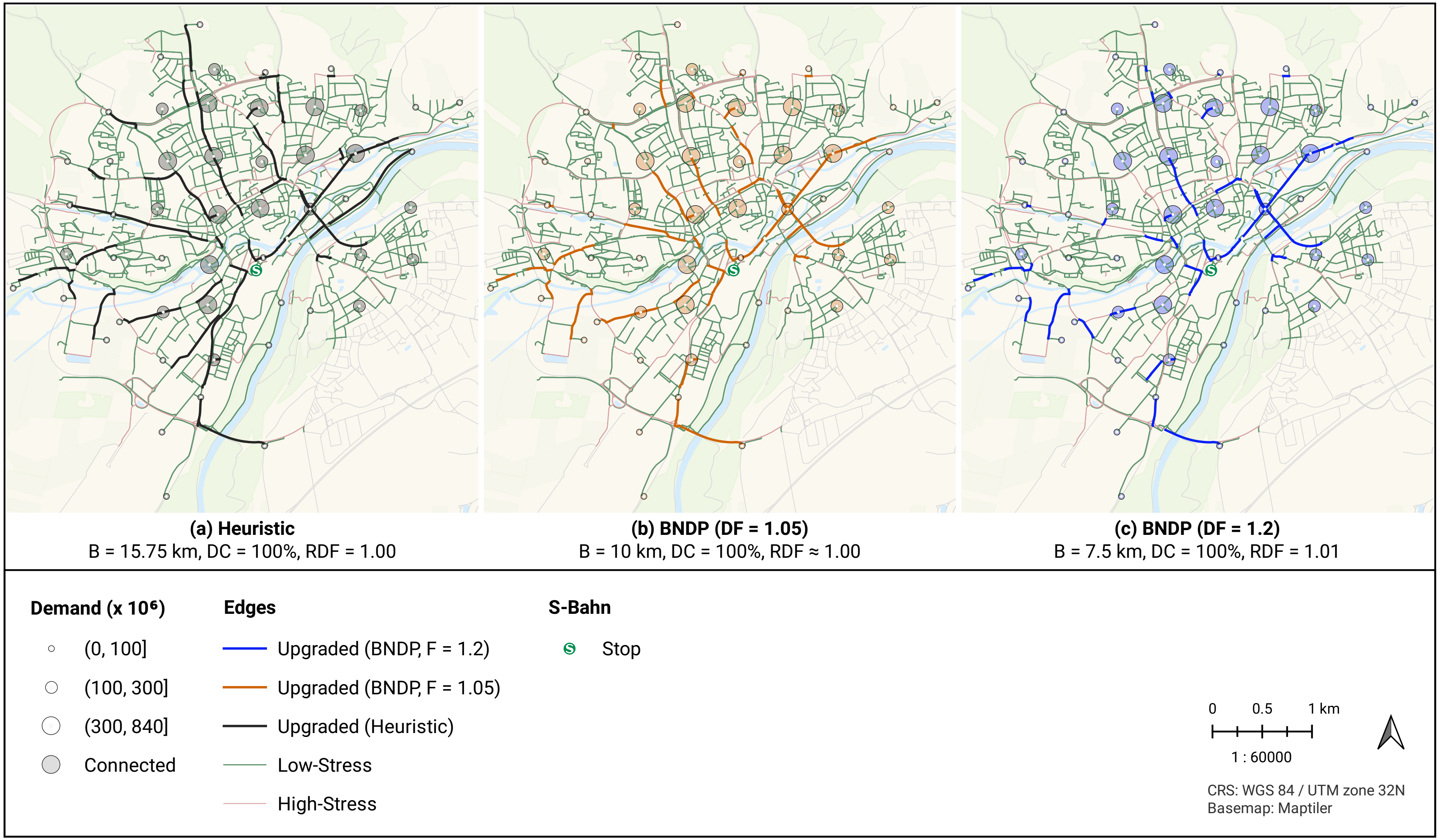


Figure 4.13 Runtime of B+RNDP evaluation scenarios.

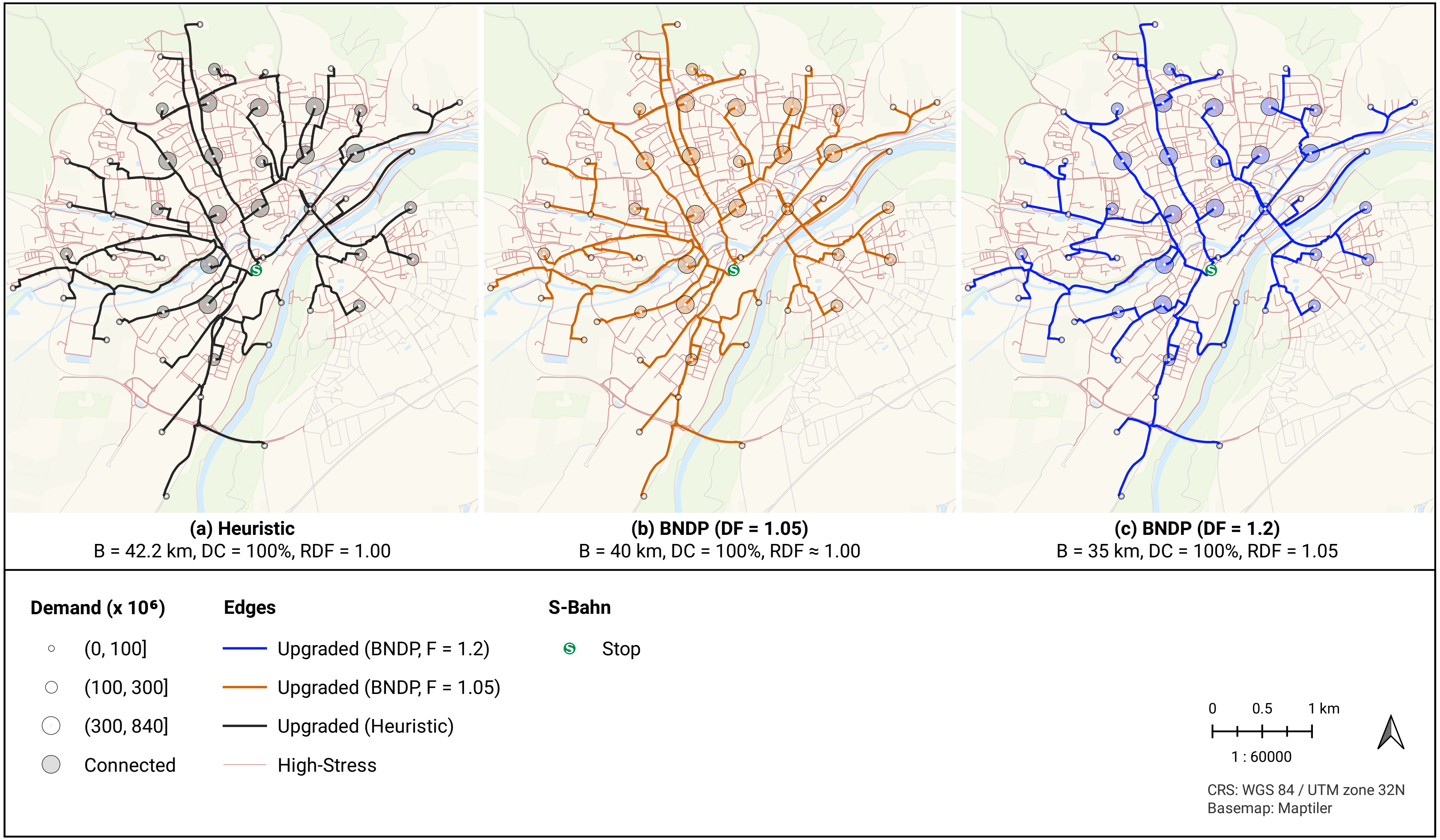


(a) Heuristic
B = 15.75 km, DC = 100%, RDF = 1.00

(b) BNDP (DF = 1.05)
B = 10 km, DC = 100%, RDF ≈ 1.00

(c) BNDP (DF = 1.2)
B = 7.5 km, DC = 100%, RDF = 1.01

Figure 4.14 B+RNDP solutions for $LTS_{target} = 2$ evaluation scenarios (full DC).



(a) Heuristic
B = 42.2 km, DC = 100%, RDF = 1.00

(b) BNDP (DF = 1.05)
B = 40 km, DC = 100%, RDF ≈ 1.00

(c) BNDP (DF = 1.2)
B = 35 km, DC = 100%, RDF = 1.05

Figure 4.15 B+RNDP solutions for $LTS_{target} = 0$ evaluation scenarios (full DC).

5 Discussion

The results of the case study are discussed in this chapter. The chapter begins with a discussion of the candidate network preparation, followed by the regional accessibility analysis and network optimization. The chapter concludes with a discussion of the limitations.

5.1 Candidate Network Preparation

The network preparation was the foundation for the accessibility analysis and network design optimization. The LTS classification was critical as it was the basis for determining the LRA. One of the strengths of the LTS method is that most of the criteria are based on geometric design, making it much less data-intensive than other quality of service measures such as the BLOS.

The implemented LTS criteria were sensitive to the German context and limited OSM data availability. In line with the implementation in R5 Conway et al. (2017), the criteria considered the infrastructure classification, speed limit, and number of lanes. The case study results indicate that the criteria are well adapted to the limitations of OSM data. Excluding minor streets, where low speeds can be assumed, assumptions were needed to classify the LTS for 12% of edges in the candidate network. Despite significantly simplifying the original criteria proposed by Mekuria et al. (2012), the approach is still considered useful, as it provides a clear and consistent way to assess the quality of the network. This allowed aspects of safety and comfort stemming from street-level design to be incorporated into the accessibility analysis and B+RNDP. By leveraging the underlying connection of the LTS to Geller's cyclist profiles (Dill & McNeil, 2016), the analyses were able to estimate the suitability of infrastructure for working-age adults.

Accessibility was calculated based on the lowest travel time between OD pairs. This included the shortest path in the candidate network for access and egress trip legs. This is typical for accessibility analyses and allows for highly efficient algorithms like Dijkstra's to be leveraged. As such, travel times can be calculated in very large, detailed graphs. However, these types of graphs can make a BNDP computationally intractable as each node and edge corresponds to additional variables and constraints in the model.

The results demonstrate the effectiveness of the network simplification procedure (Section 3.1.3) to prepare a network suitable for both applications. Applying the procedure reduced the number of nodes and edges in the graph by approximately 90%. The procedure focuses on removing superfluous nodes and edges, resulting in a "concise" graph that retains much of the original network's detail. A strength of the procedure is that it does not categorically remove minor streets and paths. This is considered important as connectivity enabled such minor network elements can nonetheless greatly influence the travel time of active modes of transport.

5.2 Regional Accessibility Analysis

The results of the accessibility analysis demonstrate how the IoRA and bicycle AP-OD centrality can be used to identify opportunities for enhancing regional B+R accessibility through bicycle network improvements. Calculating the accessibility for the LTS 2 and full candidate network scenarios allowed for the LRA to be estimated while being sensitive to the characteristics of working-age adults.

As demonstrated in the results, the IoRA is effective for assessing the spatial distribution of the increase in regional accessibility between the scenarios. The IoRA highlighted that the working-age-population-weighted mean accessibility to population within 60 minutes by B+R has the potential to increase by up to 48% as a result of improved bicycle routes to S-Bahn stops. That's a significant improvement for the 279,000 working-age adults living in the study area, especially for the 18,500 with no B+R regional accessibility in a LTS 2 scenario. These figures indicate the potential for bicycle network improvements to not only accelerate existing connections but also extend the service area of the public transport network.

Since the IoRA represents the increase in accessibility at trip origins, information pertaining to *how* said accessibility is achieved is obfuscated. To realize the LRA, it is insufficient to identify an area for improvement. Rather, the specific PuT stops to which routes should be improved must be identified. The results demonstrate how this can be achieved using the bicycle AP-OD centrality.

It's acknowledged that the benefit of the AP-OD centrality is somewhat limited in the case study as it's relatively easy to tell which stops are responsible for improving accessibility. The value of the approach as a means of identifying target stops for improvement is expected to be greater when applied in contexts with more complex networks, such as urban areas, or when the focus is on more ubiquitous modes, such as the bus. Regardless of the context, an advantage of the approach is that it is sensitive to the population for whom accessibility is improved. As demonstrated in the case study, this makes it possible to target stops that benefit the greatest number of people. For example, the IoRA indicated that accessibility was improved to a greater extent in Holzkirchen and Markt Schwaben than in Freising. Despite this, the Freising S-Bahn stop had a higher bicycle AP-OD centrality due to more people benefiting from the increase in accessibility. The approach can be applied to any population segment, making it suitable for many different use cases. For instance, the population of disadvantaged groups can be used to promote equitable network improvements.

5.3 Bicycle Network Design Optimization

In this section the results of the B+RNDP performance evaluation and the alignment of the B+RNDP formulation with the five requirements of bicycle network design are discussed.

5.3.1 Bike-and-Ride Network Design Problem Performance

When instantiated with a detour factor of 1, the B+RNDP exclusively considers the shortest paths in the network. In turn, comparing its performance to a heuristic that incrementally connects OD pairs by the shortest path isolates the benefit of approaching design from a holistic, network perspective. This is the fundamental difference between the approaches as while the heuristic makes the best choice at each step in its procedure; the B+RNDP makes the best *series* of choices. As demonstrated in the network improvement (LTS 2) and network synthesis (LTS 0) scenarios, the benefit of this alone is limited, with a peak increase in demand coverage of five and three percentage points, respectively. An efficient network design reuses edges in multiple routes to reduce construction cost, which can then go towards connecting additional OD pairs. Achieving this is difficult when only the shortest paths can be used. This is especially true in a network synthesis application, as there is no existing infrastructure to leverage.

The possibility of allowing for a detour factor is a major advantage of using an optimization approach as the additional flexibility makes it much easier to align routes along common corridors. The results indicate that the B+RNDP is particularly effective in network improvement scenarios as, with a detour factor of 1.2, it outperformed the demand coverage of the heuristic by up to 32 percentage points, significantly more than the seven percentage point peak improvement during network synthesis scenarios.

As demonstrated by the heuristic solution that covers the entire demand (Figure 4.14a), the solution involves many upgrades that are adjacent to existing, low-stress edges. This occurs when a set of low-stress edges is nearly parallel to a set of high-stress edges, with the latter being marginally shorter. Under these conditions, the heuristic is heavily penalized as it strictly considers the shortest path. This can occur regularly, for example, when a cycle path is adjacent to a roadway. In a sense, this overstates the performance of the B+RNDP as part of the benefit can be attributed to network instantiation rather than the inefficiency of the heuristic. In contrast to the heuristic, a B+RNDP with a minimal detour factor (1.05) can avoid this issue while creating routes that are, at worst, only 5% longer than the shortest path. Calculating the difference in performance between the 1.2 and 1.05 detour factor B+RNDPs serves as a conservative lower bound of the "true" performance benefit. Doing so indicates that the peak increase in demand coverage is at least 22 percentage points. Accordingly, it's maintained that the B+RNDP is highly effective for network improvement applications.

While the high sensitivity of the heuristic may inflate the performance benefit of the B+RNDP in network improvement scenarios, it is still very much a real disadvantage of approaches that strictly consider the shortest path in the network. The street network for the case study was derived from OSM, a prominent data source representative of a typical street network model. The results suggest that designing a network using an approach based on the shortest path will return low quality solutions as a consequence of having no flexibility to consider alternative routes, even if they are higher quality and only marginally longer. This further supports using an optimization approach with a detour factor, especially since allowing for a detour factor does not necessarily mean it will be realized in the solution. The results indicate efficient solutions don't typically have high (demand-weighted) realized detour factors. For example, evaluation scenarios of the B+RNDP with a detour factor of 1.2 had realized detour factors of around 1.06. This is because needlessly circuitous routes can be more expensive to construct. The inclusion of the second stage of the problem formulation also helped with this by improving the directness of OD pairs with high demand when the remainder of a budget was insufficient to cover additional demand.

As discussed in the literature review (Section 2.2.2), mathematical optimization is an inherently computationally expensive approach to network design. Complex problem formulations can severely limit their applicability to large networks. In the most complex evaluation scenario, network synthesis with a detour factor of 1.2, the maximum runtime was 47 minutes using a moderately powerful laptop. This demonstrates the viability of the B+RNDP for practical applications such as optimizing the bicycle network within an S-Bahn stop's catchment area. Much of this is attributed to the extensive network preparation (Section 3.1.3), as it significantly reduced the number of nodes and edges that needed to be included in the model.

5.3.2 Alignment with Design Requirements

The B+RNDP incorporates four of the five requirements of bicycle network design: cohesion, directness, safety, and comfort. Cohesion and directness are strongly incorporated through route continuity and route cost constraints. In line with Duthie and Unnikrishnan (2014) and Smith (2011), safety and comfort are incorporated by defining bicycle infrastructure using a quality of service measure, in this case, the LTS. Table 5.1 contextualizes the B+RNDP in relation to previous studies.

Table 5.1: Alignment of the B+RNDP with the requirements of bicycle network design, contextualized by reviewed BNDP studies.

Reference	Cohesion	Directness	Safety	Comfort	Attractiveness
Zhu and Zhu (2020)	++	++	++	++	○
Lin and Yu (2013)	++	○	++	++	++
Duthie and Unnikrishnan (2014)	++	++	+	+	○
McCormick (2024)	++	++	+	+	○
Smith (2011)	++	+	+	+	○
H. Liu et al. (2019)	○	+	++	++	○
Ospina et al. (2022)	++	++	○	○	○
Lim et al. (2022)	++	++	○	○	○
Akbarzadeh et al. (2018)	++	+	○	○	○
Mesbah et al. (2012)	+	++	○	○	○
Mauttone et al. (2017)	+	+	○	○	○
Caggiani et al. (2019)	○	++	○	○	○
Paulsen and Rich (2023)	○	++	○	○	○

Key: none / weakly implemented [○], implemented [+], strongly implemented [++]

While BNDPs should incorporate these characteristics, the extent to which they do does not necessarily reflect their usefulness as planning tools. Therefore, Table 5.1 is not to be interpreted as a "ranking" of the models. As identified in the review (Section 2.2.2), the applicability of higher complexity models is limited to relatively small graphs. The BNDP formulated by Lin and Yu (2013) included four objective functions representing nine underlying aspects: demand coverage, number of intersections, turns, traffic accidents, functional classification of roadways, type of bicycle infrastructure, wooded area along the route, reduction in space for motor vehicle traffic, and reduction in car parking. While this was, by far, the most extensive model, it was demonstrated by solving a problem with only 75 nodes, 115 undirected edges, and 66 OD pairs. A lot of detail is lost to model a network with a graph of this size. As described in Section 2.1.1, in comparison to cars, the speed of (conventional) bicycles is relatively independent of the infrastructure type. As such, considering a limited subset of the full network is a significant compromise when modeling cycling.

Like the BNDPs proposed by Lim et al. (2022), Mauttone et al. (2017), and Ospina et al. (2022), the B+RNDP instead sacrifices some model complexity in the interest of being able to solve significantly larger problems. It cannot be definitively said which of the approaches is better, as the usefulness of a given BNDP formulation depends on its intended application. It is clear, however, that adding complexity to the model is a means, not an end, and therefore, it should be carefully weighed against its implications on practical applicability.

5.4 Limitations

This section details four main limitations of the study. The first two arise from challenges associated with using OSM data, while the remainder are compromises made to reduce the computational complexity of the B+RNDP.

Intersections Not Considered in Implemented Level of Traffic Stress Criteria

One of the limitations of the study is that the implemented LTS criteria don't consider intersections. As revealed in the review of network design requirements (Section 2.1.1), intersections significantly influence safety and comfort, meaning this is an omission of an important aspect of design. The original criteria determine the LTS for unsignalized intersections based on the number of lanes being crossed and the speed limit of the lanes being crossed (Mekuria et al., 2012). This is challenging to implement using an OSM network, as the geometric orientation needs to be accounted for, and edges don't necessarily represent streets. On a higher level, this is a gap in existing research, as the effect of intersections was modeled in only three of the 12 reviewed BNDP studies.

Sensitivity of Level of Traffic Stress

The LTS is a very sensitive method due to the "weakest-link" principle by which the LTS of a route is determined. This isn't a problem in and of itself, as it allows the impact of gaps in the network to be easily identified. However, it also makes the approach prone to underestimating the network quality when there are errors of omission in the data. For instance, an unmapped cycleway on a critical edge in the network can significantly misrepresent connectivity. The potential for this is elevated when using a data source based on volunteered geographic information like OSM. As indicated by the results of the network preparation (Section 4.1), even basic attributes such as speed limits and lane counts are often missing. While this is mostly for minor streets, it raises the likelihood of a model that doesn't reflect the true conditions of the network. The combination of the LTS method's sensitivity and the variable quality of OSM data leads to the potential of overestimating the LRA, an error that subsequently propagates to the B+RNDP. In any case, this underscores the importance of network preparation and using authoritative datasets when available. Furthermore, it may be of value to consider less strict implementations of the LTS like the one in R5 (Conway et al., 2017), where high-stress edges can be used but require the speed to be reduced to that of walking.

Imperfect Alignment of Local and Regional Scales

While instantiating demand based on the accessibility flow differential allows the local scale of the B+RNDP to be aligned with the regional scale of the accessibility analysis, the approach is not without its limitations. Compared to integrating the public transport network directly into the model, the approach is a simplification. The accessibility flow differential is calculated from a fully upgraded candidate network. Therefore, it is insensitive to changes in route choice that may arise when the network is partially upgraded. Because of this, regional accessibility is only considered enhanced rather than optimized. While imperfect, this is still considered an appropriate approach, as incorporating the public transport network into the model directly would entail a prohibitively high computational cost.

Round Trips not Guaranteed

A final limitation is that B+RNDP does not guarantee that the optimized network will enable a round trip from the origin to the destination and vice versa, as only the former is considered in the problem. Adding additional OD pairs for the reverse direction is insufficient to address this, as there is still no guarantee that both directions will be connected. Therefore, a constraint is necessary. This is simple to add to the problem formulation using the constraint specified by Equation 5.1.

$$z_{ij} = z_{ji} \quad (i, j) \in OD \tag{5.1}$$

However, this makes the problem significantly more difficult to solve, requiring alternative solution techniques such as Benders decomposition (Lim et al., 2022) or metaheuristics. Alternatively, the first stage of the problem can be kept as is, and the second stage can be reformulated to minimize the construction cost of connecting the OD pairs. This is a viable approach as the second stage of the problem is much less computationally expensive. However, it comes at the cost of sacrificing some of the solution quality as the connected OD pairs are determined by only considering the forward direction.

6 Conclusion

The thesis concludes by revisiting the three research questions, discussing the broader significance of the work, and proposing directions for future research.

6.1 Research Questions

This thesis was concerned with identifying and realizing the potential of cycling and public transport integration to enhance regional accessibility in peripheral areas. Integration was studied by considering B+R, a simple, broadly applicable form representing the fundamental requirements of integration. Within this scope, the thesis set out to answer the following research questions:

> **RQ1:** What are the requirements to enable the integration of cycling and public transport in peripheral areas?
>
> **RQ2:** What is the potential of cycling and public transport integration to enhance regional accessibility in peripheral areas?
>
> **RQ3:** How can the design of local bicycle networks be optimized to enhance regional accessibility?

RQ1 was answered through a literature review (Section 2.1) that focused on bicycle network design, the principal requirement for integration. The review described how the characteristics of cycling elevate the importance of cohesion, directness, safety, comfort, and attractiveness. Cohesion and directness were emphasized as they are primarily determined by the network's topology. In contrast, safety, comfort, and attractiveness are more pertinent to street-level design.

The findings of RQ1 served as a theoretical foundation for the thesis and were incorporated into the analyses. Even though street-level design is not directly within the scope of the present work, it can significantly influence the perceived quality of the network. Therefore, an adaptation of the LTS was implemented to allow for sensitivity to aspects of safety and comfort derived from street-level design. Additionally, this allowed for the bicycle network to be defined dynamically based on the needs and preferences of a target user group. The cohesion requirement was incorporated by requiring the continuity of low-stress infrastructure along routes. Finally, directness was implemented by limiting the length of routes based on a maximum detour factor.

RQ2 was answered by developing a regional accessibility analysis methodology for identifying the LRA. The methodology involves calculating the difference in accessibility between a scenario where the entire network is considered suitable for cycling and one where the suitability reflects the current state of the network. To realize the LRA, it is important not only to know from where, but also to where bicycle routes need to be improved. The latter is not explicitly identified by location-based accessibility measures such as the IoRA. For this purpose, the AP-OD centrality was proposed, a measure of the accessibility a PuT stop facilitates when it functions as a system access point.

RQ3 was answered by developing an optimization approach to bicycle network design that aims to realize the LRA. To this end, the B+RNDP was proposed, a BNDP formulated as a two-stage MILP whose primary objective is to maximize demand coverage. The B+RNDP is distinguished by the way demand is instantiated. The demand corresponds to the disaggregated components of the AP-OD centrality, aligning the local scale of network design with the regional scale of the accessibility analysis. Consequently, the B+RNDP upgrades routes to PuT stops by considering the connected population *and* the degree to which their intermodal, regional accessibility is enhanced. It is unusual for public transport stops to be the final destination of a trip. Therefore, this is considered a superior approach to maximizing the population catchment of stops on its own.

The effectiveness of the accessibility analysis and B+RNDP in identifying and realizing the LRA is demonstrated by the case study results. The methods were applied to the periphery of Munich, where the potential of B+R integration with S-Bahn stops was analyzed for a working-age adult target user group. The estimated LRA was significant, corresponding to a 48% average increase in population accessibility within 60 minutes for the 279,000 working-age adults that live in the study area. The B+RNDP was used to optimize the catchment area of the Freising S-Bahn stop, as the AP-OD centrality indicated that improving connections to it had the largest potential to realize the LRA. For a network improvement application, the B+RNDP outperformed a shortest-path-based heuristic in demand coverage by as much as 32 percentage points, demonstrating the value of an optimization approach to network design.

6.2 Significance

While a strong result, it is unsurprising that optimization outperforms a heuristic. Perhaps more significant is that the B+RNDP can be solved in the first place. This is not trivial, given the computational complexity of this kind of optimization problem. The optimization of the Freising S-Bahn catchment area represents a practical planning application that involves a detailed representation of the network and many of the key aspects relevant to bicycle network design. While the viability of the B+RNDP is partially attributed to the efficiency of the network simplification procedure, achieving this level of computational performance ultimately required compromises with respect to the complexity of the model. However, this is not inherently a bad thing. In the spirit of George Box (1976), it is important to remember that these models are all *wrong*. Arguably, it is futile to attempt to model the entirety of aspects relevant to bicycle network design in a mathematical program, especially one made up exclusively of linear combinations of variables. The focus should not be lost on creating *useful* models that provide relevant information to planners who can then negotiate the full complexity of the real world. In this regard, it's argued that the B+RNDP strikes a good balance. The results demonstrate its ability to solve problems of a meaningful size in a reasonable amount of time without needing a very powerful computer. This enables an iterative workflow where if any part of the solution is impractical, the planner can intervene through simple modifications to the parameters or constraints.

The alignment of the local and regional scales of the B+RNDP and accessibility analysis is considered the main contribution of the thesis. The methodologies form a cohesive, analytical framework for coordinating local bicycle network design with regional accessibility planning. The accessibility measures and B+RNDP were introduced using general forms and leverage open datasets, meaning they can be easily adapted to other planning areas or applications. In this regard, this thesis supports the transition away from the car-dominant paradigm by helping develop alternative approaches to transportation planning that are aligned with the true purpose of transport: accessibility.

6.3 Directions for Future Research

Many opportunities exist for further development. The accessibility analysis can be expanded to consider additional forms of integration. Bike-on-board and bike sharing are contingent on the network's quality during the egress leg, which can be reflected in the B+RNDP demand. Furthermore, the B+RNDP can be extended to balance the network's performance in terms of local and regional accessibility. It would also be interesting to leverage the LTS to develop a BNDP that simultaneously considers the needs and preferences of multiple target users. Finally, as discussed in Section 5.4, the B+RNDP doesn't *optimize* regional accessibility, but rather *enhances* it. Future research can explore ways of incorporating the intermodal network directly into the model.

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A Candidate Network Preparation Tables

The following tables contain the criteria used to prepare the candidate network from OSM data.

Table A.1: OSM key-value pairs excluded from street network initialization.

Key	Value
highway	"no", "abandoned", "construction", "planned", "platform", "proposed", "raceway", "razed", "bridleway", "bus_guideway", "corridor", "elevator", "escalator", "track", "steps", "via_ferrata", "passing_place", "rest_area", "services", "bus_stop", "busway"
service	"private", "parking_aisle"
area	"yes"

Table A.2: Criteria for classifying cycle paths and lanes.

Infrastructure	Condition
cycle path	*cycleway*[a] = "track", *highway* = "cycleway", *highway* = "path" and *bicycle* in ("yes", "designated"), *highway* = "footway" and *bicycle* in ("yes", "designated"), *highway* in ("service", "unclassified") and *bicycle* in ("yes", "designated") and *motor_vehicle* = "no"
cycle lane	cycleway[a] = "lane"

[a] includes *cycleway*, *cycleway:both*, *cycleway:right*, and *cycleway:left* keys

Table A.3: Criteria for classifying edges unsuitable for cycling.

LTS	Condition
99	one-way[a] and *oneway:bicycle* ≠ "no"
	highway = "path" and *bicycle* not in ("yes", "designated")
999	mixed-traffic and *maxspeed* ≥ 70
	mixed-traffic and *motorroad* = "yes"
	mixed-traffic and *highway* in ("motorway", "motorway_link", "trunk", "trunk_link")
	highway = "footway" and *bicycle* not in ("yes", "designated")
	highway = "pedestrian" and *bicycle* ≠ "yes"

[a] flag applied to backward direction only

Table A.4: Assumptions in case of missing *maxspeed*.

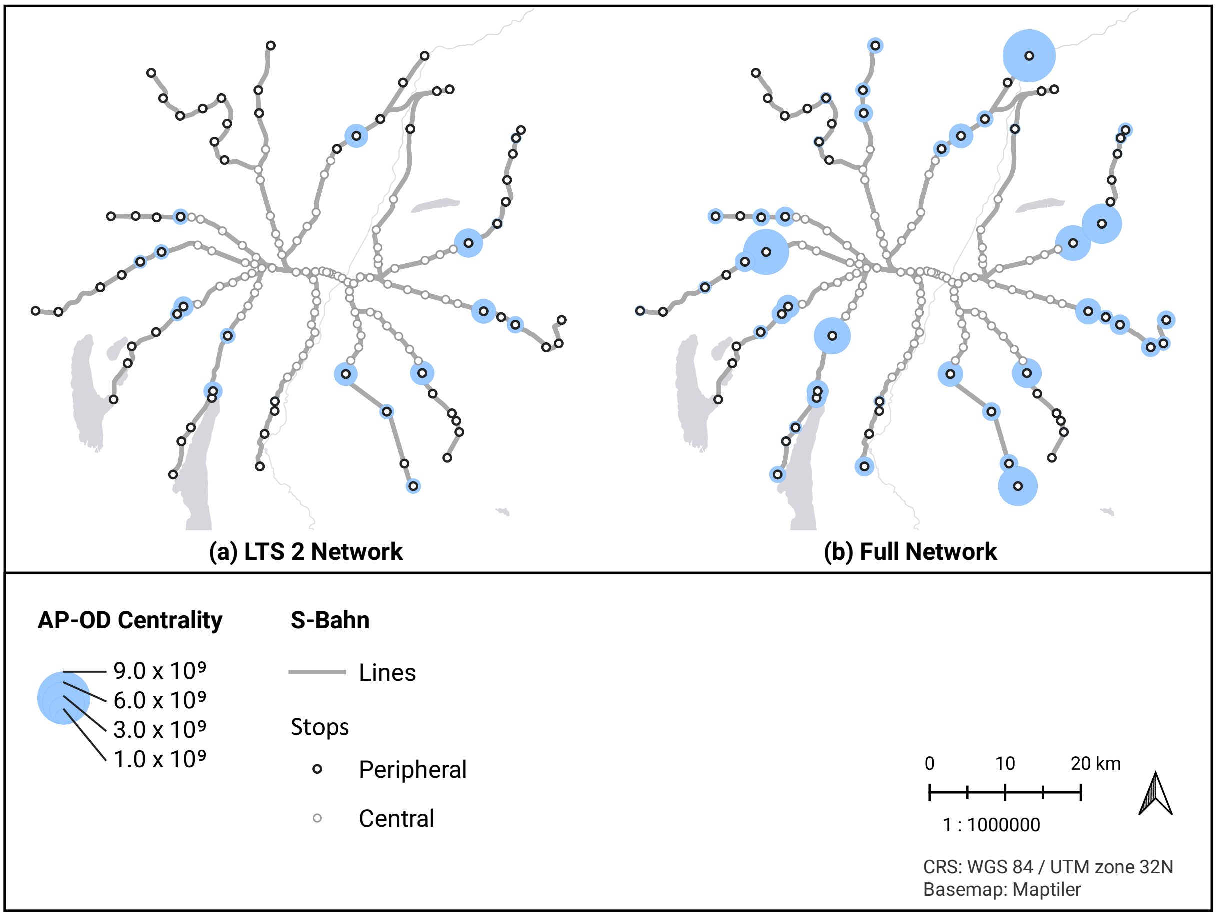
Speed	*highway*
> 50	"motorway", "motorway_link", "trunk", "trunk_link", "primary","primary_link"
50	"secondary", "secondary_link", "tertiary", "tertiary_link", "unclassified", "road"
30	"residential", "service"

B Additional Network Preparation Results

Table B.1: Candidate network length (km) by infrastructure and LTS classification.

LTS	Mixed Traffic	Cycle Path	Cycle Lane	Other	Total
1	283 (2.6%)	1719 (16.0%)	<1 (<0.1%)	7 (0.1%)	2009 (18.7%)
2	5380 (49.9%)	0	34 (0.3%)	0	5414 (50.2%)
3	70 (0.7%)	0	14 (0.1%)	0	84 (0.8%)
4	2135 (19.8%)	0	<1 (<0.1%)	0	2135 (19.8%)
99	141 (1.3%)	0	0	995 (9.2%)	1136 (10.5%)
Total	8009 (74.3%)	1719 (16.0%)	48 (0.4%)	1002 (9.3%)	10778 (100%)

C Additional Regional Accessibility Analysis Results


(a) LTS 2 Network

(b) Full Network

Figure C.1 Bicycle AP-OD Centrality for LTS 2 and full candidate network scenarios.

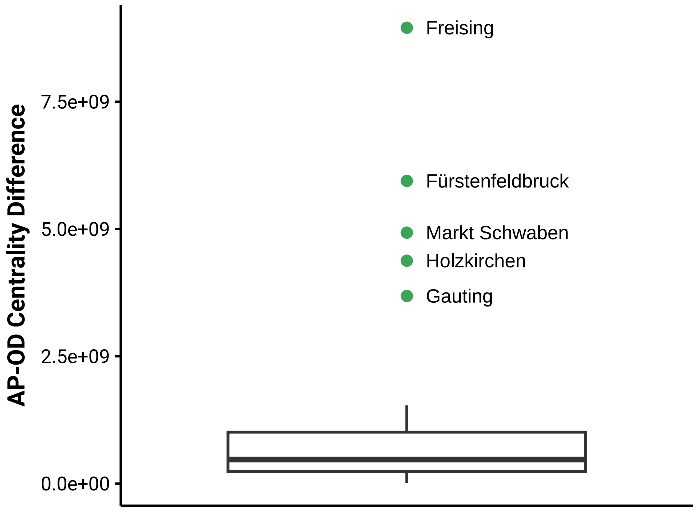


Figure C.2 Distribution of change in bicycle AP-OD centrality between LTS 2 and full candidate network scenarios. Five highest S-Bahn stops are highlighted.

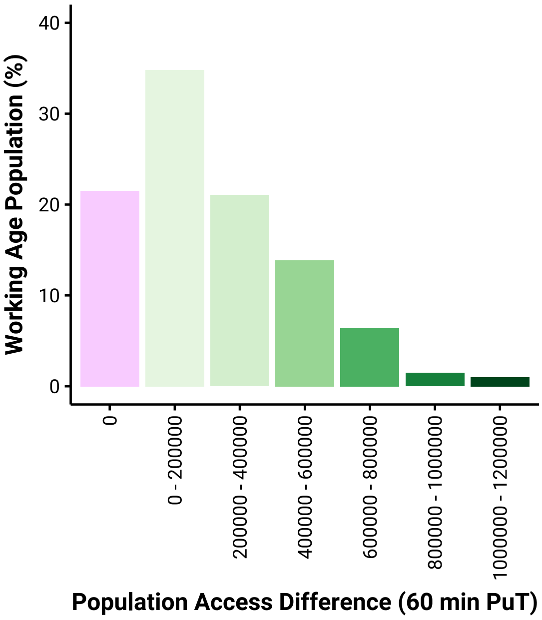


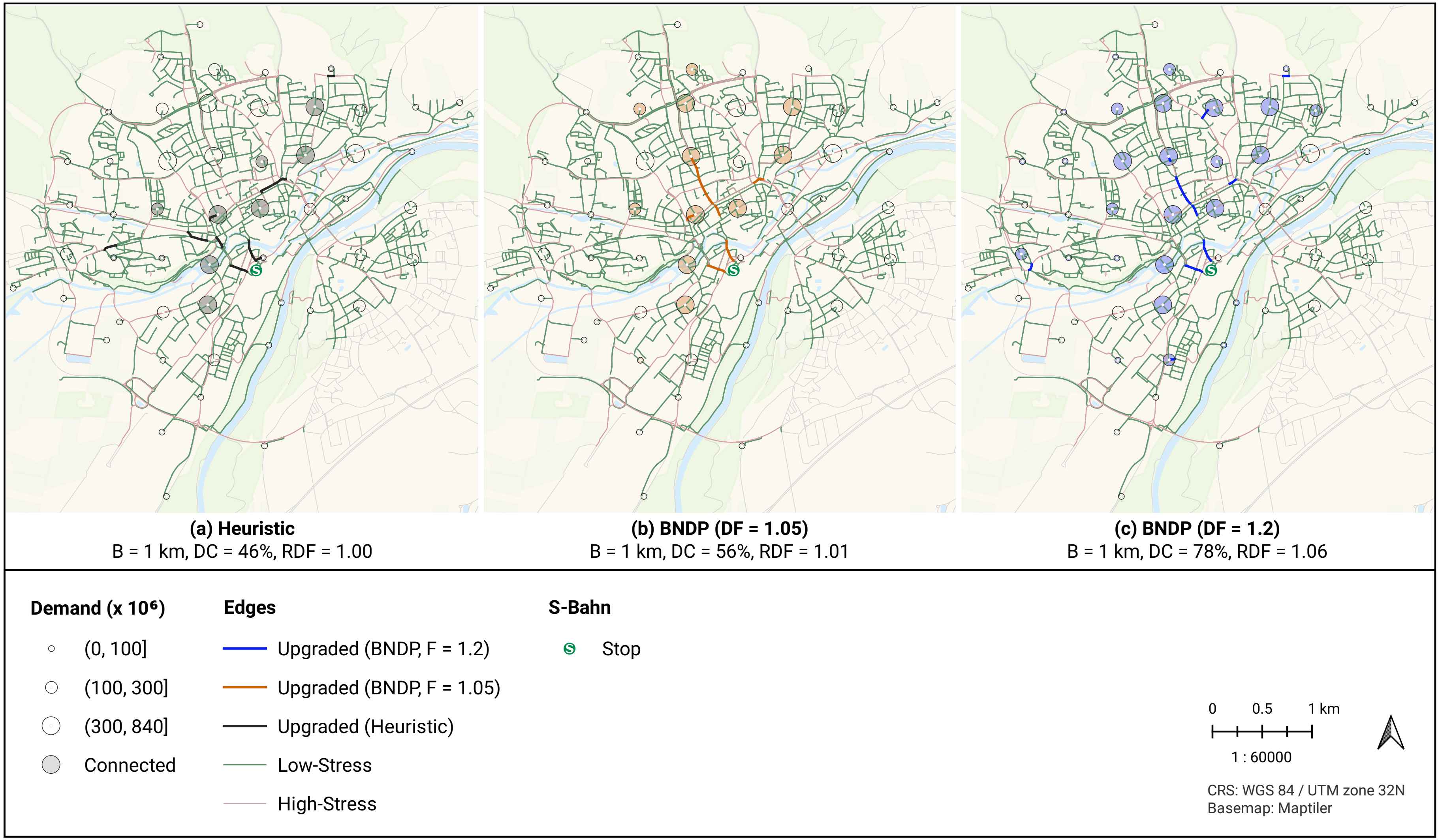
Figure C.3 Working-age population distribution of change in IoRA between LTS 2 and full candidate network scenarios.

D Additional Bicycle Network Design Optimization Results

Table D.1: Full results of B+RNDP evaluation scenarios.

LTS	Budget (km)	Heuristic DC	ΔDC			ΔRDF	
			$DF = 1$	$DF = 1.05$	$DF = 1.20$	$DF = 1.05$	$DF = 1.20$
2	0.50	29.46	4.07	16.45	29.78	0.01	0.05
2	1.00	45.78	0	10.33	32.21*	0.01	0.06
2	2.50	62.35	0.98	13.40	24.18	0.01	0.06
2	5.00	76.74	4.16*	17.15*	22.84	0.01	0.04
2	7.50	94.76	0.61	5.05	5.24	0.01	0.01
2	10.00	98.47	0.61	1.53	1.53	<0.01	<0.01
2	12.50	99.73	0.15	0.27	0.27	<0.01	<0.01
2	15.00	99.95	0.05	0.05	0.05	0	0
2	15.75	100.00	0	0	0	0	0
0	0.50	0.46	0	0	0	0	0
0	1.00	9.83	0	0	0	0	0
0	2.50	25.46	0	4.00*	4.46	0.01	0.01
0	5.00	46.26	0	0.00	3.74	0	0.09
0	10.00	68.97	0	0.52	4.00	<0.01	0.02
0	15.00	78.78	2.18*	3.80	6.96*	<0.01	0.06
0	20.00	89.91	0.24	1.87	5.00	0.01	0.06
0	25.00	96.17	0.00	1.01	2.43	<0.01	0.06
0	30.00	98.59	0.04	0.55	1.15	<0.01	0.05
0	35.00	99.71	0.01	0.20	0.29	<0.01	0.05
0	40.00	99.95	0	0.05	0.05	<0.01	<0.01
0	42.20	100.00	0	0	0	0	0

* designates that this is the largest DC improvement for the given LTS_{target}, DF combination



(a) Heuristic
B = 1 km, DC = 46%, RDF = 1.00

(b) BNDP (DF = 1.05)
B = 1 km, DC = 56%, RDF = 1.01

(c) BNDP (DF = 1.2)
B = 1 km, DC = 78%, RDF = 1.06

Figure D.1 B+RNDP solutions for $LTS_{target} = 2$, $B = 1$ km evaluation scenarios (max DC improvement for $DF = 1.2$).

(a) Heuristic
B = 15 km, DC = 79%, RDF = 1.00

(b) BNDP (DF = 1)
B = 15 km, DC = 81%, RDF = 1.00

(c) BNDP (DF = 1.2)
B = 15 km, DC = 86%, RDF = 1.06

Figure D.2 B+RNDP solutions for $LTS_{target} = 0$, $B = 15$ km evaluation scenarios (max DC improvement for $DF = 1$, $DF = 1.2$).

Chair of Urban Structure and Transport Planning
TUM School of Engineering and Design
Technical University of Munich

MASTER’S THESIS

Study Program Transportation Systems

For Mr. Bartosz McCormick
Matr.-No. 03737229

Start and End Date: 03.11.2023 – 03.05.2024

Topic: **Enhancing Intermodal Cycling and Public Transport Regional Accessibility through the Optimization of Local Cycling Networks in Suburban Areas**

Background

Since its introduction in the early 1900s, the prevailing model for urban and transport planning has overwhelmingly prioritized the car. Its speed and flexibility has enabled a sprawling, resource intensive form of development that has become increasingly difficult, if not impossible, to sustain. The dominance of the car has degraded the viability of alternative modes of transport directly, through its prioritization throughout the transport network, as well as indirectly, by supporting a form of urban development that hampers the viability of public transport service and local amenities. In the interest of a more sustainable and livable future, a transition away from this car-dominant paradigm is necessary. Through its simultaneous consideration of land use and transport, the framework of accessibility planning offers a more holistic alternative. In comparison to conventional transportation planning which prioritizes mobility, accessibility planning has a more direct connection to the purpose of transport, enabling people to perform activities distributed through time and space. While urban growth has spread towards the periphery, jobs and specialized amenities have largely remained concentrated in urban centers. In turn, the functional boundaries of cities have been pushed to the regional scale, making it the critical level at which to address prevailing transportation challenges.

The proposed research would focus on peripheral, suburban areas. Realistically, it is inevitable for these areas to generate travel demand that cannot be mitigated or satisfied locally. For this demand, public transport is the most climate-friendly and space-efficient mode. In a low-density context it is difficult to operate a financially viable, attractive service that also has a broad coverage area. Meandering alignments and frequent stop spacing compromise a service’s operational speed, resulting in a need to balance operational performance and spatial availability. This tension is the basis for public transport's "last-mile problem", the challenge associated with access to, and egress from, the system. The integration of cycling and public transport is a promising solution. Bikes are inexpensive, readily available, and are the most energy efficient mode of transport. These characteristics indicate a large potential to (a) increase the catchment area of public transport stops and (b) reduce reliance on feeder services for intermediate distances. The synergy of cycling and public transport can make travel more flexible, reliable, and faster, enabling it to compete more closely with the car.

Objectives:

The first research question is as follows: **What are the requirements to enable the integration of cycling and public transport in suburban areas? (RQ1)** To answer this question, various forms of integration will be considered. After determining the requirements, the potential of integration will be explored through the following question: **What is the potential of cycling and public transport integration to enhance regional accessibility in suburban areas? (RQ2)** A regional accessibility analysis is expected to identify areas with a high potential for improved accessibility as a result of integrating cycling and public transport. It is expected that the potential is highly contingent on a well-connected, safe, and comfortable cycling network. By taking into account the quality of the existing cycling network, it will be possible to determine the reduction in potential due to inadequate or missing infrastructure. To answer this question, a methodology for an accessibility analysis will be proposed and applied to the study area. After determining the requirements for, and the potential of, cycling and public transport integration, the proposed research aims to determine *how* this potential can be realized. The third research question is as follows: **Given a finite budget, how can the design of local cycling networks be optimized to enhance regional accessibility? (RQ3)** To answer this question, an optimization approach will be formulated and demonstrated within the study area.

Methods:

Munich, Germany will be chosen as a case study. Publicly available data will be used for modeling and analyzing cycling and public transport networks.

RQ1:

A literature review will be performed to determine the requirements of cycling and public transport integration.

RQ2:

The accessibility analysis will utilize a cycling network defined using a simplified adaptation of the level of traffic stress (LTS) methodology. The implemented LTS criteria will be sensitive to the German context and limitations of publicly available data.

RQ3:

A literature review will be performed to identify possible approaches for solving the cycling network design problem. In line with past approaches in the literature, the budget and costs of network improvements will be represented either with monetary values or abstract units.

Supervision:

The candidate will present to his supervisor, Aaron Nichols, and co-supervisor, Sebastian Seisenberger, a draft of the structure for his master’s thesis and a work plan two weeks after this approval. Other supervision meetings will be planned with the candidate when necessary. The Chair of Urban Structure and Transport Planning supports the candidate with the contact to relevant actors and or experts if needed. After two weeks of the submission of his thesis, the candidate must defend it by means of a presentation (20 minutes) and the following discussion. The results are responsibility of the author. The Chair does not take responsibility for those results. The Chair of Urban Structure and Transport Planning and the thesis supervisor are allowed to use, reproduce, distribute, and display the master's thesis and any generated data, for academic research and education purposes, provided that coordination with the student occurs.

Dr.-Ing. Benjamin Büttner

M.Sc. Aaron Nichols