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Evaluation of Street Walkability and Bikeability: A Case Study of Tianjin

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Abstract: It is necessary to evaluate street walkability and bikeablity for green transportation development. This paper proposes an evaluation system for walking and cycling environment based on the convenience, safety and comfortableness and develops the street walkability and bikeability indexes. Taking Tianjin as an example, the paper evaluates the 1 569 kilometer roadways in the urban central district and conducts correlation analysis with household travel survey data of seven residential communities. The results show that walking environment in Tianjin central district is generally better than cycling environment. Walkability indicator and bikeability index decrease from the central district to suburban district as the city going through different development stages. The degree of convenience declines the most followed by the safety. Walkability indicator has a positive and significant correlation with residents' travel mode share of walking, while bikeability index has no significant impact on travel by bike. Finally, the paper provides suggestions on how to improve walking and cycling environment in Tianjin.
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Keywords: street; evaluation; walkability indicator; bikeablity indicator; Tianjin

1 Research background

The rapid development of automobile brings about increasingly severe urban traffic congestion and air pollution, and people begin to resort to non-motorized modes of transportation. Recently, bicycle has become one of the main travel modes with the emergence of bicycle sharing system. However, street environment problems have been highlighted by lack of non-motorized vehicle lanes, illegal on-road parking, and lack of shading facility for pedestrians. The central and local governments have issued policies, measures and technical guidelines for improving the street environment. In 2013, the Ministry of Housing and Urban-Rural Development of the People's Republic of China issued the *Guideline for Urban Pedestrian and Bicycle Transportation System Planning and Design* [1], and then local governments began to explore specific strategies of street design and environmental improvement. From 2016 to 2017, the city of Shanghai and Kunming took the initiative in releasing urban street design guidelines to promote a high-quality urban space, and pedestrian and bicycle friendly street space [2–3].

Residents' daily walking and cycling behavior is affected by street environment. However, existing research methods of evaluating street environment have the following limitations: the translation of street environment parameters into quantitative index is only confined to the microscale due to extensive labor force costs [4–5]; and the "Crowdsourcing" method to collect residents' views is subject to bias [6]. How to quantify street environment metrics and measure the quality of walking and cycling environment has become an important issue for designers and planners. Many quantitative evaluation tools for non-motorized mode have emerged in the fields of urban planning, transportation and public health field. Frank et al. [7] included land mix entropy, residential density and street connectivity into walkability indicator system, thus enabling the match between objectively measured urban forms and human's physical activities. Frank et al. [8] evaluated the association of a single index of walkability that incorporated land use mix, street connectivity, net residential density, and retail floor area ratios, with health-related outcomes (active travel, body mass index, vehicle miles traveled, air pollutants) in King County,

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Washington. Van Dyck et al. [9] defined the community walkability through geographic and observational data. Millington et al. [10] proposed the Scottish Walkability Assessment Tool (SWAT) to record the functionality, safety, aesthetics, and accessibility of the physical walking environment. Carr et al. [11] proposed a method of calculating facility accessibility on a large scale based on distance decay by using Points of Interest (POI) data. However, these studies mainly focus on facility accessibility, and ignore quality of street space in human scale.

In recent years, Chinese scholars have also carried out studies on walkability evaluations. Lu [12] established a community walkability evaluation framework based on three dimensions of walking demand (use frequency, use variety, and distance). Wu et al. [13] calculated the walkability indicator based on the accessibility of daily service facilities in Futian District, Shenzhen, China, and found that it was consistent with the spatial pattern of Sina Weibo check-in data. Liu et al. [14] evaluated the walking environment comfortableness of Tianjin historic districts by constructing a three-dimension framework consisting of 15 indicators. However, in the context of China's cities, how to jointly integrate the facility accessibility and quality of street space into the street environment evaluation for non-motorized traffic mode remains to be further explored. Some periphery of metropolitan cities still have the problems of car parking on sidewalks and the lack of pedestrian crosswalks, which need to be further reflected in the evaluation system. In addition, it is also of increasing significance to evaluating the street environment for cycling, concerning the soaring cycling demand, but relevant studies are mainly focusing on the coordination between non-motorized vehicle lanes and motor vehicle lanes at present [15–16], and the measurement of cycling environment itself needs to be further addressed.

Since current street environment evaluation methodology overlooks quality of street space, cycling environment, and localized street environment indicators, this paper proposes a street walking and cycling environment evaluation method to include safety and comfortableness dimension into traditional walkability and bikeability measured majorly by accessibility, and take in localized indicators to reflect the characteristics of Chinese cities. This walkability and bikeability evaluation method is applied to the city of Tianjin, to present an effective measurement for street environment design and livable street environment promotion for non-motorized mode

2 Data processing and methods

2.1 Data collection

The data in this paper are mostly acquired from open-source portals. The data of road network vector and rail transit network of Tianjin are from Open Street Map (OSM). The POIs of urban central district is from Gaode map. The street view images are from Tencent website to identify the objects of sidewalks, non-motorized vehicle lanes, insulator between motorized and non-motorized traffic, green shade ratio (the proportion of the length of the shaded road to the length of the road section), on-road parking, and road crossing facilities (pedestrian crosswalks, pedestrian overpasses, pedestrian underpasses). And building footprint data are obtained through commercial channels. The overall geospatial database of the central district of Tianjin is shown in Figure 1.

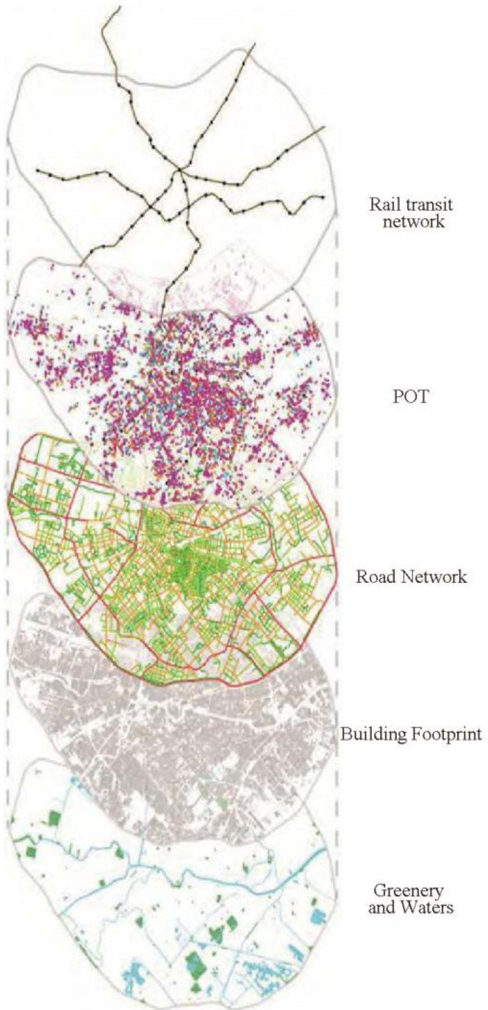


Figure 1 Geospatial database of Tianjin central district

The household travel survey data include seven residential communities with different locations, building forms, and years of construction: Tianjin Causeway Bay Garden, Longting Home, Beining Bay Peaceful Home, Jinshuipan Home, Jiachun Garden, Lily Spring and Tianjin Kaifali (Figure 2 and Table 1). We collect the travel diary data of 998 households in winter of 2016, including travel purpose, travel mode, travel time, number of family member, household income, and car ownership.

Figure 2 Location and satellite map of residential communities

Source: Baidu map

Table 1 Basic characteristics of the selected residential communities

Residential community	Building form	Number of floors	Location	Year of construction
Causeway Bay Garden	Point block	Above 11	Urban central district	2004
Longting Home	Point block	Above 11	Peri-urban central district	2008
Beining Bay Peaceful Home	Point block	Above 11	Peri-urban central district	2011
Jinshuipan Home	Slabs	4–6	Suburb	2006
Jiachun Garden	Slabs	7–11	Suburb	2010
Spring Lily	Town house	Above 11	Suburb	2010
Tianjin Kaifali	Slabs	Above 11	Peri-urban central district	2000

2.2 Evaluation methods of street walkability and bikeability

With reference to the street index by Gu et al.[17], we propose the walkability and bikeability indicators for 1 569 km roads in Tianjin based on convenience, safety, and comfortableness (Table 2). Convenience indicator takes account of road network density, road crossing density, and the accessibility of daily facilities. The safety of walking and cycling environment is guaranteed by necessary facilities that sidewalks and non-motorized vehicle lanes should be set up on the roads. Pedestrian road crossing should be installed at intersections, and parking on sidewalks and non-motorized vehicle lanes should be discouraged. Therefore, this paper measures the safety of walkability by whether there are sidewalks, whether there are road crossing at road intersections, and the proportion of on-sidewalk parking; and measures the safety of bikeability by calculating whether there are non-motorized vehicle lanes, whether there are road crossing at road intersections, and the proportion of parking on non-motorized vehicle lanes. For comfortableness, small-scale streets with consistent building interfaces and shading will improve walking experience. Therefore, we measure the comfortableness of walkability by the distance between opposite building facades, consistency ratio of building front to property line, and green shade ratio; and measure the comfortableness of bikeability by the insulator between motorized and non-motorized traffic, and the green shade ratio.

In the ArcGIS, the road is simplified to centerline for topological processing, and a total of 5 652 road segments are obtained. We form a matrix composed of m roads segments and n indicators in Formula (1):

$$X=\{X_{ij}\}_{m\times n}\ (0\le i\le m,\ 0\le j\le n), \quad (1)$$

where $\{X_{ij}\}$ is the value of the indicator j for road segment i.

For the convenience indicators, we cut the roads into K equidistant points at interval of 50 meters, to calculate the road network density, road crossing density and the accessibility of daily facilities within the buffering circle of an area of 1 km^2. The road network density X_{i1} is measured by the road network length in the 1 km^2 buffering circle with the equidistant point as the center/(km·km^{-2}). The road crossing density X_{i2} is measured by the ratio of the number of road crossing to the length of the road network in the buffering circle /(km·km^{-2}). For the accessibility of daily facilities X_{i3}, we select nine kinds of POIs which are frequently visited by local residents according to survey and interviews, namely food mart, convenience stores, hotels and restaurants, shopping malls and supermarkets, places of entertainment and recreation, banks, hospitals, bus stations, rail transit stations. we firstly calculate the nearest road distance Dis_p, $p\in\{1, 2, 3, 4, 5, 6, 7, 8, 9\}$ from the equidistant point to each type of the daily facility on ArcGIS platform, and then use the distance decay Formula (2) to get the accessibility coefficient of the equidistant point to each type of daily facility.

Table 2 Indicator of walkability and bikeability

Dimension		Indicator	Variable
Convenience	Walkability and bikeability	Road network density	X_1
		Road crossing density	X_2
		Accessibility of daily facilities	X_3
Safety	Walkability and bikeability	Whether there is road crossing	X_4
	Walkability	Whether there are sidewalks	X_5
		Proportion of on-sidewalks parking	X_6
	Bikeability	Whether there are non-motorized vehicle lanes	X_{10}
		Proportion of parking on non-motorized vehicle lanes	X_{11}
Comfortableness	Walkability and bikeability	Green shade ratio	X_7
	Walkability	Distance between opposite building facades	X_8
		Consistency ratio of building front to property line	X_9
	Bikeability	Whether there is insulator between motorized and non-motorized traffic	X_{12}

$$\mathrm{Acc}_p=\begin{cases}1,\ Dis_p\le 400\\ 188\,177\times\dfrac{Dis_p}{Dis_p^{2.947\,5}+34\,259\,163},\ 400<Dis_p<2\,400\quad p\in\{1,2,3,4,5,6,7,8,9\}\\ 0,\ Dis_p\ge 2\,400\end{cases}. \quad (2)$$

The accessibility of a certain point on road i is:

$$X_{i3}=\sum_{p=1}^{9}Acc_p\times\frac{1}{9}. \quad (3)$$

The road network density, road crossing density and daily facility accessibility on road segment i is the average value of that of K equidistant points on road segment i:

$$X_{ij}=\sum_{k=1}^{K}X_{ij}^{k}\times\frac{1}{K},\ j\in\{1,2,3\}. \quad (4)$$

As for indicators X_{i4}, X_{i5} and X_{i10}, we refer to street image to define whether there are road crossing, sidewalks, and non-motorized vehicle lanes respectively on road i (1 for yes, 0 for no). For the proportion of on-sidewalks parking X_{i6}, the proportion of parking on non-motorized vehicle lanes X_{i11}, and the green shade ratio X_{i7} (the proportion of the length of the shaded road to the length of the road section), we also refer street image to estimate the proportion. We assign 100% to X_{i6} for non-sidewalk street segments, and 100% to X_{i1} for street segments without non-motorized vehicle lanes. For the consistency ratio of building front to property line X_{i9}, we adopt the method proposed by Jiang et al. [18], to determine the property line on the ArcGIS platform, and then calculate the ratio of the building façade width to the property line. The distance between opposite building facades X_{i8} includes the building setback distance on both road sides and road width. For whether there is an insulator between motorized and non-motorized traffic X_{i12}, it is determined as the following: 0—there is no insulator; 1—there is painted insulator on road; 2—there is pole insulator; 3—there is green belt insulator.

2.3 Using information entropy weighting to derive indicators

Information Entropy Weighting method has an advantage of overcoming the subjectivity of artificially determined weighting, avoiding information overlapping among multiple indicators, and having strong adaptivity. It is adopted in this paper to derive the final street indicator for walkability and bikeability, as well as indicators in sub-dimensions. The workflow is as the following:

1) Firstly, we construct a matrix of m road segments and n indexes where X_{ij} is the value of the j^{th} indicator ofthe i^{th} road segment: $X=\{X_{ij}\}_{m\times n}\ (0\le i\le m,\ 0\le j\le n)$.

2) Secondly, since different indexes differentiate in terms of dimension and unit, we compute the dimensionless X'_{ij} for each index using the following equations:

$$X'_{ij}=\left(X_{ij}-\min\{X_j\}\right)/\left(\max\{X_j\}-\min\{X_j\}\right), \quad (5)$$

$$X'_{ij}=\left(\max\{X_j\}-X_{ij}\right)/\left(\max\{X_j\}-\min\{X_j\}\right) \quad (6)$$

Here, the indexes meeting the requirements of the positive hypotheses (X_1, X_2, X_3, X_4, X_5, X_7, X_8, X_9, X_{10}, X_{12}) in Table 2 are calculated with Formula (5), while the indexes meeting the requirements of the negative hypothesis (X_6, X_{11}) are calculated with Formula (6).

3) Thirdly, we calculate the proportion of the index R'_{ij}:

$$R'_{ij} = X'_{ij} / \sum_{i=1}^{m} X'_{ij}. \quad (7)$$

4) The fourth step is to calculate the entropy of the j^{th} index e_j:

$$e_j = \frac{1}{\ln n} \sum_{i=1}^{m} R'_{ij} \ln R'_{ij}, \quad (8)$$

If $R'_{ij} = 0$, then $\ln R'_{ij}$ is deemed as 0.

5) In the fifth step, we calculate the imbalance coefficient g_j of the j^{th} indicator:

$$g_j = 1 - ej. \quad (9)$$

6) The sixth step is to calculate the weight of the j^{th} indicator W_j:

$$W_j = g_j / \sum_{j=1}^{n} (1 - g_j). \quad (10)$$

7) In the seventh step, we calculate the value of the j^{th} indicator of the road segment i:

$$V_{ij} = W_j X'_{ij}. \quad (11)$$

8) The eighth step is to calculate the walkability indicator of road segment i:

The walkability indicator V_i^{w}, walkability convenience indicator V_i^{w1}, walkability safety indicator V_i^{w2}, and walkability comfortableness indicator V_i^{w3} of road i are calculated as following:

$$V_i^{w} = \sum_{j=1}^{q} V_{ij},\ q \in \{X_1, X_2, X_3, X_4, X_5, X_6, X_7, X_8, X_9\}, \quad (12)$$

$$V_i^{w1} = \sum_{j=1}^{q} V_{ij},\ q \in \{X_1, X_2, X_3\}, \quad (13)$$

$$V_i^{w2} = \sum_{j=1}^{q} V_{ij},\ q \in \{X_4, X_5, X_6\}, \quad (14)$$

$$V_i^{w3} = \sum_{j=1}^{q} V_{ij},\ q \in \{X_7, X_8, X_9\}. \quad (15)$$

The walkability indicator $V_i^{w'}$, walkability convenience indicator $V_i^{w1'}$, walkability safety indicator $V_i^{w2'}$, and walkability comfortableness indicator $V_i^{w3'}$ are normalized between 0–100 respectively, applying the followed equations:

$$V_i^{w'} = 100 \times \left(V_i^{w} - \min\{V_i^{w}\}\right) / \left(\max\{V_i^{w}\} - \min\{V_i^{w}\}\right), \quad (16)$$

$$V_i^{w1'} = 100 \times \left(V_i^{w1} - \min\{V_i^{w1}\}\right) / \left(\max\{V_i^{w1}\} - \min\{V_i^{w1}\}\right), \quad (17)$$

$$V_i^{w2'} = 100 \times \left(V_i^{w2} - \min\{V_i^{w2}\}\right) / \left(\max\{V_i^{w2}\} - \min\{V_i^{w2}\}\right), \quad (18)$$

$$V_i^{w3'} = 100 \times \left(V_i^{w3} - \min\{V_i^{w3}\}\right) / \left(\max\{V_i^{w3}\} - \min\{V_i^{w3}\}\right). \quad (19)$$

9) The street bikeability indicator and the value for three dimensions of bikeability convenience, safety, and comfortableness are obtained with similar methods.

3 Result

3.1 Descriptive statistics

As shown in Table 3, the quality of street walking environment (score 59) is generally better than the cycling environment (score 45) in Tianjin central district. Among the indicators of three dimensions, the safety of both walkability and bikeability is the highest, reaching 80 and 49 respectively. From Table 4, the overall road network density is not high, with an average value of only 6.70 km ·km^{-2}; the daily facility accessibility is comparatively good, with an average value of 0.85. The 81.98% of the roads are paved with sidewalks on both sides, but the proportion of roads without non-motorized vehicle lanes is as high as 65.54%. The 5.39% of the sidewalks and 14.54% of the non-motorized vehicle lanes are subject to on-road parking problems. We find that although many roads do not have non-motorized vehicle lanes, their cycling safety index is still high because the proportion of roads with road crossing is relatively high and the problem of parking on non-motorized vehicle lanes is not significant. From the perspective of cycling comfortableness, the consistency ratio of building front to property line and green shade ratio are below 50%, and there is only a few insulators between motorized and non-motorized traffic. The physically insulated road sections only account for 6.51%, which cannot effectively guarantee the coherence and comfortableness of the cycling environment.

Table 3 Statistics of walkability indicator and bikeablity indicator

Dimension	Minimum	Maximum	Average
Walkability	0	100	59
Convenience	0	100	49
Safety	0	100	80
Comfortableness	0	100	52
Bikeability	0	100	45
Convenience	0	100	46
Safety	0	100	49
Comfortableness	0	100	29

3.2 Walkability in different city development phases

The city of Tianjin has gone through vicissitudes in history, which has shaped the street with distinct styles and characteristics. We analyze the walkability indicators in different development periods, and explore the evolution in urban environment of different development phases. We divide the city of Tianjin into four regions spatially based on its development phases (figure 3). When comparing the walkability indicators of different regions (figure 4), we find that the total scores gradually decrease with the expansion of city, and the discrepancy between individual road segments in outer layers is larger than that in inner region. Additionally, the decline of convenience index is the most obvious; the decline of safety index is relatively gentle; and the comfortableness index maintains a stable level for all regions except the outmost one that has a much lower indicator.

Table 4 Statistics of basic indicators

Dimension	Basic index	Variable	Minimum	Maximum	Average
Convenience	Road network density (km·km^{-2})	X_1	1.12	18.49	6.70
	Road crossing density (number·km^{-1})	X_2	0.00	3.90	1.69
	Accessibility of daily facilities	X_3	0.00	1.00	0.85
Safety	Whether there is road crossing	X_4	0.00	1.00	0.66
	Whether there are sidewalks 1)	X_5	0.00	1.00	0.87
	Proportion of on-sidewalks parking/%	X_6	0.00	100.00	5.39
	Whether there are non-motorized vehicle lanes 2)	X_{10}	0.00	1.00	0.33
	Proportion of parking on non-motorized vehicle lanes %	X_{11}	0.00	100.00	14.54
Comfortableness	Green shade rate/%	X_7	0.00	100.00	30.70
	Distance between opposite building facades/m	X_8	3.00	73.00	23.00
	Consistency ratio of building front to property line/%	X_9	0.00	100.00	36.00
	Whether there is insulator between motorized and non-motorized traffic 3)	X_{12}	0.00	4.00	0.46

1) The proportion of roads with sidewalks on both sides is 81.98%; the proportion of roads with sidewalks on one side is 5.06%; the proportion of roads without sidewalk is 12.96%. 2) The proportion of roads with non-motorized vehicle lanes on both sides is 31.17%; the proportion of roads with non-motorized vehicle lanes on one side is 3.29%; the proportion of roads without non-motorized vehicle lanes is 65.54%. 3) The proportion of roads without non-motorized vehicle lanes is 65.54%; the proportion of roads with painted insulator on road is 27.95%; the proportion of pole insulator is 3.26%; and the proportion of green belt insulator is 3.25%.

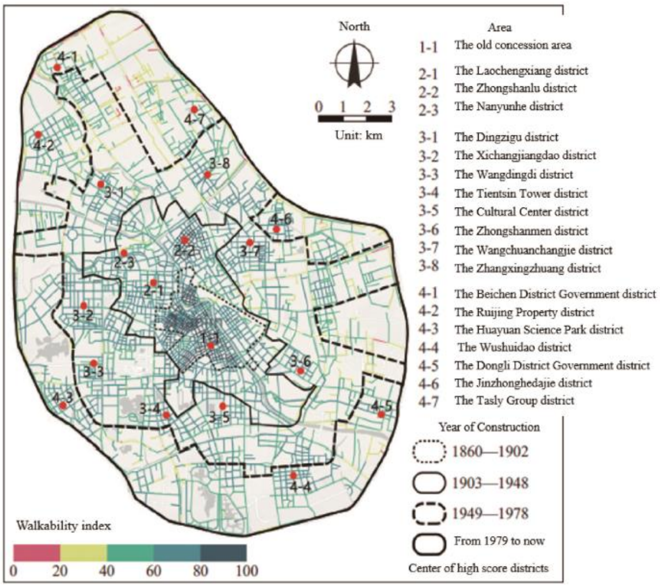


Figure 3 Spatial distribution of walkability indicator in different development periods

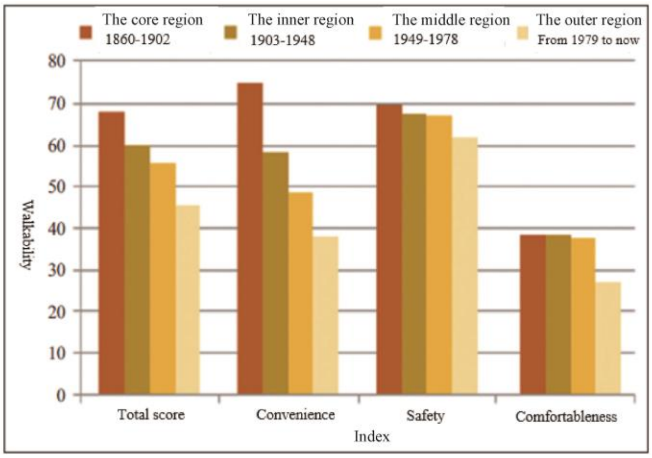


Figure 4 Walkability indicator of four zones

1) The core region was formed during the period of concession expansion and road construction (1860–1902) [19]. Since different countries adopted their own concepts of road planning, there is little consistency between the street pattern in each concession area. For example, the Japanese concession was dominated by small-scale grids, while the British concession was mostly in radial pattern.

The boundary of the core region almost coincides with the road segments of the highest walkability in central district, indicating that the walking environment left over from the old concession period in the early days and renovated later on is still very livable and pleasant now. Its western style is well maintained for walkable environment in its high road network density, high road crossing density, and high consistency ratio of building front to property line.

2) The inner region was formed during the ruled time of Chinese Nationalist Party, occupation time of the Second Sino-Japanese War, and the recovery time of the post Second World War (1903–1948). The Haihe River was dredged to level up the southwest part of the old city and expand the city to Hebei District and the Hedong District. At the same time, Japanese military bases were expanded and residential lands in city center soared up sharply due to the influx of the refugees.

The high-indicator area is mainly located in the old city center district (or the Laochengxiang District), the Zhongshanlu District, and the Nanyunhe District. The Laochengxiang district originated from the Tianjin garrison town in 1404, but has changed into modern street pattern after the demolition of the city wall. In 2003, the old city center was revitalized as the historic district by preserving historic buildings, dismantling narrow hutongs and dilapidated houses, and building corridors oriented north and south and passing through Drum-Tower. Then the roads were widened to allow motorized vehicle lanes. The high walkability indicator of the Laochengxiang District results from high daily facility density and convenient daily facility accessibility. Zhongshan Road, with the Jingang Bridge as the starting point in the Zhongshanlu District, is the major channel connecting the Haihe River North District and Tianjin North Railway Station. Many old residential blocks mixed with new apartments built after 2000s stand along the Zhongshan road. Zhongshan Park locates at east side of Zhongshan Road, creating a livable atmosphere of neighborhoods. Zhongshanlu district is high in convenience and comfortableness, mainly due to high accessibility of daily facilities, high density of road crossing, high green shade ratio, and high consistency ratio of building front to property line. Nanyunhe district where many slab buildings situate is also high in safety and accessibility of daily facilities, especially due to the pleasant waterfront landscape.

3) The middle region was formed during the Planned Economic Period (1949–1978). It was dominated by 10 scattered industrial zones and surrounding residential communities. At the same time, the central district further expanded to the north, forming a pattern that residential and commercial areas are in the city center; the industrial area mixed with some residence are in the middle; universities and scientific parks mixed with residential areas are in the southwest; and industrial zones mixed with residence are at periphery.

The high-indicator districts include Zhangxingzhuang District of many residential areas and Tientsin Tower District of many government buildings, as well as the Cultural Center District, the Dingzigu District, the Xichangjiangdao District, the Wangdingdi District, the Zhongshanmen District, and the Wangchuanchang Street District. Among them, the Cultural Center and Tientsin Tower Districts are the places for hosting cultural activity, with high accessibility of daily facilities, high green shade ratio, high consistency ratio of building front to property line, and thus good convenience and comfortableness. As to the residential areas with high walkability indicators, they are usually high in all three dimensions of convenience, safety, and comfortableness due to higher road network density, daily facility accessibility, road crossing density, green shade ratio, and the consistency ratio of building front to property line.

4) The outer region was formed during the China Market Economy Period (since 1979). During this period, the city expansion was dominated by Technical Economic Development Areas (such as Huayuan, Beichen, and Meijiang), large-scale ecological parks (such as water parks), and gated residential communities. Driven by capital in development area and real estate projects, the city of Tianjin fast expanded over the loop of the expressway.

The high-indicator districts are mainly where the government of the new development zone is located (such as the Beichen Government District and Dongli Government District), the industrial park (such as the Tasly Group District, Huayuan Science Park District, and Ruijing Property District), and new residential areas (such as the Wushui Road District and Jinzhonghe Street District). These districts are high in convenience and comfortableness when equipped with multiple kinds of daily facilities, but are still low in daily facility density.

Zooming into the districts with high walkability indicators, we can find that the factors effectively contributing to high indicators are the accessibility of daily facilities, the green shade ratio, the consistency ratio of building front to property line, the density of road crossing, and the density of road networks, ranked by importance, which provide suggestions to planners as barometers to measure the street environment of Tianjin.

3.3 Walkability indicator on convenience, safety, and comfortableness

In addition to walkability indicator in variation with urban development phases, we also consider the walkability variation in regions divided by rings of highway and variation with road hierarchy (Figure 5).

Figure 5 Roadway classification in Tianjin

Source: Tianjin Urban Planning & Design Institute

1) Convenience: the high-indicator districts are in a pattern of one major core (the old concession) and other scattered dots.

It can be seen from Figure 6a that the traditional districts, such as the old concession, the Five Avenues District, and the Zhongshan Park Districts, are in high convenience indicator due to dense road network and rich daily facilities. The industrial parks outside the loop of the expressway (such as the Heavy Machinery Industrial Area in the north and the Tianmu Town Urban Industrial Park District) are severely segregated from residential area, and lack many daily facilities. The residential areas outside the loop of the expressway (such as the Liuyuan and Meijiang Districts) are sparse in road network and lack corresponding daily facilities, scoring low in convenience. In the region between outer ring highway and loop of expressway, the road crossing density is extremely low, and some roads are over-wide. Even worse, the road crossing there is blocked and the green belt insulators are cut off occasionally.

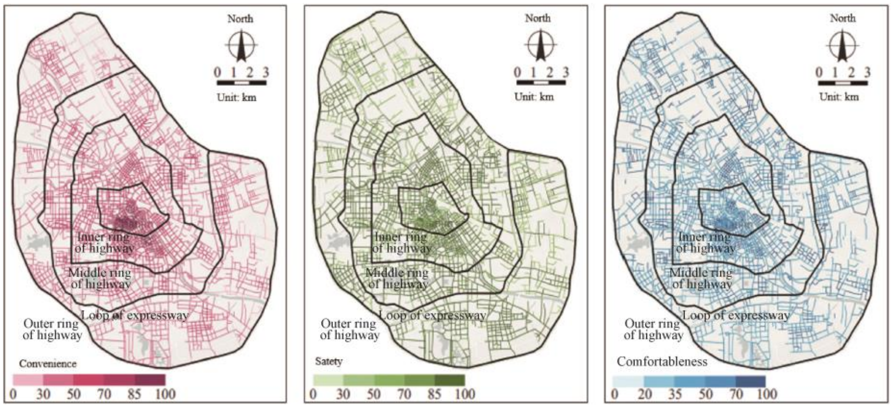
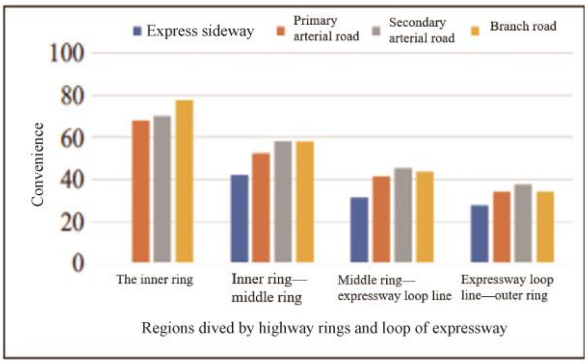
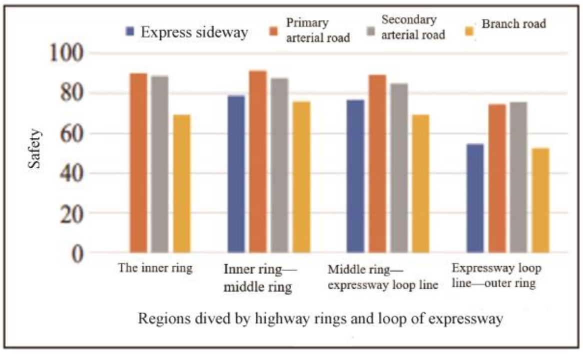


Figure 6 Spatial distribution of walkability indicator



a Convenience



b Safety

c Comfortableness

Figure 7 Correlation of roadway classification and walkability indicator in different districts

As is shown in Figure 7a, that expressway sideway in different regions all have the lowest walking convenience indicators. The branch roads reach the highest in convenience indicator within the inner ring of the highway, but drop sharply in ranking at the region between loop of expressway and the outer ring of highway. This means that there are not enough daily facilities around streets in residential areas at urban periphery, which may lead to higher dependence on automobiles.

2) Safety: the city periphery is lower than the city center and there exists a vacuum zone.

Figure 6b shows that the districts of high safety are mainly concentrated in the Heping District and the Hexi District, and the districts of low safety are mainly in newly built districts at city periphery. The low-safety streets are usually poorly configured for walking space.

When referring to Figure 7b, we find that the region in-between expressway loop and the outer ring of highway is low in safety due to lack of road crossing, insufficient insulator between motorized and non-motorized vehicle lanes, and problems of on-sidewalk parking in residential areas. The on-sidewalk parking within the inner ring of highway is also prominent, directly affecting the safety of walking environment. In addition, the safety indicator of primary and secondary arterial roads is higher than that of branch road for each ring road regions because that the width of branch road is too limited to set up separate sidewalks, and people tend to park along the street due to scarce parking space. In this regard, it is necessary to improve the walking environment of the branch road and monitor on-sidewalk parking.

3) Comfortableness: the high indicator districts are fragmented.

As shown in Figure 6c, the districts of low comfortableness are mainly scattered at periphery (such as the Hongqiao District in the northwest, the Dongli District in the east, and the Meijiang District in the south). The low comfortableness results from narrow width of sidewalk, road occupation by traffic and infrastructures, lack of barrier-free facilities, cut-off of green belt insulators, oversized setback occupied by parking, low density of daily facilities, and negative interface of the continuous walls.

Figure 7c shows that the walking comfortableness is highly correlated with road hierarchy: the higher road hierarchy leads to the lower comfortableness. The express sideway and primary arterial road are usually of enclosed walls, large setbacks, and poor street interface continuity. In contrast, the branch road is high in comfortableness because of more continuous street interface with abundant daily facilities, human-scale building facade and pavement, and sufficient tree shading especially in old city center.

3.4 Bikeability

Figure 8 shows the distribution of non-motorized vehicle lanes in central district of Tianjin. The northwest is better than the southeast where the insulator of motorized vehicle lanes and non-motorized vehicle lanes are almost absent. It can be seen from Figure 9 that the bikeability indicator shows a trend of decrease from the city center to the periphery, where the decrease of convenience ranks the first and the decrease of safety ranks the second. The districts of high bikeability are overlapped with those of high walkability, showing the consistence between walking and cycling environment. More specifically, the vehicle parking on non-motorized vehicle lanes is mainly concentrated in the urban center, and the streets of good green shade ratio are mostly in-between the middle ring of highway and loop of expressway. The districts of lower bikeability indicator are mainly the Qingyunqiao District on the west and the Jinbinqiao District on the east at city periphery, which were developed from rural area into urban area under real estate projects boom after 1978, but with little road construction planning and non-motorized vehicle lanes

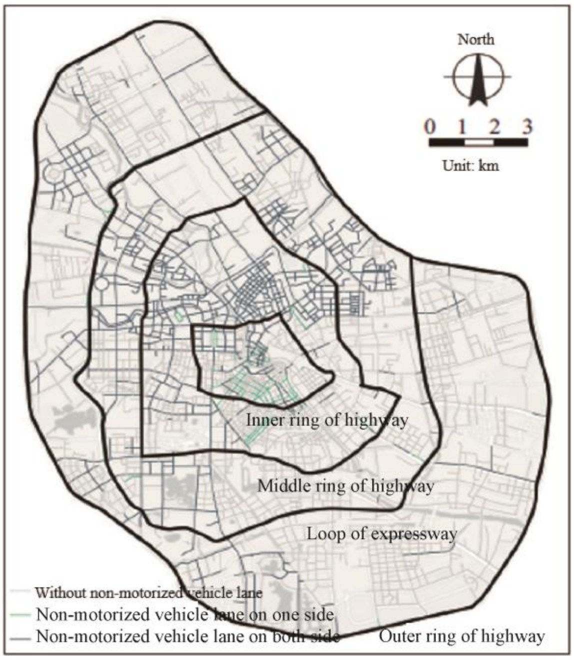


Figure 8 Distribution of non-motorized vehicle lane in Tianjin

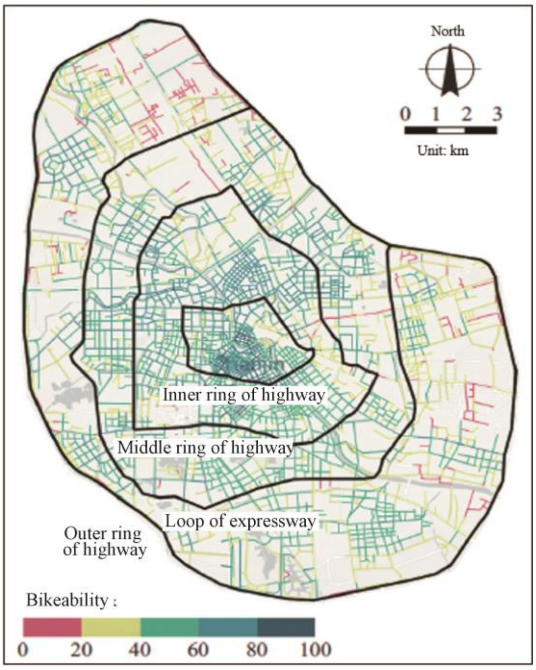


Figure 9 Distribution of bikeability index

As shown in Figure 10, streets of high bikeability are mainly distributed along the urban primary arterial roads, but not very obvious. And there is no continuous cycling lane of high bikeability. Primary arterial road is usually of the highest bikeability, while the branch roads are of lower bikeability due to limited space to set non-motorized vehicle lanes.

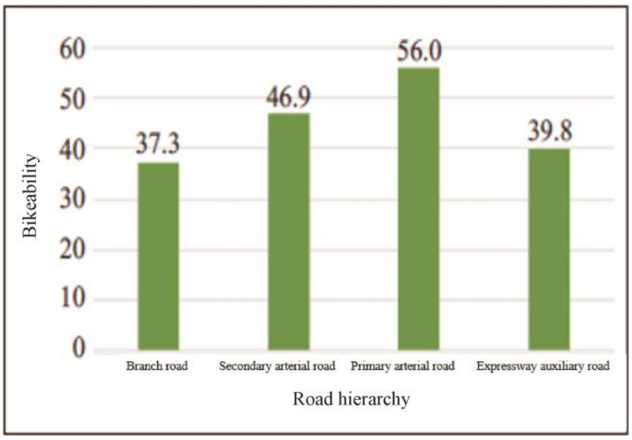
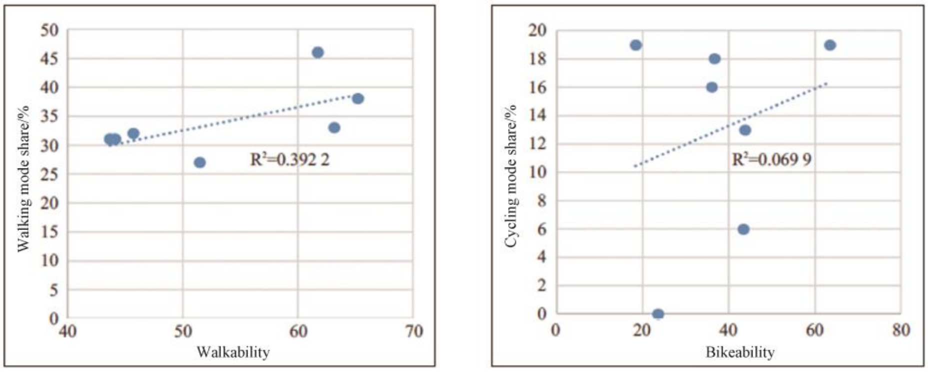


Figure 10 Bikeability index of different level of roadways

In general, the districts with low bikeability indicator have problems on right of the way, road crossings, parking facilities, road maintenance, and environment. In terms of right of way, the width of non-motorized vehicle lanes is limited and there is a lack of non-motorized vehicle lane signs; the parking spaces are insufficient; road work blocks the non-motorized vehicle lanes; some non-motorized vehicle lanes are designated as legal parking spaces, thus destroying its continuity; bus station conflicts with cycling traffic. As for the road crossing, there is a lack of specific



a Correlation of walkability and walking mode share   b Correlation of bikeability and cycling mode share

Figure 11 Correlation of walkability indicator and bikeability index with travel mode share

crossing facilities for bicycles, cycling signal phase, and traffic signs for bicycle left-turns. As to parking facilities, there is a lack of bicycle lock poles on streets. For road maintenance, there is a problem of poor drainage and uneven surface for non-motorized vehicle lanes. In aspect of environment, there is a problem of lacking cycling shading along certain overwide streets.

3.5 Correlation of walkability and bikeability with travel behavior

We conducted a survey on 2 013 interviewees from seven residential communities about their travel behavior. And we calculated the walkability and bikeability of the streets within 500 m-radius buffering circle of seven residential communities to generate Pearson correlation coefficient of street walkability and bikeability with corresponding mode share (Figure 11). There is a positive correlation between the walkability and the walking mode share, with the correlation coefficient of 0.63 significantly at confidence interval of 0.95, which indicates that the street walking environment is an important factor for walking choice behavior of Tianjin residents, and a favorable walking environment is conducive to guiding citizens to shift from motorized mode to walking.

The bikeability is positively correlated with the cycling mode share, but the correlation coefficient is not significant. This is possibly because that cycling is majorly for daily commuting, thus less affected by the cycling environment. Therefore, it is more important for urban planners and city government to construct continuous non-motorized vehicle lanes on the urban scale to connect residential clusters to working places, rather than focusing on the small-scale buffering areas around the residential communities.

4 Discussions

As presented by the fourth Tianjin household travel survey [20]: 1) non-motorized mode share decreased significantly from 85.65% in 2000 to 68.9% in 2011; the walking mode share maintains at a stable level; the cycling mode share declined very fast, from 51.00% in 2000 to 25.60% in 2011; the drop in cycling mode share was transferred to electric bicycles and private cars; for home-based trips, walking is still the dominated mode, accounting for up to 52.9%. 2) The distances of all modes have increased, with an average increase from 4.4 km in 2000 to 4.8 km in 2011; the walking distance increased from 1.1 km in 2000 to 1.4 km in 2011, while the cycling distance declined from 3.6 km in 2000 to 3.0 km in 2011.

It can be seen from the mode share structure that the demand for walking is gradually increasing, while the demand for cycling is gradually decreasing. It may be because that the quality of the walking environment in Tianjin is overall better than that of the cycling (see Table 3). In fact, since the time of China's Reform and Opening-up, Tianjin has been characterized by renowned by mass construction of non-motorized vehicle lanes in the central district, with the cycling as the primary mode for medium and short distance commuting trips. However, with the urban expansion, the roads at southeast districts in-between the inner ring of highway and outer ring of highway (such as the Hedong District, Hexi District, Dongli District) have been widened with multi-lanes for motorization, but are not equipped with sufficient non-motorized vehicle lanes (such as the Cultural Center District in Tianjin). Even worse, the urban-rural fringe zones, especially in Jinbinqiao District, have the problems of overly narrow road, unclear rights of way, and mixed traffic that is unfriendly to bicycles. It is shown that the convenience indicators for walking and cycling environment are close to each other, but walkability safety (score 80) and comfortableness (score 52) are much higher than bikeability safety (score 49) and comfortableness (score 29). The main reason might be insufficient allocation of non-motorized vehicle lanes and insulators between motorized lanes and non-motorized lanes which may discourage the cycling experience.

Therefore, the government needs to put much importance on improving the level of service and street environment of non-motorized vehicle lanes to increase cycling mode share, and needs to improve the street walking environment so as to meet the increasing walking demand. We provide the following suggestions as policy implication for promoting sustainable transportation in Tianjin:

1) Improve the street walking environment to meet local travel demand

For the streets within the inner ring of highway, the key to improvement of the overall walking environment is to tackle on-sidewalk parking for safety and increase the green shade ratio for comfortableness. The land scarcity makes it difficult to achieve good convenience, safety, and comfortableness simultaneously, which requires more precise and exquisite treatment of street design and road construction engineering. The streets in-between expressway loop and outer ring of highway need to be improved on safety problems such as the lack of crossing facilities, the high proportion of mixed traffic patterns, and vehicle parking on sidewalks around residential areas. The large development area in-between the loop of expressway and outer ring of highway, and the areas between residential communities need to be further enhanced on walkability convenience and comfortableness, and particularly for the urban-rural fringe zones. In addition, for streets of different hierarchies, the secondary arterial roads need to be equipped with sufficient daily facilities of many kinds to encourage people to turn from cars to walking for short-distance trips; the express sideway and primary arterial roads need to form continuous street interface with the arrayed buildings and walls when there are large-scale street setbacks.

2) Create an urban-scale bicycle friendly street environment

In recent years, the emergence of bicycle sharing system in Tianjin has contributed to the rise in cycling mode share, which alleviated the last-mile problem for public transportation. Nevertheless, the bicycle may be oversupplied if without proper cycling network and bicycle parking space, which may jeopardize the non-motorized street environment. Therefore, it is of great significance to create a bicycle friendly street environment which meets the short-distance travel demand in different urban districts, solve the uncontrolled parking problems on non-motorized vehicle lanes in the city center, form a continuous network of non-motorized vehicle lanes for roads of various hierarchies, and optimize the cycling lane allocation for branch roads.

5 Conclusion

It is admitted that the walkability and bikeability proposed in this paper are the idealized indicators from the perspective of pedestrians and cyclists. In fact, walkability and bikeability vary from district to district with differences of road hierarchy, urban development phase, and street styles, so it is unrealistic to form a uniform walkability and bikeability pattern spatially. For example, the streets in industrial parks on city periphery are usually subject to sparse distribution of daily facilities, and the branch roads are subject to limited width for separate non-motorized vehicle lanes. Nevertheless, the walkability and bikeability indicators provide much insight on measuring street built environment on a large scale with little bias and subjectivity, as an evaluation method to develop future goals and strategies. How to improve existing walking and cycling street environment according to different road hierarchies and how to formulate continuous non-motorized networks on urban scale should be the key considerations for planners and government.

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