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Research Article

Operational Efficiency Comparison and Transportation Resilience: Case Study of Nanjing, China

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With the changes in global climate, adverse weather events appear to be more frequent. The efficiency, reliability, and safety of transportation operations can be compromised by extreme weather conditions. It is critical to analyse the spatiotemporal effects of extreme weather on the operational efficiency of transportation operational efficiency for meeting people's travel and transport needs and formulating emergency management operation to prevent road congestion. It is also important to improve the resilience of transportation system. We compared the changes in transportation operational efficiency in Nanjing during normal weather on January 23 and snowstorm on January 25, 2018, using real-time travel data from Gaode Map. The results indicate that there are differences in the distribution of accessibility changes from different residential areas to the main city area in the morning peak. Overall, 90% of the accessibility change values are concentrated in −10 to 10 minutes, while 65% are concentrated in −5 to 5 minutes, and 70% of the rangeability of accessibility is concentrated in −20% to 20%. In a word, the travel in Nanjing in the snowstorm weather is basically normal. This observation is mainly due to the overnight snow removal and the reduction in the number of small car trips. In addition to the Xinjiekou area, the Hexi business district and the exit area of the cross-river tunnel should also be included in the key management areas for taking emergency management operation in the future.

1. Introduction

Transport plays an important role in urban systems. However, extreme weather results in the reduction of operational efficiency, reliability, and safety of transport [1–6]. In the context of global climate change, extreme weather events become more frequent [7]. Scholars are gradually focusing on the impact of extreme weather on the transport system, especially on indicators reflecting the resilience of the transport system, such as changes in vehicle speed and travel delays [8–11]. Under extreme weather conditions, residents will reduce their nonrigid demand and prefer to travel by public transport. Therefore, it is of great practical significance to analyse the changes in transport operational efficiency affected by extreme weather at the urban scale. On the one hand, the commuting delays revealed by this study can provide humanized and important traffic information for citizens to facilitate the rational arrangement of commuting trips. On the other hand, the results of the study can evaluate the effectiveness of existing emergency measures of transport management departments and provide scientific references for the development of targeted management measures in the future. By responding to extreme weather in a timely manner, the management department can quickly identify the vulnerable road sections and areas, optimize the allocation of emergency personnel and emergency resources, and guide the operation, maintenance, and improvement of the corresponding traffic infrastructure to effectively prevent traffic congestion and ensure the reliability of the road network. It is also significant to promote the refined management of urban transport and enhance the resilience of urban traffic.

This paper uses spatial and temporal accessibility as the main evaluation index of public transport operational efficiency. Accessibility refers to the convenience of people using the transportation system to overcome resistance to get from the origin to the destination and is a common indicator used by managers to develop fair and effective transportation management policies. It is influenced by four main factors: time factors, such as commuting time; transportation factors, such as transportation infrastructure and travel mode; land use factors, such as the type of land use between the origin and destination and the number of employment opportunities; and traveler economic and social attribute factors, such as age and income [12–14]. Based on real-time travel data obtained from Gaode Map route planning API, this paper selects six typical residential neighborhoods in Xianlin, Dongshan, and Jiangbei, the three major subcenters of Nanjing, as the study area. Obviously, big data, that is, travel assumption, obtained from route planning API increases the accuracy of accessibility measurement and reliability of analysis results. The objective of this paper, measuring resilience of the variation and rangeability in accessibility, commuting delays, and section speed from residential neighborhoods to various locations in the main urban area during morning peak hours (8:15–8:45) on January 25, 2018 (snowstorm), is a kind of methodology for estimating the impact of snowstorms on the efficiency of transportation operations. The outcome of this paper will provide a basis for the traffic management department to formulate emergency management and congestion prevention measures in response to extreme weather, which can improve the reliability of residents' commuting time and enhance the resilience of the urban transportation system.

2. Review

2.1. The Concepts and Assessment Methods of Transport Resilience. The concept of resilience was first used to describe the ability of ecosystems to withstand damage and return to a stable state under stress and has since been introduced into other fields. With the rise of planning concepts such as healthy cities and resilient cities, resilience has also received attention from scholars in urban planning. The key features of resilience include multidiversity, redundancy, robustness, resilience, connectivity, adaptability, and the ability to learn and transform. Transport resilience, as an important component of urban resilience, was initially reflected as the connectivity between different areas of the city or the accessibility of road and transport networks. However, with its further enrichment, transport resilience also includes the inclusiveness and convenience of urban transport, the efficiency and accessibility of transport facilities, the timeliness and accuracy of transport management, and the synergy between transport systems and other systems.

Previous studies on transport resilience mostly focused on impact factors, assessment methods, evaluation systems, development strategies, and so on [15–20]. The main evaluation indicators of transport resilience of traffic resilience include operational performance based on spatial and temporal effects, central connectivity based on large networks, construction costs based on risk reconstruction, statistical indicators based on real-time monitoring and evaluation, and qualitative indicators based on experience or expert opinion, and transport resilience assessment methods can be divided into six categories as follows [21]:

(i) *Assessment Method Based on Big Data*. According to the data acquisition channel, the assessment data can be divided into car GPS data reflecting information on the urban road network, public transport operation data (revenue, trips, etc.) reflecting the urban public transport network (including bus and metro), and flight record data reflecting the urban air transport network [22, 23].

(ii) *Simulation*. Multiple scenario comparisons can be made using the simulation approach but it requires greater processing power [24, 25].

(iii) *Modelling*. For example, researchers use GIS to simulate the resilience of traffic networks to floods and use adaptive traffic signal systems to optimize urban traffic signals and alleviate urban congestion [26].

(iv) *A Graph Theory and Complex Network-Based Approach*. Nodes and routes are used to simplify the system to assess system centrality and connectivity reflecting the resilience of the system [27, 37].

(v) *A Probability-Based Approach*. Adaptability and resilience are assessed through probabilistic models [28].

(vi) *Other Methods*. Multiple methods are used to evaluate urban transport resilience [29].

2.2. Impact of Extreme Weather on Traffic. Scholars have conducted a large number of studies on the impact of extreme weather on commuter railways and urban and rural highways, and they have found that there are different reactions to extreme weather in different regions and roads [30–36]. Due to data limitations, previous studies often focused on a limited number of routes or a specific road section, which made the research results related to characteristics of certain road section [3–40]. There is a lack of studies that investigate the spatial differences in the impacts of extreme weather from a spatial perspective for large-scale transportation networks [41]. Obviously, understanding the degree of traffic impact in different regions has more practical value for emergency management and early warning analysis of traffic management departments. In terms of the selection of research indicators, most of the existing studies focus on the degree of impact of extreme weather conditions on traffic such as traffic volume [29, 33, 39], vehicle speed [36, 40, 42, 43], travel time [41, 44], traffic delays [45], travel costs [5, 42], and traffic accidents [46, 47] and adopt statistical methods to quantitatively analyse the degree of change of the above indicators caused by different weather conditions, different intensity of weather conditions, or different weather conditions interaction. Few of them involve accessibility indicators based on traffic trips. However, studies on traffic volume, speed, and other indicators of limited road sections are not only difficult to reveal the travel delays ultimately caused by extreme weather from the travel perspective but also difficult to reveal the areas of traffic congestion triggered by extreme weather for traffic management. It also does not help to explain the resilience of urban transportation systems in extreme weather.

In recent years, with the popularity of the Internet and the continuous improvement of computer data processing capabilities, the new data environment consisting of big data and open data is gradually being established [48]. The Web Service API of Internet Maps provides real-time travel times from origin to destination, providing an accurate and reliable source of data for studying changes in accessibility over a wide range [49]. In a word, the impact of extreme weather on traffic can be evaluated more accurately by using big data.

3. Material and Method

3.1. Study Area. Nanjing is an important central city in the eastern region of China and there is a relatively complete urban road network in Nanjing. Based on the scope of the main city defined in the Nanjing Master Plan (2011–2020), this paper selects the main city area enclosed by the Yangtze River and the Beltway Highway in Nanjing as the study area. The area is around 360 km^2 and is highly concentrated with manufacturing employment and services industries (Figure 1). In the plan, three subcities were identified outside the main city, namely, Xianlin in the northeast, Dongshan in the northwest, and Jiangbei in the south. In addition, the Xinjiekou area, located in the center of the study area, is the center of service industry employment and overall employment in Nanjing [50, 51]. The Hexi business district, located in the southwest of the research area, is gathering modern service industries such as the financial industry, information service industry, and high-end retail industry. It will be the business and trade center and modern international urban center, as well as the new center of Nanjing.

This paper selects 6 typical residential districts located in different subcenters (Jiangbei, Dongshan, and Xianlin) in Nanjing as study objects. The commercial housing communities in each area are closer to the subway station than the subsidised housing communities. But all neighborhoods are roughly equal in distance from the city center, the Xinjiekou area. The aim is to avoid the impact of distance from the city center and distance from rail traffic on the study results as much as possible. The specific characteristics of the residential neighborhoods are shown in Table 1.

3.2. Research Data and Methods. The study data is derived from the driving path planning interface of Gaode Map. The driving path planning interface is an HTTP interface that queries the commuting scheme from the origin to the destination by car and returns the commuting scheme data in JSON data format. The commuting scheme includes the total travel time from the departure point to the destination, the travel trajectory, the length of each road section, and road passage time. The travel time and road passage time take many factors into account, such as the road capacity, traffic congestion, and road restrictions. So the data has a high degree of reliability [49]. As commuting time is the most important factor affecting accessibility during the morning peak hours, it can reflect the impact of extreme weather to the greatest extent. It is also the most important concern for residents' commuting and can provide guidance for traffic management departments to formulate emergency measures. Therefore, this paper uses the real-time travel time of driving trips as a measure of accessibility.

$$A_{ij} = t_{ij}. \quad (1)$$

In the above equation, i is the notation for the residential district i; j is the notation for the jth grid in the main city; t_{ij} is the notation for the real-time travel time from residential district i to area j in the main city; and A_{ij} is the notation for the accessibility of traffic from residential district i to area j in the main city.

We applied the grid obtained after the equal division of the study area as the basic spatial unit. If the radius of the grid is too large, the grid center is not representative of the internal space of the grid. Meanwhile if the radius of the grid is too small, it increases the amount of data and prolongs the data collection time, resulting in poor real-time data performance. After repeated experiments, this paper concluded that a grid with a radius of 200 metres is suitable. The grid of this radius can be seen as the mean space to represent travel inside the grid. What is more, it can ensure that the data collection time is controlled within 30 minutes and guarantee the real-time travel time from residence to employment travel time.

Therefore, this paper firstly divided the study area into 200×200 m grid and used ArcGIS related tools to obtain the latitude and longitude of the form centers. The center of the grid is used as the place of employment.

After excluding the grid-shaped cores that fall into the waters, mountains, and green land, the study finally obtained a total of 7034 employment sites.

Secondly, the data of commuting plan was collected by a Python program. The total travel time, the length of each section, and the travel time were interpreted from the commuting plan. We tried to use the program to collect data on the morning peak hours (8:15 ~ 8:45) on January 23, 2018 (Tuesday, normal weather), and January 25, 2018 (Friday, snowstorm), from six typical residential areas to various employment locations (grid mass centers) in the main urban area. Finally, we got 84408 commuting plans ($2 \times 6 \times 7034$). After processing, the residence-employment matrix was input into ArcGIS to analyse the change of section speed, the change of transport accessibility, and the rangeability of accessibility.

The reduction in roadway trip speeds during extreme weather events directly results in commuting delays, which are calculated as

$$V_i = \frac{\sum_{j=1}^{n} L_i/T_j}{n}. \quad (2)$$

In the above equation, V_i is the notation for the travel speed of district i; n is the notation for the number of times the "Drive Path Planning" API returns to segment i; L_i is the notation for the length of road district i; and T_j is the notation for travel time of grid j.

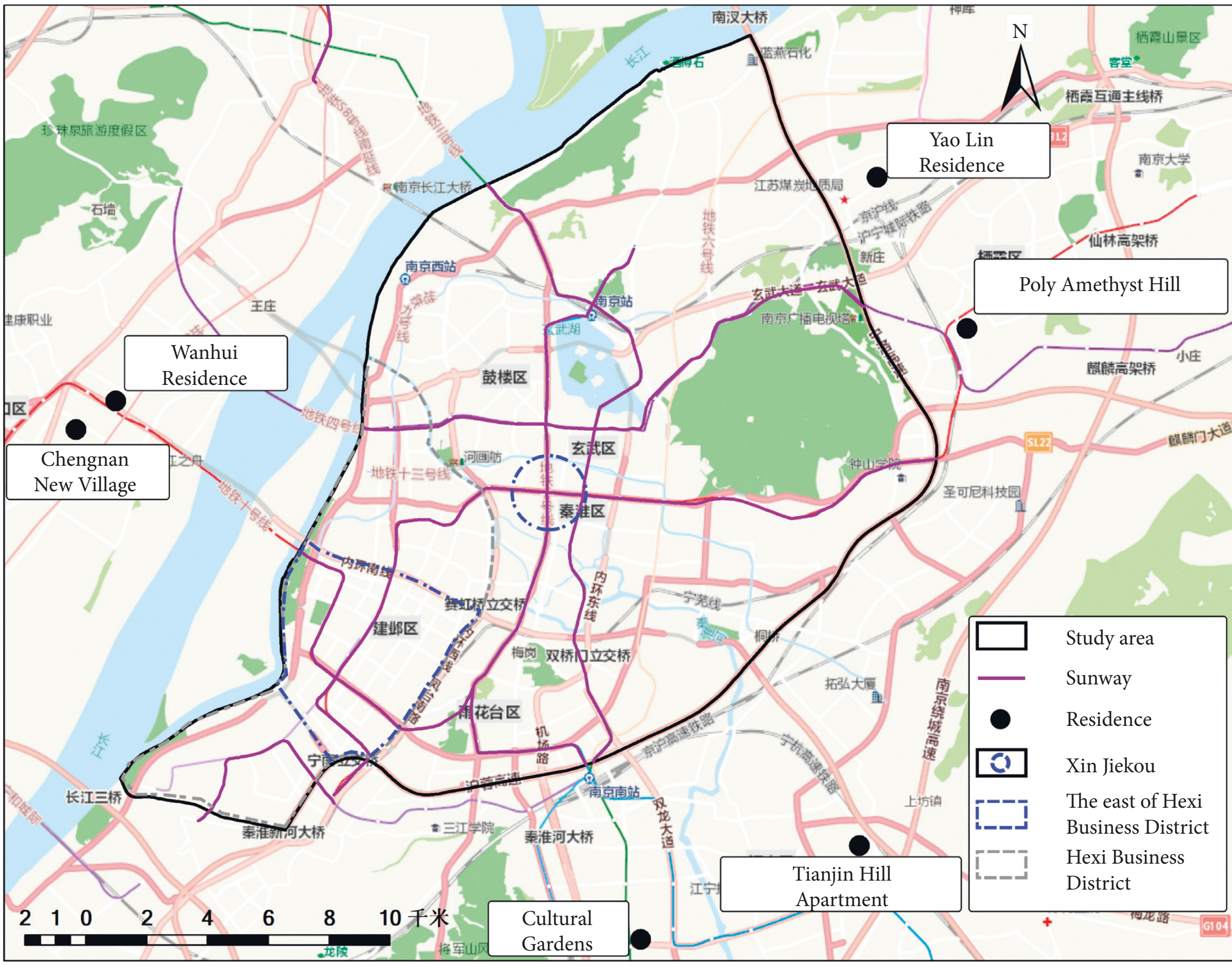


Figure 1: Location of the study area and the residential area.

Table 1: Information on residential communities.

Name	Area	Distance from Xinjiekou (km)	Features
Wanhui Residence	Jiangbei	12.1	Close to Metro Line 10
Chengnan New Village	Jiangbei	13.1	Sheltered housing, far from metro station
Cultural Gardens	Dongshan	12.7	Close to Metro Line 3
Tianjin Hill Apartment	Dongshan	13.2	Sheltered housing, away from the metro station
Poly Amethyst Hill	Xianlin	12.6	Close to Metro Line 2
Yao **Lin** Residence	Xianlin	12.8	Sheltered housing, away from the metro station

The variation in accessibility C_{ij} and the rangeability in accessibility R_{ij} can provide residents with information on travel delays from residential area i to destination j. The spatial distribution pattern of C_{ij} and R_{ij} is a good indicator for predicting areas of traffic congestion and judging the effectiveness of existing emergency measures. The change in section speed V_i will help traffic management deal with extreme weather. Variation in accessibility, C_{ij}, is defined as

$$C_{ij} = A_{\text{adverse}\,ij} - A_{\text{normal}\,ij}. \tag{3}$$

In the above equation, C_{ij} is the notation for variation in accessibility from residential neighborhood i to the main urban grid j during the morning peak hours under the influence of a snowstorm; $A_{\text{adverse}ij}$ is the notation for the accessibility of the residential neighborhood i to the main city grid j during the morning peak hours of the 25 January snowstorm; and $A_{\text{normal}ij}$ is the notation for the accessibility of residential neighborhood i to the main urban grid j during the morning peak hours in normal weather on January 23.

The rangeability in accessibility R_{ij} is defined as

$$R_{ij} = \frac{\left(A_{\text{adverse}\,ij} - A_{\text{normal}\,ij}\right)}{A_{\text{adverse}\,ij}}. \tag{4}$$

In the above equation, R_{ij} is the notation for the rangeability in accessibility from residential neighborhood i to the main urban grid j during the morning peak hours under the impact of the snowstorm.

4. Results and Analysis

4.1. Spatial Patterns of Accessibility in Normal Weather. On January 23, the travel time of residents in the morning peak of normal weather was mostly within 1 hour and 10 minutes (Figure 2). Since Nanjing's annual traffic report showed that the maximum travel time that most Nanjing residents can tolerate was 45 minutes, the study compared the extent of 45 minutes for different subcenter residential communities and different types of residential communities to reach the main urban area.

The results showed that the average 45-minute reachable range of the main urban area for residential areas in Jiangbei was the smallest in the three regions (Jiangbei, Xianlin, and Dongshan). Wanhui Residence only reached 53.4% of the main urban area in 45 minutes and Chengnan New Village reached 42.6%. This is due to the fact that the residential areas in Jiangbei need to travel across the river to the main urban area through the congested Yangtze River Tunnel and Yingtian Avenue Elevated Highway. In addition, the ratios of short distance travel (20 minutes) reachable range and 45-minute reachable range in Jiangbei residential area are 0% and 0%. The ratios of 30-minute reachable range and 45-minute reachable range in Jiangbei residential area are 9.0% and 5.1%, which are much less compared to those in Dongshan and Xianlin (Table 2). Poly Amethyst Hill and Yao Lin Residence in Xianlin had the largest reachable area in 45 minutes, with 80.6% and 75.1% of the main city area, respectively, while Cultural Gardens and Tianjin Hill Apartments in Dongshan could only reach 45.8% and 66.0% of the main city area in 45 minutes (Table 2).

Overall, the accessibility range to the main city of the subsidised housing estates in Jiangbei and Xianlin (Chengnan New Village and Yao Lin Xianju) was smaller than that of the commercial housing located in the area (Wanhui Residence and Poly Amethyst Hill). The gap between the accessibility ratios of affordable housing (Chengnan New Village) and commercial housing (Wanhui Residence) in Jiangbei was as high as 10.8%. Although Tianjin Hill Apartments in Dongshan was affordable housing, due to its close proximity to Dongshan hub and Gaoqiaomen hub, it could reach the main city in 45 minutes, which is better than the commercial housing community in Dongshan (45.8%) (Table 2).

4.2. Analysis of the Impact of Extreme Weather Events on Accessibility

4.2.1. Analysis of Variation in Accessibility. This paper analysed variation in accessibility under the influence of blizzard weather for trips with less than 45 minutes of normal weather on January 23. The proportion of the variation in accessibility from Jiangbei Wanhui Residence and Chengnan New Village to the main city was only 6.2% and 14.1% in the range of −5 to 5 minutes, showing a bimodal distribution pattern. However, the proportion of the remaining four residential areas with accessibility changing between −5 and 5 minutes is above 66.6%, indicating that the travel time of the Jiangbei residential area was most seriously affected by the snowstorm. The travel time fluctuations of Poly Amethyst Hill and Yao Lin Residence in Xianlin were the smallest, with 93.9% and 92.9% of the accessibility variation in −5 to 5 minutes, respectively. 84.2% of the accessibility variation of Cultural Garden in Dongshan was gathered in −5 to 5 minutes. Tianjin Mountain Apartments Chunxiu Yuan travel time was mainly increasing, with 84.2% accessibility variation in the range of 0 to 10 minutes (Figure 3(a)). In addition, the overall distribution of the frequency of variation in all residential areas showed that 66.7% of the variation in accessibility was within 5 minutes and 92.6% was within 10 minutes (Figure 3(b)).

Some studies have shown that extreme weather affects residents' travel speed, travel comfort, and travel time reliability, which in turn affects their flexible travel needs such as recreational and sports activities and shopping. Therefore, the travel volume of the rest day with the flexible travel needs is affected seriously by the extreme weather [52, 53]. However, the study period (January 25, January 23 morning peak 8:15 ~ 8:45) was mostly for work, school, and other nonflexible commuting trips, so the total travel volume in the main city on the day of the snowstorm (January 25) was basically unchanged. On the one hand, a large number of bus lines in Nanjing were temporarily suspended during the snowstorm that day, so the ground bus passenger flows poured into the subway. The data released by the Nanjing Metro Group showed that the entire rail transit network carried 3.155 million passengers, but the passenger flow of Line 1, Line 2, Line 3, and Line 10 in the urban area increased by less than 6.3%, 4.9%, 4.0%, and 6.9%, respectively. The passenger flow of Line 4 in the urban area increased by only 25,000. Therefore, it can be considered that the growth of passenger flow in rail transit mainly comes from the ground bus outage. However, a small number of private car owners might choose the subway mode to commute and some employment units allowed employees to postpone their work hours during blizzard weather. So it can be assumed that the total number of car trips during the morning peak hours is relatively small and the reduction was not significant. Therefore, the increase (less than 7%) in subway traffic and the relative reduction in car trips were not major factors in the reduction of pressure on surface roads and would not cause a significant reduction in commuting time by car mode during snowstorms.

On the other hand, for the same origin and destination, there was a possibility that the morning peak accessibility under both normal kinds of weather is not exactly the same, which results in a negative error in accessibility change. The absolute variation of 92.6% in 10 minutes was within a reasonable error range, indicating that the delay of morning peak travel in Nanjing under the influence of snowstorm was not obvious. The traffic management strategy, overnight snow removal and other works, was effective and ensured the normal commute.

Exploring the spatial distribution of accessibility variation to reveal the scope of travel delay and traffic congestion in each region, we found that there were significant spatial differences in the distribution of accessibility variation in the

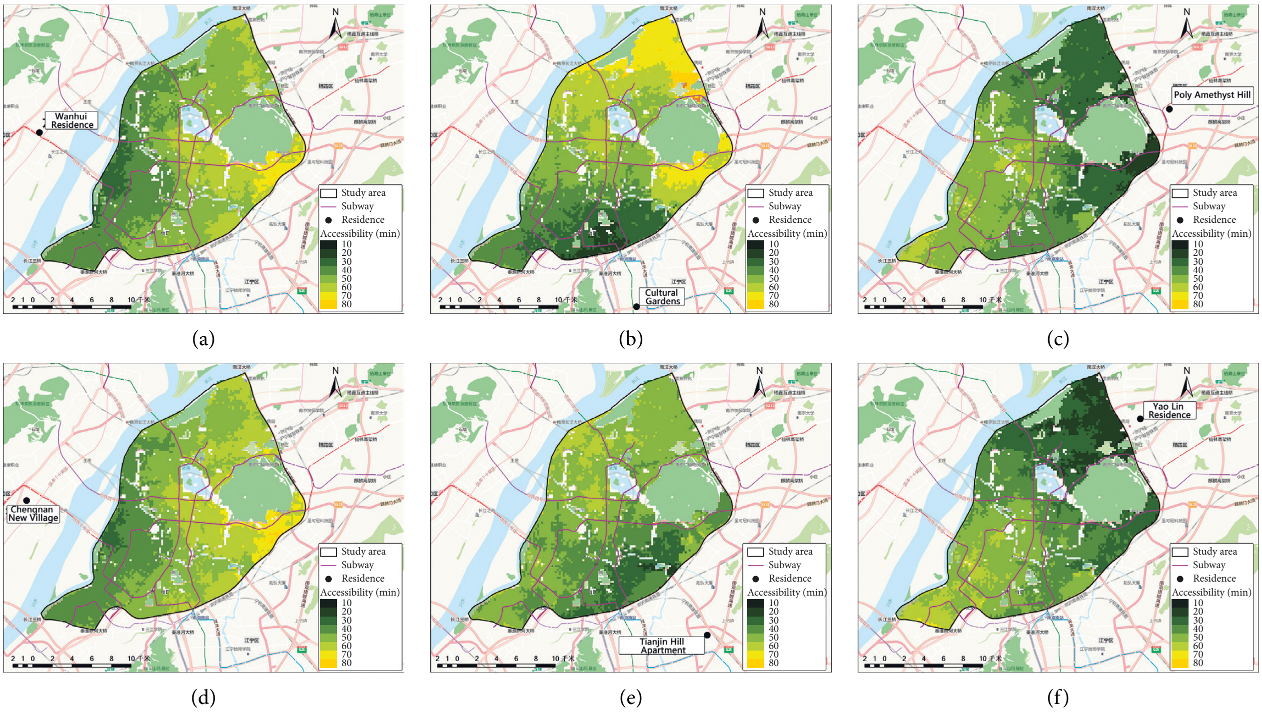
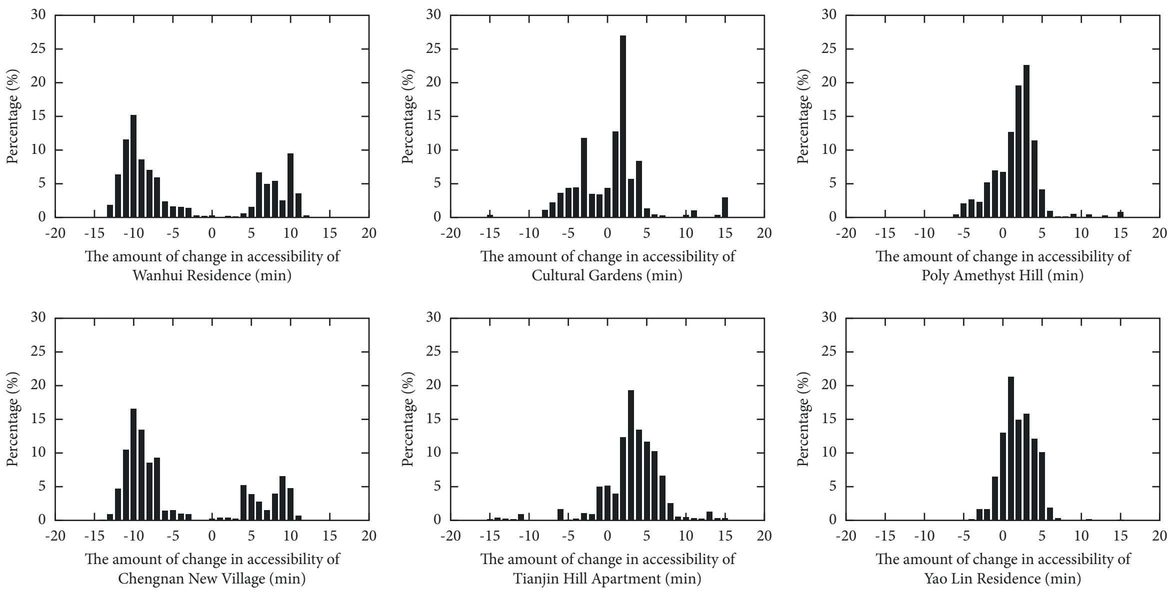


Figure 2: Access to the main city by residential areas in the morning peak on January 23 (normal weather). Commercial housing blocks: (a) Jiangbei Wanhui Residence, (b) Dongshan Culture Gardens, and (c) Xianlin Poly Amethyst Hill. Sheltered housing: (d) Jiangbei Chengnan New Village, (e) Dongshan Tianjin Hill Apartments, and (f) Xianlin Yao Lin Residence.

Table 2: Proportion of different reachable ranges from each residential area to the main city in the morning peak on January 23 (normal weather).

Name	Area	Characteristic	45-minute reachable area/ area of study (%)	10-minute reachable range/ 45-minute reachable range (%)	20-minute reachable range/ 45-minute reachable range (%)	30-minute reachable range/ 45-minute reachable range (%)	40-minute reachable range/ 45-minute reachable range (%)
Wanhui Residence	Jiangbei	Commercial	53.4	0	0	9.0	65.3
Chengnan New Village	Jiangbei	Subsidised	42.6	0	0	5.1	66.3
Cultural Gardens	Dongshan	Commercial	45.8	0	6.8	37.4	77.9
Tianjin Hill Apartments	Dongshan	Subsidised	66.0	0	1.0	16.2	57.7
Poly Amethyst Hill	Xianlin	Commercial	80.6	0.2	5.6	41.1	73.5
Yao Lin Residence	Xianlin	Subsidised	75.1	0.2	15.4	45.2	82.1

study area. The traffic accessibility variation of Wanhui Residence and Chengnan New Village in Jiangbei residential area was divided by the exit of the Yangtze River Tunnel, and the travel time decreased by 5 to 10 minutes to the south and increased by 0 to 10 minutes to the north (Figures 4(a) and 4(d)). In the online map, Yangtze River Tunnel, Yangtze River Avenue, Zhenghe Middle Road, Huaidingmen Street, east Shofu Road, and so on are selected for the planning of cross-river travel routes in Jiangbei residential areas. Commuting times on these roads were the most affected and were congested during heavy snowstorms. For example, the Yangtze River Tunnel's passage time rose from 6.76 minutes to 13.71 minutes on January 23, leading to an increase in travel time to the north. In contrast, the passage time of the Yangtze River Tunnel in the south during snowstorms was 5.9 minutes, and the road conditions were clear. While it



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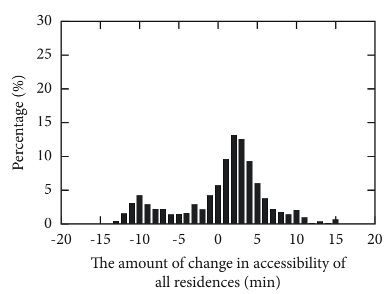
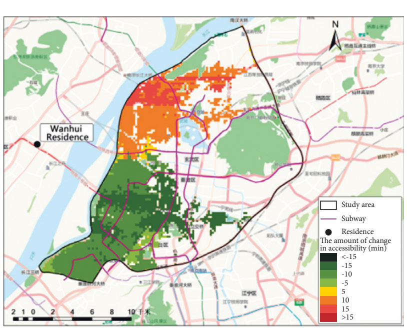


(b)

Figure 3: Frequency distribution of the amount of variation in temporal accessibility for each residential district (a) and all residential districts (b). (a) Various residential communities. (b) All residential communities.



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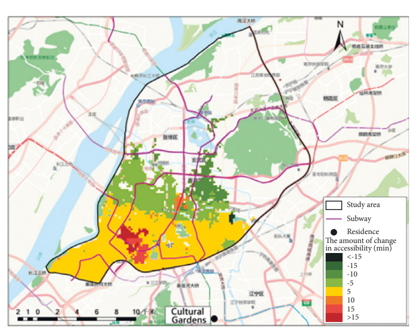

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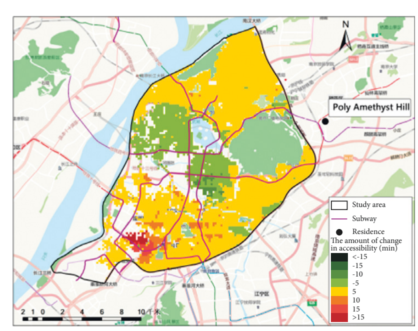
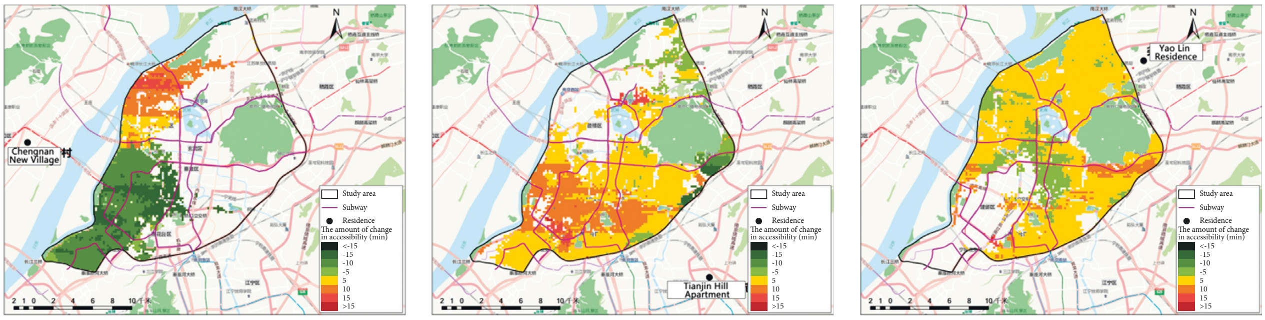


(c)

Figure 4: Continued.



(d) (e) (f)

Figure 4: Amount of change in traffic accessibility under the impact of 25 daily snowstorms. (a) Jiangbei Wanhui Residence, (b) Dongshan Culture Park, (c) Xianlin Poly Amethyst, (d) Jiangbei Chengnan Xincun, (e) Dongshan Tianjingshan Apartments Chunxiu, and (f) Xianlin Yao Lin Xianju.

took 10.8 minutes to pass the road on January 23, the travel time of the south tunnel exit was reduced meantime.

The change in accessibility of Dongshan and Xianlin residential areas showed a decrease of 0–10 minutes in travel time (Figures 4(b), 4(c), and 4(f)) and an increase of 0–10 minutes in travel time in the peripheral study areas (Figures 4(b), 4(c), 4(e), and 4(f)). The decrease in travel time in the city center was partly due to the relative reduction in the number of car trips but more importantly due to the overnight snow removal by hundreds of thousands of people in Nanjing on January 24. The outer areas of the study area were not the key area of the snow removal work, so the travel time increased by 0~10 minutes due to the impact of the snowstorm on the road's skid resistance and travel speed.

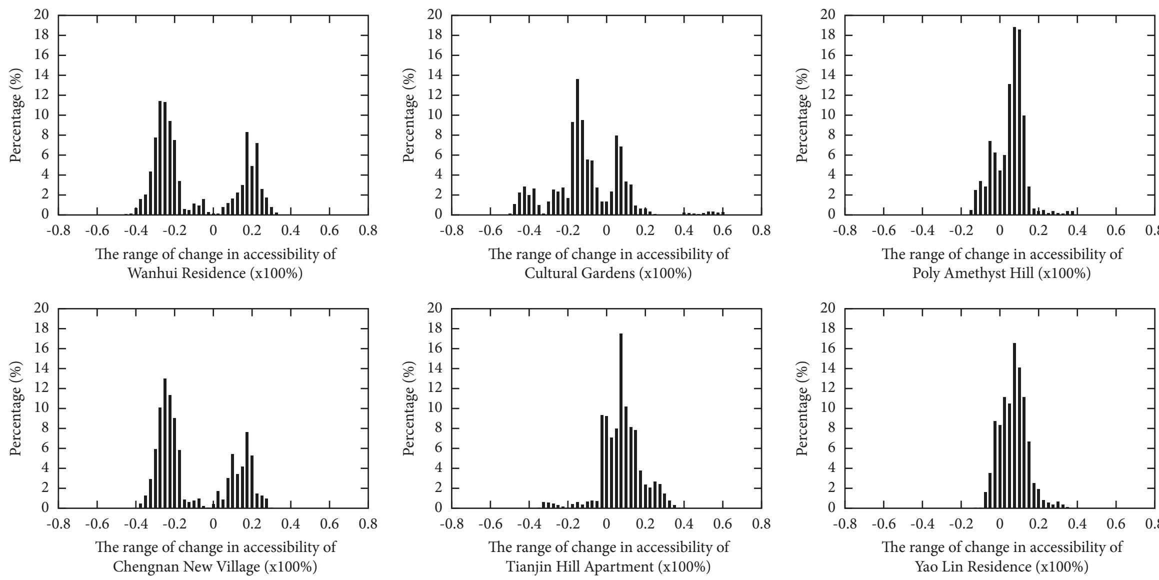
In particular, the commuting time around the sections of Hexi Street along Jiangzhongdong Road, Lushan Road, Huangshan Road, Taishan Road, and Fengtai South Road in the Hexi business district increases by 10~15 minutes or even more than 15 minutes (Figures 4(b), 4(c), and 4(e)). As a subemployment center, the Hexi business district has wide roads, such as Mengdu Avenue and Hexi Avenue, with a red line width of 50 to 80 meters on the main road and 35 to 40 meters on the red line of the secondary trunk road. Reliability of travel times for cars is highly dependent on road conditions. Wide roads are conducive to car trips in normal weather conditions. However, in the case of blizzard weather, the travel time of the car increased by up to 17.69 minutes compared with normal weather. Due to its close proximity to the Dongshan hub and Gaoqiao Gate hub, the accessibility of Tianjin Hill Apartments is closely related to the hub's operational status. Highways are strongly affected by extreme weather. Therefore, 87% of the commute time within the 45-minute reachable study area of Tianjin Hill Apartments increased under the impact of snowstorm (Figure 4(e)).

According to the results of the analysis, the current snow removal work carried out by the traffic management authorities did work. Most residents had travel delays within 10 minutes and the commuting time to Xinjiekou was reduced. But the actual capacity of the Hexi business area, the exit area of the cross-river tunnel, and the road sections near the transportation hubs were greatly affected during the snowstorm and became the main areas of commuting delays. These road sections should be viewed as important areas for traffic management to implement measures to prevent traffic congestion in extreme weather and to enhance the resilience of the transport system in the future.

4.2.2. Analysis of Rangeability in Accessibility. For all trips in normal weather on January 23, this paper analysed the rangeability in accessibility under the influence of the snowstorm.

The frequency distribution of the change in accessibility from Wanhui Residence and Chengnan New Village in Jiangbei to the main city area shows a bimodal pattern, with 81.3% in the range of −40% to −20% and 82.2% in the range of 20% to 40%, respectively. While 75.6% of the variation in accessibility of Dongshan Cultural Garden ranged from −20% to 20%, the variation of Tianjin Hill Apartments was overwhelmingly positive, with 78% of the variation ranging from 0 to 30%. The frequency distribution of the change in accessibility of Poly Amethyst Hill and Yao Lin Residence in Xianlin to the main city shows a symmetrical pattern, and both of them have a frequency of change of more than 96.0% between −20% and 20%, respectively, indicating that the accessibility of Xianlin residential area to the main city is minimally affected by the snowstorm (Figure 5(a)). The distribution of the total frequency of accessibility changes in the six residential communities shows that 72.1% of the frequencies are located at −20%–20% (Figure 5(b)).

Similarly, the spatial distribution pattern of accessibility rangeability is consistent with the accessibility variability pattern. For example, the variability in accessibility from residential area in Xianlin to the city center, the Xinjiekou area, is less than −20%, while that to peripheral areas is concentrated in 0–20%. The rangeability in accessibility from residential area to the Hexi business district is relatively large by 20%–40% (Figure 6). The results of the analysis also indicate that the traffic management department should focus on the implementation of management in the future when dealing with snowstorms. The results of the analysis also show that when the traffic management department responds to blizzard weather, it is necessary to include the Hexi business district in the implementation focus of the management work.



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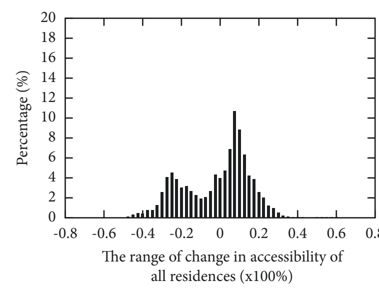
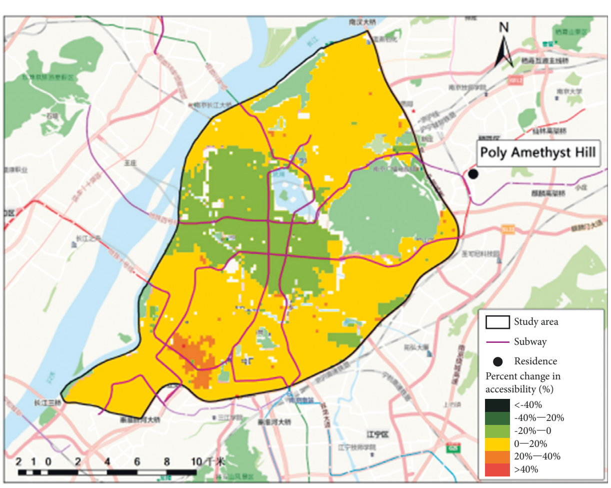
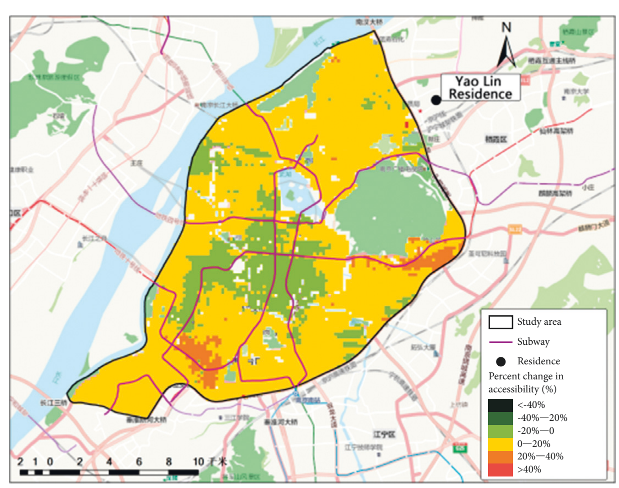


(b)

FIGURE 5: Frequency distribution of the rangeability in temporal accessibility for each residential area (a) and all residential areas (b). (a) Various residential communities. (b) All residential communities.



(a)



(b)

FIGURE 6: Rangeability in accessibility to Xianlin under the impact of snowstorms. (a) Xianlin, Poly Amethyst Hill, commercial housing complex. (b) Xianlin, Yao Lin Residence, sheltered housing.

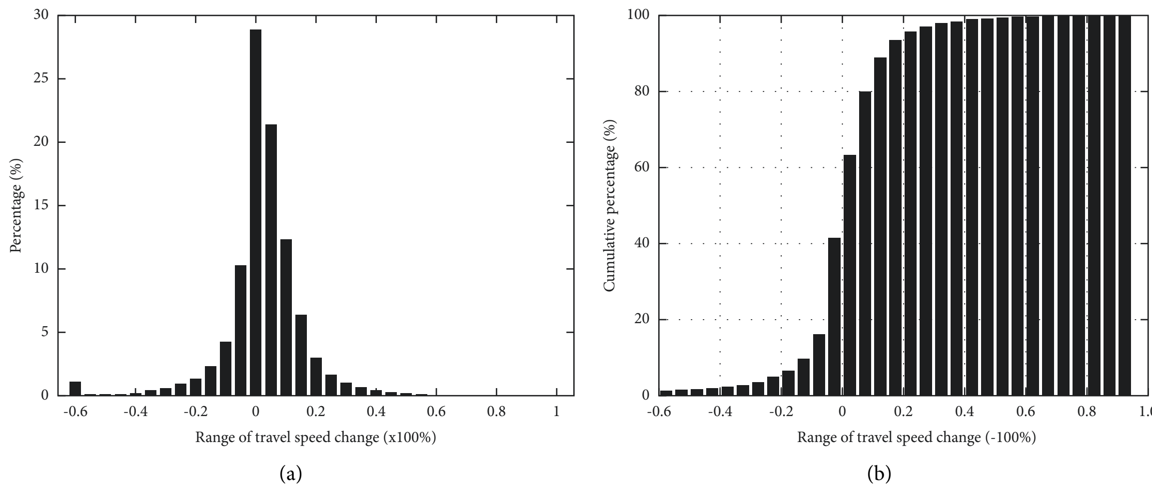


Figure 7: (Snowstorm) Frequency distribution of the magnitude of travel speed changes (a) and cumulative frequency distribution (b) by road section during the morning peak hour.

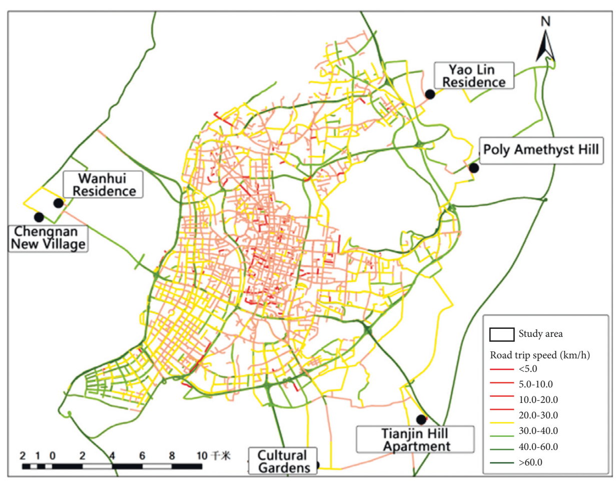


Figure 8: Spatial distribution of journey speeds by road section in the morning peak on January 23 (normal weather).

4.3. Analysis of the Impact of Extreme Weather Events on Section Speeds. The heavy snow weather has an impact on the accessibility of residents by affecting the capacity of roads, including the section speed and the travel time of the road section. Therefore, it is necessary to analyse the changes in section speed before and after the snowstorm to further identify the weak road sections and areas in the road network. Another purpose is to explore the main roads which lead to the difference between the spatial distribution of the accessibility change and the change range to provide the traffic management departments with a more accurate distribution of the affected roads.

The results show that 4.9% of the morning peak travel speed increased during the snowstorm (January 25), while 95.1% of the road travel speed decreased. In terms of the speed-decreased road section, 88.8% concentrated in the decline of 20%, 9.9% concentrated in the decline of 20% to 25%, and only 1.3% concentrated in the decline of more than 50% (Figure 7). The result proves the effectiveness of emergency management. Variation in trip speed within 20% on downtown sections is shown in Figure 8. The sections with obvious reduction in speed are concentrated in the Yangtze River Tunnel, Caochangmen Street, Dinghuaimen Street, Hanzhongmen Avenue from Jiangbei across the river to the main city, Yuhua West Road, Jiangdong Middle Road, Leshan Road, Yicheng Road, and various transportation hubs leading to Hexi business district (Figure 9). The above section directly causes significant commuting delays to the Hexi business district.

Although Metro Line 3 shared the travel volume for cross-river travels in Jiangbei District, the cross-river tunnels and tunnels exits were most severely affected by the snowstorm, and then led to serious congestion. Downtown with Xinjiekou as the center was the key area of Nanjing's snow removal work, so the travel speed change was not large in this region. In the Hexi business district, the traffic flow during the morning rush hour on the roads is large, and the speed of the trips on the main roads is reduced obviously,

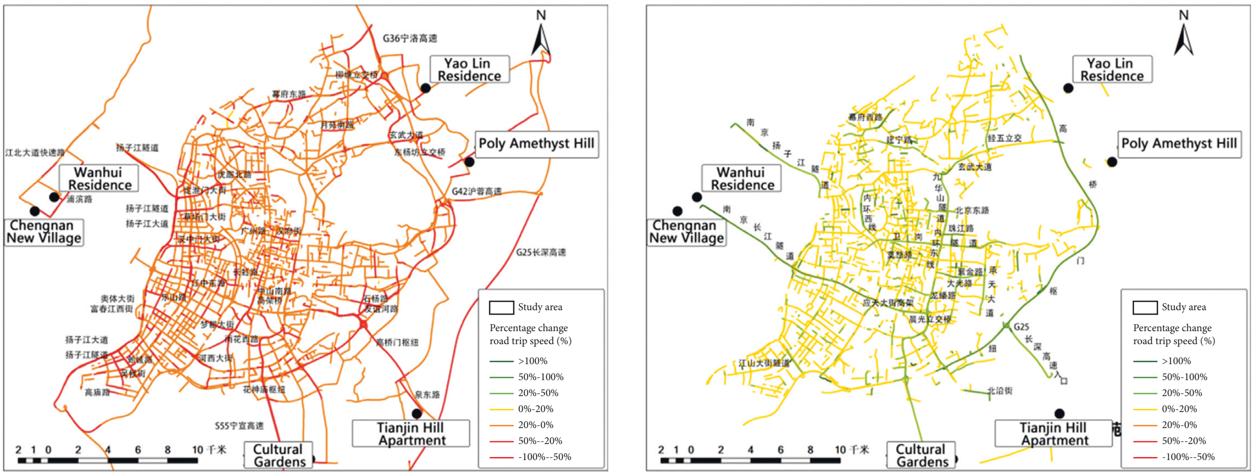


FIGURE 9: Spatial distribution of trip speed variation by road section in the morning peak on January 25 (snowstorm).

which causes the change of the accessibility in the area to exceed 15 minutes and the change range is as high as 20%~40%. In the future, it should be a key area for traffic management departments to deal with extreme weather.

5. Conclusions and Future Work

The widespread use of big data provides a new means to study the impact of extreme weather events on transport operational efficiency. Using real-time travel data from Gaode Map, this paper analyses the changes in the accessibility of residents to Nanjing's main city area on snowstorms from the time and space dimensions and probes the potential influencing factors. The outcomes of this study will help decision-makers formulate emergency management operations and measure the resilience of transport system. The main findings are as follows:

(1) The result of variation in accessibility for trips within 45 minutes shows that the Jiangbei residential neighborhood has the largest fluctuations in accessibility. The variation in accessibility in Xianlin residential district is the smallest with over 90% within 5 minutes. However, 90% of the 45-minute travel variation in all residential areas is within 10 minutes. In terms of spatial distribution, the travel time from Xianlin and Dongshan residential areas to the main city decreases in the downtown area and increases in the peripheral areas. The Jiangbei residential area is divided into a north-south pattern with boundary of the Yangtze River Tunnel.

(2) The result of variation in accessibility for all-time trips shows that over 70% of the variation in accessibility is between −20% and 20%, with 95% in the Xianlin residential area. In addition, the spatial distribution pattern of the rangeability of accessibility is consistent with that of the variable.

(3) The traffic travel in Nanjing in the snowstorm weather during morning peak is basically normal, which is mainly attributed to the overnight snow removal. The intensity of snow removal efforts, changes in road conditions on major sections of the travel path, the proximity of residential neighborhoods to transport hubs, the traffic volume, and road design of destinations are all potential influencing factors for changes in accessibility.

(4) The section speed of Nanjing's cross-river passages, tunnel exit sections, and roads in the Hexi business district are affected by the snowstorm by a relatively large margin, and the commuting delays in the Hexi business district are most pronounced. In formulating measures to deal with snowstorms in the future, the traffic management departments should not only focus on snow removal in the Xinjiekou area but also strengthen efforts on emergency management directed at the cross-river channel, Hexi Street in the Hexi business district, Mengdu Street, Olympic Sports Street, and Yecheng Road. The above road sections are key to avoiding morning peak traffic congestion in the Hexi business district as well as to ensuring the reliability of commuting times for residents from Jiangbei, since the decline in actual capacity is the main cause of travel delays for residents.

This paper has some limitations due to the availability of data compared to existing achievements. For example, the methodology employed in this paper fails to take employment into consideration in the calculation of accessibility. However, destination attractiveness has an impact on resident travel. In addition, due to the lack of traffic flow data, we failed to combine the change of road travel speed with the change of traffic flow for analysis, which is weak in mechanism explanation. In the future, the researchers should try to break through the limitation of data in snow days and build a model to analyse the relation between the intensity of snow and accessibility, which will assist managers to set up a reasonable traffic management measures, provide travel delays warning information for urban residents, and promote the development of urban traffic management in the direction of the refinement. It will also make the assessment of urban resilience more accurate and scientific [54–56].

Data Availability

All of the travel data in this manuscript were taken from the application programming interface (API) of Gaode Map, a famous and the largest map navigation app in China owned by ALIBABA. The key data, real-time travel time or travel time consumption, are obtained from Route Planning API of Gaode Map. Travel speed of each road is obtained from Traffic Situation API of Gaode Map.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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