How Accessible Are Beijing's Streets for People with Disabilities? A Network-Based Study of Urban Mobility and Inclusion

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Abstract. Urban mobility and inclusion for people with disabilities (PWDs) remain critical challenges globally, particularly in rapidly developing megacities like Beijing, where physical and institutional barriers often restrict travel to essential and short-distance trips, a pattern termed "survival-oriented mobility." Existing research frequently overlooks the nuanced travel experiences of PWDs, relying on aggregate metrics biased toward non-disabled norms, which perpetuates systemic neglect. To address this gap, this study employs a network-based spatial analysis framework for Xicheng District, Beijing, integrating geospatial data with scenario-based simulations of barrier-free facility availability. Our principal results reveal two key findings: only 17.69% of intersections have barrier-free facilities, with severe spatial inequity between core and peripheral areas; a 20% reduction in barrier-free infrastructure acts as a critical threshold, beyond which detour ratios increase sharply, especially for essential services (e.g., medical, shopping). The study concludes that urban accessibility planning must move beyond abstract efficiency metrics by directly incorporating the lived experiences and needs of PWDs. Prioritizing equitable infrastructure distribution, particularly at intersections and routes to key destinations, is imperative to mitigate detour burdens and advance truly inclusive urban development.

Keywords: Accessible Detour Ratio; Urban Accessibility; People with Disabilities; Network Analysis; Barrier-free Facilities; Survival-oriented Mobility; Inclusive Design.

1. Introduction

Amid global urbanization and urban expansion, the needs of people with disabilities (PWDs) have often been overlooked and inequitably addressed, particularly in countries of the Global South. By 2024, there are over 27 million PWDs in China [1], residing across both large cities and small towns. Although efforts have been made to improve their socio-economic inclusion, urban environments continue to fall short in providing full accessibility. Critical components of urban infrastructure, such as continuous walkways, intuitive signage systems, barrier-free public transport, and appropriately sloped ramps, often remain poorly implemented, designed without meaningful insights from or consideration of PWDs. This oversight perpetuates systemic exclusion and neglect, discouraging mobility and social participation among PWDs. Evidence suggests that inaccessible streets significantly reduce travel willingness among PWDs, leading to self-restricted mobility and diminished quality of life [2]. For instance, in Beijing, many PWDs report confining their travel to essential trips within a very narrow radius due to pervasive physical barriers, a pattern termed "survival-oriented mobility" [3]. Against this background, improving street-level accessibility is not only a matter of social justice in urban contexts but also a vital step toward achieving Sustainable Development Goal 11, making cities safe, inclusive, resilient, and sustainable.

Existing research on pedestrian mobility has systematically overlooked the real travel experiences of PWDs, limiting both the relevance and equity of its findings. Much of the literature relied on aggregate metrics such as the Pedestrian Detour Ratio (PDR)--which compares the actual distance to the idealized straight-line route--and reports values such as 1.558 in high-density urban settings (Loo et al., 2024). However, these macro-level network analyses fail to capture the nuanced mobility constraints faced by PWDs, as they are predominantly based on the walking norms of non-disabled individuals [4]. This traditional approach obscures the complex realities of navigating urban environments with disabilities and neglects the critical effects of infrastructural barriers.

Current methodologies in street accessibility evaluation exhibit an evident bias by mainly assessing barriers based on non-disabled walking experiences. This methodological bias is compounded by a lack of scenario-based assessments that could present how discrete infrastructural improvements, such as continuous walkways or accessible ramps, might enhance network-wide travel capacity for PWDs. By prioritizing abstract efficiency over lived experience, prevailing methodologies perpetuate a narrow understanding of urban accessibility.

In developing countries, research on people with disabilities (PWDs) remains scarce due to limited data and academic inattention. While studies have extensively covered cities in developed regions or well-studied Asian hubs like Hong Kong and Singapore, major Global South metropolises like Beijing are overlooked. This gap is concerning given Beijing's distinct urban context: rapid development, socio-political complexity, and a hybrid layout mixing traditional hutongs with modern superblocks. Existing works usefully identify physical barriers, narrow sidewalks, and missing ramps but largely neglect how these interact with socio-cultural factors like stigma, driver bias, and passive segregation [5]. Institutional barriers, such as fragmented enforcement and uncoordinated fiscal mechanisms, also receive inadequate attention. Although granular analyses exist elsewhere, for example, 69.8% of sidewalks in George Town are under 1.5 meters wide [6], comparable context-sensitive research is lacking in Beijing, where unique urban forms exacerbate mobility constraints. Highlighting these disparities is vital both to alert society to the marginalization of PWDs and to inform effective policy interventions.

To address these gaps, this study adopts a network-based spatial analysis framework to evaluate street-level accessibility for PWDs in Beijing's Xicheng District. It is guided by two central research questions: (1) How accessible are Beijing's streets for PWDs, and can we give a quantitative measurement? and (2) Are there some differences in accessibility across different travels? If so, how do they vary? Through quantitative assessment of detour costs and multi-scenario simulation of infrastructure conditions, this research aims to refine the theoretical understanding of "detour burdens" and procedural barriers encountered by PWDs.

This study contributes to the fields of disabled studies, urban studies, and social justice in three primary ways. Theoretically, it challenges ableist assumptions inherent in conventional transport planning by centering the embodied experiences of PWDs and advancing a more nuanced and multi-dimensional concept of accessibility that integrates physical, social, and perceptual facets. Methodologically, it introduces a scenario-based simulation technique capable of capturing non-linear relationships between infrastructure, especially barrier-free facilities, loss, and mobility justice. Empirically, it offers one of the first systematic, high-resolution analyses of street-level accessibility in a major Chinese city, generating feasible evidence for context-sensitive policy interventions.

The paper is structured as follows: section 2 reviews multiple relevant pieces of literature on pedestrian infrastructure as well as daily travel behavior and identifies detailed research gaps to be improved; section 3 details the research design, including data sources, network modeling, and simulation approaches; section 4 presents and discusses the results; and section 5 concludes with theoretical and policy implications.

2. Literature Review

2.1. Pedestrian Infrastructure Challenges

Previous studies focusing on walk detours often pay much attention to aggregate metrics such as the Pedestrian Detour Ratio (PDR), which compares actual walking distance to straight-line distance. Study in Hong Kong suggest an average PDR of 1.558, indicating that pedestrians walk approximately 1.5 times the ideal distance due to physical obstructions like roadways, parking lots, and topographic barriers [7]. While such metrics are informative, they are predominantly derived from non-disabled walking experiences, thereby perpetuating a form of systemic neglect toward the mobility needs of PWDs. Moreover, conventional detour models rarely incorporate disability-specific requirements, such as the need for wider turning radii for wheelchair users or continuous accessible pathways, which are critical for safe and independent travel [8]. This omission reflects a deeper bias that excludes the lived experiences of PWDs from urban mobility research.

Digital navigation tools further exemplify this systemic neglect. Platforms like Google Maps prioritize shortest-path algorithms without integrating essential accessibility features, such as ramp availability or step-free routes, resulting in recommendations that are often impractical or unsafe for PWDs [9]. Such technological oversight reinforces existing inequalities and heightens travel burdens, forcing users into longer and riskier detours.

In addition, the heavy reliance on macro-level network indicators masks the nuanced travel experiences of PWDs. Studies that aggregate pedestrian behavior tend to neglect the compounded effects of environmental and infrastructural barriers, such as missing curb ramps or irregular pavement surfaces, which may force detours far exceeding those experienced by non-disabled pedestrians [4]. This lack of granularity conceals the true extent of navigational challenges faced by PWDs.

Furthermore, high PDR values are frequently correlated with car-dominated areas where pedestrian infrastructure is compromised or absent, intensifying mobility exclusion for PWDs [10]. This oversight not only increases physical and cognitive effort but also reinforces "passive segregation," where fragmented pedestrian networks discourage walking among vulnerable groups [5].

Street design plays a pivotal role in shaping mobility experiences. Streets can be classified into pedestrian-priority (e.g., pedestrian malls), mixed-use (e.g., shared pedestrian/vehicle areas), and vehicle-dominant types (e.g., vehicle lanes alone), with the latter posing acute challenges for PWDs. In George Town, Malaysia, for example, 69.8% of sidewalks on car-dominated streets were narrower than 1.5 meters and frequently obstructed, forcing wheelchair users to enter vehicular lanes [6]. Accessibility features such as ramps and tactile paving are often treated as add-ons rather than integral elements of street design, leading to non-compliant installations, such as excessive slopes (e.g., ramp slopes exceeding 1:12) or disrupted tactile guidance [3]. This reflects a systemic pattern where pedestrian infrastructure is compromised in favor of vehicular flow.

Beyond physical design, sensory barriers such as traffic noise can disorient individuals with visual or hearing impairments, intensifying navigational difficulties [11]. The neglect of multi-sensory accessibility within street design underscores a lack of holistic consideration for PWDs. Underlying these issues is a persistent policy-implementation gap. Although legislation like the U.S. Americans with Disabilities Act (ADA) mandates accessibility, local enforcement remains inconsistent. Only 13% of U.S. municipalities have adopted fully compliant transition plans, most lacking concrete timelines or accountability mechanisms [12]. This implementation deficit is even more pronounced in rapidly urbanizing contexts like Beijing, where traditional hutongs and modern superblocks coexist, creating a fragmented accessibility landscape.

Signage systems are vital for orienting PWDs in urban space, yet they often fail to accommodate diverse disabilities. Research in Seoul revealed that visually impaired users struggled with overcrowded, multilingual subway signage, which increased cognitive load and forced reliance on slower tactile or auditory cues [13]. Similarly, real-time information displays rarely offer braille or voice output, necessitating external assistance and reducing autonomy [14]. This reflects a broad oversight wherein information delivery is designed for normative users, thereby excluding people with sensory disabilities.

Prohibitory signs (e.g., “No Wheelchair Access”) further reinforce systemic neglect by emphasizing exclusion rather than facilitating inclusion [15]. International standards such as ISO 7001 promote uniformity in symbolic representation but seldom address the varied requirements across disability types. For example, individuals with intellectual disabilities may benefit from simplified pictograms, while those with visual impairments need high-contrast colors and tactile elements [16]. The growing dependence on digital navigation tools risks masking underlying infrastructural deficiencies, creating a cycle of "technological band-aids" that fail to resolve structural problems (Litman, 2024).

2.2. Travel Behavior of PWDs

Empirical studies show that PWDs exhibit highly constrained travel patterns, characterized by shorter distances, longer durations, and reduced frequency compared to non-disabled individuals [3]. Infrastructure barriers, including missing ramps, narrow sidewalks, and discontinuous tactile paving, can reduce mobility among PWDs by 30–50%, further severely limiting their engagement with the urban environment [17]. In London, 67% of wheelchair users reported abandoning long-distance travel when public transport lacked step-free access [2]. Similarly, research in Seoul found that PWDs primarily traveled within a 1-kilometer radius to access essential services such as clinics and grocery stores, with limited participation in cultural or recreational activities [18]. This "survival-oriented mobility" underscores how physical barriers coupled with inequitable resource allocation systematically restrict the mobility rights of PWDs.

It is important to note that the disability community is highly heterogeneous. Mobility-impaired individuals may prioritize ramp gradient and width, while those with sensory disabilities depend on accessible information delivery, such as audio signals or tactile guides [14]. However, a significant methodological bias persists in transportation research: the tendency to homogenize PWDs, treating them as a monolithic group. This oversimplification ignores critical intersections between disability type, severity, age, gender, and socioeconomic status, thereby obscuring nuanced mobility needs and constraints [3]. By failing to disaggregate experiences and requirements, such studies perpetuate a form of epistemic exclusion that limits the validity, applicability, and equity of urban mobility policies.

PWDs frequently experience "time poverty," spending around 40%-60% more time traveling equivalent distances due to unavoidable detours, waiting for assistance (e.g., platform lifts), or navigating suboptimal routes [5]. In George Town, Malaysia, 75% of wheelchair users wasted 15-30 minutes daily circumventing obstacles like parked cars or damaged sidewalks [6]. Navigation tools often exacerbate these inefficiencies by prioritizing shortest paths over those that are safe or accessible, forcing users to choose between efficiency and safety [9].

Such trade-offs reveal a deeper methodological bias toward "efficiency fetishism," valuing speed over safety, comfort, and equity [4]. This bias not only distorts research priorities but also influences planning practices, resulting in infrastructure that fails to meet the actual needs of PWDs. Prolonged travel times can lead to social isolation, especially among elderly PWDs, who may withdraw from social activities and experience deteriorated mental health as a result [19]. Thus, temporal costs are not merely logistical but also psychosocial, affecting overall well-being and quality of life.

Travel frequency among PWDs is influenced by a complex interplay of economic and cultural factors. In India, only 22% of PWDs used public transport more than three times per week, compared to 58% of the general population [17]. Inconsistent infrastructure upgrades—such as in the U.S., where only 7% of cities implemented comprehensive network upgrades—create "accessibility islands" that disrupt continuous mobility [12]. Cultural norms and stigma further constrain mobility. In Thailand, for example, women with disabilities often face social discouragement from traveling alone [20]. Yet, such socio-cultural dimensions remain under-quantified in transport research, which tends to prioritize engineering and spatial variables over human experience and social context.

3. Research Design

3.1. Research Framework

This study employs a network-based spatial analysis framework to evaluate the accessibility of urban street networks for PWDs in a selected urban area (Figure 1). By integrating geospatial data processing, street network modeling, and scenario-based simulations, the research quantifies the impact of barrier-free facilities on PWDs' mobility, with a focus on detour ratios and accessibility.

The methodology combines empirical data analysis with computational techniques to address physical, spatial, and socio-institutional barriers to inclusive urban mobility.

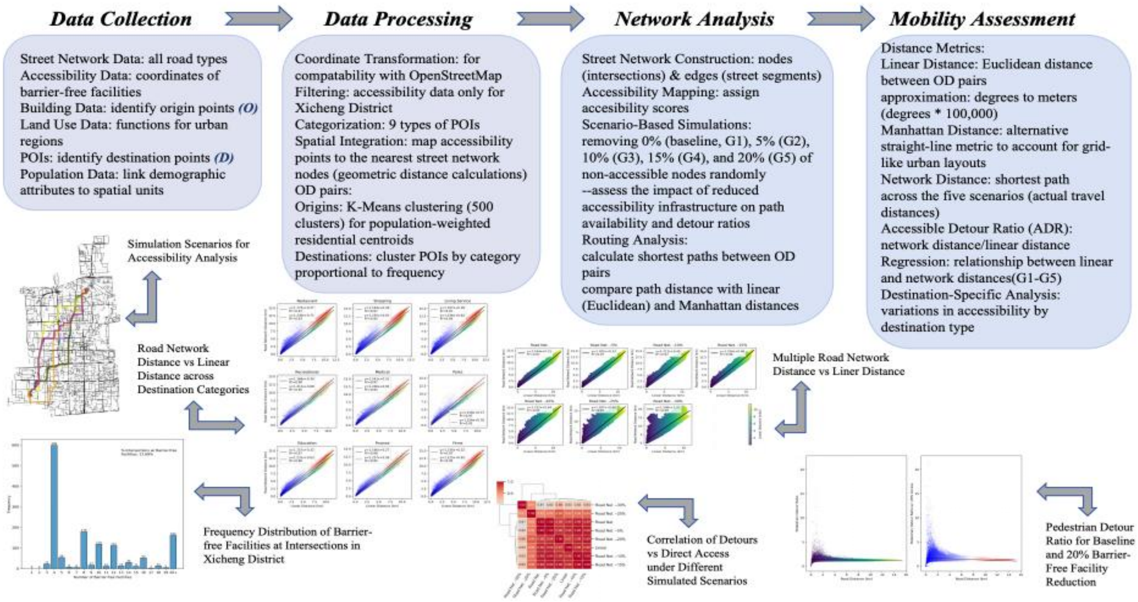

Figure 1. Research Framework of this Study.

3.2. Case Study: Beijing

Beijing presents a compelling case for investigating urban accessibility due to its unique combination of rapid modernization, complex urban fabric, and substantial policy efforts toward barrier-free environments. As a meta-city with a large population of PWDs, it embodies both the challenges and opportunities typical of densely populated urban context in developing countries. Despite its 14th Five-Year Plan (2021–2025) allocates 2.3 billion RMB for barrier-free infrastructure upgrades (Beijing Disabled Persons' Federation, 2023), the city continues to face physical and institutional barriers that impair inclusive mobility. These include fragmented tactile paving, insufficient ramps, and operational issues like obstruction of tactile paths by e-bikes—all of which mirror common issues in rapidly urbanizing regions globally.

The uniqueness of Beijing lies not only in its scale and socio-spatial complexity, from historic hutong neighborhoods to modern central business districts, but also in its proactive adoption of technological and planning innovations. For instance, AI-assisted crosswalks in the CBD have helped reduce pedestrian incidents by 37%, demonstrating how technology can mitigate accessibility barriers in high-density settings. Such interventions offer valuable insights for other large cities confronting similar mobility challenges.

Furthermore, the insights derived from Beijing possess high universality. The city's experience with multi-agency management of accessibility infrastructure, the stark core-periphery disparities in facility quality, and the varying travel behaviors of PWDs (such as "survival-oriented mobility" within 1-km radii) provide a rich empirical basis for understanding urban accessibility under diverse constraints [3, 13, 18]. In addition, the use of open and municipal data (Table 1), coordinate transformations, and network analysis ensure accurate mapping of barrier-free facilities, facilitating reproducible and evidence-based analyses for disability-inclusive urban design globally.

Table 1. Data Sources for Accessibility Analysis.

Data type	Data source
Street	OpenStreetMap (via osmnx)
Building	Building.gpkg (building footprints)
Land use	EUUC_China_20.gpkg (global land use/cover data)
Points of interest (POIs)	POI_BJ.csv (filtered to Xicheng District)
Access	Beijing's accessibility data

4. Methodology

The study utilizes multiple datasets to characterize the spatial and demographic context of Xicheng District, Beijing. Data from Beijing's accessibility data is filtered for Xicheng District, with Baidu Map coordinates converted to standardized coordinates using the transbigdata library to ensure global geospatial compatibility and exported with facility counts by category (e.g., transportation, public services). Street network data, retrieved from OpenStreetMap via the osmnx library, captures all road types (pedestrian, vehicular, and mixed-use).

Population statistics are merged with administrative boundary polygons to link demographic attributes, such as elderly (65+) population, to spatial units. Land use data from "EUUC_China_20" is clipped to Xicheng District boundaries for contextual analysis. Points of Interest (POIs) are filtered within a geographic bounding box for Xicheng District, selecting relevant categories (e.g., restaurants, medical facilities) for later analysis.

The study constructs a street network model to represent the urban mobility environment of Xicheng District, Beijing, by integrating geospatial and accessibility data to quantify the availability of barrier-free infrastructure. Using the osmnx library, the OpenStreetMap street network is transformed into a directed graph, with nodes representing intersections and edges denoting street segments, each node assigned attributes reflecting accessibility status (e.g., presence of ramps or tactile paving) derived from the processed dataset.

Barrier-free facilities are spatially joined to the nearest nodes through geometric distance calculations, with the access attribute capturing the count of nearby facilities and missing values set to zero, a process that aggregates facility counts to nodes and reveals that only 17.69% of intersections possess at least one barrier-free facility, highlighting "accessibility islands." Nodes are further categorized by accessibility levels, ranging from 1 to 19 facilities, with a 20+ category for highly equipped locations, enabling the analysis of spatial disparities, such as the concentration of facilities in core areas like transportation hubs.

Origins, representing residential locations, were generated using K-Means clustering (500 clusters) on residential building centroids, weighted by population data from the National Population Census Statistics 2020 to reflect realistic population distribution. Destinations, representing POIs, were derived by clustering POIs from 9 different categories into 500 points, with the number of points allocated for each category proportional to its frequency in the region. This process resulted in a total of 500 * 500 = 250,000 potential origin-destination (OD) pairs for subsequent routing analysis.

To evaluate the impact of infrastructure degradation on mobility, five scenarios were simulated by selectively removing non-accessible nodes from the network: a baseline scenario (G1) with no removal, followed by the random removal of 5% (G2), 10% (G3), 15% (G4), and 20% (G5) of nodes where access equals 0. A fixed random seed was employed to ensure reproducibility of the stochastic removal process.

For each scenario, the shortest path between every OD pair was computed. Path distances were recorded where routes existed; unreachable pairs were flagged as None. For comparative baseline assessment, both Euclidean and Manhattan distances were estimated for all OD pairs by converting coordinate degrees to meters (approximated as degrees * 100,000).

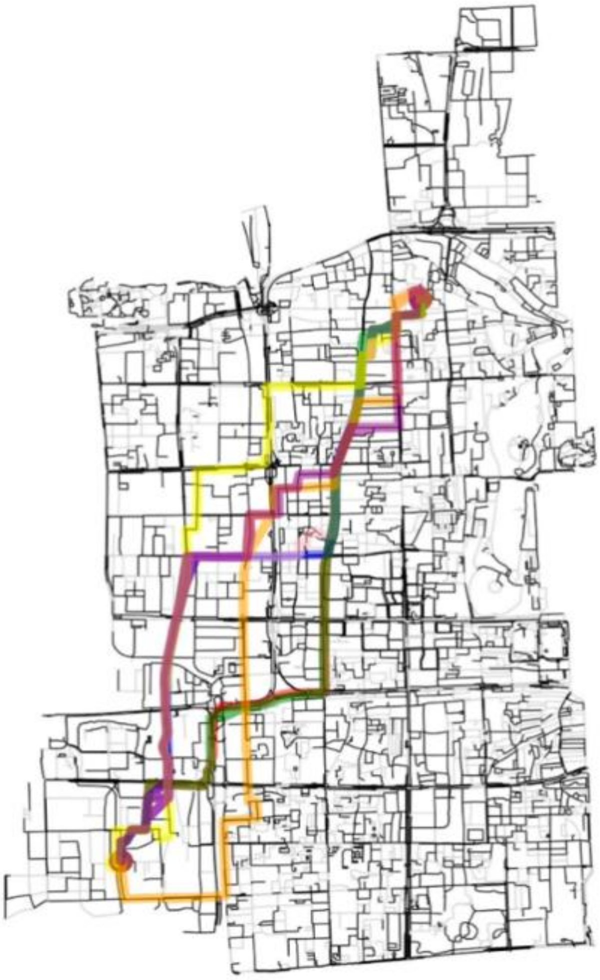

Figure 2. Simulation Scenarios for Accessibility Analysis.

Figure 2 illustrates the shortest paths between a defined start point (39.94, 116.37) and end point (39.88, 116.33) across five network scenarios in Xicheng District. The base layer features the original graph (G1) in light gray, overlaid with the modified graph (G2) in black. Shortest paths are highlighted in different colors: red for the original (G1), blue for 5% nodes removed (G2), pink for 10% removed (G3), green for 15% removed (G4), and orange for 20% removed (G5).

The Accessible Detour Ratio (ADR), defined as the ratio of road network distance to linear distance, is analyzed using regression models to quantify detour severity, with a baseline slope of 1.164. Visualizations later presented in this paper include a bar chart (Figure 3) showing that only 17.69% of intersections have barrier-free facilities, a heat map (Figure 4) correlating detour ratios across scenarios (high similarity at -5% to -15%, disruptions at -25% to -30%), scatter plots comparing linear and network distances by scenario (Figure 5) and destination category (Figure 6), and a scatter plot (Figure 7) highlighting increased detour ratios under a 20% facility reduction, underscoring the impact of infrastructure loss on travel efficiency.

5. Results and Discussion

5.1. Inaccessible Barrier-Free Facilities at Intersections

We analyze the frequency distribution of barrier-free facilities across street network intersections in Xicheng District, Beijing, as visualized in the bar chart below (Figure 3). The X-axis, labeled "Number of Barrier-free Facilities," spans from 1 to 19 with an additional 20+ category. The Y-axis scales from 0 to 600, indicating the count of intersections per category. The bars display exact frequencies atop each (e.g., 599 for 4 facilities). We find that only 17.69% of street crossings in the district possess at least one barrier-free facility, indicating a notably low baseline of accessibility.

Notably, intersections with exactly 4 barrier-free facilities are the most common, with 599 intersections accounting for 42.30% of the total. This suggests a substantial gap in accessibility infrastructure, aligning with earlier studies which point to pedestrian challenges in car-centric zones, where features such as ramps and tactile paving are often treated as secondary additions rather than integral essentials. As a result, PWDs are compelled to take detours, underscoring that current infrastructure fails to adequately support their mobility needs.

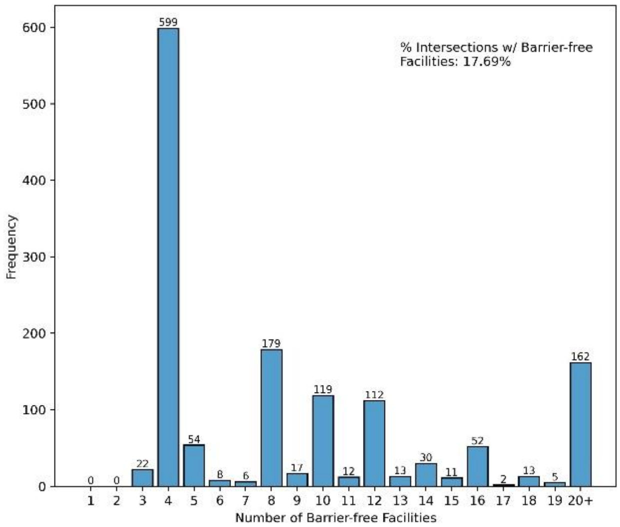

Figure 3. Frequency Distribution of Barrier-free Facilities at Intersections in Xicheng District.

It is worth mentioning that the 162 intersections in the 20+ category form an outlier. We interpret these are likely located near key destinations for PWDs, such as transportation hubs or public service facilities, reflecting intentional investment in high-traffic areas. However, this also highlights spatial inequities, suggesting that central districts such as Xicheng may receive disproportionately more resources and attention compared to outskirt areas.

We analyze the classification and distribution of travel destinations selected by PWDs in Xicheng District, Beijing (Table 2). A total of nine categories is included, each listed with its corresponding number(N) and percentage (%).

Table 2. POIs in Xicheng, Beijing.

Type	N	%
Restaurant	5,113	14.3%
Shopping	9,543	26.7%
Living	7,549	21.1%
Recreational	950	2.7%
Medical	1,693	4.7%
Parks	1,019	2.9%
Education	3,699	10.3%
Finance	1,589	4.4%
Firms	4,591	12.8%

We find that essential daily services dominate PWD travel patterns. For instance, Shopping (26.7%), Living (21.1%), and Restaurant (14.3%) collectively account for the majority of all destinations, suggesting these services are vital in the everyday lives of PWDs. Interestingly, Medical (4.7%) and Education (10.3%) facilities also make up notable shares, implying that access to healthcare and educational institutions is crucial. It is worth mentioning that less frequent categories, such as Recreational (2.7%) and Parks (2.9%), show considerably lower representation, reflecting either their dispersed spatial distribution or perceived lower priority among PWDs. The analysis shows clear variability in destination type prevalence, indicating that travel choices are influenced by both necessity and accessibility.

5.2. Inaccessible Barrier-Free Facilities at Intersections

We analyze the correlation among various simulated road network scenarios with reduced barrier-free facilities (Figure 4). The color gradient, ranging from light (around 0.8) to dark (1.0), indicates the strength of correlation, with values closer to 1.0 representing stronger positive relationships. Both axes include eight scenarios: "Road Net. -30%", "Road Net. -25%", "Road Net.", "Road Net. -5%", "Road Net. -20%", linear, "Road Net. -10%", and "Road Net. -15%", each representing a level of reduction in barrier-free facilities relative to the baseline.

The analysis shows a high degree of correlation across most scenarios. We find that many cells, especially along the diagonal, exhibit a value of 1.00, indicating that minimal reductions (e.g., -5%, -10%, -15%) remain highly similar to the baseline and to each other. This suggests that moderate decreases in barrier-free facilities do not substantially alter detour ratios or travel efficiency for PWDs.

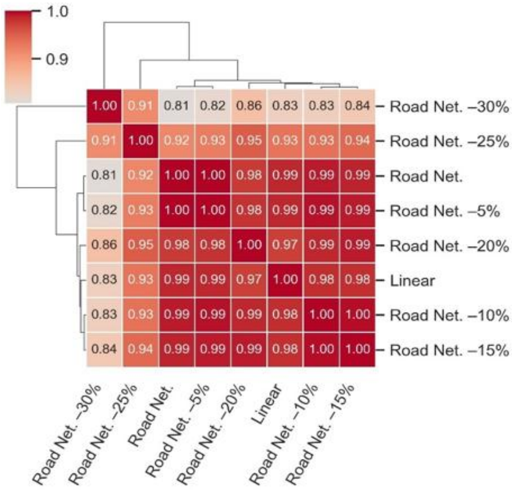

Figure 4. Correlation of Detours vs. Direct Access under Different Simulated Scenarios.

However, the presence of lower correlations, such as 0.81 between "Road Net. -30%" and "Road Net.," or 0.82 between "Road Net. -30%" and "Road Net. -5%," validates that more substantial reductions introduce noticeable differences in detour and travel distances. It is worth mentioning that these weaker correlations imply that larger cuts (e.g., -30%, -25%) likely disrupt accessible path networks, potentially increasing the Accessible Detour Ratio (ADR) by forcing PWDs to navigate longer or less convenient routes.

A gradient of correlation strength is shown by the most significant drops occurring as reductions increase from -20% to -30%. This pattern suggests a threshold effect, where beyond a certain point, network modifications begin to compromise the integrity of accessibility features. This phenomenon can potentially lead to "passive segregation" [5].

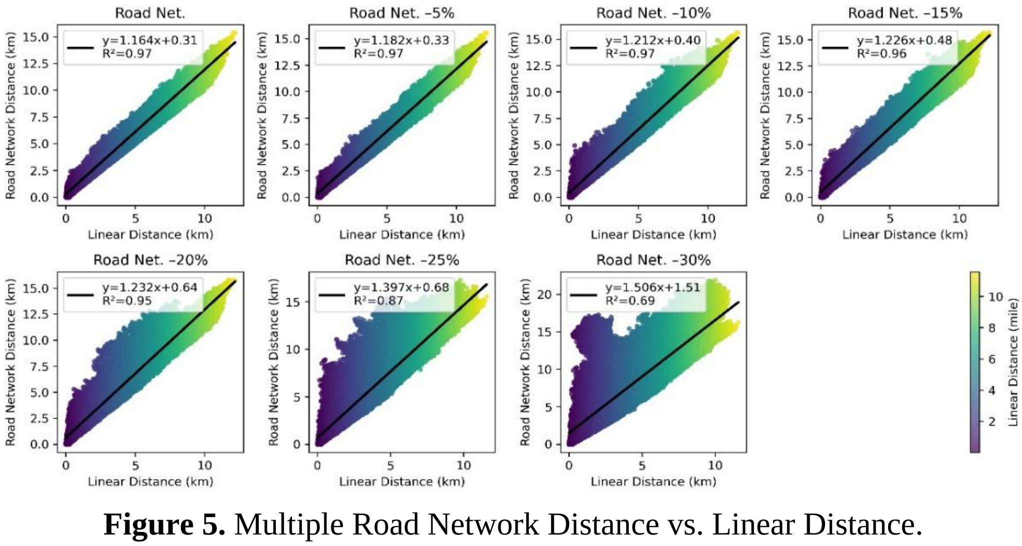

Figure 5. Multiple Road Network Distance vs. Linear Distance.

We analyze seven scatter plots depicting the relationship between linear distance and road network distance under varying levels of barrier-free facility reductions (baseline to -30%) in Xicheng District, Beijing (Figure 5). Each plot uses a color gradient (purple to yellow) to indicate data density, along with a fitted regression line including its equation and R^2 value.

We find that the baseline ("Road Net.") exhibits a slope of 1.164 and R2 of 0.97, implying that actual road distance is, on average, 16.4% longer than the linear distance: consistent with existing detour ratio theory [7]. With increasing reduction of barrier-free facilities, the regression slope rises steadily: -5% (1.182), -10% (1.212), -15% (1.226), -20% (1.232), -25% (1.397), and -30% (1.506). This suggests that reduced accessibility infrastructure amplifies detour effects, especially beyond the -20% threshold. Interestingly, the R2 value declines consistently from 0.97 (baseline) to 0.69 (-30%), implying a reduced reliability of the linear model under severe facility reductions. It is worth mentioning that the rising y-intercept further indicates additional fixed detour distances introduced in these extreme cases.

We also observe that data points cluster notably at moderate linear distances, with sparser points at shorter ranges, implying that travel inefficiencies become more evident over longer trips. Notably, the decreased R2 and increased slope values in the -25% and -30% scenarios reinforce that significant infrastructure loss leads to unpredictable and burdensome detours for PWDs, supporting the notion of a threshold beyond which accessibility deteriorates substantially.

5.3. Inaccessible Barrier-Free Facilities at Intersections

We analyze the relationship between linear distance and road network distance across nine distinct travel destination categories for PWDs in Xicheng District, Beijing (Figure 6). Each plot includes two regression lines: a solid line representing the baseline scenario and a dashed line reflecting a 20% reduction in barrier-free facilities, enabling clear comparison of accessibility under different infrastructure conditions.

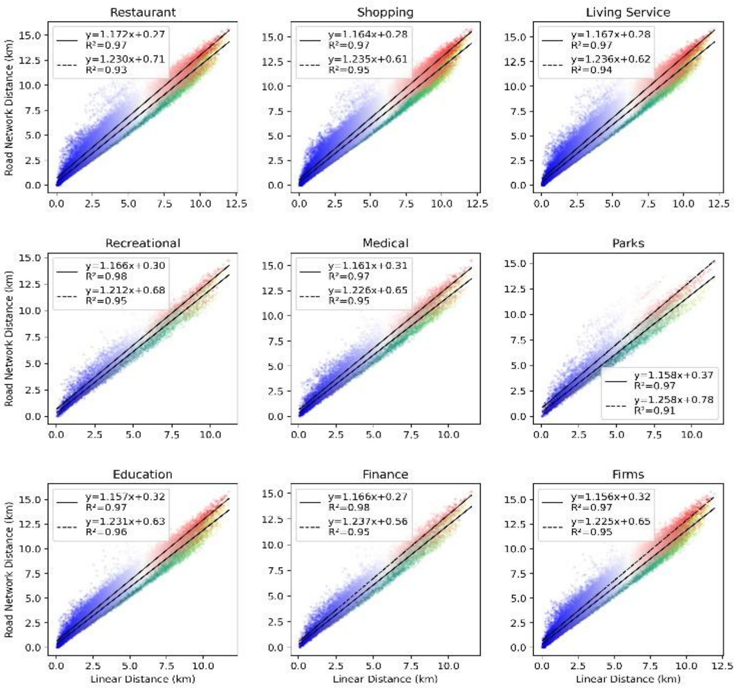

Figure 6. Road Network Distance vs. Linear Distance across Destination Categories.

We find that detour patterns are consistent across all categories, yet accessibility challenges are noticeably amplified under the 20% reduction scenario. The analysis shows baseline regression slopes ranging from 1.156 (Firms) to 1.172 (Restaurants), indicating detour ratios between 15.6% and 17.2% above the ideal linear path. Under the 20% reduction, these slopes increase substantively, suggesting significantly longer detours. High R^2 values (mostly above 0.90) reflect a strong linear relationship across categories.

Notably, destination-specific analyses highlight varying detour burdens, with the 20 % reduction scenarios exacerbating these challenges. For example, the Restaurant category shows a slope increase from 1.172 (baseline) to 1.230 (20% reduction), accompanied by a higher intercept, implying greater detours. Similar increases occur in Shopping (1.164 to 1.235) and Living Service (1.167 to 1.236). Recreational, Medical, Parks, Education, Finance, Firms categories all follow this pattern.

Data density varies meaningfully across categories. We observe high clustering around the 5–10 km linear distance range in essential services such as Restaurants, Shopping, and Living Services, indicating frequent travel within this range and supporting the notion of "survival-oriented mobility." By contrast, Recreational and Parks destinations show more dispersed data patterns, suggesting less frequent or more variable travel behavior.

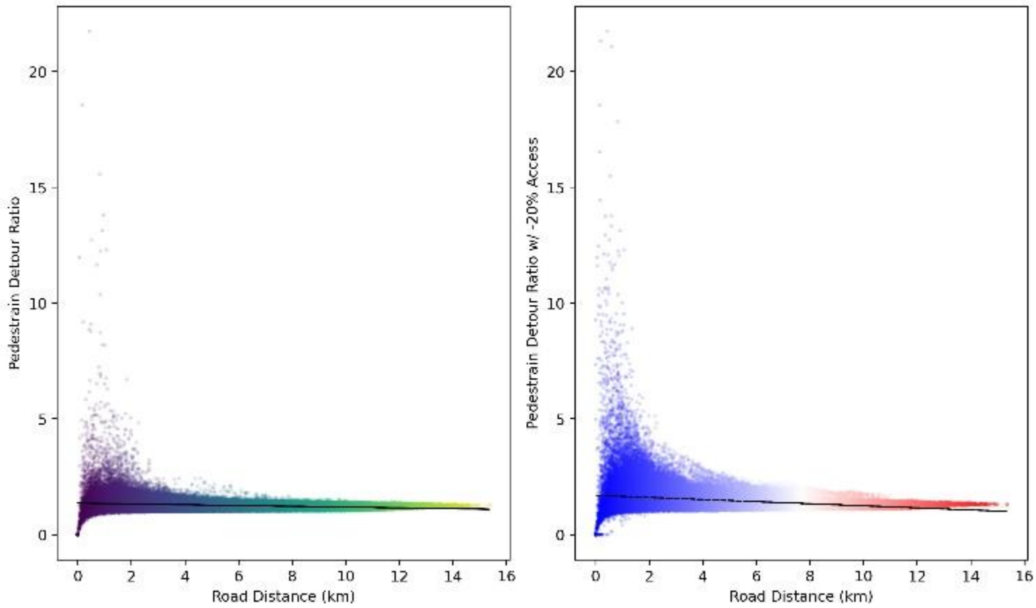

Figure 7. Pedestrian Detour Ratio for Baseline and 20% Barrier-Free Facility Reduction.

We analyze the distribution of pedestrian detour ratios for PWDs under both baseline and 20% barrier-free facility reduction scenarios (Figure 7). The X-axis represents road network distance (0–16 km), while the Y-axis in each plot shows detour ratios, baseline on the left and under 20% reduction on the right.

We find that the 20% reduction scenario exacerbates detour ratios across travel distances. The analysis shows that, while the baseline condition maintains generally low detour ratios, the 20% reduction in barrier-free facilities results in a more dispersed distribution of points, with notably higher ratios occurring even at shorter distances. It is notable that the increased spread and frequency of high detour ratios under the 20% reduction reveal a threshold effect, indicating that accessibility deteriorates substantially once barrier-free infrastructure falls below a critical level.

6. Conclusions and Implications

Ensuring accessible urban mobility for PWDs remains a critical yet understudied dimension of inclusive urban development, often constrained by systemic neglect, methodological biases, and data limitations. This research constructed a network-based spatial analysis framework to evaluate street-level accessibility for PWDs in Xicheng District, Beijing. By integrating multi-source geospatial data, simulating infrastructure removal scenarios, and calculating detour ratios, the study systematically assessed how the availability of barrier-free facilities affects travel efficiency. The results reveal significant spatial disparities in accessibility and highlight how facility deficiencies exacerbate travel burdens for PWDs.

Our analysis reveals that only 17.69% of intersections were equipped with at least one barrier-free facility, with a majority clustered in core areas, showing evident insufficiency in accessible facilities for PWDs. This key finding underscores the severe spatial inequity in the distribution of barrier-free facilities throughout Xicheng District. This inequitable configuration forces PWDs to have prolonged detours, with a baseline ADR of 1.164, indicating that actual travel distances are 16.4% longer than the ideal straight-line distance. Such inefficiencies reinforce survival-oriented mobility patterns, where travel is predominantly limited to essential services within narrow radii, therefore constraining broader social participation.

A simulated reduction of just 20% in barrier-free infrastructure serves as a critical threshold, beyond which detour ratios rise sharply across all destination types. Together with other simulations, scenario analyses further demonstrate that the urban mobility network for PWDs is highly fragile and reductions in barrier-free facilities disproportionately affect travel across different types of destinations. This decline is most acute for travel to essential services such as restaurants, shopping, and medical. Those destinations not only constitute a major share of travel demand but also prove most vulnerable to facility loss. These findings illustrate that infrastructural gaps do not merely increase travel distance; they systematically undermine the functional usability of urban space for PWDs, reinforcing patterns of exclusion, particularly in peripheral zones.

These findings offer concrete, empirically grounded insights into urban planning and policy. First, the pronounced insufficiency of necessary barrier-free facilities targeted improvements at intersections, with a priority of achieving equitable coverage, especially in peripheral zones where deficiencies are most severe. Second, the simulation reveals that a 20% removal of barrier-free facilities serves as an important sensitivity threshold; this benchmark should inform the minimum resilience standard in barrier-free network planning. Third, given the heightened vulnerability of trips to essential services like restaurants, shopping, and healthcare, policies must prioritize continuous accessible routes to these key destinations for PWDs. Implementing those targeted interventions would turn our findings into actionable pathways for mitigating detour burdens and advancing mobility for PWDs.

Although utilizing main residential areas and major facilities as travel origins and destinations can provide a reasonable approximation of primary travel demands for PWDs, the absence of fine-grained, more accurate data means certain behavioral nuances may not be fully captured and observed. Moreover, while the focused region of Xicheng District offers a valuable and internally consistent case, the universal applicability of findings to cities with significantly different spatial structures or development stages requires further validation. Future research would benefit from incorporating empirical travel surveys specific to PWDs and expanding the methodological framework to diverse urban settings to enhance universality and robustness.

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