Received January 20, 2021, accepted January 29, 2021, date of publication February 2, 2021, date of current version February 16, 2021.
Digital Object Identifier 10.1109/ACCESS.2021.3056523

Review of the Cycling Network Planning and Design in Chinese Cold-Climate Cities

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This work was supported by the Fundamental Research Funds for the Central Universities under Grant 2572019CP03.

ABSTRACT Bicycle use is an important measure to promote energy saving in the urban transportation field and reduce the environmental deterioration caused by motorized vehicle development in both warm- and cold-climate cities. However, the severe winter climate makes it harder to set up bicycle lanes in cold-climate cities than in other cities. Considering international and Chinese practice, this article analyzes bicycle travel characteristics in cold-climate cities, summarizes bicycle development patterns and proposes corresponding development strategies. The paper reviews the research status of cycling network planning and design in cold-climate cities in China and worldwide and summarizes the relevant methods that can be used in China. The results showed that compared with other seasons, in winter, the bicycle share rate of Chinese cold-climate cities decreases significantly, and the larger the temperature difference is, the greater the decrease is. In addition, the bicycle traffic flow is volatile and does not strictly maintain a regular straight line. It is necessary to select bicycle traffic development patterns and formulate corresponding strategies according to bicycle travel characteristics. Temperature and wind are two climatic factors that need special attention when planning cycling networks in cold-climate cities. The consideration of solar radiation and electric bicycles is beneficial for optimizing the design of bicycle lane width in cold-climate cities. Isolation forms can be selected according to the bicycle development patterns. The pavement materials, maintenance technology and colored bicycle lanes with anti-freezing function are very important to improve the comfort and safety of bicycle lanes.

INDEX TERMS Bicycles, cold-climate cities, development patterns, network layout, space design.

I. INTRODUCTION

The term cold-climate city refers to a special group of urban areas distributed in the Northern Hemisphere. There are over 600 million people worldwide who live in cold-climate cities. Because of the different climatic characteristics of cold-climate cities in different countries, a unified definition of the term has not yet formed. The term ''cold-climate city'' was first proposed at the International Urban Forum in Edmonton, Canada, in 1986, and defined as a city with an average temperature lower than 0°C in January and latitude higher than 4° [1]. Then, to avoid the latitude limit, the Canadian researcher Norman Pressmen defined the cold-climate city as a city where the maximum daytime temperature is lower than 0°C for 2 months or more in a year [2]. In China, scholars are accustomed to using the ''Code for thermal design of civil buildings (GB 50176-2016)'' promulgated by the National Standardization Management Committee to determine the climatic zoning, which divides the area into 5 categories: severe cold, cold, hot summer and cold winter, hot summer and warm winter, and mild. Among them, the standard of severe cold area applies to cities with an annual coldest monthly average temperature lower than −10°C or a daily average temperature lower than 5°C for more than 145 days. The standard of a cold area applies to cities whose annual coldest monthly average temperature is higher than −10°C and lower than 0°C or whose daily average temperature is lower than 5°C for over 90 days but less than 145 days [3]. The cold-climate cities mentioned in this article refer to the areas with severe cold and cold climatic characteristics.

Bicycles include traditional bicycles and electric bicycles (because traditional bicycles and electric bicycles share the same lane, in this article, bicycles refer to the coexistence of the two or the nonmotorized modes of transportation) and are among the cleanest and the least resource-consuming transportation mode. Bicycles can solve the problem of ''the

The associate editor coordinating the review of this manuscript and approving it for publication was Michail Makridis.

last kilometer'' in the city and are the most ideal transportation mode to undertake medium- and short-distance travel and transfer [4]. In many countries, because electric bicycles are a recreational activity with relatively little use, the subjects of use and research are mostly traditional bicycles. At the beginning of the 20th century, the traditional bicycle was the main mode of urban passenger transportation in many countries before a large number of private cars emerged. With the mass production of Ford cars and the development of the social economy, its position in the world's major cities has declined [5]. After the oil crisis broke out in the 1970s, Denmark, Germany, Netherlands, Switzerland, and other European countries ''returned'' bicycles, which had been gradually ''abandoned'', to a position of equal strength with cars with the aim to save energy and protect the environment. Among them, Copenhagen in Denmark is the most successful and has developed into the world's leading ''bicycle city,'' with infrastructure supporting the bicycle in priority [6]. Since then, the United States, the United Kingdom, and other countries have also begun to follow in the footsteps of these cities. The American Urban Transport Association aims to create a safe and happy cycling environment and has compiled ''Urban Bikeway Design Guide [7].'' London Streets of Transport for London focuses on bicycle space and formulated the ''London Cycle Design Standards [8].'' Moreover, the Abu Dhabi Urban Planning Board aims at sustainable green development and compiled the ''Abu Dhabi Urban Street Design Manual [9]''. In recent years, the advantages of electric bicycles, such as requiring no gasoline or parking space, have gradually enhanced their popularity and use abroad; for example, the sales of electric bicycles in Copenhagen have increased by approximately 10% [10].

In China around the 1980s, the number of traditional bicycles increased explosively, the infrastructure improved and some cities built bicycle lanes, bicycle overpasses, underground bicycle storage garages, etc., according to the bicycle flow [11]. However, in 1994, the Chinese government promulgated the ''automobile industry policy'' and proposed that ''the state encourages individuals to buy cars [12],'' marking China's entry into the era of automobile dominance. Although the large use of cars improved travel efficiency and promoted urban development, it also inevitably brought about traffic congestion, environmental pollution and other problems. During this time, the bicycle has been ignored and unsupported [10], and the sustainable development of cities has been greatly challenged. To curb the environmental costs of motorized development in cities and develop green transportation, in 2010, the Ministry of Housing and Urban-Rural Development of the People's Republic of China (MOHURD) launched the ''Demonstration project of the urban pedestrian and bicycle transportation system'' in 12 cities in China. In 2012, the MOHURD, the National Development and Reform Commission and the Ministry of Finance of the People's Republic of China published the ''Guidance on strengthening the construction of the urban pedestrian and bicycle transportation system [13].'' In October 2012, the State Council of the People's Republic of China put forward the requirement of ''giving priority to develop public transportation and improving the conditions of pedestrian and bicycle transportation [14].'' In 2013, the ''Opinions of the State Council on strengthening the construction of urban infrastructure'' clearly proposed that ''green transportation should be advocated, and the traffic development mode of excessive dependence on cars should be changed effectively [15].'' In the report of the 19th National Congress in 2017, it was also proposed that ''we should advocate a simple and moderate, green and low-carbon lifestyle, and carry out actions such as creating an economical and green travel mode [16].'' In addition, the number of electric bicycles increased significantly due to the ban on the use of motorbikes in some Chinese cities and the gradual rise of ''take-out fever,'' and in some cities, they even outnumber traditional bicycles. It can be said that the bicycle has been receiving increasing attention in China.

However, in Chinese cold-climate cities, the development of bicycle is facing many difficulties. First, the severe climate conditions in winter affect the choice of residents' travel mode. Among them, low temperature and cold wind are the most important factors that bring discomfort. Although more solar radiation and longer exposure time can alleviate the discomfort, due to the short illumination time in winter in cold-climate cities, the degree of relief is very limited [17], [18]. Under such conditions, the use of bicycles without any protection is limited, with adverse effects on not only the choice of bicycle travel mode but also the bicycle travel behavior and traffic flow characteristics [19], [20]. Second, the bicycle development pattern, referring to the bicycle development idea, development mode and development effect reflecting the position, proportion and function of bicycles in a city [21], needs to be determined according to the city's development goals and travel characteristics before the government builds bicycle facilities. Therefore, when the bicycle travel characteristics change, the choice of development patterns also needs to be reconsidered. Third, the economic development of Chinese cold-climate cities is generally relatively backward, the construction of rail transit, such as the subway and light rail, is lagging, the emerging public transport modes, such as BRT, are often not promoted, and the main means of public transport is generally conventional public transport [22]. Therefore, the ground traffic pressure of Chinese cold-climate cities is much greater than that of warmer cities. The competition for road resources is more intense, and the requirements for the rational allocation and integration of motorized and nonmotorized traffic resources are higher and more challenging. In the face of this series of problems, the governments of some cold-climate cities in China, such as Harbin and Changchun, believe that the cold climate in winter is not conducive to bicycling and that motorized transportation needs more road space, so they choose not to develop bicycle infrastructure all year round, and the construction level of bicycle lanes is very low. For example, an investigation of bicycle infrastructure in more than 30 typical areas with the most intensive and complex flows of people showed that Harbin has the following problems: low density of cycling network, uneven width of bicycle lanes (some widths are 0.5 m, some widths are 3 m), little physical isolation (only 12%), the interference of motor vehicles with bicycles, approximately 7% of bicycle lanes with parking spaces for motor vehicles, approximately 40% of bicycle lanes with illegal parking, and very rare bicycle parking facilities [23]. Other cold-climate cities in China, such as Shenyang and Qiqihar, have ignored the changes in bicycle travel characteristics in winter and blindly "Copenhagenized." Although the construction level of bicycle lanes is high, due to less bicycle travel in winter and low utilization rate of bicycle lanes, the already tense road resources are greatly wasted in winter. The use status of bicycle lanes in Harbin and Shenyang is shown in Fig. 1 and 2.

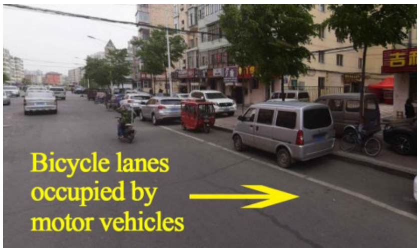

FIGURE 1. **The use status of bicycle lanes in Harbin, China: bicycle lanes are occupied by motor vehicle parking.**

FIGURE 2. **The use status of bicycle lanes in Shenyang, China: bicycle lanes are idle, and the motor vehicle lanes are crowded.**

The set level of bicycle lanes represents the "competitiveness" of bicycle development and is an important means to establish green traffic, curb the excessive development of cars, and ensure sustainable urban development [24]. How to face severe climate conditions and fully consider climate factors, such as temperature, wind and sunshine, in the construction of bicycle lanes in cold regions to make the natural environment and traffic environment interdependent is a key issue to be considered in the development of bicycle infrastructure. Since there is no study that comprehensively elaborates the development of bicycle and bicycle lane setting methods in cold-climate cities in China, and there is a lack of comparison with other international cities. Therefore, this article will consider international and Chinese practice, analyze the characteristics of bicycling in cold-climate cities in China, and on this basis, explore what kind of bicycle development patterns should be selected in Chinese cold-climate cities and the strategies to realize these development patterns in China and abroad. Moreover, this article will summarize the planning and design methods of bicycle lanes in cold-climate cities in China and the innovative and successful experiences in this field in other countries, notably Japan, North America and Europe, to provide valuable help for the construction of bicycle lanes in China's cold-climate cities and be a reference for cold-climate cities in other countries.

II. BICYCLE TRAVEL CHARACTERISTICS IN CHINESE COLD-CLIMATE CITIES

A. TRAVEL MODEL CHOICE

Understanding the selection rules of residents' travel modes is the premise of the scientific planning and construction of the urban transportation system, and mastering the ratio of bicycle trips in cold-climate cities is the basis for determining bicycle development patterns and choosing reasonable bicycle lane setting methods [25].

In other countries, the research on bicycle travel mode selection is mostly aimed at traditional bicycles. These studies basically show that the use of traditional bicycles is affected by the climate, and bicycling is a seasonal activity in cold-climate cities [26]. For example, one study [27] points out that the tendency of choosing traditional bicycles in Canada, and the Midwest and the Northeast of the United States is lowest in winter and higher in summer than in spring and autumn. Different regions have different degrees of reduction in the proportion of traditional bicycle travel in winter. The temperature decrease in cold areas is greater than that in warm areas in winter [28]. Other factors that affect the use of traditional bicycles include the gender and age of bicyclers, traffic distance and time, lack of facilities, poor network connection and friendliness, poor support policy for bicycles, lack of sufficient sunlight for safe riding, and need to travel for work [29], [30].

At present, there are few studies on bicycle travel mode selection in Chinese cold-climate cities. However, one study comparing the travel mode selection of residents in cold-climate cities in different seasons, found that the bicycle sharing rate (including traditional bicycles and electric bicycles) in Chinese cold-climate cities is the smallest in winter, being is approximately 45%-85% lower than that in other seasons, and the greater the temperature difference is, the greater the decline is [31]. Generally, the bike sharing rate begins to increase in March (spring) when the weather turns warm until September (summer), and then it decreases as the weather turns cold [22]. Due to the long duration of winter, residents' choice of travel mode produces inertia [32], and extreme weather in winter often occurs in spring or autumn. Therefore, the bicycle sharing rate in summer is usually higher than that in spring and autumn. The sharing rate of more comfortable and safe motorized travel modes, such as cars, taxis and public transport, increases with the decrease in

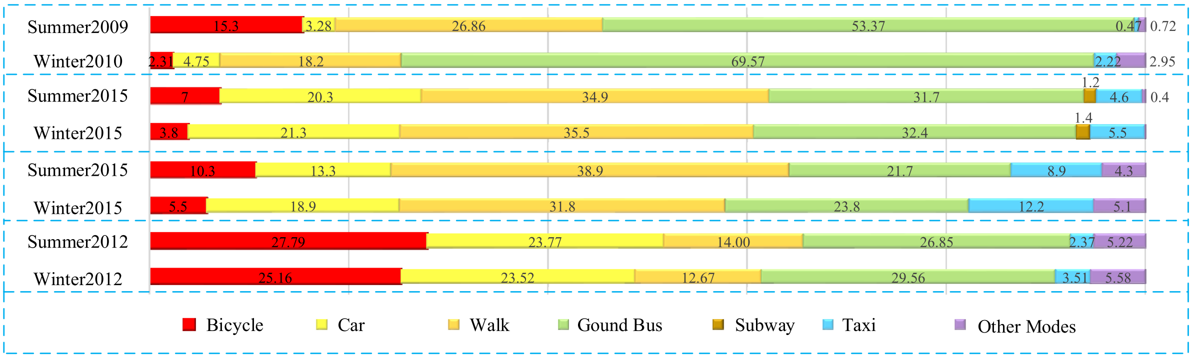

FIGURE 3. Residents' travel mode selection in winter and summer in some Chinese cold-climate cities [23].

temperature. The choice of travel modes in winter and other seasons in some cold regions of China is shown in Fig. 3.

As in foreign countries, there are many factors that affect residents' choice of bicycle travel in Chinese cold-climate cities. Fig. 4 summarizes them from four aspects: human, vehicle, road and environment. ① Human: Related studies show that differences in individual attributes and psychological needs lead to certain preferences in the choice of transportation modes. The age of bicyclers in Chinese cold-climate cities is mostly between 36 and 65 years old in summer. In winter, due to security considerations, the number of elderly and young bicyclers is significantly reduced. As women are more inclined to travel in comfort and safety than men, the decrease in female bicyclers in winter is larger than the decrease in male bicyclers [33]. A study [22] that carried out a survey regarding residents' travel in three provinces of Northeast China, a typical cold region in China, found that bicyclers are mainly full-time workers with regular commuting behavior. Based on the psychological needs of fast and cheap travel, low-income earners may be willing to use bicycles, and the utilization rate generally decreases with the increase in residents' income [34]. In winter, the users are mainly food take-out delivery staff [35]. ② Vehicle: Statistics show that the number of motor vehicles owned by households in Chinese cold-climate cities is not higher than that in noncold-climate cities because of the climate, but it has a significant impact on the choice of travel mode [36]. One study [22] shows that when the family does not own a motor vehicle, the proportion of bicycle and pedestrian travel in winter is 14% (bus 71%, motor vehicle 1%, taxi 14%). When the family owns one motor vehicle, the proportion of bicycle and pedestrian travel in winter is 10% (bus 42%, motor vehicle 34%, taxi 14%). When the family owns two motor vehicles, the proportion of bicycle and pedestrian travel in winter is 6% (buses 23%, motor vehicles 61%, taxis 10%). In addition, relevant studies show that individuals owning a bicycle at home are more likely to form the habit of riding a bicycle and more likely to use a bicycle [37]. ③ Road: Existing research points out that the cycling network layout affects the travel distance, which also affects the use of bicycles. Therefore, the network layout is one of the main influencing

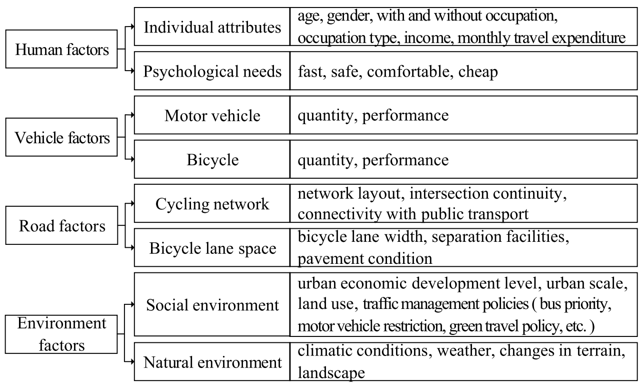

FIGURE 4. The major factors influencing the choice of bicycle travel in Chinese cold-climate cities [44]–[46].

factors [38]. A very continuous and accessible intersection obviously attracts more bicyclers because it means that the travel time of bicyclers will be shorter and the riding speed will be faster [39]. When the cycling network easily connects to other modes of transport, people can ride longer in winter; thus, it can be said that the greater the accessibility is, the more bicycles will be used [40]. In addition, the width and isolation of bicycle lanes are important factors promoting bicycle use. ④ Environment: The relationship between the social environment and residents' travel characteristics has long been the focus of traffic planning research. According to the survey, the proportion of bicycle use in small and medium-sized cities is relatively high. With the expansion of city scale, bicycle use gives way to public transport [42]. Urban land use is the fundamental source of bicycle travel demand. The functional layout, nature and development intensity of land play a decisive role in bicycle travel demand. The natural environment restricts residents' physiological conditions and likewise restricts their travel decision-making behavior, especially limiting their use of bicycles, which offer no protection from the elements [43].

According to the above analysis, the existing studies in China and abroad have pointed out that cold-climate city residents' choice of travel mode in winter differs from their choice in other seasons, and the bicycle utilization rate drops sharply, with lower temperature leading to a greater decline. While the most significant factor contributing to this change in statistics is climate, other factors directly or indirectly affect the use of bicycles. This issue has been studied in detail in foreign countries and in China, but there is still a lack of research on how the influencing factors affect bicycle use and their degree of influence, which requires further exploration.

B. TRAVEL BEHAVIORS

Analyzing travel behaviors and summarizing travel rules is an indispensable part of urban transportation system planning and construction and can provide the basis for relevant departments to formulate traffic management policies [47].

Across the globe, climate has emerged as an important topic in travel behavior research and transport planning, but there are few studies on the impact of climate on bicycle travel behaviors, and most of the studies are about traditional bicycles and focus on Europe, North America and Australia [48]–[50]. One survey shows that people reduce not only the use of bicycles in winter but also the travel distance and travel time. For example, the longest travel distance of traditional bicycles in Sweden is 20 km in summer and 10 km in winter [51], and the travel time is approximately 10-30 min in winter. In addition, since snow and gravel reduce the width of bicycle lanes, bicyclers in winter prefer to ride near motor vehicle lanes [77].

The research on bicycle travel behavior in China mostly focuses on the macro statistical analysis of travel distance and travel time, with less attention to the microlevel [28], [52]. The existing research shows that bicycle travel behavior in winter differs from that in the other seasons in Chinese cold-climate cities [26], [53]. For example, the average travel distance of bicycles (including traditional bicycles and electric bicycles) in winter is slightly lower than that in summer, mainly involving short-distance travel of approximately 2-3.5 km [54]. The average travel time of a single trip in winter is shorter than that in other seasons, being approximately 7-20 min, slightly lower than the time spent driving cars or walking to public transport. The traffic volume of bicycles presents obvious changes in the morning and evening peak periods of travel, and the travel distribution is relatively similar at other times throughout the day [33]. Several Chinese scholars have investigated intersections, key nodes of bicycle lanes. Pan *et al.* [55] implemented a riding experiment measurement system and applied a questionnaire to confirm that cyclists mainly perceive the threat from motor vehicles on the left. Liu [56] studied the time Chinese bicyclers were willing to wait to cross the street under four temperature ranges, $<0°C$, 0-15°C, 15-30°C, and $>30°C$, and found that they presented the longest wait time of approximately 17-19 s at 0-15°C and 15-30°C, mainly because the temperature in this range is very comfortable and suitable for bicyclers to stay outdoors for a long time. When the temperature is lower than 0°C or higher than 30°C, bicyclers want to leave as soon as possible because of the low temperature or the intense solar radiation, and the wait time ranges from 8.85 s to 9.49 s. In addition, the existence of isolation bars has a great impact on bicyclers, and bicycles, especially electric bicycles, frequently enter motor vehicle lanes on roads without isolation bars. This phenomenon is more common in winter because snow covers bicycle lanes [57].

Based on the above analysis, the travel distance and travel time of cold-climate cities in China and in other countries in winter are shorter than those in other seasons. However, in the same season, the bicycle travel distance and travel time in cold-climate cities in winter are longer in foreign countries than in China; this may be because the winter climate of the studied foreign cities is milder than that of Chinese cities, and they have more perfect cycling policies and network, an aspect that will be mentioned later. In China and abroad, bicyclers' crossing behavior in cold-climate cities has also been studied. Although the research contents are different, the results can provide support for the intersection design of bicycle lanes in cold-climate cities.

C. TRAFFIC FLOW CHARACTERISTICS

The cold degree, snowfall, and road freezing can produce an effect on traffic flow. Mastering the bicycle flow characteristics in cold-climate cities not only is the prerequisite and basis for bicycle flow management and control but also can provide a theoretical basis for bicycle facility design aspects, such as the width setting of bicycle lanes, which is of great significance for improving the safety and comfort of cyclists in cold-climate cities [58], [59].

Among the previous studies worldwide, few address bicycle traffic flow characteristics. Most studies focus on motor vehicle traffic, not to mention the effect of severe winter climate on bicycle traffic flow characteristics [60]. Relevant studies have shown that in foreign countries, the speed of traditional bicycles is mainly distributed in the range of 15-25 km/h, subject to normal distribution or logarithmic normal distribution [61], [62]. The range of lateral spacing between two cyclists is 1.35-2.36 m [63].

In China, with the rapid development of electric bicycles, there is almost no single traditional bicycle traffic flow or single electric bicycle traffic flow on urban roads. The traffic flow in the bicycle lanes is basically a mixed bicycle flow composed of traditional bicycles and electric bicycles [64]. Therefore, the study of bicycle traffic flow characteristics is mainly focused on the mixed traffic flow. One study [65] conducted statistical analysis and found that the average speed of Kunming electric bicycles is approximately 22 km/h, approximately 47% faster than the average speed of traditional bicycles under the same traffic conditions, which was 7 km/h. Due to the significant difference in speed between electric bicycles and traditional bicycles, there can be conflicts when the two are mixed, increasing the complexity of traffic flow characteristics [66]; this issue is more serious in cold-climate cities. The influence of climate on bicycle traffic flow characteristics has also been studied in China. One study [46] took surveys to find that the average speed of bicycles is approximately 10-35 km/h in spring, summer, and autumn, 9-10 km/h in winter without snowfall and 8-9 km/h in winter with light snow, and there are basically no bicycle in conditions with moderate snow and heavy snow. In addition, studies have shown that traditional bicycles cannot stand upright stably by themselves, so the riders need to swing their gravity around the forward axis in a serpentine way. However, an icy or snowy pavement and cyclists' heavy clothes and protective equipment can weaken their operation ability and visual field, and when overtaking or passing other bicycles, the traffic flow can sway greatly, with the width of the lateral swing basically covering the entire bicycle lane [62]. Moreover, although the bicycle traffic flow generally does not strictly maintain the regular straight line and advance in groups, the severe riding conditions in winter make cyclists pass or lag behind each other for a distance because of security, and then, the traffic flow presents characteristics of independence [67].

Based on the above analysis, the measured speed of bicycle traffic flow in foreign countries is higher than that in China. The mixed bicycle traffic flow is one of the research hotspots in China and abroad due to its complex characteristics, but the related theories and methods are not mature enough. The traffic flow characteristics of mixed bicycles are highly complex in winter in cold-climate cities. To optimize urban road facilities, it is necessary to further study the traffic characteristics of mixed nonmotorized vehicles in cold-climate cities.

III. BICYCLE DEVELOPMENT PATTERNS AND STRATEGIES IN CHINESE COLD-CLIMATE CITIES

A. DEVELOPMENT PATTERNS

Different development patterns affect the formulation of strategic planning, policies, regulations, standards and norms and determine the level and quality of bicycle lane setting. Therefore, the determination or selection of a suitable development pattern is the most important step in urban cycling network planning and design [68].

Because of the rapid development of bicycle use in some countries, the bicycle system is relatively complete and mature; such bicycle development patterns can be used as a reference model [69]. We can summarize these patterns in three categories. Pattern 1: Use bicycles as the main travel tool and give priority to developing bicycles. The representative countries are Denmark and the Netherlands, which attach great importance to bicycles in the urban traffic system. Copenhagen is a typical city supporting bicycle use, and its entire city area is served by efficient and convenient bicycle transportation systems [70]. Pattern 2: Use bicycles as a transfer tool to reasonably guide bicycle development. The representative cities are Paris, London and Berlin. In Paris, the successful experience of the "Public Bicycle Program" laid the foundation for the green travel mode of "Bus + Bicycle [71]." Pattern 3: Use bicycles as a leisure fitness tool rather than a transportation tool for major urban trips. The representative cities are Singapore and Hong Kong, the most typical of which is Singapore, where bicycles are usually located at tourist attractions [72]. It is worth noting that cold-climate cities in other countries also develop bicycle use patterns according to these types. This is mainly because climate is not considered a serious obstacle to increase cycling. Compared with temperature, other factors may have a greater impact on the bicycle utilization rate [73]. A considerable number of studies have also proved that if bicycle lanes are safe and comfortable, more people will choose to travel by bicycle in winter. For example, in Canada, although the climate is much colder than that of the United States, the cycling rate is much higher [74]. Also, the highest level of cycling in North America is in Yukon and Northwest Territories, two of the northernmost and coldest parts of Canada [73]. Certainly, such an approach has also been questioned. Some scholars believe that although the advantages of bicycles have been recognized worldwide, it is obviously a very unpopular practice to cede road space resources in places where bicycles travel less, as increasing bicycle resources is equivalent to reducing the resources of other transportation modes [75].

Chinese scholars call the above three types of bicycle development patterns the Copenhagen pattern, the Paris pattern and the Singapore for simplicity [76]. At present, Chinese noncold-climate cities have realized the importance of the bicycle, and the bicycle development pattern is changing to reflect any one of the three patterns. However, it is still uncertain which pattern should be selected in cold-climate cities [77]. As mentioned above, there are two extremes regarding which kind of bicycle development pattern should be adopted in Chinese cold-climate cities. Some cold-climate cities do not develop bicycles and adopt the Singapore pattern. Others pay attention to the development of the bicycle and adopt the Copenhagen pattern. However, due to the lack of consideration of climate characteristics and the low proportion of bicycle travel in winter, road space resources are often wasted.

Chinese scholars generally believe that giving priority to the development of bicycle and pedestrian is the core of the "low carbon city," and "giving up the bicycle is to give up the future of the sustainable development of Chinese cities [78], [79];" therefore, Chinese cold-climate cities cannot directly give up bicycle utilization. Among them, cities in cold regions with relatively mild winter climate and a relatively small bicycle travel rate decrease can choose the Copenhagen or Paris pattern. For cold-climate cities with a severe winter climate and a large seasonal decline in the rate of bicycle travel rate, climatic conditions should be fully considered. At present, Chinese scholars have proposed the combination of two or three patterns to develop bicycles in different seasons [80], [81] (Fig. 5). That is, in spring, summer and autumn, considering the characteristics of the pleasant climate, the Copenhagen or Paris pattern can be chosen to compensate for the adverse effects of the winter climate on the city. In winter, considering the longer winter period, more extreme climate, and lower bicycle travel in cold-climate cities compared with cities in regions with milder winters, along with the often limited ecological environment carrying capacity of such cities, the resource reserves are

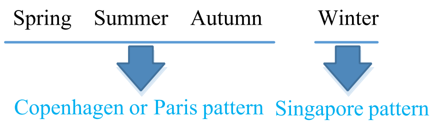

FIGURE 5. **Combined development patterns by season in Chinese cold-climate cities.**

shrinking, and the economic development is lagging behind. It is usually very difficult to build safe and comfortable bicycle lanes, and the benefits of investing in bicycle facilities are uncertain. Therefore, most cities select the Singapore pattern. First, bicycles are not developed as the main means of transportation, and funds and road resources can be used for other purposes. Second, bicycles are developed as leisure and fitness tools for fighting against winter "hibernation [1]."

In general, the bicycle utilization rate of some foreign cold-climate cities is higher than that of noncold-climate cities, which offers an advantage to Chinese cold-climate cities; that is, satisfactory bicycle lanes can offset the impact of adverse climatic conditions on cyclists and help cities realize the Copenhagen or Paris pattern. For cities with extremely harsh winter climate conditions that are unsuitable for the development of bicycles, the flexible development pattern can not only avoid the abandonment of bicycle use but also make effective use of road resources and enhance the sustainable characteristics of cold-climate cities, which is crucial to China's sustainable development [82].

B. STRATEGIES FOR DEVELOPING THE COPENHAGEN AND PARIS PATTERN

Chinese and international scholars have long studied bicycle transportation theoretically and empirically, seeking to determine how to realize the Copenhagen or Paris pattern. After several stages in the evolution of related research, the focus of international scholars is currently on the healthy and systematic development of cities and the construction of a harmonious atmosphere among humans and society. Several strategies, such as the isolation of people and bicycles, traffic calming, and shared streets, have been put forward [83]. Research in China focuses on transportation development, urban planning, and sustainable development and has produced relatively rich results. For example, Xiong *et al.* [84] theoretically described bicycle traffic planning according to factors such as traffic development background, traffic safety, and travel efficiency. In Shanghai, a new concept involving a slow traffic core, slow traffic island, and slow traffic corridor was put forward. Gan [85] proposed a new idea of intensive mixed land use. In general, although the research perspectives in China and in other countries are different, it is basically agreed that the provision of more and better bicycle lanes and bicycle support policies is the most effective strategy for cold-climate cities to achieve the Copenhagen or Paris pattern [86]. According to the analysis of the four types of influencing factors in the previous chapter, the following aspects should receive attention when setting up bicycle lanes: improving network layout, optimizing intersections, connecting public transportation, ensuring a certain width, improving isolation forms, and paving. Policy should be formulated based on human, vehicle and environment factors to make it more directional and targeted. This section first combines the human, vehicle, and environment characteristics in Chinese cold-climate cities and then summarizes relevant domestic and foreign policies applicable for Chinese cold-climate cities to achieve the Copenhagen or Paris pattern, see Table 1. The method for setting bicycle lanes will be discussed in detail in the fourth and fifth parts of the paper.

As shown in Table 1, in terms of human factors, to attract young people or women to choose bicycles, a wide range of educational campaigns and cycling events can be organized, or a bicycle playground can be built, as in Copenhagen [87]. Policies such as open streets in Chicago and Sunday streets in San Francisco, which support closing streets on Sundays and encourage cycling, walking, and traveling with other non-motorized modes in car-free streets for recreation, can also greatly promote cycling. Considering that the main purpose of winter cycling in cold-climate cities in China is commuting, employers can provide financial support, free bicycles or changing rooms to improve the probability of employees cycling [73]. It is also very important to improve the convenience and safety of travel and reduce the cost of bicycle use. In terms of vehicle factors, restricting the use of motor vehicles in winter is the most effective way to improve the bicycle travel rate, even if it may not be popular [51]. Public bicycles are mainly used for commuting or transferring, and when put in places with many travelers, cycling can be made attractive [53]. In terms of environment factors, investment in bicycle infrastructure can be increased. For example, the Dutch Ministry of Transport and Public Works implemented a policy favoring the use of the bicycle in the form of National Bicycle Tracks Grant Act [88]. The implementation of a package of investment measures for BRT, pedestrians and cyclists can not only promote the use of such travel modes but also minimize the loss of market share among these modes. Among the countries implementing this policy, Bogota in Colombia has achieved very good results [89]. In addition, attention must be given to bicyclers' rights and increased law enforcement; for example, in Portland, plainclothes policemen catch motorists guilty of endangering bicyclers and then require the offending motorists to take a special "share the road" safety class. Given the natural environment of cold-climate cities, increasing road maintenance is the most important and direct method to support bicycle utilization [51], [90]. One study [51] proposed that by improving winter maintenance service levels on bicycle lanes, it might be possible to increase the number of bicycle trips in winter by 18%, representing a corresponding decrease of 6% in the number of car trips.

C. STRATEGIES FOR DEVELOPING THE SINGAPORE PATTERN

For patterns relevant to cold-climate cities that do not develop bicycle use in winter, Montreal's practice is worthy of

TABLE 1. **The policy management strategies for chinese cold-climate cities realizing the copenhagen or paris pattern [24], [53], [87], [51], [91].**

Factor	Type	Specific Measures
Human factors	Consider individual attributes	Organize children's fun cycling activities, build bicycle playgrounds, etc. to attract young people and children to ride bicycles
		Carry out training and examination of riding skills for young people and children, such as CAN-BIKE courses in Canada
		Organize Car-Free days, Bike-to-Work days, Bike-to-School days, food and wine tours by bike, etc. to promote cycling and promote cycling for men, women and children
		Employer provision of financial support for commuting by bicycle to attract more employees to commute by bicycle
		Employer provision of free bicycles for employees' short-distance business trips
		Employer provision of a bicycler changing room for the staff
	Consider psychological needs	Establish a convenient internet route navigation system for riders, providing traffic routes, travel time, transfer information, etc. The building of a flexible route selection system for riders to choose the shortest route according to individual preference or the most comfortable route with low traffic volume. Provide riding route maps in places with high bicycle flow and in the landscape
		Improve the lighting of parking places, equip the caretakers or set up monitoring to ensure safety while riding
		Carry out push and pull policies, that is, reduce the rent of public bicycles, make competing modes more expensive
		Carry out green travel discount policy, that is, offer one membership for users to travel by bus, subway, and public bicycle and receive some transfer discount on public transportation
Vehicle factors	Consider motor vehicle	Implement direct restrictions on the use of motor vehicles to reduce the rate of motor vehicle travel
		Implement policies, such as increasing parking fees for motor vehicles and levying environmental taxes on large-displacement motor vehicles, to indirectly restrict the use of motor vehicles and reduce the rate of motor vehicle travel
	Consider bicycle	Implement zero import tariff on bicycles for stimulating residents to buy and increase the number of bicycles
		Put public bicycles near large public places, scenic spots and commercial areas
		Used studded tires in winter
Environment factors	Consider social environment	Provide government funds for facilities construction, policy making, propaganda, etc.
		Carry out the package of investment measures in BRT, pedestrian and bicycle
		Build compact cities, link high-density urban areas with the use of bicycles
		Build a functional hybrid neighborhood structure (including convenience stores, office space, fast-food restaurants, hospitals, apartments, etc.) to shorten travel distance
		Set up a bicycle management department under the "vehicle management office"
		Ensure that traffic police and courts strictly enforce traffic laws for protecting the road right of bicyclers
		Promulgate exemption clauses for cyclists, except for those who break traffic rules intentionally
		Require riders to wear protective equipment, such as helmets and kneepads, regulate their travel behavior, and ensure that they obey the traffic rules
	Consider natural environment	Carry out the package of investment measures in BRT, pedestrian and bicycle
		Build compact cities, link high-density urban areas with the use of bicycles

reference. Montreal built the BIXI bicycle rental system in 2009; considering its own climatic characteristics, it set the running time between April and November of each year. During cold winter months, BIXI is discontinued, and the bicycle lanes are used for snow storage [73]. In addition, to ensure the demand for bicycle travel for leisure and fitness, government guidance and facilities improvement are the most common strategies adopted worldwide [92]. For example, Amsterdam proposed the ''White Bicycle Project,'' which provided free white bicycles in forest parks.

Chinese scholars have proposed the use of bicycle lanes on both sides of urban roads for other modes of transportation or snow accumulation when developing the Singapore pattern in winter. Some scholars have proposed that, considering the low utilization rate of bicycle lanes in winter and aiming to relieve road traffic pressure and effectively use road space resources, bicycle lanes can be reserved for buses, cars or motor vehicles for parking [93], [94]. Some scholars have suggested that when the road service level in winter is relatively high, unaffected by the climate, the bicycle lanes can be used as spaces for temporary snow clearing to reduce the interference of snowdrifts and snow clearing work on pedestrians and motor vehicles [95] or for creating cultural landscapes, such as ice lamps or snow sculptures, to make a seasonal supplement to the travel environment, gradually develop tourism resources, and create a positive image of winter cities [96]. To ensure the demand of bicycles for leisure and fitness, Harbin, a cold-climate city in China, built 6 greenways for pedestrian and bicycle travel with a total length of 25 km in the Sun Island scenic area (see Fig. 6). Changchun, Baotou, and other cold-climate cities have also built bicycle leisure greenways based on natural landscapes and historical and cultural resources. In winter, the trees on both sides of greenways are covered with snow, which increases the interest in and attractiveness of winter riding.

FIGURE 6. **The Sun Island scenic greenways in Harbin, a cold-climate city in China.**

In general, there are few studies on the adaptation of bicycle design and planning to climate in China and abroad, but it is clear that interdisciplinary methods are becoming more common. At present, the study of regional residence in architecture has been extended to the study of regional climate adaptability planning in China [39]. Although it has long been agreed that bicycle lanes should be used for other purposes in winter, no plan has been implemented.

IV. CYCLING NETWORK PLANNING IN CHINESE COLD-CLIMATE CITIES

A. NETWORK LAYOUT

The cycling network is the key to create a bicycle-friendly travel environment, and a reasonable layout plays an important role in improving the urban road network [48].

The cycling network is composed of different types of bicycle lanes. Classifying the bicycle lanes into different types can not only avoid the influence of the context of motor traffic but also differentiate the allocation of cyclists right to the road and support the planning of all types of networks [97]. Because Chinese and international scholars have different research aims, their classification methods are also different. Table 2 summarizes several common methods for classifying bicycle lanes in China and abroad. It can be seen that both Chinese and foreign classifications are based on the function and orientation of bicycle lanes. Cold-climate cities have not yet proposed a separate applicable bicycle lane classification method but use these methods for classification. Considering the different levels of transportation infrastructure construction and economic conditions across cities, the classification methods do not have to be the same [98].

Regarding the methods for designing the cycling network layout, there are few related studies worldwide, but there is much gray literature (design standards, reports from civil organizations) [107]. In foreign countries, city-level governments set up the comprehensive cycling infrastructure network. They build bicycle lanes along urban corridors, either main or secondary streets, connecting places of high demand. In addition, routes are direct and have few stops; this is also the case for cold-climate cities. Many countries, especially those in North America and Europe, are innovating and proactive on cycling, proposing many novel cycling network layout and optimization methods [108]. For example, Antonio Mauttone *et al.* proposed an urban bicycle network design framework that considers both users (requiring shortest paths) and planners (requiring budgets) to design urban cycling networks [107]. In the United States, the Nashville Area Metropolitan Planning Organization created a 100-point scoring system to determine the priority locations for expanding bicycle and pedestrian infrastructure in the region [109]. In London, the Cycle Route Implementation and Stakeholder Plan (CRISP) was proposed, which allows bicyclers to take part in discussions at the highest level because they are very good at identifying potential risks in the complex urban environment and have much useful knowledge for designers [110]. In addition, regarding the type of bicycle lanes, the Transport and Planning Department of Delft University proposed a road in the late 1960s, Woonerven, where bicyclers and pedestrians share the road with motor vehicles without clear separation marks and facilities. Motor vehicles have to be careful and slow, and bicyclers and pedestrians have priority over motor vehicles regarding the right of way [108]. Jan *et al.* [111] proposed that female cyclists preferred off-road paths over on-road lanes, so providing bicycle lanes that are highly separated from motor vehicles is likely to be important for increasing transportation cycling among under-represented population groups, such as women. Traffic-calmed residential streets can serve as convenient, comfortable, and safe bike routes, even with no special bicycle facilities. Many Dutch, Danish, and German cities, for example, impose speed limits of 30 km/h or lower on most residential streets, often accompanied by infrastructure modifications, such as speed humps, chicanes, median islands, traffic circles, street narrowing, curb extensions, raised intersections and crosswalks, special pavement, and mid-block street closures with pass-throughs for bicycles [73]. Bicycle boulevards are streets with low motorized traffic volumes and speeds designed to give bicycles priority. Increasing numbers of cities in North America are building such roads. In Groningen [108], a traffic-cell-traffic-calming scheme was proposed to divide the city into ''environmental cells'' linking bicycle and PT roads, with no through routes for cars between cells. In Amsterdam, the ''Plus Nets'' system was proposed, which is a new method for classifying bicycle lane types based not on land use but on transport modes. In this system, there are no more than two modes of transport on a street to avoid the need to accommodate all transport modes on each street.

In China, there is abundant literature on the network layout of bicycle lanes. Although such networks are rare for cold-climate cities, the basic idea of the network layout of bicycle lanes in cold-climate cities can still be summarized, as shown in Fig. 7. In cold-climate cities, the difference from traditional thinking is that when conducting bicycle traffic surveys and demand forecasting, the travel characteristics and travel demand in winter and in other seasons should be considered separately for determination of bicycle development patterns. When formulating a scheme, it is necessary to identify the bicycle traffic core (the core area where bicycle traffic occurs) and the bicycle traffic zone (divide the city into different bicycle activity areas according to regional conditions and

TABLE 2. Classification methods of bicycle lanes.

Source		Classification methods
Foreign countries	Urban bikeway design guide [7]	Bike lanes: conventional bike lanes, buffered bike lanes, contra-flow bike lanes, left-side bike lanes Cycle tracks: one-way protected cycle tracks, raised cycle tracks, two-way cycle tracks
	City of Berkeley bicycle plan [99]	According to the transfer convenience of intercity rail stations, they divide bicycle lanes into levels 1, 2, 2.5, and 3
	Code for design of riding traffic in London [8]	According to whether there is loading and unloading cargo and parking demand, they divide bicycle lanes into mandatory bicycle lanes and recommended bicycle lanes
	Copenhagen bicycle priority planning 2011-2025 [100]	According to the function, they divide bicycle lanes into bicycle expressways, bicycle priority roads, and bicycle green roads
China	Guideline for the planning and design of urban pedestrian and bicycle transportation systems [101]	According to the function and the level of urban roads, they divide bicycle lanes into bicycle exclusive lanes and bicycle lanes arranged along both sides of urban roads (Level1, Level2, Level3)
	Shanghai central city slow traffic system planning [102]	According to the connection function of bicycle lanes in the slow-moving island or between islands, they divide bicycle lanes into corridors, passageways, and leisure lanes
	Hangzhou slow traffic system planning [103]	According to function and effect, they divide bicycle lanes into corridors, collector-distributor lanes, passageways, and leisure lanes
	Shenzhen pedestrian and bicycle transportation system planning [104]	According to function and effect, they divide bicycle lanes into main corridors, passageways, and leisure lanes
	Reference [105]	According to function and effect, they divide bicycle lanes into exclusive lanes, main passageways, permissive lanes, and ordinary lanes
	Reference [106]	According to the surrounding buildings and the environment, they divide bicycle lanes into tree-lined bicycle lanes, roadside bicycle lanes, shared sidewalks-separate lanes, and shared sidewalks-mixed lanes

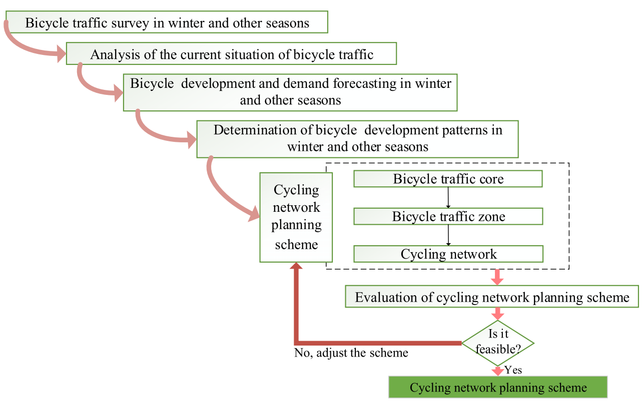

FIGURE 7. The basic thinking of the bicycle lane network layout in cold-climate cities of China.

TABLE 3. The value range of cycling network quantitative indexes in china.

Source	Cycling network density [km/km^2]	Bicycle lane interval [m]
Guideline for the planning and design of urban pedestrian and bicycle transportation systems [101]	5-18	110-400
Code for the design of urban road traffic (GB 50220-95) [114]	1.5-15	150-1200
Standard for urban comprehensive transport system planning (GB/T 51328-2018) [115]	Cycling network density should not be less than 8 km/km^2 in areas with high and medium land use intensity	-
Guideline for the planning and design of urban pedestrian and bicycle transportation systems in Jiangsu Provinces [116]	1.5-8	250-1300
Guideline for the planning and design of urban pedestrian and bicycle transportation systems in Shenzhen [117]	10-28	75-250

the scale of short-distance travel, etc.) and then classify and lay out the cycling network based on the travel demand and functions of interior areas, adjacent areas, and separated areas. It is also necessary to pay attention to the value of quantitative indexes, such as network density and average distance between roads, during the layout design [112] to avoid wasting road resources or failing to meet travel needs. Table 3 lists the value ranges of the quantitative indexes for the cycling network according to Chinese standards, specifications, and guidelines. In application, the network needs to be adjusted according to the actual situation [113]. It is more difficult and costly to conduct large-scale traffic surveys in cold-climate cities in winter than in other seasons. Therefore, in Chinese cold-climate cities, the travel characteristics of residents in only spring, summer, or autumn are used to forecast the traffic demand for the whole year, and no attention is given to the particularity of residents' winter travel characteristics. Because of this, planning schemes are often unable to well address the urban traffic problems in winter [44]. In recent years, the problem of traffic demand forecasting under low temperature and snowfall conditions has been observed in China, and many new models have been developed for forecasting urban residents' travel patterns. For example, one study [44] considered the influence of low temperature and snow on the constituent elements and parameters of a four-step model and included a variation function of residents' winter travel in the trip generation model, putting forward methods for forecasting trip production and the traffic demand distribution in winter in cold-climate cities based on the eigenvector of the 5-order origin moment. The authors also provided a method for calculating the winter road delay function in the traffic assignment model.

During the design layout of cycling networks in cold-climate cities, special attention should be paid to the two climatic factors of temperature and wind, and the discomfort caused by unfavorable factors should be reduced through spatial enclosure and shelter from the prevailing wind in winter [118]. Currently, cities in cold regions across the world design buildings and landscaping to protect pedestrians from northerly winds, orient pockets of public spaces to capture low-angle sunlight from the south, or use canopies, arcades or similar overhead structures to protect pedestrians from rain and snow [1]. An optimal method is the use of a closed three-dimensional transportation system for bicycles, such as arcades covered with a glass roof on the ground floor, glass-enclosed air corridors in upper stories that pass through main public buildings, such as commercial and office buildings in the central areas of a city, or souterrains underground that connect subway stations, railway stations, commercial office buildings and other public facilities [119]. Such corridors can not only provide "a steady-state, thermally neutral environment" for bicyclers and pedestrians but also improve road network connectivity. For example, in Toronto's underground pedestrian system, the temperature is set at 22°C year-round [120]. In addition, because an incorrect, nonaerodynamic profile of a road bank may cause snow accumulation on the road, in Saarelainen and Seppala, roads are raised 2-3 m above the surrounding ground to allow the wind to sweep the road surface and reduce the snow occupying the bicycle lanes [121]. The three-dimensional transportation system is also common in China, but most of these systems are only accessible to pedestrians. Therefore, it is necessary to learn from the successful experience of foreign countries and appropriately adjust this pedestrian-centered model to meet the needs of bicycle travel. Many cities in China have developed windbreaks; for example, in Suiling County of Heilongjiang Province, a cycling network has been established with a three-layer windbreak sequence in the form of a windbreak greenbelt outside the city, a botanical zone of pine and cypress in the city, and a crowd zone in residence areas, which has notably reduced the intrusion of cold wind into the city [122]. In addition, trees, shrubs and structures are established in the northwest to block the prevailing wind in winter, with a wind-proof effect. Deciduous trees are also commonly configured on the sunny side to open areas to sunshine in winter and form a wind-avoiding sunny space for bicyclers [123].

In addition, Chinese and foreign scholars have sought to improve the quantitative and scientific planning methods. A foreign study [124] used population distribution data and public bicycle riding data to determine the relationship between the distribution of start-end points and the distribution of population and the common bicycle routes and then proposed a method for planning the bicycle lane network layout based on GIS, data mining and multistandard analysis methods. Another study [125] reconstructed the gravity model through the analysis of current bicycle travel characteristics based on cellular signaling data. The study verified that the model has high accuracy in predicting the distribution of bicycles and can provide scientific support for network planning. A Chinese scholar [126] used residents' trip data, urban POI point data, and shared bicycle big data to determine the bicycle travel characteristics and routes of Chengdu and support the efficient planning of the bicycle lane network. Another study [127] calculated the grading ratio of expressways, major roads, collector roads, and branch roads according to relevant standard regulations to set up reasonable pedestrian and bicycle networks based on the theory of network capacity supply and demand balance. The grading ratio of sidewalks and bicycle lanes was added to the road traffic system to form a grading ratio of fast and slow roads suitable for cities of different sizes.

Overall, foreign countries focus on building dense cycling networks, while China relies mainly on travel demand. The methods in North America and Europe are very advanced and detailed and can thus provide useful reference for China. Due to China's unique closed residential areas and streets, the road length becomes longer, which is not conducive to bicycle travel. Therefore, woonerven, traffic-calmed residential streets, bicycle boulevards, and high separation from motor vehicles, such as off-street bicycle lanes, are more suitable for Chinese cities in all seasons. Although the ground-level bicycle lanes are exposed to snow and monsoons, the potential of windbreaks and internal road networks in residential areas to support bicycle traffic can be fully exploited to provide a comfortable wind environment for bicycle travel in winter and reduce the negative effects of wind. In addition, scholars in China and in other countries use traffic big data and mathematical modeling to plan the cycling network. This avoids the limitation of traditional planning methods, which rely too much on the subjective judgment of planners, and provides new ideas for the cycling network planning [128].

B. INTERSECTIONS OPTIMIZATION

The nodes of the cycling network, intersections, traffic capacity, service level, and facility settings all directly affect the continuity and accessibility of the cycling network and determine whether cyclists can pass safely and quickly [129]. The essence of intersections makes it difficult for bicycles to be completely separated from motor vehicles and pedestrians. However, certain measures can be adopted to minimize delays at intersections, enhance safety, and improve the cycling network [130]. Based on the research in China and internationally, eliminating the conflict in right turn lanes, designing guidelines for channelization, optimizing signal timing and setting up safety facilities are effective means to optimize intersections. Table 4 summarizes the methods for optimizing intersections with bicycle lanes that are suitable for cold-climate cities worldwide. Since the basic principles of various

TABLE 4. Methods for bicycle intersection optimization in cold-climate cities [7], [98], [101].

Type	Specific Measures
Eliminate conflict at right turn lanes	Occupy parts of sidewalk space as right-turn lanes for bicycles and use barriers or road markings to isolate motor vehicles
	Near the intersections, guide bicycles to the sidewalk and use the sidewalk space to turn right
	Guide the right-turning motor vehicles to bicycle lanes and merge them with the right-turning bicycles to transfer the vehicle-bicycle conflict to the road section and relieve the pressure of intersections
	Rationalize the turning radius to reduce the turning speed of motor vehicles and avoid conflict
	Near the intersections, increase the distance between bicycle lanes and vehicle lanes to prevent conflict between bicycles and right-turning motor vehicles
Design guidelines for channelization	Draw guidelines to make the running routes and directions of each transportation mode clear and to separate and control the traffic flow
	Set up bicycle signs at intersections to provide guidance for riders
	Draw bicycle stop lines in front of the vehicle lanes for providing space for riders to wait for red light
Optimize signal timing	Install dedicated signal lights for bicycles and adjust signal timing scheme
	Adjust the signal cycle to provide a green wave for riders rather than motor vehicles during peak travel periods
Set up safety facilities	Set up bicycle safety mirrors at intersections to provide a better view for oversize vehicles when turning a corner
	Lay cobble pavement at intersections to remind drivers to pay attention to riders when turning a corner
	Install an active warning beacon for bike routes at unsignalized intersections to remind drivers to give way
	Set up median refuge islands in the center of the street to provide a safe parking space for bicycles crossing the street

methods in China and abroad are similar, they are not listed separately.

Since the conflict between right-turn vehicles and bicycles at intersections is a key cause of traffic delays and accidents [131], it is essential to eliminate the conflict between them. At present, foreign countries mainly provide a combined bike lane/turn lane for bicyclers to reduce the conflict at the intersection. This kind of bicycle lane is generally arranged inside the vehicle turn lane, and the space between bicycles and motor vehicles is divided by a dashed line or shared lane markings. When configured in the intersection, it can be regarded as a mixing zone, as shown in Fig. 8 [7]. China has not yet proposed a guide specifically for right-turning traffic and generally sets up isolation facilities and reduces the turning radius of intersections to avoid conflict [132]. According to the analysis of the characteristics of bicycle travel in section 2, it can be seen that in winter, bicycles frequently enter motor lanes in Chinese cold-climate cities. Therefore, these cities need to set up isolation facilities to ensure the separation of motor vehicles and bicycles at intersections. Reducing the turning radius of the intersection is also one of the major ways to optimize the intersection because this means that the right-turn vehicle speed is not

FIGURE 8. Combined bike lane/turn lane [7].

too high. Although China's current standard regulations that can be used to plan intersections—the "Code for the planning of intersections on urban roads (GB 50647-2011)" and the "Specification for design of intersections on urban roads (CJJ 152-2010)"—have stipulated the range of the turning radius, they cannot be directly used in practical construction engineering because they do not conform to traffic safety [133]. A study [134] based on the above two methods revealed the formation of vehicle blind spots and inner wheel differences and put forward a new method involving a small radius and corner closure for designing right-turning areas (as shown in Fig. 9). The study recommended isolation between motor vehicles and bicycles and offered a method for calculating the turning radius. According to this method, the end of isolation barriers close to the intersections on the side of the bicycle lanes is compressed to prevent high-speed bicycles from hitting the barriers at the corner, the length L_m of barriers to be compressed should be 6-8 m, and the direction of barriers should be consistent with the end of the barriers in the right-turning area. The width d_m of barriers to be compressed depends on the end position of barriers, and the turning radius should ensure that most of the vehicles can pass through with the same curvature. These methods have good applicability in noncold-climate cities, but when applied in cold-climate cities, the impact of snowfall on the driver's sight-line [135], the space demand of pedestrians and cyclists, and the space demand for snow storage should also be considered [136].

Channelization can guide and control bicycles, motor vehicles, and pedestrians through intersections in an orderly manner without conflict. The setting method of placing the bicycle stop line in front of the motor vehicle stop line or sidewalk, which is widely used in foreign cities at present, can effectively use the intersection's space resources and improve the traffic efficiency of bicycles and motor vehicles [137],

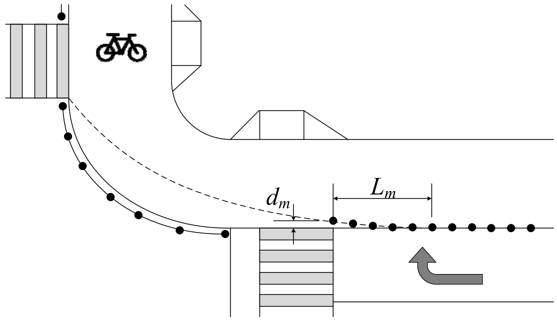

FIGURE 9. **Schematic diagram of the end of the isolation barriers close to the intersection compressing bicycle lanes [134].**

as shown in Fig. 10. The two-stage turn queue box offers a safe way for bicycles to turn left from the right bicycle lane or turn right from the left bicycle lane. It can be set at signalized or unsignalized intersections to guide cyclists through safely, as shown in Fig. 11 [138]. The cycle track intersection approach is a kind of setting method by removing isolation barriers or parking lanes or reducing elevated bicycle lanes to street height and then moving the bicycle lanes close to or into the adjacent motor vehicle lanes, as shown in Fig. 12 [139]. In China, the design of intersection channelization is relatively simple. The most common method is to set a special bicycle access zone on the inner side of the crosswalk to guide the passage of bicycles and pedestrians across the street and reduce the degree of interference between them, as shown in Fig. 13 [23]. The method of the pre-stationed bicycle stop line is widely used in noncold-climate cities. Chinese scholars have proposed that when bicycle travel occupies a certain proportion of urban transportation, the number of waiting bicycles in peak periods exceeds 20, there are at least 2 lanes at the intersections, and the road width exceeds 50 m, a waiting area for bicycles should be set up. When the bicycle stop line is in front of the motor vehicle stop line, it is necessary to step back 4-5 m, and the waiting area should not be less than 40 m^2 [140]. There is no doubt that cold-climate cities can use this method as well; even if they adopt the Singapore pattern in winter, they can use the bicycle stop line as secondary parking for motor vehicles to reduce the hidden danger caused by ice and snow on the road.

FIGURE 10. **Schematic diagram of the bicycle stop line and pre-stationed motor vehicle stop line at intersection.**

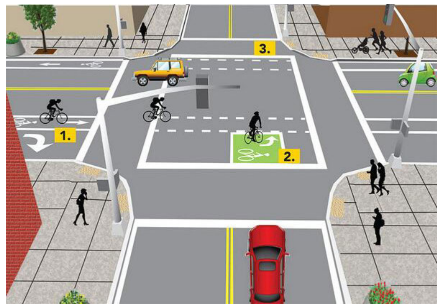

FIGURE 11. **Two-stage turn queue boxes [138].**

FIGURE 12. **Cycle track intersection approach [139].**

FIGURE 13. **Special bicycle access zone.**

Generally, an intersection with good traffic conditions may include markings, colors, signal lights and other elements. To reduce the occurrence of conflicts, traffic designers worldwide are committed to separating bicycles and motor vehicles. The research in foreign countries is more in-depth than that in China, entailing clear requirements for optimization means and effective application. Whether we can apply these methods to China needs to be judged by considering the factors specific to the city and the bicycle lane type.

C. CONNECTION WITH PUBLIC TRANSPORTATION

For cold-climate cities, it is not enough to build a wide and dense cycling network for the complete operation of the bicycle traffic system. It is necessary to strengthen the connection of bicycles and other transportation modes by integrating road space and facilities, etc., to facilitate the "bicycle-vehicle" transfer and "bicycle-pedestrian" transfer [141]. Among them, the transfer between bicycle and public transportation is more frequent than that among other modes, which directly affects the usage rate of bicycle lanes [113], [142].

For integrating bicycles and public transport, foreign countries mainly adopt measures such as setting up sufficient bicycle parking places at rail transit stations, allowing bicycles to get on the subway or buses, setting bicycle frames in carriages, and providing bicycle rental services at bus stations [143], [144]. Among them, parking lot scan provide racks for short-term parking, bike lockers for long-term parking, and even repair services. Poland has adopted "bike corrals", which are 1 to 2 parking spaces for motor vehicles converted to hold 10-20 bicycles [73]. Some countries impose time restrictions for bicycles on public transportation; for example, Singapore, Calgary, and Sao Paulo only allow bicycles get on public transportation during off-peak periods or weekends [75]. For bicycles to enter the rail transit station more conveniently, elevators for bicycles have been installed in Washington [73]. China mainly focuses on motorization transportation, such as rail transit and conventional public transit, while studies on the connection between rail transit and bicycle or pedestrian traffic are relatively rare, and the existing research focuses on transfer behavior, transfer demand forecast, transfer station layout, etc., ignoring methods for optimizing the connection [145]. In China, the bicycle parking lot setting method is planned according to the process of status survey, demand forecast, site selection, layout planning, and parking scale determination [146]. Stations should be connected to the main bicycle lanes, parking lots should be within 1-50 m of the transfer stations, and the scale of parking lots should adequately accommodate the parking demand. The parking lots should be scattered and mainly small and medium-sized, on the left, right, or back sides of the exit and entrance of stations and in the gap areas between trees [101]. One study [126] pointed out that the spacing of parking lots along the main bicycle lanes should be 1-1.5 km, the size of parking spots should be 20-50 m^2, and the spacing and size of parking lots on the priority lanes should be 0.5-1 km, 10-30 m^2. When space resources are limited, the installation angle should be 45° or 60°. When space is allowed, integrated bicycle parking facilities can be established [147]. It should be noted that, when designing parking lots, the sharing of parking time and parking spaces between bicycles and motor vehicles should be considered in cold-climate cities. For example, in a city that adopts the Singapore pattern in winter, the bicycle parking lots can be used by motor vehicles in winter and returned to bicycles in spring, summer and autumn.

In general, setting up bicycle parking is the major way for supporting the integrated development of bicycles and public transportation. Its significance to the development of bicycle use is as important as motor vehicle parking for motor vehicles. Both domestic and foreign countries are increasing the number of parking lots near public transportation. Although the "combined trip" of bicycles on public transport is common abroad, cold-climate cities in China still need to consider whether bicycles pose an inconvenience for public transportation in winter.

V. BICYCLE LANE SPATIAL DESIGN IN CHINESE COLD-CLIMATE CITIES

A. LANE WIDTH

After forming the cycling network, it is necessary to make full use of the limited road space resources to provide safe and comfortable riding space for cyclists.

If the climatic characteristics of cold-climate cities are not considered, theoretically, the number of bicycle lanes is calculated based on the peak hour flow of bicycles and the traffic capacity of bicycle lanes, and then, the width of bicycle lanes can be obtained. At present, because of the differences in research methods, construction levels of transportation infrastructure, riding habits, and trip purposes across countries, there are also large differences in the value of the traffic capacity of a single bicycle lane, which is basically between 1300-2700 bicycles/h [64]. Because the bicycle lane space need not be divided by lane lines, and the traffic flow has the characteristics of lateral swing and irregularity, different from motor vehicle traffic, determining the width of the bicycle lanes is more important than determining the number of bicycle lanes [148]–[150]. The "Guide for the Development of Bicycle Facilities" issued by the National Highway and Transportation Association recommends that the width of an independent bicycle road be 3 m, that the width of bicycle lines which the bicycle traffic volume is low be not less than 2.4 m, and that the width of a single bicycle lane be 1.2 m [151]. The British "Road Engineers Handbook" stipulates that bicycle lanes on two-way main lines be generally set to 3.5 m, those on two-way secondary trunk lines be generally set to 2.7 m, and those on one-way lines be generally set to 2.7 m [152]. China's "Traffic engineering manual" states that the width of a bicycle lane should be 1 m according to the width of the traditional bicycle body and lateral clearance, and considering the width of the marginal strip, the width of a bicycle lane should be 1.5 m [153]. Many Chinese standard regulations and the research results for some cities have also put forward corresponding regulations and requirements for the width of bicycle lanes, as shown in Table 5. However, in practical construction engineering in China, the width of bicycle lanes needs to be further adjusted according to the urban space development, road network planning, lane function, pavement evenness, etc. When considering the winter climate characteristics of cold-climate cities, Chinese scholars propose that, based on the characteristics of bicycle travel in the cold-climate city of Harbin, if the peak travel volume is taken as the calculation standard for the width of bicycle lane, road resources will be idle in off-peak period. Therefore, it is suggested that in Harbin, the minimum value in road planning specification be reduced; that is, the bicycle lane width should be not less than 3 m when adopting physical isolation and 2 m when adopting lined isolations [154].

It should be noted that the above suggestions for the value of the bicycle lane width are all based on traditional bicycles. In recent years, with the increasing popularity of electric

TABLE 5. The relevant standard regulations and their requirements for bicycle lane width in china.

Source	Specific Requirements
Code for the design of urban road engineering (CJJ 37-2012) [155]	The width of bicycle lanes arranged along both sides of urban roads ≥2.5 m, the width of bicycle-exclusive lanes ≥3.5 m
Standard for urban comprehensive transport system planning (GB/T 51328-2018) [115]	The minimum width of one-way bicycle lanes should be 3.5 m, two-way bicycle lanes should be 4.5 m
Guideline for the planning and design of urban pedestrian and bicycle transportation systems [101]	The width of bicycle lanes graded level 1 should be 3.5-6.0 m, level 2 should be 3.0-5.0 m, and level 3 should be 2.5-3.5 m
Code for the planning and design of urban road space (DB 11/1116-2014), Beijing [156]	The width of bicycle lanes should not be less than 2.5 m
Guideline for the planning and design of urban pedestrian and bicycle transportation systems in Shenzhen [117]	The width of main corridors should be 2.0 m, 2.5 m, or 3.0 m; the width of passageways should be 1.5 m or 2.0 m; and the width of leisure lanes should be 1.5 m

bicycles, overtaking incidents have become more frequent. Overtaking interference affects the value of the bicycle lane width, and in winter, traditional bicycles swing more during overtaking and occupy more bicycle lane space. Therefore, the bicycle lane width needs to be reconsidered [157]. Foreign countries pay little attention to the width of bicycle lanes when electric bicycles and traditional bicycles are mixed. Existing studies are also limited to the lateral distance between two bicycles and the behavior during overtaking. Although Chinese scholars have carried out many studies on the change in the lateral distance between two bicycles during overtaking, focusing on the vehicle-bicycle isolation forms, traffic signs of bicycle lanes, gender and age of riders, protective equipment conditions, etc., the research object was mainly the traditional bicycle [158]–[160]. In recent years, the research focus has begun to shift to the interference between traditional bicycles and electric bicycles. The results show that increasing the minimum distance between two bicycles during overtaking is the primary means to reduce overtaking interference. However, if the lane is too wide, more serious overtaking interference events may result. One study [161] based on the analysis of the traditional bicycles and electric bicycles' traveling track proposed an electric bicycle overtaking interference intensity index and graded it through a clustering algorithm. The authors then determined that the bicycle lane width should be 1.1-1.3 m, and the speed limit of 25 km/h for electric bicycles is the best for ensuring the safety of cyclists.

In addition, when setting up bicycle lanes in cold-climate cities, the problems of solar radiation and snow accumulation need to be considered [162]. In general, the bicycle lanes are arranged along both sides of urban roads, and each side only has one traffic direction. However, because the sunshine conditions on different sides of the street are differently affected by the orientation and number of floors of the buildings along the street, some cold-climate cities across the world adopt asymmetrical patterns for designing bicycle lanes to enable cyclists to obtain more street space under the sun and improve riding comfort, for example, by setting up two-way bicycle lanes on the side of urban roads with a small shadow area. On the one hand, this area experiences longer irradiation time to supplement the heat source, and on the other hand, it can be used as a snow storage space for accelerating snowmelt [163]. A two-way bicycle lane on one side of Helsinki is shown in Fig. 14. In addition, to reduce the occupation of bicycle lanes by snow, in Japan, a cross-sectional road design method was designed according to the width of snow piles. This method establishes the calculation formula of the first snowdrift width (the width required when snow is temporarily stacked on the side of the road before being compacted by vehicles) and the secondary snowdrift width (the width required for the existing snow to be transported outside the road). When designing the cross-section, the formula is used to determine the width required for snow piling, and then the remaining space on the road is allocated to bicycles, pedestrians, motor vehicles, etc., [164]. At present, this aspect is insufficiently considered in China. Two-way bicycle lanes are only common in parks and landscapes. Although some cold regions are also discussing the need to reserve the width of snowdrift—for example, Harbin proposed to increase the sidewalk by 1 m to ensure the quality of slow traffic [93]—no plan has been implemented.

FIGURE 14. Two-way bicycle lane on one side of the road in Helsinki.

In general, to reduce the severity of overtaking interference, it is necessary to adjust the bicycle lane space through facility design in China and abroad, but the width needs to be determined by a variety of factors. Among them, solar radiation and snow accumulation space are important factors that cannot be ignored in cold-climate cities. Optimizing the cross-sectional design of urban roads offers a new perspective considered in foreign countries for calculating the required width of bicycle lanes according to the amount of snow, which has a good reference for Chinese cold-climate cities.

B. ISOLATION FORMS

Whether in cold-climate cities or noncold-climate cities, isolation facilities are the main means to realize the separation between pedestrians and bicycles and between bicycles and motor vehicles and to protect the road right of bicycles, as well as force or guide road users to go their own ways [165], [166].

At present, the most common isolation facilities are pedestrian-bicycle isolation facilities, including green belts, barriers, curb stones, partitions separating pedestrians and cyclists on the same plane, and pedestrians and cyclists on the same plane. Without considering the climatic characteristics of cold-climate cities, it is most effective to set up continuous green belts and barriers or use curbs to raise sidewalks, which can realize the complete separation of pedestrians and riders and is suitable for roads with a large traffic volume of pedestrians and bicycles [167]. It is worth noting that, at present, there is little research on the foundation for setting pedestrian-bicycle isolation facilities by Chinese and foreign scholars, and the existing studies mostly take the critical value of pedestrian and bicycle traffic volume as the only reference basis, which is a one-sided perspective [168]. The design of pedestrians and cyclists on one plane is common in North America and is set in parks or along river for recreational cycling, such as the well-known Seawall and Central Valley Greenway in Vancouver, the Midtown Greenway in Minneapolis, and the Lakefront Trail in Chicago [73]. While the design with pedestrians and cyclists on one plane is the least recommended form according to Chinese standards, specifications, or guidelines, when there are objective difficulties and such a design has to be used, different materials or colors can be laid on the two areas, or street trees, street furniture, isolation piers and other forms can be used for ''flexible'' isolation [13], [24], [168]. One study [169] addressed the conditions that are not suitable for setting up pedestrian-bicycle isolation facilities and proposed that when the road width is less than 2.5 m or the traffic volume of pedestrians and bicycles is small and the structural proportion is imbalanced, shared-use roads can be used. Another study [167] pointed out that compared to the intermittent green belts that give bicycles space to ride on the sidewalk, barriers are better, but this method is not conducive to fire protection; therefore, it is suggested to adopt curb stones to reduce the interference between pedestrians and bicycles.

The common forms of vehicle-bicycle isolation facilities include linear isolations, physical isolations, spatial isolations, parking strip isolations and vehicle-bicycle mix [170], [171]. Among them, linear isolations save the most space, but they cannot guarantee against the occupation of motor vehicles. Physical isolations are the safest, mainly through curb stones, barriers, green belts, etc. When setting up these isolations in cold-climate cities, it is necessary to select suitable isolation facilities according to the transportation development patterns of bicycle. In foreign countries, linear isolation is the most commonly used method because they are considered most comfortable. New York, Portland, San Francisco, and Washington are also equipped with buffered bike lanes, which are diagonally striped lanes between bicycle lanes and motor vehicle lanes, as shown in Fig. 15 [172], [173]. In Asahikawa, in the central part of Hokkaido, Japan, tall trees were planted to isolate vehicle lanes and bicycle lanes, not only for greening the environment but also for sheltering from snow (see Fig. 16) [95]. At present, many Chinese studies have considered the establishment of vehicle-bicycle isolation facilities, but they basically focus on the changes in traffic conflict rate and motor vehicle speed before and after the installation of isolation facilities, as well as the impact of the continuous length and the height of isolation facilities on the operation of motor vehicles, and a system or a specific method has not yet been formed [170]. One study [174] investigated the set conditions of vehicle-bicycle isolation facilities and proposed that when the width of a 4-lane road exceeds 20 m and the width of a 2-lane road exceeds 14 m, it is appropriate to set up vehicle-bicycle isolation facilities. The setting of 0.2 m-high barriers at bus stations and 1.1-1.2 m-high barriers between stations has a positive effect. When the road width does not meet the standard, linear isolations and the vehicle-bicycle mix are the crucial measures. In addition, considering the characteristics of bicycle travel in Chinese cold-climate cities, a study [154] proposed that Harbin, a Chinese cold-climate city, should adopt linear isolations to realize the transformation of the bicycle lane function for avoiding idle bicycle lane space and wasting road resources.

FIGURE 15. Buffered bike lanes [7].

FIGURE 16. The bicycle lane isolation form in Asahikawa, Japan.

In general, full isolation of bicycle lanes from motor vehicle lanes is most desirable in China and abroad. There are many forms of isolation, and the choice of which one to use needs to be informed regarding many factors. However, when adopt the Singapore pattern in winter, the problem of the space transformation of bicycle lanes needs to be considered.

C. PAVEMENT FORMS

It is necessary to study the surface characteristics of bicycle lanes, which not only determine the traffic function of bicycle lanes but are also an important factor of a comfortable and safe riding environment. Most of the existing research is based on the principles of easy riding, travel safety, reasonable color matching, durable materials, and high identifiability, etc., and considers paving materials, maintenance technology, and paving colors [136]. Affected by low temperature, ice and snow, and other climatic conditions, cold-climate cities have higher requirements and attach great importance to these aspects.

European countries and Japan lead the world in the research regarding winter road paving materials, maintenance technology and related research in cold-climate cities. To prevent freeze bulge on roads, Japan has developed a paving technology with an anti-freezing function. First, salinization agents, such as sodium chloride and calcium chloride, are added into bituminous concrete to reduce the freezing point of ice and snow. Second, the roughness of the surface layer and the amount of elastic deformation of pavement can be increased through the rough type and deformation type paving methods to facilitate the stripping of snow and ice [175]. In recent years, scholars and urban planners have constantly sought new materials. For example, in the United States, a new pavement type supported by epoxy and dolomitic limestone has been developed, which can melt snow rapidly while preventing skid. These materials can not only optimize the pavement structure but also make the pavement have a certain ‘‘stress’’ [176]. In addition, foreign scholars conducted a questionnaire survey on cyclists in winter and found that cyclists need more frequent snow plowing in the early morning to clear continuous routes, leaving no parts uncleared, to prevent ice from making the road uneven [51]. Snow plowing is a method commonly used in Sweden, Norway, Finland and Denmark to clear snow from bicycle lanes. In the past, Sweden used sand, grit or abrasive (crushed stone aggregate) for skid control on bicycle lanes. Although this method can enhance the friction, it is useless for black ice and can easily puncture bicycle tires. Although the cost of salt is low, salt can easily cause the bicycle chain to rust, and the traditional bicycle cannot cope well with dry salt because of its lightweight. Therefore, it is proposed to use brine, which is a saturated salt solution that contains approximately 20 to 25 percent NaCl by weight. Other cities, such as Calgary, use sanding chip mixture (3% salt, 97% fine gradient) to melt snow and ice when the temperature is below −5°C [40]. In Finland, bicycle lanes are required to kept clear from 6 a.m. to 10 p.m., and snow and ice need to be cleared within 6 hours, including 4 hours for snow removal and 2 hours for deicing. Potholes and other faults on the road should be repaired before winter sets in because they hinder the clearing of snow and cannot be seen through a thin layer of snow, which poses a danger to cyclists. In addition to changing the physical or chemical characteristics of the road surface to remove snow, snowmelting and deicing system can be installed under the ground to prevent snow from freezing on the road. The road snowmelting and deicing system is generally composed of an underground heat exchanger, control device, mainfold and snowmelting pipeline, etc., and to melt ice and snow, it uses some media to absorb geothermal energy and transmit it to the road surface. At present, this technology has been widely studied and applied in the United States, Japan, Northern Europe, Switzerland, Iceland, Norway, Poland, and other countries. It is common to use solar energy on the road for paving solar bicycle lanes. In 2014, Holland laid the world's first solar bicycle lane, with a length of 70 m, which is composed of 27 modules of 2.5 m × 3.5 m. Its structure is composed of tempered glass in the surface layer, solar cells in the middle layer, and concrete floor. The electricity generated can be used for the lighting, monitoring, and ice melting of bicycle lanes in winter, and the surplus power can be connected to the local power grid [177]. Germany launched the first solar bicycle lane in 2018, with a length of 90 m. Its structure is composed of anti-slip recycled glass, solar cells, anti-crack safety glass, and rubber. We estimate that the annual power generation capacity can reach 16000 kw·h, as shown in Fig. 17 [178], [179]. At present, there are few studies on the paving materials of bicycle lanes in cold-climate cities in China, while the paving materials of bicycle lanes in noncold-climate cities and motor vehicle roads in cold-climate cities are relatively abundant and are not introduced here.

FIGURE 17. **Solar bicycle lanes in Holland and Germany.**

Colored bicycle lanes can not only enhance road visibility but also stimulate the optic nerve of travelers, thus strengthening their traffic direction and sense of orientation. Considering the cold climate, withered vegetation, and monotonous color in cold-climate cities in winter, to enrich the urban environment color and increase winter vitality, colored bicycle lanes should be set up in cold-climate cities [180], [181]. At present, the selection standards of bicycle lane paving color in different countries are not uniform. The commonly used colors are red, blue, yellow, and green. Copenhagen adopts red and yellow, and Denmark and the United Kingdom use light blue. The common paving methods of colored bicycle lanes include color asphalt mixture, emulsified asphalt layering, color material sprayed on the surface, and colored cement-grouted asphalt concrete pavement [182], [183]. One study [184] compared the composition, thickness, color retention time, structural stability, and unit price of the above-mentioned pavement forms and concluded that the epoxy color spraying material is the best. However, it is worth noting that due to the economic level and climate conditions, Chinese cold-climate cities cannot blindly copy foreign cities.

According to the survey of Beijing citizens on the improvement in bicycle lanes, one study [185] concluded that colored pavement is the least urgent problem to be solved, and it is proposed that too many colored roads cannot serve as a warning, that colored paving should be used in road sections and intersections where the conflict between bicycles and vehicles is serious, and that at most two colored bicycle lanes should be laid in one intersection.

In general, snow-melting materials and snow-melting technology provide the possibility for the sustainable development of bicycle utilization in cold-climate cities. Relevant foreign scholars and urban planners continue to uncover new materials and new technologies, which can provide methodological support for Chinese cold-climate cities. However, when methods such as solar bike lanes and paving colored roads are applied to Chinese cold-climate cities, it is necessary to account for the city's situation, the priority of the project, and the early construction costs and later maintenance costs.

VI. CONCLUSION

As the bicycle is a ''new engine'' leading cities to realize low-carbon development and green development, it is important to vigorously develop bicycle utilization worldwide, including in cold-climate cities. There are many factors affecting the development of bicycle utilization, and among them, the set level of bicycle lanes has the greatest impact. However, understanding how to plan and design bicycle lanes requires more consideration in cold-climate cities than in noncold-climate cities. In general, the severe weather conditions in winter in cold-climate cities affect the bicycle travel characteristics, which are the basis for determining the development pattern of bicycle utilization, affecting the formulation of standards and norms and determining the level and quality of bicycle lane setting. Therefore, before the construction of bicycle lanes in cold-climate cities, it is necessary to analyze the bicycle travel characteristics of the city and select the appropriate development pattern. When planning and designing bicycle lanes, it is necessary to fully consider climatic factors, such as temperature, wind and sunshine; focus on the bicycle travel needs of women and young people; pay attention to the safety, comfort and convenience of the bicycle lanes; fully consider the bicycle traffic potential of windbreaks and the internal road network of residential areas; reasonably select the types of bicycle lanes; and construct a moderately connected three-dimensional traffic system. Coordination with the whole city, other transportation modes and landscapes also needs to be considered. Moreover, the influence of electric bicycle interference and snow on the width of the bicycle lane should be fully considered. The selection of isolation forms should also consider the demand for the functional transformation of the bicycle lane. The pavement materials, pavement maintenance technology and color of bicycle lanes in winter should also be considered.

In the future, to further optimize the planning and design methods of bicycle lanes in cold-climate cities, we should gain a deeper understanding of the factors that hinder women's winter riding and the behavior of teenagers in winter riding. Other factors that affect the winter use of bicycles in cold-climate cities also need to be understood. However, it should be noted that there are still many intangible factors that require further exploration. The value ranges of planning indicators, such as road network density and the connectivity of the three-dimensional transportation system, also need to be further studied through quantitative analysis and research methods. In addition, considering the growing popularity of the bicycle, it is necessary to re-target various model parameters or establish new models for predicting urban residents' travel structure. For example, with the development of underground space, whether bicycles will also transfer from the ground level to the underground in spring, summer and autumn and whether the ground space can be used by motor vehicles have a great impact on the analysis model, requiring detailed and in-depth exploration. In the future, it is necessary to pay attention to the connection with other plans, change the inherent research ideas, and carry out the integrated planning and design of travelers' activity spaces, urban development, land use, and municipal administration. Moreover, with the development of computer simulation, mathematical modeling and other technologies, the use of interdisciplinary theories and methods, and the use of more quantitative and technical means as scientific and technical support for planning, design and management decision-making are also worthy of further in-depth study.

At present, China has not formed a set of mature measures on how to develop bicycle in cold-climate cities. Although there are a series of strategies, large and small, that can be used to realize the Copenhagen pattern, Paris pattern or Singapore pattern, most of them use the experience of foreign countries with better bicycle transportation development for reference. Although the application of these patterns in China can achieve immediate results, such patterns cannot be directly implemented and blindly followed. Considering its own bicycle travel characteristics, economy, customs and other factors, China must put forward a flexible development model based on seasonal characteristics, which can not only compensate for the negative impact of the adverse winter climate on the city but also make effective use of road resources, providing new ideas for the development of bicycle utilization in cold-climate cities. For the planning of the cycling network, the existing standards and specifications in China and abroad basically do not consider the climate characteristics of cold-climate cities. Among them, foreign countries focus on building dense cycling network. Although China focuses on layout according to the travel demand, the planning method remains at the qualitative level. At present, there is no special design guide for right-turning traffic in China. While the current standard specifications for optimizing intersections stipulate the value range of the turning radius, some of them do not conform to the design concept of traffic safety. Foreign intersection optimization methods, such as through the bicycle lane and two-stage turn queue boxes, mainly focus on identifying the path of turning bicycles to reduce the conflict. With regard to the optimization of the connection between bicycles and public transportation, setting up bicycle parking lots at public transportation stations and reasonably setting the spacing and size of parking lots are the main means adopted in China. This is also true for foreign countries, but in foreign countries, bicycles are also allowed on public transportation, which further promotes the integration of bicycles with public transportation. For the value of the bicycle lane width, the existing standards in China and abroad only consider traditional bicycle. However, in recent years, Chinese scholars have gradually carried out research on bicycle lane width under the condition of the mixed use of electric bicycles and traditional bicycles, and foreign scholars have considered solar radiation and snow. Given these results, cold-climate cities in China and abroad can learn from each other. There are many isolation forms of bicycle lanes both in China and abroad, and the selection is generally made based on the critical value of traffic volume, which has certain limitations. Although China has also proposed the consideration of cold climate characteristics when selecting the isolation form, a relevant theoretical basis is lacking. Because bicycles are a priority in other countries, the isolation form receives more attention regarding comfort. In terms of pavement materials, road maintenance technology and pavement color, there are few studies in China that consider cold-climate conditions. Even when studies consider the cold climate, they basically cover motor vehicle roads. Although foreign countries have not put forward a perfect system for setting these aspects, their research and practical guidelines still have reference significance for Chinese cold-climate cites.

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