Horizontal and vertical dimensions of pedestrian accessibility to public transport stops in Liberec and Zlín

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ABSTRACT This study examines pedestrian accessibility to public transport stops through a two-dimensional framework integrating horizontal (network-based walking distance) and vertical (elevation difference) components. The analysis deliberately isolates the walking access stage and does not assess service frequency, travel time, or network performance. The framework is applied to Liberec and Zlín, two medium-sized Czech cities with hilly terrain and contrasting urban structures. For built-up areas, network walking distances and elevation differences to the nearest stop were calculated and combined into a synthetic horizontal–vertical accessibility typology. Results show that both cities have generally favourable proximity to stops, but terrain substantially modifies accessibility patterns, especially in Liberec. The combined framework identifies short-but-steep and far-but-flat areas that remain hidden when distance and elevation are evaluated separately. The study offers a transparent, transferable approach for assessing pedestrian stop accessibility in topographically complex urban environments and provides a spatially explicit basis for further accessibility analysis.

KEY WORDS pedestrian accessibility – public transport stops – network distance – elevation difference – terrain

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1. Introduction

Accessibility is a central concept in transport geography and urban studies, commonly used to assess how effectively transport systems connect people to activities, services, and opportunities. In the context of public transport, accessibility is most often evaluated through indicators related to service performance, such as frequency, travel time, or network connectivity. While these approaches provide important insights into system efficiency, they tend to overlook a more fundamental layer of everyday mobility: the physical effort required to reach public transport infrastructure on foot.

Pedestrian access to public transport stops constitutes a necessary precondition for any subsequent use of public transport services. Even in cities with dense networks and frequent services, unfavourable walking conditions may limit the practical usability of public transport, particularly for populations with reduced mobility or in environments shaped by complex urban morphology and terrain. Despite this, pedestrian stop accessibility is frequently treated as a secondary or implicit component of broader accessibility assessments, rather than as an analytical dimension in its own right.

A growing body of research has highlighted the conceptual ambiguity surrounding the term "public transport accessibility", which is used to describe analytically distinct phenomena ranging from spatial proximity to infrastructure to service quality and social inclusion. This diversity reflects the coexistence of time-based usability simulations, service-oriented evaluations, and normative perspectives concerned with transport disadvantage and transport justice (Bernard 2022, Lucas 2012, Martens 2016). Without clear conceptual separation, these perspectives risk being conflated, complicating interpretation and limiting comparability across studies. In response, this paper adopts a deliberately narrow and explicit focus on pedestrian accessibility to public transport stops, defined as the conditions under which individuals can reach the nearest stop on foot. The term pedestrian accessibility is used throughout the paper to distinguish walking access to stops from barrier-free accessibility, which refers to infrastructure-related or user-specific constraints such as platform design, boarding conditions, or reduced mobility.

Pedestrian accessibility is shaped by multiple spatial factors, of which horizontal distance and terrain-related effort are particularly important. Network-based walking distance captures the spatial configuration of streets and paths, while elevation differences influence walking effort and comfort, especially in hilly urban environments. Analysing these dimensions separately, however, may obscure locations where physical constraints accumulate. Their combined assessment therefore offers a more comprehensive understanding of pedestrian access conditions than one-dimensional distance-based approaches.

Medium-sized cities provide a particularly relevant context for examining pedestrian stop accessibility. Compared to large metropolitan areas, they often exhibit lower redundancy in public transport networks, greater sensitivity to urban form, and a stronger influence of local topography on everyday mobility. In Central Europe, many such cities are characterised by hilly terrain, historically layered urban structures, and compact but spatially heterogeneous development patterns. In such contexts, terrain represents a structural constraint for urban mobility systems, influencing public transport network design and operation in hilly cities (Papa, Santo Zarnik, Vukašinović 2022). These characteristics make them suitable case studies for investigating how distance and terrain related constraints interact in shaping pedestrian accessibility. At this spatial scale, lower network redundancy and stronger sensitivity to urban form make stop accessibility particularly dependent on spatial configuration and local conditions (Korczyński 2019).

This study applies a two-dimensional analytical framework integrating horizontal and vertical components of pedestrian accessibility to two medium-sized Czech cities with hilly terrain: Liberec and Zlín. A key advantage of the proposed approach is that it relies exclusively on publicly available spatial data, enabling transparent, reproducible, and easily transferable analyses without the need for proprietary datasets. This lowers barriers to comparative research and facilitates application in diverse urban contexts.

The paper addresses the following research questions:

1. How do horizontal and vertical dimensions of pedestrian accessibility to public transport stops differ between Liberec and Zlín?
2. To what extent does terrain influence spatial patterns of pedestrian stop accessibility within built-up areas?
3. Does the combined assessment of horizontal and vertical accessibility reveal areas of cumulative physical constraints that remain hidden in one-dimensional analyses?
4. To what extent is the proposed analytical framework transferable to other medium-sized cities with complex terrain?

By explicitly separating and recombining horizontal and vertical dimensions of pedestrian accessibility, the study aims to contribute both empirically and methodologically to ongoing debates on accessibility measurement in transport geography.

2. Approaches to public transport accessibility and performance

When evaluating spatial units in terms of public transport provision, accessibility represents one of the most widely applied analytical concepts. Existing research labelled as public transport accessibility, however, encompasses a broad spectrum of approaches ranging from infrastructure proximity and spatial coverage to service performance, temporal availability, and system efficiency. Accessibility-based evaluations therefore provide an effective framework for examining the spatial distribution of transport infrastructure and services, as well as their relationship to population distribution and urban form, but they also differ substantially in their analytical focus and underlying assumptions.

One of the most frequently used data standards in public transport research is the General Transit Feed Specification (GTFS), which enables the standardised representation of public transport schedules and spatial information on stops, routes, and trips (GTFS 2024). The static GTFS feed consists of mandatory files describing agencies, stops, routes, trips, stop times, and service calendars, complemented by optional files addressing transfers, fares, or service exceptions. GTFS datasets are typically published by transport operators and are increasingly available as open data. In combination with other spatial datasets – such as OpenStreetMap, census data, and national geodatabases – GTFS provides a robust basis for analysing public transport accessibility and efficiency in urban and regional settings.

GTFS-based analyses have been applied across a wide range of thematic contexts. Farber, Morang, Widener (2014) used GTFS data to model the temporal variability of transit-based accessibility to essential services, while Tao, Rohde, Corcoran (2014) examined the impacts of newly introduced transport services. Luo et al. (2019) focused on travel cost and impedance modelling, and Andrei, Luca (2021) analysed operational efficiency during peak periods. Interactive visualisation tools and decision-support systems based on GTFS data have also been developed, including PubtraVis (Prommaharaj et al. 2020).

An alternative to GTFS consists of timetable datasets published directly by individual transport operators. These datasets, however, often lack standardisation and interoperability, which complicates their direct analytical use. In such cases, web scraping and data transformation techniques may be employed to convert heterogeneous timetable formats into structured datasets suitable for spatial analysis.

From a methodological perspective, research on public transport accessibility and efficiency can be grouped into several broad thematic areas according to the primary analytical focus and the parameters under consideration. Beyond distance-based accessibility, public transport systems have also been examined using complex network analysis to capture structural properties such as connectivity and node importance (Háznagy et al. 2015).

The first thematic area addresses infrastructure-based and spatial accessibility. Studies in this category typically evaluate walking distance to public transport stops, the configuration of street networks, and the spatial relationship between population distribution and transport infrastructure. A frequently applied approach in this context is the Public Transport Accessibility Level (PTAL) method, which combines proximity to stops with service frequency and network connectivity. Although PTAL extends beyond pure pedestrian stop accessibility by incorporating service frequency and network characteristics, it illustrates how proximity to stops is typically embedded within broader composite indices highlighting the need to analytically isolate the pedestrian access component. Tiran, Mladenović, Koblar (2015) applied PTAL to assess public transport accessibility in Ljubljana, while Alamri et al. (2023) evaluated transport networks, service periodicity, and street typologies by transport mode. Kaszczyszyn, Sypion-Dutkowska (2019) analysed the proportion of street length within different accessibility intervals. These studies increasingly rely on GIS-based spatial indicators derived from openly available data to evaluate stop coverage, network configuration, and the spatial adequacy of public transport provision (Alamri et al. 2023; Andrei, Luca 2021; Roşu, Blageanu 2015). In Central Europe, Puławska, Wiesław (2011), and Puławska (2014) examined infrastructure accessibility in relation to service quality and tariff conditions.

Related approaches assess ideal and actual stop accessibility using buffer-based coverage indices and distance thresholds (Foda, Osman 2010). These methods provide a straightforward representation of spatial coverage but often neglect network configuration and terrain-related constraints.

A growing body of research emphasises the importance of terrain and hypsometric conditions in shaping public transport accessibility. Elevation differences and slope affect the physical effort required to reach public transport stops and influence walking propensity, particularly in hilly urban environments. Djurhuus et al. (2014), Kaszczyszyn, Sypion-Dutkowska (2019), and Nandan et al. (2022) demonstrate that uneven terrain can significantly reduce effective accessibility even in areas with dense stop coverage. Rissel et al. (2012) highlight that increased walking effort associated with uphill gradients may limit the ability of public transport users to meet physical activity recommendations. Empirical evidence further suggests that walking to stops in hilly areas may discourage public transport use altogether (El-Geneidy et al. 2013, Su et al. 2023).

Integrating hypsometric analysis into accessibility studies enables a more nuanced understanding of spatial barriers. Ford et al. (2015) and Su et al. (2023) demonstrate that combining walking distance with elevation change provides a more realistic representation of access conditions than distance-based indicators alone. GIS-based analyses further support the identification of spatial disparities by mapping elevation-related constraints in relation to public transport networks (Hino et al. 2013).

Another strand of research focuses on user perception and perceived accessibility, recognising that objective measures do not fully capture how individuals experience access to public transport. Lättman, Friman, Olsson (2016) show that perceived accessibility is often lower in areas characterised by poor pedestrian permeability and pronounced elevation differences. Survey-based approaches incorporating subjective evaluations of walking effort and comfort have been used to complement spatial analyses (Djurhuus et al. 2014).

The second thematic area addresses temporal accessibility and service frequency. Studies in this category examine travel time, waiting time, and service periodicity, often with a focus on peak periods. Goliszek, Połom (2016) combined accessibility measures with service frequency. Goch et al. (2018) examined the temporal accessibility of Warsaw's city centre. Comparative analyses of public and private transport performance across different times of day were conducted by Goliszek (2019, 2021). In the Czech context, Fitzová, Matulová, Tomeš (2018) and Fitzová, Matulová (2020) evaluated temporal accessibility alongside transport efficiency indicators. Chowdhury, Ceder, Velty (2014) combined quantitative and qualitative indicators, including transfer smoothness and information availability. Such approaches demonstrate that accessibility patterns vary substantially over time, whether assessed through large-scale national monitoring frameworks or through analyses of daily mobility rhythms captured by timetable and intelligent transport system data (Horák et al. 2014; Mulíček, Osman, Seidenglanz 2015; Kraft, Blažek, Marada 2022).

The third thematic area encompasses synthetic efficiency indices and comprehensive evaluations typically aggregating spatial coverage, service intensity, and network characteristics into a single compensatory score, often combining GTFS data with population statistics or gravity and centrality-based formulations (Sha Al Mamun, Lownes 2011; Kaeoruean et al. 2020; Yang et al. 2019). Differences between supply and demand have been examined using composite indicators by Kaeoruean et al. (2020) and Żochowska et al. (2022). Roşu, Blageanu (2015) developed a composite stop efficiency index incorporating functionality, utilisation, connectivity, and population catchment. Korczyński (2019) evaluated peripheral towns using indicators such as the number of lines, population within catchment areas, and service frequency. Other approaches integrate geographical, environmental, and operational factors within comprehensive assessment frameworks (Corazza, Favaretto 2019).

Recent research increasingly relies on GIS-based analyses of large urban and regional units and their comparison across different spatial contexts. In addition to conventional network-based approaches, Voronoi diagram methods are increasingly applied as an alternative spatial allocation technique, assigning each location to the nearest public transport stop based on defined proximity rules (Wang et al. 2014). While GTFS-based datasets and timetable-derived indicators form the backbone of many contemporary public transport accessibility and performance studies, they primarily capture service availability and temporal characteristics of transport systems. As such, they are not directly suited for analysing the walking pre-boarding stage of public transport use, which is the focus of the present study.

Based on these approaches, the present study adopts a two-dimensional framework of pedestrian accessibility that explicitly distinguishes between horizontal (distance-based) and vertical (terrain-related) components.

3. Methodology

3.1. Study areas

The analysis was conducted for two medium-sized Czech cities with pronounced terrain variability: Liberec and Zlín. Both cities function as regional centres and operate integrated public transport systems, yet they differ substantially in urban morphology and topographic context.

Liberec is situated in a mountainous environment in northern Czechia. The city's built-up area extends across steep slopes and valley floors, with an altitude range from approximately 301 m to 1,010 m above sea level, resulting in an overall elevation amplitude of nearly 710 m within the wider study area. This pronounced topographic variability strongly influences pedestrian movement and access conditions.

Zlín is located in eastern Czechia and is structured primarily along a central valley corridor with adjacent hillside development. The altitude of the study area ranges from approximately 184 m to 541 m above sea level, corresponding to an elevation amplitude of about 360 m, which is substantially lower than in Liberec but still significant in relation to everyday pedestrian mobility.

The spatial extent and location of both study areas are presented in Figure 1. As public transport systems in both cities operate beyond municipal boundaries, stops belonging to the integrated regional systems were included irrespective of administrative limits. To minimise boundary effects in network-based calculations, a 1 km buffer beyond the administrative boundaries of each city was applied to all spatial layers except population data, which were retained strictly within municipal boundaries.

3.2. Data sources

The analysis is based exclusively on open and reproducible data sources, ensuring transparency and methodological transferability. The pedestrian street network was derived from OpenStreetMap (OSM 2024), which provides detailed spatial information on urban transport infrastructure and was used solely as a spatial input for network-based calculations.

Public transport stop locations were obtained from official datasets provided by the relevant local and regional transport authorities operating within the

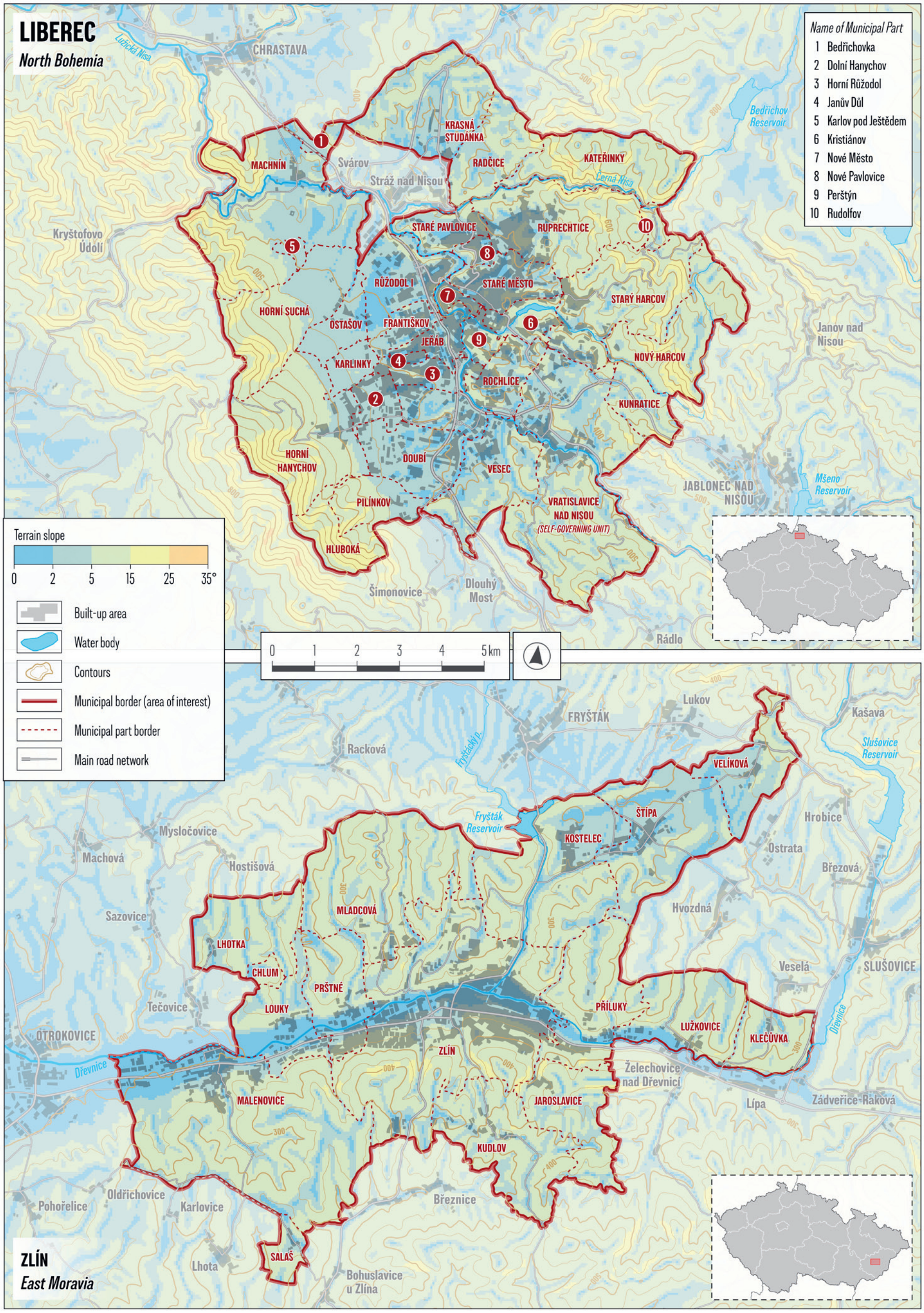

Fig. 1 – Location, delimitation, land-cover profile, and topographic context of the studied cities of Liberec and Zlín. Source: Author's own processing based on a combination of publicly available data (see Data sources).

integrated transport systems of Liberec and Zlín (DPMLJ 2024, DSZO 2024, IDOL 2024, IDZK 2024).

Terrain characteristics were represented using a digital elevation model from the Copernicus programme (OpenTopography 2024), which enables the derivation of elevation differences relevant for pedestrian accessibility analysis.

Population data at the building level, derived from address-point data with information on the number of residents based on the 2021 Population and Housing Census (CZSO 2024), were used to contextualise accessibility patterns within built-up areas and to ensure that the analysis focuses on spatially relevant residential environments rather than sparsely populated land. For analytical purposes, built-up areas were delineated using the Urban Atlas land-cover classification (Urban Atlas Land-Copernicus 2022), which was applied strictly as a land-cover mask to distinguish urbanised from non-urban areas.

3.3. Horizontal accessibility: network-based walking distance

Horizontal accessibility was operationalised as the shortest walking distance along the pedestrian network from any location to the nearest public transport stop. Network-based distance measures were employed to reflect actual pedestrian routes and spatial barriers (Foda, Osman 2010; El-Geneidy et al. 2013). Network-based modelling is therefore preferred over simple Euclidean buffers when the objective is to represent physically realistic pedestrian access conditions (Kraft 2016). Stop catchment areas were spatially generalised using Voronoi (Thiessen) polygons, where each polygon represents the area for which a given stop is the nearest according to the selected proximity rule (Wang et al. 2014).

For analytical clarity and inter-city comparability, horizontal accessibility was classified into three categories, where shorter network distance indicates better (higher-quality) accessibility and longer distance indicates worse accessibility:

- High horizontal accessibility (best): ≤400 m: (short walking distance; stop is easily reachable on foot)
- Medium horizontal accessibility: 401–800 m (moderate walking distance; accessibility is acceptable but may reduce convenience)
- Low horizontal accessibility (worst): >800 m (long walking distance; stop reachability is relatively poor).

These breakpoints correspond to walking-distance ranges frequently reported in empirical studies of pedestrian access to public transport and are used here as descriptive analytical classes rather than strict behavioural thresholds (El-Geneidy et al. 2013; Kaszczyszyn, Sypion-Dutkowska 2019). The same classification was applied in both cities to ensure comparability.

3.4. Vertical accessibility: elevation difference along pedestrian routes

In this study, the term "vertical accessibility" is used as a shorthand for terrain-related walking effort, operationalised through cumulative elevation difference along pedestrian routes rather than as an independent accessibility concept. Vertical accessibility was defined as the cumulative elevation difference between a given location and the nearest public transport stop, calculated along the pedestrian network. Elevation values were derived from the digital elevation model and assigned to network segments to compute route-based elevation change (Ford et al. 2015).

Previous research indicates that increasing elevation gain and slope reduce walking propensity and increase perceived effort, particularly in hilly urban environments (Djurhuus et al. 2014, Hino et al. 2013, Rissel et al. 2012, Su et al. 2023). Accordingly, vertical accessibility was included as a separate analytical dimension, where smaller elevation difference indicates better (higher-quality) accessibility and larger elevation difference indicates worse accessibility. Empirical evidence further shows that even moderate slope can reduce walking activity, justifying the treatment of elevation-related effort as a separate accessibility dimension (Meeder, Aebi, Weidmann 2017).

For interpretative purposes, vertical accessibility was grouped into three categories representing increasing terrain-related effort:
- High vertical accessibility (best): ≤10 m (minimal elevation change; low physical effort barrier)
- Medium vertical accessibility: 11–40 m (moderate elevation change; increased physical effort likely)
- Low vertical accessibility (worst): >40 m (substantial elevation change; strong terrain-related barrier).

These classes constitute an analytical classification designed to provide an interpretable three-level scale of terrain-related effort and to enable consistent cross-city comparison within the subsequent 3 × 3 synthetic typology. They do not represent universal physiological thresholds; rather, they support transparent comparative interpretation.

3.5. Synthetic classification of pedestrian accessibility

To capture cumulative pedestrian accessibility conditions, the three horizontal and three vertical categories were combined into a two-dimensional synthetic classification. Each spatial unit was assigned to one of nine categories representing all possible combinations:

1. High horizontal – High vertical (best overall pedestrian accessibility: short walk and minimal elevation change)
2. High horizontal – Medium vertical
3. High horizontal – Low vertical (short walk, but strong terrain barrier)
4. Medium horizontal – High vertical
5. Medium horizontal – Medium vertical
6. Medium horizontal – Low vertical
7. Low horizontal – High vertical (long walk, but minimal terrain barrier)
8. Low horizontal – Medium vertical
9. Low horizontal – Low vertical (worst overall pedestrian accessibility: long walk and strong terrain barrier).

This cross-classification preserves the analytical distinction between distance-related and terrain-related constraints and allows the identification of areas where limitations in both dimensions coincide, without collapsing them into a single compensatory score.

4. Results

4.1. Horizontal accessibility

Horizontal accessibility within the built-up areas of Liberec and Zlín is dominated by locations classified in the High horizontal accessibility category, defined by a network walking distance of up to 400 m from the nearest public transport stop.

In Liberec, areas with High horizontal accessibility cover 60.4% of the total built-up area. These areas form spatially extensive and largely continuous zones concentrated within the compact urban core and along the main axes of residential development. The Medium horizontal accessibility category (401–800 m) accounts for 29.0% of the built-up area and is typically arranged in transitional belts surrounding the High-accessibility zones. Areas classified as Low horizontal accessibility (>800 m) represent 10.6% of the built-up area and occur primarily as spatially fragmented patches located at the margins of the urbanised area.

In Zlín, the dominance of High horizontal accessibility is even more pronounced. Areas within this category cover 70.6% of the built-up area and form highly continuous spatial patterns reflecting the linear structure of the city and the dense alignment of public transport stops along its main development corridors. The Medium category represents 22.7% of the built-up area and is mainly associated with secondary residential areas adjacent to the primary urban structure. Low horizontal accessibility is limited to 6.8% of the built-up area and appears predominantly as small, isolated patches situated at the outer edges of the built-up area.

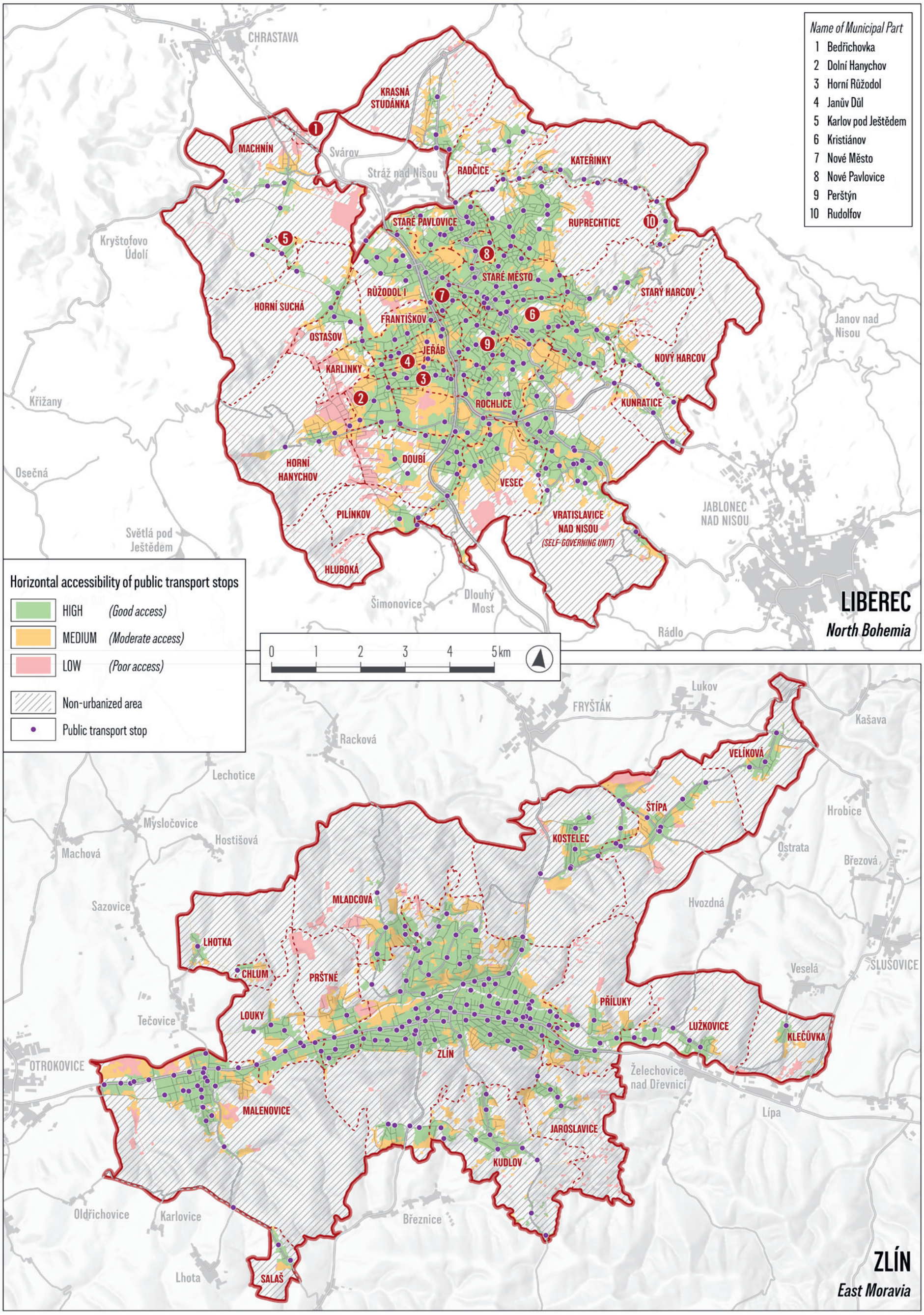

Fig. 2 – Horizontal (network-based) accessibility of public transport stops for urbanised areas of Liberec and Zlín in 2024. Source: Author's own processing based on a combination of publicly available data (see Data sources).

A comparison of both cities indicates that while High horizontal accessibility prevails in both cases, Liberec exhibits a more heterogeneous spatial pattern with a higher proportion of Medium and Low categories. In contrast, Zlín shows a stronger spatial continuity of High-accessibility areas within its built-up area. Beyond the general distribution of horizontal accessibility categories, Figure 2 reveals distinct transition zones between areas of high and medium accessibility, particularly at the interface between compact urban cores and more fragmented residential structures. In both cities, areas with High horizontal accessibility form relatively continuous zones in central parts of the built-up area, where stop density and pedestrian network connectivity are highest. These zones typically extend along main urban corridors and around central transport nodes.

In contrast, Medium horizontal accessibility often appears in spatially fragmented belts surrounding highly accessible cores. These belts represent transitional areas where walking distances remain moderate but the spatial continuity of high accessibility begins to weaken. Low horizontal accessibility is predominantly located at the edges of built-up areas and in morphologically fragmented zones, where stop spacing increases and pedestrian routes become less direct. In Liberec, these low-accessibility areas tend to form spatially dispersed clusters, whereas in Zlín they are more frequently arranged in elongated peripheral strips following the linear structure of the city.

4.2. Vertical accessibility

Vertical accessibility, expressed as cumulative elevation difference along pedestrian routes to the nearest public transport stop, displays a distinct but internally consistent spatial structure in both cities.

In Liberec, areas classified as High vertical accessibility (≤10 m elevation difference) account for 55.7% of the built-up area. These areas are predominantly located in morphologically flatter parts of the city and form relatively continuous zones within the urban fabric. The Medium vertical accessibility category (11–40 m) covers 39.2% of the built-up area and is widely distributed across the city, reflecting the prevalence of moderate slopes within residential areas. The Low vertical accessibility category (>40 m) represents 5.0% of the built-up area and is spatially concentrated in locations characterised by pronounced terrain variation, forming compact clusters rather than dispersed patches.

In Zlín, High vertical accessibility covers 58.1% of the built-up area and similarly forms extensive zones associated with flatter sections of the urban area. Medium vertical accessibility accounts for 35.9% of the built-up area and is spatially widespread, while Low vertical accessibility represents 6.0% of the built-up area. Areas within the Low category are concentrated in topographically

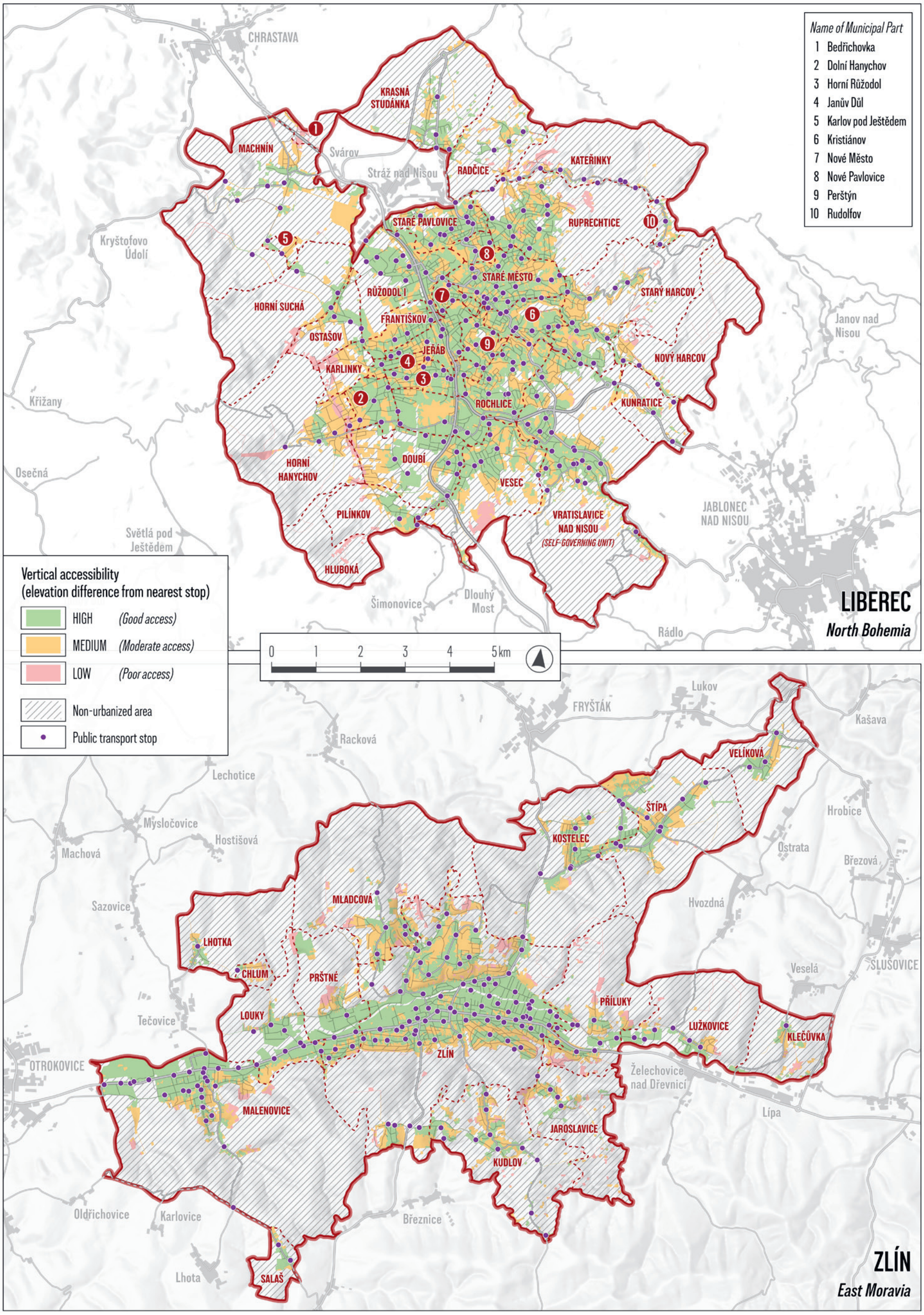

Fig. 3 – Vertical accessibility of public transport stops for urbanised areas of Liberec and Zlín in 2024. Source: Author's own processing based on a combination of publicly available data (see Data sources).

more demanding locations, where elevation differences between residential areas and public transport stops are substantial.

In both cities, the Medium vertical accessibility category constitutes a significant proportion of the built-up area, indicating that moderate terrain-related effort is a common characteristic of pedestrian access to public transport stops. Areas with Low vertical accessibility remain limited in spatial extent but are clearly identifiable as compact terrain-related clusters. The spatial configuration of vertical accessibility categories shown in Figure 3 exhibits a higher degree of internal heterogeneity than horizontal accessibility. High vertical accessibility is largely concentrated in valley floors and flatter sections of the built-up area, forming spatially continuous zones with minimal elevation change. These areas are particularly evident in Zlín, where low-relief corridors create extended zones of favourable vertical accessibility.

Medium vertical accessibility functions primarily as a transition category, occurring along slopes connecting valley floors with elevated residential areas. These zones often appear as fragmented or ribbon-like patterns rather than compact areas, reflecting gradual changes in terrain rather than abrupt breaks. Low vertical accessibility forms spatially coherent clusters in steeper hillside areas, especially in Liberec, where pronounced elevation differences generate large contiguous zones of terrain-related constraint. In Zlín, low vertical accessibility is more spatially limited and appears in smaller, discontinuous patches embedded within otherwise moderately accessible areas.

4.3. Synthetic accessibility

Synthetic accessibility integrates horizontal and vertical accessibility into a 3 × 3 classification, capturing cumulative pedestrian accessibility conditions across the built-up areas of Liberec and Zlín.

In Liberec, the largest share of the built-up area is occupied by combinations characterised by High or Medium horizontal accessibility combined with High or Medium vertical accessibility. These categories form spatially extensive and interconnected zones within the central parts of the city and along its main residential corridors. Combinations that include Low horizontal accessibility, Low vertical accessibility, or both are spatially limited and occur mainly at the periphery of the built-up area or in locations affected by pronounced terrain constraints.

In Zlín, favourable synthetic accessibility combinations are even more spatially dominant. Areas combining High horizontal and High vertical accessibility form large, continuous units structuring the core of the built-up area. Categories involving Medium accessibility levels are primarily located in transitional zones, while combinations including Low horizontal or Low vertical accessibility are

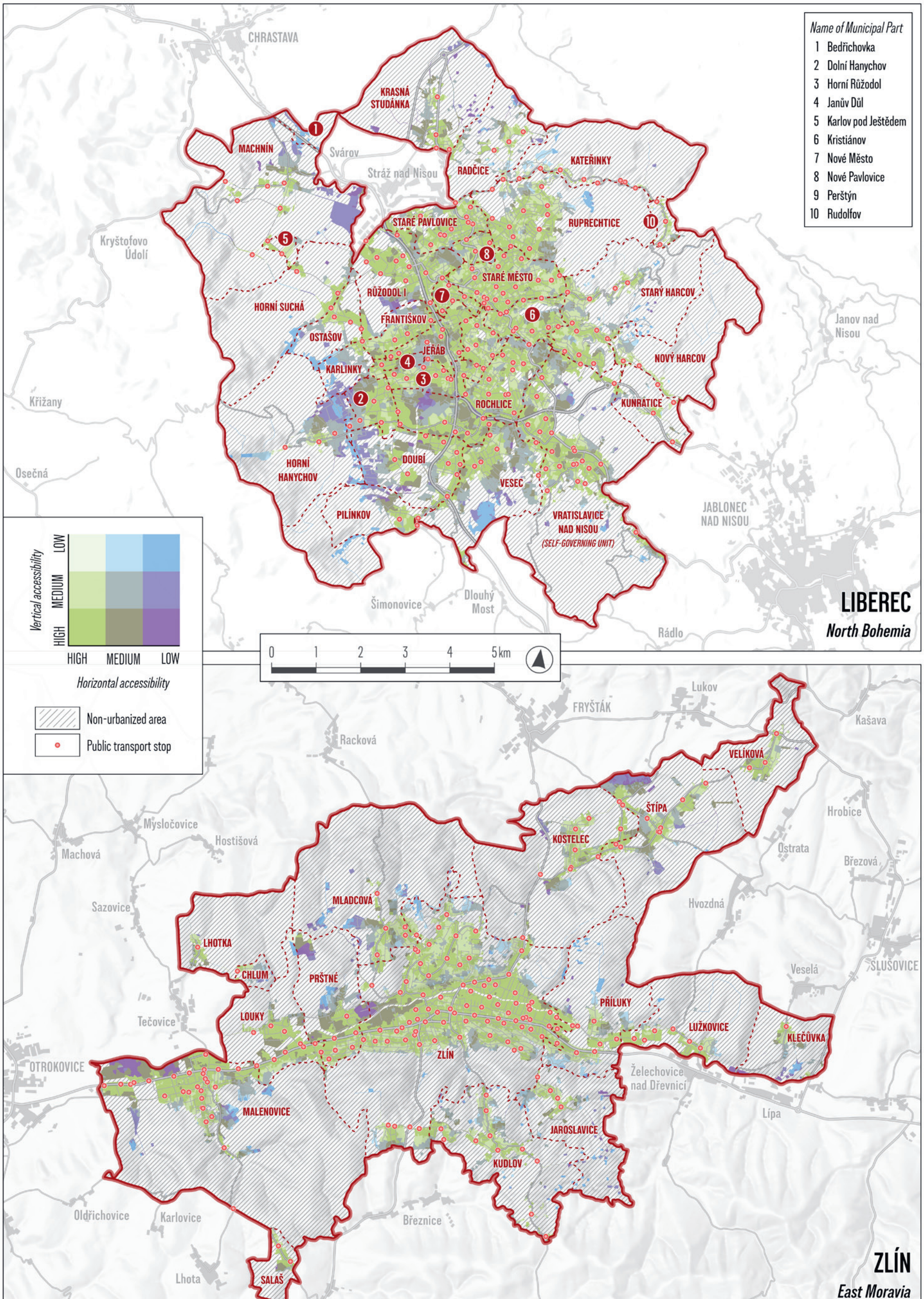

Fig. 4 – Synthetic accessibility of public transport stops for urbanised areas of Liberec and Zlín in 2024. Source: Author's own processing based on a combination of publicly available data (see Data sources).

restricted to small, fragmented patches situated at the edges of the urbanised area.

Across both cities, the synthetic accessibility classification reveals a clear spatial differentiation between areas where pedestrian access to public transport stops is constrained by distance, terrain, or both, and areas where such constraints are limited. While the overall structure of synthetic accessibility is similar in Liberec and Zlín, differences in spatial continuity and configuration reflect contrasts in urban form and topographic setting. The synthetic horizontal–vertical accessibility map presented in Figure 4 provides a comprehensive overview of cumulative pedestrian accessibility conditions by combining distance-related and terrain-related dimensions. The resulting 3 × 3 typology highlights pronounced differences not only between the two cities but also within their built-up areas.

Areas characterised by High horizontal – High vertical accessibility represent locations with both short walking distances and minimal elevation change. These areas form spatially continuous cores within the built-up area in both cities, although their extent differs markedly. In Zlín, high–high accessibility zones are more spatially coherent and elongated along the central valley axis, whereas in Liberec they are more fragmented and interspersed with zones affected by terrain-related constraints.

At the opposite end of the spectrum, Low horizontal – Low vertical accessibility identifies locations where long walking distances coincide with substantial elevation differences. These areas are spatially concentrated in peripheral and topographically complex sections of the built-up area. In Liberec, low–low accessibility zones form relatively extensive and contiguous clusters, reflecting the combined influence of dispersed development and steep terrain. In Zlín, such areas are less extensive and appear primarily as isolated pockets rather than large continuous zones.

Between these two extremes, a substantial share of the built-up area is characterised by intermediate combinations of horizontal and vertical accessibility. Among these, combinations involving High horizontal – Medium vertical accessibility are particularly prominent. These zones indicate areas where stops are spatially close but access involves moderate elevation change. In Liberec, such combinations are widespread along sloping residential neighbourhoods adjacent to central areas. In Zlín, they appear mainly along hillside development bordering the valley floor.

Combinations involving Medium horizontal – High vertical accessibility are also present, especially in flatter peripheral zones where walking distances are moderate but terrain-related barriers are limited. Conversely, Medium horizontal – Low vertical and Low horizontal – Medium vertical combinations represent areas where either distance or terrain begins to dominate accessibility conditions, often resulting in fragmented spatial patterns. These categories tend to form transitional zones rather than compact areas, linking highly accessible cores with areas of cumulative constraint.

Overall, the synthetic classification reveals that uniformly favourable or unfavourable conditions represent only a portion of the built-up area. A significant share is instead characterised by mixed accessibility conditions, underscoring the importance of analysing horizontal and vertical dimensions jointly rather than in isolation.

4.4. Intermediate combinations and cumulative accessibility patterns

Beyond areas characterised by uniformly favourable or unfavourable conditions, the synthetic accessibility map reveals extensive zones defined by intermediate combinations of horizontal and vertical accessibility, which together account for a substantial share of the built-up areas in both cities (Fig. 4).

In Liberec, large areas combine High horizontal accessibility with Medium vertical accessibility, indicating locations where public transport stops are spatially close but pedestrian access involves moderate elevation differences. These zones form coherent spatial units, particularly in residential neighbourhoods situated on sloping terrain adjacent to the urban core. In contrast, areas combining Medium horizontal accessibility with High vertical accessibility are primarily located in flatter peripheral parts of the built-up area, where stop density is lower but terrain-related constraints are limited.

Zones characterised by Low accessibility in both dimensions form spatially coherent clusters in parts of the built-up area associated with dispersed development and pronounced terrain variability. Although these zones occupy a relatively small proportion of the built-up area, they represent locations where distance-related and terrain-related constraints co-occur.

In Zlín, intermediate accessibility combinations are generally less extensive and more spatially constrained. Areas combining High horizontal accessibility with Medium vertical accessibility form predominantly linear spatial patterns following hillside development adjacent to the central valley axis. Combinations involving Low horizontal accessibility are comparatively rare and occur mainly as small, fragmented patches at the edges of the built-up area.

4.5. Summary of spatial patterns of pedestrian accessibility

Taken together, the results demonstrate clear inter-city differences in the spatial structure of pedestrian accessibility to public transport stops within built-up areas. While both Liberec and Zlín exhibit substantial areas classified as having favourable pedestrian accessibility conditions, Zlín is characterised by more spatially continuous patterns of combined horizontal and vertical accessibility. In contrast, Liberec displays a higher degree of spatial heterogeneity, primarily associated with terrain-related variability.

The synthetic horizontal–vertical accessibility framework provides a spatially explicit representation of cumulative pedestrian accessibility conditions and constitutes the core empirical output of this study. The identified patterns summarise the distribution and internal differentiation of pedestrian accessibility within the built-up areas of both cities and form the empirical basis for further interpretation in the discussion section.

5. Discussion

5.1. Interpretation of horizontal and vertical accessibility patterns

The results demonstrate that pedestrian accessibility to public transport stops cannot be adequately captured by a single indicator. The explicit separation of horizontal (network-based distance) and vertical (terrain-related) accessibility reveals structurally different accessibility patterns in Liberec and Zlín, despite both cities being of comparable size and operating integrated public transport systems.

In terms of horizontal accessibility, the dominance of areas classified as High accessibility in both cities corresponds with findings from studies focusing on walking distance to public transport stops (Foda, Osman 2010; Kaszczyszyn, Sypion-Dutkowska 2019). However, the spatial configuration of these areas differs substantially. Zlín exhibits a more spatially continuous pattern of high horizontal accessibility, reflecting its linear urban structure and concentrated alignment of stops along the valley axis. In contrast, Liberec displays greater spatial heterogeneity, with a higher proportion of Medium and Low horizontal accessibility within the built-up area.

The analysis of vertical accessibility highlights terrain as an independent and structurally significant constraint. Liberec is characterised by more extensive and contiguous clusters of low vertical accessibility, corresponding to pronounced elevation differences within the urban fabric. Similar terrain-related effects have been identified in studies examining the influence of hypsometric conditions on pedestrian access to public transport (Djurhuus et al. 2014, Rissel et al. 2012, Su et al. 2023). In Zlín, terrain-related constraints are more spatially limited and embedded within otherwise accessible zones, resulting in lower overall heterogeneity.

Taken together, these findings confirm that horizontal and vertical dimensions of pedestrian accessibility differ not only in magnitude but also in their spatial configuration, thereby addressing the first research question.

5.2. Terrain as a modifying factor of pedestrian accessibility

The second research question addressed the extent to which terrain influences spatial patterns of pedestrian accessibility within built-up areas. The results indicate that terrain functions not merely as a background characteristic but as a modifying factor that can significantly alter accessibility outcomes derived from distance-based measures.

In Liberec, short network distances to public transport stops frequently coincide with substantial elevation differences, producing accessibility conditions that would be classified as favourable under distance-only approaches but appear less favourable when terrain is considered. Comparable discrepancies between distance-based and terrain-adjusted accessibility have been reported in previous studies integrating elevation or slope into accessibility assessment (Ford et al. 2015, Su et al. 2023). This suggests that distance-based indicators alone may systematically overestimate pedestrian accessibility in topographically complex cities.

In Zlín, terrain-related constraints are more closely aligned with the overall urban structure, resulting in fewer locations where distance-based and terrain-based indicators diverge sharply. This observation supports findings by Hino et al. (2013), who emphasise the role of urban morphology in mediating the impact of terrain on pedestrian accessibility.

5.3. Added value and positioning of the synthetic accessibility framework

The third research question examined whether combining horizontal and vertical accessibility dimensions can reveal cumulative physical barriers that remain hidden when each dimension is analysed separately. The synthetic horizontal–vertical accessibility typology represents the principal empirical contribution of this study.

The results show that areas characterised by uniformly favourable (High–High) or uniformly unfavourable (Low–Low) conditions account for only a limited share of the built-up area. A substantial proportion of urban space is instead defined by intermediate combinations, such as High horizontal – Medium vertical or Medium horizontal – Low vertical accessibility. These mixed configurations identify locations where pedestrian accessibility is constrained by one dimension but not the other.

This finding is consistent with arguments that multidimensional accessibility measures provide a more nuanced and spatially explicit representation of access conditions than single-indicator approaches (Sha Al Mamun, Lownes 2011; Żochowska et al. 2022). Importantly, the non-compensatory structure of the proposed framework preserves the analytical distinction between distance-related and terrain-related constraints, avoiding the masking effects associated with aggregated composite indices.

A substantial body of accessibility research has focused on temporal variability, operational performance, and service-based accessibility, often relying on timetable-derived or GTFS-based indicators (Goliszek, Połom 2016; Goliszek 2019; Goliszek 2021; Prommaharaj et al. 2020). Dynamic approaches enable the analysis of peak-hour deviations, temporal mismatches between supply and demand, and service reliability (Goch et al. 2018; Tao, Rohde, Corcoran 2014). While such methods provide valuable insights into service accessibility, they do not explicitly capture the physical effort required to reach the public transport system itself.

Similarly, network connectivity measures and composite accessibility indices integrate multiple dimensions – such as distance, frequency, and network structure – into single indicators, either through graph-based connectivity metrics or through aggregated accessibility scores (Chowdhury, Ceder, Velty 2014; Háznagy et al. 2015; Tiran, Mladenović, Koblar 2015). Although these approaches are useful for strategic planning and benchmarking, they may obscure the specific mechanisms through which pedestrian accessibility constraints arise.

In contrast, the framework applied in this study deliberately avoids collapsing heterogeneous dimensions into a compensatory score. By maintaining an explicit distinction between horizontal and vertical components of pedestrian accessibility, the approach enables the identification of cumulative barriers that remain concealed in aggregated indices. This methodological positioning aligns with calls for greater conceptual clarity and transparency in accessibility research (Corazza, Favaretto 2019).

5.4. Methodological implications and transferability

From a methodological perspective, the study demonstrates the feasibility of modelling pedestrian accessibility using open and reproducible data sources. The reliance on OpenStreetMap, Copernicus elevation data, and official public transport stop datasets enables straightforward replication across different urban contexts without the need for proprietary data or specialised software environments.

Recent studies have highlighted the potential of open GIS tools and openly available datasets for analysing public transport accessibility and performance at various spatial scales (Andrei, Luca 2021; Alamri et al. 2023). By combining widely accessible data sources with a transparent analytical workflow, the proposed framework offers a transferable methodological template for medium-sized cities with complex terrain. The transferability of the framework is supported by its reliance on globally available spatial data, a clearly defined analytical workflow, and a non-compensatory classification logic, although specific threshold values may require contextual calibration to local topographic conditions and walking norms.

5.5. Limitations and directions for further research

Several limitations of the study should be acknowledged. First, the analysis focuses exclusively on pedestrian accessibility to public transport stops and does not incorporate service characteristics such as frequency, reliability, or timetable coordination. While this represents a deliberate conceptual choice, it limits direct comparability with studies adopting broader definitions of public transport accessibility.

Second, vertical accessibility is operationalised using cumulative elevation difference and does not explicitly account for slope variability or walking speed. More refined indicators, such as slope-weighted walking time, could further enhance the representation of terrain-related effort (Ford et al. 2015).

Third, the analysis does not incorporate user-specific characteristics or perceived accessibility, which have been shown to influence transport behaviour and accessibility outcomes (Lättman, Friman, Olsson 2016). Integrating perception-based data and socio-demographic characteristics represents an important avenue for future research.

Although population data were available at the building level, the analysis deliberately focuses on spatial patterns of pedestrian accessibility within built-up areas rather than on population-weighted accessibility indicators. This choice reflects the study's emphasis on the physical structure of accessibility conditions rather than on distributional or equity-based outcomes.

5.6. Positioning within the broader accessibility literature

By explicitly distinguishing pedestrian stop accessibility from service-based accessibility, the study contributes to ongoing debates regarding the conceptual clarity of accessibility research. As noted in the literature, studies labelled as addressing "public transport accessibility" often examine fundamentally different phenomena, ranging from infrastructure proximity to service performance and broader issues of social inclusion (Corazza, Favaretto 2019). From an equity-oriented perspective, accessibility analyses are increasingly used to identify spatial disparities and transport disadvantage, reinforcing the need to distinguish analytically between physical access conditions and service-based accessibility outcomes (Eldeeeb, El-Baky, Masoumi 2024; Pereira, Schwanen, Banister 2017).

The present study positions pedestrian accessibility as a necessary precondition for effective public transport use rather than as a substitute for service-based measures. In doing so, it complements existing accessibility frameworks and provides a focused analytical tool for examining the spatial foundations of public transport accessibility.

6. Conclusion

This study set out to examine the pedestrian accessibility of public transport stops by explicitly distinguishing between horizontal (network-based walking distance) and vertical (terrain-related elevation difference) components. By isolating the pre-boarding stage of public transport use from broader notions of service accessibility, the analysis addressed a foundational yet often underexplored dimension of everyday mobility: the physical effort required to reach the nearest stop on foot.

Using Liberec and Zlín as comparative case studies, the results demonstrated that pedestrian accessibility to public transport stops cannot be adequately characterised by horizontal distance alone. Although both cities exhibit substantial areas with close proximity to stops, the incorporation of terrain-related constraints revealed pronounced differences in the internal structure and spatial continuity of accessibility conditions. These findings directly respond to the first research objective formulated in the introduction, confirming that horizontal and vertical dimensions of pedestrian accessibility differ not only in magnitude but also in their spatial configuration across cities.

The analysis further showed that terrain acts as a significant modifying factor of pedestrian accessibility rather than a secondary background condition. In Liberec, elevation differences frequently intersect with areas of otherwise favourable proximity to stops, producing heterogeneous accessibility patterns within the built-up area. In Zlín, terrain-related constraints are more closely aligned with the city's linear urban structure and are spatially more contained. This comparison addresses the second research question and highlights the importance of considering the interaction between urban morphology and topographic conditions when assessing pedestrian access to public transport.

A central contribution of the study lies in the development and application of a synthetic horizontal–vertical accessibility framework. By combining distance-related and terrain-related dimensions in a non-compensatory manner, the framework revealed spatial configurations – such as short-but-steep or far-but-flat areas – that remain concealed when each dimension is analysed separately. The identification of such cumulative physical barriers responds directly to the third research question and underscores the analytical value of multidimensional approaches to pedestrian accessibility.

The fourth research question concerned the transferability of the proposed framework to other urban contexts. The application of a uniform analytical logic and classification scheme to two structurally different cities demonstrated that the framework is transferable in structure and methodological logic, even though specific threshold values may require contextual adaptation. A key strength of the approach lies in its reliance on open and widely available data sources, including OpenStreetMap, Copernicus elevation data, and official public transport stop datasets. This reliance enhances transparency, reproducibility, and applicability across different cities without the need for proprietary data or specialised software environments.

Beyond its empirical findings, the study contributes conceptually by clarifying the distinction between pedestrian stop accessibility and broader forms of public transport accessibility that incorporate service characteristics such as frequency, reliability, or travel time. By positioning pedestrian accessibility as a necessary precondition for effective public transport use rather than a substitute for service-based measures, the paper helps to sharpen conceptual boundaries within accessibility research and supports more targeted analytical and planning applications.

Several limitations of the study should be acknowledged. The analysis focuses exclusively on pedestrian accessibility and does not account for service-level characteristics or user-specific factors such as age, mobility constraints, or perceived effort. While this represents a deliberate analytical choice, future research could integrate the proposed framework with timetable-based accessibility measures, slope-weighted walking time, or socio-demographic data to provide a more comprehensive assessment of accessibility and equity implications.

In summary, this study demonstrates that a two-dimensional horizontal–vertical framework provides a more nuanced and spatially explicit understanding of pedestrian accessibility to public transport stops than conventional distance-based approaches. By revealing cumulative accessibility constraints and highlighting differences between cities with similar overall characteristics, the proposed framework offers a robust and transferable tool for comparative research and context-sensitive urban transport analysis.

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