A centrality-based accessibility to assess the impact of Beijing metro stations on the concentration of population and economic activity

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With the rapid urbanization process, large-scale constructions of metro are underway across China. As metro network extends, it is essential to evaluate a station's accessibility by considering its network characteristics. This study proposed a centrality-based accessibility to assess the impact of metro stations on the concentration of population and economic activity through regression analysis at two spatial scales: voronoi cell and grid cell, where gridded population data and nighttime light data are used. The application of the proposed index for Beijing metro reveals that there is no clear linear or logarithmic relationship at grid cell level, but a logarithmic correlation between the proposed centrality-based accessibility of metro stations and population-economic activity at voronoi cell level. In addition to assessing network performance of new metro lines, the proposed index is suitable for studies targeted to metro, because it facilitates the identification of evaluating the attractiveness of city center or other functional urban areas for both city dweller and economic activity. Overall, this study offers significant insights that could be beneficial for planners to design rational urban spatial layout through integrated transport and land use planning.

Key Words : *Beijing metro, centrality, VIIRS DNB, GPWv4, population and economic concentration*

1. INTRODUCTION

The global urbanization is projected to continue in next decades and will add another 2.5 billion people to urban population by 2050, with 37% of the increase concentrated in China[1)]. The large-scale constructions of metro are underway across China, aiming to address traffic congestion caused by overpopulated urban and rapid motorization in populous cities[2)].

Urban rail transit (URT) system is a significant factor influencing livability, economic activity, urban transformation and social development through an interconnected network. Cities determine the shape of metro network at first, and after that urban spatial layout will be impacted by metro network in a long term. As metro network extends, it is essential to evaluate a station's accessibility by considering its network characteristics[3)].

Network centrality, identifying the importance of nodes within a network, has become increasingly pervasive and necessary in the field of network analysis. Previous studies on transport network using network centrality give insights into numerous aspects such as: understanding the underlying topological properties of networks[4)], analyzing system performance on connectivity on the occasion of the happening of dysfunctional stations or disconnected links[5)], evaluating the impact of network design on travel with travel survey data, and integrating transport and land use to better understand urban dynamic[6)]. Whereas, advance in the combination of abstract topological and actual spatial aspect is still scarce. Furthermore, due to limited availability of spatially-disaggregated data in developing countries, it is urgently needed to probe into the substitution of open data for socio-economic survey data.

In this paper, we intend to incorporate actual spatial distance into topological properties of metro network. The ultimate goal of this study is to develop a new accessibility index based on network centrality to assess the impact of Beijing metro stations on the concentration of population and economic activity, which is considered to significantly contribute to urban spatial planning and construction of new stations.

The rest of this paper is organized as follows. Section 2 outlines the data used in the analysis of Beijing metro network. Section 3 introduces our methodology, including the introduction of basic network centrality characteristics and the investigation of proposed centrality-based accessibility index at two spatial scales: voronoi cell and grid cell. Section 4 presents the results and discusses the impact of metro stations on population-economic concentration through regression analysis. Finally, section 5 concludes with some key implications and future tasks to the current research.

2. DATA SOURCE

This study focuses on Beijing metro network at the end of year 2014. Metro in this paper refers to URT with exclusive right-of-way, whether underground, at grade, or elevated, also referred to as subway.

Beijing is a province-level municipality and comprises 16 county-level divisions (districts) with a total population of 21.5 million. By the end of year 2014, Beijing metro has 18 lines (including 1 airport rail) and 268 operating stations (interchange stations are not double-counted), spanning over 527 km with the coverage of 11 districts. The study area shown in Fig.1 is bounded by an irregular rectangular area, where the boundary is 0.03 degree of latitude/longitude far away from the furthest stations on X-axis and Y-axis direction. Generally, one degree of longitude or latitude is approximately 111 kilometers apart. The setting of boundary line is in consideration of accessible distance even for walking from given termini stations.

Gridded Population of the World, Version 4 (GPWv4) is a gridded data product of globally-integrated national population data, which provides a spatially-disaggregated population layer for use in research[7]. GPWv4 models population distribution on a continuous raster surface that consists of grid cells using a proportional allocation gridding algorithm. UN-adjusted population density grids for 2010, which is a data set of GPWv4 adjusted to match United Nations country totals with an output resolution of 30 arc-seconds (approximately 1 km resolution at the equator), is disaggregated with a higher resolution (smaller cells) of approximately 50m in our case.

Be released globally since 2013, average radiance composite images using nighttime light data from the Visible Infrared Imaging Radiometer Suite (VIIRS)

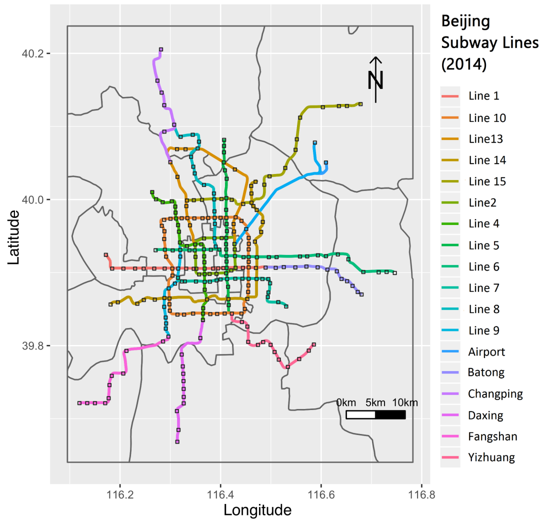

Fig.1 Beijing metro in study area.

Day/Night Band (DNB) is filtered to exclude data impacted by stray light, lightning, lunar illumination, and cloud-cover, and has a relatively high spatial resolution (15 arc-sec, approx. 500 m) and wide detection range (a spectral range of 500-900 nm) as well[8].

VIIRS DNB data assists multiple applications in various fields, such as estimation of urbanization dynamics and CO2 emissions, etc. VIIRS DNB data is preferable to be a better proxy for monitoring socioeconomic[9]. The disaggregation of VIIRS DNB data with the same resolution as processed GPWv4 is used in our analysis.

3. RESEARCH METHODOLODY

(1) Network centrality

Centrality indices identify the most important nodes (stations) within metro network, providing theory to distribute passenger flows more evenly, and even to help forecast ridership related to the opening of new lines. There are many categories of centrality indices, but the present paper focuses on betweenness centrality and closeness centrality that are suitable for use in metro network.

The relationship among stations (nodes) can be transferred to an adjacency matrix (a_{ij}) consisted of ones and zeros, where a one indicates the presence of a connection. In metro network, connections (links) between stations are treated as non-directional, which leads a_{ij} to be symmetric. Degree centrality is simple in concept, which is defined as the number of links incident upon a node by ignoring any patterns among nodes, i.e. the sum of a row in $a_{ij\cdot}$. In a metro network, the degree centrality of a station denotes the number of stations connected to it.

a) Betweenness centrality

Betweenness centrality quantifies the number of times a node acts as a bridge along the shortest pathway between two other nodes. Betweenness centrality emphasizes the importance of a node lied on paths as a transfer point between any pairs of nodes, which considers that geographic location has strong influence on flows passing among nodes. Betweenness centrality is also convenience to examine network reliability on the occasion of the happening of dysfunctional nodes or disconnected links. Normalized betweenness centrality of a node can be rescaled by dividing through by the total number of pairs of nodes not including the focal node, which is (n-1) (n-2) /2 for undirected network, and is formulated as follows.

$$C_b(i) = \sum_{i \neq j \neq k} \frac{d_{jk}(i)}{d_{jk}} \cdot \frac{2}{(n-1)\cdot(n-2)} \tag{1}$$

Where d_{jk} is the number of shortest paths from node j to node k, and $d_{jk}(i)$ is the number of those paths that go through node i.

b) Closeness centrality

Closeness centrality depends on the length of the pathways from a node to all other nodes in the network, and is defined as the inverse total length. Closeness is an indicator that identities how close a station is to all the other stations in terms of a sum of the shortest distances. The normalized closeness centrality of a node is the average length of the shortest path between the node and all other nodes in the network. Thus the more central a node is, the closer it is to all other nodes.

$$C_c(i) = (n-1) \Big/ \sum_{j=1}^{n} d_{ij} \tag{2}$$

$$d_{ij} = \min\,(x_{ih} + \cdots + x_{hj}) \tag{3}$$

Where d_{ij} is the shortest path and h are intermediary nodes on paths between node i and j.

(2) Centrality-based accessibility (CbA)

At level of grid cell, we integrate actual distance with centrality by considering negative distance as an exponential function. In terms of betweenness and closeness, the centrality-based accessibility can be described as follow.

$$ACC_b(i) = \sum_{j=1}^{n} C_b(i) \cdot \exp\,(\text{-}md_{ij}) \tag{4}$$

$$ACC_c(i) = \sum_{j=1}^{n} C_c(i) \cdot \exp\,(\text{-}md_{ij}) \tag{5}$$

Where n represents the number of stations, md_{ij} represents the direct distance (km) from grid cell i to grid cell j.

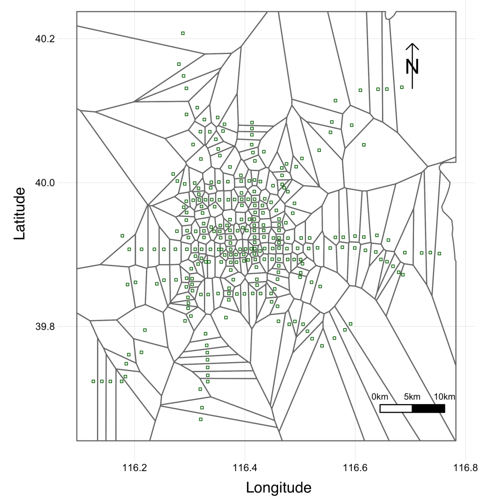

Fig.2 Voronoi regions of Beijing metro stations .

(3) Spatial autocorrelation

Spatial autocorrelation is a measure to analyze the degree of dependency among observations in a geographic space. Spatial autocorrelation analysis is able to study the entire regional pattern and detects whether the pattern displays clustering or not. Accordingly, spatial autocorrelation can help us look at the exists of population and economic concentration from a regional aspect in advance.

Moran's I is the most common way to measure autocorrelation, which we used to analyze each similarity based on GPWv4 and VIIRS DNB data.

(4) Logarithmic Regression

The regression analysis is used to assess the association between CbA and GPWv4, and between CbA and VIIRS DNB data. The investigation on the impact of metro stations on population and economic activity agglomeration is conducted at two spatial scales: voronoi-cell level and grid-cell level.

A Voronoi diagram is a partitioning of the given space onto regions, with bounds determined by distances to a specified set of sites. The Voronoi diagram allows the identification of coverage areas and regions of influence in space called voronoi cells, therefore it is able to be adopted to divide the service areas of stations. Fig.2 illustrates voronoi regions of Beijing metro stations. Inside each voronoi cell, the station is the one that is closest to a city dweller. Furthermore, the average values of CbA, GPWv4, and VIIRS DNB in each voronoi cell are calculated for regression analysis.

It should be noted that termini stations have a betweenness of 0 since they can never be on the pathway between two other nodes. Additionally, regardless of population density, airport are commonly the most brightest location in VIIRS DNB image[10]. Hence, at voronoi cell level, regression

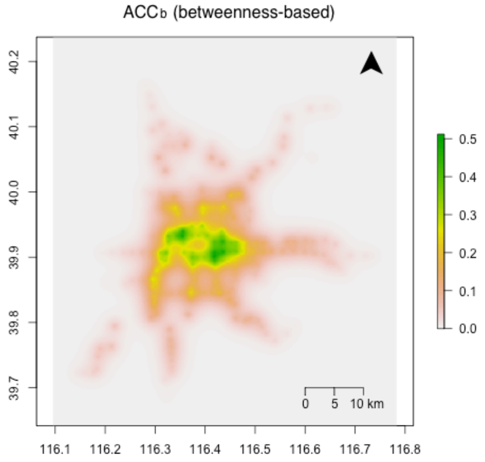

Fig.3 Betweenness-based accessibility.

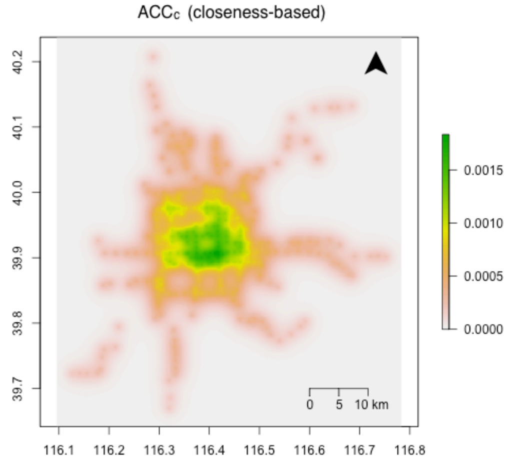

Fig.4 Closeness-based accessibility.

analysis excludes the voronoi regions of airports when ACC_c is involved in calculation, and excludes the voronoi regions of both airports and termini stations when ACC_b is involved in calculation.

A grid cell denotes a spatiall-disaggregrated area with a resolution of approximately 50 meters.

4. RESULTS AND ANALYSIS

The results of spatial autocorrelation for GPWv4, and VIIRS DNB are 0.889 and 0.932 respectively, which means there are clustered patterns existing in the land cover, thereby we can probe into the estimation of how much metro stations have affected the concentration of population and economic activity.

(1) Grid cell level

At grid cell level, the proposed CbA are calculated and shown in Fig.3 for betweenness-based value (ACC_b) and in Fig.4 for closeness-based value (ACC_c).

In URT network, betweenness reveals the importance of a station's transfer function and location, while closeness reveals the distance of a station located away from city center. Therefore, with respect to those residents who travel by metro daily, ACC_b can be interpreted as residential location preferences on the access to all greatly active areas of social activity and economic activity, while ACC_c can be interpreted as residential location preferences on the access to city center. The CbA clearly reflects location choices of those who consider metro as a daily mean of transport in this study.

The regression analysis demonstrates that there is no linear or logarithmic relationship between CbA and GPWv4, nor between CbA and VIIRS DNB at grid cell level. This can be considered as that residential quarters not necessarily located in the place as close as possible to transport hubs, instead traffic flow moving from low CbA to high CbA is visually illustrated. Additionally, choosing a residential quarter somewhere is a decision for all concerned rather than just the function of a station. Moreover, locations with relatively high value of CbA are highly potential for residential quarter development across the city, which is becoming highly valued by developer as one of its core developing strategies.

Therefore, sound urban planning agenda by providing well-managed public transportation and housing is pivotal to make cities more productive and inclusive as they get bigger and more complex. More concretely, a station might be heavily used because of its transfer function or in the vicinity of urban functional regions, but not necessarily to be a preferred option to live in the vicinity of the station due to regional diversity such as travel-to-work area, commuter catchment area, and commuting zones, etc.[11].

(2) Voronoi cell level

Voronoi diagram allows us to concentrate our attention on the coverage area of stations. Apart from the regression analysis at grid cell level, the regression analysis at voronoi cell level identified that CbA has good association with the concentration of population and economic activity (Fig.5).

In the case of ACC_b, the R-squared value for ACC_b and GPWv4 was 0.376, and for ACC_b and VIIRS DNB was 0.516. In the case of ACC_c, the R-squared value for ACC_c and GWPv4 was 0.418, and for ACC_b and VIIRS DNB was 0.536. In each case, the R-squared value for CbA and VIIRS DNB is higher than that for CbA and GPWv4. Furthermore, the R-squared value of ACC_c from GPWv4 and VIIRS DNB was a little higher than that of ACC_b from GPWv4 and VIIRS DNB.

The ACC_c seems more relevant to the concentra-

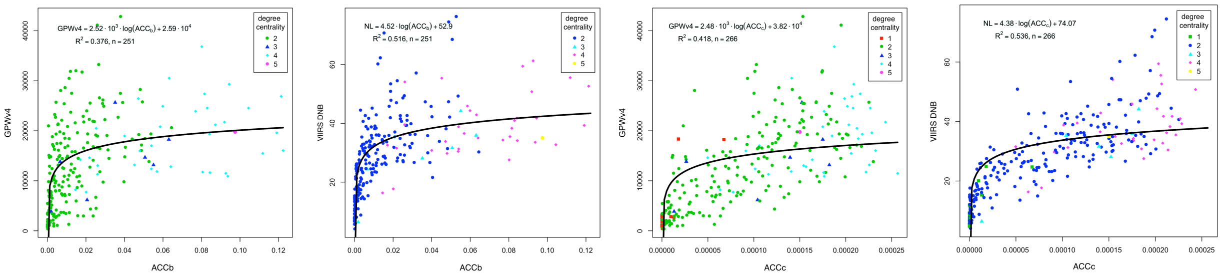

Fig.5 The logarithmic regressions at voronoi cell level.

tion of population and economic activity than the ACC_b. This verified that traffic hub has a positive effect on the concentration of population and economic activity, and with the increase in importance of traffic hub, this effect becomes stronger. In each coverage area of a station, the distance to city center is the preferred consideration of locating rather than the distance to functional urban areas. More specifically, commuting is a more significant factor influencing the choice of location than other urban activities. The results also demonstrate that stations, especially traffic hub, give instruction in urban spatial layout owing to the mobility and convenience in transportation and preference in residential location decisions, which is a great implication for urban spatial planning by considering the underlying network pattern.

The R-squared value for each case is tested to range from 0.37 to 0.53. Besides metro stations, there are various exogenous factors that affect urban activities and urban spatial layout, for instance, income discrepancy, conservation of historic sites, the diversity of individual preferences, and varied policy direction. Nonetheless, the proposed CbA that evaluates the preference of considering metro as a daily mean of transport in order to commute or carry on other urban activities, is in expectation of being applied to decision making for policy makers in integrated transport and land use plans. Proper intervention through design rules and investment decisions could make cities more interconnected with high efficiency.

Urban transition towards transport sustainability not only seeks ways to relieve the pressure of urban traffic, but look forward to further promoting urban development. As key policy strategy of putting emphasis on Metro, Beijing metro system is expected to guide urban sprawl towards a rational spatial distribution in consistence with urban development. With the advantages of providing sustainable mobility, inducing purposive urban expansion and not causing urban population growth[12], metro benefits both residents and socio-economic activities.

5. CONCLUSIONS

This study demonstrates that metro stations have significant impact on population and economic concentration, and it is more practicable in respect to actual application at voronoi cell level. The investigation of proposed CbA for Beijing metro system values the importance of traffic hub in inducing rational urban spatial layout through integrated transport and land use planning.

In addition to assessing network performance of new metro lines, the proposed CbA is suitable for studies targeted to metro, because it facilitates the identification of evaluating the attractiveness of city center or other functional urban area for both city dweller and economic activity.

A megacity is used to illustrate the method, where a complex subway network is formed. The applicability of proposed index is questionable to be introduced into small and medium-sized cities. It should be not neglected there are limitations in this study such as validity and accuracy of substituting VIIRS DNB for socio-economic activities due to limited availability of spatially-disaggregated data in China. Despite the adverse condition, spatially disaggregated data processed from remotely sensed datasets is pivotal to diminish overly dependent on social survey in urban spatial planning.

As a proposal for future work, it is suggested that the development of proposed CbA by taking into account travel cost and ridership should be advanced and the applications of CbA into the network of other traffic modes should be extended to as well.

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