Working paper

Assessing Physical Environment of TOD Communities around Metro Stations

USING BIG DATA AND MACHINE LEARNING

January 2020

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Acknowledgement

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1.INTRODUCTION

Transit-oriented Development (TOD) is a planning strategy that aims to cluster jobs, housing, services, and amenities around public transport stations to promote urban development that is compact, mixed-use, pedestrian- and bicycle-friendly, and closely integrated with mass transit[1]. Since the introduction of the concept of TOD to China in the early 2000s, this new development theory has attracted plenty of research attention and triggered broad discussions ranging from macro-level policy recommendations on urban planning and land uses to micro-level guidelines on facility layout and space design around public transit hubs. However, at the implementation level, a systematic monitoring and evaluation framework to track the impacts of adopting TOD principles on the quality of physical environment has to yet to be established.

The quality of the physical environment in TOD communities really matters because it largely determines transit access[2] and experience for riders, therefore affecting their choice and frequency of transit use—a crucial factor that shapes the development of a TOD community. It might be true that considerable improvements in physical environment in TOD communities could lead to possible displacement of pre-existing residents from the area who are the originally intended beneficiaries. However, it could eventually result in wider adoptions of transit use, bringing increased convenience and vibrancy to the neighborhood.

1.1 Research Context

In recent years, scholars and practitioners have been exploring alternative analytic tools to study the existing conditions and inform the continued application of TOD principles in urban development across Chinese cities. Among all the efforts, evaluation of the quality of the physical environment in TOD communities emerges as an urgent task, as the results often play a vital role in helping policy makers, planning practitioners, private investors and the public benchmark the areas around Metro stations against each other and monitor the improvement over time.

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[1] Salat, Serge; Ollivier, Gerald. 2017. Transforming the Urban Space through Transit-Oriented Development: The 3V Approach. World Bank, Washington, DC. © World Bank. https://openknowledge.worldbank.org/handle/10986/26405

[2] Chorus, P., Bertolini, L., 2011. An application of the node place model to explore the spatial development dynamics of station areas in Tokyo. J. Transp. Land Use 4, 45–58.

1.2 Research question

Traditional ways of evaluating the physical environment around metro stations are often faced with three major challenges:

- Lack of comprehensive quality analysis: the evaluation of the quality of physical environment often focuses on one or two aspects that are of interest to the evaluator, while a holistic view is missing;

- Lack of low-cost and effective ways of evaluation: the evaluation process is expensive and time-consuming when people need to visit the sites, walk around, and collect information manually;

- Lack of standardized and replicable ways of evaluation: there have not been standardized and measurable indicators, which can readily be used for comparison across locations or over different time periods.

In response to the three challenges of physical environment evaluation, we are looking into ways to comprehensively, effectively, and repeatedly evaluate the physical environment of the transit-oriented communities around metro stations. Recent development in information technologies and their application in urban service delivery has opened opportunities to use new analytic tools with new formats of data to achieve this goal. In this study, we use millions of street view photos and machine learning models to come up with quantitative assessment of the physical environment in areas around metro stations from multiple dimensions.

1.3 Scope of research

This evaluation exercise has been conducted in the context of Beijing City. The reason for choosing Beijing is that, with nearly 400 stations in operation, it offers a degree of diversity with respect to the quality of physical environment, and meanwhile makes the task comprehensive enough that would otherwise become difficult if using the traditional approaches. The study covers 201 stations (about 50% sampling) within the 5th Ring Road of Beijing, where high-resolution street-view photos are available.

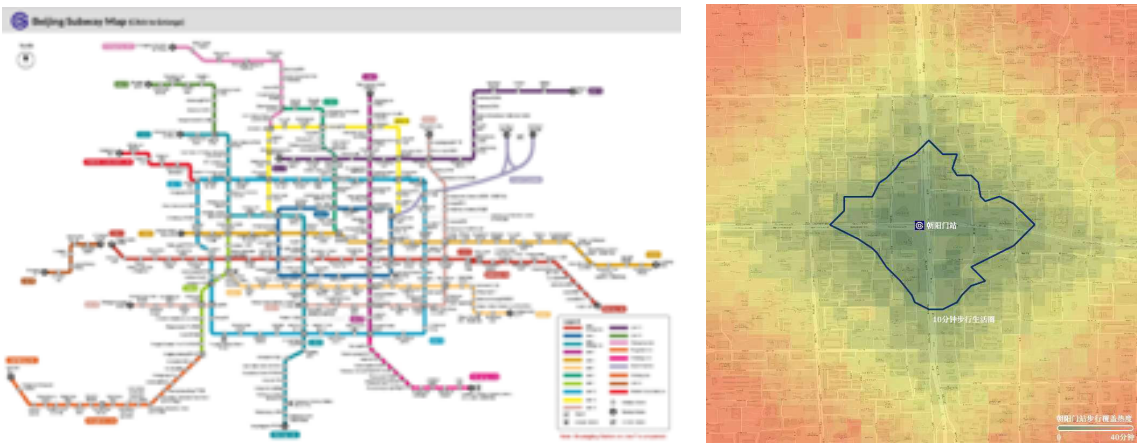


Figure 1 Beijing Subway Map (left) and sample 10-min walk isochrones at Chaoyangmen Station (right)
Sources: Beijing Metro Group, World Bank research team.

The core area of potential TOD communities is commonly defined based on a radius of 400m to 800m (as a proxy of five-to-ten-minute's walk) from a major Metro station, which was proposed by Peter Calthorpe in the 1990s, and has been adjusted according to local circumstances. However, a fixed radius cannot always reflect the actual service catchment of the stations, due to differences in urban functionalities, street networks, and natural barriers. With spatial analysis tools, it is now possible to estimate the areas that can be covered by foot from a Metro station in any given time. In the light of this, the scope of this study is defined as the areas within a 10-minute walking distance from the 201 Metro stations.

2. METHODOLOGY AND DATA SOURCE

This study uses different methodologies to extract key information from the street view photos including image/pattern recognition and urban space perception powered by machine learning models. Fueled by various formats of big data, spatiotemporal analysis has been conducted wherever needed.

2.1 Pattern recognition

Urban space usually consists of various elements, from static facilities (e.g., landscaping, signage and street furniture) to mobile parts (e.g., cars, bikes and pedestrians), the aggregation and interaction of which help people form their understanding of the quality of the physical environment. Pattern recognition using street view photos can provide unique perspectives on the quality and usage of urban space, such as the level of vibrancy and crowdedness, and its relations with local socioeconomic development. Advanced machine learning techniques now enable accurate delineation of different elements in a dynamic urban space, the calibration of the spatial distribution and the density of certain elements in real time. This has unlocked huge potential for the application of street-view-based analysis at a greater scale.

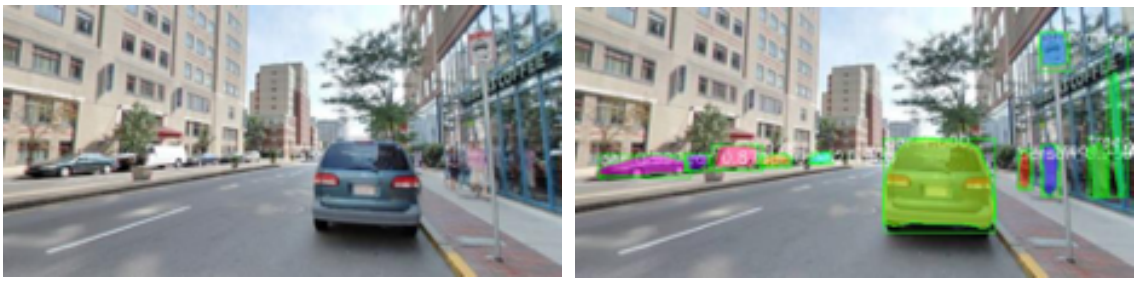


Figure 2 Using pattern recognition to identify elements of physical environment from street view photos
Sources: Google Map street view photo, pattern recognition processed by Citorytech.

2.2. Urban space perception

Different from image recognition, urban space perceptions are subjective human perceptions of urban space and its elements. They can be measured from multiple dimensions such as safety, attractiveness or aesthetics.

Figure 3 Street perception rating system (PC version and mobile version)
Source: Street perception rating system developed by Citorytech.

Based on a data-driven machine-learning approach, a deep learning model, trained on millions of human ratings of street-level imagery, was used to predict human perceptions of a street view image. The training data originated from two parts: ratings of street view photos within a range of 0-10 scores by urban study professionals, and choices of street images based on certain indicators between groups of two images by the public. Using street perception rating system developed by CitoryTech, the model achieved a high accuracy rate in predicting two human perceptual indicators, safety and aesthetics, that are essential in evaluating the physical environment.

2.3 Spatiotemporal analysis

Urban functionalities around Metro stations reflect the level of land use development and differences in attracting different groups of riders. A Metro station with urban functionalities that are reasonably laid out, mixed-used and great in number is usually located in a well-developed TOD community or a relatively prosperous area. This type of Metro station has a potential to become the node of future urban growth. Using phone signaling, points of interest, and ridership data from City Information Modeling, a spatiotemporal analysis was conducted on the number and type of urban functionalities around Metro stations.

3. FRAMEWORK FOR EVALUATING THE PHYSICAL ENVIRONMENT

Physical environment evaluation is a process in which information is collected to assess the quality of the physical environment for meeting people's needs. The purpose of conducting such evaluations is to understand the gaps in existing physical environment and inform target interventions for improvement.

Urban rail transit systems play an increasingly important role in people's daily interaction with cities, so establishing a systematic framework for evaluating the physical environment around Metro stations is crucial for us to further understand and improve the systems.

3.1 Principles

The evaluation of the physical environment around Metro stations follows three principles. A good TOD physical environment should be able to:

- ***Expand transportation options***, increase travel efficiency and save commute time to enhance access to job opportunities and services for residents of all income levels.

- ***Help improve residents' living conditions***, bringing greater convenience with smaller carbon footprint and making the area more livable.

- ***Coordinate with and facilitate urban development,*** creating agglomeration effects to boost a city's competitiveness.

3.2. Indicators

Reviewing main TOD indicators in the international literature, TOD typologies aimed to help assess the physical environment of TOD communities chiefly consist of indicators of two dimensions—"Transit" and "Development". "Transit" indicators[3,4,5,6,7,8] include daily frequency of Metro services, number of directions served by the Metro, number of directions served by buses, number of stations within 20 min of travel by Metro, number of passengers served per day by Metro, etc. "Development" indicators[9,10,11,12], in comparison, include number of residents, number of jobs, number of workers in retail/hotel and catering, number of workers in education/health/culture, degree of functional mix, etc.

A study[13] in 2016 expanded the TOD topologies by adding a new dimension "Oriented" to quantify the degree of orientation of transit and development components towards each other. Selected based on Beijing context, “Oriented” indicators include average distance from station to jobs, average distance from station to residents, length of paved foot-path per acre, intersection density, average block size, and walk scores (calculated based on distance to various categories of amenities). However, as noted in the study, the selection of indicators has limitations due to the lack of publicly available data and possible bias from experts.

Informed by the literature and previous practices, this analysis measures the quality of the physical environment of TOD communities from four aspects, i.e., convenience, comfort, vibrancy and characteristics, using 14 subsets of indicators as shown in below.

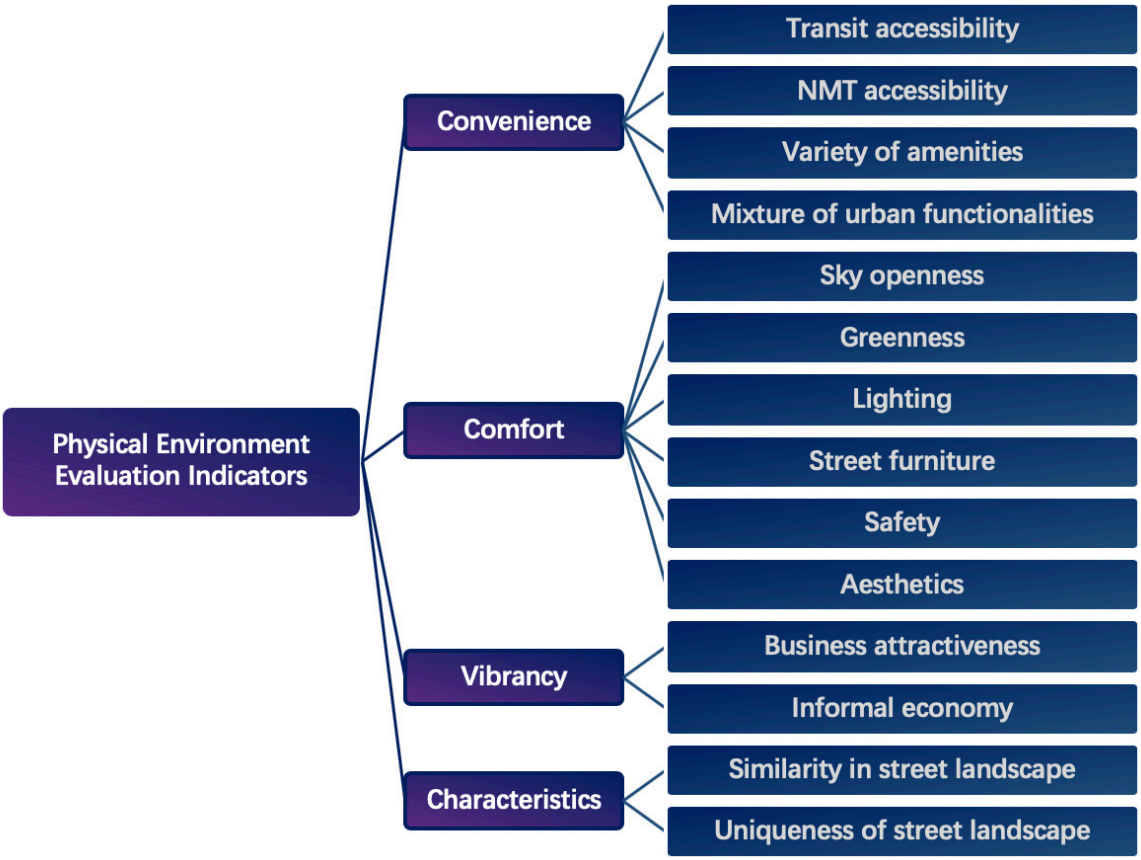


Figure 4 Key indicators to measure quality of physical environment
Source: World Bank research team.

[3] Bertolini, L., 1999. Spatial Development Patterns and Public Transport: The Application of an Analytical Model in the Netherlands. Plan. Pract. Res. 14. https://doi.org/10.1080/02697459915724

[4] Dittmar, H., Ohland, G., 2012. The new transit town: best practices in transit-oriented development. Island Press.

[5] Monajem, S., Nosratian, F.E., 2015. The evaluation of the spatial integration of station areas via the node place model; an application to subway station areas in Tehran. Transp. Res. Part D Transp. Environ. 40, 14–27.

[6] Reusser, D.E., Loukopoulos, P., Stauffacher, M., Scholz, R.W., 2008. Classifying railway stations for sustainable transitions–balancing node and place functions. J. Transp. Geogr. 16, 191–202.

[7] Vale, D.S., 2015. Transit-oriented development, integration of land use and transport, and pedestrian accessibility: Combining node-place model with pedestrian shed ratio to evaluate and classify station areas in Lisbon. J. Transp. Geogr. 45, 70–80.

[8] Zemp, S., Stauffacher, M., Lang, D.J., Scholz, R.W., 2011. Classifying railway stations for strategic transport and land use planning: Context matters! J. Transp. Geogr. 19, 670–679.

[9] Atkinson-Palombo, C., Kuby, M.J., 2011. The geography of advance transit-oriented development in metropolitan Phoenix, Arizona, 2000–2007. J. Transp. Geogr. 19, 189–199.

[10] Chorus, P., Bertolini, L., 2011. An application of the node place model to explore the spatial development dynamics of station areas in Tokyo. J. Transp. Land Use 4, 45–58.

[11] Shastry, S., 2010. Spatial assessment of transit oriented development in Ahmedabad, India.

[12] Singh, Y.J., Fard, P., Zuidgeest, M., Brussel, M., van Maarseveen, M., 2014. Measuring transit oriented development: a spatial multi criteria assessment approach for the City Region Arnhem and Nijmegen. J. Transp. Geogr. 35, 130–143.

[13] Lyu, G., Bertolini, L., Pfeffer, K., 2016. Developing a TOD typology for Beijing Metro station areas. J. Transp. Geogr. 55, 40–50. https://doi.org/10.1016/J.JTRANGEO.2016.07.002

4. RESULTS FROM THE PHYSICAL ENVIRONMENT EVALUATION

Using indicators listed in the physical environment evaluation framework, the research evaluates the physical environment of the Metro stations from four perspectives: convenience, comfort, vibrancy, and characteristics, and the results of analyses are summarized in this section.

4.1 Convenience

Convenience has been assessed from four aspects: transit accessibility, Non-Motorized Transport (NMT) accessibility, variety of amenities, and mixture of urban functionalities.

4.1.1 Transit accessibility

Definition of indicator. The transit accessibility is measured by rail transit accessibility (number of Metro lines and entrances/exits at the Metro station) and feeder transit accessibility (number of bus lines and stations within 10-min walking distance from the Metro station). The calculation of accessibility is enabled by using Gaode Maps API.

Number of Metro lines and entrances/exits. Number of Metro lines ranges from 1 to 3, while that of entrances/exits ranges from 1 to 11. As the Beijing Metro system has a mixture of circle and radial lines, large stations with multiple lines passing through and multiple entrances/exits built are usually located at high-density areas in the central city with a high hierarchy of road network, but also at important nodes closer to the suburban area where easy transfer to radial lines is available. Stations with more than 5 entrances are often located along main avenues or under the intersections of elevated expressways, where it is not convenient for people to cross the road.

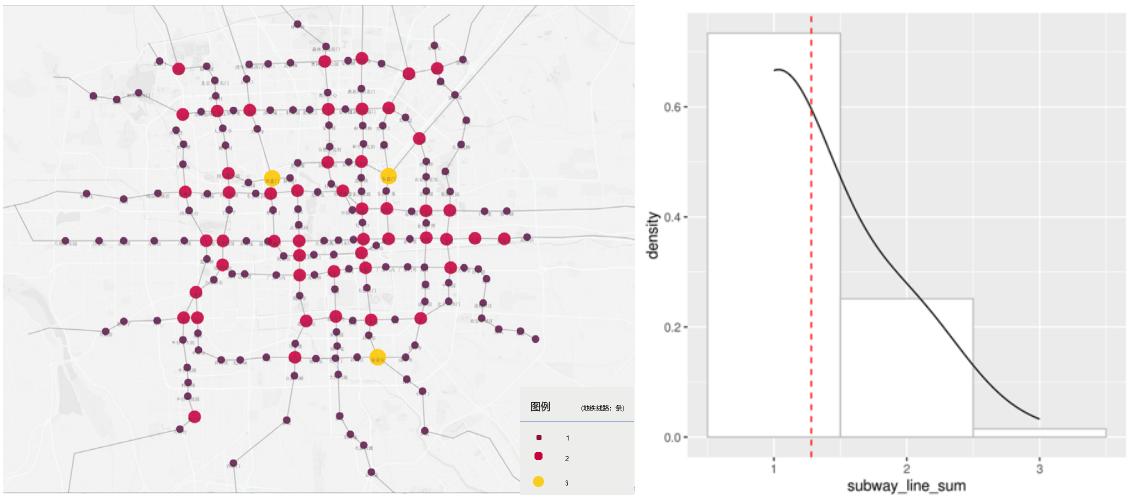


Figure 5 Stations by number of Metro lines (left) and the distribution curve (right)
Source: World Bank research team.

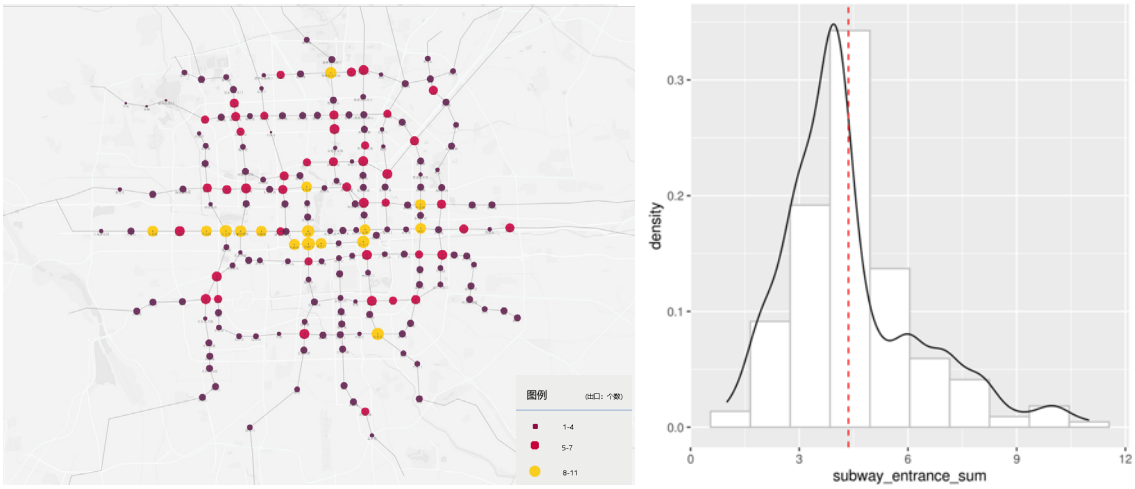


Figure 6 Stations by number of Metro entrances/exits (left) and the distribution curve (right)
Source: World Bank research team.

Number of bus lines and stations. The number of bus lines and stations is highly relevant with the density of road networks and urban functionalities in the TOD communities. A station with good feeder transit accessibility tends to be located in high-density neighborhoods with a great number of residential and office areas, a high volume of passengers, and a dense road network.

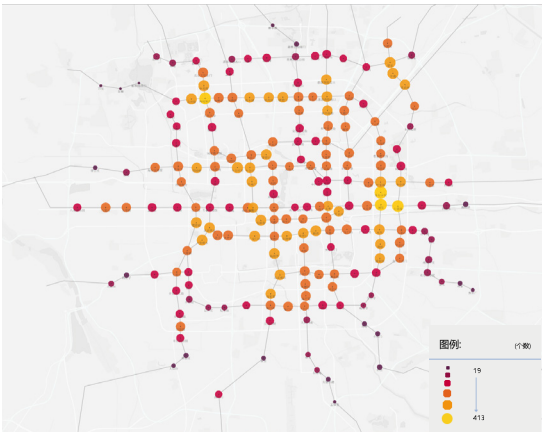


Figure 7 Stations by number of bus lines nearby (left) and the distribution curve (right)
Source: World Bank research team.

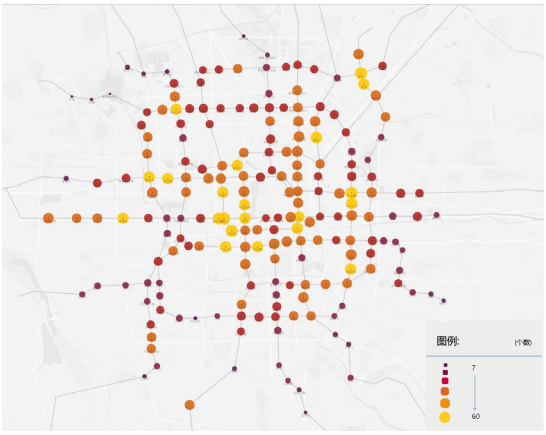


Figure 8 Stations by number of bus stations nearby (right) and the distribution curve (right)
Source: World Bank research team.

4.1.2 NMT accessibility

Definition of indicator. Non-Motorized Transport (NMT) accessibility is measured by the size of areas within the reach of 10-min walking and 5-min biking, considering the network distance enabled using online maps API.

Area coverage by 10-min walking. The number ranged from 53 to 208 hectares. For the majority of Metro stations, this number is between 150 and 200 hectares. Station areas with larger catchment areas by walking are usually located at spots with a dense road network, reasonably-layout urban functions, and a pedestrian-friendly environment.

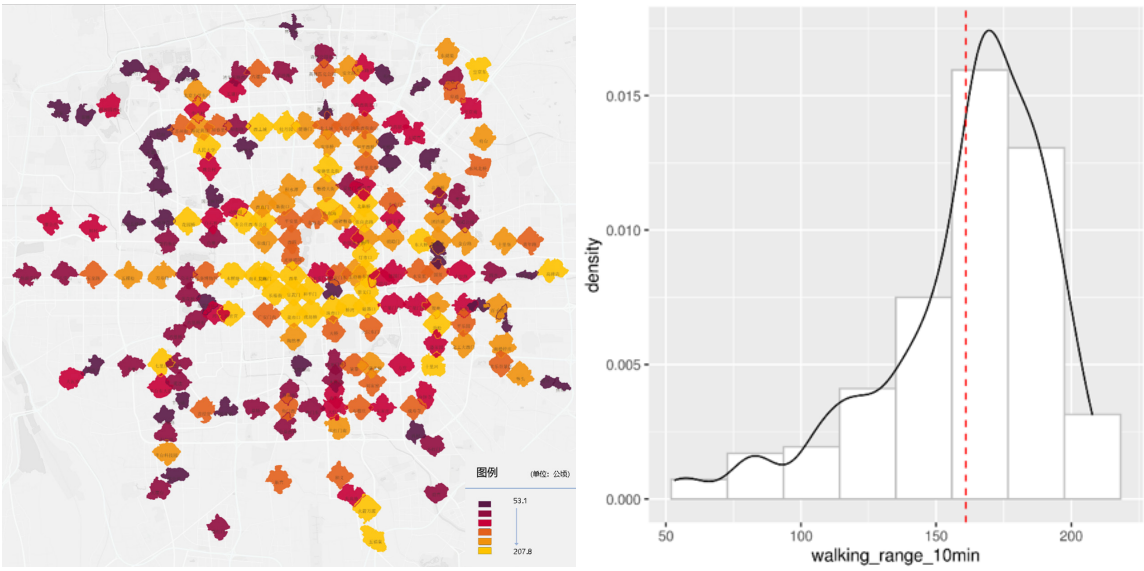


Figure 9 Stations by area coverage (hectares) by 10-min walking (left) and the distribution curve (right)
Source: World Bank research team.

Station areas with low NMT accessibility by walking are mainly located at West 3rd Ring Road, 4th Ring Road, and 5th Ring Road. These station areas usually have highways or elevated bridges (e.g. Muxidi Station), poor road network (e.g. Huagong Station) or disconnected streets (e.g. Yongdingmenwai Station), and natural barriers like river or green land (e.g. Huoqiying Station).

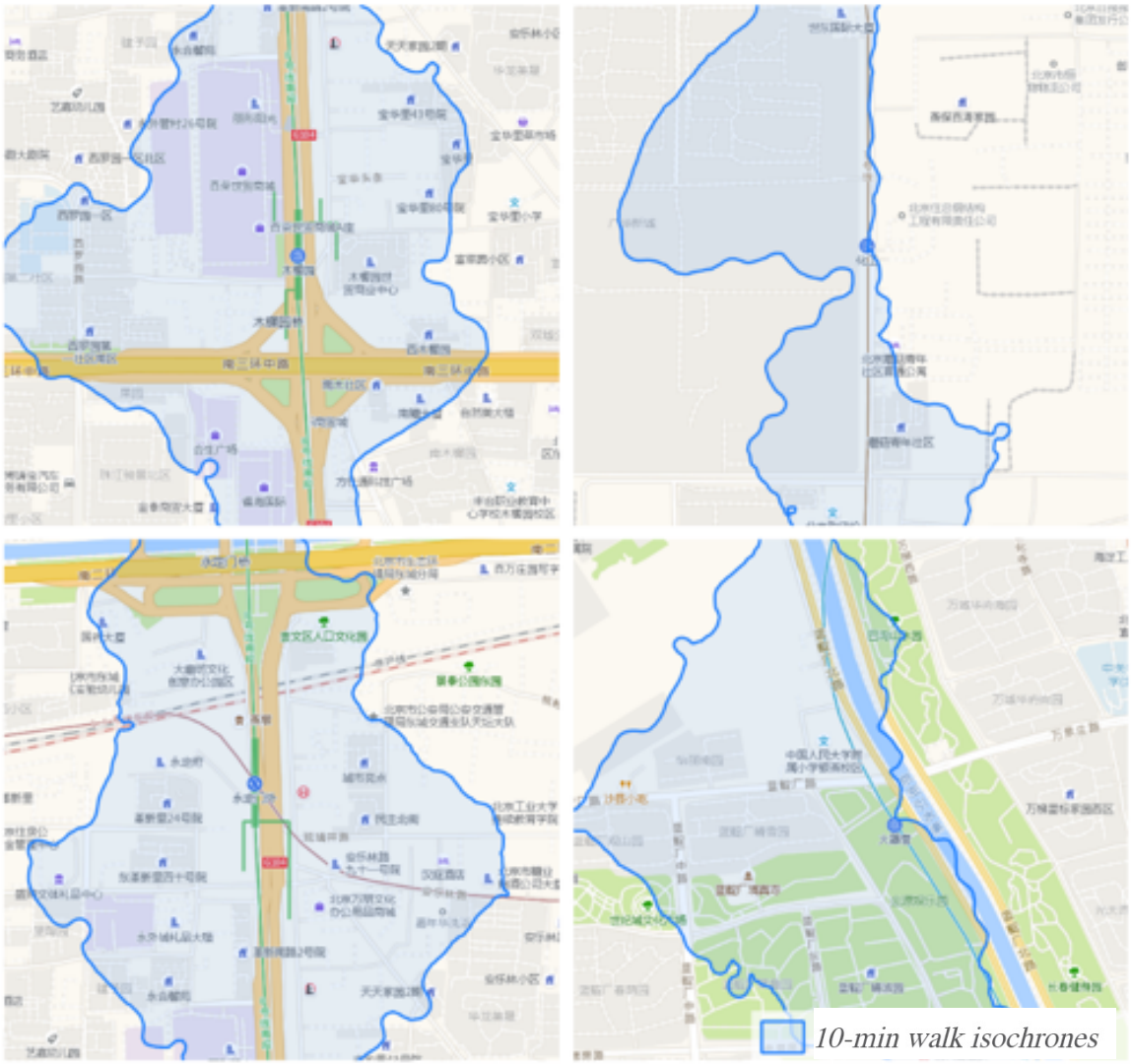


Figure 10 Muxidi Station (top left), Huagong Station (top right), Yongdingmenwai Station (bottom left), Huoqiying Station (bottom right) with 10-min walk isochrones
Source: Base map from Gaode (AMap) Maps, isochrones generated by World Bank research team.

Area coverage by 5-min biking. The number ranged from 9.5 to 311 hectares. For the majority of Metro stations, this number is between 200 and 300 hectares. Station areas with high NMT accessibility by biking are mainly located within 2rd ring road (e.g. Shichahai Station) or along line 5 where there is dense road network, protected bike lanes or slower motor vehicles as a result of narrow streets. In contrast, station areas close to highways, elevated bridges, tunnels or disconnected streets are not quite bike-friendly (e.g. Haidian Wuluju Station) and hence have lower NMT accessibility.

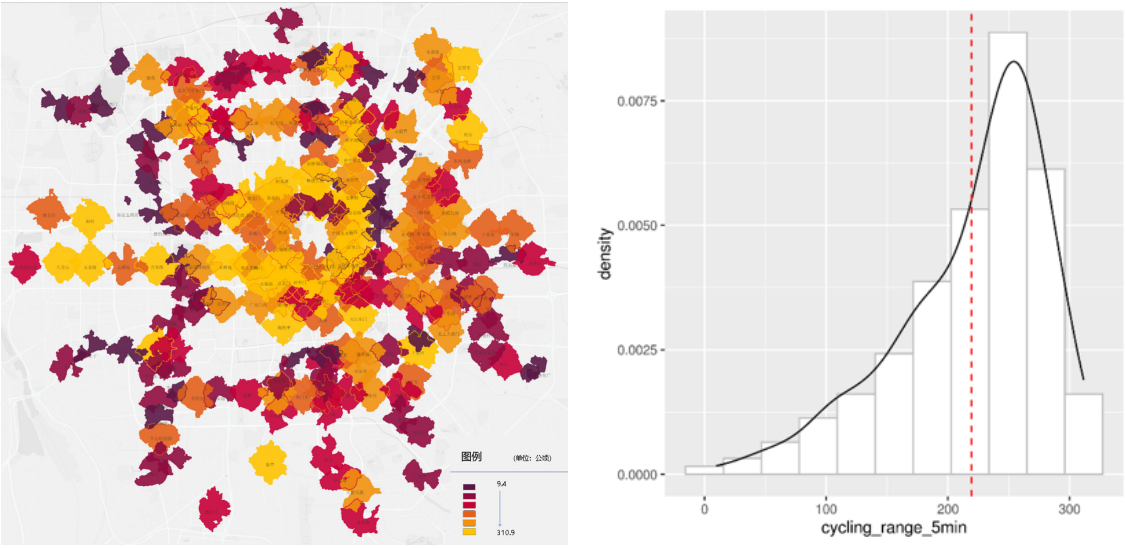


Figure 11 Stations by area coverage (hectares) by 5-min biking (left) and the distribution curve (right)
Source: World Bank research team.

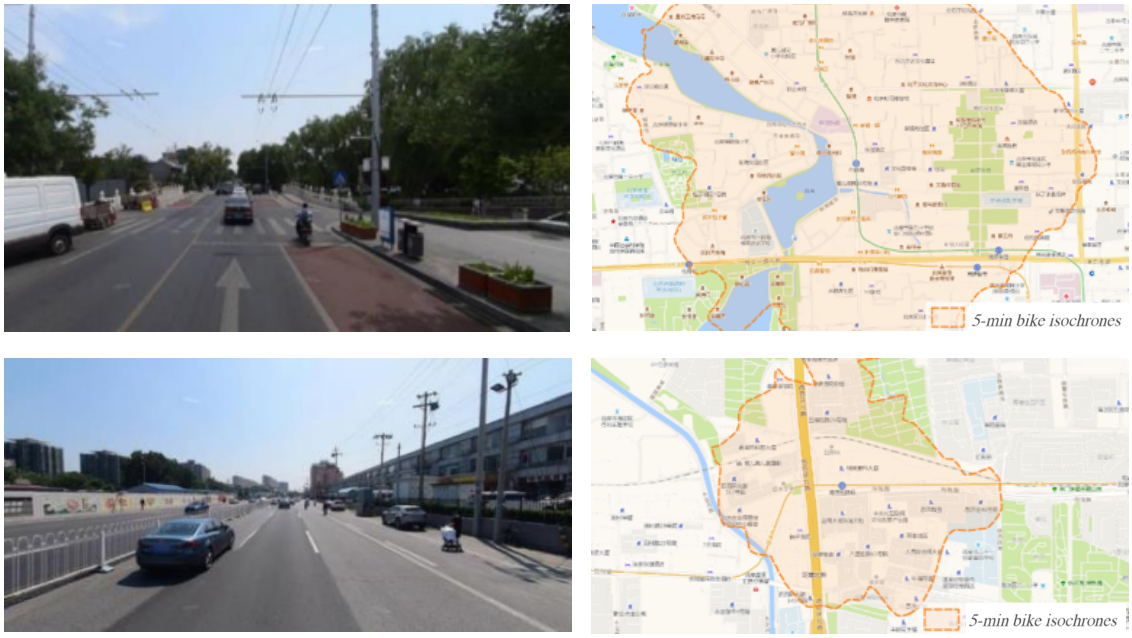


Figure 12 Shichahai Station (top), Haidian Wuluju Station (bottom) with 5-min bike isochrones
Sources: Base map from Gaode (AMap) Maps, isochrones generated by World Bank research team.

4.1.3 Variety of amenities

Definition of indicator. The variety of amenities is measured by number of restaurants, shopping centers, hotels, sports facilities and recreational facilities.

Number of restaurants. Station areas with a high density of restaurants are mainly located at city centers, business districts or other areas with a high volume of passengers like Wangjing or Zhongguancun area.

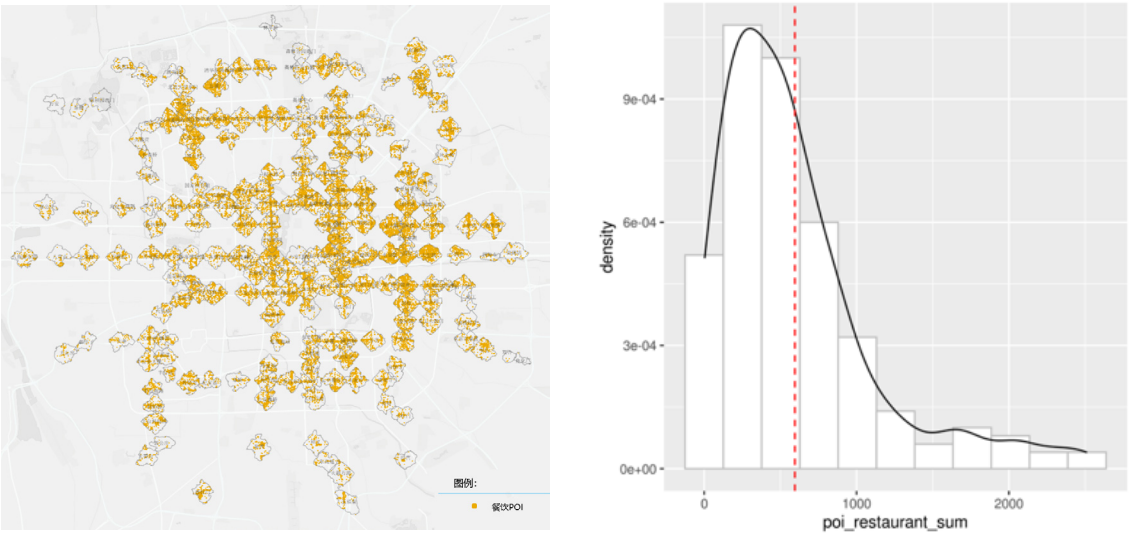


Figure 13 Stations by number of restaurants (left) and the distribution curve (right)
Source: World Bank research team.

Number of shopping centers. Station areas with a high density of shopping centers are located along main streets in the central areas of the city.

Figure 14 Stations by number of shopping centers (left) and the distribution curve (right)
Source: World Bank research team.

Number of hotels. Station areas with a large number of hotels are often located at business districts, major scenic spots or transportation hubs.

Figure 15 Stations by number of hotels (left) and the distribution curve (right)
Source: World Bank research team.

Number of sports facilities. Sports facilities are mostly located at station areas in Haidian and Chaoyang district where schools and young people are concentrated, but less in the south and west part of the city.

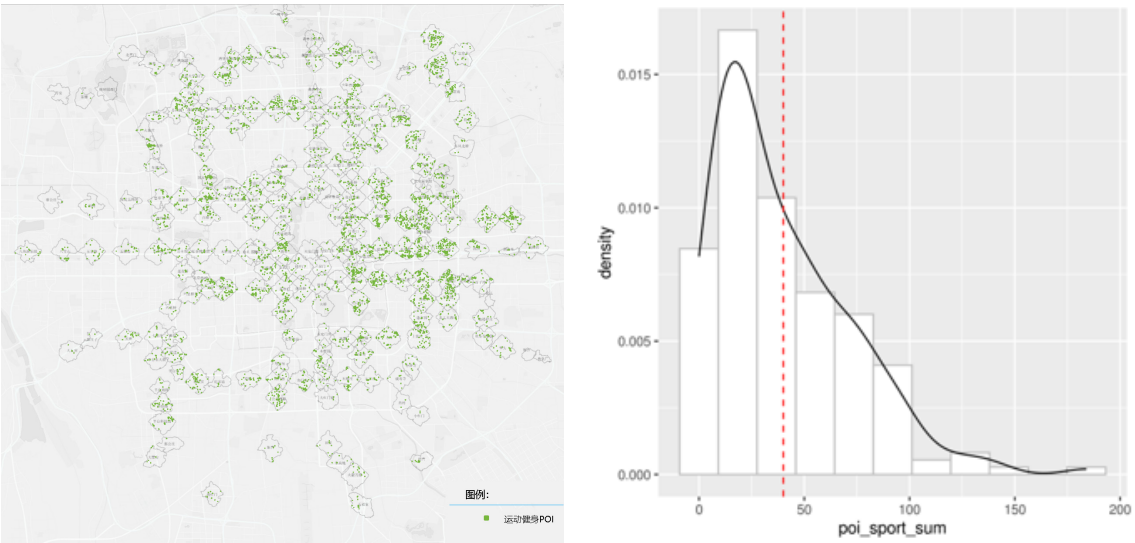


Figure 16 Stations by number of sports facilities (left) and the distribution curve (right)
Source: World Bank research team.

Number of recreational facilities. Similar to sports facilities, recreational ones are also unevenly distributed in the city. They are highly concentrated in Guomao, Zhongguancun, and Wangjing area but less around large parks and open spaces.

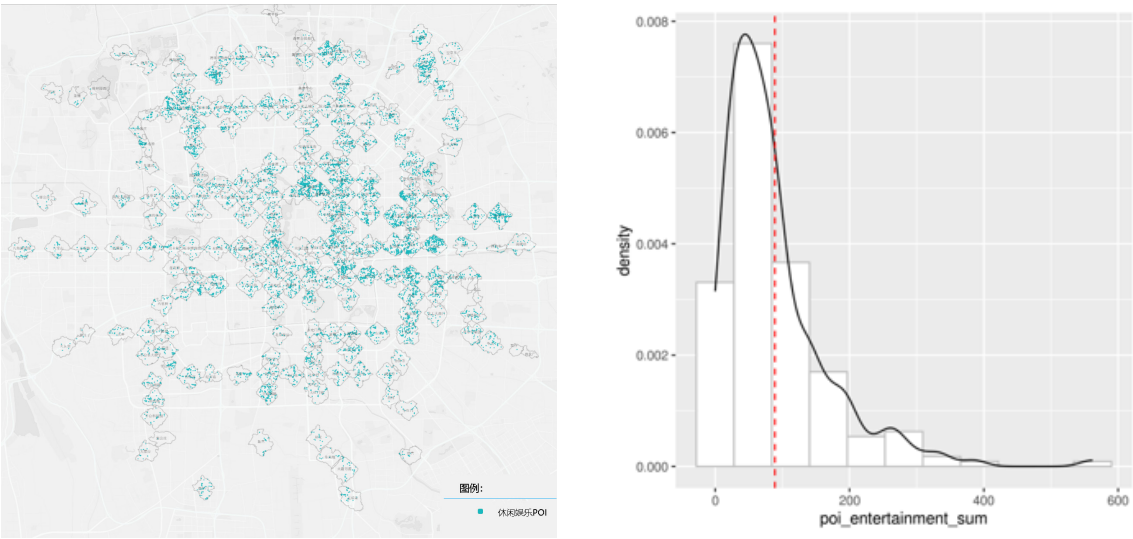


Figure 17 Stations by number of recreational facilities(left) and the distribution curve (right)
Source: World Bank research team.

4.1.4 Mixture of urban functionalities

Definition of indicator. The mixture of urban functionalities is measured by the number of businesses and residential units, indicating the degree of convenient commuting.

In addition, the number of top-ranking amenity types is also displayed below but not included in the calculation of the indicator. Points of interest are categorized into ten types: community services, cultural facilities, recreational facilities, sports facilities, restaurants, hotels, leisure facilities, offices, shopping centers, and others. For each station area, an amenity type will be counted only if POIs of that type ranked top 10 among all station areas.

Number of businesses. The distribution of businesses, usually as destinations in the morning commute, is relatively uneven. Plenty of businesses are located around Zhongguancun and Guomao Metro Stations, and other stations of line 2 and line 10. Fewer are located in the south, west part of Beijing and areas around the Forbidden City.

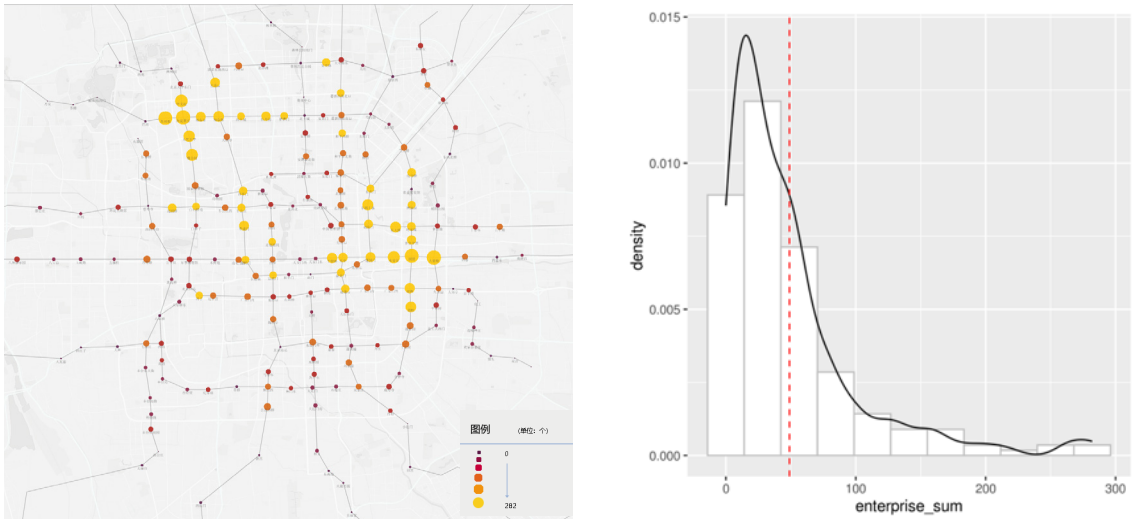


Figure 18 Stations by number of businesses (left) and the distribution curve (right)
Source: World Bank research team.

Number of residential units. Stations with densely distributed residential units inside the 5th ring road are mainly concentrated in the western and northern areas inside the 2nd ring road, as well as some stations along the 3rd and 4th ring road, such as Liujiayao Station, Shuangjing Station, and Shilibao Station.

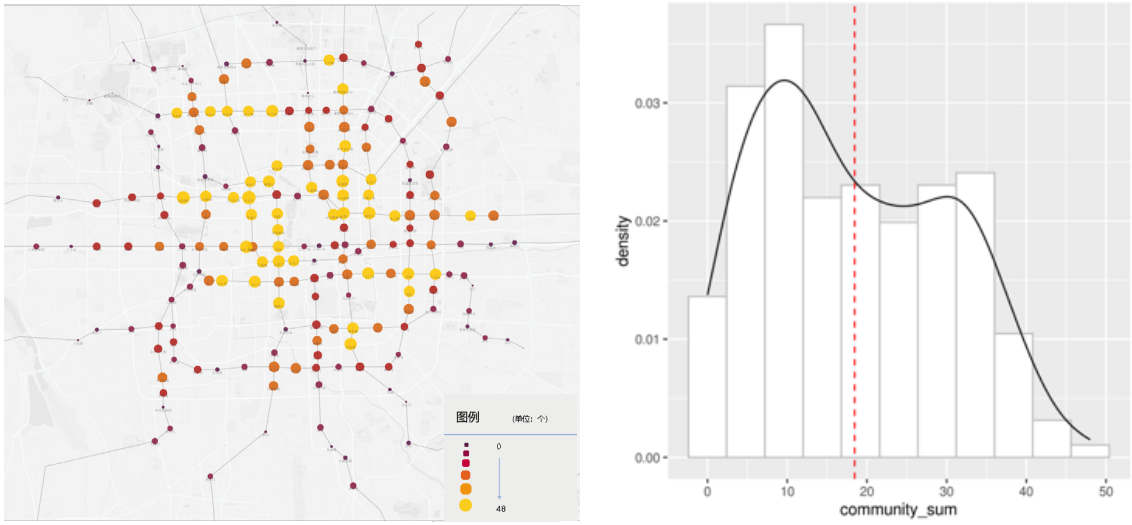


Figure 19 Stations by number of residential units (left) and the distribution curve (right)
Source: World Bank research team.

Number of top-ranking amenity types. Station areas in the northeastern part of the city have highly-mixed land uses and diversified urban functionalities. The top three POI types are community services, shopping centers, and restaurants. One of the peaks is the Central Business District (CBD) as shown in below.

Most new development took place in this area during the past 5-10 years, when the idea of building transit-oriented, multi-functional communities gained momentum in China.

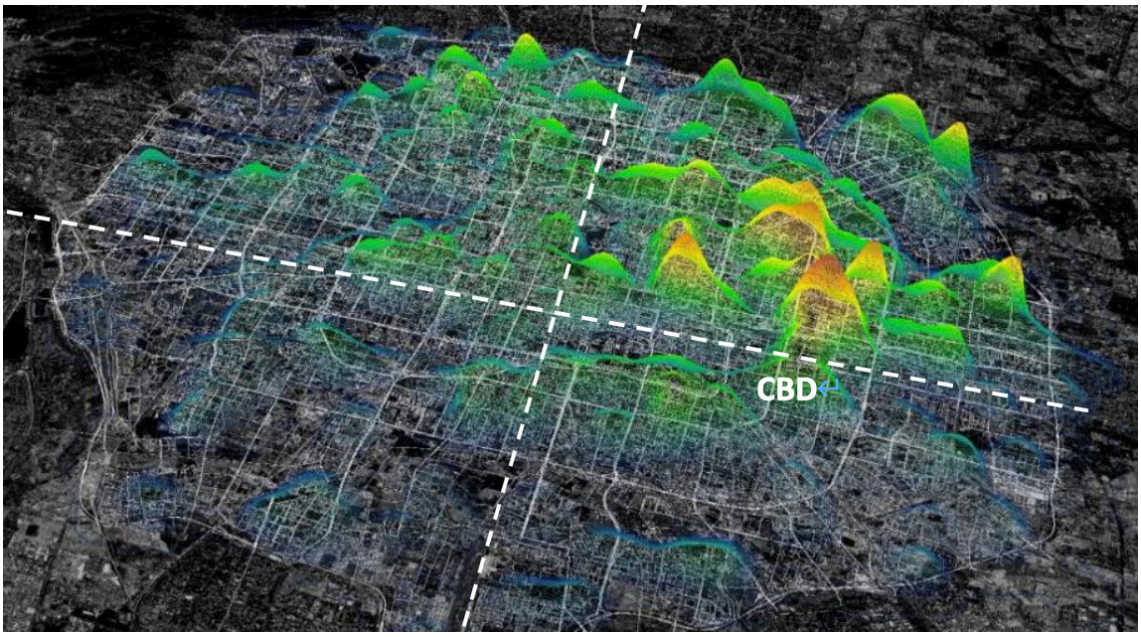


Figure 20 Heatmap of mixture of urban functionalities in Beijing
Source: World Bank research team.

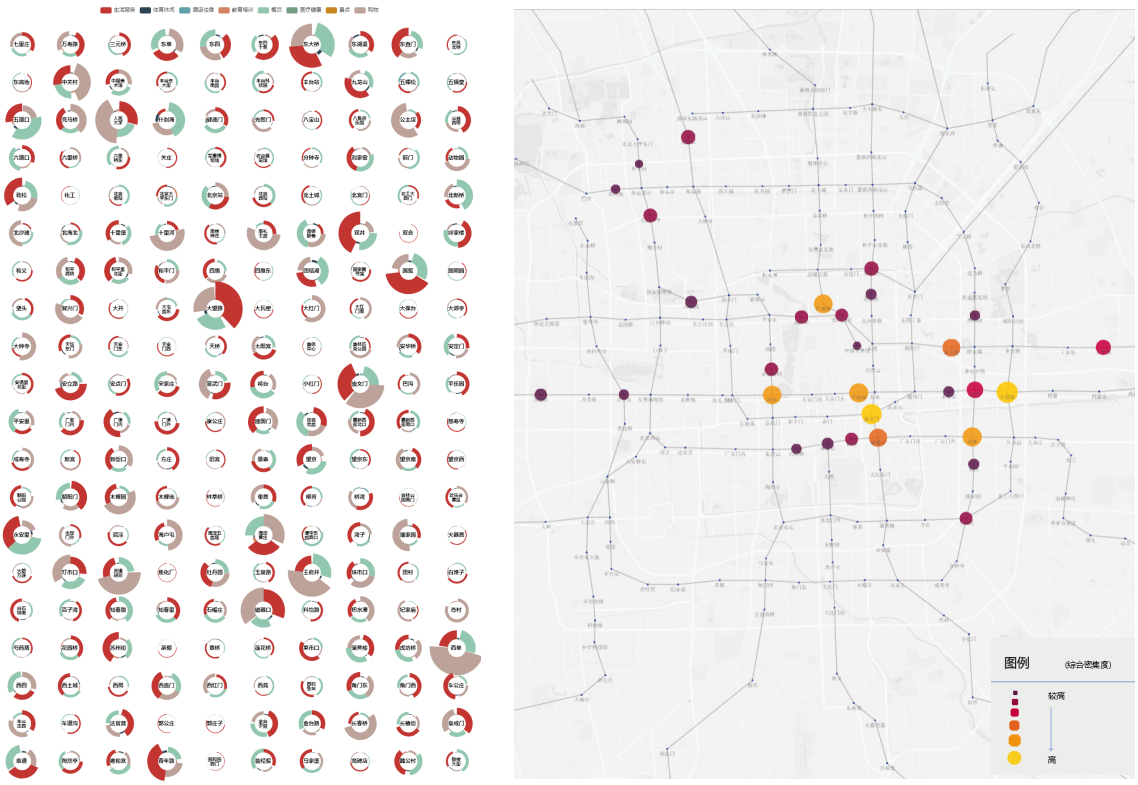


Figure 21 Stations by ratio and size of POI type (left), Stations by number of top-ranking amenity types (right)
Source: World Bank research team.
Note: size of the pie chart represents land use intensity and colors illustrate different functionalities.

4.2. Comfort

Comfort consists of six components: sky openness, greenness, lighting, street furniture, safety and aesthetics.

4.2.1 Sky openness

Definition of indicator. Sky openness is measured by a comfort index that is calculated from the proportion of sky view. The latter was first generated using an image recognition approach empowered by a machine learning model. Intuitively, the relationship between sky openness and comfort is non-linear. Too much sky view may indicate the lack of human-scale design and sheltering. With the help of street perception rating system, the research used the data collected to establish a model for score conversions from the proportion of sky view to the comfort index. At last, the comfort index is calculated as a proxy to measure sky openness.

Figure 22 Sky view calculation using a machine learning model
Source: World Bank research team.

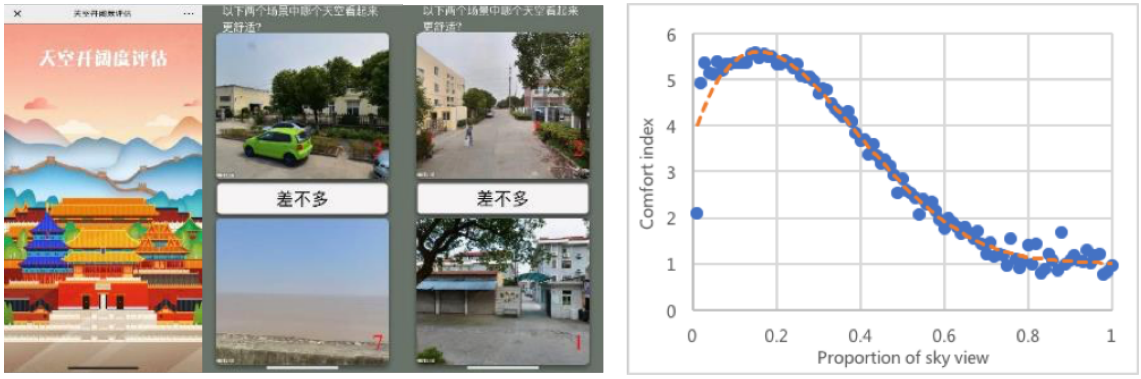


Figure 23 Calculation of a comfort index using street perception rating system (left),
Comfort index vs. proportion of sky view (right)
Source: World Bank research team.

Comfort index (calculated from the proportion of sky view). Citywide, most of the station areas have a low proportion of sky view because of narrow streets, dense buildings and large green space (e.g. Haidianhuangzhuang Station and Suzhoujie Station as displayed below). Station areas outside the 4th ring road (e.g. Wangjing East Station) and around train stations or central scenic spots (e.g. Tian'anmen West Station) have the most sky view due to low development density and wide avenues.

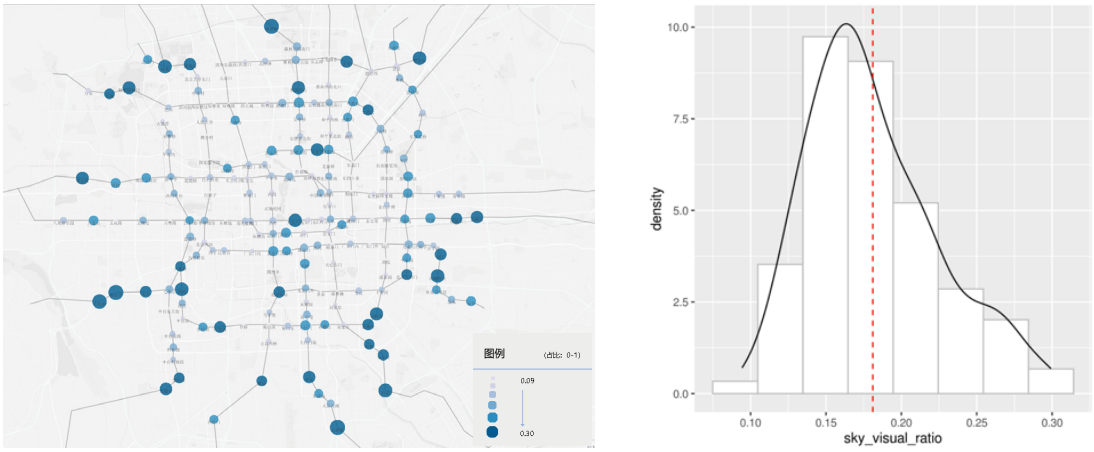


Figure 24 Stations by proportion of sky view (between 0 and 1) (left) and the distribution curve (right)
Source: World Bank research team.

Figure 25 Haidianhuangzhuang Station (top left), Suzhoujie Station (top right), Tian'anmen West Station (bottom left), Wangjing East Station (bottom right)
Source: World Bank research team.

Influenced by the density of surrounding green space, the height of surrounding buildings, street width, the type of amenities nearby and other factors, the relationship between the comfort index and the proportion of sky view is not as simple as linear. Station areas with a high comfort index usually have a

medium proportion of street view, large green space, medium width of street, and appropriate space layout with pedestrian-friendly designs (e.g. Wangjing Station and Keyilu Station).

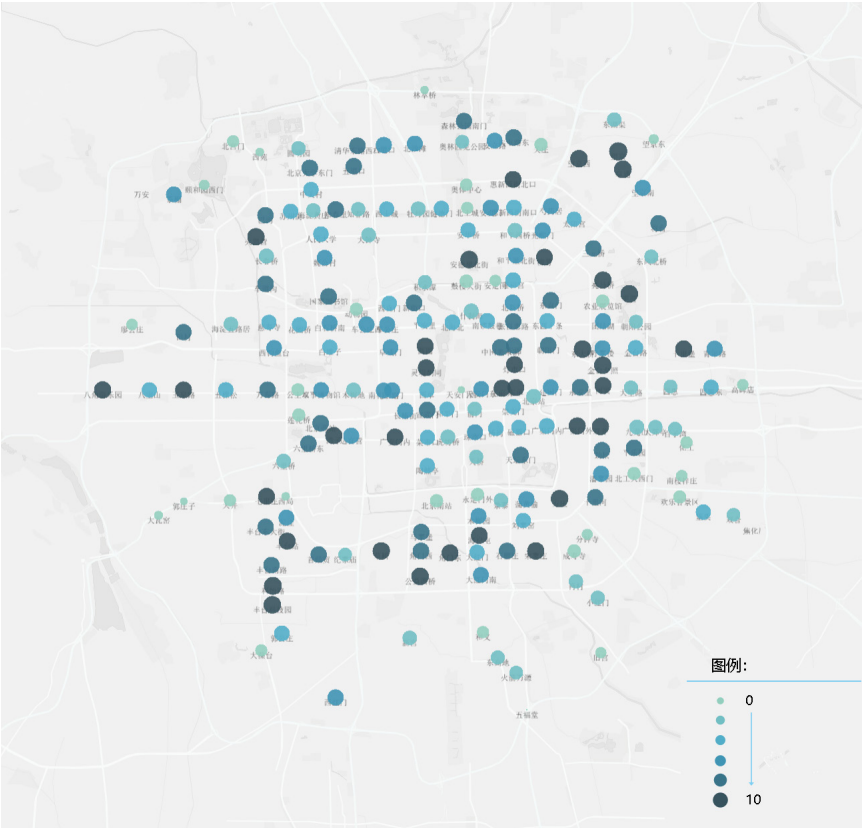


Figure 26 Stations by comfort index (left) and the distribution curve (right)
Source: World Bank research team.

Figure 27 Wangjing Station (top left), Keyilu Station (top right), Wangjing East Station (bottom left), Wufu Tang Station (bottom right)
Source: World Bank research team.

4.2.2 Greenness

Definition of indicator. Greenness is measured by the proportion of visible green space using a similar image recognition approach.

Proportion of visible green space. Station areas in the northwest part of Beijing have the highest vegetation coverage as they are close to parks, green space, and universities (e.g. National Library Station, Xitucheng Station). Station areas in the southeast part of Beijing, in comparison, have pretty low proportion of visible green space (e.g. Yong'anli Station).

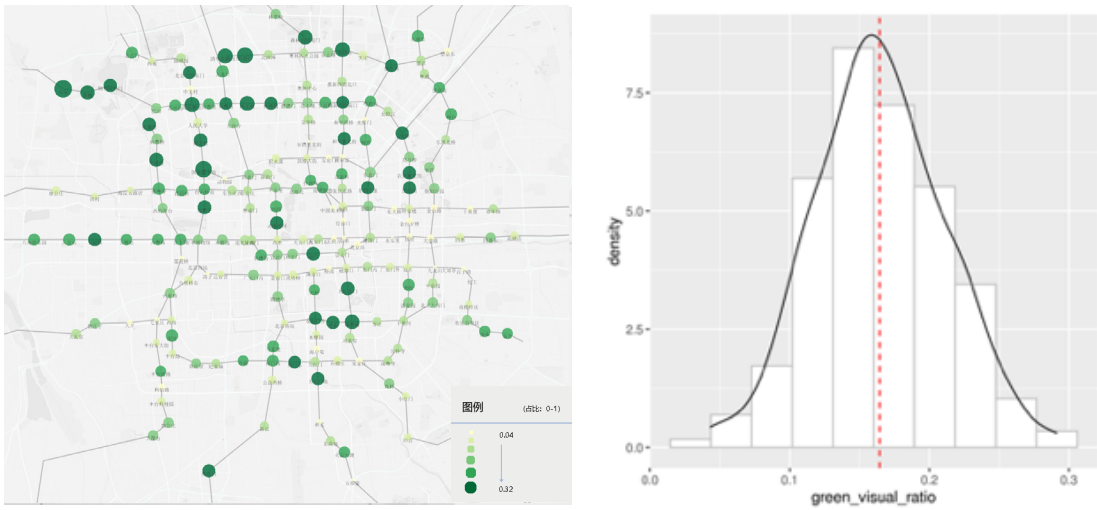


Figure 28 Stations by proportion of visible green space (between 0 and 1) (left) and the distribution curve (right)
Source: World Bank research team.

Figure 29 National Library Station (top left), Xitucheng Station (top right), Dongdan Station (bottom left), Yong'anli Station (bottom right)
Source: World Bank research team.

4.2.3 Lighting

Definition of indicator. Lighting is measured by the density of street lamps (number of lighting/hectare). Stations with low density of lighting may increase the safety risk of pedestrians.

Density of lighting. The density of lighting appears to be highly relevant with the hierarchy of its corresponding road network but not its distance to the city center. Station areas with a high density of lighting are also located at places with plenty of elevated bridges on which street lamps are often placed.

Figure 30 Stations with street lamps
Source: World Bank research team.

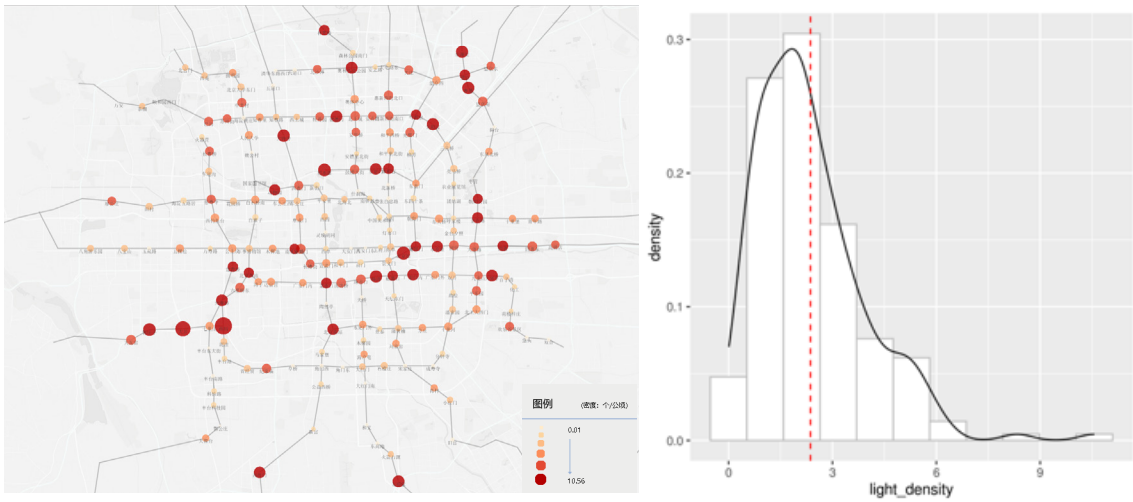


Figure 31 Stations by density of lighting (number of lighting/hectare) (left) and the distribution curve (right)
Source: World Bank research team.

4.2.4 Street furniture

Definition of indicator. Street furniture is measured by the density of benches (number of benches per hectare).

Density of benches. Station areas with a high density of benches are mainly located in street centers or business districts.

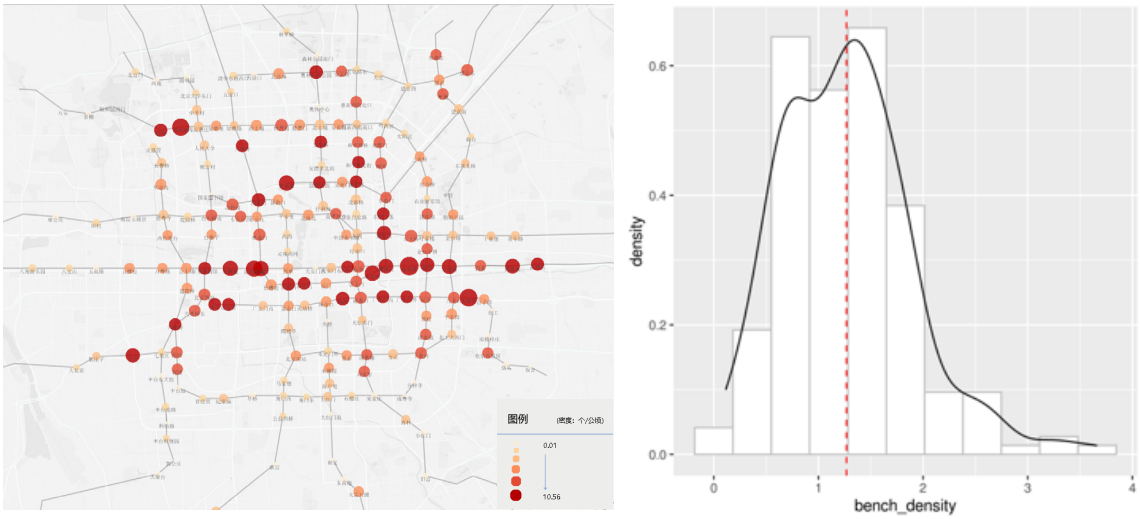


Figure 32 Stations by density of benches (number of benches/hectare) (left) and the distribution curve (right)
Source: World Bank research team.

4.2.5 Safety

Definition of indicator. Trained on millions of human ratings of street-level imagery provided by MIT and local professionals, a deep learning model achieved a high accuracy rate in predicting two human perceptual indicators, safety and aesthetics, and was used to predict human perceptions of street view photos of targeted station areas in Beijing. Safety is thus measured by scores calculated using the model.

Figure 33 Street perception rating system
Source: Street perception rating system developed by Citorytech.

Safety score. Station areas rated as safe are mostly job centers and commercial complexes, with a complete set of facilities and plenty of what Jane Jacobs called “eyes on the street”. There is usually a steady flow of pedestrians and a concentration of ground floor shops along the street that allows people inside buildings to easily observe street life (e.g. Shuangjing Station, Caoqiao Station).

Station areas that were considered unsafe are usually located around construction or less developed areas (Beitucheng Station, Jijiamiao Station).

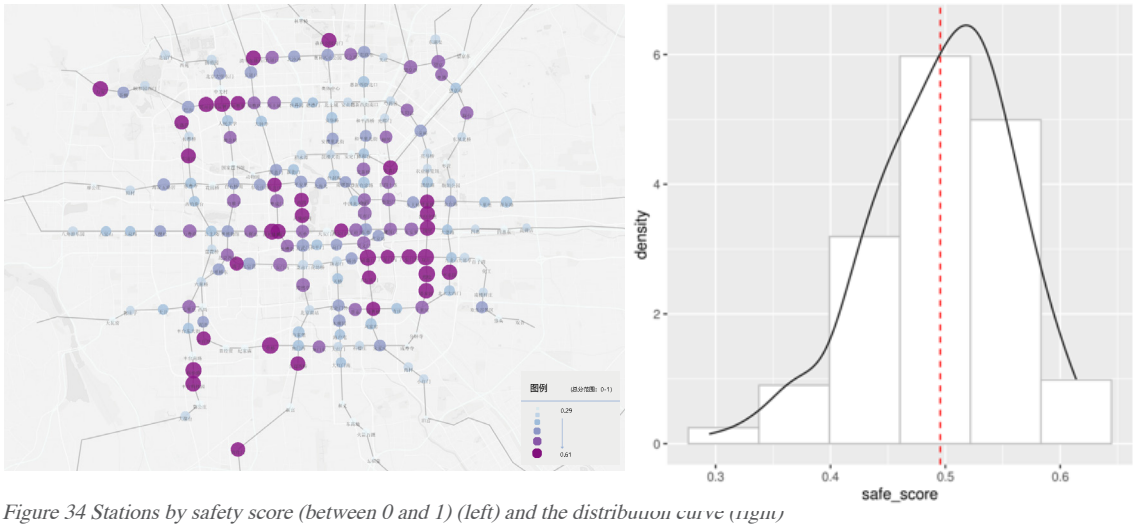


Figure 34 Stations by safety score (between 0 and 1) (left) and the distribution curve (right)
Source: World Bank research team.

Figure 35 Shuangjing Station (top left), Caoqiao Station (top right), Beitucheng Station (bottom left), Jijiamiao Station (bottom right)
Source: World Bank research team.

4.2.6 Aesthetics

Definition of indicator. Like safety, aesthetics is also measured by scores calculated using similar machine learning approach.

Aesthetic score. Appealing station areas partially overlap with safe ones. They are featured by human-scale street design and high-quality amenities (e.g. Haidianhuangzhuang Station). Similar to unsafe station areas, unappealing ones are usually close to parking lots, construction areas, elevated bridges, or high walls (Chapeng Station, Lingjing Hutong Station).

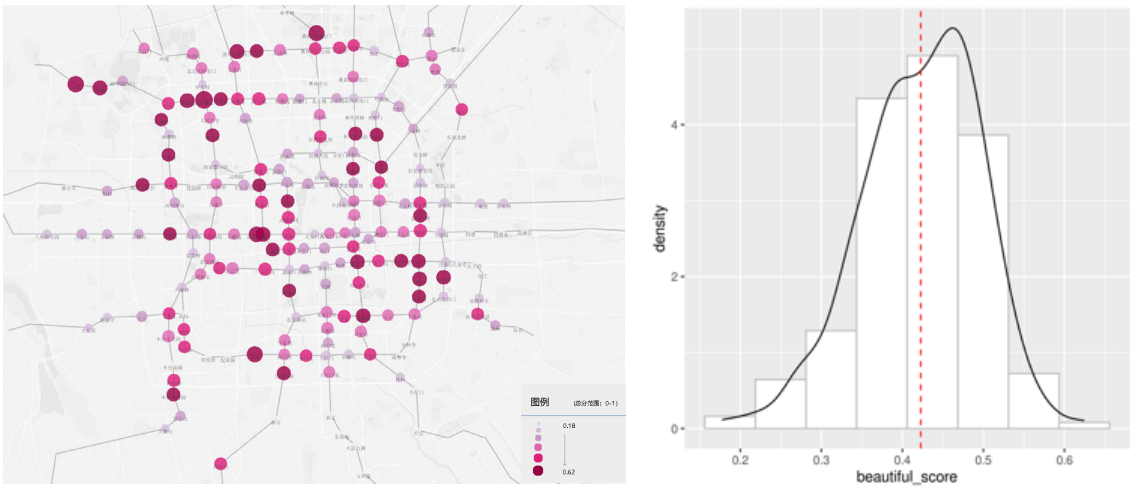


Figure 36 Stations by aesthetic score (between 0 and 1) (left) and the distribution curve (right)
Source: World Bank research team.

Figure 37 Haidianhuangzhuang Station in Summer and Spring (top)
Chapeng Station (bottom left), Lingjing Hutong Station (bottom right)
Source: World Bank research team.

4.3 Vibrancy

Vibrancy is formed by business attractiveness and the presence of informal economy.

4.3.1 Business attractiveness

Definition of indicator. Business attractiveness is measured by the density of pedestrians, bikes and automobiles (including parking ones) using an image recognition approach.

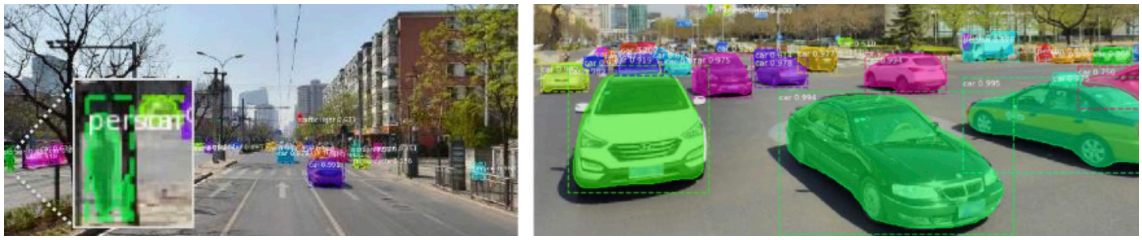


Figure 38 Image recognition of pedestrians, bikes, automobiles
Source: World Bank research team.

Density of pedestrians. Station areas with a high density of pedestrians share the same pattern as those with high passenger volumes. To deepen our understanding of pedestrian distribution in station areas, the research further evaluates passenger volumes in three circular belt areas based on 0-5 min, 5-10 min, 10-15 min walking distance from each station.

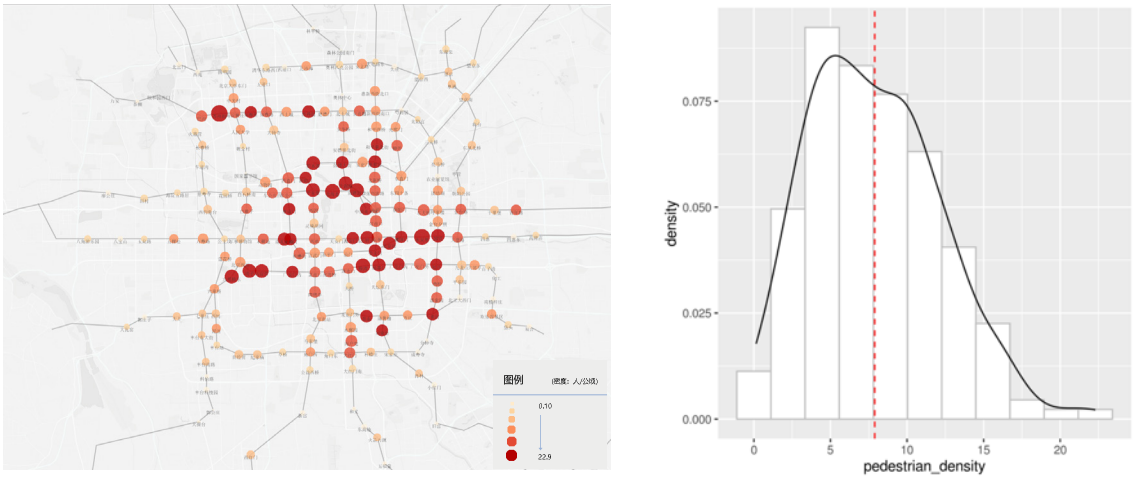


Figure 39 Stations by density of pedestrians (left) and the distribution curve (right)
Source: World Bank research team.

Density of bikes. Station areas with a high density of bikes are mainly located in areas with a bike-friendly environment like Suzhoujie, Zhongguancun, Nanluoguxiang, etc. These areas often have narrow streets, dense ground-floor stores, and protected bike lanes, encouraging more people to choose biking for first-mile and last-mile travel.

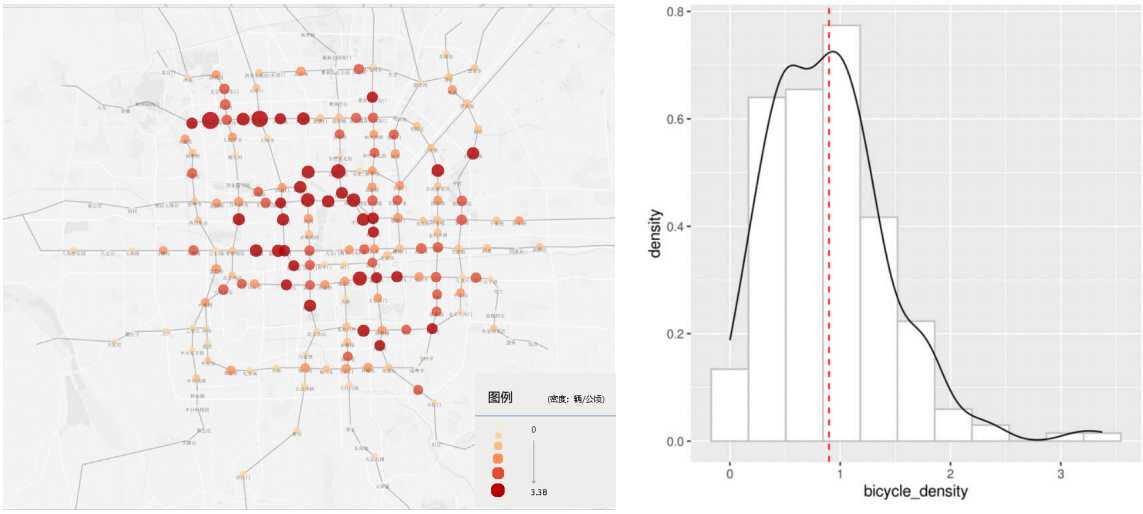


Figure 40 Stations by density of bikes (left) and the distribution curve (right)
Source: World Bank research team.

Density of automobiles. Station areas with a high density of automobiles are chiefly concentrated in business and office districts, major corridors with congested traffic flows sometimes, as well as low-density areas closer to the end of a Metro line where people “park and ride”.

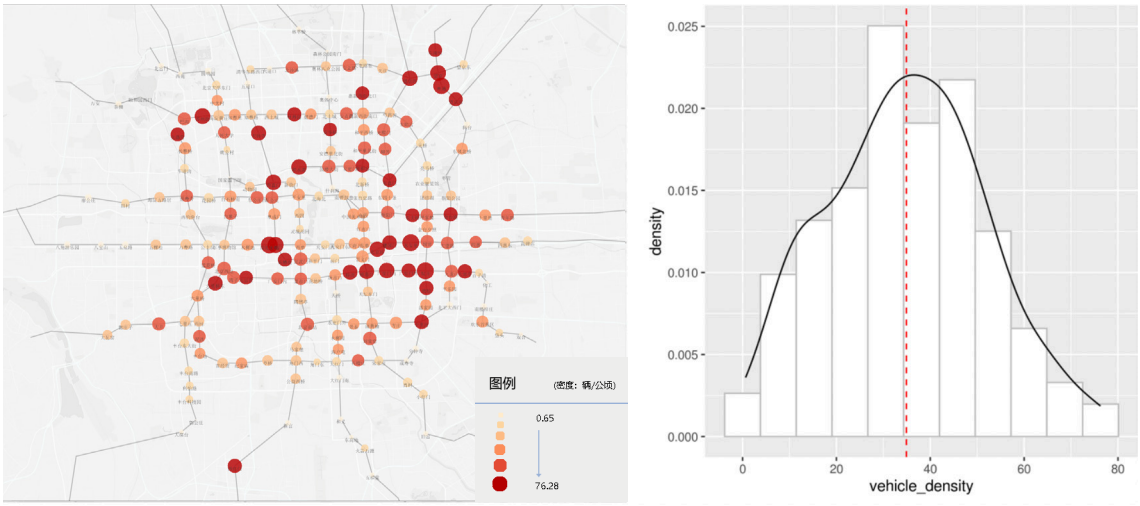


Figure 41 Stations by density of automobiles (left) and the distribution curve (right)
Source: World Bank research team.

4.3.2 Informal economy

Definition of indicator. Informal economy is measured by the number of street vendors by image recognition approach. A convolutional neural network model was trained on a large number of street vendor images and used to detect street venders from street view photos of targeted station areas in Beijing.

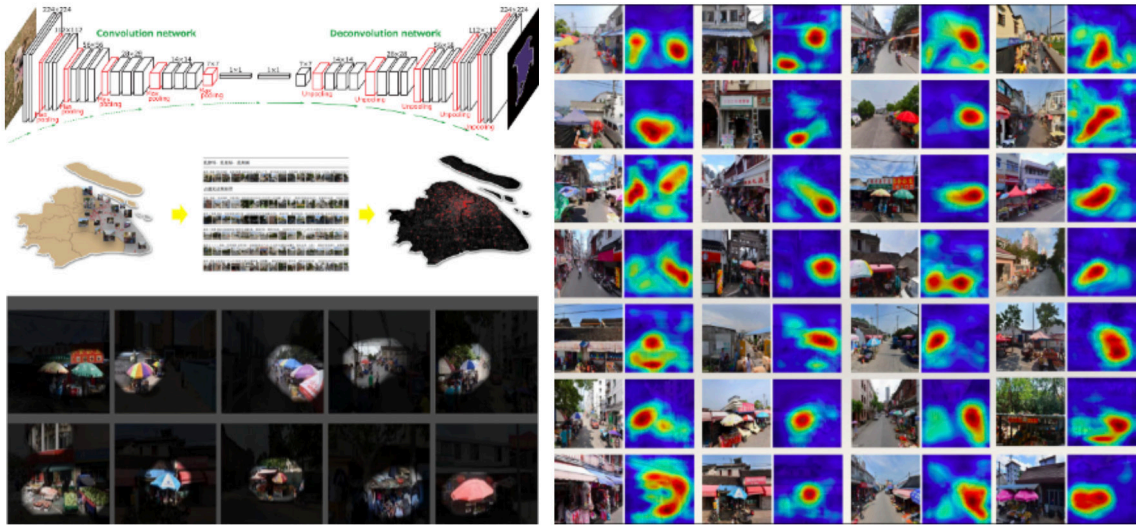


Figure 42 Image recognition of street vendors by employing convolutional neural network model
Source: World Bank research team.

Number of street vendors. Street vendors cluster around stations in inner city with pedestrian-friendly environment and loose regulations and in the southeastern district that is short of shopping centers. Station areas close to the Royal Gardens have strict street vending rules and thus lack informal economy.

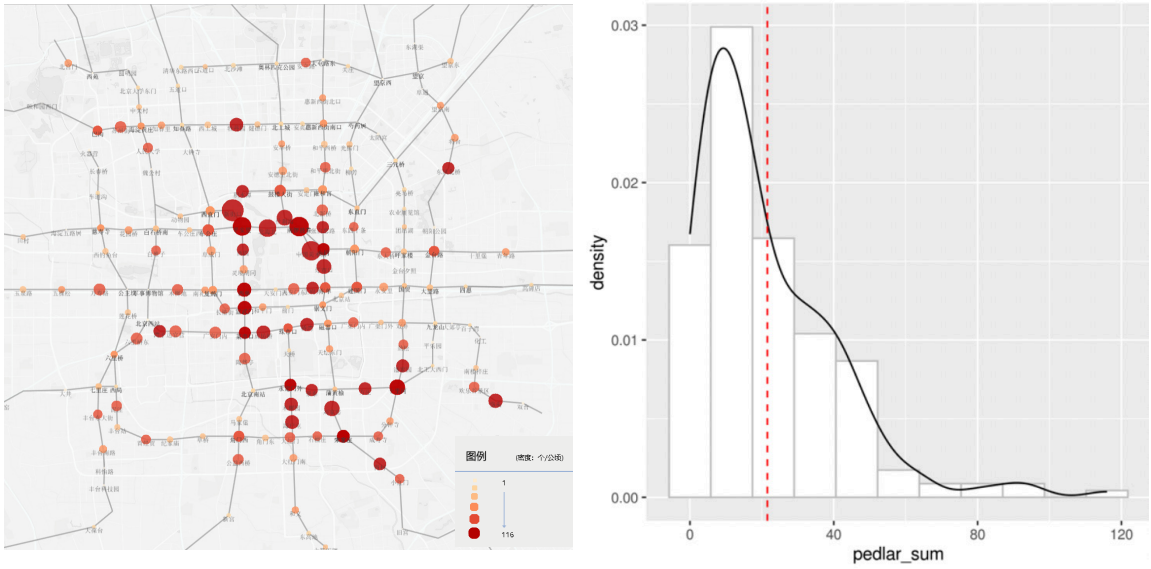


Figure 43 Stations by density of street vendors(left) and the distribution curve (right)
Source: World Bank research team.

4.4 Characteristics

Characteristics are divided into two parts: the similarity and the uniqueness of street landscapes around Metro stations.

4.4.1 Similarity

After training, testing, and applying a neural network model on 2 million street view photos, the research studied the similarity of a street landscape within station areas.

The similarity index for Futong Station and Wangjing Station is 0.5759. Both station areas have high-rise buildings, good green space coverage, and wide roads filled with a great number of vehicles.

Figure 44 Physical environment around Futong Station (top three) and Wangjing Station (bottom three)
Source: World Bank research team.

The similarity index for Shichahai Station and Nanluoguxiang Station is 0.5631. Both station areas have historic buildings and a pedestrian-friendly environment.

Figure 45 Physical environment around Shichahai Station (top three) and Nanluoguxiang Station (bottom three)
Source: World Bank research team.

4.4.2 Uniqueness

Definition of indicator. The uniqueness of a street landscape is calculated by taking the reciprocal of total similarity index for each station.

The three most unique stations are Keyilu Station, Jiugong station, and Sanyuanqiao Station.

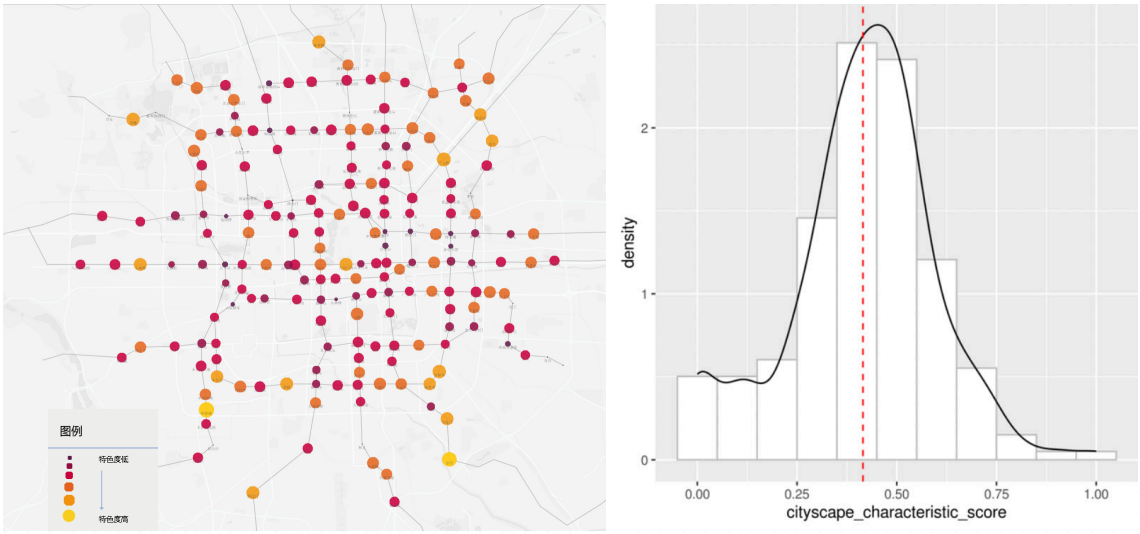


Figure 46 Stations by level of uniqueness (left) and the distribution curve (right)
Source: World Bank research team.

5. CONCLUSION

5.1 Macro-level: citywide comparison among stations

An integrated assessment model is built to aggregate tier 3 indicators using linear regularization and Analytic Hierarchy Process (AHP) in order to get scores of three main dimensions (tier 1 indicators) for each station area: convenience, comfort, and vibrancy. In addition, based on respective unique characteristics, station areas are also grouped into six categories. This quantitative assessment enables us to do quick screening of areas in urgent need of improvement.

Methodology. Linear regularization is conducted to transform the indicators into a range between 0 and 100. Tier 2 indicator (e.g. transit accessibility) is an average of regularized tier 3 indicators (e.g. number of Metro lines, number of bus stations). Tier 1 indicator (e.g. convenience) is a weighted average of regularized tier 2 indicators (e.g. transit accessibility). Specific weights (listed in Table 1) assigned to tier 2 indicators are calculated using AHP to reflect the landscape category of the target Metro station.

Figure 47 Methodology of indicator aggregation
Source: World Bank research team.

Table 1 Weights assigned to tier 2 indicators based on stations' landscape categories

Tier 1 indicators	Tier 2 indicators	High-rise landscapes	Suburban landscapes	Urban park landscapes	Green urban landscapes	Historic cultural landscapes	Commercial office landscapes
Convenience	Transit accessibility	33%	31%	30%	28%	23%	31%
	NMT accessibility	21%	34%	38%	27%	48%	24%
	Variety of amenities	21%	16%	20%	24%	20%	15%
	Mixture of urban functionalities	25%	19%	12%	21%	9%	30%
Comfort	Sky openness	9%	9%	8%	10%	6%	9%
	Greenness	12%	13%	21%	17%	8%	11%
	Lighting	19%	20%	8%	15%	13%	20%
	Street furniture	11%	7%	12%	10%	12%	11%
	Safety	34%	40%	29%	36%	31%	34%
	Aesthetics	15%	11%	22%	12%	30%	15%
Vibrancy	Business attractiveness	83%	61%	39%	79%	67%	81%
	Informal economy	17%	39%	61%	21%	33%	19%

Source: World Bank research team.

Convenience. Figure 48 displays how the four factors (i.e., transit accessibility, NMT accessibility, variety of amenities, and mixture of urban functionalities) contribute to the convenience at each station area.

Most of the Metro stations with high convenience are located in a business district, which is usually an interchange station with multiple Metro lines passing through and multiple entrances/exits. In addition, the area often has a dense street network, a friendly environment for both pedestrians and cyclists, abundant amenities, and mixed land use.

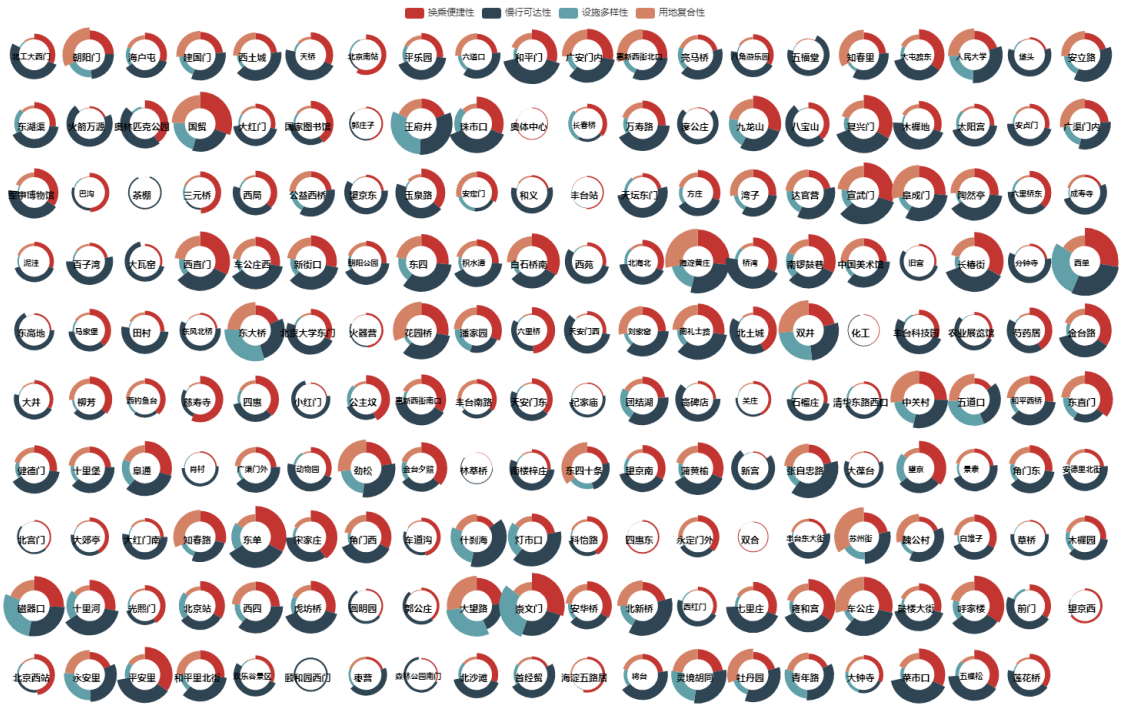


Figure 48 Stations by convenience indicators
Source: World Bank research team.

Figure 49 Low convenience: Shuanghe Station (left), Medium convenience: Andingmen Station (middle), High convenience: Chongwenmen Station (right)
Sources: Base map from Gaode (AMap) Maps, isochrones generated by World Bank research team.

Level of comfort. Figure 50 shows how the six factors (i.e., safety, aesthetic score, sky openness, greenness, street furniture and lighting) contribute to the level of comfort at each station area.

Figure 50 Stations by comfort indicators
Source: World Bank research team.

The scores of comfort dimension of each Metro station are relatively balanced when compared to those of convenience dimension. Most of the Metro stations with high level of comfort have parks or green spaces, or residential areas with ground-floor retail. These areas usually have plenty of tall trees, street furniture such as benches and bike parking racks, and a friendly walking space along the street.

Figure 51 High level of comfort: Suzhoujie Station (left), Nanlishilu Station (middle), Qinghuadongluxikou Station (right)
Source: World Bank research team.

Figure 52 Low level of comfort: Huagong Station (left), Fenzhongsi Station (middle), Chengshousi Station (right)
Source: World Bank research team.

Vibrancy. Figure 53 shows how business attractiveness and informal economy shape the level of comfort at each station area.

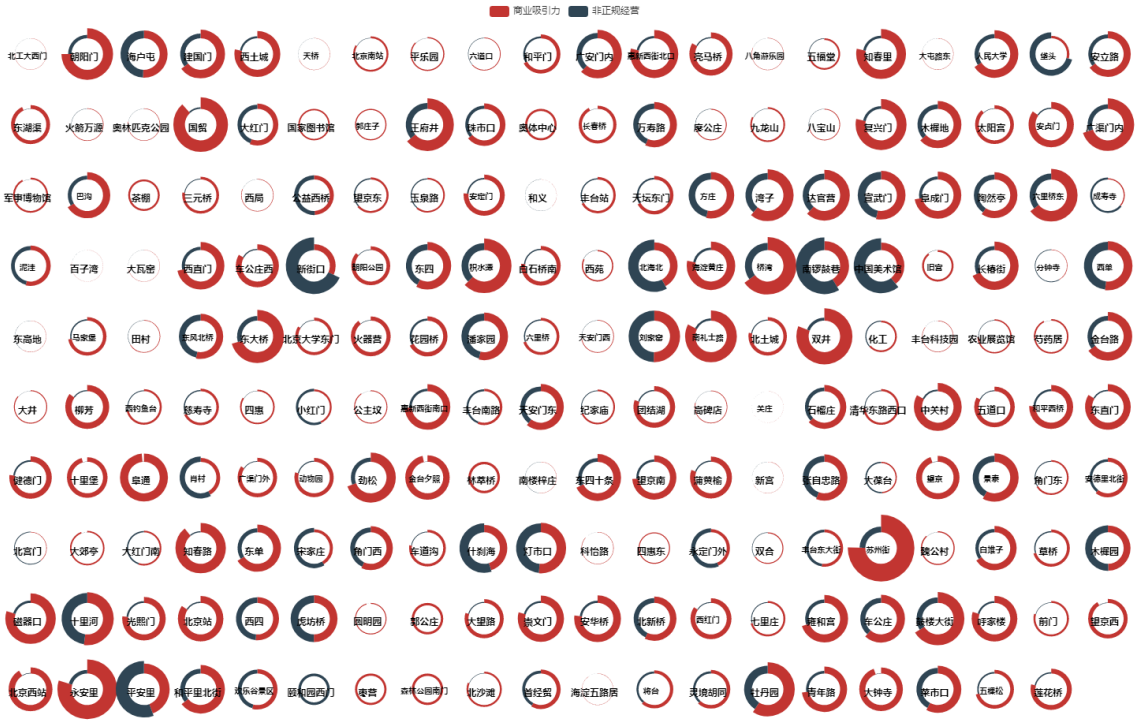


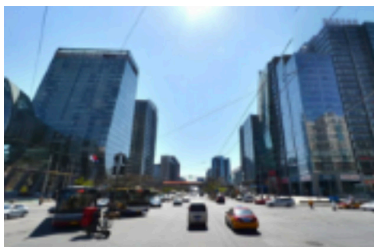
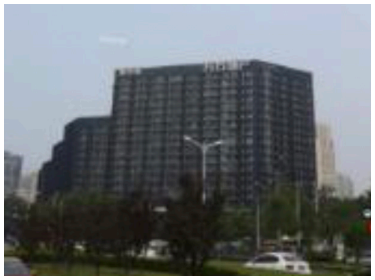
Figure 53 Stations by vibrancy indicators
Source: World Bank research team.

Most of the Metro stations with high vibrancy are surrounded by traditional blocks or connected narrow streets and alleys. With many of them located around scenic spots, these areas usually have a small scale of blocks, a friendly environment for both pedestrians and cyclists, and densely populated small stores.

Figure 54 Low vibrancy: Jiugong Station (left), Medium vibrancy: Jiandemen Station (middle), High vibrancy: Nanluoguxiang Station (right)
Source: World Bank research team.

Level of characteristics. Using clustering algorithms, 201 station areas are categorized into six groups as displayed in Table 2: high-rise landscapes, suburban landscapes, urban park landscapes, green urban landscapes, historic cultural landscapes, and commercial office landscapes.

Table 2 Stations by landscape categories

Type	Characteristics	Imagery
High-rise landscapes	Areas with a plenty of high-rise residential & office buildings and shopping centers that are under construction or already completed.	
Suburban landscapes	Areas with low-rise buildings, low-density development, wide vehicle lanes, and limited green space.	
Urban park landscapes	Areas with few buildings but a variety of vegetation coverage along the streets.	
Green urban landscapes	Areas with high-density development, good green space coverage, wide vehicle lanes, and later-developed modern buildings.	
Historic cultural landscapes	Areas with low-density historic structures usually with wide vehicle lanes and long narrow sidewalks.	
Commercial office landscapes	Areas with high-rise office buildings, good green space coverage, and wide streets.	

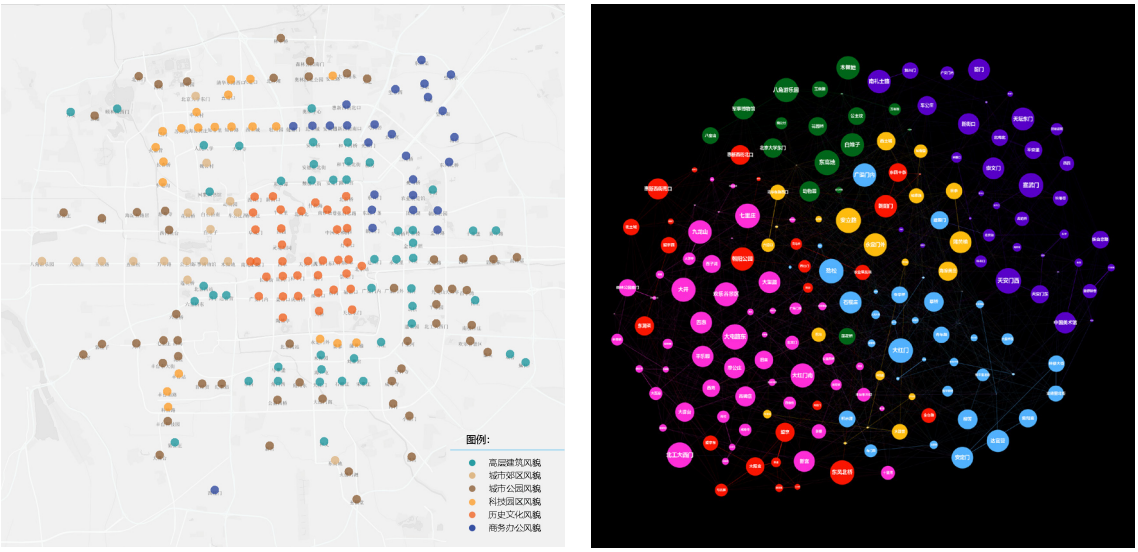


Figure 55 Stations by landscape categories (left), Relationship of stations based on landscape clustering and level of similarity (right)
Source: World Bank research team.

5.2 Micro-level: detailed diagnosis for individual station area

Utilizing the integrated assessment model, the research takes a deeper look at ten popular Metro stations based on big data analysis on internet traffic flow and ten low-scoring Metro stations, and provides some recommendations accordingly. Evaluations of three popular ones are displayed here:

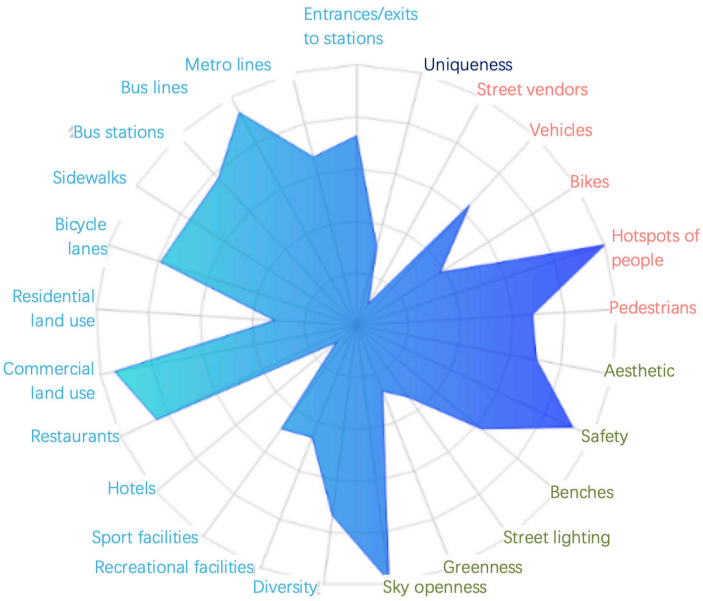


Figure 55 Guomao Station
Source: World Bank research team.

Located at the core area of Central Business District and surrounded by a bunch of high-rise luxurious office buildings, Guomao Station has high scores on convenience and vibrancy.

High convenience. As a transfer station for line 1 and line 10, it has abundant feeder transit services, a diversity of amenities, and highly mixed urban functionalities.

Medium level of comfort. The sky openness and greenness of Guomao Station area are very much influenced by its dense high-rise buildings in the area. However, it is considered safe with a direct access to shopping centers.

Later-developed modern structures also make the overall physical environment more appealing and comfortable.

High vibrancy. Filled with high-end offices and shopping centers, the area attracts large passenger volumes and numbers of automobiles every day.

Low level of characteristics. A homogeneous environment of high-rise buildings makes the station area less unique in terms of characteristics.

Possible improvements include expanding the diversity of vegetation coverage (medium feasibility), adding cultural or artistic elements that are compatible with the neighborhood (high feasibility), and forming a more bike-friendly environment (medium feasibility).

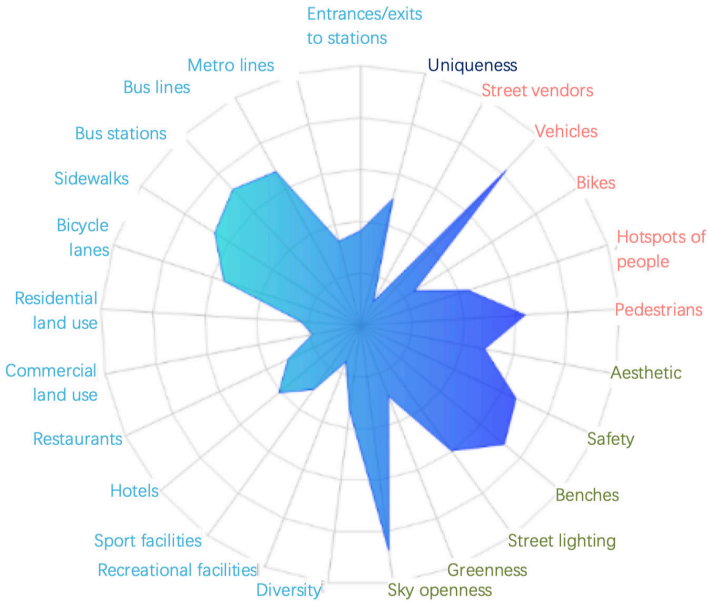


Figure 56 Beijing Railway Station
Source: World Bank research team.

Beijing Railway Station performs really well on comfort and vibrancy but has room for improvement on convenience and characteristics.

Low convenience. The area has well-connected feeder bus services and a bike-friendly environment but a single Metro line considering the rail transit might be a preferred way of travel as people get to the train station. It also has limited types of amenities and urban functionalities.

High level of comfort. With abundant lighting and benches, the area has a highly comfortable physical environment. It is also rated safe with an appropriate proportion of sky view.

High vibrancy. As a transit hub connecting intra-city and inner-city transportation networks, the area attracts large passenger volumes and numbers of automobiles.

Medium level of characteristics. Characteristics are also worth plenty of effort because, every day, tens of thousands of visitors go through this area—the place that becomes the first or the last image of Beijing in their mind for a period of time.

Possible improvements include expanding transportation options by Metro (low feasibility), building more diverse amenities (medium feasibility), and increasing unique characteristics of the station area (medium feasibility). While infrastructure improvements may be long-term, an expansion of bus services that directly connects to other transportation hubs will increase the accessibility in this area.

Tian'anmen West Station naturally performs well on characteristics but not the other three indicators.

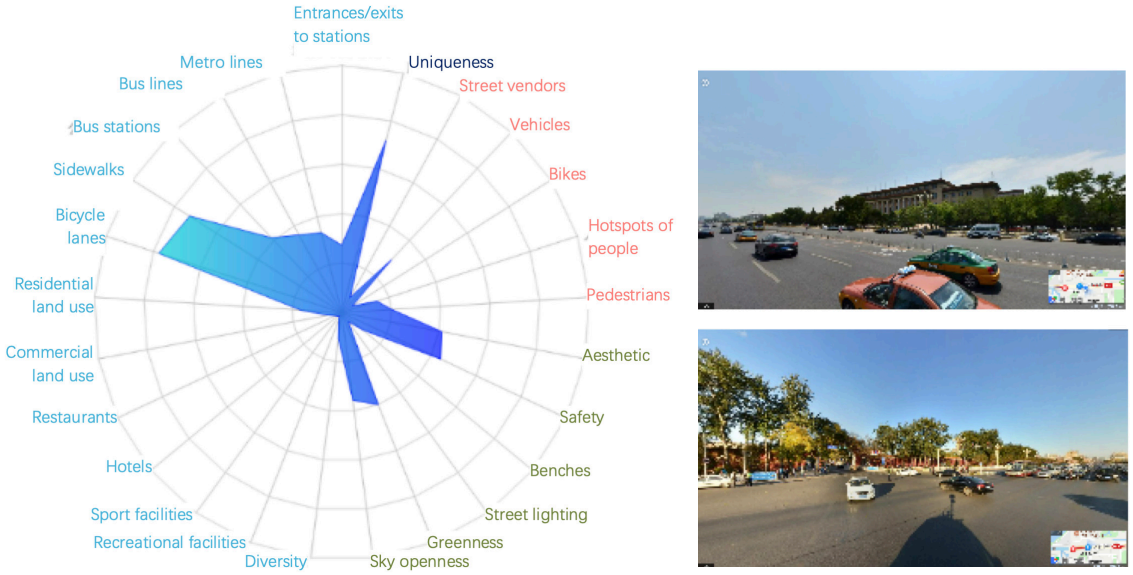


Figure 57 Tian'anmen West Station
Source: World Bank research team.

Low convenience. Located at the cross of Chang'an Avenue and Nanchang Street, it has a bike-friendly environment and is the closest Metro station to the Forbidden City. However, the area has a very limited number of feeder transit services and amenities and few types of urban functionalities for historic preservation purpose.

Medium level of comfort. The area is considered fairly comfortable in terms of openness, safety, and aesthetics, but the green space coverage and the amount of lighting and benches seems limited.

Low vibrancy. As a historic preservation area with few types of amenities, it has a very limited passenger volume. The total volume of mobile crowd is dynamically controlled and street vending is strictly prohibited.

High level of characteristics. The historic characteristic is unique in this station area.

A possible improvement is to build more diverse amenities while preserving the unique characteristics of the station area (medium feasibility).

5.3 Areas of future research

For areas of future research, the outputs can be further interpreted and attributed by making connections to relevant information from other data sources to enrich the comprehensiveness of the existing framework.

Physical environment outside Metro stations. For instance, the research above mentioned what Jane Jacobs called "eyes on the street". An analysis of the density of ground floor stores around Metro stations may provide additional insights on the evaluation of safety and comfort. A study of the distribution of stations with rain shelter facilities would also help better evaluate the two indicators.

Figure 58 Street view photos with ground floor stores (left) and with rain shelter facilities (right)
Source: World Bank research team.

An understanding of the number and the visibility of wayfinding signs around Metro stations can also help better understand equitability and convenience. Additionally, the existence of unlicensed motorcycle taxis around stations is a good indication of lacking last-mile feeder services and a complementary perspective for convenience.

Figure 59 Street view photos with wayfinding signs (left) and motorcycle taxis (right)
Source: World Bank research team.

Physical environment inside Metro stations. The research so far has focused on the physical environment outside Metro stations. An expansion of the scope to the physical environment inside the station is very necessary. With some initial studies, possible indicators include convenience, recognition, comfort, equitability, and safety.

5.4 Conclusion

The rationale and advantage of assessing the quality of physical environment using street view photos and machine learning models lies in:

- Evidence-based planning: the integrated assessment model can be also used to support evidence-based city planning and zoning by deploying specific interventions at the targeted locations as identified from the analytic results. Potential utilization of the framework also includes the development of benchmarking for strategic TOD planning.

- Replicable monitoring: with a comprehensive framework of indicators and an easy access to the data source, the evaluation approach can now be standardized and replicable, making it possible to conduct a comparative analysis on the physical environments of TOD communities at different levels of granularity (e.g. city level, corridor level or station level), at different cities or over a period of time.

- Future potential of expanding the study: the outputs can be further interpreted and attributed by making connections to relevant information from other data sources to enrich the comprehensiveness of the existing framework, identify feasibility of intervention, and study the potential causal relationship among various factors.

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