Transportation Research Part D 83 (2020) 102335

Contents lists available at ScienceDirect

Transportation Research Part D

journal homepage: www.elsevier.com/locate/trd

Built environment effects on the integration of dockless bike-sharing and the metro

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ARTICLE INFO

Keywords:
Bike-sharing
Built environment
Feeder mode
Metro
Shenzhen

ABSTRACT

Bike-sharing provides a convenient feeder mode for connecting to a metro and is believed to be an efficient way to solve the first- and last-mile problem. Despite the increasing attention paid on the use of bike-sharing, few studies have investigated how built environment factors affect the integrated use of dockless bike-sharing (DBS) and the metro. Using data from one of the largest DBS operators in China (Ofo), this paper employed a series of negative binomial regressions to examine the effect of the built environment on the integrated use of DBS and the metro, using Shenzhen as a case study. The findings show that mixed land use is positively related to integrated use. Residential areas have higher access-integrated rates during the morning peak hours, while industrial areas are associated with more integrated uses, connecting factories and metro stations. Furthermore, parks and public squares encourage both access- and egress-integrated use during peak times. Transportation facility features, including bus stops and dedicated bike lanes, are positively related to integrated use, while areas with dense metro distribution and main streets with many intersections are negatively related. Transfer distance also plays a crucial and negative role in integrated use. In addition, metro stations that are closer to the city center with a higher number of passengers are more likely to be integrated with bike-sharing. These findings can be used to collectively facilitate a connection between cycling and metro transit by creating a bicycle-friendly environment.

1. Introduction

In 2012, the US Department of Transportation identified a general lack of connectivity as one of the main challenges of developing public transit (Chandra and Quadrifoglio, 2013). This defines the problem associated with the first- and last-mile connectivity from home and transit to the destination. On the other side of the Pacific, coupled with rapid population growth and urban expansion, urban China has also been confronting first- and last-mile connectivity challenges over the last two decades. One possible solution is to provide a variety of feeder modes and efficient feeder transit services. Compared to other typical feeder modes, cycling is a relatively fast, flexible, environment-friendly, and economical way to connect with transit services (Keijer and Rietveld, 2000). There are four main patterns of access/egress by bicycle: bicycle-and-transit, transit-and-bicycle, bicycle-transit-bicycle, and bicycle-carry on transit-bicycle (Martens, 2004; Krizek and Stonebraker, 2010). In around 2008, bike-sharing began to grow in popularity in many cities around the world, with the widespread installation of third-generation bike-sharing. By acting as a feeder mode, bike-sharing creates a multimodal integration of smarter, greener, and more economical cycling without the concerns of theft, vandalism, maintenance, and limited parking space on transit carriages (Shaheen et al., 2010).

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https://doi.org/10.1016/j.trd.2020.102335

In one form or another, bike-sharing has existed for more than fifty years. Along with the development of technology (e.g., mobile payments and QR codes), new bike-sharing programs without fixed dock stations have appeared on the market, and in this paper, they are referred to as dockless bike-sharing (DBS). Since the first market operation in 2015 in China, many DBS programs have been rolled out rapidly (e.g., Ofo and Mobike), and the number of DBS bikes in China reached over 23 million within two years (Gu et al., 2019a). Compared to docked bike-sharing (public bicycles), the feature that allows DBS bikes to be parked freely, offers users immense flexibility in terms of route choice, and ensures a greater availability of bikes (Wu et al., 2019). Without the limitation of being locked to dock stations, DBS systems enable users to access bike-sharing more efficiently than traditional docked-type bicycles. To date, however, the connection between DBS and metro transit has not been adequately studied.

As one of the significant determinants of travel demand, the built environment affects mode choice and travel behavior (Cervero, 2002; He, 2011; Lee et al., 2017). Studies exploring the effect of the built environment on bike-sharing-transit use (docked bikes) have emerged in recent years (Ma et al., 2015, 2018a; Ji et al., 2017; Zhao and Li, 2017; Lin et al., 2018; Gu et al., 2019b). These empirical studies reveal several built environment elements related to urban design, land use, and transportation facilities that significantly affect bike-sharing-transit use in their case cities. For instance, the positive factors may include job density and the length of bicycle lanes, while the negative factors may include street intersections and distance to the city center. The impact of urban roads on bike-sharing-transit integrated use differs depending on the type of road (including highways, main roads, branch roads, and bicycle lanes), and it is also difficult to determine the effect of public bus services. However, few studies have investigated how built environment factors affect the integrated use of DBS and the metro. There is a particular lack in an understanding of how such impacts vary between the first and last mile. Furthermore, the question remains: how can planning strategies related to the urban built environment be utilized to encourage DBS–metro use?

To fill the research gaps identified above, we conducted an empirical study by examining the Ofo DBS program in Shenzhen, China. The study aims to address three research questions: (1) Is there any variance in the integrated use of DBS and metro transit according to the time of the day and across urban space? (2) What are the different effects of built environment features on access-/egress-integrated use? (3) How do these effects vary between morning and evening peak times? The study findings have the potential to inform and support the design of seamless connections between DBS and metro transit. This support may come in the form of improved design and infrastructure to create cycling-friendly and transit-oriented environments. Furthermore, policy and intervention programs emphasizing environmental features for biking related to land use and transportation facilities help increase green urban mobility.

2. Literature review

The built environment is an essential factor of the structural context, and Handy et al. (2002) categorized it generally into three components: land use, transportation system, and urban design. In essence, the spatial distribution of various land-use types influences accessibility and proximity to origin/destination; the transportation system, which includes physical transport-related infrastructure (e.g., roads), supports human activities and determines how easy it is for individuals to reach their destinations from their points of departure; and urban design refers to the appearance and arrangement of physical elements (e.g., tree shade) and affects mode choice by potentially changing individuals' judgment of attractiveness or perception of safety. However, most of the literature related to the effects of the built environment on bike-sharing use or integrated bike-sharing–metro use focuses on land use and transportation systems, while the urban design of the built environment is scarcely included; hence, it is also omitted here. In each of the subsections below, we will first review the effect of the built environment on bike-sharing use, followed by its effect on bike-sharing–metro integrated use.

2.1. Land use: Urban density, land-use type, and points of interests (POIs)

Urban land use correlates with urban density through the distribution of population and employment. It is commonly used by urban planners to redirect urban forms that are dense, compact, or diverse, which facilitates shorter trips and affects mode choices, including cycling (Cervero and Kockelman, 1997). The impacts of different land-use types on travel demand for different trip purposes and mode choices differ (Boarnet and Crane, 2001; Zhang, 2004). Furthermore, human activities are associated with land-use patterns, thus the distribution of activity opportunities around the home and workplace also affect feeder mode choices.

2.1.1. Bike-sharing use

High population density/flow and job density could encourage bike-sharing use, and the city's dense urban form provides an excellent opportunity for a well-designed bike-sharing system to run successful (Rixey, 2013; Faghih-Imani and Eluru, 2017; Zhang et al., 2017). However, some studies have also found that the impact of population/employment on bike-sharing use is insignificant (Mateo-Babiano et al., 2016; Wang et al., 2016) or even negative (Ding, 2016). One possible explanation is that population density varies among urban contexts in Asia, North American, Europe, and Australia, as well as due to the different cycling cultures in each country.

Land-use types, mainly residential and commercial patterns, help explain the volume of bike-sharing stations, which makes bike-sharing an ideal mode choice for commuting (Midgley, 2011). Allocating bike-sharing around these two patterns of land use will encourage bike-sharing flows (Kim et al., 2012; Mateo-Babiano et al., 2016). Two measurements of land-use mixture – number of land-use types and the entropy index of land use – have been positively related to bike-sharing use (Wang et al., 2016; Zhang et al., 2017). The presence of dock stations near shopping malls may lead to high demand for bike-sharing use, as a station that covers a shopping mall can attract users that enter the mall for leisure or work (Zhang et al., 2017). However, the type of retail shops and non-food shops has a limited impact (Wang et al., 2016). Restaurant density and the density of retail foodservice enterprises were found to correlate with an increase in bike-sharing use (Faghih-Imani et al., 2014; Tran et al., 2015; Faghih-Imani and Eluru, 2016; Wang et al., 2016; Faghih-Imani et al., 2017). However, education places (schools and university campuses) have an unclear impact due to the variation of morning/evening peaks and weekdays/weekends (Kim et al., 2012; Faghih-Imani et al., 2014; Wang et al., 2016).

2.1.2. Bike-sharing–metro integrated use

Regarding bike-sharing–metro integrated use, the role of population and job density remains inconclusive. For the US cities of Minneapolis and Washington, DC, suburban areas with lower population density seem to induce transit users to integrate bike-sharing and the metro (Martin and Shaheen, 2014). However, for some Chinese cities like Beijing and Nanjing, integrated bike-sharing–metro use tends to be concentrated in denser areas, such as city centers (Lin et al., 2018). The disparity is in part due to the poorly distributed public transportation and bike-sharing systems in suburban areas of China (Ma et al., 2018a). In terms of employment reflecting demand for travel, a consensus has been reached that a denser job distribution attracts more bike-sharing–metro integrated use because of a higher proportion of commute-related trips (Flamm, 2013; Ma et al., 2015; Lin et al., 2018).

Residential, commercial, and educational land-use types are often associated with more integrated use of bike-sharing as a feeder mode for the metro. Of these, residential and commercial land uses are related to commute trips, which makes bike-sharing necessary as a feeder mode during peak times. However, college students living on campus tend to combine bike-sharing and the metro for non-commuting trips on the weekend to, for example, go shopping downtown (Gu et al., 2019b). However, the impact of residential areas on bike-sharing-transit integrated use becomes insignificant in already densely populated Chinese cities, such as Beijing (Zhao and Li, 2017). Overcrowded residential areas may cause congested traffic, and thus, policies related to residential density may not be an effective approach for enhancing integrated use (Zhao, 2014). Moreover, comparative studies examining Taipei, Tokyo, and Beijing have indicated that land mixture is positively related to bike-sharing use (Lin et al., 2018). Mixed land use in the catchment areas of metro stations could result in short trips between metro stations and residential, employment, or recreational locations. The distribution of POIs around metro stations should affect integrated use; however, empirical studies have revealed mixed results. One study (Ji et al., 2017) showed that retail shopping-, leisure-, and food-related locations near catchment areas have no significant impact on the bike-sharing use of the connecting metro, while another study indicated that shopping malls and pubic parks are related to integrated use (Zhao and Li, 2017). Zhao and Li (2017) found that having more shopping malls in a metro area discourages the use of cycling to access a metro station. This is possibly due to the large number of parking spaces that are available, which attracts the use of automobiles rather than cycling. On the other hand, having more public parks around metro stations increases the probability of cycling to stations, as cyclists may cycle through the park to avoid traffic, injury, or waiting for traffic lights.

2.2. Transportation systems: Bicycle infrastructure, road service, and public transportation facilities

2.2.1. Bike-sharing use

Most previous studies have demonstrated a positive correlation between bike-sharing ridership and bicycle lanes because bicycle lanes provide a safe and convenient cycling environment for cyclists (Rixey, 2013; Mateo-Babiano et al., 2016; Zhang et al., 2017), whereas other studies have found no such correlation (Ding, 2016; Wang et al., 2016). The inconsistency might be because, in some European cities where cycling is ubiquitous, bike-sharing users who are familiar with street conditions are less affected by the presence of bicycle infrastructure (Martens, 2007). Different levels of urban roads also affect bike-sharing use with varying impacts on the use of bike-sharing. The length of a minor/branch road within the particular buffer of a station positively impacts the bike-sharing use rate, while the length of a major/main road negatively impacts it (Faghih-Imani et al., 2014; Zhang et al., 2017). This may be because the intersections along the major roads increase the time delay of cycling trips for bike-sharing users (El-Assi et al., 2017). However, the impact of bus service near dock stations on the use of bike-sharing is not recognized. For short- to medium-length entire trips, bike-sharing may, in fact, replace public buses, and hence, the density of bus stops is perhaps negatively associated with bike-sharing use or even has no impact (Rixey, 2013; Faghih-Imani et al., 2014; Zhang et al., 2017). For segment trips, however, bike-sharing does work as a feeder mode for public buses (Ding, 2016). Similarly, the distribution of metro stations near dock stations significantly affects bike-sharing use. There is a virtual consensus as evidenced by the considerable quantity of empirical evidence that having more metro stations around dock stations (or even the presence of a metro station) will enhance bike-sharing use (Kim et al., 2012; Faghih-Imani et al., 2014; Tran et al., 2015; Gu, Kim, and Currie, 2019b).

Another factor that should be taken is the distribution of dock stations (density of dock stations) and their adjacency (distance to nearby dock station). The demand at one station may be associated with demand at nearby stations because they serve a similar catchment, and hence, a spatial correlation exists (Zhang et al., 2017). When dock stations are not widely distributed across a city, more dock stations around or at a shorter distance to nearby stations help to increase the demand (Faghih-Imani et al., 2014; Ding, 2016). However, when dock stations have already been distributed widely, the complementary effect among nearby stations will be replaced by the competitiveness effect when the number of nearby dock stations increases, resulting in a decrease in the flow of dock stations (Wang et al., 2016; Zhang et al., 2017).

2.2.2. Bike-sharing–metro integrated use

Bicycle infrastructure (e.g., bike-lanes, bicycle boulevards, and bicycle parking facilities) is crucial for supporting the bicycle's mobility role in connecting transit stations (Martens, 2007; Cervero et al., 2013). With integrated bike-sharing and transit planning, practices in Chicago and Austin have demonstrated the importance of bicycle facilities on facilitating bike-sharing connectivity to rail transit (Griffin and Sener, 2016). In addition to cycling facilities, the higher overall road density in urban areas could correlate with heavier on-road traffic and more bus lines, such that commuters tend to walk or take the bus to metro stations rather than using bike-sharing (Ma et al., 2018a). In particular, a larger number of local/branch roads, rather than major/main roads, around metro stations favors motorized feeder mode choices, such as driving and taking the bus (Zhao and Li, 2017), thereby making transferring by bike-sharing dangerous. Furthermore, bike-sharing–metro use declines in places where there are both more streets and arterial intersections along the route to the metro station or within the metro area (Ma et al., 2015, 2018a; Lin et al., 2018). In these places, street intersections between bike paths and major roads inhibit heavy traffic, cause time delays, and increase the risks of injury and accidents.

As for public transportation facilities, the presence of more bus routes or more bus stops near metro stations increases the likelihood of bus use, which substitutes bike-sharing as a feeder mode (Zhao and Li, 2017). When more bus stops are provided near metro station entrances, a portion of bike-sharing–metro integrated use will shift to bus-metro integrated use. Importantly, metro station coverage determines the demand for bike-sharing–metro integrated use. Some empirical evidence in China indicates that having a higher density of metro stations reduces the potential for integrated use because bike-sharing can be replaced by walking as a feeder to the metro (Lin et al., 2018; Ma et al., 2018a). When the density of metro stations increases, it results in a decreasing access/egress distance to and from metro stations, and thus, supports walking by transit users. However, at the metro station level, several studies have confirmed that a higher density of docking stations within the catchment area of a metro station increases the possibility of metro users searching for bikes, thereby promoting their willingness to select bike-sharing as a feeder mode (Zhao and Li, 2017; Gu et al., 2019b).

2.3. Other factors: Location and ridership of the metro

Location attributes refer to the distance from the station to a central business district (CBD) and whether the station is located in an urban center. The expectation is that stations closer to a CBD or in an urban center, which is normally better equipped with cycling facilities and metro systems, will encourage more bike-sharing use as well as bike-sharing–metro use. This expectation has been proven by several studies (e.g., Ji et al., 2017; Ma et al., 2018a; Gu et al., 2019b). Beyond the location factor, station attributes of daily ridership also affect people's mode choice of connecting to the railways. It has been suggested that bike-sharing usage is positively associated with metro ridership (Ma et al., 2015). That is, stations with a higher ridership usually have a greater potential demand for bike-sharing–metro use than other stations. In addition, transfer stations (stations where more than two metro lines intersect) are usually correlated with more entries, and thus, are able to elicit more transfer trips by bike-sharing from different directions (Ji et al., 2017; Ma et al., 2018b).

To conclude, bike-sharing–metro use is more likely to be concentrated in areas with higher employment density, whereas the effect of population density on integrated use remains unclear. Mixed land use is believed to increase the demand for feeder trips by bike-sharing, and residential, commercial, and educational areas attract many integrated uses. However, the impact of the distribution of POIs on integrated use is mixed (i.e., insignificant effects of leisure-, retail shopping-, and food-related locations, positive effects of parks, and negative effects of shopping malls). Additionally, having bicycle infrastructure within metro catchment areas is considered a reason for transferring via bike-sharing. Although urban roads support cycling, a local/major road with many intersections decreases metro users' willingness to choose bike-sharing as a feeder mode. Moreover, the appropriate density of metro stations, neither too dense or too scarce, makes bike-sharing attractive as a feeder mode of the metro. Generally speaking, metro users also prefer to transfer using bike-sharing in areas with an ample distribution of dock stations. However, public bus services around metro stations can reduce bike-sharing–metro use. As for the metro station itself, those that are near the CBD, have high ridership, or serve as transfer stations are believed to attract more bike-sharing–metro use than other stations.

3. Method

3.1. Study context and data

3.1.1. Study context

Located on the southern coast of China, Shenzhen is a special economic zone. In 2017, Shenzhen had a permanent population of 12.52 million and a total administrative area of 1997 km^2. The urban administrative system, with three hierarchies, includes 10 administrative districts (Qu), 56 sub-districts (Jiedao), and 695 neighborhoods (Juweihui) across the city. Shenzhen is also a multi-centric mega-city, with Nanshan district, Futian district, and Luohu district included as the downtown areas. In the "Master Plan of Shenzhen City (2010–2020)," Qianhai–Nanshan and Futian–Luohu are planned as two city centers within downtown (Shenzhen Government, 2010). Additionally, there are four first-level job centers in the urban space of Shezhen: High-tech Park, Bao'an Center, Futian CBD, and Caiwuwei CBD. Furthermore, another five sub-centers in suburban areas are planned as secondary job centers: Guangming, Longhua, Longgang, Yantian, and Pingshan (Fig. 1).

Over 40% of public transportation trips in Shenzhen are undertaken via the metro. Until the end of 2017, there were eight metro lines with a total length of 285 km and 166 metro stations across six administrative districts, with a daily ridership of 4.53 million. Overall, metro-covered areas are normally located in downtown areas, which have been developed relatively more in terms of transportation facilities, public service, and business coverage. On the other hand, job–housing spatial imbalances exist between downtown and suburban areas. Most job opportunities are concentrated around the four job centers mentioned above. However, due to the convenient transportation and high price of rent, workers tend to live in suburban areas. Therefore, tremendous traffic burdens

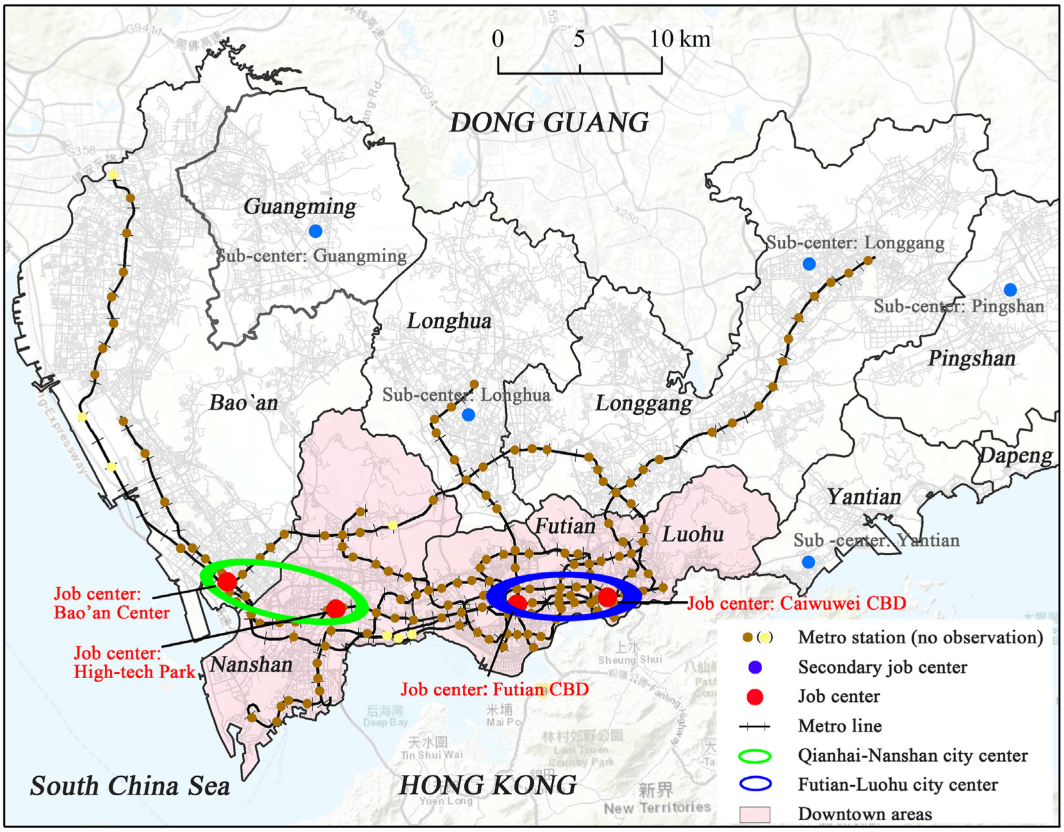

Fig. 1. Study area.

are imposed between the downtown and suburban areas with an early morning peak from 07:00 to 09:00 and a later evening peak between 17:30 and 19:30 (Shenzhen Traffic Police Bureau, 2017).

Shenzhen launched its first DBS program (Mobike) in September 2016, followed by the Ofo program in December of the same year. As of early 2018, approximately 900,000 DBS bikes have been put into use, with 20 million members. The Shenzhen government has implemented several transportation policies to manage DBS and guide integrated use. For instance, more bicycle lanes will be built, with a goal of providing an additional 600 km by the end of 2020, and more bicycle parking areas will be established around metro stations and bus stops.

3.1.2. Data

The bike-sharing data used in this study are from Ofo, one of the largest DBS operators in China. The 24-h location data (including ID, time, and X,Y location) of bikes were web-scraped from the Ofo online app with an interval time of 3–7 min. However, the data are static, which indicates the geographic location of a specific DBS bike had a unique ID associated with the web-scraping time. Within each time interval, there are approximately 220,000 static location data points across Shenzhen. Due to data limitations, we only selected data from three weekdays (September 26, 27, and 28, 2017) to address the potential day-to-day differences. The selected days were Tuesday, Wednesday, and Thursday, and the cloudy and sunny weather on these days was relatively suitable for cycling, with an average temperature ranging from 27 to 32 degrees Celsius. In some empirical studies, it was found that the daily use of DBS had consistent characteristics across the five weekdays (Horowitz, 2018; Tu et al., 2019; Yang et al., 2019). Therefore, we assume that the three days selected in our study are representative of DBS use on weekdays.

In terms of the data source, population and employment data were obtained from the traffic analysis zone (TAZ) shapefile provided by the Shenzhen Transport Committee and were then adjusted by metro catchment area. Spatial and vector data for urban roads (i.e., highway, main, and branch roads), dedicated bike lanes, bus facilities, and metro stations/lines were then extracted from OpenStreetMap (2017), which is a reputable open data source for road-related elements of the built environment (Winters et al., 2013; Mateo-Babiano et al., 2016; Zhao and Li, 2017). However, the data for POIs, including secondary schools, parks, public squares, restaurants, and shopping malls, were obtained from BaiduMap, using an API interface (BaiduMap, 2017) that is publicly available (Wu et al., 2019; Zhao et al., 2019). Land-use data were obtained from the 2016 land-use map from the Urban Planning, Land, and Resources Commission of Shenzhen. Moreover, the ridership data comprise the average daily ridership of metro stations in February 2018, taken from the monthly operation report of the Shenzhen Metro Company. Finally, the 2010 population census was used to capture the socioeconomic features of metro areas, and these features include gender, age, education, and rental status.

Note that, of the 166 total metro stations, 7 (Airport, Airport North, Bitou, Hongshuwan South, Shenwan, Shenzhen Bay Park, and Tanglang) are excluded because of no observed integrated use.[1]

3.2. Measuring the variables

3.2.1. Measuring the dependent variable: DBS–metro integrated use

The dependent variable was the average of DBS–metro integrated use at a metro station over three days. Unlike traditional docked bike-sharing, the integrated use of DBS was defined as the total number of valid uses of Ofo bikes within the "parking ring" near the metro station, a concept that we are proposing in this study. We define "parking ring" as the most plausible parking area around a metro station. This was calculated using a Kernel density approach by applying the extracted location data of bikes used within a 100-meter buffer of each metro station entrance (Fig. 2). Regarding the parameter settings, the search radius was 50 m, with a pixel size of one unit. By applying the nature break method, three classifications were obtained and marked as high, middle, and low areas, which account for 11.03%, 35.16%, and 53.81% of the 100-meter buffer area of the metro station entrance, respectively. Of these, the high and middle areas were combined to form the "parking ring" given the relatively high likelihood of parking bikes.

The processes for identifying integrated use are illustrated in Fig. 3. There were three main steps: 1) identify valid movement, 2) establish a parking ring for each metro station, and 3) obtain access-/egress-integrated use by extracting the origin and destination of a simulated trip route.

We separated the modeling of two types of integrated bike-sharing–metro use: access-integrated use and egress-integrated use. Due to the variance in integrated use during the morning peak hours (AM peak) and evening peak hours (PM peak), we estimated four models with the following dependent variables: 1) access-integrated use during the AM peak, 2) access-integrated use during the PM peak, 3) egress-integrated use during the AM peak, and 4) egress-integrated use during the PM peak.

Using the approach of the three-step identification, access- and egress-integrated uses were calculated at two peak times for three consecutive weekdays. The results in Table 1 indicate that access-integrated use during the morning peak is approximately 50% more than during the evening peak at an average level (19,412 compared to. 13,494), while egress-integrated use is very close at the two peak times (14,725 compared to 14,796). Additionally, access-integrated use, measured by the sum of the morning and evening peaks, is larger than egress-integrated use.

3.2.2. Measure of built environment variables and control variables

The built environment variables in this study were categorized into land use and transportation facilities, in accordance with existing research. In transportation studies, the 85th percentile value of the cumulative distribution of transfer distance is used to confirm the search radius or catchment area (e.g., Wang and Cao, 2017; He and Giuliano, 2018; Zuo et al., 2018). The 85% cumulative distributions of transfer distance in our study correspond to 1960 m for access trips and 2040 m for egress trips, based on which we chose 2000 m as the search radius to measure the built environment attributes surrounding metro stations.

The category of land use includes variables related to urban density, land-use patterns, and POIs. Specifically, for the urban density category, we included population and employment density, both of which are expected to encourage integrated use. We also included land-use mixture, which was calculated from nine land-use types (i.e., industry, commercial, residential, urban village, green, education, healthcare, office, and commercial). In addition, the percentage rates of several land-use patterns (including residential, office, commercial, and industrial) within the catchment areas of the metro stations were measured. It was anticipated that DBS–metro integrated use would tend to occur near residential communities and commercial areas. Moreover, we included only secondary schools as primary students under the age of 12 are not allowed to use DBS. The school effect on bike-sharing–metro integrated use may perhaps vary between the AM and PM peaks (Kim et al., 2012). Other POI variables include the number of parks and public squares, restaurants, and shopping locations within 2000 m of each metro station.

The variables related to transportation facilities were categorized into two minor groups: public transportation facilities and cycling/road services. In terms of the first group, the number of bus stops was considered because public buses compete with bike-sharing as a feeder mode. The number of metro stations counted within the catchment as well as the distance to the nearest metro station were measured to show the competition for integrated use between metro stations. Moreover, the length of a metro line in the metro catchment was also included in the model. For the second group of cycling and road services, dedicated bike lanes, which are explicitly designated for cycling and exclude motorized vehicles, were considered to explore the influence of cycling-related facilities on access/egress use. The number of street intersections per kilometer of branch and main roads were calculated separately, whereas the total length of highways within the catchment area was measured directly. The expectation was that the branch or main roads with many street intersections (e.g., grid-pattern urban roads) would impede the integration of DBS and the metro.

The control variables include two categories: the attributes of metro stations and the socioeconomic characteristics of the catchment area. As for the metro station attributes, the transfer distance to the metro station is one of the key factors affecting accessibility. In this study, transfer distance was measured under four scenarios, corresponding to morning access, morning egress, evening access, and evening egress. The transfer distance was aggregated at the metro station level by calculating the average

[1] Hongshuwan South, Bitou, Tanglang, and Shenwan stations are almost completely surrounded by commercial housing, which was still under construction until the end of 2019, and thus, no integrated use exists at these stations. Moreover, the entrances to the other stations are located either in a park (i.e., Shenzhen Bay Park station) or the airport (i.e., Airport and Airport North station), which results in a lack of integrated use during rush hour.

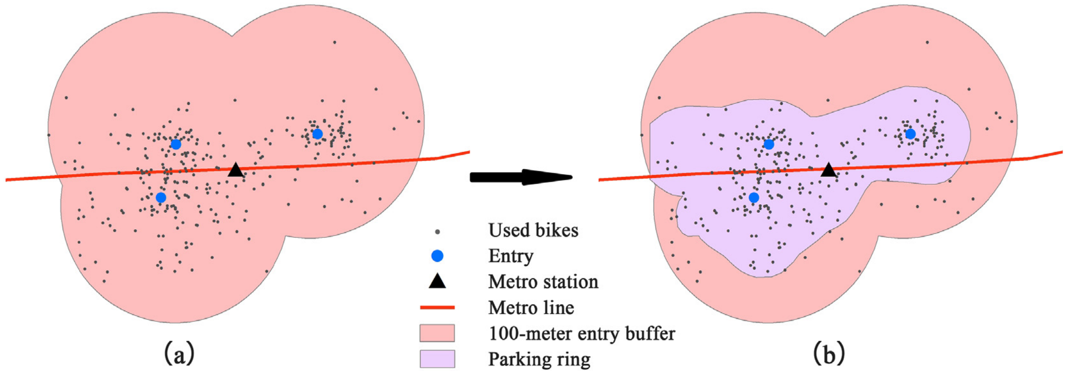

Fig. 2. (a) 100-meter entry buffer; (b) Parking ring.

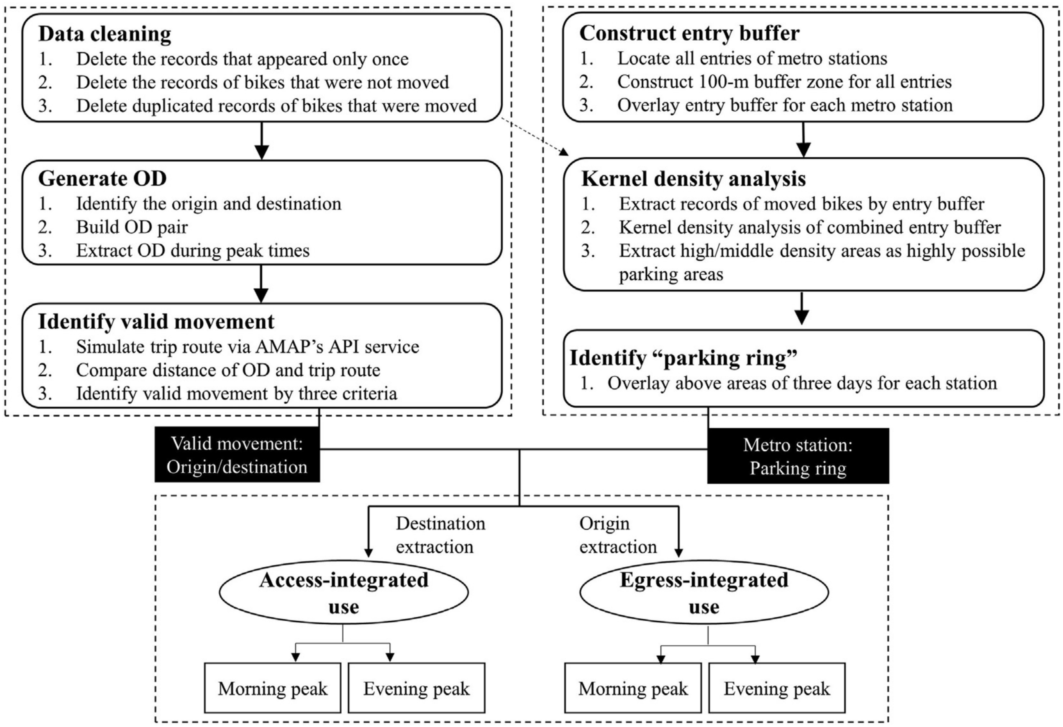

Fig. 3. Process for identifying integrated use.

Table 1
Summary of access- and egress-integrated use at two peak times.

Date	Access-integrated use		Egress-integrated use	
	Morning peak	Evening peak	Morning peak	Evening peak
Sep. 26	19,752	11,662	15,018	12,966
Sep. 27	19,003	14,660	14,412	16,032
Sep. 28	19,481	14,160	14,744	15,389
Average	19,412	13,494	14,725	14,796

simulated trip route distance of all integrated uses. In addition, the distances from the metro station to the nearest job center and the secondary job center were measured to indicate job accessibility at the city and regional levels, respectively. For metro ridership, the daily averages of both inbound and outbound ridership at each station were included, with correspondence to access and egress feeder trips from the metro, respectively. Furthermore, whether a station was a transfer station and the location of a metro station (suburban or not) were considered. In terms of the socioeconomic characteristics of the metro stations' catchment areas, we included

Table 2
Definition and descriptive analysis of the built environment variables and control variables (N = 159).

Variables	Description	Mean	Std.	Min	Max
Dependent Variables					
Access-integrated use (AM peak)	Access-integrated use of metro station during the AM peak	116.686	114.676	0	544
Egress-integrated use (AM peak)	Egress-integrated use of metro station during the AM peak	86.604	82.507	0	484
Access-integrated use (PM peak)	Access-integrated use of metro station during the PM peak	78.969	75.480	0	484
Egress-integrated use (PM peak)	Egress-integrated use of metro station during the PM peak	86.623	71.032	0	303
Built Environment					
Urban density					
Population density	Total population divided by area (thousand/km2)	15.026	12.013	2.864	53.953
Employment density	Employed people divided by area (thousand/km2)	16.369	10.785	2.036	52.199
Land use and POIs					
Land-use mixture	Mixture entropy of nine land-use patterns	0.811	0.058	0.638	0.904
Percent residential	The percentage of residential land (%)	53.624%	12.968%	17.808%	75.423%
Percent office	The percentage of office land (%)	5.515%	5.021%	0	19.170%
Percent commercial	The percentage of commercial land (%)	7.245%	3.935%	0.097%	20.833%
Percent industry	The percentage of industrial land (%)	18.753%	16.274%	0.030%	64.042%
Secondary school	Number of secondary schools	6.006	3.242	0	14
Park/public square	Number of parks and public squares	8.222	5.507	0	22
Shopping	Number of shopping malls and supermarkets	80.252	44.625	8	207
Restaurant	Number of restaurants	497.484	372.784	5	1564
Public Transportation facility					
Bus stop	Number of bus stops	175.025	64.324	18	330
Metro station	Number of metro stations	6.698	3.937	1	17
Distance to nearby station	Distance to the nearest metro station (km)	0.956	0.410	0.377	3.065
Metro line	Length of metro lines (km)	10.975	5.918	2.190	26.668
Cycling and road service					
Dedicated bike lane	Length of dedicated bike lanes (km)	11.123	9.289	0.036	43.940
Highway	Length of highway (km)	9.455	5.119	1.413	28.139
Intersection/main road	Number of street intersections divided by a main road (per km)	12.453	3.758	5.452	25.007
Intersection/branch road	Number of street intersections divided by a branch road (per km)	14.209	3.557	6.634	30.518
Control Variables					
Attributes of metro stations					
Transfer distance (AM access)	Average transfer distance of access trips in the morning (km)	1.102	0.338	0	2.526
Transfer distance (AM egress)	Average transfer distance of egress trips in the morning (km)	1.150	0.418	0	2.905
Transfer distance (PM access)	Average transfer distance of access trips in the evening (km)	1.132	0.385	0	2.587
Transfer distance (PM egress)	Average transfer distance of egress trips in the evening (km)	1.159	0.355	0	2.178
Distance to job center	Distance to the nearest job center (km)	5.669	5.847	0	26.544
Distance to the secondary job center	Distance to the nearest secondary job center (km)	12.089	4.452	1.1705	23.180
Ridership (outbound)	Daily outbound ridership of metro passengers (ten thousands)	1.361	1.153	0.040	8.030
Ridership (inbound)	Daily inbound ridership of metro passengers (ten thousands)	1.361	1.112	0.040	7.920
Transfer station	Dummy variable (1 = transfer station, 0 = other station)	16.981% (dummy = 1)			
Location (suburban)	Dummy variable (1 = suburban, 0 = downtown)	12.579% (dummy = 1)			
Socioeconomic characteristic of catchment areas					
Gender (% male)	Percentage of males (%)	52.714%	2.494%	45.904%	58.781%
Age (% under 30)	Percentage of people under 30 (%)	50.116%	6.493%	38.465%	70.260%
Education status (% without bachelor's)	Percentage of people who have less than a bachelor's degree (%)	70.461%	14.943%	32.488%	95.569%
Rental status (% renting)	Percentage of people who rent (%)	60.534%	18.313%	19.539%	94.577%

gender (% of males), age (% under 30), education status (% without a bachelor's degree), and rental status (% renting) in the model. These variables are measured by matching the sub-district with the associated metro station.

Several variables, such as the presence of a university and the number of hospitals and companies, were initially considered but subsequently excluded due to a lack of consistent data. Descriptive statistics of the variables are presented in Table 2.

3.3. Models

The dependent variable of integrated use comprises the number of access or egress trips (non-negative integer). We adopted the negative binomial model (Cameron and Trivedi, 1988) because our dependent variable is count data and there is a substantial proportion of zero entries in our dependent variable. The method is widely used to explore the effects of a built environment on bike-sharing use (Corcoran et al., 2014; Gebhart and Noland, 2014; Wang et al., 2016).

We selected Y_i as the dependent variable, and its value is $k \in \{0, 1, 2, 3, \cdots\}$, representing the counted number of DBS–metro uses at i station. We also selected $X_1, X_2, \cdots, X_n$ as the independent variables of the features of the built environment, station attributes, and socioeconomic characteristics. $Pr(Y_i = k)$ is the probability that the counted number of integrated uses is equal to k, given the independent variables $X_1, X_2, \cdots, X_n$. Accordingly, the negative binomial regression model considered in this study has the following form:

$$\Pr(Y_i = k \mid X_1, X_2, \cdots, X_n) = \frac{\Gamma(k+\frac{1}{\alpha})}{\Gamma(k+1)\Gamma(\frac{1}{\alpha})}\left(\frac{\frac{1}{\alpha}}{\frac{1}{\alpha}+\lambda}\right)^{\frac{1}{\alpha}}\left(\frac{\lambda}{\frac{1}{\alpha}+\lambda}\right)^{y_i}, y_i = 0, 1, 2, 3\cdots \tag{1}$$

where,

$$\lambda = E(Y_i) = \exp(\beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_n X_n + \varepsilon), n = 1, 2, 3, \cdots, n \tag{2}$$

where $\exp(\varepsilon)$ has a gamma (Γ) distribution with mean 1, and variance α ($\alpha \geq 0$) is the dispersion parameter. The variance is given by formula (3), which allows for overdispersion.

$$Var(Y_i) = \lambda + \alpha\lambda^2 \tag{3}$$

In accordance with the four dependent variables of morning access-integrated use, morning egress-integrated use, evening access-integrated use, and evening egress-integrated use, four negative binomial regression models were developed accordingly.

In addition, to explore the impact of the uneven distribution of public transportation facilities on integrated use, the models also examine several interaction terms of public transportation facilities and location variables. To avoid the multicollinearity problem, the variance inflation factor (VIF) value of the selected explanatory variables was calculated. By following the rule of thumb (Kutner et al., 2004), variables with VIF larger than 10 were excluded from the model (i.e., restaurant, metro line, and distance to the secondary job center).

4. Results and analysis

4.1. Spatial and temporal variation of DBS–metro use

Daily access- and egress-integrated use are illustrated in Fig. 4. It is evident that there are two wave peaks during the day for both access- and egress-integrated use, with the highest peak at approximately 08:00 and another at approximately 06:30. Before 06:00, very little integrated use occurs, possibly due to occasional uses of DBS that occur near the metro station. Beyond the two peak times (07:00–09:00 and 17:30–19:30), there is still a non-negligible number of integrated uses in the middle of the day and after 21:00. Another interesting finding is that egress use during the AM peak has a one-hour delay of access use, while there is a 45-mins delay

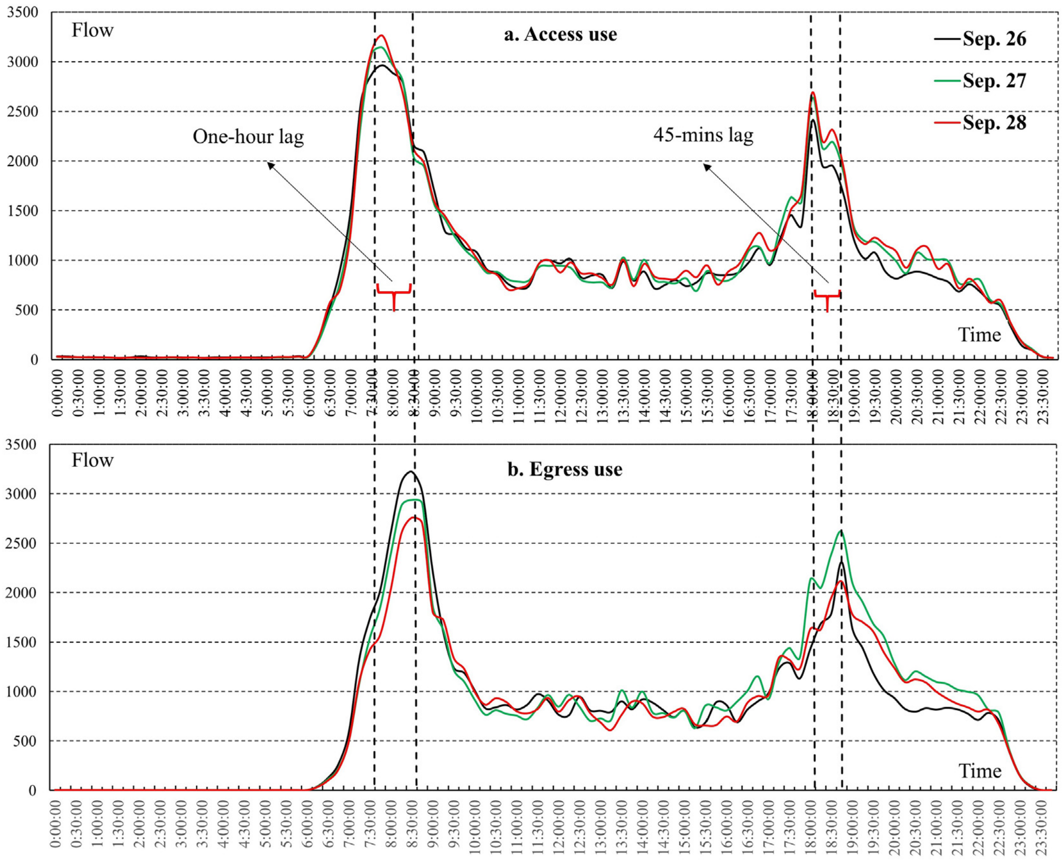

Fig. 4. Dynamics of access and egress use: 24-h changes on Sep. 26, 27, and 28.

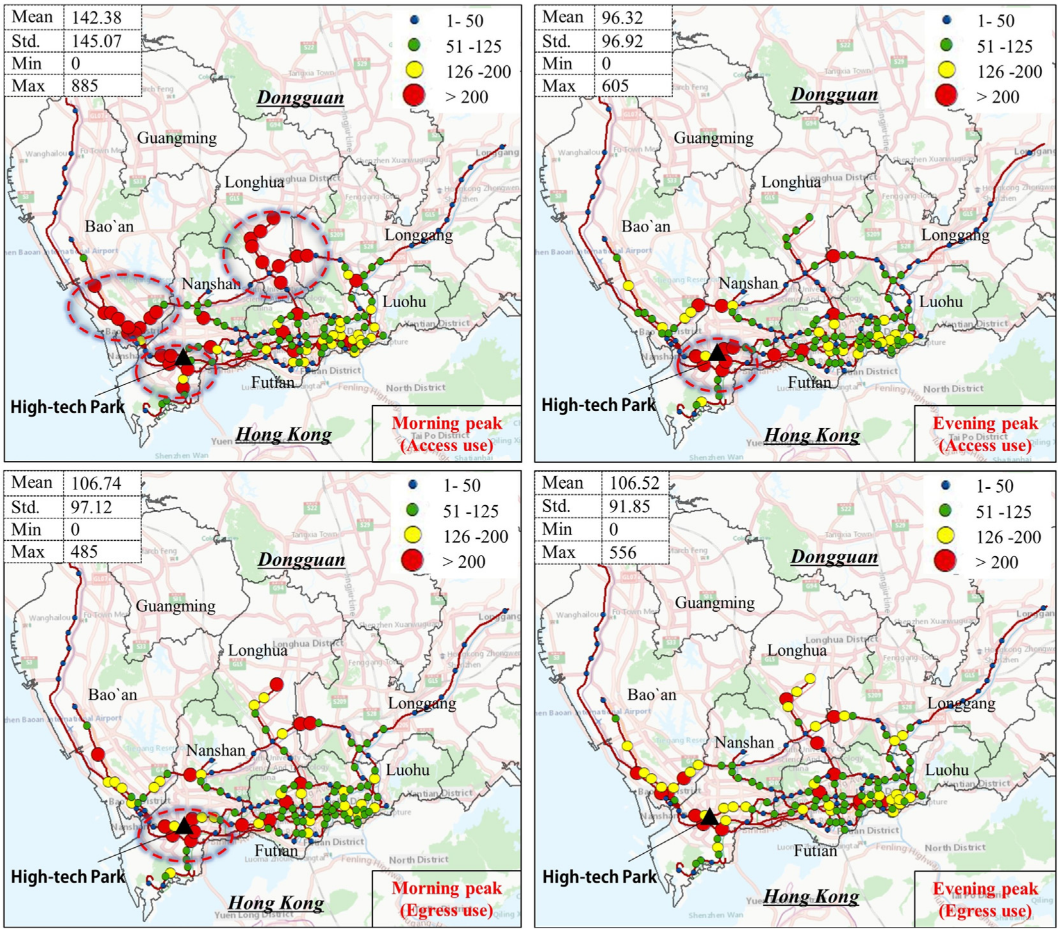

Fig. 5. Distribution of access-/egress-integrated uses during the AM and PM peaks.

during the PM peak. This indicates that metro travel time during the AM peak is approximately one hour on average, while during the PM peak, it is 45 min.

With the aggregation of integrated use by metro stations, Fig. 5 illustrates the spatial distribution of access- and egress-integrated use during the two peak times and the statistical description. Statistically, access use during the AM peak is approximately 50% higher than the PM peak, but egress use during the morning and PM peaks are relatively close at the average level. The distribution indicates that very few integrations of DBS and the metro are adopted by commuters in exurban areas covered by few metro stations, including west of Bao'an district and east of Longgang district. By contrast, the suburban areas where residential communities are dominant attract a large amount of integrated use (i.e., south of Bao'an district and south of Longhua district). It is notable that, of the four job centers, a great deal of integrated use only occurs near High-tech Park and not at Bao'an Center, Caiwuwei CBD, or Futian CBD. This is possibly correlated with the density of metro stations in these four areas. At High-tech Park, as Fig. 5 illustrates, the metro system is not much less densely distributed than at the other three job centers. Thus, there is less competitiveness with the nearby metro stations at High-tech Park, thereby increasing its integrated use rates.

Access uses are highly concentrated during the AM peak in suburban areas that are close to job centers. High-tech Park in Nanshan district, which is agglomerated with a large number of high-tech companies, is the only hotspot region during the PM peak. As for egress-integrated use, spatial distribution tends to be less concentrated during the AM peak, with the exception of High-Tech Park. The features of high access-integrated use in suburban areas and high egress-integrated use at High-tech Park during the AM peak indicate a spatial imbalance between job–housing allocations. In Shenzhen, the well-known Nanshan High-tech Park has created nearly 300,000 jobs within an 11.5 km^2 area, attracting thousands of companies. However, the high rent in employment centers has forced people to live further afield, such as in southern Bao'an district or southern Longhua district.

4.2. Modeling results

After including all of the variables in the negative binomial regression analysis, the modeling results for the relationship between the built environment and integrated use during the AM and PM peaks are presented in Table 3. The overdispersion parameters α in

Table 3
Modeling results of negative binomial regression.

Variables	Morning				Evening			
	Access use		Egress use		Access use		Egress use	
	Coef.	*p*	Coef.	*p*	Coef.	*p*	Coef.	*p*
Built Environment								
Urban density								
Population density	0.004	0.791	0.009	0.466	0.004	0.750	0.001	0.904
Employment density	**−0.048***	0.097	0.008	0.778	0.026	0.346	−0.002	0.935
Land use and POIs								
Land use mixture	3.253	0.103	**4.465****	0.019	**3.080***	0.082	2.329	0.170
Percent residential	**2.666***	0.093	1.483	0.345	−0.012	0.994	1.141	0.430
Percent office	4.431	0.161	4.222	0.178	2.777	0.332	0.771	0.780
Percent commercial	3.545	0.177	2.984	0.217	2.042	0.361	3.640	0.117
Percent industry	2.830	0.105	**3.960****	0.021	**2.727***	0.081	2.182	0.146
Secondary school	−0.023	0.636	−0.046	0.345	−0.016	0.725	−0.014	0.756
Park/public square	**0.045****	0.044	**0.063*****	0.004	**0.069*****	0.001	**0.036***	0.061
Shopping	0.003	0.550	0.001	0.866	0.003	0.530	−0.001	0.854
Public Transportation facility								
Bus stop	**0.010*****	0.006	**0.006***	0.079	0.001	0.761	**0.007****	0.015
Bus × suburban	−0.014	0.126	**−0.048*****	0.009	−0.016	0.262	**−0.024****	0.036
Metro station	−0.034	0.541	**−0.130****	0.012	**−0.084***	0.066	−0.024	0.608
Metro × suburban	0.359	0.600	0.702	0.328	−0.534	0.406	0.045	0.950
Distance to nearby station	**−0.925****	0.036	−0.495	0.233	**−1.001****	0.013	**−1.051*****	0.007
Cycling and road service								
Dedicated bike lane	0.019	0.164	0.019	0.166	**0.023***	0.077	**0.026****	0.038
Highway	0.021	0.324	0.014	0.486	0.013	0.480	0.025	0.169
Intersection/main road	**−0.117*****	0.002	**−0.095*****	0.006	**−0.112*****	0.000	**−0.125*****	0.000
Intersection/branch road	−0.030	0.282	−0.023	0.392	−0.017	0.480	−0.003	0.904
Control Variables								
Attributes of metro stations	**−0.425***	0.097	**−0.482****	0.024	−0.056	0.806	**−0.569***	0.014
Distance to job center	−0.042	0.324	**−0.079***	0.064	**−0.095****	0.017	−0.028	0.452
Ridership	**0.375*****	0.001	**0.247****	0.011	**0.258*****	0.003	**0.359*****	0.000
Transfer station	−0.039	0.851	−0.172	0.386	−0.089	0.627	−0.120	0.512
Location (suburban)	−2.219	0.219	−0.154	0.939	0.044	0.982	−1.126	0.564
Socioeconomic characteristics of catchment areas								
Gender (% of males)	2.894	0.700	−8.212	0.232	−4.290	0.504	−1.169	0.858
Age (% under 30)	3.140	0.284	**5.009***	0.073	**4.703***	0.066	**4.291***	0.092
Education status (% without a bachelor's)	0.272	0.832	−1.367	0.254	−1.375	0.203	−0.859	0.437
Rental status (% renting)	0.182	0.856	0.673	0.453	0.165	0.837	−0.138	0.869
constant	−2.540	0.598	2.788	0.533	3.457	0.402	1.563	0.705
α	**0.385*****	0.000	**0.344*****	0.000	**0.283*****	0.000	**0.284*****	0.000
log-*likelihood*	−573.213		−537.802		−524.244		−531.910	
Pseudo R2	0.119		0.136		0.148		0.144	

Note: ***$p < 0.01$; **$p < 0.05$; *$p < 0.1$.

each model are all significantly different from 0. This indicates that an overdispersion exists in our data and that we should use the negative binomial model.

4.2.1. Effects of land use: Urban density, land-use types, and POIs

The results in Table 3 demonstrate that population density is not a significant factor, which is consistent with the findings of some previous studies (Ji et al., 2017; Zhao and Li, 2017; Lin et al., 2018; Ma et al., 2018a). However, employment density is negatively related to access-integrated use during the AM peak (similar to the findings of Ma et al., 2018a). One of the possible reasons for this unexpected association might be that areas with dense employment may be associated with few residences, thereby generating few demands for access-integrated uses (most such uses being from home to a metro station) during the AM peak.

Mixed land use is found to be positively associated with morning egress-integrated use and evening access-integrated use. It shows that, compared to residential locations, mixed land use of metro areas could result in more short trips between employment locations and metro stations, thereby facilitating DBS–metro use. Table 3 also indicates that residential land use in the catchment area is positively associated with the rate of access-integrated use during the AM peak. This suggests that commuters are more likely to use DBS from home to a metro station for the first segment of their trip. The result supports the aforementioned statement on employment density. This also explains why operators always distribute DBS bikes around residential communities early in the morning, making it convenient for residents traveling to a metro station (access-integrated use).

For industrial land use, the results demonstrate that integrated use increases where there is a higher percentage of industrial land, that is, areas where many manufacturing factories are concentrated. In many suburban areas of Shenzhen, there are still many factories producing electronic products, and these are labor-intensive enterprises. To compensate for the low salary they receive from these factories, most workers live in dormitories provided by the factory to avoid high housing rents, and thus, this allows them to save money despite the poor living conditions (i.e., eight workers per room). For these workers, there are few demands for access-integrated use during the AM peak because they live at their workplaces. Beyond the workers living in factory dormitories, some workers prefer to rent houses outside of the factories for which they are entitled to a small subsidy from the factories. By sharing rooms (2–3 people), they can obtain better living conditions than in the factory dormitories, even though it is more expensive. These workers contribute to egress use during the AM peak when they go to work as well as to the access use during the PM peak when they return home.

The number of parks and public squares is positively related to the choice of DBS for cycling to or from a metro station during the AM and PM peaks, and this corroborates the findings reported by Zhao and Li (2017). As the number of parks and public squares around the metro station increases, the likelihood of transferring by DBS also increases. One of the primary reasons is that DBS–metro users may cycle through the park to avoid traffic and traffic lights. Also, public squares around the metro station provide cyclists with an open space for cycling, thereby making the transfer trips convenient, quick, and safe. This result suggests that creating more green and open space in the catchment areas of metro stations may facilitate more access- and egress-integrated use by DBS.

4.2.2. Effects of transportation facilities: Public transportation and cycling/road services

Among the public transportation facility factors included, the number of bus stops in metro areas positively affects the role of DBS as the feeder mode for the metro. It was not our expectation that public buses would generally play a substitution role for bike-sharing (Fishman et al., 2014; Martin and Shaheen, 2014). However, as the number of bus stops in the catchment increases, buses must stop and pick up passengers more frequently, resulting in increased waiting times for passengers. Moreover, greater availability because of an increase in the number of bus stops leads to more commuters taking public buses directly to their destinations, which then makes the public bus more crowded. Therefore, the negative benefits of increasing the number of bus stops (i.e., increasing wait time and increasing crowdedness) make public buses less attractive or even motivates some bus–metro integrated users to become DBS–metro users. However, in suburban areas where public bus services and metro systems are not well developed, public buses still play a significant role in the substitution of the integrated use as expected but only of the egress-integrated type.

Another interesting finding is that the number of metro stations within the catchment area negatively affects integrated use, possibly at the workplace (i.e., egress-integrated use during the AM peak and access-integrated use during the PM peak). This is possibly related to the competitiveness between DBS and walking as a metro feeder mode. Some empirical studies have suggested a moderate range of cycling distance in urban China: 0.8–1.5 km in Shanghai and 1–3 km in Beijing (Pan et al., 2010; Zhao and Li, 2017). This means that walking replaces cycling when the distance is less than the lower value, whereas taking a taxi or bus are alternatives when the distance is greater than the upper value. Therefore, an increase in the number of metro stations in areas with an already dense metro system might result in walking outperforming DBS because of the decreased transfer distance. This negative relationship is particularly significant at job centers, which are associated with many integrated trips connecting to workplaces. The insignificant interaction term of metro station by location (suburban) also supports this assumption indirectly. That is, the change in metro station density in suburban areas, where the metro system is not well developed, will not affect integrated use. Additionally, a denser distribution of metro stations also may mean a closer proximity of nearby metro stations, further increasing the competitiveness between two close metro stations because they may serve a large part of the same catchment area. The negative association between integrated use and the distance to a nearby station in Table 3 demonstrates this assumption. In Shenzhen, the average distance to a nearby metro station is 976 m, indicating a high metro coverage throughout the urban space. Therefore, increasing the number of metro stations, particularly in the areas with an already densely distributed metro system, not only reduces the transfer distance but also further decreases the average distance to nearby stations, thereby decreasing demand for DBS–metro integration.

In relation to the cycling infrastructure and road services, dedicated bike lanes can promote integrated use during the PM peak, instead of the AM peak. This is possibly because some private cars usually illegally park on the dedicated bike lane for a whole night until the next morning (Zhao and Li, 2017). Another reason could be the popularity of the motorcycle taxi (one type of vehicle for carrying one or two passengers) in the suburban areas of Shenzhen. Motorcycle taxi drivers usually pick up and drop off passengers around metro stations in the morning, and they also prefer to ride on the dedicated bike lanes and sidewalks (Xu, 2010). As a result, dedicated bike lanes are not exclusively used by bicycles but are occupied by cars and motorcycle taxis, thereby weakening metro users' willingness to engage in DBS–metro integrated usage. Table 3 also illustrates that the main roads with many street intersections are negatively associated with DBS–metro integrated use, whereas branch roads are unrelated. This is because intersections along the main roads (e.g., grid-pattern streets) are usually equipped with traffic lights, and hence, cyclists must stop and wait. As for branch roads, it is relatively easy for cyclists to cycle through the intersection without stopping or slowing down.

4.2.3. Effect of station attributes and socioeconomic characteristics

Three of the four station attributes considered had a significant impact on integrated use: transfer distance, distance to job center, and ridership. As expected, transfer distance is negatively associated with DBS–metro use. This suggests that, within a distance range of 2000 m from metro stations, metro users usually prefer to transfer within a relatively shorter distance because it is less physically exhausting. The access-integrated rate during the AM peak and the egress-integrated rate during the PM peak are expected to decrease when the station is farther from the job center, as indicated by the negative coefficient of the distance to job center variable. By contrast, stations with a larger total ridership per day are more likely to have higher access- and egress-integrated uses during the two peak times. It is easy to understand that more people commuting by metro leads to a higher likelihood of integrated use. Therefore, it is safe to speculate a co-location hypothesis (Levinson and Kumar, 1994), indicating the close relationship between ridership and rate of integrated use for a metro station. The regression results in Table 3 also illustrate that, among several of the socioeconomic features of a catchment area, only age was related to integrated rates. A metro station with a high ratio of people under 30 in its catchment areas has a higher demand for integrated use than other metro stations. This is because, compared to older people, younger people prefer cycling (Martens, 2007).

5. Conclusion and policy recommendations

As a promising path towards urban sustainability, bike-sharing is being embraced by cities across the globe. With the ability to improve the transportation sector by reducing its environmental impact, relieving congestion, and increasing physical activity without sacrificing accessibility, the integration of DBS and metro transit could be a way to achieve efficient and sustainable urban transport. This study contributes to the bike-sharing literature by exploring the effect of the built environment on bicycle–metro integration with a focus of DBS programs as well as comparing the effects of the first and last mile at peak hours. By focusing on the Ofo program in Shenzhen, we reveal a number of findings, summarized in the following paragraphs.

(1) There are two evident peaks for DBS–metro integrated use throughout a day, and the egress-integrated uses gave a one-hour and 45-mins lag in access-integrated use during the AM and PM peaks separately. Furthermore, access use is concentrated in periphery areas that are close to job centers during the AM peak, while the job center at High-tech Park attracts a considerable degree of access-integrated use during the PM peak and egress-integrated use during the AM peak.
(2) Areas with higher levels of employment usually have less access-integrated use during the AM peak. Mixed land use generates integrated use during peak times; residential land use can attract access-integrated use during the AM peak, and a higher share of industrial land use around metro stations also encourages factory workers to connect to metro stations and factories with DBS. Furthermore, parks and public squares are positively associated with both access- and egress-integrated use during peak times.
(3) Transportation-related built environment features significantly affect DBS–metro integrated use. Increasing the number of public bus stops results in some negative effects, such as increasing crowdedness and wait times. Thus, bus–metro users are motivated to become DBS–metro users, particularly in downtown areas. The coverage of metro stations should be moderate to cater to transfer trips via cycling, but empirical evidence from Shenzhen demonstrates that as the number of metro stations in close proximity to one another increase, the less likely it is that transit users will select DBS as their feeder mode. Dedicated bike lanes are a facilitating factor for integrated use during the PM peak, while main roads with many street intersections make transfer trips by DBS less attractive.
(4) Transfer distance plays a crucial and negative role in determining integrated use. However, metro stations with a higher ridership are more likely to have more seamless integration with DBS, whereas those stations that are closer to job centers are associated with a higher demand for integrated use from or to workplaces. Moreover, metro areas with more younger people also have a greater demand for integrated use.

These findings have important policy and operation implications both for governments and operators. First, the rebalance issue across time variation and urban space is crucial for a more seamless connection between DBS and transit, which is also true for traditional bike-sharing (Mateo-Babiano et al., 2016). Although the free-floating feature of DBS could contribute to a metro–home/workplace balance on the micro-scale, operators should still pay attention to the temporal–spatial imbalance at the city level. The job–housing imbalance characteristic and population movement throughout a day indicate that a reasonable increase in DBS is necessary, with a focus on residential/employment locations to cater to the great demand for access- and egress-integrated use. Importantly, rebalance strategies for these metro stations need to consider whether the station is close to the four job centers in Shenzhen and take ridership into account. To make the strategies more efficient, it is better to concentrate more bikes at the metro station near job centers. Additionally, allocating more bikes near metro stations with high ridership is also suggested.

Second, the proper distribution of urban land use can encourage DBS–metro use by spatial means. In particular, operators should cater to transit users by providing more bike-sharing at a relatively fixed time and sites near residential communities during AM peak, although DBS bikes cannot generally enter residential communities in urban China. Regular reallocation and visible parking sites around residential communities during peak times reduces the search time for bikes. Another possible strategy for improving integrated use is to add DBS around factories (i.e., around factory entrance gates and dormitories) as well as around metro stations close to these factories. This will be helpful and allow workers to find bikes quickly and ride them towards or away from metro stations. Considering the role that green/open spaces play in promoting cycling during peak times, we suggest that some bikes be added at parks and public squares near metro stations.

Third, the allocation of DBS bikes must be in accordance with the moderate distribution of public transportation in an urban space to achieve seamless DBS–metro integration. In central urban areas where bus stops are dense, increasing the number of bus stops will induce bus–metro users to become DBS–metro users, whereas the same strategy encourages more commuters to become bus–metro users in suburban areas with poorer public facilities. That is, public buses are more attractive than DBS in terms of serving as a feeder mode for suburban areas. Therefore, it is helpful for operators to locate bikes with some priorities across urban space by considering the competitiveness of public buses. When metro system coverage increases, particularly in downtown areas, the competition effect among metro stations will begin to manifest and the walking mode will also begin to replace DBS for connecting to metro stations. Thus, when allocating bikes, bike-sharing operators should take the density of metro stations into account. They should avoid distributing too many bikes in areas that already have many metro stations, while we suggest distributing bikes in places with a moderate density of metro stations.

Fourth, it is important that a bicycle-friendly environment be established for feeder trips to and from metro stations by improving the distribution and condition of urban roads. This study indicates that bike lanes play a positive role in facilitating DBS–metro integration. However, Shenzhen still lacks sufficient bikeways along urban roads, and many cyclists (including DBS users) ride bikes on shared sidewalks or even on motorized vehicle lanes. This is very dangerous, with the potential for injuries, particularly during peak hours. Compared with installing more dedicated bike lanes along arterial roads specifically, a strategy of diverse bikeways, such as shared bike lanes, on-road bike lanes, and informal on-road bike lanes (Mateo-Babiano et al., 2016), is more suitable for Shenzhen due to its relatively limited road space. Moreover, improving the road conditions and connection of bikeways along main roads with fewer intersections is essential. Not only that, much attention should also be paid to the issue of safety on the bikeways due to the potential for collisions with pedestrians and vehicles, particularly during peak times. Another suggestion is to add cycling signs along feeder routes to or from metro stations to offer an improved cycling environment.

This research has a number of limitations. Only three days of parking location data for DBS were applied, which means that the results cannot fully represent the full characteristics of DBS–metro use for every weekday. The results also may lack details regarding the variance of integrated use between weekdays and weekends, and the approach for identifying integrated uses has some room for improvements. In addition, we did not consider impacts at the individual level, which is also crucial for mode choice. Therefore, this research could be extended by applying a longer period of parking record data to reveal the variance of integrated use across a week, a month, or even a year, discussing the impact of the built environment with a time series. Further research into the association between the built environment and DBS–metro use might focus on self-selection and attitudinal factors.

CRediT authorship contribution statement

Yuanyuan Guo: Conceptualization, Methodology, Formal analysis, Data curation, Writing - original draft, Writing - review & editing, Visualization, Funding acquisition. **Sylvia Y. He:** Supervision, Conceptualization, Methodology, Writing - review & editing.

Acknowledgments

This study is supported by the Peking University-Lincoln Institute Dissertation Scholarship, granted to the first author. We would like to thank Wenke Huang from Shenzhen University for his research assistance.

References

BaiduMap, 2017. Available at: http://lbsyun.baidu.com.
Boarnet, M.G., Crane, R., 2001. The influence of land use on travel behavior: specification and estimation strategies. Transp. Res. Part A: Policy Pract. 35 (9), 823–845.
Cameron, A.C., Trivedi, P.K., 1988. Regression Analysis of Count Data. Cambridge Press, New York.
Cervero, R., 2002. Built environments and mode choice: toward a normative framework. Transp. Res. Part D: Transp. Environ. 7, 265–284.
Cervero, R., Caldwell, B., Cuellar, J., 2013. Bike-and-ride: "Build it and they will come". J. Public Transp. 16, 83–105.
Cervero, R., Kockelman, K., 1997. Travel demand and the 3Ds: density, diversity, and design. Transp. Res. Part D: Transp. Environ. 2, 199–219.
Chandra, S., Quadrifoglio, L., 2013. A model for estimating the optimal cycle length of demand responsive feeder transit services. Transp. Res. Part B: Methodol. 51, 1–16.
Corcoran, J., Li, T., Rohde, D., Charles-Edwards, E., Mateo-Babiano, D., 2014. Spatial-temporal patterns of a Public Bicycle Sharing Program: the effect of weather and calendar events. J. Transp. Geogr. 41, 292–305.
Ding, W., 2016. The Relationship of Built Environment and Weather with Bike Share – Evidence from the Pronto Bike Share System in Seattle. Master's thesis. University of Washington, Seattle.
El-Assi, W., Mahmoud, M.S., Habib, K.N., 2017. Effects of built environment and weather on bike sharing demand: a station level analysis of commercial bike sharing in Toronto. Transportation 44 (3), 589–613.
Faghih-Imani, A., Eluru, N., El-Geneidy, A.M., Rabbat, M., Haq, U., 2014. How land-use and urban form impact bicycle flows: evidence from the bicycle-sharing system (BIXI) in Montreal. J. Transp. Geogr. 41, 306–314.
Faghih-Imani, A., Eluru, N., 2016. Incorporating the impact of spatial-temporal interactions on bicycle sharing system demand: a case study of the New York CitiBike system. J. Transp. Geogr. 54, 218–227.
Faghih-Imani, A., Eluru, N., 2017. Examining the impact of sample size in the analysis of bicycle-sharing systems. Transp. A: Transp. Sci. 13, 139–161.
Faghih-Imani, A., Hampshire, R., Marla, L., Eluru, N., 2017. An empirical analysis of bike sharing usage and rebalancing: evidence from Barcelona and Seville. Transp. Res. Part A: Policy Pract. 97, 177–191.
Fishman, E., Washington, S., Haworth, N., 2014. Bikeshare's impact on active travel: evidence from the United States, Great Britain, and Australia. J. Transp. Health 2 (2), 135–142.
Flamm, B.J., 2013. Determinants of bicycle-on-bus boardings: a case study of the Greater Cleveland RTA. J. Public Transp. 16, 67–84.
Gebhart, K., Noland, R.B., 2014. The impact of weather conditions on bikeshare trips in Washington, DC. Transportation 41, 1205–1225.
Griffin, G.P., Sener, I.N., 2016. Planning for bike share connectivity to rail transit. J. Public Transp. 19, 1–22.
Gu, T., Kim, I., Currie, G., 2019a. To be or not to be dockless: empirical analysis of dockless bikeshare development in China. Transp. Res. Part A: Policy Pract. 119, 122–147.
Gu, T., Kim, I., Currie, G., 2019b. Measuring immediate impacts of a new mass transit system on an existing bike-share system in China. Transp. Res. Part A 124, 20–39.
Handy, S.L., Boarnet, M.G., Ewing, R., Killingsworth, R.E., 2002. How the built environment affects physical activity: views from urban planning. Am. J. Prev. Med. 23, 64–73.
He, S.Y., 2011. The effect of school quality and residential environment on mode choice of school trips. Transp. Res. Rec. J. Transp. Res. Board 2213, 96–104.
He, S.Y., Giuliano, G., 2018. School choice: understanding the trade-off between travel distance and school quality. Transportation 45, 1475–1498.
Horowitz, N., 2018. Sustaining DBS based on Business Principles. Master's thesis. New Jersey Institute of Technology, New Jersey.
Ji, Y., Fan, Y., Ermagun, A., Cao, X., Wang, W., Das, K., 2017. Public bicycle as a feeder mode to rail transit in China: the role of gender, age, income, trip purpose, and bicycle theft experience. Int. J. Sustain. Transp. 11, 1–23.
Keijer, M.J.N., Rietveld, P., 2000. How do people get to the railway station? The Dutch experience. Transp. Plan. Technol. 23, 215–235.
Kim, D., Shin, H., Im, H., Park, J., 2012. Factors influencing travel behaviors in bikesharing. In: 91st Annual Meeting of the Transportation Research Board, Washington, DC.
Krizek, K., Stonebraker, E., 2010. Bicycling and transit a marriage unrealized. Transp. Res. Rec. J. Transp. Res. Board 2144, 161–167.
Kutner, M.H., Nachtsheim, C.J., Neter, J., 2004. Applied Linear Regression Models, fourth ed. McGraw-Hill, Irwin.

Lee, J., He, S.Y., Sohn, D.W., 2017. Potential for converting short car trips to active trips: the role of the built environment in tour-based travel. J. Transp. Heal. 7, 134–148.
Levinson, D.M., Kumar, D., 1994. The rational locator: why travel times have remained stable. J. Am. Plan. Assoc. 60 (3), 319–332.
Lin, J., Zhao, P., Takada, K., Li, S., Yai, T., Chen, C., 2018. Built environment and public bike usage for metro access: a comparison of neighborhoods in Beijing, Taipei, and Tokyo. Transp. Res. Part D: Transp. Environ. 63, 209–221.
Ma, T., Liu, C., Erdoğan, S., 2015. Bicycle sharing and transit: does Capital Bikeshare affect Metrorail ridership in Washington, D.C.? Transp. Res. Rec. J. Transp. Res. Board 2534, 1–9.
Ma, X., Ji, Y., Jin, Y., Wang, J., He, M., 2018a. Modeling the factors influencing the activity spaces of bikeshare around metro stations: a spatial regression model. Sustain. 10, 3949.
Ma, X., Ji, Y., Yang, M., Jin, Y., Tan, X., 2018b. Understanding bikeshare mode as a feeder to metro by isolating metro-bikeshare transfers from smart card data. Transp. Policy 71, 57–69.
Martens, K., 2004. The bicycle as a feedering mode: experiences from three European countries. Transp. Res. Part D: Transp. Environ. 9 (4), 281–294.
Martens, K., 2007. Promoting bike-and-ride: the Dutch experience promoting bike-and-ride. Transp. Res. Part A: Policy Pract. 41, 326–338.
Martin, E.W., Shaheen, S.A., 2014. Evaluating public transit modal shift dynamics in response to bikesharing: a tale of two U.S. cities. J. Transp. Geogr. 41, 315–324.
Mateo-Babiano, I., Bean, R., Corcoran, J., Pojani, D., 2016. How does our natural and built environment affect the use of bicycle sharing? Transp. Res. Part A: Policy Pract. 94, 295–307.
Midgley, P., 2011. Bicycle-sharing Schemes: Enhancing Sustainable Mobility in Urban Areas. United Nations, Department of Economic and Social Affairs.
OpenStreetMap, 2017. Available at: http://www.openstreetmap.org.
Pan, H., Shen, Q., Xue, S., 2010. Intermodal transfer between bicycles and rail transit in Shanghai, China. Transp. Res. Rec. J. Transp. Res. Board 2144, 181–188.
Rixey, R.A., 2013. Station-level forecasting of bikesharing ridership. Transp. Res. Rec. J. Transp. Res. Board 2387, 46–55.
Shaheen, S.A., Guzman, S., Zhang, H., 2010. Bikesharing in Europe, the Americas, and Asia. Transp. Res. Record: J. Transp. Res. Board 2143, 159–167.
Shenzhen Government, 2010. The Master Plan of Shenzhen (2010–2020). Available at: http://pnr.sz.gov.cn/ywzy/ghzs/201710/t20171024_443924.html.
Shenzhen Traffic Police Bureau, 2017. What is the Restriction Time of Non-Shenzhen License Plate Vehicle? Available at. http://szjj.sz.gov.cn/YWZSK/TXZZS/201711/t20171128_11792233.htm.
Tran, T.D., Ovtracht, N., Faivre, B., 2015. Modeling bike sharing system using built environment factors. Procedia CIRP 30, 293–298.
Tu, Y., Chen, P., Gao, X., Yang, J., Chen, X., 2019. How to make dockless bikeshare good for cities: curbing oversupplied bikes. Transp. Res. Record: J. Transp. Res. Board 2673, 618–627.
Wang, J., Cao, X., 2017. Exploring built environment correlates of walking distance of transit egress in the Twin Cities. J. Transp. Geogr. 64, 132–138.
Wang, X., Lindsey, G., Schoner, J.E., Harrison, A., 2016. Modeling bike share station activity: the effects of nearby businesses and jobs on trips to and from stations. J. Urban Plan. Dev. 142, 1–9.
Winters, M., Brauer, M., Setton, E.M., Teschke, K., 2013. Mapping bikeability: a spatial tool to support sustainable travel. Environ. Plan. B Plan. Des. 40, 865–883.
Wu, X., Lu, Y., Lin, Y., Yang, Y., 2019. Measuring the destination accessibility of cycling transfer trips in metro station areas: a big data approach. Int. J. Environ. Res. Public Health 16, 2641.
Xu, J., 2010. Motorcycle Taxi Drivers and Motorcycle Ban Policy in the Pearl River Delta. Master's thesis, University of Hong Kong, Hong Kong.
Yang, Y., Heppenstall, A., Turner, A., Comber, A., 2019. A spatiotemporal and graph-based analysis of dockless bike sharing patterns to understand urban flows over the last mile. Comput. Environ. Urban Syst. 77, 101361.
Zhang, M., 2004. The role of land use in travel mode choice: evidence from Boston and Hong Kong. J. Am. Plan. Assoc. 70 (3), 344–360.
Zhang, Y., Thomas, T., Brussel, M., van Maarseveen, M., 2017. Exploring the impact of built environment factors on the use of public bikes at bike stations: case study in Zhongshan, China. J. Transp. Geogr. 58, 59–70.
Zhao, D., Ping, G., Wang, W., Jian, X., 2019. Effect of the built environment on shared bicycle reallocation: a case study on Nanjing, China. Transp. Res. Part A: Policy Pract. 128, 73–88.
Zhao, P., 2014. The impact of the built environment on bicycle commuting: evidence from Beijing. Urban Stud. 51, 1019–1037.
Zhao, P., Li, S., 2017. Bicycle-metro integration in a growing city: the determinants of cycling as a transfer mode in metro station areas in Beijing. Transp. Res. Part A: Policy Pract. 99, 46–60.
Zuo, T., Wei, H., Rohne, A., 2018. Determining transit service coverage by non-motorized accessibility to transit: case study of applying GPS data in the Cincinnati metropolitan area. J. Transp. Geogr. 67, 1–11.