Unveiling travel communities of people with disabilities using smart card data: A case study of Nanjing

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Abstract
Mobility barriers for people with disabilities remain a critical issue in many cities, especially in developing countries. This study uses metro smart card data from Nanjing, China, to explore the spatiotemporal patterns and network-based community structures of metro travel among disabled individuals. Results show a distinct "dual-peak" travel pattern and a "core-periphery" spatial structure, with higher network centrality during peak hours. Community detection reveals four types of travel clusters—commuting-oriented, residence-dominated, mixed-function, and special-node—each shaped by both travel purpose and urban functions. Spatial regression analysis highlights transit accessibility and land-use mix as key factors influencing travel flow. These findings offer insights for promoting transport equity and optimizing accessible transit planning.

Key words: Spatial-temporal patterns travel communities people with disabilities smart card data

1. Introduction

In recent years, the mobility challenges faced by people with disabilities (PWDs) in urban environments have attracted increasing scholarly and policy attention worldwide, especially in rapidly urbanizing developing countries where infrastructure development and social inclusion often lag behind economic growth (Guo et al., 2022; Liu et al., 2018). According to the latest report from the World Health Organization (WHO), over 1.5 billion people worldwide—nearly 20% of the global population—live with some form of disability. In China alone, official statistics from the China Disabled Persons' Federation (CDPF) indicate that approximately 85 million individuals, accounting for 6% of the national population, are classified as disabled. This sizable demographic represents a critically underserved group whose urban mobility constraints significantly restrict their access to essential services, economic opportunities, and social participation. Consequently, improving transportation equity for PWDs has emerged not only as a matter of human rights and social justice but also as a key indicator of urban sustainability, inclusivity, and resilience (Liu et al., 2018).

Despite substantial efforts and investments in barrier-free infrastructure, including ramps, elevators, tactile paving, and auditory guidance systems, there remains a pronounced disconnect between the provision of accessible facilities and the lived travel experiences of PWDs. Existing research has often emphasized infrastructural availability or static accessibility indices, which inadequately capture the complexity and dynamism of disabled individuals' mobility behaviors (Ma, 2023). Such approaches risk oversimplifying the multifaceted barriers PWDs encounter—ranging from physical environment constraints, psychological apprehensions, to temporal variability in travel demand and purpose. Without a comprehensive understanding of actual travel patterns and their spatial-temporal heterogeneity, urban planners and policymakers face challenges in designing truly inclusive transport systems that accommodate diverse needs effectively.

As a vital backbone of urban public transport systems, metro networks offer inherent advantages of safety, speed, reliability, and weather protection, making them an increasingly preferred mode of travel for many PWDs in dense metropolitan areas (Zheng et al., 2024). The rapid expansion of metro systems in Chinese cities provides a valuable opportunity to leverage detailed smart card transaction data to examine mobility patterns at an unprecedented granularity. However, most extant studies focus primarily on aggregated station-level indicators—such as boarding/alighting volumes or accessibility scores—without delving into the dynamic, directional flows that connect different nodes in the network (Chen et al., 2023; Kolkowski et al., 2023). This station-centric perspective neglects the underlying network topology and the interdependencies among stations, which are essential for revealing the functional structure of travel behavior.

Particularly underexplored is the application of complex network theory and community detection algorithms to model and interpret the travel flows of PWDs. Considering that PWDs often exhibit more regularized and constrained travel patterns due to physical limitations and environmental barriers, their mobility networks may reveal distinct spatial clusters or “mobility communities” that differ fundamentally from those of the general population (Wei et al., 2024). Identifying these communities and their temporal dynamics is critical for detecting underserved areas, optimizing resource allocation, and tailoring targeted interventions to enhance the equity and efficiency of accessible transport services (Liu et al., 2024). Such an approach transcends traditional accessibility measures by incorporating the relational and flow-based characteristics of urban mobility.

To fill these research gaps, this study employs metro smart card data from Nanjing, China, integrating network analysis with temporal community detection techniques to investigate the spatiotemporal characteristics of metro travel flows among people with disabilities. Specifically, this research aims to answer three key questions: (1) What are the spatiotemporal travel patterns of PWD metro users across different times of day and week? (2) How do the underlying network structures and community configurations evolve temporally, and what does this reveal about the organization of disabled mobility? (3) Which built environment and socio-spatial factors influence travel behaviors within the identified mobility communities? By addressing these questions, this study contributes a novel analytical framework and empirical insights to the growing discourse on urban transport equity, thereby supporting evidence-based policy formulation to promote inclusive, accessible, and resilient urban transport systems.

2. Methodology

2.1 Study area and data

Nanjing, the capital city of Jiangsu Province in eastern China, encompasses a total area of approximately 6,587 square kilometers and had a permanent resident population of about 9.28 million as of 2019. For the purpose of spatial analysis, the study area is delineated into two primary concentric zones (Figure 1): the Central Urban District (CUD) and the Suburban and Urban Distant (SUD) zone. The CUD comprises most parts of Gulou, Qinhuai, Xuanwu, and Jianye districts, alongside sections of Yuhuatai, Qixia, Jiangning, and Pukou districts. This zone represents the city’s core urban fabric, characterized by dense residential, commercial, and institutional land uses. In contrast, the SUD zone includes the peripheral districts of Liuhe, Lishui, and Gaochun, which are relatively less urbanized and often represent the city’s suburban fringe and outlying rural-urban transition areas. According to the latest Nanjing Statistical Yearbook, the city is home to approximately 595,000 people with disabilities, accounting for 6.4% of its total population, reflecting a substantial demographic group whose mobility needs are critical for inclusive urban development.

In recent years, Nanjing has witnessed rapid expansion and modernization of its urban rail transit system. The metro network now comprises 10 operational lines, servicing a total of 159 stations dispersed across the urban and suburban areas. This expansive metro system has become an increasingly vital mode of transportation for the city’s residents, especially for people with disabilities, as a result of continuous improvements in barrier-free infrastructure such as accessible station designs, elevators, tactile guidance paths, and inclusive mobility policies aimed at reducing travel barriers. These efforts have positioned the metro as a backbone of accessible urban mobility, facilitating safer, more reliable, and convenient travel for PWDs within a sprawling metropolitan environment.

This study utilizes smart card data provided by the Nanjing Metro Group Co., Ltd., covering 315,685 metro trip records made by people with disabilities over 20 weekdays and 8 weekend days in 2019. Built environment data were collected from multiple sources: building and land-use data from the Nanjing Planning Bureau, point-of-interest (POI) data from AMap, and transportation facility vector data from OpenStreetMap. Given the average walking speed of people with disabilities (approximately 0.8 m/s), a 15-minute walking distance (equivalent to a 480-meter radius) is adopted as the service buffer threshold around each metro station.

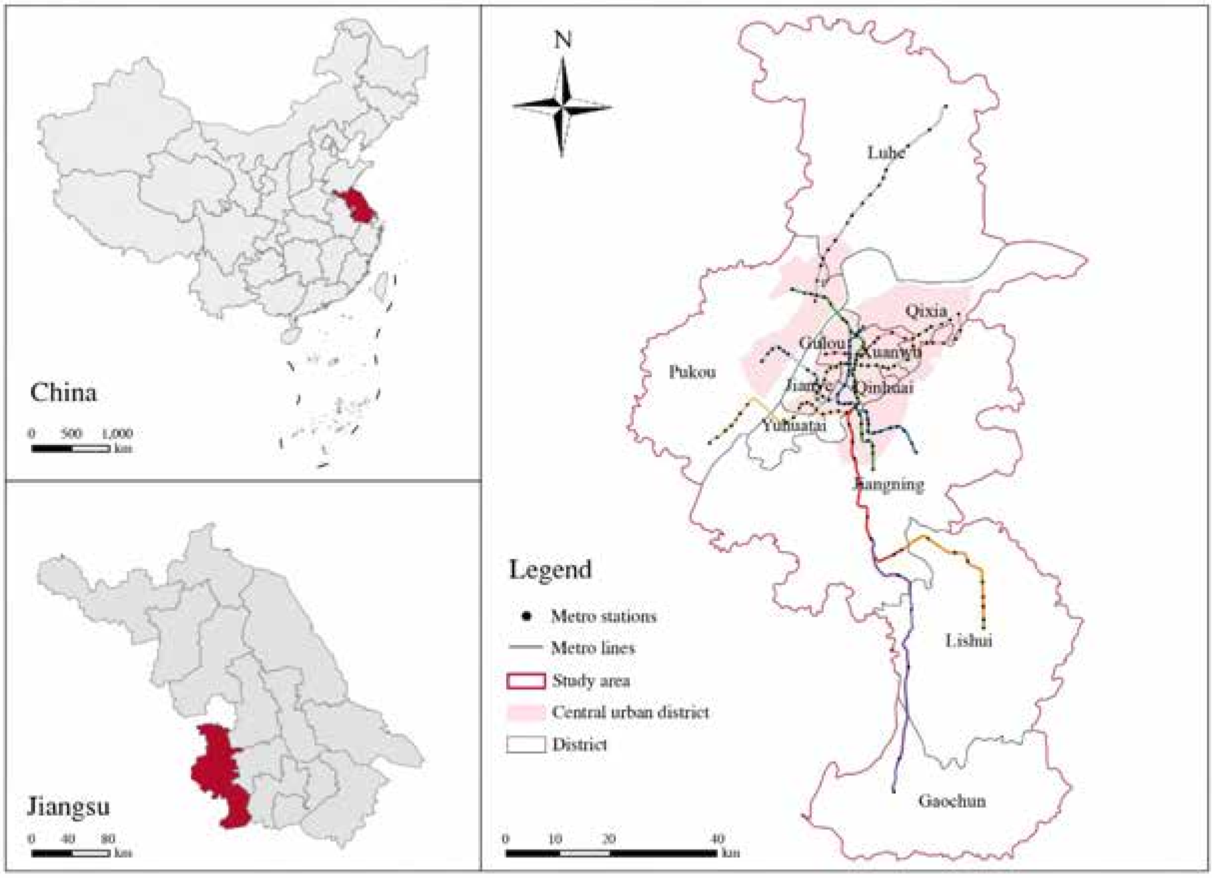

Figure 1 Study area.

2.2 Measurement of Time-Specific Travel Networks

Based on metro smart card data, this study first extracted the daily sequence of entry and exit times for each trip. By analyzing temporal fluctuations in ridership, three representative periods were identified: morning peak, off-peak, and evening peak hours. These periods serve as key time windows for analyzing the commuting-related travel behavior of people with disabilities. For each period, the origin and destination stations of individual trips were extracted. Metro stations were treated as network nodes, and travel flows between stations were represented as directed weighted edges, thereby forming a directed and weighted metro travel network. To characterize the structural properties of these networks, we calculated basic topological metrics such as number of nodes and edges, node degree, and weighted centrality (J. Liu et al., 2023), revealing the spatial structure and connectivity patterns of disabled individuals' metro travel.

2.3 Community Detection Based on Travel Flows

To uncover latent structures within the travel network, we adopted the Leiden community detection algorithm, which has been shown to outperform traditional methods in terms of computational efficiency and partition quality (Chang et al., 2023). This approach enables the identification of functional "mobility communities" by maximizing modularity, a measure that captures the strength of within-group connections. Unlike conventional methods based on administrative boundaries or individual station attributes, community detection allows for a more behaviorally grounded analysis, capturing actual spatial associations and functional regions formed through disabled travelers' movement patterns. By analyzing the size, spatial distribution, and internal flow characteristics of these communities, the study further identifies inter-community differences and group-specific mobility preferences.

2.4 Exploring the Determinants of Travel Flows: Regression Modeling

To examine the factors influencing metro travel flows across different communities, we constructed spatial regression models using average hourly metro ridership of people with disabilities (during weekdays) as the dependent variable. Independent variables included a set of built environment indicators surrounding each metro station, such as land-use mix, road network density, facility accessibility, and the number of disability-specific service facilities .Given the over-dispersion observed in the dependent variable, Poisson regression models were employed. Data subsets were constructed for three key weekday periods—morning peak, midday, and evening peak—and further stratified by mobility community for group-wise modeling. This approach accounts for both temporal variation and spatial heterogeneity in travel behavior across different community types. The modeling outputs include regression summaries and coefficient tables for each group, allowing for comparative analysis of the determinants shaping travel flow intensity across spatiotemporal units.

3. Result

3.1 Spatial-temporal characteristics of metro ridership of people with disabilities

Figure 2 illustrates the temporal distribution of metro trips made by people with disabilities on weekdays and weekends. On weekdays, the travel pattern exhibits a clear “dual-peak with off-peak differentiation” structure, with distinct morning (7:00–9:00) and evening (16:00–18:00) peaks. Travel volumes during off-peak hours are considerably lower. In contrast, weekends show a smoother dual-peak curve, reflecting non-commuting, leisure-driven travel behavior. In addition, notable differences are observed in the average hourly ridership across metro stations in central urban districts and suburban areas, indicating that the metro trips of people with disabilities are primarily concentrated in the urban core. Given the significant reduction in average trip volumes during weekends, this study focuses on weekday travel patterns, and classifies daily metro flows into three periods for further analysis: morning peak (7:00–9:00), noon off-peak (9:00–16:00), and evening peak (16:00–18:00). This classification enables a detailed comparison of travel flows and network structures across different time windows.

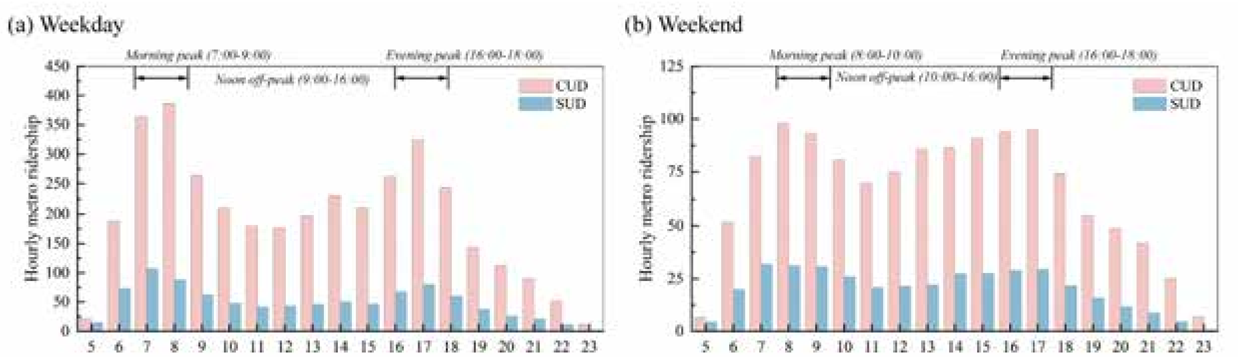

Figure 2 Temporal distributions of hourly metro ridership during weekdays and weekends.

Figure 3 illustrates the spatial and temporal differentiation of metro travel flows and station-level ridership of people with disabilities during weekdays. In the morning peak period, the OD flow pattern shows a strong centripetal tendency, with the highest observed hourly flow reaching 526 trips from Maigaoqiao to Gulou. Notably, 70% of the top 10 OD pairs represent commuting flows from suburban areas to the urban core. During the noon off-peak period, travel flows become more bidirectionally balanced, exemplified by the Maigaoqiao-Gulou link, where flows in both directions remain around 400 trips per hour. In the evening peak (T3), a clear centrifugal pattern emerges, with flows shifting from central areas to the periphery. The flow from Xinjiekou to Maigaoqiao reaches a peak of 421 trips per hour, marking a 22.3% increase over the same direction during the morning peak. Furthermore, aggregated station-level ridership across all time periods highlights a consistent core–periphery disparity. Metro stations in central urban districts exhibit significantly higher passenger volumes than those in suburban areas. In particular, Xinjiekou and Gulou serve as peak flow nodes during rush hours, a pattern closely associated with the high density of employment centers, public services, and superior metro accessibility in these areas.

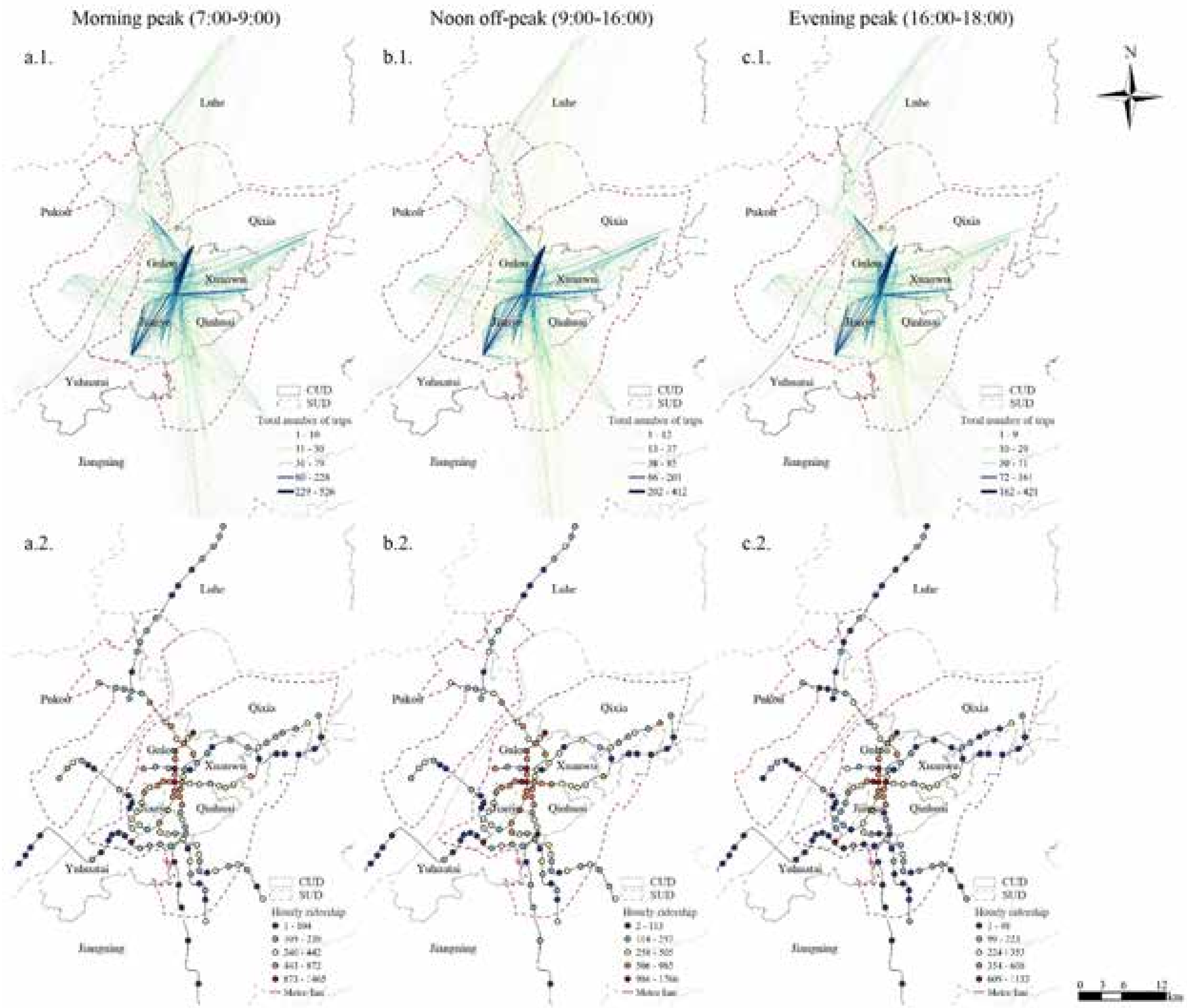

Figure 3 Spatial temporal variations of metro ridership on weekdays.

3.2 Network characteristics analysis

This study conducted a time-segmented analysis of node importance in the metro travel network of people with disabilities using the weighted degree centrality metric. The results reveal significant temporal variations in network structure. During the morning peak, stations such as Maigaoqiao, Difangqiao, and Gulou serve as critical hubs within the disabled passengers' travel network. In the noon off-peak period (T2), the overall network centrality decreases slightly (ranging from 0.003 to 0.041). However, the relative dominance of high-centrality nodes becomes more pronounced, with the maximum centrality increasing by 5.1% compared to the morning peak. For instance, Xinjiekou Station's centrality rises sharply to 0.0410, surpassing Maigaoqiao as the most important node. Meanwhile, Shanghai Road and Gulou stations maintain high centrality scores, highlighting the growing importance of commercial centers during non-commuting hours. In the evening peak, the network centrality strengthens markedly, with the distribution shifting upward (range: 0.004 to 0.047). Xinjiekou Station reaches a daily peak centrality of 0.0466, while Maigaoqiao Station, located at the urban fringe, regains its status as a secondary core node. Together with Difangqiao, these stations form a dual-core structure in the evening peak travel network. Overall, these spatiotemporal dynamics further illustrate the "core–periphery" structure of the metro travel network for people with disabilities, with higher network concentration observed during peak hours. The most central stations are predominantly located in the historic urban core, whereas peripheral stations exhibit significantly lower importance in the daily travel network of disabled passengers.

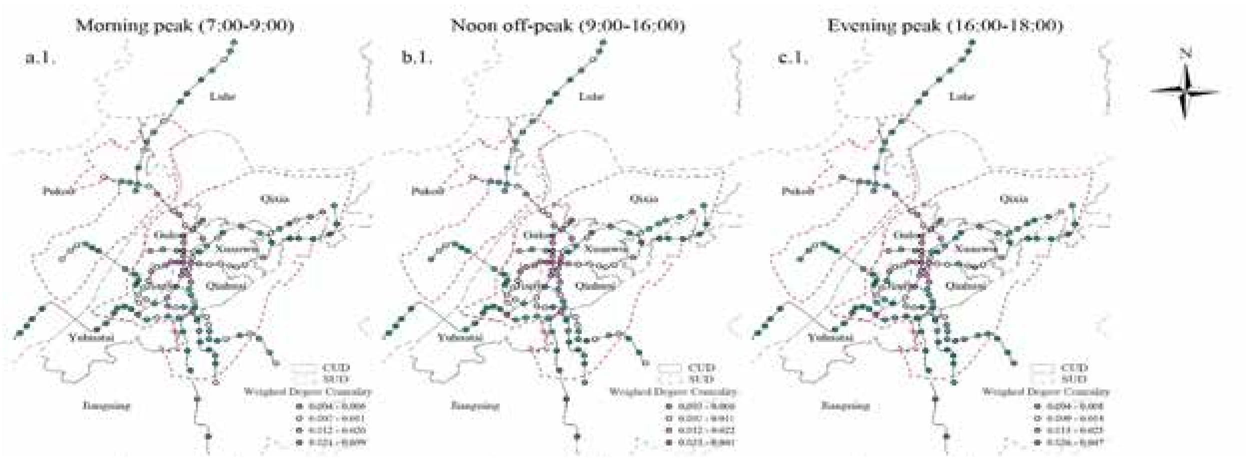

Figure 4 Spatial distribution of weighed degree centrality during the different period

3.3 Community detection analysis

Using a complex network community detection algorithm, this study analyzed the community structure of the metro travel network for people with disabilities across different time periods (Figure 5). The results reveal a high similarity between the morning and evening peak travel networks, whereas distinct differences emerge when comparing peak periods with the noon off-peak period. During peak hours, four prominent communities (C1–C4) are identified, each showing a significant alignment with the metro lines' spatial layout. Specifically, Community 1 (C1) is primarily concentrated along Metro Lines 2, 10, and the S3 line, exhibiting clear line homogeneity. Community 2 (C2) is mainly distributed along the north–south oriented Lines 3 and S8. Community 3 (C3) covers the interchange section between Lines 1 and part of Line 4. In contrast, Community 4 (C4) centers on the Yuhuatai and Jiangning districts, encompassing the S1 line and reflecting the suburban commuting network's relative independence, likely corresponding to a residentially oriented, single-function area. During the noon off-peak period, community structure shows stronger line intermixing with the number of communities reduced to three. Stations from different lines increasingly cluster within the same communities, indicating that the diversified travel purposes during non-commuting hours weaken spatial differentiation.

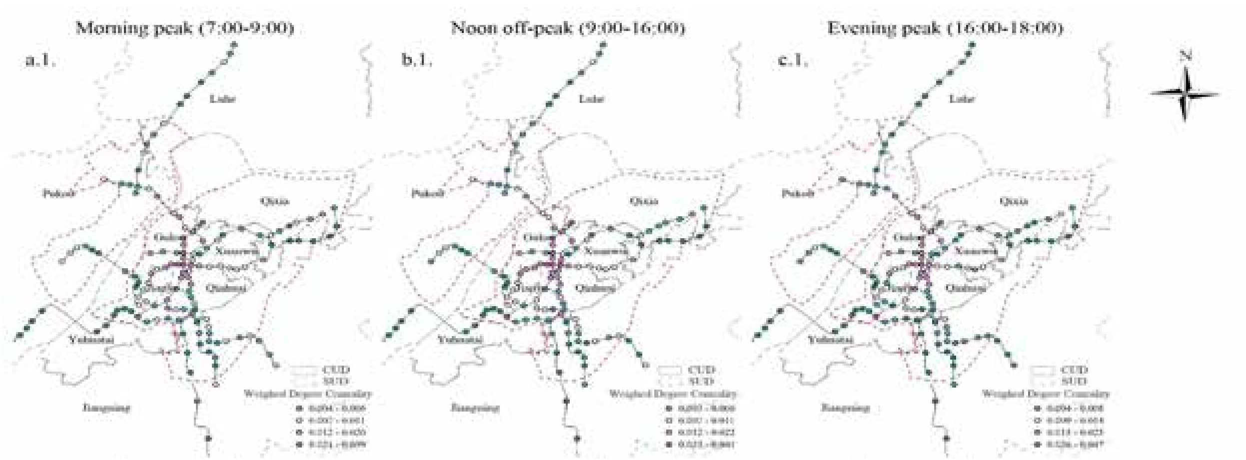

Figure 5 Detected communities for people with disabilities during different period

3.4 Potential Factors Influencing Community Formation

To better understand the formation of these community structures and the differences in travel activity patterns among communities, this study focuses on the morning peak travel network on weekdays, where community differentiation is most pronounced. We statistically analyzed the built environment characteristics of the four identified communities (Figure 6) and further explored the relationships between travel flows and urban built environment features within each community (Table 1).

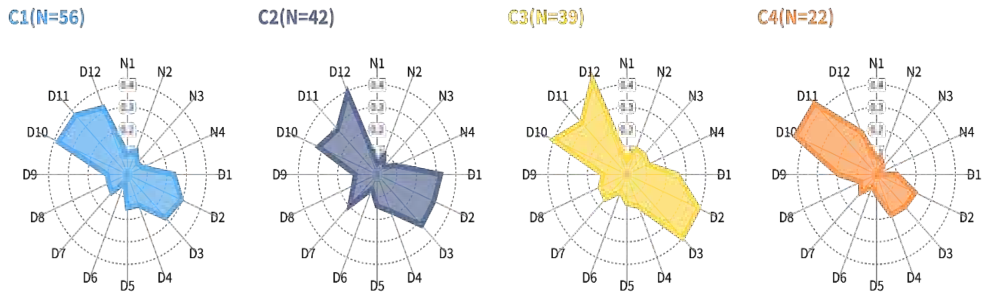

Figure 6 Indicator visualization results for each community during morning peak hours.

The study identified four distinct community types with differing built environment influences on disabled individuals' metro travel flows. Cluster 1, the commuting-oriented community (35% of total), exhibited a significant transportation-commercial synergy, where metro connectivity (β = 0.666*) and bus accessibility (β = 1.812*) combined with commercial facilities (β = 0.811*) to drive travel volume. Travel demand decreased by 1.576 units per kilometer from the CBD ($p < 0.01$), confirming the effectiveness of the traditional TOD model. Cluster 2, the residence-dominated community (26%), displayed typical "bedroom city" characteristics, with leisure facilities (β = 2.398*) and medical resources (β = 0.641*) as main attractors, while enterprise presence (β = -2.002*) and functional mix (β = -2.239*) exerted significant inhibitory effects, indicating spatial job-housing imbalance. Cluster 3, the mixed-use community (25%), reflected balanced development, with medical services (β = 1.792*) and bus coverage (β = 1.351*) as core drivers and minimal impact from distance variables, highlighting the effectiveness of the "15-minute city" concept. Cluster 4, the special-node community (14%), showed pronounced monopolar characteristics, where metro connectivity (β = 264.413*) and medical resources (β = 60.169*) had extraordinary impacts, but road network density (β = -6.840*) strongly suppressed travel, revealing its role as a specialized regional hub. Overall, transportation accessibility consistently underpinned all communities (all D12 coefficients $p < 0.01$), while differences in functional composition constituted the key dimension of community differentiation.

Table 1 Results of factors impacting metro ridership across different communities based on Poisson regression model.

Variables	Morning peak			
	Cluster_1	Cluster_2	Cluster_3	Cluster_4
Intercept	4.609***	6.077***	4.952***	5.594***
Node features				
Metroline(N1)	0.666***	-0.308***	0.101*	264.413***
NumBFAF(N2)	-0.208***	-1.232***	-0.288	-439.975***
NumBFIF(N3)	-0.172	1.122***	0.798***	172.118***
NumBFSF(N4)	0.133**	0.117	0.107	0.000***
Density				
FAR(D1)	0.501***	-0.163*	-0.117	-3.434***

DensRoad(D2)	0.142**	-1.232***	0.874***	-6.840***
DensPop(D3)	1.322***	1.419***	-0.650***	5.542***
Diversity				
POI Mix(D4)	-1.946***	-2.239***	0.213	10.700***
Parks(D5)	0.366***	0.367***	-0.426***	4.929***
Medical services(D6)	0.524***	0.641***	1.792***	60.169***
Shopping facilities(D7)	0.811***	0.136**	0.264***	-16.371***
Recreational facilities(D8)	-0.199	2.398***	0.823***	-12.679***
Companies(D9)	-0.067	-2.002***	-0.306**	1.148
Distance				
Distance to CBD(D10)	-1.576***	-5.702***	-0.301***	360.984***
Distance to sub center(D11)	0.848***	3.896***	-0.062	-365.035***
Availability of bus stop(D12)	1.812***	0.840***	1.351***	1.860***
Statistics				
Pseudo_R2	0.790505961	0.656166405	0.844541082	0.89870978

Note.
*: Significant at the 0.1 level; **: Significant at the 0.05 level; ***: Significant at the 0.01 level.

4. Discussion and conclusion

4.1 Key findings

This study reveals the community structure within the metro travel network of people with disabilities and systematically explores the potential factors influencing travel volumes within each community across different time periods. The findings highlight significant temporal and spatial variations in travel patterns, network characteristics, community structures, and their driving factors between peak and off-peak periods. Methodologically, this research integrates transit card data analysis, complex network modeling, and community detection algorithms, establishing a replicable analytical framework that contributes to urban transport equity research and offers valuable insights for meeting the daily travel needs of people with disabilities, optimizing accessible infrastructure, and promoting transport fairness.

From a temporal perspective, metro travel on weekdays exhibits a typical "double-peak" commuting pattern, with passenger volumes significantly higher during morning and evening peaks compared to off-peak periods, reflecting the rigid travel demands associated with employment or scheduled services for some people with disabilities. Weekend travel patterns are comparatively flatter, indicating that leisure-oriented trips dominate while commuting demands sharply decline. Spatially, travel activities of people with disabilities are highly concentrated in central urban areas, especially in employment-dense and service-rich zones. This concentration correlates closely with the accessibility level of the urban built environment, suggesting that despite rapid expansion of the metro network, people with disabilities tend to favor activity in resource-intensive core areas.

Topological analysis of the travel network shows a typical "core-periphery" structure. Network centralization significantly increases during peak hours, with a few core stations such as Xinjiekou, Maigaoqiao, and Gulou serving as critical hubs. This reflects the concentration of travel destinations during commuting periods and reveals spatial imbalance in metro system service capacity, with peripheral stations showing relatively weaker connectivity and attractiveness. During off-peak hours, the network structure is more dispersed, and the centrality of certain nodes increases, indicating that travel during service- or medical-oriented periods relies more on individual preferences and functional orientation rather than large-scale commuting flows.

Further community detection results identify distinct differences among the metro travel communities of people with disabilities during peak hours and their association with the built environment. The four identified community clusters show pronounced heterogeneity in spatial structure, metro line orientation, and functional attributes. The commuting-oriented community (Cluster 1) is closely linked to the urban core and main metro lines, demonstrating the spatial influence of TOD patterns; the residential-dominated community (Cluster 2) is mainly distributed in urban peripheries, reflecting spatial contradictions of job-housing imbalance and mono-functionality; the mixed-function community (Cluster 3) embodies the phased achievements of the "15-minute living circle" planning, where balanced layouts of transportation and service facilities reduce sensitivity to distance; and the special-node community (Cluster 4) shows extreme hub characteristics, revealing the strong attraction of certain medical and special facilities to people with disabilities. These findings indicate that community structures are shaped not only by commuting behaviors but also by the interplay of diverse travel purposes and the functional spatial organization of the city.

4.2 Limitations

Due to data availability constraints, this study has several limitations. First, the smart card data used only cover metro travel, which may overlook trips made by other modes of transportation. Future research should consider incorporating multi-source travel data to provide a more comprehensive understanding of the daily travel behaviors and spatiotemporal network characteristics of people with disabilities. Second, although this study explored built environment factors influencing intra-community travel flows, it lacks causal inference and does not examine other potential longitudinal factors such as weather conditions or policy changes. Future studies could further investigate these key determinants affecting public transit use by people with disabilities to offer stronger insights for urban planning interventions (Kim, 2018).

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