

Proximity and the countryside: Assessing the potential for proximity-centered accessibility by bicycle in rural Germany

Caro Huth^{a,b,*}, Franziska X. Meinherz^a

^a Institute of Geography and Geoecology (IFGG), Karlsruhe Institute of Technology (KIT), Kaiserstr. 12, 76131 Karlsruhe, Germany

^b Department of Cycling Transport, Technical University of Applied Sciences Wildau (TH Wildau), Hochschulring 1, 15745, Wildau, Germany

ARTICLE INFO

Keywords:
Accessibility
Proximity
Cycling
Rural areas
X-minute city
Place-based
E-bike

ABSTRACT

Proximity-centered accessibility has gained increasing attention in transport and land-use planning, but research remains strongly focused on walking and dense urban environments. This study examines the potential of cycling, particularly e-bikes, to enable proximity-centered accessibility across different rural spatial contexts. With Germany as a case study, we develop a methodological approach for measuring cycling-based accessibility at the municipal level. We combine the quantity and diversity of destinations that can be reached within 30 min, thus using the underlying principles of the x-minute city as an analytical framework to assess accessibility beyond urban cores in less densely populated areas. In a large-scale analysis of rural Germany, accessibility is calculated for different bicycle types and safety needs regarding infrastructure through different assumptions in the routing process. The results reveal substantial spatial differences in cycling-based accessibility. Accessibility systematically decreases towards more rural settlement structures, primarily reflecting lower densities of reachable destinations, while functional diversity remains comparatively robust. E-bikes considerably expand accessibility compared with conventional bicycles, with particularly pronounced benefits in less densely populated areas, although they do not eliminate underlying spatial disparities in opportunity provision. Moreover, location-quotient analyses reveal systematic differences in the functional composition of accessible opportunities across spatial contexts and cycling scenarios.

Overall, the findings highlight the considerable potential of cycling and especially e-bikes to extend proximity-centered accessibility beyond dense urban environments, while also demonstrating its dependence on settlement structure, infrastructure and provision of amenities. The proposed open-data framework provides a transferable approach for evaluating cycling-based proximity-centered accessibility in heterogeneous rural contexts.

1. Introduction

Accessibility has become one of the central concepts in transport and spatial planning because it reflects how land-use and transport systems enable people to participate in everyday life (Geurs & van Wee, 2004; Geurs & Van Wee, 2026; Handy, 2020; Mouratidis, 2026). Existing research highlights structural challenges resulting in accessibility gaps in suburban and rural regions. Those include lower densities, limited service diversity, and weak public transport, which all lead to higher car dependency (Poltimäe et al., 2022). Rural accessibility planning requires navigating a fundamental trade-off: on the one hand, promoting socially inclusive access by shortening distances to essential services; on the other hand, preserving economically efficient, centralized service provision that relies on high levels of mobility (Pot & Piesch, 2024). Half

the world's population lives in suburban, peri-urban, or rural areas (European Commission, 2025) but research on active mobility and accessibility is mainly concentrated on city areas. To achieve meaningful progress toward sustainable and just transport and spatial planning, research must extend to areas beyond the urban core (Poorthuis & Zook, 2023).

In recent years, proximity-centered accessibility has been promoted as an alternative to car-oriented planning, emphasizing short distances and active travel (cycling, walking) (Silva et al., 2023). Planning concepts such as the 15-min city have further strengthened this perspective by shifting attention from increasing mobility towards improving the local accessibility of essential services (Moreno et al., 2021; Silva et al., 2023). The idea of this concept is that people have a higher quality of life if central functions can be fulfilled within 15 min. By definition, the

* Corresponding author at: Institute of Geography and Geoecology (IFGG), Karlsruhe Institute of Technology (KIT), Kaiserstr. 12, 76131 Karlsruhe, Germany.
E-mail address: caro.huth@kit.edu (C. Huth).

15-min city concept has largely focused on densely populated urban areas, where proximity to everyday services can be more easily achieved. In such contexts, a critical mass of residents sustains local amenities, while well-developed walking, cycling, and public transport infrastructure enable efficient access to them (Poorthuis & Zook, 2023). Recently, the concept has been extended into the x-minute city, to account for different local contexts with varying time thresholds (Knap et al., 2023; Mouratidis, 2026). However, to date, few studies analyzed adaptations beyond dense inner-city areas.

In this regard, bicycles, and e-bikes in particular, offer potential as an (additional) mobility option. In the past decades, cycling has gained political and scholarly attention as an affordable, sustainable, and health-promoting mode of transport. The rise of e-(cargo-)bikes has expanded the practice of cycling to longer trips and different population groups, such as elderly, families and people living in rural areas (Kohlrautz & Kuhnimhof, 2024; Philips et al., 2025; Plazier et al., 2023). However, more research is needed on how such socio-technological developments reconfigure the potential of cycling to bridge accessibility gaps in low-density areas (Plazier et al., 2023; Poltimäe et al., 2022). Specifically, there is still a need for research that analyzes the potential for proximity-oriented accessibility in different spatial contexts beyond urban cores (Arias-Molinares et al., 2025; Birkenfeld et al., 2023; Maciejewska et al., 2025; Poorthuis & Zook, 2023; Teixeira et al., 2024; J. Wang et al., 2025).

To address this research gap, we tackle the following research question: What is the potential of cycling, particularly with e-bikes, to enable proximity-centered accessibility in different spatial contexts in rural areas of Germany? In addressing this question, we use the underlying principles of the x-minute city as an analytical framework for examining how proximity-centered accessibility principles can be interpreted under the heterogeneous spatial conditions of rural and less densely populated areas, by empirically exploring the idea of a potential 30-min territory. Rather than proposing a fixed new planning concept, we (1) develop a conceptual framework for analyzing proximity-centered principles beyond the urban core, (2) operationalize this framework through a methodological approach for measuring bicycle-based accessibility, and (3) conduct a large-scale analysis across rural Germany to assess how the resulting accessibility potential and the functional composition of accessible destinations vary between spatial contexts and cycling conditions. Although we analyze the case of Germany, we expect that our methodology, which relies on open-source data, can be easily adapted to other contexts.

The remainder of the paper is structured as follows. Section 2 reviews the literature on rural mobility and cycling, proximity-oriented accessibility, and approaches to measuring cycling-based accessibility. Section 3 introduces the study area and the operational definition of rural areas in Germany. Section 4 presents the methodological framework for assessing cycling-based accessibility based on the 30-min territory concept, including the underlying data, accessibility measures, and routing scenarios. These scenarios capture differences between conventional bicycles and e-bikes as well as between routing limited to safer cycling infrastructure. Section 5 presents the empirical results, which are discussed in Section 6. Section 7 concludes the paper.

2. Literature review

2.1. Mobility and cycling in rural areas

As early as 1979, Moseley described accessibility as “the rural challenge” caused by lower density and spatial dispersion (Moseley, 1979). Processes of urbanization, centralization, and in some regions

population decline, together with the withdrawal of jobs, shops, services, and schools, exacerbate accessibility challenges in rural areas (Milbourne & Kitchen, 2014; Poltimäe et al., 2022; Wiersma et al., 2017). Limited demand and a lack of economies of scale result in poorly developed public transport services, characterized by a sparse network, low frequencies and limited operating hours (Arias-Molinares et al., 2025; Gray et al., 2001; Poltimäe et al., 2022; Velaga et al., 2012; J. Wang et al., 2025). As a result, car mobility has become a defining feature of rural life, and has developed conjointly with a spatial organization based on centralized and sparse facilities (Delbosc & Currie, 2011; Gray et al., 2001; Milbourne & Kitchen, 2014; Poltimäe et al., 2022; Pot et al., 2020). This structural necessity often leads to forced car ownership, where low-income households incur significant financial burdens to maintain a vehicle because no practical public transport alternative exists (Carroll et al., 2021). Those without reliable car access, including low-income households, older people, children, and persons with disabilities, face heightened risks of transport poverty and social exclusion (Berg & Ihlström, 2019; Graham et al., 2018; Gray et al., 2001; Isetti et al., 2020; Lucas, 2012; Nutley, 2003; Pot et al., 2023b). Since Moseley’s introduction of the term, the “rural challenge” has only intensified: rural areas increasingly face difficulties in providing sufficient and inclusive accessibility (Delbosc & Currie, 2011; Pot et al., 2023b). In addition, there is a significant imbalance in terms of research on mobility, accessibility, and spatial planning, which has traditionally prioritized urban contexts (McCarthy, 2008; Poorthuis & Zook, 2023).

Cycling may provide an alternative to car-based mobility, but its role differs considerably between urban and rural contexts. Although rural residents generally travel longer distances to reach everyday destinations, these distances are predominantly facilitated by car use. For active modes, a different pattern emerges: rural residents who walk or cycle tend to travel shorter distances than their urban counterparts, and their acceptance of longer distances by active modes is also comparatively lower. (Pot & Piesch, 2024). Where low-density spatial structures and longer travel distances limit the potential of conventional cycling to reduce car dependency and enhance accessibility in rural areas, e-bikes hold considerable potential (Plazier et al., 2023; Poltimäe et al., 2022). The e-bike functions as a “range extender” compared to conventional cycling, making distances of approximately up to 20 km acceptable (Kohlrautz & Kuhnimhof, 2024; Plazier et al., 2023) and allow residents to cover distances typically four to eight kilometers longer than those possible with conventional bicycles (Brüchert et al., 2022). E-bikes flatten topographies and mitigate physical effort. Peripheral areas, with their hilly or sparsely populated areas and longer uninterrupted routes, enable riders to fully benefit from the higher speeds of e-bikes. Therefore, in rural and peri-urban areas, e-bikes are effectively competing with motorized modes (Kohlrautz & Kuhnimhof, 2024; Plazier et al., 2017, 2023; Rérat, 2021). E-bike ownership and usage rates are indeed higher in suburban and rural areas than in metropolitan cores. In such regions, where public transport availability is limited, e-bikes harbor a high potential to substitute car trips (Kohlrautz & Kuhnimhof, 2024; Meijering & Weitkamp, 2024; Philips et al., 2025; Plazier et al., 2023). For households with children or those with lower socio-economic status, the e-bike serves as a flexible, cost-effective alternative to owning a second car, thereby promoting social inclusion and accessibility while significantly reducing transport-related costs and carbon emissions (Philips et al., 2025; Plazier et al., 2023). However, the widespread adoption of e-bikes in rural areas faces significant infrastructure barriers. These include narrow, unsafe paths that are difficult to navigate at higher speeds and a lack of separated lanes that can accommodate traffic of varying speed levels (Brüchert et al., 2022;

Meijering & Weitkamp, 2024). There is also a significant geographical mismatch, as e-bicycle ownership is most prevalent in sparsely populated rural areas and regions with marginal public transit service, yet these locations offer the lowest access to high-quality residential parking. While urban centers benefit from higher probabilities of secure and accessible storage, rural residents often adopt e-bicycles as essential mobility tools to compensate for limited transit options despite a lack of adequate infrastructure to protect these high-value vehicles (Lachapelle et al., 2026).

Current planning debates advocate for a shift from merely subsidizing personal mobility to improving local accessibility. Nevertheless, to create truly inclusive rural environments, municipalities are encouraged to invest in multi-modal infrastructures that integrate active travel like e-biking into the broader transport network while ensuring safety e.g. through improved path design (Brüchert et al., 2022; Naumann, 2023).

2.2. Proximity-centered accessibility and the limitations and potentials for applying the x-minute city concept beyond the urban core

Accessibility is a foundational concept in transport and land-use planning, geography, and geoinformatics and has become an established dimension of quality of life (Mouratidis, 2026; Silva et al., 2023). Accessibility has been defined and operationalized in multiple ways (Geurs & van Wee, 2004). Our understanding of accessibility for this study is built on Handy's definition (2020), which stipulates that "the level of accessibility from a given place reflects the distribution of destinations around it, the ease with which those destinations can be reached by various modes, and the amount and character of the activity found there" (Handy, 2020, p. 1). This understanding combines (i) travel impedance, meaning the ease or difficulty of reaching destinations (often expressed through time, distance, or cost), and (ii) opportunities, meaning the number, distribution, and attractiveness of destinations (Handy, 2020; Handy & Niemeier, 1997; Mouratidis, 2026).

Accessibility research commonly distinguishes between two contrasting paradigms: mobility-centered and proximity-centered accessibility. Mobility-centered accessibility seeks to improve travel speed to reduce travel time. (Levine et al., 2012; Silva et al., 2023; Silva & Altieri, 2022; Soukhov et al., 2025; Teixeira et al., 2024; Urry, 2004). Historically, this has resulted into longer travel distances and urban sprawl (Silva et al., 2023; Silva & Altieri, 2022). In response, a renewed focus on accessibility through proximity emerged, emphasizing local living and decentralized provision of everyday services (Handy, 2020; Maciejewska et al., 2025). Proximity-centered accessibility couples spatial and temporal dimensions and aims to shorten distances so that daily needs can be met locally (Silva et al., 2023). It supports multi-modal use of infrastructures, reduced car dependence, and greater independence for vulnerable users (Ewing & Cervero, 2010; Handy, 2020; Murgante et al., 2024), and offers a foundation for equity-oriented analyses (Levine et al., 2019; Pira & Hansson, 2025). In addition to transport and environmental benefits, proximity is frequently associated with, active mobility, urban vitality, inclusive environments that promote social interaction and community engagement, public health, and higher quality of life (Murgante et al., 2024; Sepehri & Sharifi, 2025).

A prominent concept for assessing proximity-centered accessibility is the 15-min city developed by Carlos Moreno (Moreno et al., 2021, 2024). The 15-min city aims to ensure that residents can access all essential everyday activities within 15 min by walking, cycling, or using public transportation (Allam et al., 2023; Moreno et al., 2021; Poorthuis & Zook, 2023; Sepehri & Sharifi, 2025; Teixeira et al., 2024). According

to Moreno, these essential functions are living, working, commerce, healthcare, education and entertainment. The built urban structure should therefore reflect principles of proximity, diversity, density, ubiquity and Digitalization (Moreno et al., 2021). Next to inspiring urban planning strategies in cities around the world, the 15-min or x-minute city has also been applied in numerous empirical studies that analyze 15- or x-minute accessibility patterns at the city and neighborhood level (Bartzokas-Tsiompras & Bakogiannis, 2023; Birkenfeld et al., 2023; Calafiore et al., 2022; Guzman et al., 2024; Murgante et al., 2024; Papadopoulos et al., 2023; Staricco, 2022; Staricco & Brovarone, 2022; Zhang et al., 2023), or assess which extent specific municipalities correspond to the 15-min city ideal (Ferrer-Ortiz et al., 2022; Gaglione et al., 2022; Guzman et al., 2024; Logan et al., 2022; Megahed et al., 2025; Noworól et al., 2022; Poorthuis & Zook, 2023). In this vein, researchers have developed different indicators (e.g., network-based measures, walkability, and multimodal accessibility metrics) to measure x-minute accessibility (Knap et al., 2023; Logan et al., 2022; Olivari et al., 2023; Poorthuis & Zook, 2023; Zhang et al., 2023). Studies work with different basic social functions to which access should be guaranteed, though they generally agree on categories such as education, healthcare, retail (especially food), and recreation (Calafiore et al., 2022). Although the initial concept emphasized multi-modal accessibility by walking, cycling, and public transport, most of these empirical studies focus on accessibility by walking. Only few studies analyzed accessibility by active means of transport (walking and cycling) and very few specifically by cycling (Chiaradia et al., 2024; Feng et al., 2025; Hosford et al., 2022; Knap et al., 2023).

Recognizing that urban concepts cannot simply be transferred to less densely populated regions, Moreno introduced the concept of the 30-min territory, providing a more appropriate framework for suburban and rural contexts (Moreno et al., 2021; Poorthuis & Zook, 2023). The 30-min territory extends the original idea to less densely populated areas and puts more emphasis on public transportation and complementary mobility services to increase accessibility over longer distances. Both the 15-min city and 30-min territory revolve around the ideas of proximity-centered planning to reduce reliance on cars and promote fewer and shorter trips (Arias-Molinares et al., 2025; Mouratidis, 2024, 2026). Siedentop and Gerten (2023) adapted this concept to the German context and argue for applying the concept to rural areas, to reduce car dependency outside urban areas. Similarly, Poorthuis and Zook (2023) conclude that the 30-min territory concept is crucial to address the realities of suburban and rural contexts and for extending proximity-centered planning beyond dense urban cores.

Though, transferability of the concept to different spatial contexts has been questioned (Guzman et al., 2024; Maciejewska et al., 2025; Mahmoudpour & Shirazi, 2026; Marquet et al., 2025; Mouratidis, 2024). Critics argue that the model's reliance on high-density, compact urbanism cannot be replicated in low-density suburbs or rural areas where essential services are dispersed across larger areas (Maciejewska et al., 2025). Indeed, the 15- or x-minute concept has mainly been studied in and applied to urban cores. Notable exceptions include two recent studies that examine suburban contexts in Dubai and Chinese megacities (Alawadi et al., 2025; J. Wang et al., 2025), one that investigates the Liverpool City Region, including both the central city and its surrounding areas (Calafiore et al., 2022), and one that provides a literature review that explicitly considers peripheral areas (Arias-Molinares et al., 2025). The authors of this review highlight pronounced core-periphery gradients in accessibility in such areas, which makes a uniform 15-min threshold neither realistic nor equitable. Their findings mirror those of scholars who warn that a "one-size-fits-all" approach risks ignoring

existing structural differences and may even increase overall travel volumes because decentralization means that specialized services are moved away from efficient transit nodes (Mahmoudpour & Shirazi, 2026; Mouratidis, 2024).

Overall, research on x-minute accessibility remains predominantly urban and walking-focused, with limited attention to cycling and rural areas, while uniform accessibility thresholds insufficiently account for the heterogeneity of spatial contexts, especially in rural areas.

At the same time the critiques do not invalidate the broader principles of accessibility-based planning (Pot et al., 2026). According to Pot et al. (2026), the main challenge lies in the prescriptive interpretations of accessibility concepts as the 15-min city. Rather than prescribing spatial outcomes, planning should recognize transport and land-use systems as complex and context-specific and shape regulatory and socio-cultural conditions that enable locally appropriate accessibility configurations to emerge. Therefore, they propose a place-based accessibility planning framework that combines spatial accessibility, travel behavior, and perceived accessibility to better understand local accessibility conditions and provide a context-sensitive basis for adaptive and participatory planning (Pot et al., 2026).

2.3. Measuring cycling-based accessibility in rural areas

Measuring cycling-based accessibility poses methodological challenges because conventional transport models and datasets are predominantly designed for motorized travel and often fail to represent the spatial and behavioral characteristics of cycling (Iacono et al., 2010; Saghapour et al., 2017). A key issue is spatial resolution. Large analysis units such as traffic analysis zones or census tracts can obscure short-distance accessibility patterns and introduce aggregation effects (e.g. the modifiable areal unit problem (MAUP)) (Iacono et al., 2010; Lieske et al., 2025; Porter et al., 2020; Winters et al., 2013). High-resolution grid- or network-based approaches are therefore increasingly used to capture local variations more accurately (Lieske et al., 2025).

A second challenge concerns the representation of the cycling network and travel impedance. Traditional road datasets may omit separated bicycle paths and other cycling-specific infrastructures, while accessibility models frequently assume constant cycling speeds and shortest-path route choice (Iacono et al., 2010; Saghapour et al., 2017). These assumptions neglect differences in route choice and travel time resulting from bicycle type, cyclist ability, infrastructure quality, traffic stress, and topography. Particularly, gradients can substantially affect conventional cycling speeds and thus the area reachable within a given travel-time threshold (Castañón & Ribeiro, 2021; Iacono et al., 2010; Jafari et al., 2025; Kent & Karner, 2019; Knap et al., 2023; Lieske et al., 2025; Porter et al., 2020; Saghapour et al., 2017; D. S. Vale et al., 2015; Williams et al., 2024). More advanced approaches therefore incorporate elevation, heterogeneous cycling speeds, infrastructure characteristics, or Level of Traffic Stress into routing and impedance functions (Jafari et al., 2025; Kent & Karner, 2019; Knap et al., 2023; Lowry et al., 2012; Williams et al., 2024). OpenStreetMap (OSM) facilitates such network-based approaches by providing detailed and widely available information on cycling infrastructure and road characteristics as well as extensive Points of Interest (Gehrke et al., 2020; Gu et al., 2018; Iacono et al., 2010; Jafari et al., 2025; Knap et al., 2023; Lieske et al., 2025; Pajares et al., 2021; Williams et al., 2024).

In rural areas lower settlement densities, dispersed destinations, longer travel distances, and fragmented cycling infrastructure increase the importance of accurately representing network conditions and travel

times. Moreover, accessibility often follows a pronounced center-periphery gradient, requiring approaches that can capture spatial variation and functional relationships beyond individual settlements and across larger regional extents (Knap et al., 2023; Lieske et al., 2025; Nielsen & Skov-Petersen, 2018; Ospina et al., 2022; Saghapour et al., 2017). Consequently, cycling accessibility research faces a methodological trade-off between spatial and behavioral detail and the computational scalability required for regional assessments. Existing approaches often address individual aspects of cycling impedance (Iacono et al., 2010; Jafari et al., 2025; Nielsen & Skov-Petersen, 2018; Ospina et al., 2022) but rarely integrate them within a transferable framework suitable for large-scale accessibility analysis.

Gehrke et al. (2020) address these challenges of cycling accessibility measurement by using and extending the open-source routing engine GraphHopper for their Cyclist Routing Algorithm for Network Connectivity (CRANC) (Gehrke et al., 2020). Rather than relying on shortest distance or constant cycling speeds, GraphHopper represents the road network as a directed graph and determines routes based on customizable edge weights. This allows travel times to account for cyclist type, cycling infrastructure, road characteristics, and gradients derived from elevation data. It further incorporates traffic stress and permits controlled use of high-stress segments, representing trade-offs between travel time and perceived safety. Overall, Gehrke et al. (2020) demonstrate that the routing framework provides a suitable methodological foundation for analyzing cycling accessibility across heterogeneous spatial contexts and scales as well as for evaluating different cycling conditions and infrastructure scenarios (Gehrke et al., 2020; GraphHopper, n.d.).

3. Study area: rural Germany

Defining rural areas is complex, as rurality encompasses statistical, functional, and social dimensions. Statistical definitions typically rely on population or density thresholds, although criteria vary considerably between countries (Pot et al., 2020, 2023b; W. Wang et al., 2023). From a functional perspective, rurality can be understood through spatial accessibility, with rural areas characterized by fewer locally available opportunities and greater distances to essential destinations (Pot et al., 2024; W. Wang et al., 2023).

To define rural areas in the case of Germany, we used the *Regional Statistical Spatial Typology for Mobility and Transport Research (RegioStaR)*, more precisely the combined type *RegioStaR 7* typology (BMVI, 2021a). The *RegioStaR* system is a national statistical classification to differentiate regions based on settlement structure, economic functions, and spatial relationships. The *RegioStaR 7* typology provides two main categories, namely *urban* (1) and *rural* (2) regions, which are divided into subcategories (Fig. 1b). Regarding rural areas, the typology differentiates three subcategories: *Central Cities* (75) are defined as significant regional anchors with at least 40,000 inhabitants, high regional population dominance, and an employment density of at least 0.3. The category *medium cities, urban areas* (76) aggregates municipalities that are either analytically classified as “urban” or “semi-urban” by the EU’s Degree of Urbanization (DEGURBA) methodology, have over 20,000 inhabitants, or meet specific centrality indices for medium-sized towns. Finally, *small-town areas, village areas* (77) represent the most dispersed settlement type, consisting of municipalities defined as “rural” based on low population density and more village-like characteristics. For our study, we include localities within the rural subcategories (Fig. 1).

As the analysis covers all municipalities classified as rural areas in Germany, the sample comprises a total of 7468 municipalities, including

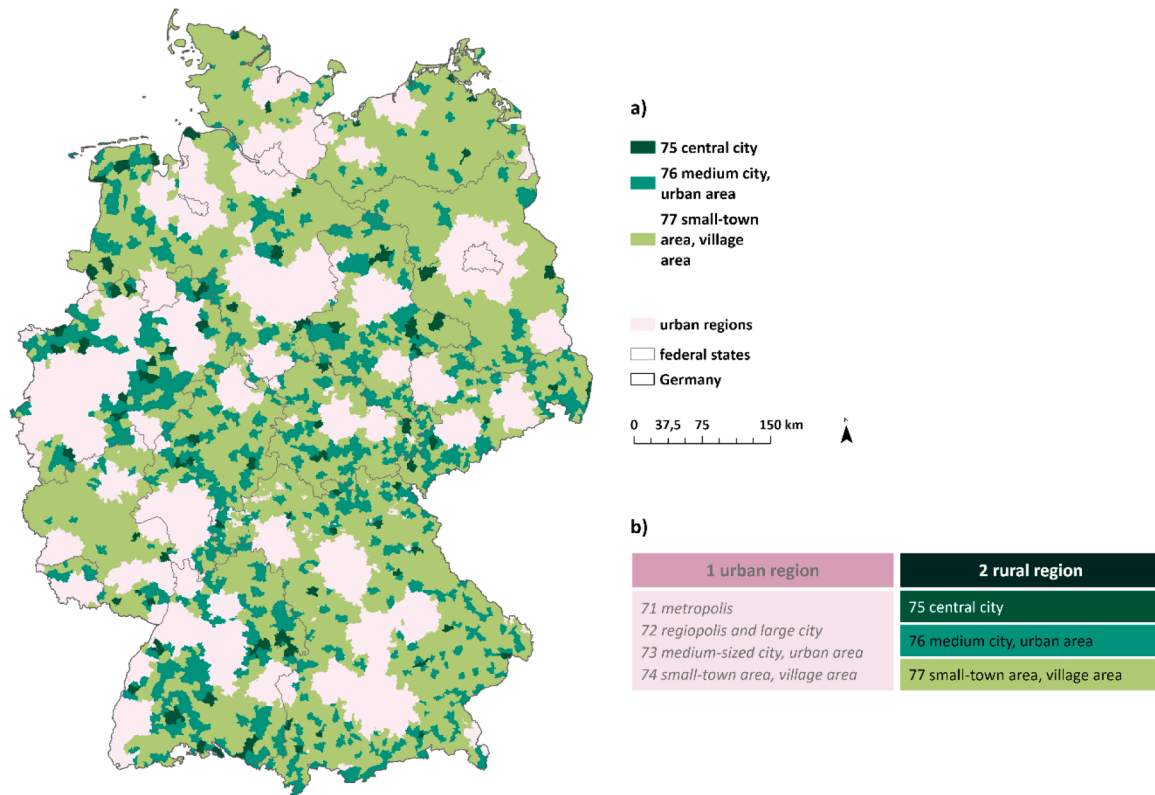


Fig. 1. Allocation of RegioStaR 7 in Germany (a) and names of all categories (b). (Source: Prepared by the authors using data for RegioStaR-Typology from BMV. Data retrieved from mobilithek Open Data Portal. <https://mobilithek.info/>).

107 central cities, 1148 medium-sized cities, and 6213 small-town/village municipalities. Approximately 30 million people (out of a German population of 83.6 million) live in this three rural subcategories, which cover an area of just under 250,000 km² (total: 358,000 km²) (BMVI, 2021b, 2021a).

The Results of the Nationwide Survey “Mobility in Germany” for the rural RegioStaR 7 categories reveals distinct mobility patterns. While mobility rates and the number of daily trips are relatively similar, average trip lengths increase from 11 km in *central cities* to 14 km in *small-town and village areas*, resulting in correspondingly higher daily travel distances. Considerable heterogeneity exists within rural regions, with central settlement cores characterized by shorter trips and higher shares of active mobility than more peripheral locations. At the same time, rural Germany is characterized by an increasing number of e-bikes per inhabitant and higher e-bike ownership rates than in urban areas. People in rural areas travel more and longer distances by e-bikes than in urban areas. Especially e-bike users in small-town and village areas travel an average of 16 km per day, compared with 13 km in both other rural categories. Whereas for conventional bicycles, rural residents are slightly less likely than urban residents to cycle at least once per month, the opposite is true for e-bikes (BMV, 2025). Therefore, e-bikes may offer potential for cycling in different rural settlement contexts. Overall, the results underline the importance of distinguishing between different rural spatial contexts rather than treating rural areas as a homogeneous category.

4. Research method and approach for assessing cycling-based accessibility in rural areas

The study employs cycling-based accessibility as a metric to assess the potential for adaptive and context-sensitive proximity-centered planning in rural areas of Germany. The x-minute city concept is being considered when evaluating this criterion. To address several of the

criticisms on the x-minute city concept, we build on existing work to adapt the concept to spatial contexts beyond the urban core and understand our study as one component of a broader place-based accessibility planning approach (Pot et al., 2026).

Proximity-centered accessibility in our empirical research is operationalized through the 3Ds framework (Arias-Molinares et al., 2025; Cervero & Kockelman, 1997). The 3Ds (density, diversity, and design) are recognized in transport and planning studies as essential for proximity-oriented planning (Arias-Molinares et al., 2025; Cervero & Kockelman, 1997; Ewing & Cervero, 2010). They also closely mirror Moreno's planning principles of density, proximity, diversity, and ubiquity/digitalization (Arias-Molinares et al., 2025).

We calculated accessibility by using the cumulative opportunity method, which is widely used by studies that assess urban territories in relation to the x-minute city (Guzman et al., 2024; Mouratidis, 2026; D. Vale & Lopes, 2023; H. Wang et al., 2025). This method counts the number of potential opportunities that can be reached within a specific travel distance or time threshold (Geurs & van Wee, 2004; Handy & Niemeier, 1997). It is relatively easy to operationalize and interpret (Bertolini et al., 2005) and well suited for comparative studies (D. Vale & Lopes, 2023). Moreno's 30-min territory concept, which expands the principles of the 15-min city to a wider range of spatial contexts and settlement types (Moreno et al., 2021; Poorthuis & Zook, 2023) is being considered for defining the 30 min time threshold. Consequently, the study can be seen as an empirical exploration of a potential 30-min territory concept that extends the underlying principles of the x-minute city beyond urban cores to rural and less densely populated areas.

We ran our accessibility analysis in three different scenarios. On the one hand, these scenarios account for the design element, by analyzing how the accessibility potential changes when only dedicated cycling infrastructure or sideroads are used ($sc_{careful}$ vs sc_{basis}). On the other hand, these scenarios compare the accessibility potential depending on whether a conventional bicycle or an e-bike is used (sc_{basis} versus

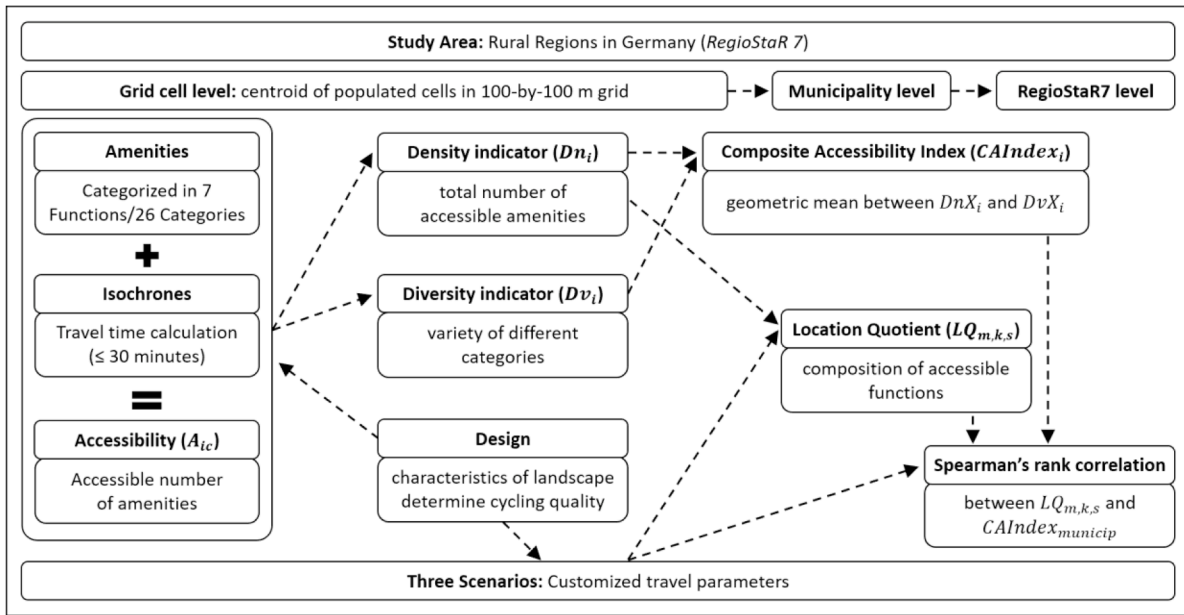


Fig. 2. Methodological framework for measuring cycling-based accessibility and the functional composition.

Table 1
Data set & sources.

Data	Purpose	Source
Amenities	Localizing relevant amenities	OpenStreetMap (OSM)
PT-Stops	Localizing relevant amenities	General Transit Feed Specification (GTFS)
Elevation	Routing	SRTM ¹ via GraphHopper
Street/Bicycle network	Routing	OSM via GraphHopper
Population grid (100-by-100 m)	Places of Residence	Zensus (2022), DESTATIS
Spatial context	Identifying different rural areas	RegioStaR (2021)
Municipal boundaries	Aggregation, Visualization	VG25 (2023), BKG

¹ Shuttle Radar Topography Mission (SRTM).

SCebike).

Our analytical approach for assessing cycling-based accessibility in rural areas and the resulting composition of accessible functions therefore consists of the following steps (Fig. 2): First, we identified and mapped relevant amenities (Section 4.2). Second, we calculated the 30-min isochrones according to the different scenarios by using the GraphHopper Isochrones API (Section 4.3). Third, we assessed accessibility based on density and diversity indicators, and a composite accessibility index that combines these two indicators (Section 4.4). To synthesize the results, we aggregated the accessibility scores from grid cell to the municipal level and subsequently the municipal-level results according to the RegioStaR 7 classification (Section 4.5). Lastly, to synthesize our results and compare different rural spatial contexts, we consolidated our findings at the level of municipalities (Section 4.5).

The processing of the model is done in Python which enables sequential, reproducible calculation. The proposed approach is generic and applicable to diverse spatial contexts and regions.

4.1. Data

This research relies on multiple open-access data sources (Table 1).

The starting points of trips are assumed to be residential houses. Data on residents is not available for individual addresses, but at the level of

grid cells in a 100-by-100 m grid. Therefore, we used the centroids of all populated cells in the study area as origin points.

Amenities, except for public transport stops, are localized via OSM tags and then assigned to the respective 26 categories. For public transport stops we used the GTFS dataset because, compared to OSM, it provides more reliable information about public transport systems and stops. Most amenities are available as point data. We kept those that were not available as point data as polygons and considered them as reached as soon as any part of the polygon intersects with the 30-min isochrone.

Elevation data were based on the CGIAR-SRTM dataset with a spatial resolution of 90 m and incorporated by GraphHopper at the network level (GraphHopper, 2026). As the 100 m grid represents the analytical unit rather than the routing resolution, no direct resampling was required.

4.2. Identifying, categorizing, and mapping relevant amenities

To identify which amenities are considered relevant to the fulfillment of basic and everyday needs for all people, we reviewed existing empirical applications of the x-minute city (namely, Calafiore et al., 2022; Capasso Da Silva et al., 2019; Chiaradia et al., 2024; Guzman et al., 2024; Knap et al., 2023; Lu & Diab, 2023; Maciejewska et al., 2025; Pira & Hansson, 2025; Silva et al., 2023; Staricco, 2022; Weng et al., 2019). This literature presents a vast array of different categorizations, subdivisions and sets of relevant amenities. Therefore, for our study, we included amenities based on criteria that directly derive from our research objectives.

First, we limited relevant amenities to those that can be expected to be available at the neighborhood level, which means that we excluded amenities such as universities or hospitals. Second, we limited relevant amenities to destinations for which cycling is an appropriate means of transport and excluded stores only selling garden furniture or large tools which cannot be transported by (cargo) bike. Third, for reasons of feasibility, we only included amenities for which georeferenced data regarding their spatial locations was available and could be filtered via OSM. Fourth, we followed the existing body of literature in excluding jobs, because people in peripheral areas tend to commute over longer distances. Furthermore, obtaining accurate and comprehensive data on job locations and individual commuting patterns has been identified as challenging (Ferrer-Ortiz et al., 2022; Guzman et al., 2024; Knap et al.,

Table 2
List of functions, categories and amenities included in this study.

Functions	Categories	Amenities (examples, not all listed)	Count ¹
Care	Day Care Facilities	childcare, kindergarten	48,891
	Long-Term Care Facilities	nursing home	1882
Education	Schools	primary to secondary schools	35,944
	Other Educational Facilities	adult education institutions	832
Health	General Doctors	primary care physician/general practitioner	37,742
	Medical Services	health care service and supply, hearing aids, optician	12,542
	Pharmacies	medical supply, herbalist, pharmacy	20,709
	Special Doctors/Therapists	dentist, orthopaedics, urologist, psychotherapist, physiotherapist, osteopathy	34,501
Mobility	PT-Stops	stations for bus, tram, metro, train	250,887
	Other Public Transport	car-rental/sharing, ferries	13,023
Recreational	Association	clubs/clubhouses for culture, astronomy, model, rabbits, traditions, social, sustainability	7574
	Entertainment/Culture	gambling/casino, cinema, clubs, culture (e.g. art, exhibitions, music) library, museum, wellness/spa	45,105
	Gastronomy	restaurants, cafes, biergarten, bars/pubs, ice cream, imbiß, playgrounds, dog parks, swimming areas, parks	217,630
	Parks/Public Spaces	community centre, social facilities, assembly halls/rooms, youth/elderly rooms	189,239
	Social Facilities	places of worship, graveyards, funeral halls, religious buildings/ places	46,616
	Spiritual Facilities	dancing, riding, tennis, golf, water sports, recreation grounds, pump tracks, sport fields/halls, dance school	112,919
	Sport Facilities	music/art school, driving school, language school	293,950
	Training Institutions	supermarkets, foodmarkets, convenience store, bakery, butcher	40,552
	Important Foods	animal supply/food, books, chemist/cosmetics, clothes, electronics, kiosk/newsagent, shoes, tobacco	109,760
	Important Shops	alcohol, chocolate/sweets/confectionary, delicatessen, tea	88,511
Retail	Other Foods	camping, sport/fitness, games/toys, jewelery, perfumery, phones, wool	10,362
	Other Shops	government/administration buildings, job centre, courthouse, police	59,567
	Administration/Authorities	repair stations, bike shops	25,665
	Bike Facilities	atm, bank, post offices, parcel locker, parcel services	11,271
Services	Posts/Bank	laundry, nail studio, veterinary, tailor, hairdresser, locksmith, shoemaker, travel agency	56,661
	Various Services		98,180

¹ Count: Number of POIs retrieved from OSM by category; total number of all retrieved POIs: 1870,515.

2023; Noworól et al., 2022; Pira & Hansson, 2025; Pozoukidou & Chatziyiannaki, 2021; Staricco, 2022). Fifth, and contrary to existing literature, we included associations / clubs, because such amenities, which act as social meeting places and host a variety of leisure time activities, tend to be more important rural than in urban contexts (BMV, 2025). Sixth, we deviated from existing literature including not only

amenities that fulfill daily needs, but also those that people visit at least once a week or on a regular basis.

Ultimately, we included amenities that fulfil the following seven main functions: Care, Retail, Education, Health, Mobility, Recreation, and Services. Within these functions, we differentiated amenities based on the frequency with which they are visited (Table 2). For instance, “care” includes childcare, which tends to be visited on a (almost) daily basis, and nursing homes, which tend to be visited less frequently (several times per month). Similarly, “retail” includes amenities that are visited almost daily (important foods, important shops in Table 1), and amenities that are visited less often yet still regularly (other foods and other shops). The categorization of individual amenities into the respective functions and subcategories emerged from structured discussions between the authors of the paper.

4.3. Calculating the isochrones according to the different scenarios

To calculate the 30-min isochrones, we relied on GraphHopper Isochrones API as routing engine, which processes street characteristics from OSM data (GraphHopper, n.d.). The routing is based on the optimal connection determined by the optimal sequence of weighted route segments with the lowest overall impedance (Gehrke et al., 2020). In addition to speed and distance, also attributes contributing to comfort are accounted for (e.g. surface, slope, and road type). Comfort features can affect the speed and result in longer travel time or a different route being selected. For example, unpaved paths tend to reduce speed and comfort, while major roads may improve travel times but negatively affect comfort due to safety and environmental concerns. By providing built-in vehicle profiles that cover some standard use cases and customizable flexible routing profiles, GraphHopper enables spatially detailed accessibility assessments by accounting for infrastructural, topographic, and behavioral differences (GraphHopper & Karussell, n.d.).

For the baseline scenario (sc_{basis}), we used GraphHopper's default profile for conventional bicycles, where the default average speed is set at 18 km/h. Sections considered unsuitable for cycling based on access restrictions or trail ratings are excluded or strongly penalized. To have higher sensitivity of travel times to terrain conditions, we modified the default slope-dependent speed settings, so that uphill segments led to stronger speed decreases, and downhill sections to stronger speed increases than in GraphHopper's standard settings (Reinfeld et al., 2023). Cycling speed is progressively reduced with increasing uphill gradients. For slopes of at least 2%, 4%, 6%, and 8%, speed is multiplied by factors of 0.90, 0.75, 0.50, and 0.40, respectively. For steeper gradients, maximum speeds are limited to 6 km/h at slopes of at least 10% and 3 km/h at slopes of at least 15%. Conversely, downhill sections allow for moderate increases in cycling speed, with adjustment factors of up to 1.25 for steeper downhill gradients.

When calculating the isochrones for cyclists using e-bikes (sc_{ebike}), which are faster, but also more voluminous and heavier, the maximum average speed is set at 25 km/h on primary roads and 22 km/h on other road types. Rather than prioritizing specific road classes, this scenario accounts for physical and infrastructural barriers. Steps as well as sections with insufficient width (<1.2 m) are excluded. Sandy surfaces and sections requiring cyclists to dismount are penalized by a factor of 0.5.

When calculating the isochrones for cyclists using only dedicated cycling infrastructure or side roads (sc_{careful}), cycleways and paths receive the strongest preference, with priority factors of 4.0 and 3.0, respectively, while residential roads and tracks are moderately preferred (1.4). In contrast, primary (0.3), secondary (0.4), and tertiary roads (0.6) are penalized. Cycling speed is limited to the assumed average bicycle speed.

4.4. Calculating the accessibility indicators according to the 3Ds

To calculate the accessibility indicators for each grid cell, for each

starting point, we counted the number of amenities of any given category which lie within the 30-min isochrone. Thus, accessibility is defined as:

$$A_{ic} = \sum_{f \in F_c} I(t_{if} \leq T) \quad (1)$$

where A_{ic} denotes the accessibility of grid cell i to facilities of category c , F_c represents the set of all facilities belonging to category c , and t_{if} is the travel time between grid cell i and facility f . $I(\cdot)$ takes the value 1 if the travel time is less than or equal to the threshold T (30 min) and 0 otherwise. On these grounds, we assessed accessibility for each grid cell based on how the cell scores on the density, diversity, and the composite accessibility indices.

4.4.1. Density

We define **density** as the number of amenities that can be reached from a starting point within 30 min. Thereby, our definition builds on but is different from how density is defined in the framework of the 3Ds, namely the intensity of land use (i.e. population or employment per unit of area), which improves a neighborhood's compactness and activity accessibility (Cervero & Kockelman, 1997; Ewing & Cervero, 2010). Moreno's definition of density is slightly different still, and refers to the optimal number of residents an area can sustainably support in terms of service provision and resource consumption and to balance environmental, economic and social needs (Moreno et al., 2021).

The density indicator Dn_i reflects the total number of amenities that can be accessed from grid cell i across all categories $c = \{1, \dots, C\}$. C corresponds to the total number of categories considered in this study ($C = 26$).

$$Dn_i = \sum_{c=1}^C A_{ic} \quad (2)$$

To normalize the density indicator Dn_i , we used min-max normalization, where $\min(Dn_i)$ and $\max(Dn_i)$ denote the minimum and maximum values observed across all grid cells to build DvX_i :

$$DvX_i = \frac{Dn_i - \min(Dn_i)}{\max(Dn_i) - \min(Dn_i)} \quad (3)$$

Accessibility values show a strongly right-skewed distribution due to very high POI densities in urban centers. Therefore, we decided to limit the influence of outliers by setting all data below the 1th percentile to the 1th percentile, and all data above the 99th percentile to the 99th percentile (Wilcox, 2003).

4.4.2. Diversity

We define **diversity** as the variety of amenities that can be reached from any starting point within 30 min; namely whether all relevant amenities can be reached. Therein, our definition of diversity mirrors the one of the 3Ds framework, which measures the mix of land uses, capturing how residential, commercial, and retail sites are spatially intermixed or vertically combined within individual buildings (Cervero & Kockelman, 1997; Ewing & Cervero, 2010). Our definition also resonates with Moreno's definition of diversity, which adds cultural diversity at the local scale and the co-existence of different identities and practices (Arias-Molinares et al., 2025; Ferrer-Ortiz et al., 2022; Khavarian-Garmsir, Sharifi, Hajian Hossein Abadi et al., 2023; Moreno et al., 2021; Murgante et al., 2024; Teixeira et al., 2024).

The diversity indicator Dv_i captures the variety of accessible categories C for grid cell i . $B(\cdot)$ is a binary indicator function that takes the value 1 if at least one facility of category c is accessible, and 0 otherwise. This indicator is based on the premise that, for instance, access to both a facility in the education and care category represents greater diversity than access to two facilities of the same category and none of the other.

$$Dv_i = \sum_{c=1}^C B(A_{ic} \geq 1) \quad (4)$$

To ensure comparability across the study area and the indicators with their differing quantities, the density and diversity indicators are normalized to a common range between 0 and 1 (Knap et al., 2023), where higher values indicate greater density and diversity, respectively.

We normalized the diversity indicator DvX_i by dividing Dv_i by the total number of categories C :

$$DvX_i = \frac{Dv_i}{C} \quad (5)$$

where a value of 1 indicates that at least one facility from every category is accessible within the defined travel time threshold.

4.4.3. Combining density and diversity to a composite accessibility index

Additionally, we established a **composite accessibility index** ($CAIndex_i$), that combines the normalized indicators through a geometric mean and is defined through the equation:

$$CAIndex_i = \sqrt{(DnX_i + \varepsilon) \cdot (DvX_i + \varepsilon)} \quad (6)$$

A small constant ($\varepsilon = 1e - 6$) was added to each indicator as a numerical safeguard prior to aggregation.

Using the geometric mean appears particularly suitable for this case since it rewards high or balanced values in both indicators while penalizing low values or unbalanced outcomes. As a result, cells with low values in either or both indicators receive a lower overall index, while cells with balanced and high values across indicators achieve better index scores.

4.4.4. Design

We define **design** as the (physical) characteristics of the landscape that determine cycling quality, such as surface, the type of available infrastructure, and topography. This definition mirrors the one of the 3Ds framework, which describes design as physical urban features, for example, walking quality, including gridded street patterns, high intersection density, and pedestrian-oriented elements like continuous sidewalks and shade trees (Cervero & Kockelman, 1997; Ewing & Cervero, 2010). Our definition also resonates with how design is used in the context of x-minute cities, wherein it refers to the built environment and connectivity that shape how amenities can be accessed and perceived. The principle of design emphasizes that proximity-centered accessibility hinges not only on the spatial distribution of amenities but also on the quality and structure of mobility systems (Arias-Molinares et al., 2025).

That is why we took these factors into account during the routing process by choosing a routing engine that provides different routing profiles and enables assessments to account for infrastructural, topographic, and behavioral differences and also calculated a scenario for cyclists with higher safety needs regarding infrastructure.

4.5. Consolidation at the level of municipalities and rural area categories

To aggregate the accessibility scores at the municipal level, we calculated for each municipality the arithmetic mean of all values in relation to the considered grid cells within their administrative boundary. This step ensures that the spatial variability at the cell level is consistently represented in a single, comparable indicator per municipality. The resulting standardized and aggregated indicators are denoted as DnX_{municip} (density) and DvX_{municip} (diversity) while the combined index is referred to as $CAIndex_{\text{municip}}$.

To explore how accessibility patterns vary across different types of peripheral regions, we subsequently aggregated the municipal-level results according to the *RegioStaR* 7 classification. Specifically, we grouped municipalities into their respective rural *RegioStaR* categories

and calculated the arithmetic mean of the municipal indicator values for each category. In this case, the indicators are denoted as $DnX_{regioStar}$, $DvX_{regioStar}$ and $CAIndex_{regioStar}$. This step allowed us to systematically compare accessibility levels across differentiated rural spatial contexts.

It should be noted that the aggregation of results introduces potential effects related to the Modifiable Areal Unit Problem (MAUP), as the observed patterns may vary depending on the chosen spatial units and level of aggregation.

4.6. Analyzing the functional composition of accessibility patterns

To assess the composition of accessible destinations relative to the overall accessibility profile of individual municipalities and spatial categories, a Location Quotient (LQ) was calculated for each municipality, function, and scenario. While the accessibility indicators capture absolute levels of access, the LQ measures the relative representation of individual functions within a municipality's accessibility profile, independent of its overall accessibility level (Zhou & Chen, 2024). The LQ compares the share of a specific function in a municipality's total accessibility with the corresponding share across the entire study area:

$$LQ_{m,k,s} = \frac{\sum_k X_{m,k,s}}{\sum_m \sum_k X_{m,k,s}} \quad (7)$$

Where $LQ_{m,k,s}$ denotes the accessibility value for function (k) in municipality (m) under scenario (s). The numerator represents the share of function (k) in the total accessibility of municipality (m), while the denominator represents the corresponding function share across all municipalities for the respective scenario.

An LQ above 1 indicates that a function is relatively overrepresented compared with the study area reference, whereas an LQ below 1 indicates relative underrepresentation and an LQ of 1 indicates an identical share. Importantly, the LQ describes relative composition rather than absolute accessibility, meaning that a high LQ can also occur in municipalities with comparatively low overall $CAIndex_{municipip}$. To compare spatial contexts, municipal LQs were grouped by RegioStaR 7 category and summarized using the median to reduce the influence of skewed values and exceptionally high LQs.

To examine whether functional composition varies with overall accessibility, Spearman's rank correlations were calculated between the function-specific LQ and the $CAIndex_{municipip}$. Municipalities were grouped by RegioStaR 7 category, and correlations were calculated across municipalities within each category separately for each function and scenario. This complements the comparison of median LQs by assessing whether the relative representation of individual functions systematically varies with overall accessibility within the same spatial context. Positive correlations indicate increasing relative representation with higher overall accessibility, whereas negative correlations indicate decreasing relative representation. Spearman's rank correlation was chosen to assess monotonic relationships without assuming linearity and to reduce sensitivity to extreme values.

5. Results

In the following, we first compare accessibility in municipalities in rural Germany according to the principles of density of reachable amenities, their diversity, and according to the composite accessibility index. We then analyze how accessibility varies across different spatial contexts in rural areas, by differentiating the RegioStaR 7 categories. Lastly, we analyze how the type of bicycle used (e-bike versus conventional bicycle) and safety needs (expressed in the kind of infrastructure that is used) affect accessibility, again highlighting differences between spatial contexts in rural areas.

5.1. Accessibility by bicycle in terms of the 3Ds

To categorize $DnX_{municipip}$, $DvX_{municipip}$ and $CAIndex_{municipip}$, we followed Mouratidis (2026) and used five classes: very low accessibility (values ≥ 0 to $\leq 0,2$), low/insufficient accessibility (values $> 0,2$ to $\leq 0,4$), medium accessibility (values $> 0,4$ to $\leq 0,6$), high accessibility (values $> 0,6$ to $\leq 0,8$), and very high accessibility (values $> 0,8$). The results are presented as maps (Fig. A.1) in the Appendix while Table 3 shows how many municipalities are assigned to each class in scbasis.

A striking finding is the discrepancy of how municipalities score on the $DnX_{municipip}$ and $DvX_{municipip}$, respectively (Table 3). The $DnX_{municipip}$ is strongly skewed towards the lowest categories (right-skewed) with a mean (0.11) that exceeds the median (0.08). Most municipalities (87.5%) exhibit low accessibility values. Only 2% of municipalities reach a medium level, and there are almost no municipalities that reach high accessibility levels.

In contrast, the distribution of $DnX_{municipip}$ is skewed towards higher values. The median (0.8) is slightly higher than the mean (0.78), indicating that a small number of municipalities with very low index values pull the average down. Over half of the municipalities (53.1%) score very high on the diversity indicator, which means that within 30 min, amenities from most categories can be reached. An additional third of municipalities (35.3%) scores high on the diversity indicator. Only

Table 4

Descriptive statistics as averages per RegioStaR 7 categories (cc – central cities, mc – medium city, stva – small town/village area) and overall averages for indicators across all municipalities (sum).

	spatial context	min	max	median	mean	Q1	Q3
$DnX_{regioStar}$	cc	0.08	0.73	0.42	0.43	0.33	0.51
	mc	0.01	0.73	0.17	0.20	0.11	0.26
	stva	0.01	0.69	0.07	0.09	0.04	0.11
	sum	0.01	0.73	0.08	0.11	0.05	0.13
$DvX_{regioStar}$	cc	0.80	1.00	0.96	0.96	0.95	0.99
	mc	0.35	1.00	0.91	0.89	0.86	0.95
	stva	0.08	1.00	0.79	0.76	0.68	0.86
	sum	0.08	1.00	0.80	0.78	0.71	0.88
$CAIndex_{regioStar}$	cc	0.26	0.86	0.63	0.62	0.56	0.71
	mc	0.06	0.86	0.39	0.41	0.31	0.50
	stva	0.02	0.83	0.23	0.24	0.17	0.30
	sum	0.02	0.86	0.25	0.27	0.18	0.33

Table 3

Count of municipalities per accessibility class for each indicator (n = 7491) in sc1scbasis and descriptive statistics.

		$DnX_{municipip}$		$DvX_{municipip}$		$CAIndex_{municipip}$	
count municipalities per accessibility class	very low	6556	(87,5%)	2	(0%)	2358	(31.5%)
	low	748	(10%)	161	(2.1%)	4013	(53.6%)
	medium	151	(2%)	707	(9.4%)	899	(12%)
	high	36	(0.5%)	2642	(35.3%)	197	(2.6%)
	very high	0	(0%)	3979	(53.1%)	24	(0.3%)
descriptive statistics	mean	0.11		0.78		0.27	
	median	0.08		0.8		0.25	
	stddev	0.10		0.14		0.14	

around 11% of municipalities score medium or low on this indicator, and the lowest category is virtually non-existent ($\approx 0\%$).

The distribution of $CAIndex_{municipip}$ is moderately right-skewed, with a mean (0.27) that is slightly higher than the median (0.25). Around 85% of all municipalities exhibit low or very low accessibility values, which is due to the fact that a high score on this aggregate indicator would require a high score on both the density and diversity indicators. Few municipalities reach moderate levels (12%), and only 197 municipalities (2.6%) fall into the second highest, and 24 municipalities ($\approx 0\%$) into the highest category.

Overall, our findings show that, while the total number of reachable opportunities ($DnX_{municipip}$) is small in most rural municipalities, a variety of categories can be reached ($DvX_{municipip}$). Nonetheless, accessibility according to the composite index ($CAIndex_{municipip}$) is relatively low across municipalities.

5.2. Accessibility across spatial contexts

Table 4 illustrates the distributions of how municipalities score on the density, diversity indicators, and the composite accessibility index according to their degree of rurality (*central city*, *medium city*, *small town/village area* in rural contexts). For all spatial categories, the indicator distributions span a wide range ($DnX_{regioStar}$: 0.01 to 0.73, $DvX_{regioStar}$: 0.08 to 1.0, $CAIndex_{regioStar}$: 0.02 to 0.86).

The $DnX_{regioStar}$ is relatively low across spatial contexts, with *central cities* scoring best but only achieving a mid-ranged median (0.42). In *small-town/village areas* the median (0.07) is close to zero. Although there are outliers reaching moderate values (max: 0.73), the large majority of municipalities exhibit very limited accessibility in terms of the number of reachable opportunities.

In contrast, the $DvX_{regioStar}$ is high across spatial contexts, with a median of 0.96 and a tight distribution in *central cities*. In *medium cities - urban areas*, the index remains high but shows greater variation (IQR: 0.09). In *small-town/village areas*, the index is lower still and more dispersed but still reaches a higher median (0.79) than the density indicator scored in any spatial category. Also in this most rural spatial category, some outlier municipalities reach the maximum diversity score of 1.0.

Like the density and diversity indicators, the $CAIndex_{regioStar}$ reaches the highest values in *central cities*, with a median of 0.63, and a relatively tight distribution (IQR of 0.14). In *medium cities*, the index drops noticeably (median: 0.39) and the distribution becomes wider (IQR: 0.18). In *small-town/village area*, the index is substantially lower still, with a median of 0.23, and a tight distribution (IQR of 0.13) in the lower part of the scale. Although there are some higher outliers reaching values up to 0.83, the majority of municipalities exhibit low combined accessibility.

The violin plots in Fig. 3 provide additional insight into the shape and concentration of the indicator distributions. The results reveal considerable differences in bicycle-based accessibility across spatial

contexts. All indicators exhibit a consistent and pronounced urban-rural gradient across all three indicators, and the distributions of the indicators also vary across spatial contexts.

For $DnX_{regioStar}$ (green), the distribution shifts markedly towards the lower end of the scale with increasing rurality. While values in *central cities* are concentrated around intermediate levels, *medium cities* show a strong concentration at low values with a pronounced upper tail. This pattern becomes even more distinct in *small-town/village areas*, where the distribution is heavily concentrated close to zero, while only a comparatively small number of municipalities extend towards higher values. $DvX_{regioStar}$ (pink) shows an almost inverse pattern: values are strongly concentrated towards the upper end of the scale in *central cities* and remain predominantly high across the other spatial contexts, although the distribution becomes broader with increasing rurality. The $CAIndex_{regioStar}$ (yellow) distributions lie between these two patterns. Their main concentration progressively shifts towards lower values from central cities to *medium cities* and *small-town/village areas*, while extended upper tails indicate that comparatively high combined accessibility is still achieved by a smaller number of municipalities in the more rural spatial contexts. The distribution across all municipalities retains the respective concentration at comparatively high or low values, reflecting the greater heterogeneity observed outside central cities.

5.3. Accessibility depending on the type of bicycle and safety needs

Fig. 4 illustrates the spatial distribution of absolute differences in accessibility according to the 30min-city indicator between the baseline scenario (sc_{basis} - non-assisted bicycle, using roads when dedicated bicycle infrastructure is absent) and the two scenarios for e-bike (sc_{ebike}), and high safety needs ($sc_{careful}$ - using only dedicated cycling infrastructure), respectively. Fig. A.1 in the Appendix shows results for all accessibility measures calculated in the scenarios.

Fig. 4a compares accessibility levels depending on whether an e-bike or conventional bicycle is used ($sc_{ebike} - sc_{basis}$). E-bikes consistently increase accessibility compared to conventional bicycles. However, the magnitude of these absolute scores ranges from -0.027 to 0.493 and varies depending on the spatial context. Accessibility gains resulting from using an e-bike are highest around urban regions. This can be attributed to the fact that though our analysis excluded urban regions, the facilities within these areas were included, and, as a result of the higher speeds and extended reach of e-bikes, those facilities can be accessed within 30 min by e-bike from surrounding rural areas. Concomitantly, the accessibility gains from using an e-bike are comparatively lower in peripheral regions (greater distance from urban regions). Notwithstanding these general trends, Fig. 4 reveals considerable heterogeneity. Within similar spatial contexts, areas where accessibility gains from using an e-bike are high are interspersed with areas where increases are more moderate. This finding emphasizes the importance of locally specific spatial configurations for overall



Fig. 3. Variety levels of density and diversity indicators and composite accessibility index in RegioStaR 7 categories and for all municipalities.

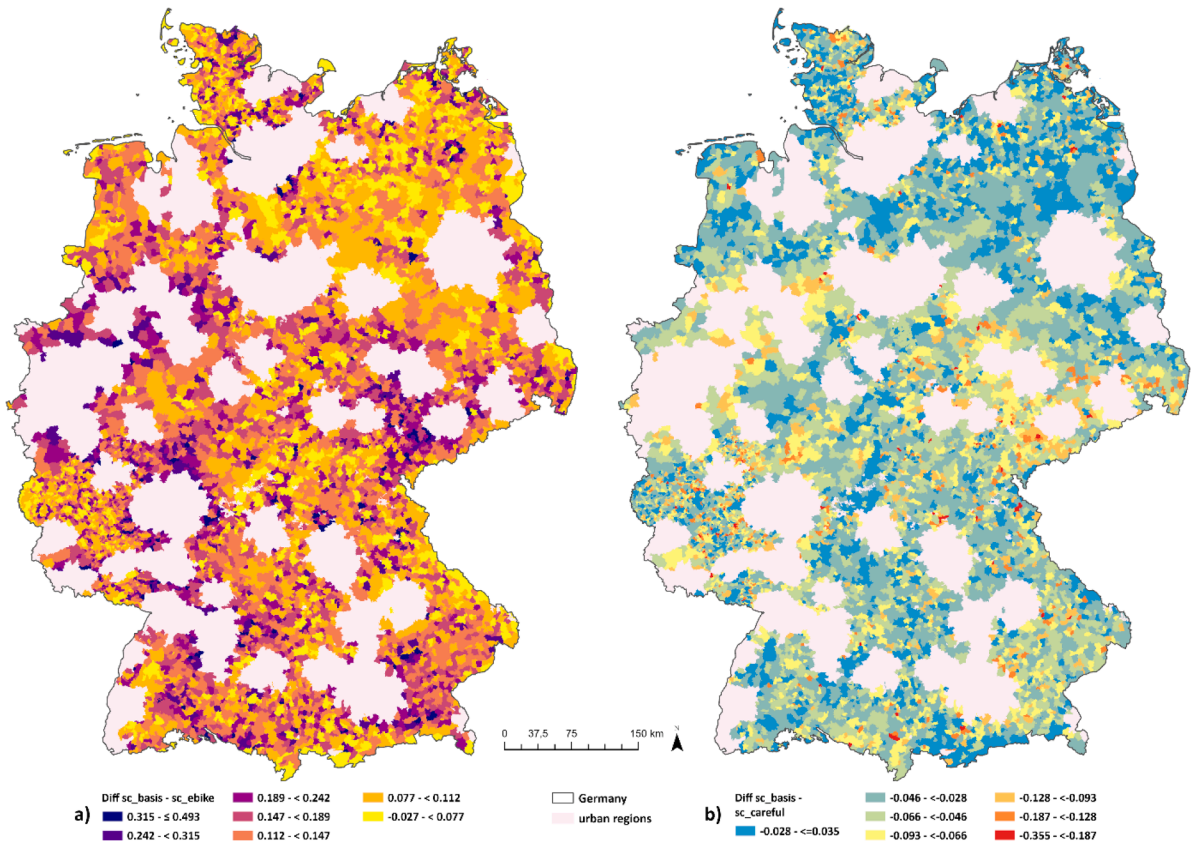


Fig. 4. Absolute differences between $sc_{ebike} - sc_{basis}$ and $sc_{careful} - sc_{basis}$ (CAIndex_{municip}).

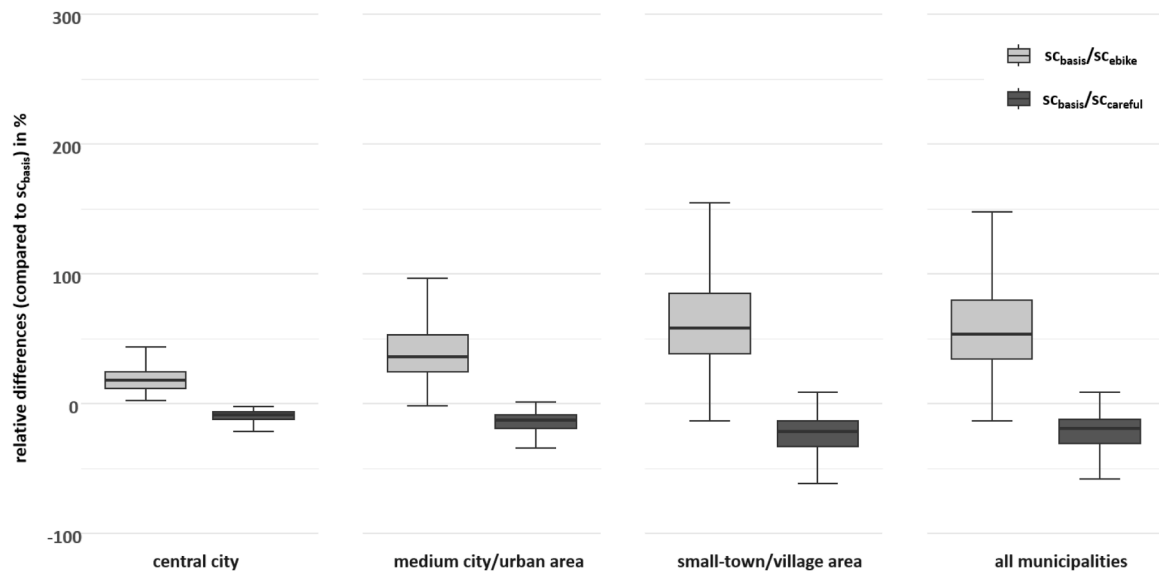


Fig. 5. Boxplot to show relative differences between $sc_{ebike} - sc_{basis}$ and $sc_{careful} - sc_{basis}$ (CAIndex_{municip}).

accessibility (e.g. settlement density, spatial distribution of opportunities, network structure). There is also a small proportion of areas where the use of e-bikes results in reduced accessibility. These are primarily found on islands and along rivers and can be explained by the exclusion of sandy surfaces, narrow paths, and steps.

Fig. 4b shows how accessibility levels change depending on safety needs (for $sc_{careful} - sc_{basis}$). When comparing the careful to the baseline scenario, accessibility levels predominantly decrease. This indicates that avoiding main roads or preferring designated cycling infrastructure

leads to longer routes or reduced network efficiency, which limits the number of reachable destinations. Again, the magnitude of this decrease varies considerably and ranges from -0.355 to 0.035 . Inversely to the e-bike scenario, accessibility losses are concentrated around urban regions, which can be attributed both to issues regarding the quantity and quality of cycling infrastructure in transition zones between urban and rural contexts, and to a higher potential for accessibility losses due to an overall higher baseline in such areas. More peripheral regions show only minimal or low differences in accessibility between those scenarios,

which suggests that route choice constraints have a comparatively smaller impact where the number of accessible destinations is already limited. Despite these general patterns, the map again reveals substantial local heterogeneity. Even within similar regional contexts, areas of higher accessibility loss are interspersed with areas of minor differences, indicating that the availability and continuity of cycling infrastructure play a key role in shaping accessibility outcomes.

The analysis of the scenarios demonstrates that accessibility outcomes in terms of the composite accessibility index vary substantially depending on the type of bicycle used and the safety needs (expressed here in the type of infrastructure used). Fig. 5 shows the relative differences in accessibility between the scenarios, calculated as proportional changes relative to sc_{basis} . It highlights, that the accessibility gains from using an e-bike are substantially higher than the accessibility losses from adopting a prudent cycling behavior. Across all municipalities, e-bikes increase accessibility in the CAIndex by a median of 54%, whereas careful cycling leads to a decrease by a median of 19 % compared to the baseline scenario.

Fig. 5 also compares the relative differences across *RegioStaR* 7 categories. In *central cities*, e-bikes provide relatively modest gains (median: + 18 %), while careful cycling results in only minor reductions (− 8 %). However, in *small-town/village areas*, the effects diverge: e-bike use increases accessibility by nearly 60 %, whereas prudent cycling leads to relatively modest losses of 21 %.

The distributional patterns further underline these differences. E-bike gains are strongly right-skewed, with up to fivefold increases in accessibility, suggesting the presence of threshold effects where conventional cycling provides only limited reach. In contrast, prudent cycling shows a left-skewed distribution, with extreme cases of complete accessibility loss (− 100 %), indicating that in some areas, avoiding major roads effectively disconnects cyclists from relevant destinations. Moreover, the variability related to both scenarios increases substantially in rural contexts. The IQR for e-bike gains rises from 0.13 in urban areas to 0.47 in rural areas, while for prudent cycling losses it increases from 0.06 to 0.20.

Fig. 6a illustrates the correlation between sc_{basis} and sc_{ebike} for the CAIndex across municipalities, differentiated by *RegioStaR* 7 categories for rural regions. The linear regression analysis reveals a strong positive linear relationship across all spatial types, indicating that municipalities with higher overall accessibility in the conventional cycling scenario also tend to achieve higher values in the e-bike scenario, whereby CAIndex values are systematically higher in sc_{ebike} than in sc_{basis} . The relatively high coefficients of determination ($R^2 \approx 0.69$ – 0.80) suggest a

robust association, confirming that the overall spatial pattern of accessibility is largely preserved when shifting from bicycles to e-bikes. All *RegioStaR* 7 follow a similar linear trend. Slightly stronger correlations are observed in *medium cities/urban areas* and *small-town/village areas*, whereas *central cities* show somewhat greater dispersion.

The relationship between sc_{basis} and $sc_{careful}$ (Fig. 6b) exhibits a strong and highly linear pattern across all *RegioStaR* 7 categories, with high explanatory power ($R^2 \approx 0.88$ – 0.95). This indicates that the overall spatial structure of accessibility remains similar across both scenarios. Nevertheless, accessibility is systematically lower in $sc_{careful}$. The relationship appears compact and differences between spatial categories are limited, although a slightly higher dispersion in *small-town/village area* suggests that the negative effects of careful cycling behavior are slightly more variable in these contexts.

5.4. Accessibility regarding its functional composition

Beyond the differences in the accessibility indicators, the composition of accessible destinations also varies across spatial contexts.

Fig. 7 shows that recreational amenities constitute the largest category across all cycling modes and spatial contexts, with particularly high shares in central and medium-sized towns. Mobility-related destinations also account for a substantial share in *central cities* but are less prominent in *small-town/village areas*. Retail and service destinations show a similar, though less pronounced, spatial pattern, whereas health, education, and care facilities generally account for smaller shares. Differences between the three scenarios are not evenly distributed across amenity categories. The additional accessibility provided by e-bikes is particularly apparent for recreational, mobility, retail, and service destinations.

The LQ further examines the compositional differences relative to the overall accessibility profile for each municipality, function, and transport mode. The results (Table 5) illustrate that *central cities* show an overrepresentation of most functions. For sc_{basis} mobility and services both reach an LQ of 1.24, while retail (1.19) and health (1.17) are also overrepresented. In *medium cities*, most functions are close to an LQ of 1, indicating a composition broadly corresponding to the reference profile. Mobility represents an exception, being underrepresented across all three cycling scenarios (0.83 for sc_{basis} , 0.82 for sc_{ebike} , and 0.74 for $sc_{careful}$).

The contrast is strongest in *small-town/village areas*, where most functions are underrepresented. For sc_{basis} , LQs range from 0.42 for mobility to 0.92 for care and education. Health is likewise

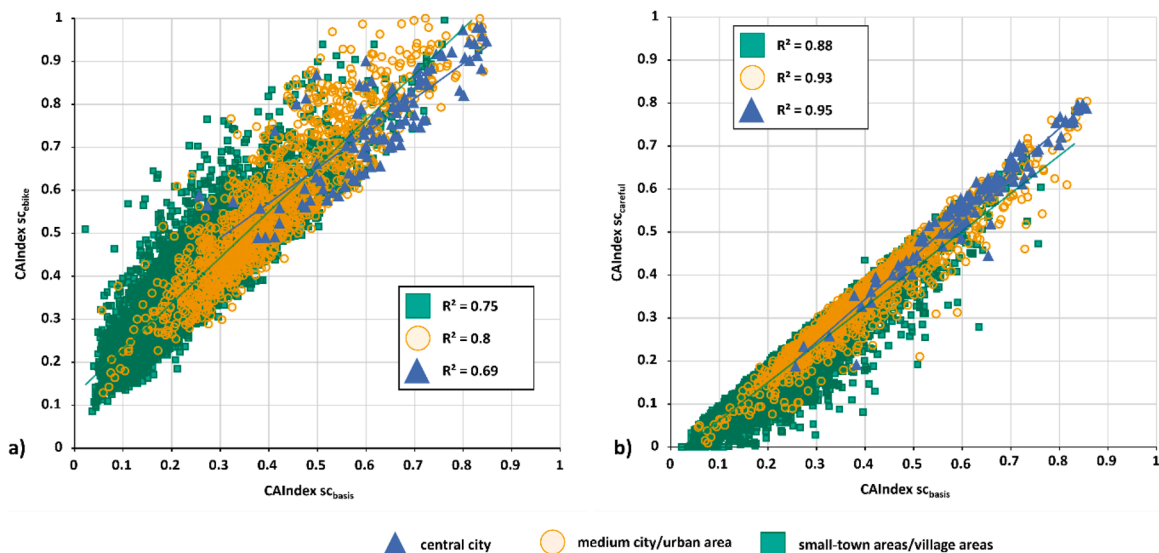


Fig. 6. Correlation between scenarios (CAIndex_{municip.}) for the three rural *RegioStaR* 7 categories.

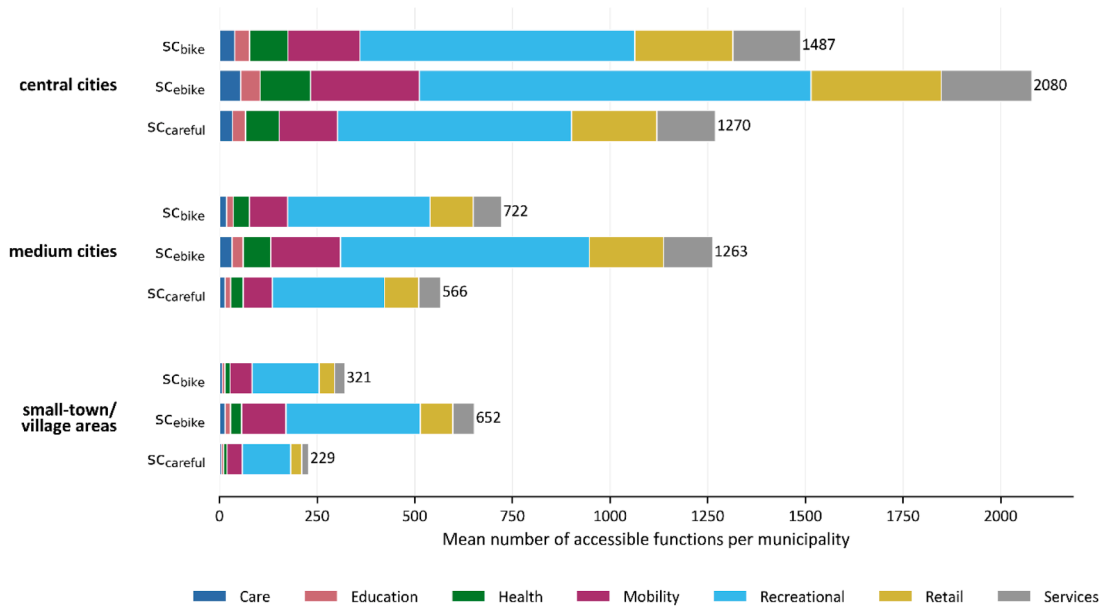


Fig. 7. Mean number of accessible functions by RegioStaR 7 categories and scenario.

Table 5

Location Quotients (LQs) of accessible functions across spatial contexts and scenarios.

Functions	SCbasis			SCebike			SCcareful		
	central cities	medium cities	small-town/village	central cities	medium cities	small-town/village	central cities	medium cities	small-town/village
Care	1.06	1.01	0.92	1.06	1.01	0.92	1.04	1.02	0.92
Retail	1.19	1.06	0.84	1.13	1.04	0.86	1.22	1.07	0.76
Education	1.09	1.02	0.92	1.10	1.02	0.94	1.09	1.01	0.87
Health	1.17	1.00	0.74	1.14	1.00	0.75	1.23	0.99	0.65
Mobility	1.24	0.83	0.42	1.09	0.82	0.50	1.40	0.74	0.00
Recreational	0.87	0.96	1.09	0.89	0.97	1.08	0.84	0.96	1.12
Services	1.24	1.03	0.86	1.20	1.02	0.87	1.27	1.02	0.81

Table 6

Spearman rank correlation coefficients (ρ) between functional LQs and the composite accessibility index (CAIndex_{municip}) by spatial context and cycling scenario.

Functions	SCbasis			SCebike			SCcareful		
	central cities	medium cities	small-town/village	central cities	medium cities	small-town/village	central cities	medium cities	small-town/village
Care	0.119	0.111***	0.154***	0.204*	0.213***	0.187***	0.049	0.027	0.134***
Retail	-0.204*	-0.036	0.230***	-0.321***	-0.039	0.241***	-0.126	0.004	0.268***
Education	0.310**	0.431***	0.504***	0.238*	0.412***	0.567***	0.378***	0.483***	0.584***
Health	0.296**	0.422***	0.325***	0.282*	0.414***	0.387***	0.278**	0.478***	0.421***
Mobility	-0.216*	-0.599***	-0.643***	-0.061	-0.581***	-0.689***	-0.253**	-0.602***	-0.712***
Recreational	-0.016	0.435***	0.600***	-0.199*	0.375***	0.631***	0.120	0.454***	0.654***
Services	0.191*	0.503***	0.544***	0.206*	0.556***	0.595***	0.211	0.506	0.604

* $p < .05$.

** $p < .01$.

*** $p < .001$.

underrepresented, with LQs of 0.74, 0.75, and 0.65 for all scenarios, respectively. Recreational functions show the opposite pattern: their LQ increases from below 1 in *central cities* (0.87–0.89) to above 1 in *small-town/village areas* (1.08–1.12). Recreational opportunities therefore

constitute a relatively larger component of the accessibility profile in *small-town/village areas*, while functions such as health and mobility are comparatively less represented.

Overall, differences between spatial contexts are more pronounced

than those between cycling scenarios. Although individual LQs vary between the scenarios, the spatial pattern remains largely stable: *central cities* show a relative concentration of retail, health, mobility, and services, whereas *small-town/village areas* are characterized by a relative shift towards recreational functions and an underrepresentation of most other functions.

The results of the Spearman's rank correlations (Table 6) further reveal that the relationship between overall accessibility and functional composition varies across spatial contexts. In *medium cities* and particularly *small-town/village areas*, higher overall accessibility is associated with a greater relative representation of retail, health, mobility, and services. In *small-town/village areas*, these relationships are strongest for retail ($\rho=0.600\text{--}0.654$), services ($\rho=0.544\text{--}0.604$), and health ($\rho=0.504\text{--}0.584$). Recreational functions show the opposite pattern, with strong negative correlations in *medium cities* ($\rho=-0.581$ to -0.602) and 77 ($\rho=-0.643$ to -0.712). This indicates that recreational functions become relatively more prominent where overall accessibility is lower. In *central cities*, relationships are generally weaker and less consistent across cycling scenarios. Overall, the results suggest that the association between accessibility level and functional composition is most pronounced in *small-town/village areas* and broadly consistent across cycling scenarios.

6. Discussion: the promises of the e-bike, and the perils of insufficient cycling infrastructure

The discussion below interprets these results in the context of cycling-based and proximity-centered accessibility, the potential of e-bikes, and barriers due to safety needs.

6.1. Rural Germany: few amenities, but which cater to different needs

Our analysis of proximity-centered accessibility by bicycle in rural areas emphasizes the heterogeneity of this spatial context and the need for fine-grained, nuanced, and place-based analyses. One important finding of this study is the consistent urban-rural gradient within rural areas across all indicators and scenarios. Nonetheless, our model also revealed that while the density of amenities is low in the most peripheral spatial contexts, with 88% of municipalities exhibiting low accessibility scores for density, their diversity remains relatively high – more than half of municipalities achieve very high values for diversity. On the one hand, this finding indicates that although the choice between providers catering to one function (e.g., different food shops) and redundancy is limited. On the other hand, this finding emphasizes that in Germany, in many peripheral spatial contexts, amenities catering to numerous functions of everyday life are available within a 30-min cycling radius. This indicates that accessibility challenges in rural areas of Germany are primarily driven by spatial dispersion and a limited number of destinations rather than a lack of functional diversity, which nuances Moseley's "rural challenge" (Moseley, 1979). Nevertheless, it should be mentioned that a single well-equipped grocery store nearby could be more important than having many of them.

Notwithstanding the high diversity of amenities, when we combined both indicators into the composite accessibility index, the resulting accessibility levels were low to moderate for all municipalities and spatial contexts. Therein, our composite accessibility index emphasizes the importance of both the quantity and variety of amenities and highlights that high diversity alone is insufficient to compensate for a lack of reachable destinations. The finding indicates a key structural constraint: even if transport performance improves, accessibility gains may remain limited where land-use patterns are sparse and mono-

functional. This pattern confirms existing literature on spatial accessibility inequality but extends it by demonstrating how these disparities manifest specifically within a bicycle-based accessibility framework (Delbosc & Currie, 2011; Milbourne & Kitchen, 2014; Pot et al., 2020).

Differences in spatial contexts concern not only the number and variety of reachable destinations but also their functional composition. First, recreational amenities constitute a substantial share of accessible destinations across all regions. While this demonstrates the importance of recreational opportunities within cycling accessibility, their high share does not necessarily indicate a general accessibility advantage. Second, the location quotient analysis shows that recreational functions are relatively overrepresented in *small-town/village areas*, while functions such as health, retail, mobility, and services are comparatively underrepresented. In *central cities*, the opposite pattern is more apparent, resulting in a stronger representation of functions related to everyday needs and services. Third, the correlation analysis reinforces this pattern, particularly in *small-town/village areas*: municipalities with higher overall accessibility tend to show a stronger relative representation of retail, health, mobility, and services, whereas recreational functions become relatively more prominent as overall accessibility decreases. Thus, the prominence of recreational functions in areas with lower accessibility appears to reflect a more functionally concentrated profile. Important to note is, that this does not imply lower absolute accessibility to recreational destinations, but rather a shift in their relative importance within the overall functional profile.

6.2. The e-bike as a range extender, to leverage rural areas' existing potential

The findings highlight the substantial potential of e-bikes to improve accessibility in rural contexts across all municipalities and spatial contexts. However, the strong correlation between our baseline scenario for bicycles without assistance, and the scenario with an e-bike, indicates that whereas e-bikes improve overall accessibility, they do not fundamentally change existing spatial disparities but rather amplify the potential of currently available amenities. The same applies to the distribution of the accessible functions with relatively small differences between $SC_{\text{ebike}} - SC_{\text{basis}}$. Across the scenarios the general functional pattern remains stable. In this sense, e-bikes act as "range extender", helping to overcome challenges related to distance and topography, particularly in peripheral regions with a low density of amenities (Kohlrautz & Kuhnimhof, 2024; Plazier et al., 2023; Rérat, 2021). Around urban areas, the results reveal pronounced spillover effects, where accessibility gains are highest due to greater service availability, indicating that e-bikes effectively connect peri-urban areas to urban services. At the same time, the observed variability points to considerable small-scale spatial heterogeneity, underscoring the importance of local factors such as settlement structure, spatial distribution of opportunities, and network connectivity in shaping accessibility outcomes. Overall, our study shows that in regions where public transport is infrequent or unavailable, the e-bike as a flexible, cost-effective means of transport harbors great promise to overcome accessibility gaps where conventional cycling reaches its limits. However, e-bikes cannot overcome structural deficiencies.

6.3. How car-centric mobility infrastructure creates accessibility gaps

Next to the importance of density and diversity in configuring accessibility, our findings also emphasized the importance of design, meaning the configuration of transport infrastructure. In the scenario where only dedicated cycling infrastructure or side roads were used,

accessibility decreased across all indicators by around 20% compared to the baseline scenario. Accessibility losses were more pronounced in more peripheral areas, where network connectivity is limited. In extreme cases, particularly in small-town and village contexts, accessibility fell to zero. The $sc_{careful}$ further emphasizes the structural differences between settlement types, in contrast to the comparison between $sc_{ebike} - sc_{basis}$, where the distribution of functions remained similar. Especially in *small-town/village areas* the results show pronounced deficits in health ($LQ = 0.65$), retail (0.76), and mobility-related functions ($LQ = 0.00$). This finding reveals a key issue in rural transport planning: reliance on high-speed road networks for car-based mobility creates unsafe conditions for active travel, which particularly affects vulnerable groups (elderly, children) and inexperienced cyclists (Stülpnagel & Rintelen, 2024). The results lead to the conclusion that in many rural contexts the only viable routes to services are main roads that are perceived as unsafe and create an accessibility barrier for careful cyclists (e.g. vulnerable groups such as children or the elderly). For those groups, the inadequacy of the transport infrastructure in rural contexts, where in many cases, amenities are only accessible over the high-speed road network, severely limits their possibilities to access fundamental amenities. The observed spatial and functional variability concerning the losses in accessibility when a careful cycling behavior is adopted further highlights that infrastructure quality and network continuity are decisive factors in shaping accessibility outcomes.

6.4. Methodological implications and limitations

The methodological approach offers several advantages for assessing accessibility in heterogeneous rural contexts. A key strength is the combination of fine-grained, grid-based analysis with network-based routing. Rather than relying on Euclidean distances or fixed catchment areas, routing accounts for the transport network through which destinations can actually be reached. This is particularly relevant in rural areas, where spatial proximity does not necessarily translate into accessibility due to fragmented networks, physical barriers, or differences in infrastructure (Knap et al., 2023; Nielsen & Skov-Petersen, 2018). The high accessibility values observed around metropolitan areas further demonstrate the strength of the grid-based approach and the use of OSM data, as accessibility is initially calculated independently of municipal boundaries and therefore captures all reachable destinations, including those located in neighboring municipalities (Gehrke et al., 2020; Gu et al., 2018; Iacono et al., 2010; Lieske et al., 2025; Pajares et al., 2021). Nevertheless, it should be mentioned that OSM data, which is user-generated, may underreport amenities in rural areas, where, in comparison to urban areas, fewer users maintain them. Calculating accessibility at the grid-cell level further captures spatial variation that would be obscured by calculations directly at the municipality level (Gehrke et al., 2020; Lieske et al., 2025). Rural municipalities often combine relatively well-served centres with peripheral or dispersed settlements. However, subsequent aggregation inevitably reduces this detail, meaning that similar municipal scores may represent different internal accessibility patterns. Future applications could therefore additionally consider within-municipality variation.

The cumulative opportunity method (isochrones) provides a static measure of potential accessibility but does not distinguish between shorter and longer travel times within the selected cutoff value (30 min in our case) (Bertolini et al., 2005; Geurs & van Wee, 2004). Future work could explore sensitivity to different time thresholds, because acceptable travel distances are subjective and vary by trip purpose and individual capability. Another limitation of the cumulative opportunity method is that it does not account for the quality of the service at the destination

nor for individual preferences. For example, “schools” is treated as a single category, but a primary school is not a substitute for a secondary school. Therefore, selection and classification of facilities influence the results. While the use of multiple categories allows for a nuanced representation of diversity, alternative classifications or integration of weighting schemes could lead to different outcomes and, to strengthen such analyses, could be determined, for example, on the basis of surveys or travel-behavior data. Also, the exclusion of jobs from the analysis, while common in x-minute city studies, remains a significant limitation, especially since rural residents often have longer commutes (Milbourne & Kitchen, 2014; Pot & Piesch, 2024). Meaning also that their daily accessibility extends beyond their residential surroundings and is also shaped by opportunities near the workplace and along commuting routes, particularly through trip-chaining. As work remains a primary driver of rural car dependency, future research could extend the residential accessibility approach by incorporating workplace locations and commute-based accessibility. For example, by considering destinations reachable with limited detours along home-work routes, thereby capturing trip-chaining and the broader daily activity spaces of rural residents.

6.5. Policy and planning implications, limitations and future research

Peripheral regions are characterized by diverse household structures, higher vulnerabilities, and distinct mobility needs that standardized transport planning approaches often fail to address (Arias-Molinares et al., 2025). Implementing proximity-centered planning concepts therefore requires context-sensitive strategies that combine density, functional diversity, and high-quality infrastructure with flexible mobility solutions. Spatial heterogeneity highlights differing priorities: in urban areas, improving safety and network connectivity is key, while in rural contexts, accessibility is not solely determined by infrastructure but also by the number and spatial distribution of services, underlining the need to integrate land-use and transport planning and maintain decentralized service provision. Nonetheless, our findings emphasize that also in rural areas, the design dimension is essential. Without continuous and safe cycling infrastructure, many amenities remain effectively inaccessible in car-oriented environments.

While achieving balanced proximity-centered planning approaches like a 30-min territory in peripheral areas is possible yet challenging, policies promoting e-bike adoption, such as subsidies, infrastructure improvements, and integration with public transport, harbor great potential. Given the high impact of e-bikes, targeted subsidies for e-bike ownership and charging infrastructure could be more effective than traditional public transport subsidies in areas where bus frequencies are inherently low. Furthermore, in the German context, such policies would accelerate a trend that already manifests in people’s mobility habits: German rural populations have comparatively high e-bike ownership rates and also use them (BMV, 2025). Also evaluated discrepancies adequate infrastructure to protect high-value bicycle vehicles suggests that cycling policy must look beyond dense urban cores and prioritize the retrofitting of secure parking solutions in suburban and rural contexts where e-bikes serve as critical car alternatives (Lachapelle et al., 2026). However, in line with x-minute city and proximity-oriented concepts in general (Silva et al., 2023), planning should not focus solely on improving mobility conditions and options but also on implementing, at least, basic local services in the most peripheral areas.

Nevertheless, it should be noted that our analysis is based on potential accessibility rather than realized accessibility and relies on assumptions regarding travel speeds and mobility habits. Such top-down accessibility analyses serve as a valuable diagnostic tool for identifying

spatial patterns, disparities, and context-specific accessibility configurations across different settlement types. Spatial accessibility indicators alone cannot fully capture accessibility needs or planning priorities, as actual travel behavior may differ due to factors such as individual preferences, affordability, perceived barriers, or weather conditions (Pot et al., 2026). As for future research, they should therefore be supplemented by behavioral evidence and measures of perceived accessibility in to assess whether spatially available opportunities translate into sufficient accessibility for different population groups.

Furthermore, our analysis does not account for socio-demographic differences or barriers to bicycle use as well as for diverse physical capabilities (e.g., older people or families with children) (Pot et al., 2023a; Vecchio & Martens, 2021). In recent reconceptualizations of accessibility, spatial, economic, social, and personal factors shaping individuals' ability to access opportunities have been emphasized (Handy, 2020; Lucas et al., 2019). These dimensions, often overlooked in the x-minute city literature, are particularly important for addressing the needs of vulnerable groups (Calafiore et al., 2022; Guzman et al., 2024; Staricco, 2022). Future research should integrate needs and perceptions of different social groups, such as the elderly or children, to provide a more comprehensive understanding of accessibility (Geurs & van Wee, 2004). By incorporating socio-demographic data, it also becomes possible to assess differences in bicycle-based accessibility across social groups (e.g., low-income) and to highlight socio-spatial disparities regarding the 30-min territory.

7. Conclusion

The accessibility analysis presented in this study represents a first step towards a context-sensitive place-based accessibility planning (Pot et al., 2026) by providing a spatial assessment to better understand accessibility conditions in different spatial contexts, particularly rural areas. We proposed a conceptual framework for analyzing proximity-centered principles in regions beyond the urban core.

We used the 30-min territory as an analytical framework for defining the time threshold and choosing amenities. By extending the temporal threshold, the study accounts for lower densities and spatial dispersion of rural areas. Grounded in a contextualized application of the 3Ds (density, diversity, and design), we operationalized accessibility through both the number of reachable amenities and their diversity, thereby bridging the gap between urban-centric concepts and peripheral realities. We accounted for the design aspect by integrating infrastructure characteristics and preferences regarding safety needs in our routing model.

For measuring bicycle-based accessibility in this framework, we established a composite accessibility index (CAIndex) by combining density and diversity through a geometric mean. The model integrates realistic routing conditions, including surface, slope, and infrastructure, which also reflects the design aspect. Therefore, the CAIndex is a significant methodological contribution and proved to be a useful measure to compare the accessibility of different municipalities and spatial contexts within rural areas. We analyzed rural Germany as a study case. Our results reveal substantial spatial heterogeneity, a clear urban-rural gradient, and a density-diversity paradox.

When implementing different scenarios, namely travelling by e-bike, and avoiding main roads, we found that those significantly alter accessibility scores. Using an e-bike compared to a conventional bicycle increases accessibility by over 50% on average, particularly in remote areas; however, though extending the range, e-bikes cannot overcome structural deficiencies related to the spatial and functional distribution of services. In contrast, careful cycling significantly reduces accessibility, especially in rural contexts. This finding emphasizes the perils of

the car-centric transport planning in rural areas, which renders territories inaccessible by other means of transport, thereby creating accessibility gaps affecting those without reliable car access, especially vulnerable groups like the elderly and children.

Through the comprehensive analysis of proximity-centered accessibility in rural Germany, our study provides the first empirical assessment of cycling-based accessibility within an x-minute city framework beyond the urban core. By operationalizing the 3Ds (density, diversity, design), it bridges the gap between urban-centric planning concepts and the spatial realities of peripheral regions, demonstrating that the 30-min territory is a viable extension of proximity-centered planning. Our findings reveal that rural areas hold significant potential for such approaches, particularly through the range extensions offered by e-bikes, but that this potential is currently constrained by low service density and insufficient infrastructure. Rather than prescribing universal planning targets, the results provide situational knowledge about the opportunities and constraints of individual places, thereby informing locally appropriate planning strategies. Consequently, a paradigm shift is required, reframing rural mobility not merely as a car-dependent challenge but as an opportunity for inclusive, active, and proximity-oriented living. This study thus provides a scalable, data-driven framework to support planners and researchers in identifying and addressing accessibility gaps across diverse spatial contexts.

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work, the authors used generative AI tools (GPT-5 and earlier versions, DeepL) exclusively to improve readability and language quality. No content, analysis, interpretations or conclusions were generated by the AI. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

CRediT authorship contribution statement

Caro Huth: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Franziska X. Meinherz:** Writing – review & editing, Supervision, Resources, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This research was supported by funding from the German Federal Ministry of Transport through the endowed Chair of “Cycling in Intermodal Transport Networks” at the Technical University of Applied Sciences Wildau.

We would like to thank Simon Metzler, who developed the tool that allowed the ideas to take shape, Christian Rudolph, who provided the resources for this analysis, and Laura Walder for her assistance during the early stages of this study.

The authors are grateful to four anonymous reviewers, whose detailed and constructive comments helped us substantially improve the article. The study also benefited from valuable feedback and discussions at several conferences.

Appendix A

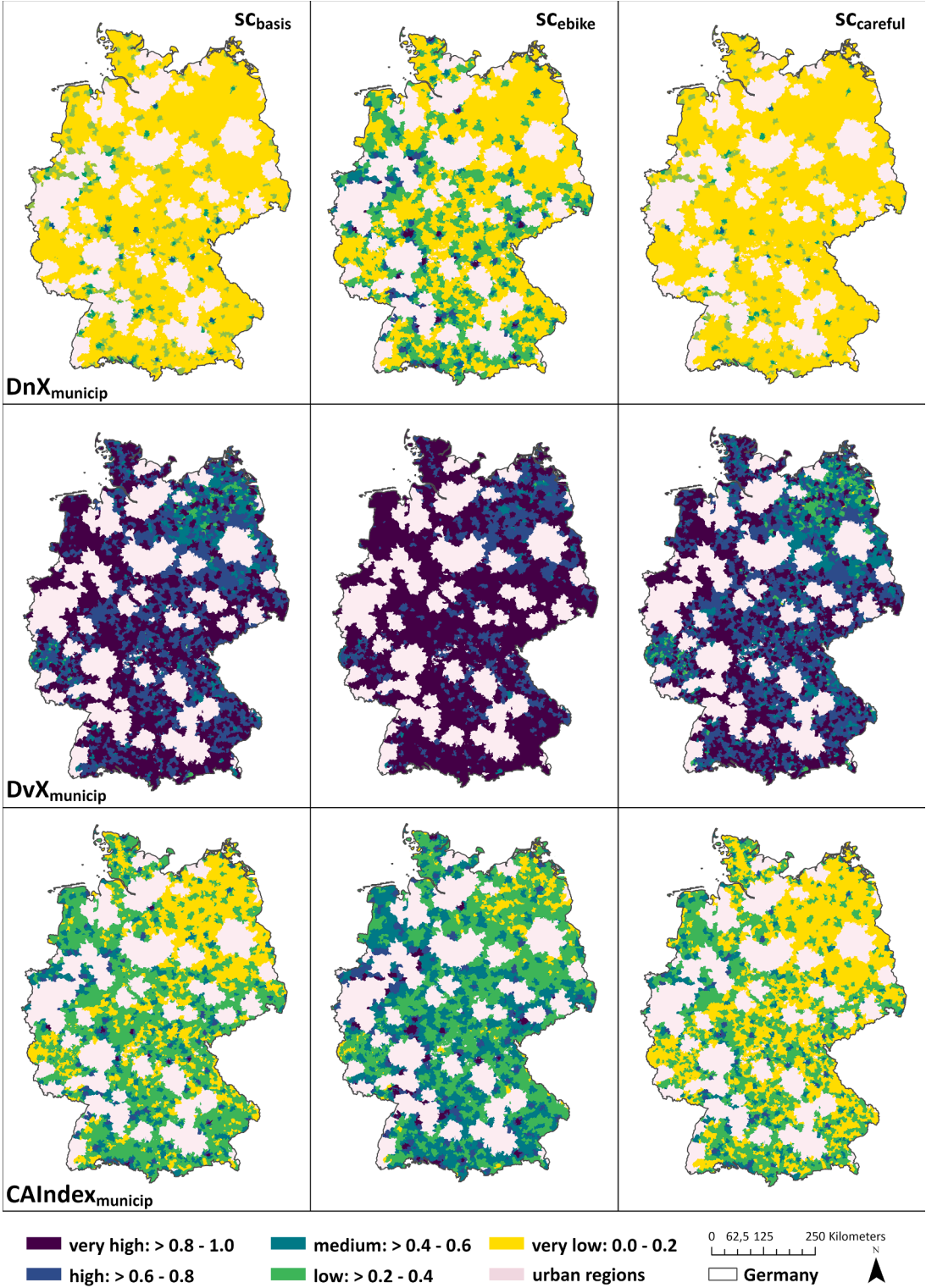


Fig. A.1. Results for DnX_{municip}, DvX_{municip} and CAIndex_{municip} (in this order) for SC_{basis}, (left) SC_{ebike} (middle) and SC_{careful} (right).

References

- Alawadi, K., Anabtawi, R., & Alshehhi, G. (2025). The Minute City: between theory and practicality in suburban landscapes. *Sustainability: Science, Practice and Policy*, 21(1), Article 2444007. <https://doi.org/10.1080/15487733.2024.2444007>
- Allam, Z., Moreno, C., Chabaud, D., & Pralong, F. (2023). Proximity-based planning and the “15-min City”: A sustainable model for the City of the future. In R. Brinkmann (Ed.), *The Palgrave Handbook of Global Sustainability* (pp. 1523–1542). Springer International Publishing. https://doi.org/10.1007/978-3-031-01949-4_178
- Arias-Molinares, D., Geurs, K. T., Grigolon, A., Ulak, B., Duran-Rodas, D., McCormick, B., Baguet, J., Van Vessel, C., Adjero, H., Dörrzapf, L., Charalampidou, G., Bobičić, O., & Esztergár-Kiss, D. (2025). Exploring the 15-Minute City concept for the urban outskirts: A systematic literature review. *European Transport Research Review*, 17(1), 50. <https://doi.org/10.1186/s12544-025-00743-8>
- Bartzokas-Tsiompras, A., & Bakogiannis, E. (2023). Quantifying and visualizing the 15-min walkable city concept across Europe: A multicriteria approach. *Journal of Maps*, 19(1), Article 2141143. <https://doi.org/10.1080/17445647.2022.2141143>
- Berg, J., & Ilström, J. (2019). The importance of public transport for mobility and everyday activities among rural residents. *Social Sciences*, 8(2), 58. <https://doi.org/10.3390/socsci8020058>
- Bertolini, L., Le Clercq, F., & Kapoen, L. (2005). Sustainable accessibility: A conceptual framework to integrate transport and land use plan-making. Two test-applications in the Netherlands and a reflection on the way forward. *Transport Policy*, 12(3), 207–220. <https://doi.org/10.1016/j.tranpol.2005.01.006>
- Birkenfeld, C., Victoriano-Habit, R., Alousi-Jones, M., Soliz, A., & El-Geneidy, A. (2023). Who is living a local lifestyle? Towards a better understanding of the 15-min-city and 30-min-city concepts from a behavioural perspective in Montréal, Canada. *Journal of Urban Mobility*, 3, Article 100048. <https://doi.org/10.1016/j.urbmob.2023.100048>
- BMV. (2025). *Mobilität in Deutschland – MID 2023 – Ergebnisbericht (p. 240)* [Studie von infas, DLR, IVT und infas 360 im Auftrag des Bundesministers für Verkehr (FE-Nr. VB600001)]. Bundesministerium für Verkehr [BMV]. www.mobilitaet-in-deutschland.de
- BMVI. (2021a). *RegioStaR: Regional Statistical Spatial Typology for Mobility and Transport Research*. Federal Ministry of Transport and Digital Infrastructure (BMVI).
- BMVI. (2021b). *RegioStaR Regionalstatistische Raumtypologie für die Mobilitäts- und Verkehrsforschung*. Bundesministerium für Verkehr, und digitale Infrastruktur [BMVI]. https://www.bmv.de/SharedDocs/DE/Anlage/G/regio-star-raumtypologie.pdf?_blob=publicationFile
- Brüchert, T., Quentin, P., & Bolte, G. (2022). The relationship between perceived built environment and cycling or e-biking for transport among older adults—a cross-sectional study. *PLOS ONE*, 17(5), Article e0267314. <https://doi.org/10.1371/journal.pone.0267314>
- Calafiore, A., Dunning, R., Nurse, A., & Singleton, A. (2022). The 20-min city: an equity analysis of Liverpool City Region. *Transportation Research Part D: Transport and Environment*, 102, Article 103111. <https://doi.org/10.1016/j.trd.2021.103111>
- Capasso Da Silva, D., King, D. A., & Lemar, S. (2019). Accessibility in practice: 20-min City as a sustainability planning goal. *Sustainability*, 12(1), 129. <https://doi.org/10.3390/su12010129>
- Carroll, P., Benevenuto, R., & Caulfield, B. (2021). Identifying hotspots of transport disadvantage and car dependency in rural Ireland. *Transport Policy*, 101, 46–56. <https://doi.org/10.1016/j.tranpol.2020.11.004>
- Castanin, U. N., & Ribeiro, P. J. G. (2021). Bikeability and emerging phenomena in cycling: exploratory analysis and review. *Sustainability*, 13(4), 2394. <https://doi.org/10.3390/su13042394>
- Cervero, R., & Kockelman, K. (1997). Travel demand and the 3Ds: density, diversity, and design. *Transportation Research Part D: Transport and Environment*, 2(3), 199–219. [https://doi.org/10.1016/S1361-9209\(97\)00009-6](https://doi.org/10.1016/S1361-9209(97)00009-6)
- Chiaradia, F., Lelo, K., Monni, S., & Tomassi, F. (2024). The 15-min City: an attempt to measure proximity to urban services in Rome. *Sustainability*, 16(21), 9432. <https://doi.org/10.3390/su16219432>
- Delbosch, A., & Currie, G. (2011). The spatial context of transport disadvantage, social exclusion and well-being. *Journal of Transport Geography*, 19(6), 1130–1137. <https://doi.org/10.1016/j.jtrangeo.2011.04.005>
- European Commission. (2025). World urbanization prospects 2025. https://regions-and-cities.ec.europa.eu/cities-portal/news-cities/world-urbanization-prospects-2025-2025-11-18_en
- Ewing, R., & Cervero, R. (2010). Travel and the built environment: A meta-analysis. *Journal of the American Planning Association*, 76(3), 265–294. <https://doi.org/10.1080/01944361003766766>
- Feng, X., Jia, N., Su, X., Adams, M. D., Deng, Y., & Ling, S. (2025). Assessing the applicability of the 15-min city: insights from a spatial accessibility perspective. *Transportation Research Part A: Policy and Practice*, 199, Article 104579. <https://doi.org/10.1016/j.tra.2025.104579>
- Ferrer-Ortiz, C., Marquet, O., Mojica, L., & Vich, G. (2022). Barcelona under the 15-min City lens: mapping the accessibility and proximity potential based on pedestrian travel times. *Smart Cities*, 5(1), 146–161. <https://doi.org/10.3390/smartcities5010010>
- Gaglione, F., Gargiulo, C., Zucaro, F., & Cottrill, C. (2022). Urban accessibility in a 15-min city: A measure in the city of Naples, Italy. *Transportation Research Procedia*, 60, 378–385. <https://doi.org/10.1016/j.trpro.2021.12.049>
- Gehrke, S. R., Akhavan, A., Furth, P. G., Wang, Q., & Reardon, T. G. (2020). A cycling-focused accessibility tool to support regional bike network connectivity. *Transportation Research Part D: Transport and Environment*, 85, Article 102388. <https://doi.org/10.1016/j.trd.2020.102388>
- Geurs, K. T., & van Wee, B. (2004). Accessibility evaluation of land-use and transport strategies: review and research directions. *Journal of Transport Geography*, 12(2), 127–140. <https://doi.org/10.1016/j.jtrangeo.2003.10.005>
- Geurs, K. T., & Van Wee, B. (2026). A five-component conceptual model of calculated and perceived accessibility: literature review and research directions. *Journal of Transport Geography*, 134, Article 104678. <https://doi.org/10.1016/j.jtrangeo.2026.104678>
- Graham, H., De Bell, S., Flemming, K., Sowden, A., White, P., & Wright, K. (2018). The experiences of everyday travel for older people in rural areas: A systematic review of UK qualitative studies. *Journal of Transport & Health*, 11, 141–152. <https://doi.org/10.1016/j.jth.2018.10.007>
- GraphHopper. (n.d.). GraphHopper Directions API (1.0.0). GraphHopper. Retrieved August 11, 2026, from <https://docs.graphhopper.com/openapi>
- GraphHopper, & P. Karussell. (n.d.). Custom Models. GitHub. Retrieved <https://github.com/graphhopper/graphhopper/blob/master/docs/core/custom-models.md>
- GraphHopper, P. (2026). GraphHopper Gets More Precise Elevation Data. March 23. GraphHopper Blog <https://www.graphhopper.com/blog/2026/03/23-more-precise-elevation-data-for-graphhopper/>
- Gray, D., Farrington, J., Shaw, J., Martin, S., & Roberts, D. (2001). Car dependence in rural Scotland: transport policy, devolution and the impact of the fuel duty escalator. *Journal of Rural Studies*, 17(1), 113–125. [https://doi.org/10.1016/S0743-0167\(00\)00035-8](https://doi.org/10.1016/S0743-0167(00)00035-8)
- Gu, P., Han, Z., Cao, Z., Chen, Y., & Jiang, Y. (2018). Using open source data to measure street walkability and bikeability in China: A case of four cities. *Transportation Research Record: Journal of the Transportation Research Board*, 2672(31), 63–75. <https://doi.org/10.1177/0361198118758652>
- Guzman, L. A., Oviedo, D., & Cantillo-Garcia, V. A. (2024). Is proximity enough? A critical analysis of a 15-min city considering individual perceptions. *Cities*, 148, Article 104882. <https://doi.org/10.1016/j.cities.2024.104882>
- Handy, S. (2020). Is accessibility an idea whose time has finally come? *Transportation Research Part D: Transport and Environment*, 83, Article 102319. <https://doi.org/10.1016/j.trd.2020.102319>
- Handy, S., & Niemeier, D. A. (1997). Measuring accessibility: an exploration of issues and alternatives. *Environment and Planning A: Economy and Space*, 29(7), 1175–1194. <https://doi.org/10.1068/a291175>
- Hosford, K., Beairisto, J., & Winters, M. (2022). Is the 15-min city within reach? Evaluating walking and cycling accessibility to grocery stores in Vancouver. *Transportation Research Interdisciplinary Perspectives*, 14, Article 100602. <https://doi.org/10.1016/j.trip.2022.100602>
- Iacono, M., Krizek, K. J., & El-Geneidy, A. (2010). Measuring non-motorized accessibility: issues, alternatives, and execution. *Journal of Transport Geography*, 18(1), 133–140. <https://doi.org/10.1016/j.jtrangeo.2009.02.002>
- Isetti, G., Ferraretto, V., Stavinoga, A. E., Gruber, M., & DellaValle, N. (2020). Is caring about the environment enough for sustainable mobility? An exploratory case study from South Tyrol (Italy). *Transportation Research Interdisciplinary Perspectives*, 6, Article 100148. <https://doi.org/10.1016/j.trip.2020.100148>
- Jafari, A., Singh, D., Gunn, L., Both, A., & Giles-Corti, B. (2025). Modelling the impact of road infrastructure on cycling moving speed. *Journal of Cycling and Micromobility Research*, 3, Article 100049. <https://doi.org/10.1016/j.jcmr.2024.100049>
- Kent, M., & Karner, A. (2019). Prioritizing low-stress and equitable bicycle networks using neighborhood-based accessibility measures. *International Journal of Sustainable Transportation*, 13(2), 100–110. <https://doi.org/10.1080/15568318.2018.1443177>
- Khavarian-Garmsir, A. R., Sharifi, A., Hajian Hossein Abadi, M., & Moradi, Z. (2023). From Garden City to 15-Min City: A historical perspective and critical assessment. *Land*, 12(2), 512. <https://doi.org/10.3390/land12020512>
- Knap, E., Ulak, M. B., Geurs, K. T., Mulders, A., & Van Der Drift, S. (2023). A composite X-minute city cycling accessibility metric and its role in assessing spatial and socioeconomic inequalities – A case study in Utrecht, the Netherlands. *Journal of Urban Mobility*, 3, Article 100043. <https://doi.org/10.1016/j.urbmob.2022.100043>
- Kohlrautz, D., & Kuhnimhof, T. (2024). E-bike ownership and usage: an analysis of Germany. *Sustainable Transport and Livability*, 1(1), Article 2336912. <https://doi.org/10.1080/29941849.2024.2336912>
- Lachapelle, U., Rérat, P., & Ravalet, E. (2026). A residential e-bicycle parking mismatch? Unpacking a neglected issue in cycling policy. *Transportation Research Part A: Policy and Practice*, 213, Article 105202. <https://doi.org/10.1016/j.tra.2026.105202>
- Levine, J., Grengs, J., & Merlin, L. A. (2019). Accessibility in social-equity evaluation. In J. Levine, J. Grengs, & L. A. Merlin (Eds.), *From Mobility to Accessibility* (pp. 101–123). Cornell University Press. <https://doi.org/10.7591/cornell/9781501716072.003.0007>
- Levine, J., Grengs, J., Shen, Q., & Shen, Q. (2012). Does accessibility require density or speed? A comparison of fast versus close in getting where you want to go in U.S. Metropolitan regions. *Journal of the American Planning Association*, 78(2), 157–172. <https://doi.org/10.1080/01944363.2012.677119>
- Lieske, S. N., Zhang, L., Leao, S. Z., Pojani, D., & Buning, R. J. (2025). Clarifying bicycling accessibility. *Journal of Transport Geography*, 129, Article 104450. <https://doi.org/10.1016/j.jtrangeo.2025.104450>
- Logan, T. M., Hobbs, M. H., Conrow, L. C., Reid, N. L., Young, R. A., & Anderson, M. J. (2022). The x-minute city: measuring the 10, 15, 20-min city and an evaluation of its use for sustainable urban design. *Cities*, 131, Article 103924. <https://doi.org/10.1016/j.cities.2022.103924>
- Lowry, M. B., Callister, D., Gresham, M., & Moore, B. (2012). Assessment of communitywide bikeability with bicycle level of service. *Transportation Research Record: Journal of the Transportation Research Board*, 2314(1), 41–48. <https://doi.org/10.3141/2314-06>

- Lu, M., & Diab, E. (2023). Understanding the determinants of x-minute city policies: A review of the North American and Australian cities' planning documents. *Journal of Urban Mobility*, 3, Article 100040. <https://doi.org/10.1016/j.urbmob.2022.100040>
- Lucas, K. (2012). Transport and social exclusion: where are we now? *Transport Policy*, 20, 105–113. <https://doi.org/10.1016/j.tranpol.2012.01.013>
- Lucas, K., Martens, K., Di Cio, F., & Dupont-Kieffer, A. (2019). In K. Lucas, & K. Martens (Eds.), *Measuring Transport Equity* (First edition). Elsevier.
- Maciejewska, M., Cubells, J., & Marquet, O. (2025). When proximity is not enough. A sociodemographic analysis of 15-min city lifestyles. *Journal of Urban Mobility*, 7, Article 100119. <https://doi.org/10.1016/j.urbmob.2025.100119>
- Mahmoudpour, A., & Shirazi, M. R. (2026). Critical debates on the 15-min city: A systematic content analysis of the literature. *Cities*, 169, Article 106576. <https://doi.org/10.1016/j.cities.2025.106576>
- Marquet, O., Anguelovski, I., Nello-Deakin, S., & Honey-Rosés, J. (2025). Decoding the 15-min City debate: conspiracies, backlash, and dissent in planning for proximity. *Journal of the American Planning Association*, 91(1), 117–125. <https://doi.org/10.1080/01944363.2024.2346596>
- McCarthy, J. (2008). Rural geography: globalizing the countryside. *Progress in Human Geography*, 32(1), 129–137. <https://doi.org/10.1177/0309132507082559>
- Megahed, G., Elshater, A., Elrefaie, M. A., & Affi, S. (2025). Chrono-urbanism and liveable urban forms: A morphological analysis of alternative x-minute city models in Rosetta City. *Cities*, 167, Article 106313. <https://doi.org/10.1016/j.cities.2025.106313>
- Meijering, L., & Weitkamp, G. (2024). 'I choose the quiet roads': everyday mobility in later life on the urban–rural continuum of the Northern Netherlands. *Journal of Transport Geography*, 114, Article 103762. <https://doi.org/10.1016/j.jtrangeo.2023.103762>
- Milbourne, P., & Kitchen, L. (2014). Rural mobilities: connecting movement and fixity in rural places. *Journal of Rural Studies*, 34, 326–336. <https://doi.org/10.1016/j.jrurstud.2014.01.004>
- Moreno, C., Allam, Z., Chabaud, D., Gall, C., & Pratlong, F. (2021). Introducing the “15-min City”: sustainability, resilience and place identity in future post-pandemic cities. *Smart Cities*, 4(1), 93–111. <https://doi.org/10.3390/smartcities4010006>
- Moreno, C., Gehl, J., & Thorne, M. (2024). *The 15-min city: A solution to saving our time and our planet*. Wiley.
- Moseley, M. J. (1979). *Accessibility: The rural challenge*. Methuen & Co Ltd.
- Mouratidis, K. (2024). Time to challenge the 15-min city: seven pitfalls for sustainability, equity, livability, and spatial analysis. *Cities*, 153, Article 105274. <https://doi.org/10.1016/j.cities.2024.105274>
- Mouratidis, K. (2026). The 15-min city revisited: A GIS approach to measuring, visualizing, and analyzing accessibility by proximity and by public transport supply. *Travel Behaviour and Society*, 42, Article 101151. <https://doi.org/10.1016/j.tbs.2025.101151>
- Murgante, B., Valluzzi, R., & Annunziata, A. (2024). Developing a 15-min city: evaluating urban quality using configurational analysis. The case study of Terni and Matera, Italy. *Applied Geography*, 162, Article 103171. <https://doi.org/10.1016/j.apgeog.2023.103171>
- Naumann, M. (2023). Mobilitätsarmut – ein Thema für die bundesdeutsche raumentwicklung? *Standort*. <https://doi.org/10.1007/s00548-023-00888-5>
- Nielsen, T. A. S., & Skov-Petersen, H. (2018). Bikeability – Urban structures supporting cycling. Effects of local, urban and regional scale urban form factors on cycling from home and workplace locations in Denmark. *Journal of Transport Geography*, 69, 36–44. <https://doi.org/10.1016/j.jtrangeo.2018.04.015>
- Noworól, A., Kopyciński, P., Halać, P., Salamon, J., & Hotuj, A. (2022). The 15-min City—The geographical proximity of services in Krakow. *Sustainability*, 14(12), 7103. <https://doi.org/10.3390/su14127103>
- Nutley, S. (2003). Indicators of transport and accessibility problems in rural Australia. *Journal of Transport Geography*, 11(1), 55–71. [https://doi.org/10.1016/s0966-6923\(02\)00052-2](https://doi.org/10.1016/s0966-6923(02)00052-2)
- Olivari, B., Cipriano, P., Napolitano, M., & Giovannini, L. (2023). Are Italian cities already 15-min? Presenting the Next Proximity Index: A novel and scalable way to measure it, based on open data. *Journal of Urban Mobility*, 4, Article 100057. <https://doi.org/10.1016/j.urbmob.2023.100057>
- Ospina, J. P., Duque, J. C., Botero-Fernández, V., & Brussel, M. (2022). Understanding the effect of sociodemographic, natural and built environment factors on cycling accessibility. *Journal of Transport Geography*, 102, Article 103386. <https://doi.org/10.1016/j.jtrangeo.2022.103386>
- Pajares, E., Büttner, B., Jehle, U., Nichols, A., & Wulforst, G. (2021). Accessibility by proximity: addressing the lack of interactive accessibility instruments for active mobility. *Journal of Transport Geography*, 93, 1–16. <https://doi.org/10.1016/j.jtrangeo.2021.103080>
- Papadopoulos, E., Sdokopoulos, A., & Politis, I. (2023). Measuring compliance with the 15-min city concept: State-of-the-art, major components and further requirements. *Sustainable Cities and Society*, 99, Article 104875. <https://doi.org/10.1016/j.scs.2023.104875>
- Philips, I., Cairns, S., De Séjournet, A., Anable, J., Azzouz, L., Behrendt, F., Brand, C., Cass, N., Darking, M., Glachant, C., Heinen, E., Marks, N., & Nelson, T. (2025). E-cargo bikes as a personal transport mode in the UK: insights from surveys and suburban trials. *Journal of Cycling and Micromobility Research*, 6, Article 100093. <https://doi.org/10.1016/j.jcmr.2025.100093>
- Pira, S., & Hansson, L. (2025). Analyzing equity in transport planning using the 15-min city approach. A case study of Oslo city, Norway. *Transportation Research Part A: Policy and Practice*, 200, Article 104633. <https://doi.org/10.1016/j.tra.2025.104633>
- Plazier, P., Weitkamp, G., & Van Den Berg, A. (2023). E-bikes in rural areas: current and potential users in the Netherlands. *Transportation*, 50(4), 1449–1470. <https://doi.org/10.1007/s11116-022-10283-y>
- Plazier, P., Weitkamp, G., & van den Berg, A. E. (2017). Cycling was never so easy!™ an analysis of e-bike commuters' motives, travel behaviour and experiences using GPS-tracking and interviews. *Journal of Transport Geography*, 65, 25–34. <https://doi.org/10.1016/j.jtrangeo.2017.09.017>
- Poltimäe, H., Rehema, M., Raun, J., & Poom, A. (2022). In search of sustainable and inclusive mobility solutions for rural areas. *European Transport Research Review*, 14(1). <https://doi.org/10.1186/s12544-022-00536-3>
- Poorthuis, A., & Zook, M. (2023). Moving the 15-min city beyond the urban core: the role of accessibility and public transport in the Netherlands. *Journal of Transport Geography*, 110, Article 103629. <https://doi.org/10.1016/j.jtrangeo.2023.103629>
- Porter, A. K., Kohl, H. W., Pérez, A., Reininger, B., Pettee Gabriel, K., & Salvo, D. (2020). Bikeability: assessing the objectively measured environment in relation to recreation and transportation bicycling. *Environment and Behavior*, 52(8), 861–894. <https://doi.org/10.1177/0013916518825289>
- Pot, F. J., Heinen, E., & Tillema, T. (2024). Sufficient access? Activity participation, perceived accessibility and transport-related social exclusion across spatial contexts. *Transportation*. <https://doi.org/10.1007/s11116-024-10470-z>
- Pot, F. J., Koster, S., & Tillema, T. (2023a). Perceived accessibility and residential self-selection in the Netherlands. *Journal of Transport Geography*, 108, Article 103555. <https://doi.org/10.1016/j.jtrangeo.2023.103555>
- Pot, F. J., Koster, S., & Tillema, T. (2023b). Perceived accessibility in Dutch rural areas: bridging the gap with accessibility based on spatial data. *Transport Policy*, 138, 170–184. <https://doi.org/10.1016/j.tranpol.2023.04.014>
- Pot, F. J., Koster, S., Tillema, T., & Jorritsma, P. (2020). Linking experienced barriers during daily travel and transport poverty in peripheral rural areas: the case of Zeeland, the Netherlands. *European Journal of Transport and Infrastructure Research*, 20(3). <https://doi.org/10.18757/ejtr.2020.20.3.4076>
- Pot, F. J., & Piesch, L. (2024). How far is too far? Urban versus rural acceptable travel distances. *Transportation Research Part D: Transport and Environment*, 137, Article 104474. <https://doi.org/10.1016/j.trd.2024.104474>
- Pot, F. J., Rauws, W., Ramezani, S., Kajosaari, A. U., & Humer, A. (2026). Principles for place-based accessibility planning. *Journal of Transport Geography*, 132, Article 104588. <https://doi.org/10.1016/j.jtrangeo.2026.104588>
- Pozoukidou, G., & Chatziyiannaki, Z. (2021). 15-Min City: decomposing the new urban planning utopia. *Sustainability*, 13(2), 928. <https://doi.org/10.3390/su13020928>
- Reinfeld, N., Weiß, C., Pillat, J., Knese, D., & Forkert, S. (2023). ModelRad: die Modellierung des radverkehrs—Einflussfaktoren und parametrisierung (Bundesministerium für Verkehr und digitale Infrastruktur, Ed.). https://www.fra-nkfurt-university.de/fileadmin/standard/Hochschule/Fachbereich_1/FFin/Neue_Mobilitaet/Veroeffentlichungen/2023/ModelRad_Abschlussbericht_final.pdf
- Rérat, P. (2021). The rise of the e-bike: towards an extension of the practice of cycling? *Mobilities*, 16(3), 423–439. <https://doi.org/10.1080/17450101.2021.1897236>
- Saghapour, T., Moridpour, S., & Thompson, R. G. (2017). Measuring cycling accessibility in metropolitan areas. *International Journal of Sustainable Transportation*, 11(5), 381–394. <https://doi.org/10.1080/15568318.2016.1262927>
- Sepelhi, B., & Sharifi, A. (2025). X-minute cities as a growing notion of sustainable urbanism: A literature review. *Cities*, 161, Article 105902. <https://doi.org/10.1016/j.cities.2025.105902>
- Siedentop, S., & Gerten, C. (2023). ILS-IMPULSE (03/2023) Von der „15-Minuten-Stadt“ zum „30-Minuten-Land“—Die Reduzierung der Autoabhängigkeit muss auch abseits der Städte ein Anliegen sein. 4. [doi:10.58122/vpzz-1g58](https://doi.org/10.58122/vpzz-1g58)
- Silva, C., & Altieri, M. (2022). Is regional accessibility undermining local accessibility? *Journal of Transport Geography*, 101, Article 103336. <https://doi.org/10.1016/j.jtrangeo.2022.103336>
- Silva, C., Büttner, B., Seisenberger, S., & Rauli, A. (2023). Proximity-centred accessibility—A conceptual debate involving experts and planning practitioners. *Journal of Urban Mobility*, 4, 1–13. <https://doi.org/10.1016/j.urbmob.2023.100060>
- Soukhov, A., Pereira, R. H. M., Higgins, C. D., & Páez, A. (2025). A family of accessibility measures derived from spatial interaction principles. *PLOS One*, 20(11), Article e0335951. <https://doi.org/10.1371/journal.pone.0335951>
- Staricco, L. (2022). 15-, 10- or 5-min city? A focus on accessibility to services in Turin, Italy. *Journal of Urban Mobility*, 2, Article 100030. <https://doi.org/10.1016/j.urbmob.2022.100030>
- Staricco, L., & Brovarone, E. V. (2022). Livable neighborhoods for sustainable cities: insights from Barcelona. *Transportation Research Procedia*, 60, 354–361. <https://doi.org/10.1016/j.trpro.2021.12.046>
- Stülpnagel, R., & Rintelen, H. (2024). A matter of space and perspective – Cyclists', car drivers', and pedestrians' assumptions about subjective safety in shared traffic situations. *Transportation Research Part A: Policy and Practice*, 179, Article 103941. <https://doi.org/10.1016/j.tra.2023.103941>
- Teixeira, J. F., Silva, C., Seisenberger, S., Büttner, B., McCormick, B., Papa, E., & Cao, M. (2024). Classifying 15-min Cities: A review of worldwide practices. *Transportation Research Part A: Policy and Practice*, 189, Article 104234. <https://doi.org/10.1016/j.tra.2024.104234>
- Urry, J. (2004). The 'system' of automobility. *Theory, Culture & Society*, 21(4–5), 25–39. <https://doi.org/10.1177/0263276404046059>
- Vale, D., & Lopes, A. S. (2023). Accessibility inequality across Europe: A comparison of 15-min pedestrian accessibility in cities with 100,000 or more inhabitants. *Npj Urban Sustainability*, 3(1), 55. <https://doi.org/10.1038/s42949-023-00133-w>
- Vale, D. S., Saraiva, M., & Pereira, M. (2015). Active accessibility: A review of operational measures of walking and cycling accessibility. *Journal of Transport and Land Use*. <https://doi.org/10.5198/jtlu.2015.593>
- Vecchio, G., & Martens, K. (2021). Accessibility and the capabilities approach: A review of the literature and proposal for conceptual advancements. *Transport Reviews*, 41(6), 833–854. <https://doi.org/10.1080/01441647.2021.1931551>

- Velaga, N. R., Beecroft, M., Nelson, J. D., Corsar, D., & Edwards, P. (2012). Transport poverty meets the digital divide: accessibility and connectivity in rural communities. *Journal of Transport Geography*, 21, 102–112. <https://doi.org/10.1016/j.jtrangeo.2011.12.005>
- Wang, H., Tsoi, K. H., & Loo, B. P. Y. (2025). An assessment framework for 15-min Cities: progress worldwide and the impact of urban form. *Transportation Research Part A: Policy and Practice*, 199, Article 104583. <https://doi.org/10.1016/j.tra.2025.104583>
- Wang, J., Kwan, M.-P., Liu, D., Liu, Y., & Wang, Y. (2025). 15-min city beyond the urban core: lessons from the urban-suburban disparity in PCR accessibility within the X-minute framework. *Transportation Research Part A: Policy and Practice*, 198, Article 104546. <https://doi.org/10.1016/j.tra.2025.104546>
- Wang, W., Espeland, S., Barajas, J. M., & Rowangould, D. (2023). Rural-nonrural divide in car access and unmet travel need in the United States. *Transportation*. <https://doi.org/10.1007/s11116-023-10429-6>
- Weng, M., Ding, N., Li, J., Jin, X., Xiao, H., He, Z., & Su, S. (2019). The 15-min walkable neighborhoods: measurement, social inequalities and implications for building healthy communities in urban China. *Journal of Transport & Health*, 13, 259–273. <https://doi.org/10.1016/j.jth.2019.05.005>
- Wiersma, J., Bertolini, L., & Straatemeier, T. (2017). Adapting spatial conditions to reduce car dependency in mid-sized 'post growth' European city regions: the case of South Limburg, Netherlands. *Transport Policy*, 55, 62–69. <https://doi.org/10.1016/j.tranpol.2016.12.004>
- Wilcox, R. R. (2003). *Applying Contemporary Statistical Techniques*. Elsevier. <https://doi.org/10.1016/B978-0-12-751541-0.X5021-4>
- Williams, T., Bonsma-Fisher, M., Nelson, T., Whitehurst, D. G. T., & Winters, M. (2024). Cycling towards complete communities: estimating access to destinations via low traffic stress cycling. *Transportation Research Interdisciplinary Perspectives*, 26, Article 101179. <https://doi.org/10.1016/j.trip.2024.101179>
- Winters, M., Brauer, M., Setton, E. M., & Teschke, K. (2013). Mapping bikeability: A spatial tool to support sustainable travel. *Environment and Planning B: Planning and Design*, 40(5), 865–883. <https://doi.org/10.1068/b38185>
- Zhang, S., Zhen, F., Kong, Y., Lobsang, T., & Zou, S. (2023). Towards a 15-min city: A network-based evaluation framework. *Environment and Planning B: Urban Analytics and City Science*, 50(2), 500–514. <https://doi.org/10.1177/23998083221118570>
- Zhou, C., & Chen, J. (2024). Can cycling compensate the distributional inequity of public service facilities? Evidence from Shenzhen, China. *Socio-Economic Planning Sciences*, 95, Article 101999. <https://doi.org/10.1016/j.seps.2024.101999>