Spatial accessibility of emergency medical services under inclement weather: A case study in Beijing, China

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Abstract

The accessibility of emergency medical services (EMSs) is not only determined by the distribution of emergency medical facilities but is also very vulnerable to weather conditions. Inclement weather could affect the efficiency of the city's traffic network and further affect the response time of EMSs, which could therefore be an essential impact factor on the safety of human lives. This study proposes an EMS-accessibility quantification method based on selected indicators, explores the influence of inclement weather on EMSs accessibility, and identifies the hotspots that have difficulty in

25 accessing timely EMSs. A case study was implemented in Beijing, which is a typical

26 megacity in China, based on the ground-truth traffic data of the whole city in 2019. The

27 results show that inclement weather has a general negative impact on EMSs

28 accessibility. Under inclement weather scenario, the area in the city that could get EMSs

29 within 15 minutes would decrease by 13% compared to normal scenario (the average

30 state of weekdays without precipitation), while in some suburban townships, the

31 population that could get 15-min EMSs would decrease by 40%. We found that snowfall

32 has a greater impact on the accessibility of EMSs than rainfall. Although on the whole,

33 the urban area would have more traffic speed reduction, towns in suburban with lower

34 baseline EMSs accessibility are more vulnerable to inclement weather. Under the worst

35 scenario in 2019, 12.6% of population (about 3.5 million) could not get EMSs within

36 15 minutes, compared to 7.5% with the normal condition. This study could provide a

37 scientific reference for city planning departments to optimize traffic under inclement

38 weather and the site selection of emergency medical facilities.

39

40 **Keywords**

41 Emergency medical services (EMSs), spatial accessibility, inclement weather, service

42 area coverage

1 Introduction

Emergency medical services (EMSs) are a pivotal part of the public health system, and the response time of EMSs is a vital factor in decreasing morbidity and improving survival (Blackwell and Kaufman, 2002). In China, the EMS system is mainly composed of prehospital emergency services and in-hospital emergency services. Prehospital emergency service refers to on-site emergency treatment, guardianship in transit, and handover with in-hospital emergency institutions. The efficiency of emergency services is highly vulnerable to inclement weather conditions such as rain, snow, frog, etc. The reason why inclement weather conditions would reduce the efficiency of emergency services is that inclement weather conditions would reduce road capacity, increase transfer time, and sometimes block roads completely (Agarwal et al., 2006; Chang et al., 2013; Cools et al., 2010; Suarez et al., 2005; Zhang and Chen, 2019), which leads to the reduction of spatial accessibility and delay of response time. In addition, accidents such as traffic accidents and lightning accidents are more prone to occur in inclement weather, which increases the demand for EMSs (Edwards, 1996; Ramgopal et al., 2021). For example, on July 21, 2012, Beijing was hit by a rainstorm, with the average cumulative rainfall reaching 170.0 mm, caused 63 roads to be seriously flooded. This rainfall event led to a one-third increase in the number of calls to the emergency center, and the transfer time of ambulances was significantly prolonged, taking approximately 1.5~2 hours for each evacuation during the rainstorm. Usually, the transfer time would not be more than 1 hour. (Wang et al., 2013; Beijing Evening,2012) On February 6, 2022, in Cleveland, US, an ambulance got stuck in the snow causing a long delay getting the patient to the hospital (Fox 8 News, 2022). On August 3, 2021, in Chattogram, Bangladesh, a daily rainfall of 190.6 mm caused many

67   ambulances with patients stuck in different areas of the city (Business Standard, 2021).

68   In the context of global climate change and rapid urbanization, extreme inclement

69   weather events strike cities more frequently (Huber and Gulledge, 2011; Stott, 2016;

70   Stott et al., 2016), the problem of urban rainstorms and waterlogging (the phenomenon

71   of a stagnant water disaster in an urban area due to heavy rainfall or continuous

72   precipitation) has become increasingly prominent. It is therefore of great importance to

73   investigate the influence of inclement weather on the spatial accessibility of EMSs.

74   The spatial accessibility of EMSs is defined by the travel impedance (distance or

75   time) between service locations and the scene (Guagliardo, 2004). A large body of

76   research on spatial accessibility is concerned with access to hospitals (Luo and Wang,

77   2003; Mao and Nekorchuk, 2013; Pan et al., 2018; Yang et al., 2020; Yin et al., 2021)

78   and first-aid stations (Hashtarkhani et al., 2020; Jones and Bentham, 1995; Shin and

79   Lee, 2018). To measure the EMSs accessibility, the two-step floating catchment area

80   (2SFCA) method is one of the common methods (Chen and Jia, 2019; Kanuganti et al.,

81   2016; Li et al., 2021; Luo and Qi, 2009). The 2SFCA method considers accessibility to

82   be mediated by not only the distance decay but also the interactions between supply

83   and demand (Chen and Jia, 2019), which is more suitable for normal scenarios. While

84   in the studies focusing on the influence of inclement weather on EMSs, people are more

85   concerned about the transportation situation, instead of the interaction between supply

86   and demand. The coverage analysis method (Coles et al., 2017; Green et al., 2017; Yu

87   et al., 2020) or shortest path analysis method (Albano et al., 2014; Andersson and

88   Stålhult, 2014) are more widely used. These methods could better characterize the

89   reduction of accessibility caused by the road service degradation. For example, Yu et

90   al. (2020) analyzed the accessibility of emergency service in England and identified

91   vulnerability hotspots by quantifying the EMSs coverage of area and population within

92   different time radii under different flood scenarios; Coles et al. (2017) measured the

93   travel time and service area coverage of EMSs in York, UK under flood scenarios by

94   using FloodMap-HydroInundation2D to model flood inundation; Yin et al. (2021)

95   assessed the vulnerability of EMSs to surface water flooding in Shanghai, China by

96   quantifying accessibility in terms of service area, population coverage and response

97   time, and the results show that EMS coverage could decrease up to 13% under 100-

98   year surface water flooding; Andersson and Stålhult (2014) used network analysis

99   methods to generate the shortest paths from hospitals to various administrative areas in

100   Manila, Philippines, and evaluated the impact of different flood events on these paths.

101   Most of these studies assumed that roads are impassable or traffic speed has a certain

102   degree of reduction when the flooded water depth reaches a specific depth, and further

103   evaluated the impact of rainstorm on EMSs accessibility. Due to insufficient recorded

104   traffic data, relatively few studies have been performed to analyze the impact of road

105   access capacity on EMSs accessibility according to actual traffic speed variation.

106   In this study, we explore the impact of inclement weather on traffic and EMS

107   accessibility based on ground-truth traffic data. Beijing which is the capital of China is

108   used as a case study. The reductions in EMSs accessibility of Beijing under inclement

109   weathers in 2019 are quantified, and the urban-rural disparities in the distribution of

110   emergency medical facilities are further analyzed. Our study provides an approach for

111   evaluating the effectiveness and fairness of EMSs based on ground-truth traffic data,

112   and the results can not only provide reference for the optimization of EMSs in Beijing,

113   but also provide reference cases for other cities, which has a great practical significance.

114

2 Study area and dataset

2.1 Study area

Beijing, the capital of China, is located in the northern part of the North China Plain, with a total area of 16,410.54 square kilometers (Figure 1a). According to the seventh national census (National Bureau of Statistics, 2021), Beijing has a population of 21.89 million. As one of the largest metropolises in the world, Beijing has a monsoon-driven humid continental climate, with an average annual precipitation of approximately 600 mm, 80% of which is concentrated from June to September (Song et al., 2014). The terrain of Beijing is high in the northwest and low in the southeast, which is conducive to the formation of heavy rain and triggers strong convective weather. Beijing has a typical monocentric urban structure, and the area within the Six Ring Road is generally recognized as the urban core area. It is obvious that the density of transportation network and medical facilities in the urban area of Beijing are much higher than those in the suburbs (Figure 1b).

(a) (b)
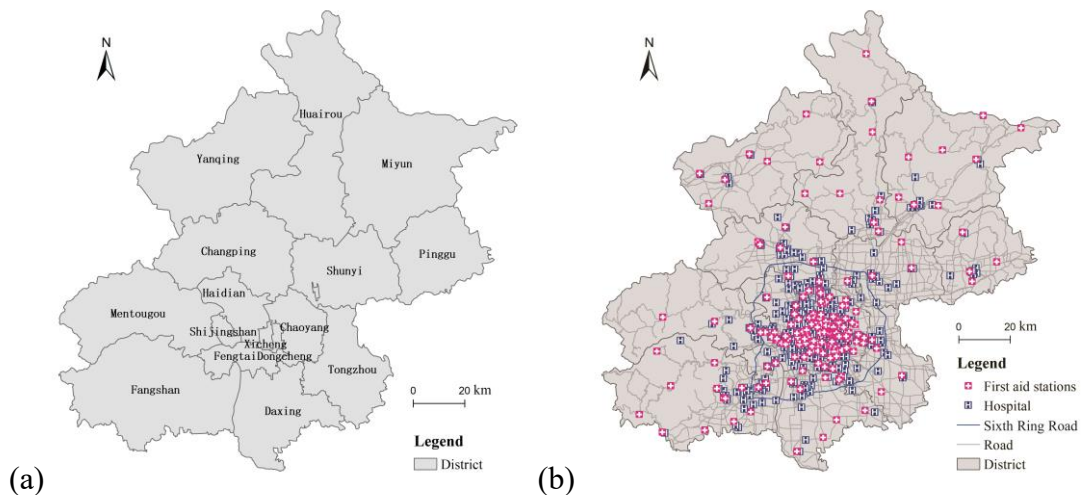
Figure 1. (a) Administrative division of Beijing and (b) EMS facility locations in Beijing, produced in ArcGIS 10.8.

133

2.2 Dataset

The data involved in this paper mainly include traffic data, meteorological data, EMSs data, and demographic data. Based on traffic data and meteorological data, we could build a topology road network (using node and edge primitives to describe interconnected linear features (roads) and points (roads junctions) on a map) with transfer time as impendence under inclement weather conditions and corresponding normal weather conditions. Combining the topology road network with medical facility locations and the distribution of the population by ArcGIS 10.8, we could further analyze the spatial accessibility of EMSs.

2.2.1 Traffic and road network data

The traffic data of Beijing are obtained from the Beijing Municipal Commission of Transport. The data span is from January 1, 2019, to December 31, 2019, including the average traffic speed (m/s) of each road section, updated every 2 min. The road network data contain 71,188 nodes and 81,523 edges, which can basically cover all the main roads in the whole Beijing area.

2.2.2 Meteorological data

The meteorological data utilized in this paper are TRMM (Tropical Rainfall Measuring Mission) precipitation data obtained from NASA, with a spatial resolution of 0.1°×0.1° (approximately 10 km×10 km) and a temporal resolution of 30 minutes. The whole city of Beijing is covered by 175 grids.

According to the classification of precipitation, moderate rain is defined as the rainfall is 5.0~14.9 mm per 12 hours (China Meteorological Administration, 2012). We

158 chose intermediate value of the interval and average it to each hour. In this study, we

159 set a rule that if the precipitation of more than 10 grids (over 5% area of the city) in

160 Beijing is greater than 1.5 mm in 2 hours, it is considered a precipitation event. The

161 average precipitation of the whole city on each date is averaged by the precipitation of

162 all grids. In 2019, 19 working days of rainfall and 3 working days of snowfall were

163 selected.

164

2.2.3 Medical facilities data

166 The medical facilities mentioned in this paper mainly refer to two categories. One is

167 the first-aid stations, and the other is hospitals, as shown in Figure 1b. The locations of

168 these first-aid stations were obtained from the distribution map of first-aid stations

169 (Beijing Emergency Medical Center, 2021), including 72 stations in the downtown area

170 and 98 stations in the suburbs. The hospital point data were extracted from the online

171 map point of interest (POI) data of Beijing in 2019 (Gaode Maps, 2021). After

172 coordinate correction and deduplication, it contains a total of 630 general hospitals, 76

173 of which are third-level grade-A hospitals (the highest level in the evaluation system of

174 hospitals in mainland China).

175

2.2.4 Demographic data

177 The demographic data of 2019 were obtained from WorldPop (2018) with a spatial

178 resolution of 100 m×100 m. The data records present the population size.

179

3 Methodology

181 Figure 2 illustrates the methodology of this study. We first divide the weather

182   conditions into two categories, inclement weather conditions and normal weather

183   conditions, according to precipitation data. Second, the time impedance of each road

184   section is analyzed based on the road network and traffic speed for both inclement and

185   normal weather conditions, and the respective coverage rate of first-aid stations and the

186   shortest transfer time to hospitals are calculated. Finally, the spatial accessibility to the

187   population is calculated, and hotspots are identified. Both the service area analysis and

188   the OD Cost Matrix analysis are GIS-based, and were done in ArcGIS 10.8. In this

189   study, we made the following assumptions: (1) The ambulances move at the average

190   speed all the time and would always take the shortest path in space; (2) In network

191   analysis, the location of facilities is approximately considered to be on the nearest road

192   point vertically; (3) In OD analysis, we use the centroid as the origin point to represent

193   the whole grid, and the shortest path to hospital of all points within the grid is the same;

194   (4) The prehospital EMSs is divided into two parts: the ambulances depart from the

195   first-aid station to the scene and from the scene to the nearest hospital; (5) According

196   to the report by Beijing Municipal Health Commission, the average response time of

197   pre-hospital emergency treatment in Beijing is about 15 minutes for the year of 2022.

198   We therefore chose 15-min as the boundary of EMSs response time in our study.

199   (Beijing Youth, 2022). The case where patients transfer directly from the scene to an

200   EMS facility via private transportation will not be considered in this study.

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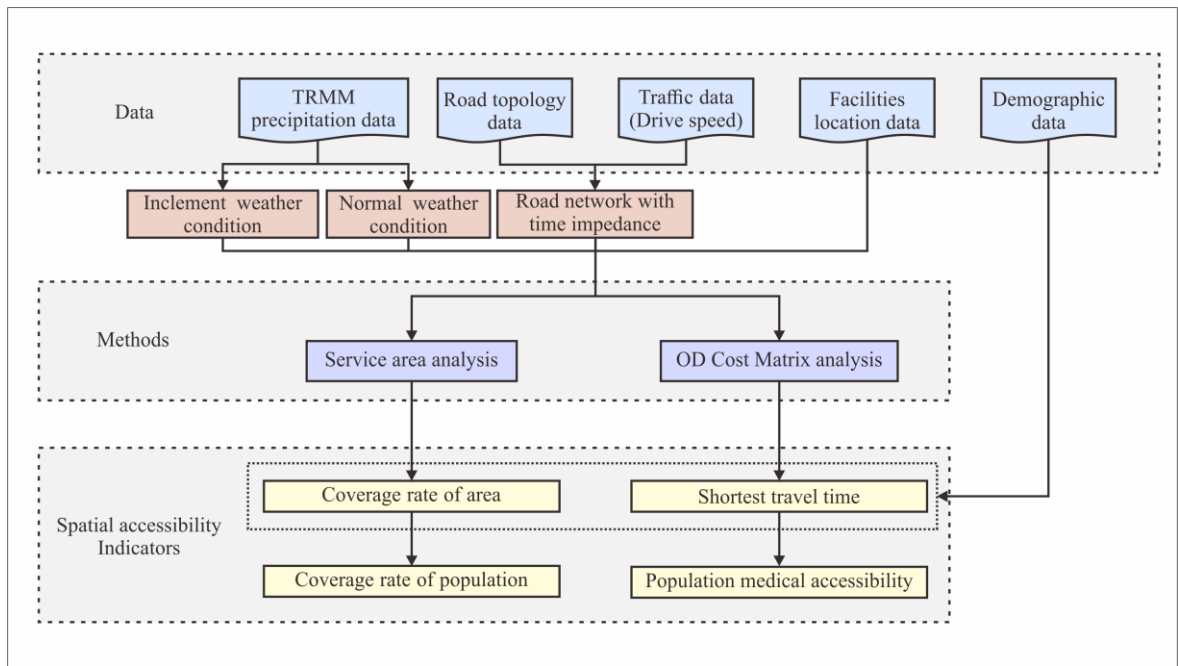
Figure 2. Methodology of this study, produced in CorelDraw 2019.

202

3.1 Fluctuation of traffic speed under inclement weather

203

204   For each weekday with precipitation, the traffic speed data of the selected period are

205 extracted and averaged. To avoid the inherent temporal variations of traffic speed

206 resulting from the day-of-week effects, holiday effects (Cools et al., 2007), season, and

207 other non-meteorological related factors, we introduce baseline days for inclement

208 weather days in this study to calculate the traffic speed fluctuation. For a given

209 precipitation day, we search for the same day of week in the two weeks forward and

210 backward to obtain the corresponding baseline days without precipitation. Only

211 nonholidays without precipitation events are selected as baseline days; otherwise, we

212 would continue to look forward or backward until four baseline days are found. The

213 average speed data of the four baseline days in the selected period were then averaged

214 as the baseline speed for the given precipitation day, and the traffic speed reduction rate

215 was calculated by eq. (1):

216
$$r_c = \frac{v_p - \frac{\Sigma_{j=0}^{m} v_{d_j}}{m}}{\frac{\Sigma_{j=0}^{m} v_{d_j}}{m}} \quad (1)$$

217 where r_c is the traffic speed reduction rate in the selected period of the precipitation

218 day to its corresponding baseline days; v_p is the traffic speed in the selected period of

219 the given precipitation day; v_{d_j} is the traffic speed in the selected period of a baseline

220 day, and m is the number of baseline days. In this case, m equals 4. The average traffic

221 speed reduction rate is obtained by averaging the reduction rates of all roads with

222 reduced speed in the city.

223 **3.2 Analysis of coverage rate**

224 **3.2.1 The coverage rate of area**

225 A service area is a region that encompasses all roads that are accessible within a

226 specified impedance. Either distance or time can be used as impedance. In this study,

227 the time needed to pass through the road is calculated by the length of each road divided

228 by its corresponding traffic speed, and the service area analysis is carried out with time

229 as the impedance. The core idea of the service area analysis function is to generate

230 service area polygons by setting each first-aid station as the starting point and the

231 traveling time as the driving radius. Under the inclement weather conditions and their

232 corresponding baseline conditions, the service area analysis of the 15-minute arrival

233 time was carried out. The total area of the obtained service area polygon is calculated

234 to obtain the EMS coverage. The coverage rate of area is calculated by eq. (2):

235
$$r_a = \frac{\Sigma A_s}{A} \times 100\% \quad (2)$$

236 In eq. (2), r_a is the coverage rate of the area; A is the total area of the city, and A_s is

237 the area of the service area.

3.2.2 The coverage rate of population

To analyze the matching degree between the EMS coverage and the population distribution and identify the hotspots whose EMS coverage of the population is most affected in inclement weather, we downscaled the calculation to the township scale. Based on the grid population data of WorldPop and the coverage areas of EMSs under different scenarios analyzed by service areas, we calculated the coverage rates of EMSs of the population for each township. In each scenario, the polygon of service area obtained from the result of service area analysis is used to mask the population grid, and the covered population divided by the total population is the population coverage of the township (eq. (3)).

$$r_p = \frac{\sum P_s}{P} \times 100\% \qquad (3)$$

In eq. (3), r_p is the coverage rate of the population; P is the total population of the township, and P_s is the population that is covered by the service area.

3.3 The spatial accessibility to hospitals

The spatial accessibility to hospitals is quantified by two indicators: the shortest transfer time and the total transfer time. The shortest transfer time is calculated by the OD (Origin-destination) cost matrix analysis method, which can find and measure the minimum cost path from multiple starting points to single or multiple destinations in the network. In this study, we calculate the minimum transfer time od_i required for each population grid centroid to reach the nearest hospital. To reduce the calculation cost, the population grid data with 100 m resolution are aggregated and converted into 1000 m resolution. This could be interpreted as a sampling method, because we use the centroid point of the grid to represent the other possible starting points in the grid, and

262   we ignored the tolerance caused by the travel time inside the grids.

263   The total transfer time is introduced to quantify the cumulative transfer time for each

264   population grid based on its population size, which is the number of potential users of

265   EMSs. It is defined in this study by the shortest transfer time of each population grid to

266   the nearest hospital multiplied by its population. For each population grid centroid i, its

267   total transfer time (T) is calculated by eq.(4):

268
$$T = od_i \times P_i \qquad (4)$$

269   In eq. (4), od_i is the minimum transfer time, P_i is the population of the grid.

270

271 **4 Results**

272   Based on the characteristics of morning and evening rush traffic flow on weekdays,

273   the diurnal variation in traffic can be divided into four periods: morning rush hours

274   (7:00-9:00), daily regular hours (9:00-17:00), evening rush hours (17:00-19:00), and

275   evening regular hours (19:00-22:00). We compared EMS coverage at different periods

276   of the day, and the results show that the period of morning rush hours has the most

277   significant negative impact on the accessibility of EMSs. We divided the city into the

278   inner city and suburban areas along the Sixth Ring Road. Taking the average 15-minute

279   coverage of the area of all Mondays in November as an example: (1) in the whole city

280   (both inner city and suburban), the coverage rate of EMSs is 38.72% in morning rush

281   hours, compared with 40% (±0.3%) in the remaining periods; (2) in the inner city, the

282   coverage rate is 77.37% in morning rush hours, compared with 83% (±0.6%) in the

283   remaining periods. Therefore, the accessibility of EMSs during the morning rush period

284   deserves more attention. Hence, our subsequent analysis is mainly concentrated on the

285   morning rush period.

286

4.1 Impact of inclement weather on the traffic and EMSs coverage

4.1.1 The correlation between precipitation and traffic speed

Figure 3 shows the relationship between average precipitation during morning rush hours in the city and the average traffic speed reduction rate of all roads that have speed loss in the city on weekdays. The unit of precipitation data is mm/2h, which indicates the total precipitation in the 2 hours of morning rush hours. The negative values indicate that the traffic speed decreases in inclement weather conditions. We could see that the average traffic speed would decrease 10%~15% on most precipitation days. The average speed decreases most on July 1st, July 9th, September 10th and December 16th, reached 18%~25%. July 1st (Party's Day) and September 10th (Teachers Day) are special days in China and the traffic speed is affected by both the inclement weather and traffic control. December 16th was a snowy day with a precipitation of 0.13 mm/2h, and snowfall has a greater impact on traffic than a rainfall with the same precipitation (Agarwal et al., 2005). Figure 4 illustrates the spatial difference of traffic speed reduction and distribution of precipitation on precipitation days. A large number of red roads (with traffic speed reduction over 10 km/h) can be observed in the 4 days mentioned above. By comparing the distribution of precipitation and traffic speed reduction on different dates in Figure 4, it can be found that the precipitation in the four days with the most severe speed reduction was moderate, and the precipitation distribution of the whole city was relatively uniform. Compared with other rain days, although the precipitation on July 5, August 9 and September 19 was larger and concentrated in the inner city, the traffic speed reduction of the whole city was not as serious as the four days mentioned above, which may be caused by the decrease of people's willingness to travel with the increase of rain.

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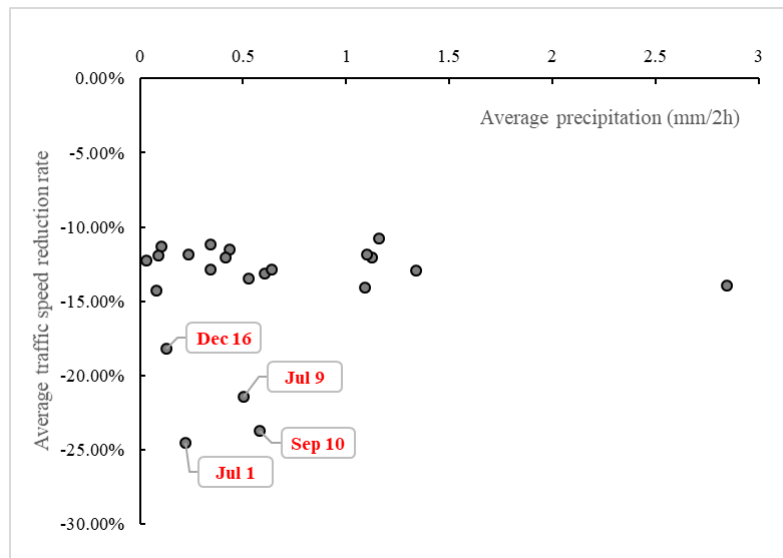


Figure 3. The correlation between average precipitation and average traffic speed reduction rate,

produced in Excel 2016.

314

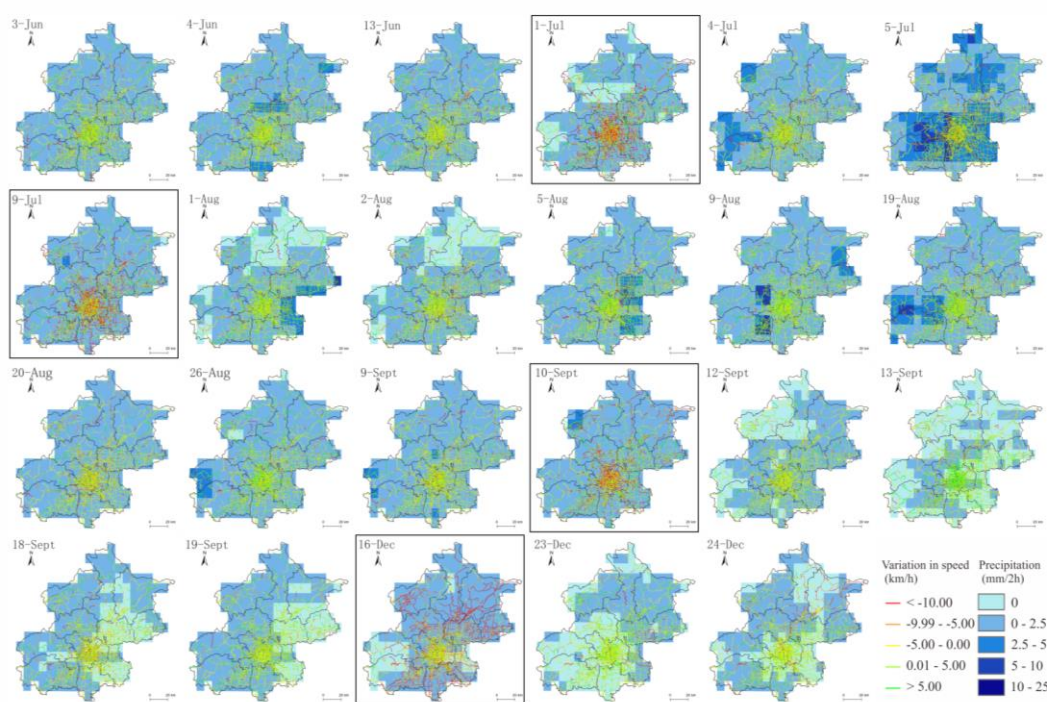



Figure 4. Variation in drive speed and distribution of precipitation on selected precipitation days

(the 4 subfigures with black borders shows the 4 most affected scenarios), produced in ArcGIS 10.8

and CorelDraw 2019.

4.1.2 The correlation between precipitation and EMSs coverage rate

The change in the coverage rate of EMSs was calculated by subtracting the coverage

320   rate under the inclement weather condition from that under the corresponding baseline

321   condition. Figure 5 shows the correlation between the average precipitation during

322   morning rush hours and the relative change values of the EMS coverage rate of the area.

323   The negative values indicate that the coverage of EMSs decreases in inclement weather

324   conditions. Consistent with the pattern of the traffic speed reduction, the worst loss of

325   coverage rate also occurred on three rainy days: 1st July (Mon), 9th July (Tue), and 10th

326   September (Tue), and one snowy day: 16th December (Mon), in which the 15-minute

327   EMS coverage rate reduced by 4.6%, 5.6%, 4.2% and 13.3%. Combined with the spatial

328   distribution of precipitation and traffic variation (Figure 4), the snowfall on December

329   16th caused a large traffic speed reduction of the suburban roads, which led to a

330   significant reduction in overall EMS coverage. In previous studies, Yin et al. (2021)

331   found that 5- and 20-year pluvial flooding both exerted less than 1% reduction in EMSs

332   coverage rate of Shanghai, China; Coles et al. (2017) found that the coverage of Fire

333   and Rescue Stations services showed a 6% reduction overall under their modelled

334   floods events in York, UK. In our study, the precipitation was less than 3mm/2h, and

335   the corresponding coverage reduction was less than 3%, except for the special four days.

336   The results are comparable to previous findings. In the following, we chose these four

337   days as the worst weather scenario of the year and analyzed the spatial differences of

338   medical accessibility in the whole city.

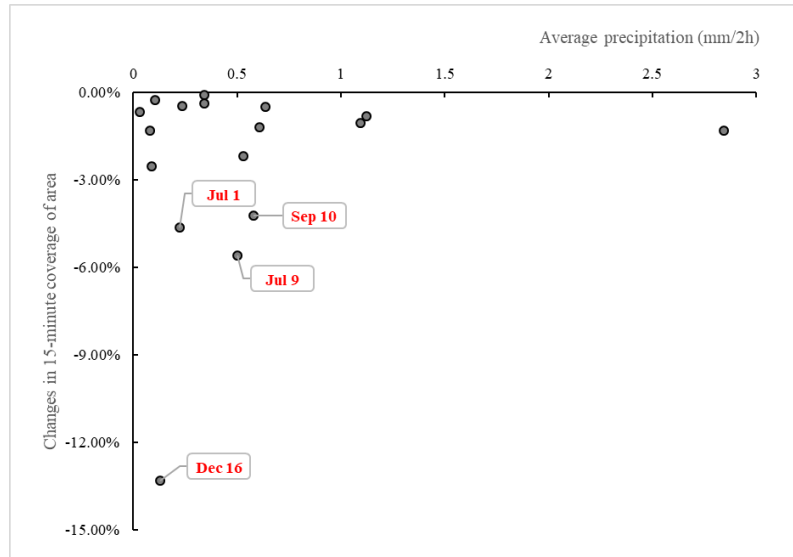



Figure 5. The correlation between the average precipitation and the relative change of the EMS coverage rate of the area, produced in Excel 2016.

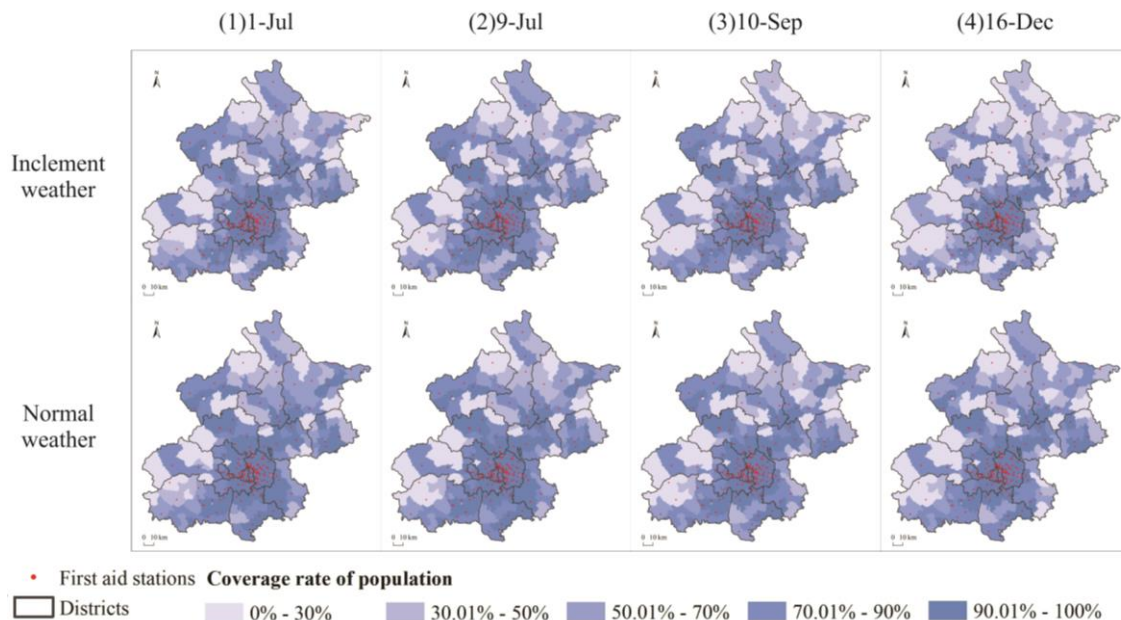
4.2 The spatial distribution of EMS accessibility under the worst scenario

4.2.1 EMSs coverage rate of population

We calculated the 15-minute EMS coverage rate of the population under the four most severely affected inclement weather conditions of 1st July, 9th July, 10th September, and 16th December and their corresponding baseline conditions at the township scale in Beijing. Figure 6 shows the 15-minute EMSs coverage rate of population under four most severely affected inclement weather conditions of 1st July, 9th July, 10th September and 16th December and their corresponding baseline conditions at the township scale in Beijing. The results demonstrate that most parts of downtown areas, including Dongcheng District, Xicheng District, Haidian District, and Chaoyang District, could have 90%–100% population coverage of EMSs, regardless of the weather conditions. In the large area of suburbs, the coverage rate of the population varied from lower than 30% to 90%. Under inclement weather conditions, the coverage rate in some towns in the suburbs would drop sharply, with the worst townships having

357 a 40% reduction. The reason behind this difference is that the distribution of first-aid

358 stations in Beijing is similar to the distribution of the road network, which is dense in

359 the central urban area and sparse in the suburbs.

361 **Figure 6.** The EMSs coverage rate of population in townships under the inclement weather condition

362 and normal weather condition on 1st July, 9th July, 10th September and 16th December, produced in

363 ArcGIS 10.8 and CorelDraw 2019.

365   To illustrate the impact of inclement weather on the EMS coverage rate of the

366 population more clearly, Figure 7 shows the change in the EMS coverage rate of the

367 population in townships in inclement weather relative to normal weather on the four

368 days. The results identify several townships in the outer suburbs (Miyun, Huairou,

369 Pinggu and Yanqing districts) that would experience the most severe decrease in

370 population coverage under inclement weather conditions, with a maximum reduction

371 of more than 40%. These areas are hotspots that need to draw attention in EMS

372 construction planning. The suburb areas, such as Shunyi, Daxing, and Tongzhou, are

373 more vulnerable to inclement weather as they have less distribution of medical facilities

374 and sparser road networks, as well have a relatively higher proportion of the elderly

population over the age of 80. The average proportion of the elderly is 1.88% in the whole city, 1.37% in the inner suburbs and 2.04% in the outer suburbs. On December 16th, 12.6% of population (3.5 million) could not get EMS within 15 minutes, compared to 7.5% with the baseline condition.

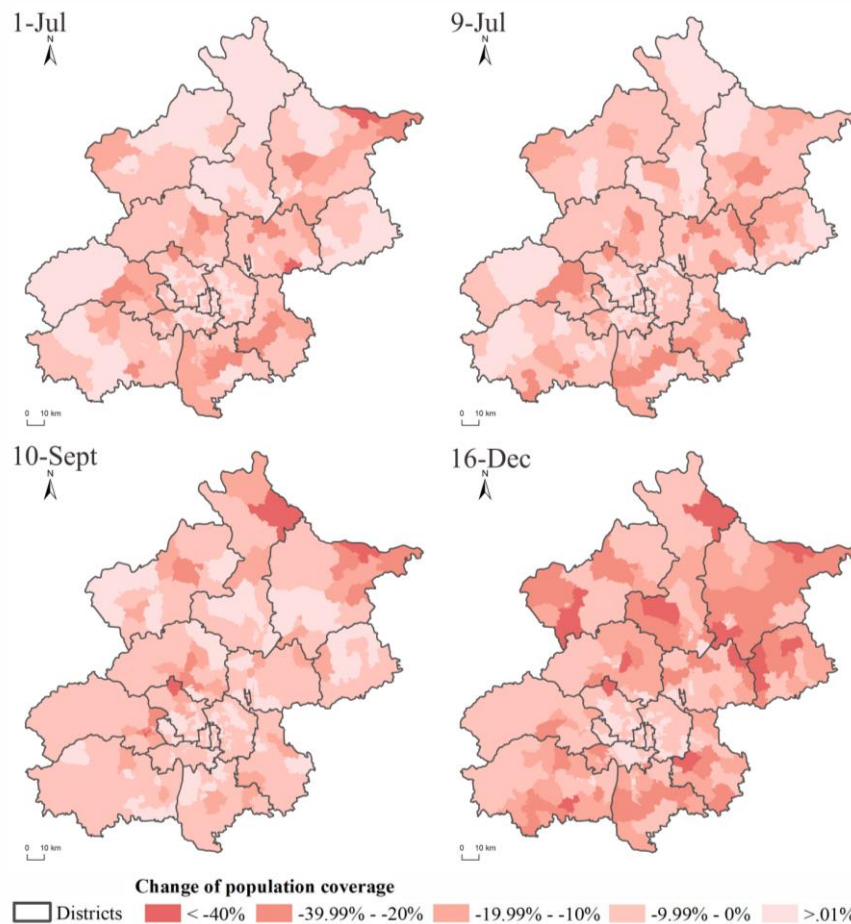



Figure 7. The change in EMS coverage rate of the population in townships in inclement weather relative to normal weather on 1st July, 9th July, 10th September, and 16th December, produced in ArcGIS 10.8 and CorelDraw 2019.

Figure S1 shows the correlation between the baseline EMS coverage rate of the population of each township and its reduction under inclement weather. The results reveal that the population of the towns with low baseline EMS coverage rate would lose more EMS coverage under inclement weather, especially on snowy day. The average traffic speed reduction in the urban area (within the Sixth Ring road) was -26.64%, -

388   23.27%, -25.20% and -15.77% on 1st July, 9th July, 10th September, and 16th

389   December, while that in the suburban area (outside the Sixth Ring Road) was -19.59%,

390   -19.08%, -17.27% and -23.21%. Based on the results, we analyzed the reasons why that

391   suburban area would become more vulnerable under inclement weather. Combined

392   with the traffic speed reduction and the EMS coverage reduction, on rainy days,

393   although the urban area has more traffic speed loss, the suburban area still experiences

394   more EMS coverage loss. Once the inclement weather affects the traffic on some road,

395   the urban areas still have many other roads than can bypass, but not in suburbs. On

396   snowy days, the suburban area has more traffic speed reduction, and with the sparser

397   road network, the EMS coverage in the suburban area would shrink much more than

398   rainy days.

399

400   **4.2.2 The accessibility to hospitals**

401   Figure 8 shows the increased transfer time from each population grid to the nearest

402   hospital under the four inclement weather conditions of 1st July, 9th July, 10th September,

403   and 16th December relative to the baseline condition. The value indicates the impact of

404   inclement weather on accessibility to hospitals. The situation is slightly different on

405   rainy days and snowy days. On rainy days, the shortest time to reach the nearest hospital

406   generally could increase by 0–10 minutes in most parts of Beijing due to slower traffic

407   speed on the roads caused by rain. Although in some small parts of suburban areas, the

408   shortest time to the nearest hospital would be slightly shortened on indicating that the

409   traffic will be smoother in some areas when it rains, which may be due to the reduction

410   of traffic demand (Maze et al., 2006). While on 16th December, affected by snow, the

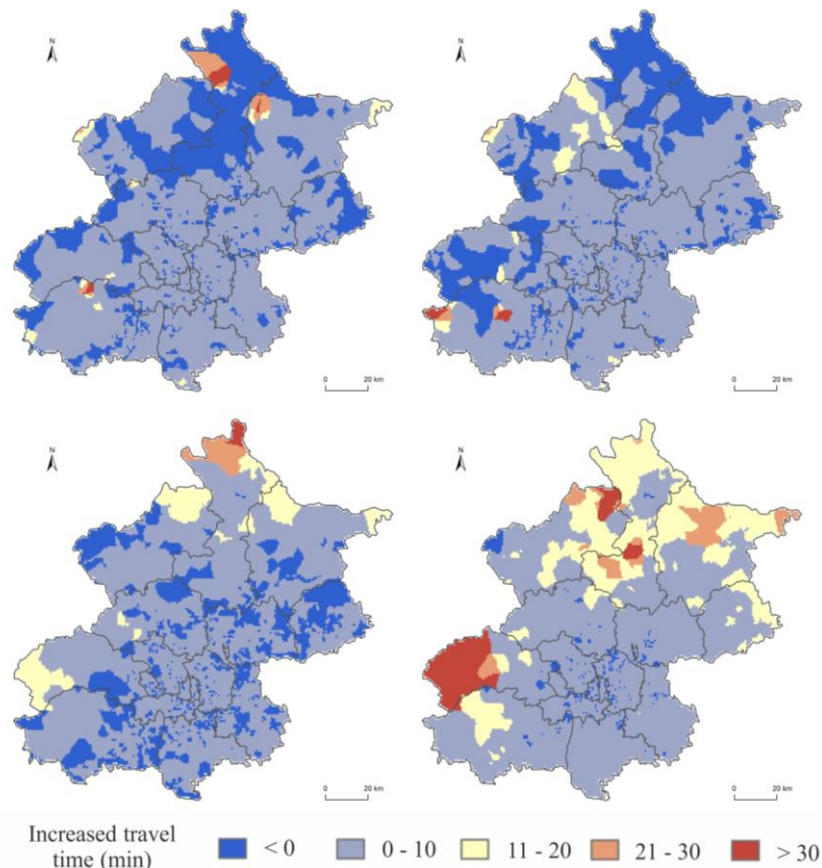
411   whole city's road traffic generally slowed down, and the transfer time to the nearest

412   hospital increased by 10–40 minutes. The western part of Mentougou District and a

413 small part of the northern Yanqing District were the most affected, with the time needed

414 to reach the nearest hospital prolonged by more than 30 minutes, up to 45 minutes. In

415 Huairou district, the eastern part of Yanqing district, and the northern part of Miyun

416 district, the transfer time was also prolonged by 11–30 minutes.

417

418 **Figure 8**. Increased transfer time to hospitals on 1st July, 9th July, 10th September, and 16th

419 December, produced in ArcGIS 10.8 and CorelDraw 2019.

420 We did a zonal statistic of the average baseline transfer time to hospital and the

421 average increased transfer time to hospitals to each town, and the correlation between

422 the two indicators shown in Figure S2 indicate the similar pattern with the EMS

423 coverage, which is the towns with low baseline accessibility to hospitals would also

424 more affected by inclement weather.

425 Overlaying the demographic grid data, the size of the population affected by a

426 delay of over 10 minutes would be 0.02 million on 1st July, 0.03 million on 9th July,

427 0.05 million on 10th September, and 0.3 million on 16th December.

428   Figure 9 shows the change in the total transfer time under inclement weather

429 conditions on 1st July, 9th July, 10th September, and 16th December, relative to the

430 baseline conditions. The results show that on three rainy days, 1st July, 9th July, and 10th

431 September, within the Sixth Ring Road extent, the total transfer time increased

432 significantly under inclement weather, which means that, although the transfer time

433 would not increase much in urban areas, due to the high population density, the

434 cumulative delay time for total potential demand would be significant. In the suburbs,

435 the total transfer time would increase slightly or even decrease, especially in some areas

436 of Huairou, Yanqing, and Miyun districts, which means that, although the transfer time

437 would increase greatly, due to its low population density, the cumulative delay time for

438 total potential demand would not be serious. However, due to the influence of snowfall

439 on 16th December, the total transfer time in the whole city was slightly or moderately

440 increased, and there were almost no regions where the total transfer time decreased,

441 which means snowfall would cause an even cumulation of delay time for total potential

442 demand across the whole city, both urban and suburban.

443

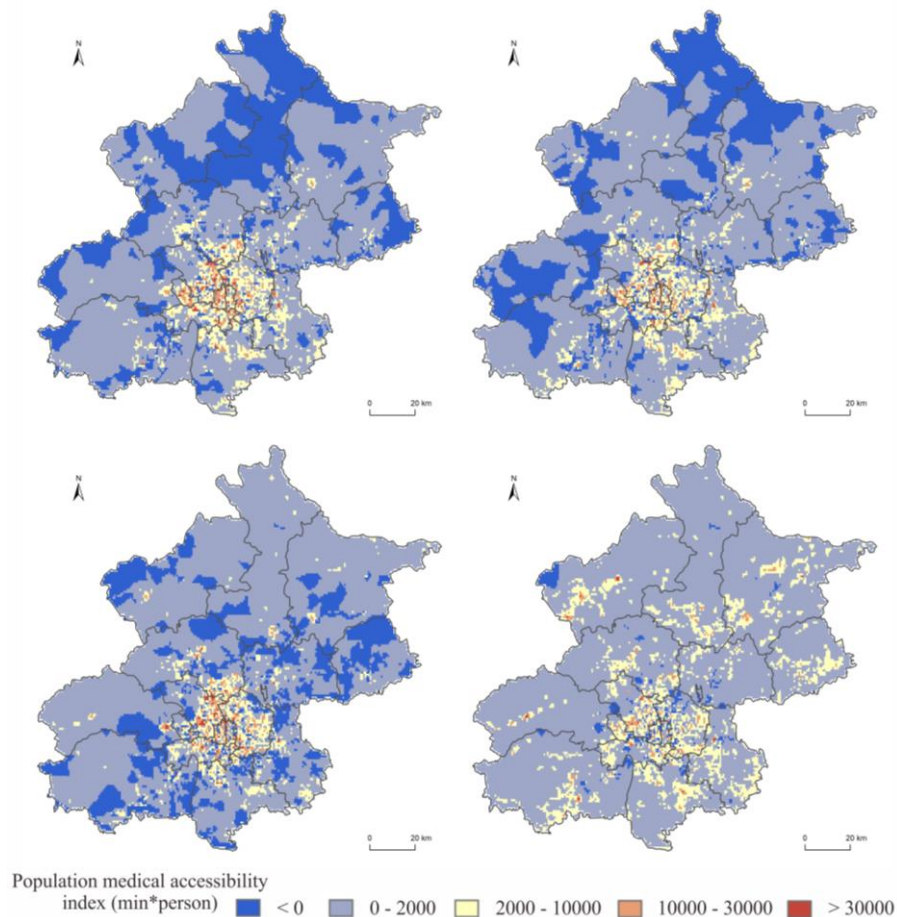



Figure 9. The change in the total transfer time on 1st July, 9th July, 10th September, and 16th December, produced in ArcGIS 10.8 and CorelDraw 2019.

446

5 Conclusions and discussion

Our study evaluates the spatial accessibility of EMSs in Beijing under different weather conditions in 2019 based on city-scale ground-truth traffic data updated every 2 minutes. The spatial accessibility of EMSs was quantified by the coverage rate of the first-aid stations' service area, the coverage rate of first-aid stations' service population, and the shortest transfer time to the nearest hospital. Our study reveals the influence of precipitation on the accessibility and equity of EMSs, which could help guide EMS construction planning in cities, get prepared for extreme weather conditions, and finally assist the decision-making of the corresponding government departments. The main

456 conclusions are as follows:

457   First, the results show that inclement weather, such as rainfall and snowfall, could

458 have a negative impact on the accessibility of EMSs overall. Precipitation reduces the

459 driving speed of vehicles on the road, thus reducing EMS coverage. In severe cases, the

460 EMS coverage rate of the area can be reduced by more than 10%. Besides, snowfall has

461 a greater impact on EMSs accessibility than rainfall.

462   Second, the EMSs accessibility is more affected by inclement weather in places with

463 low baseline accessibility to EMSs. And the results reveal a serious rural-urban

464 disparity in emergency medical facilities distribution in Beijing: The EMSs

465 accessibility of population in some townships of the outer suburbs is very low and

466 would also greatly reduce under inclement weather.

467   Third, some specific days may affect the traffic flow, which has an amplification

468 effect on the traffic congestion caused by inclement weather. When they encounter the

469 inclement weather, there are potential risks of decrease of traffic efficiency and EMSs

470 accessibility, which should be given sufficient attention.

471   To the best of the authors' knowledge, this study provides a first attempt to analyze

472 the spatial accessibility of EMSs under inclement weather based on city-scale ground-

473 truth traffic data and meteorological data, where the former is usually difficult to obtain.

474 In previous literature, simulation methods were widely used on the research on EMSs

475 accessibility or traffic capacity under inclement weather. The ground-truth traffic data

476 that covers every road in the whole city, was hardly used in the previous studies of the

477 impact of weather on traffic and accessibility. Our study could be a good empirical

478 verification in this field of study. The reduction extent of EMSs accessibility was

479 comparable to previous studies (Yin et al., 2021; Coles et al., 2017). We also found that

480 snowfall may have a greater impact, which is hard to find out using flood simulation

481   methods. The results from this study provide a scientific reference for city planning

482   departments in Beijing to optimize the site selection of emergency service facilities and

483   get prepared for traffic dispersion on inclement weather. The relevant methods

484   mentioned in this paper are also suitable for both holidays and workdays and can be

485   easily applied to other cities once traffic data or empirical formulas regarding the impact

486   of inclement weather on road traffic can be obtained.

487   There are also some parts in our research that can be improved in future research.

488   First, we averaged the traffic speed reduction rate of all the roads in the city, as well as

489   the precipitation data, which could conceal congestion hotspots. In further studies, with

490   higher resolution precipitation, along with corresponding traffic data, we could narrow

491   the scale to blocks, pay more attention to local congestions, and analyze the correlation

492   of precipitation and traffic speed on a finer scale. Second, due to the data limitation, we

493   could only analyze the EMSs accessibility in 2019, and the precipitation intensity in

494   this year was not quite high. If we had longer time series precipitation and traffic data,

495   we could analyze the impact of precipitation magnitude to the traffic and accessibility,

496   instead of simply dividing the days in a binary manner into inclement and non-

497   inclement weather days. Under such precipitation conditions, the EMSs accessibility

498   has been affected to a certain extent, and it would be much more difficult to get timely

499   EMSs under even more extreme inclement weather condition. Future studies should

500   take extreme precipitation events into account. Third, due to the lack of high-resolution

501   DSM (Digital Surface Model) data, we did not run a hydrological flood simulation in

502   Beijing, which could reveal the relationship of precipitation and the actual amount of

503   water on the streets. This could be improved in the future studies with more high-

504   resolution topographic data. Fourth, we used the "15-minutes arrival time" as a main

505   boundary in this study, however, the proper response time would vary in different

506 countries or cities. The setting of response time boundary should be adjusted

507 considering the actual situation of the city when the method in this paper is applied to

508 other cities. Fifth, we aggregated the population grid evenly in the city. If a varying

509 resolution could have been applied with a finer grid in the heavily populated center, and

510 a coarser grid towards the outskirts, it may capture more of the dynamics in a metropolis

511 with varying population and infrastructure densities.

Data availability

513 All raw data can be provided by the corresponding authors upon request.

Author contributions

515 KL planned the research; JZ, ML provided the traffic data; YZ and KL analyzed the

516 data, YZ wrote the manuscript draft; KL, XN, MW, and DY reviewed and edited the

517 manuscript.

Competing interests

519 The authors declare that they have no conflict of interest.

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