Characterizing the stocks, flows, and carbon impact of dockless sharing bikes in China

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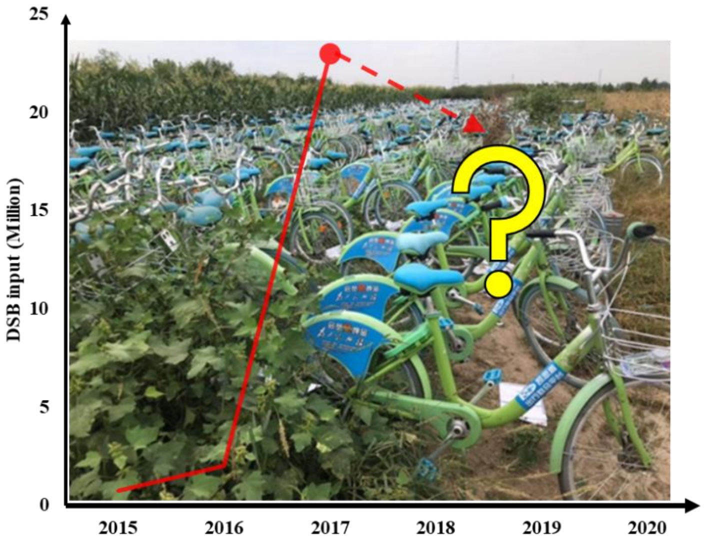
Abstract

The booming dockless sharing bikes (DSBs) in China, as a new sharing economy business model, have attracted increasing public and academic attention after 2015. The impact of DSBs development on the stocks and flows of bikes and the resource and climate consequences of short-lived DSBs, however, remain poorly understood. In this study, we characterized the stocks and flows of both DSBs and regular private bikes in China from 1950 to 2020 and evaluated the carbon cost and benefit of booming DSBs. We found China's bike consumption and stock decreased slightly after a fast development from the late 1970s and then a peak in the mid-1990s, resulting in a relatively low ownership of approximately 0.3 unit per person and 70% of production being exported in recent years. Despite a temporal boost, the unsustainable development of DSBs may affect the bike industry in the long term, because of its skyrocketing market share (from less than 1% to 80%) and short lifetime. Nevertheless, DSBs development still leads to an overall climate gain in China, due to its higher stock efficiency and potentials to substitute more carbon intensive trips. We suggest an urgent need for more empirical studies on the use (e.g., substitution ratio for other transportation models) of DSBs in China and a necessity for better management of DSB development with efforts of all relevant stakeholders.

Keywords: Dockless sharing bikes, Bike-share programme, Bike ownership, Transportation modes, Stocks and flows, Carbon emissions

Graphic abstract



1. Introduction

Transportation contributes to around one-quarter of global energy-related greenhouse gas emissions (McCollum et al., 2018), and is thus widely regarded as a big roadblock to global climate change mitigation (Creutzig et al., 2015) and sustainability transition. Among various transportation modes, bikes are thought the most sustainable from environmental, societal, and economic perspectives (Pucher and Buehler, 2017). For example, the direct environmental impact (e.g., almost no impact in use) and indirect impact (e.g., for bike manufacturing and infrastructure) of bikes are much lower than other transportation modes (Rajé and Saffrey, 2016). Besides, they change the sedentary lifestyle and lead to significant health benefits (Buekers et al., 2015). Cycling promotion could also create significant economic benefit for the society and people due to the reduced travel time budget, motorized vehicle use, and infrastructure (Brey et al., 2017).

China, the country once known as a “kingdom of bicycles”, has witnessed the boom and bust cycles of bike development. Bikes were not introduced until the late 19th century in China as a complement to walking, rickshaw, and a sedan chair. They then gradually spread across the country from the 1950s to the 1990s (Rhoads, 2012), when the bike was regarded as one of the four most stylish home goods and became one of the main transportation tools in cities (Zhang et al., 2014). Since the late 1990s, however, bikes were gradually phased out in daily transportation in the motorization and urbanization process (Zhang et al., 2014). In 2015, a new generation of sharing bike program (SBP) with dockless sharing bikes (DSBs) appeared in China, which people can start to use after scanning a barcode with a smartphone and return anywhere (Gu et al., 2019). This innovation (known as one of China’s “four great new inventions” in modern times (Chinadaily, 2017)) provided convenience to urban citizens as a solution to the “last mile” challenge (e.g., between home, workplace, and public transportation stations) and dragged some urban residents back to two-wheeler life. Consequently, these DSBs flooded the market quickly and the DSB input boomed in 2017 and surpassed the available sharing bikes elsewhere in the world in 2016 (Felix, 2018).

However, the concept and practice of sharing bikes are not new. The global history of SBPs can be dated back to over five decades ago and they can be categorized as four main models (Fig. 1). Starting from white bikes in Amsterdam in 1960 (SBP 1.0), it took about three decades to shift to coin-based sharing bikes in Copenhagen (SBP 2.0) and Information Technology (IT) based SBP 3.0, and then another two decades to SBP 4.0 in China (Chaoze, 2017; Shen et al., 2018). These dockless sharing bikes penetrated the market in Chinese cities quickly after 2015 and boomed in 2017. Such renaissance of bikes came with an immediate cost due to the flooding venture capital investment and lack of regulation. Oversupply of DSBs vastly outpaced demand, colonized city streets, and caused various problems such as road occupation, massive vandalized bikes and bike graveyard, and bankruptcy of many DSB firms (DeMaio, 2009; Peter, 2011; Shaheen et al., 2010; Shen et al., 2018), which call for an optimized approach for planning and management (Awasthi and Omrani, 2019; Sayyadi and Awasthi, 2018).

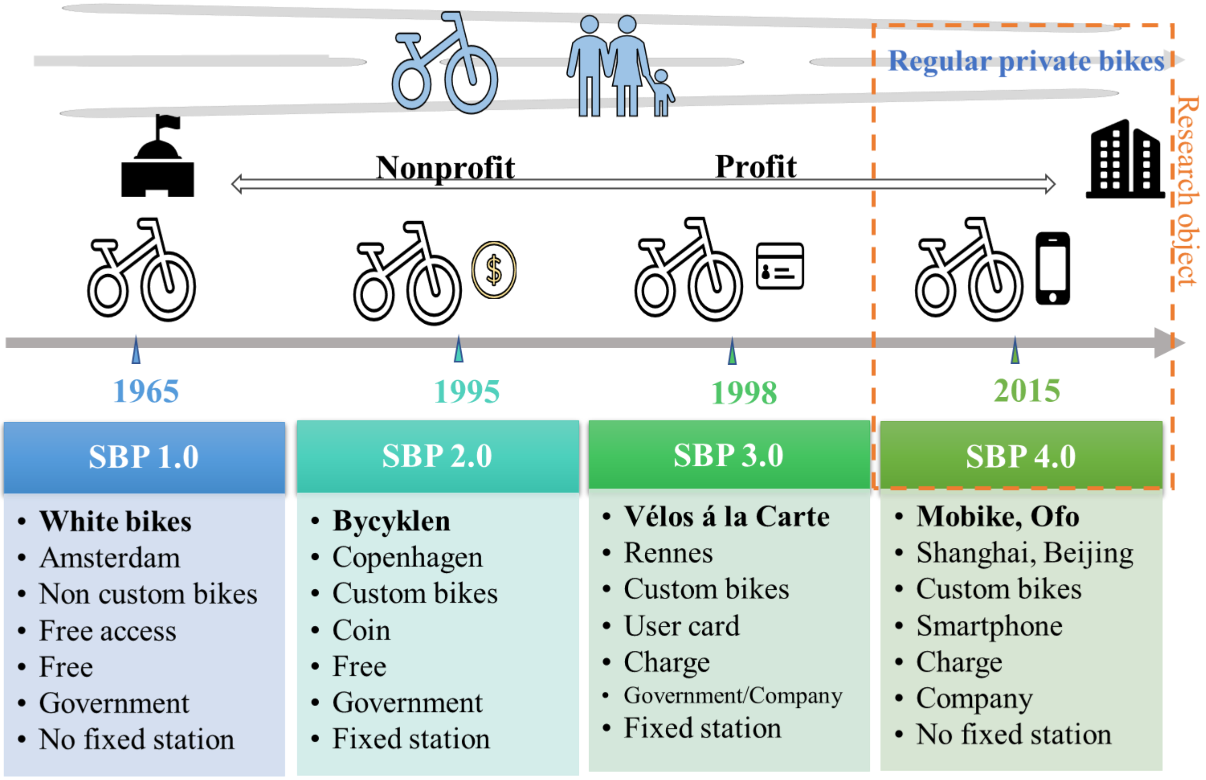


Fig. 1 The historical evolution of regular private bikes (hereafter as regular bikes, vis-à-vis sharing bikes) and four key models of sharing bike programs (SBPs) based on (DeMaio, 2009; Peter, 2011; Shaheen et al., 2010; Shen et al., 2018).

In parallel with SBP development, the past decade has seen an increasing amount of publications on SBPs and DSBs across the world (Si et al., 2019). Most of these studies focus on how socioeconomic, spatial, and behavioral factors such as bike accessibility (the distance between use and station) and availability (possibility to find a bike) (Kabra et al., 2018), customer characteristics (Guo et al., 2017; Ji et al., 2017), behaviors (Li et al., 2018) and travel patterns (Du and Cheng, 2018), and built environment (Zhang et al., 2017)) could affect the adoption and use of sharing bikes (Efthymiou et al., 2013; Yang and Long, 2016). Since the spatial and temporal imbalance between demand (Gervini and Khanal, 2019; Zhou et al., 2018) and (re)distribution (Ho and Szeto, 2017; Li et al., 2016) of sharing bikes is identified as the key to successful SBP development, some researchers have used different repositioning technologies and models to optimize the station position and address congestion or starvation issues of IT-based SBP (Forma et al., 2015; Ghosh et al., 2017; Szeto and Shui, 2018). This is of particular importance for DSBs due to their flexibility without docking stations, so demand forecasting (Xu et al., 2018), static (Liu et al., 2018) and dynamic repositioning problems (Shui and Szeto, 2018), optimizing location (Sun et al., 2019) and optimizing transportation planning (Sayyadi and Awasthi, 2018) are the key focuses of DSBs research as well in the transportation literature.

As the immense public attention and media coverage on China's DSBs fever brings both the pros and cons of DSBs into the spotlight, their environmental benefit and impact became an important question (Standing et al., 2019), which this paper aims to contribute to as well. On the one hand, shifting more motorized trips to DSBs for "the last mile" could boost public transportation use (Zhang and Zhang, 2018) and help create environmental benefit (Gu et al., 2019; Zheng et al., 2019). For example, through an analysis based on big data, DSB use was found to save energy and decrease emissions (e.g., CO_2 and NO_x) in Shanghai (Zhang and Mi, 2018). On the other hand, the additional materials use, such as electronics in DSBs and especially the significant amounts of short-lived DSBs in the graveyard due to fierce market competition, could cause an extra impact on resource, waste, and environment. For example, some life cycle analysis (LCA) based studies reveal a higher environmental impact of DSBs than station-based SBP (Bonilla- Alicea et al., 2019; Luo et al., 2019) and breakeven point of its environmental impact in Beijing was calculated as 1.7 years of DSBs use (Chen and Chen, 2018).

These abovementioned studies provide an initial assessment of the environmental impacts of DSB development for two sides of the same coin, but a few knowledge gaps remain.

- First, previous studies on the development and impact of SBPs and DSBs often only cover a short period of time and are insufficient to reveal their impacts on the dynamics (stocks and flows) of the bike industry (including regular bikes) and patterns and efficiency of bike use.
- Second, the resource and environmental implications of the significant amount of short-lived DSBs due to oversupply and fierce competition driven by venture capitals to capture the market share has not yet been quantitatively addressed in previous studies.
- Third, the carbon impacts are usually discussed in static snapshots and on a functional unit using LCA, therefore they could not capture the dynamics of bike stocks and their aggregated effects.

Therefore, we aim to address these gaps in this study by tracking the stocks, flows, and use of both DSBs and regular bikes in China from 1950 to 2020, and further comparing the carbon cost in production, operation, and end-of-life management of DSBs and their carbon benefit in use as a substitution to other transportation modes. The impact of DSBs development on the bike industry and policy implications on DSBs management are consequently discussed.

2. Methods and materials

2.1 Characterizing stocks and flows of regular bikes and DSBs

We used a dynamic material flow analysis (MFA) approach to simulate the evolution of in-use stocks and flows of bikes (both regular bikes and DSBs) from 1950 to 2020. To capture the role of DSBs in the background of bikes development, we have included both regular bikes and DSBs in this study. However, bikes that are not human-powered (e.g., motorized or electric bikes) and the small quantity of sharing bikes in old SBP models before 2015 were not included.

For development from 1950 to 2017 (when the latest empirical data are available), the historical in-use stocks and scrapped bikes are quantified by considering the historical sales of bikes and their lifetime, as widely used to estimate the in-use stock of consumer products such as TV sets (M. Wang et al., 2018) and refrigerants (Duan et al., 2018), as shown in equations (1) and (2).

$$Stock_{i,t} = \int_{t_0}^{t} (S_i - R_i)\mathrm{dt} \qquad (1)$$

$$R_i = \int_{t_0}^{t} L_i(t,t') * S_i\,(t')dt' \qquad (2)$$

Where i represents different bike categories, S_i is sales of $bike_i$ measured in quantities, $R_i$is the amount of scrapped bike, and $L_i(t,t')$ is the probability that bike i sold at time t will get scrapped at time t'.

For regular bikes, since long time series of sales data are unavailable, apparent consumption which equals to production P_i plus import I_i and minus export O_i is used as an alternative (shown in equation (3)) by assuming market inventory is eligible. For DSBs, the annual sales are directly taken as DSBs input on market (Hao, 2018; Sharing Economy Research Center of National Information Center, 2018).

$$S_i = P_i + I_i - O_i \qquad (3)$$

The simulated historical stocks of bikes from the abovementioned top-down approach can be validated by scaling up some independent bottom-up bike ownership estimations by a factor of population, as shown in equation (4). This comparison could help us identify the best fit for the lifetime assumption of regular bikes (which ends up as 16.2 years, see Fig. 2 (b)), a key parameter that unfortunately has almost no empirical data.

$$Stock_{i,t} = P_t \times O_{i,t} \qquad (4)$$

Where P_t is the quantities of household in year t, $O_{i,t}$ is the bike *i* ownership per household in year *t*.

For bike demand and scrapped bikes generation in the recent years between 2017 (the reference year when the latest empirical data are available) and 2020 (the target year for many plans and regulations on DSBs in China), due to lack of empirical data yet, we used a stock-driven approach (Müller, 2006) to simulate the stocks and flows under different assumed development scenarios as shown equation (5).

$$S_{i,t} = Stock_{i,t} - Stock_{i,t-1} + R_{i,t} \quad (5)$$

Where $S_{i,t}$ is the sales of bike *i* (both regular bikes and DSBs) in year *t* and $R_{i,t}$ is the scrapped bikes in year *t*.

Similarly, due to data gaps on trade after 2017, we assumed an unchanged trade pattern between 2017 and 2020 and consequently estimated the bike production (P) based on bike sales (S) and the average share of domestic production in apparent consumption (A) from 2000 to 2017.

$$P = S/A \qquad (6)$$

Stock performance (SP), as a measurement for the use efficiency (Wang et al., 2018), is calculated as the service provided (cycling distance) divided by stock (number of bikes).

$$SP = \frac{Service}{Stock} = \frac{D_a \times P}{O \times P} = \frac{D_a}{O} \qquad (7)$$

Where *Da* is the cycling distance per person per year and *O* represents the bike ownership.

2.2 Carbon cost and benefit of DSBs

Bikes are normally considered as a zero-emission transportation mode. But processes such as materials production and bike manufacturing will generate emissions. In addition, DSBs would lead to extra carbon emissions due to the production of electronic equipment and the operation of DSBs.

The carbon emission intensity for the full life cycle (production, maintenance, redistribution, and end-of-life management) of one DSB was taken as 76 kg CO_2 equivalent (Chen and Chen, 2018), as detailed in the Supporting Information **Table S2**. Total carbon emission caused by DSBs is thus determined by the DSB input (N) and carbon emission intensity of one DSB (E_{DSB}).

$$C_{DSB} = N * E_{DSB} \tag{8}$$

When DSBs substitute other transportation modes (especially motorized trips), they will generate environmental benefits (Fishman et al., 2014; Martin and Shaheen, 2014). We calculated such carbon emission reduction benefits (r) by total cycling distance (D_{DSB}), substitution ratio (R) of DSBs for other transportation modes, and the carbon intensity per kilometer (C_t) of the substituted transportation mode t.

$$r = D_{DSB} * R * C_t \tag{9}$$

2.3 Data collection

Multiple data sources are used in our analysis, as detailed and elaborated in the online Supplementary file. In short, historical data on bike production were collected from China Light industry Yearbook (National Bureau of Light Industry). Trade data on the bikes were collected from China Light Industry Yearbook (National Bureau of Light Industry)(before 1992) and the United Nations Comtrade Database (UN Comtrade) (after 1992). Private bike stock data were mainly from China Statistical Yearbook (CSY)(National Bureau of Statistics of China). Data on bike ownership and cycling distance of other countries are mainly from relevant bicycle associations. Data on DSBs are based on our interview and related reports of DSB companies.

2.4 Scenarios setting

Since the emergence of DSBs in recent years has dominated the bike industry and market, we assume future stock of regular bikes will follow its current trend (an annual decrease by 12.9 million units) in the next years. Due to increasing awareness of the side effect and management challenges of the DSB fever in China, very strict regulations on the market growth have already been introduced in many cities. Based on various industry and government planning documents, we set a ceiling of 28.4, 31.4, and 35.0 million (**Tab. 1**), respectively, as the saturated DSB stock by 2020, for low, medium, high scenarios of future DSB stock development. Justifications of these stock ceiling assumptions in 2020 are detailed in the supplementary file.

The short lifetime of DSBs is at the core of the fierce debate on the resource and environmental impacts of DSB development in China. Due to lack of empirical data, we set three-lifetime values in the scenario (sensitivity) analysis to explore the impact of a lifetime on carbon emissions: 3 years as a benchmark (the maximum allowed lifetime in the regulation proposed by governments), 6 years (double the current maximum value for environmental benefits), and 1.5 years (assumed as an extreme based on the current short-lives and close to the lifetime of the break-even point (Chen and Chen, 2018)) (see **Tab. 1**).

Tab. 1 Scenarios for DSB stock in 2020 and lifetime

Scenario	Stock scenario	Stock in 2020 (million)	Lifetime distribution	Lifespan (years)
S1	Low	28.4	Normal distribution	1.5
S2	Low	28.4	Normal distribution	3
S3	Low	28.4	Normal distribution	6
S4	Medium	31.4	Normal distribution	1.5
S5	Medium	31.4	Normal distribution	3
S6	Medium	31.4	Normal distribution	6
S7	High	35.0	Normal distribution	1.5
S8	High	35.0	Normal distribution	3
S9	High	35.0	Normal distribution	6

Cycling distance information for 2016 and 2017 was accessed from an official report on the sharing economy development in China (Sharing Economy Research Center of National Information Center, 2018). Cycling distance for 2015 was estimated based on a scaling factor of the DSB input (the amount in 2015, which was very small, to that in 2017). We assumed the cycling distance of DSBs from 2018 to 2020 the same as 2017 due to the already high DSB stock and the tightening regulation on DSBs input.

Regarding the substitution ratio of other transportation modes by DSBs, there is unfortunately no China-specific evidence on the city level, except one single study for station-based sharing bikes in Ningbo, a city in eastern China (Lu et al., 2017). Therefore, we chose to explore the impact of this critical parameter in a range of scenarios by using substitution ratios of Ningbo and cities in the U.S., U.K., and Australia, which are based on surveys on station-based sharing bike users as well with questions like "what mode will you choose if you don't use sharing bike". Scenarios 1-7 are direct results from these studies (Fishman et al., 2014; Lu et al., 2017; Luo et al., 2019), and Scenarios 8 and 9 are extreme assumptions for 100% substitution of cars and buses to investigate the potential maximum impacts of substituting motorized vehicles (**Tab. 2**). The life cycle carbon emissions of car and bus are set as 251 g/km (Wu et al., 2019) and 101 g/km (Dong et al., 2018) respectively.

Tab. 2 Substitution ratio of other transportation modes by sharing bikes

Scenarios	New trip	Car	Bus	Bike	Walk	City	Source
r1	1%	22%	49%	15%	13%	Ningbo	(Lu et al., 2017)
r2	1%	20%	40%	9%	30%	Melbourne	(Fishman et al., 2014)
r3	2%	24%	44%	8%	22%	Brisbane	(Fishman et al., 2014)
r4	4%	14%	45%	6%	31%	Washington, D.C.	(Fishman et al., 2014)
r5	13%	22%	20%	8%	37%	Minnesota	(Fishman et al., 2014)
r6	3%	6%	57%	8%	26%	London	(Fishman et al., 2014)
r7	3%	20%	44%	8%	25%	-	Assumption in Luo et al., 2019

r8	0%	100%	0%	0%	0%	-	Extreme assumption
r9	0%	0%	100%	0%	0%	-	Extreme assumption

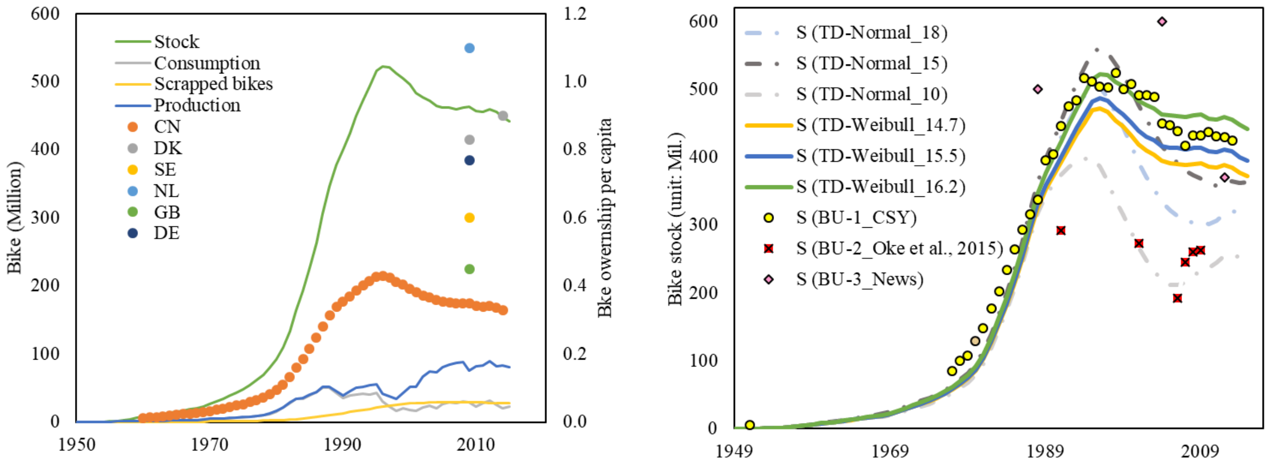
3 Results

3.1 Historical patterns of bike and DSB development

Figure 2 (a) below shows that bike production and consumption remained at a low level before the 1970s in China but started to increase since its open and reform policy in the late 1970s. Annual bike production was around 77.8 million after 2000. Annual bike sales hovered around 37.6 million units from 1980 to 1995. After 1995, bikes were more considered as a barrier of urban transportation in a motorized vehicles dominating way of urbanization (Zhang et al., 2014), and thus China's domestic bike consumption started to decrease and then fluctuated between 20 to 25 million units after 2000. Meanwhile, the share of domestic consumption is around 30% (ranging from 24% to 39%) of domestic production (Figure S1). The exported bikes (**Figure S2**) increased gradually to around 58 million units of bikes and takes up around 70% of domestic production (mainly to the United States, Japan, and Indonesia) with around half of total export in recent years.

As a result of the stagnating consumption of bikes in the recent two decades, the total stock of bikes in China has moderately but continually decreased from 52.3 million units in 1996 to 44.8 million in 2014. This is in clear contrast with the almost four times growth of stocks between 1980 and 1995. Although China still has the world's largest stock of bikes with around 400 million units from the total quantity point of view, its bike ownership on a per capita level (0.3 now and a peak around 0.43 in the 1990s) is much lower than that of many industrialized countries (for example 0.9 for Denmark and 1.1 for Netherland) (Fig. 2 (a)). This indicates a potential increase of bike stock in the future in China if it follows patterns of those countries, which may further increase the cycling modal share and help to alleviate problems like traffic congestion and CO_2 emissions.

It is important to mention that bike lifetime is an important yet uncertain parameter for the bike stock estimation results. When we compare our top-down bike stock estimation using different average lifetime assumptions with several independent bottom-up estimates from various data sources (as shown in Figure 2(b)), it appears that a Weibull distribution with an average lifetime of 16.2 years (and a shape parameter 18.2 and a scale parameter 1.8) fit the best for China's regular bikes. The validated average lifetime is 1.5 years longer than that often used in literature, e.g., the Japanese Lifespan Database (National Institute for Environmental Studies, 2019).



(a)

(b)

Fig. 2 (a) China's historical bike production, consumption, scrapped bikes, and stock in China (left axis) and bike ownership compared with selected industrialized countries (right axis), and (b) China's historical bike stock validated by a comparison of a top-down method (TD) and bottom-up method (BU) from 1950 to 2014 (National Bureau of Statistics of China; Oke et al., 2015). (The number after TD indicates the average lifetime assumption; detailed data sources for the three BU stock could also be found in Table S1.)

However, the introduction of DSBs in major Chinese cities since 2015 has changed the patterns of bike development. Fig. 3(a) shows the changing DSB market represented by their logos (non-exhaustive) in which Ofo and Mobike dominate the market over the years. In 2016, 34 DSB companies including 30 new start-ups have introduced in total 2 million new DSBs to the market; and in 2017, over 70 DSB companies including another 34 new start-ups have introduced in total 23 million new DSBs to cities (Fig. 3(b)), which equals almost the average of China's total annual bike sales after 2000 (Fig. 2(a)). Therefore, DSBs quickly compress the market share of regular bikes, with an increasing share in annual domestic consumption from less than 1% to 80% within only three years (Figure 3(b)). Such a DSB fever also led to a slight increase in bike stock for the first time after 1995.

The fierce competition of the DSB market due mainly to speculative ventures is also reflected by the changing number of DSB companies shown in Figure 3(a). For example, the colors of bikes, which are used as the identity of different DSB companies, are all taken, so Qicai Bike (meaning "seven colors") had to add one more color of the rainbow when it joined the war. However, except the two pioneer and duopoly companies Mobike and Ofo, which won a combined market share of 90% on the feverish battles (The Economist, 2019), only a few small players survived the increasing competition and financial crunch in the harsh market. In June 2017, Wukong bike (Chongqing) closed its operation at first (Intelligence, 2018), and 27 more DSB companies went bankrupt sequentially in the same year.

The temporary prosperity that the feverish DSB development brought to the traditional bike industry, however, will not continue in the future when a clear ceiling of DSB stock is to be set (see our assumptions in section 2.4; The results of bike production and scrapped DSBs for the last three years 2018-2020 and S1-S9 in Fig. 3(c) and (d) are based on definitions in Tab. 1). The lifetime of DSBs has a big impact on bike demand. In the extreme 1.5-year lifetime scenarios, the bike demand would still increase after 2017, which would go against the current regulations. In 2018, the bike demand would decrease for scenarios with 3-year or 6-year lifetime and the declining trend would last longer for scenarios with higher saturated DSB stocks or a longer lifetime, which lead to the further depression of the bike production industry by 2020 (Fig. 3 (c)). Nevertheless, the trend that regular bikes are gradually substituted by DSBs will continue. There were already around 5 DSBs in every 100 bikes in 2017, and this will increase to 7-8 DSBs per 100 bikes in 2020 in all scenarios.

The booming DSBs development and short lifetime caused a significant amount of extra scrapped bikes (Figure 3(d)). Before the emergence of DSBs, around 28.45 million units of bikes were scrapped annually in the 21st century (Fig. 2 (a)). In the case of extremely short lifetimes as 1.5 years (scenarios 1, 4, 7 in Table 1), these scrapped bikes will increase significantly in 2018 and slightly increase afterward. These scrapped bikes in 2020 contribute to approximately half (47%, 48%, and 51%, respectively, in scenarios 1, 4, and 7) of total scrapped bikes (both regular bikes and DSBs). If the current regulation of three-year write-off lifetime continues (scenarios 2, 5, and 8 in Table 1), scrapped DSBs in 2019 will peak (17.0-17.4 million), contributing to 39% total retired bikes. In that year, these scrapped bikes contain 265.8-271.3 Gg of steel, 29.5-30.1 Gg of aluminum, and 8.5-8.7 Gg of electronic waste. Extending the DSB lifetime would delay the peak of scrapped bikes and significantly reduce the waste generation. For example, only doubling the lifetime (to 6 years) would reduce the amount of scrapped DSBs by 57.7% to 59.2% from 2015 to 2020.

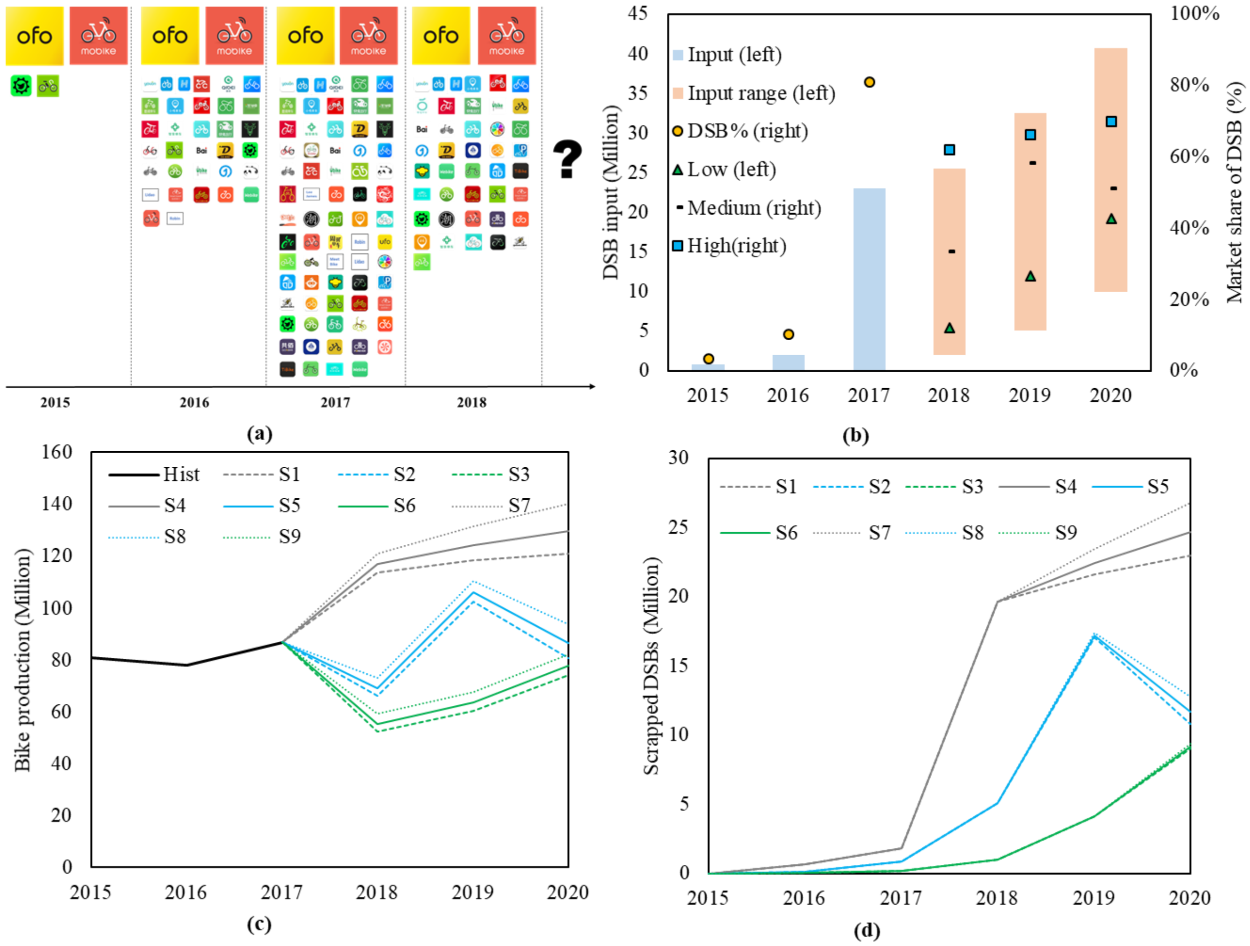


Fig. 3 (a) The changing market of DSB companies in China, (b) annual input (left axis) and market share (right axis), (c) bike production, and (d) scrapped amount of DSBs in China from 2015 to 2020.

3.2 The carbon benefit and cost of DSBs

The booming use of DSBs could substitute some trips that would otherwise be based on transportation modes with higher environmental impact. If we measure the efficiency or performance of stocks (Cabrera Serrenho and Allwood, 2016) as a total bike or DSB stocks divided by kilometers of use, DSBs have, not surprisingly as a model of sharing economy, improved such efficiency. For example, in 2017, around 23 million of DSBs were used for 29.9 billion kilometers in China, which meant that the stock efficiency of DSBs (3.6 km/bike/day) is much higher than that of regular bikes in industrialized countries such as Netherland (2.5 km/bike/day), Denmark (1.8 km/bike/day), and United Kingdom (0.3 km/bike/day).

Figure 4(a) shows that after the emergence of DSBs in 2015, the trip share of bikes in Beijing, as an example due to lack of data on the country level, did increase slightly from 14.7% to 16.7% in 2017, after the past decades' continuous decline from a high level of 62.7% in 1986. This thus comes with an environmental benefit in reducing transportation emissions. Based on different substitution rates assumed in Table 2, the carbon benefit (shown as bars with different years accumulated in Figure 4 (b))) by shifting motorized modes to cycling by 2020 in China would range between 9.2 and 13.3 million tons of CO_2 equivalent (with an extreme of 31.3 million tons if all the substituted trips are by cars). The carbon benefit by 2017 is only slightly higher than the emission cost (around 2.0 million tons of CO_2 equivalent) caused by DSBs input by 2017 (shown as dashed lines). The three solid lines in Figure 4 (b) for Scenarios 3 (low), 5 (medium), and 7 (high) (as defined in Tab. 1) show carbon emission cost due to the new DSB deployment by 2020. The carbon cost would change from 3.2 to 8.2 million tons CO_2 equivalent by 2020 for new DSB deployment for Scenarios 3 and 7, respectively. The carbon gains would increase in the next years in all the scenarios (even with high saturation stock and short lifetime), if the cycling distance and substitution rates remained the same, adding up to a saving of 1.1-23.7 million tons of carbon emissions by 2020. Considering the carbon emission of one vehicle are around 3.7 metric tons per year in China (iCET(Innovation Center for Energy and Transportation), 2018), these gains of DSBs by 2020 would be the same as removing approximately 0.3-6.4 million units of cars off roads.

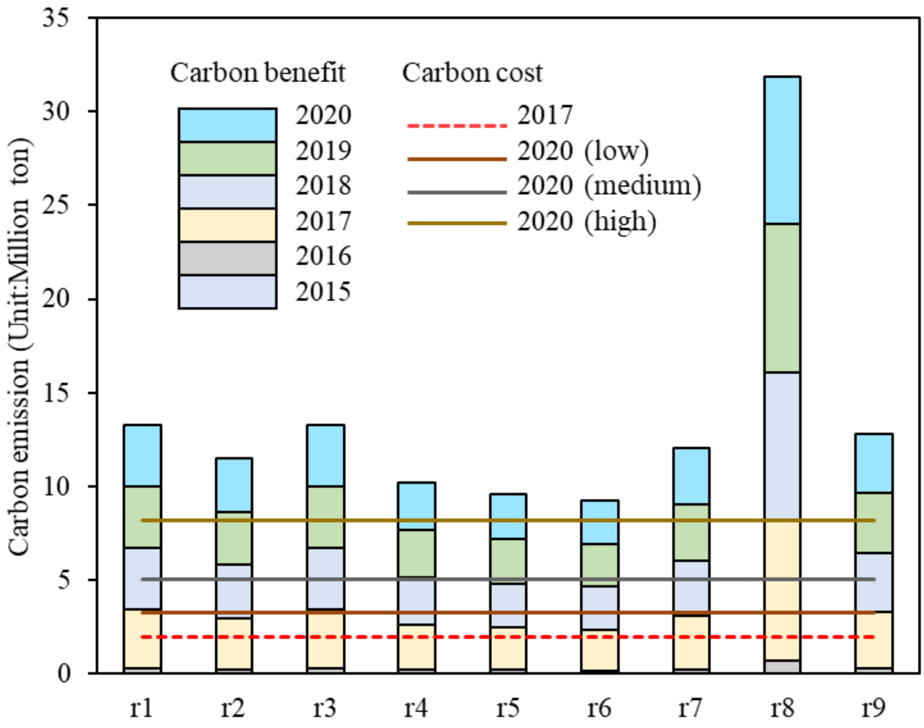


Fig. 4 The carbon benefit and cost of DSB development in nine scenarios (as defined in Table 2).

4. Discussion

Bike-sharing is an innovative business model that in theory follows the sharing economy principle with lower material stock or consumption for the same (if not more) service (Mi and Coffman, 2019). But the DSB fever triggered by venture capital investment leads to fierce market competition and thus raises questions on its benefit and cost that are not straightforward to answer. We have provided the first overview, to our own knowledge, on the stocks and flows of bikes and the role of DSBs in such dynamics in China. We found the booming development of DSBs has a significant impact on the production, sales, and use of regular bikes. Our analysis on the carbon benefit and cost of DSB development suggested that, despite the short lifetime induced climate impacts, the penetration and use of DSBs can still have climate gains under various scenarios, due to its higher stock efficiency and potentials to substitute other transportation modes.

It should be noted that, due to a lack of empirical data, our results bear several uncertainties that should be addressed in the future. First and foremost, there is very little information (only one single city reported in the literature) on the substitution ratio of DSBs to other transportation modes in China, thus we had to use data from other western cities and station-based sharing bikes in the scenario analysis. Considering the social, economic, and cultural differences, more empirical data and more field surveys on this in Chinese cities (e.g., in collaboration with DSB companies) are badly needed for a more accurate understanding of the climate impacts. Second, the emission benefit is approximated by a simple calculation of the avoided emissions with DSBs replacing more emission-intensive transportation modes such as buses and cars. We didn’t consider the marginal savings for the case of DSBs substituting buses, nor the potential climate benefit of increased use of public transportation caused by DSBs (as a “last mile” transportation option between home, workplace, and public transportation stations). These limitations could be addressed in integrating our results in a full life cycle assessment in the future. Third, the role of emerging electric bikes and other categories of impacts other than carbon emissions (such as traffic-congestion ease, health-related impacts, and indirect impacts due to the change of background socioeconomic systems) are not considered and thus worth exploring further as well.

The booming development of DSBs in China within 3 years can be explained by the DSBs business model, which mirrors that of some other similar business models driven by emerging information technologies and giant investment in recent years in China. For example, both Didi-Chuxing (a ride-hailing company competing with Uber and finally beat Uber in China) and Meituan-Dianping (a group buying website for food delivery services and consumer goods), two companies valued at $56 and $30 billion respectively now (French, 2018), went through such tough competition (e.g., turf wars and subsidy wars) fueled by cash-burning throughout the way to obtain their current market share. However, DSB used even less time and grew much faster than other technology companies to reach the threshold of over 10 million daily orders (8, 3.5, and 3 years, respectively, for Taobao, a Chinese online shopping website, Didi-Chuxing, and Meituan-Dianping): It took less than one year for Mobike to reach 2 million daily orders (Fig. S5).

Such a “high investment, high throughout” model of DSB development has profound impacts on the bike industry, urban transportation, and environmental management.

- First, the bloody market competition of DSBs resulted in oversupply in several first-tier cities (e.g., Beijing, Shanghai, Guangzhou, and Shenzhen) that goes far beyond their carrying capacity, and consequently challenges for urban transportation management (e.g., DSB congestion, illegal parking, and vandalism).
- Second, the DSB fever put the bike manufacturing industry into a spin (Feng, 2018). On the one hand, the breakneck growth of DSB made this sunset industry that is almost forgotten in public flourish again in the recent two years. It dragged people back to two-wheeler life and made riding DSB as a new fashion. On the other hand, tremendous changes in DSB orders in the quick cooling-down of DSB fever would give a hard hit to the already over-expanded bike manufacturing industry if they can’t upgrade their production chain or find alternative clients (Dong, 2018). In addition, the booming DSB cultivated travelers’ behaviors and preferences on DSB (than buying their own), which may further deteriorate the bike market.
- Third, the significant amount of scrapped DSBs and waste due to extreme short lifetime in a harsh competition and mismanagement in use (e.g., vandalism or damage in use due to quality issue) lead to escalating land occupation and waste management challenges (e.g., improper handling of electronic waste from DSBs may lead to adverse environmental

pollution as well). Most of these scrapped DSBs are left in the bike graveyard without further treatment, or in the best case, recycled only for the metal parts (especially steel). This relates mainly to the facts that there are no specific regulations in place yet and the economic motivation of recycling is low (only about 30 Chinese Yuan for the value of scrapped steel in one DSB, assuming its weight as 20 kg and price of steel as 1500 Chinese Yuan per ton, while the end-of-life management cost is very high and even surpass the cost of a new DSB). A few major DSB companies have some first initiatives to reuse the usable electronic locks and recycle other scrapped materials to make chairs, cook, and headphone(Sohu, 2018), but further upscaling and technology development are badly needed to further reduce both waste generation and carbon emissions..

Our results could help inform government and industry policies on market entrance, DSB operation, and end-of-life management of the bike and DSB industry. The abovementioned carbon gains can be further enhanced if the DSB development were better managed:

- The bike manufacturing industry should explore different ways to find new clients, such as shifting to electric bikes or export to other countries and changing their profits and business models from sales-driven to service driven. They should also address the increasing amount of scrapped DSBs from a circular economy perspective (e.g., remanufacturing, reuse of components, and modular design).
- The government should set a reasonable threshold of bike input based on better transport planning and demand forecasting. Improving the policy on market entrance check (e.g., the norm of DSB quality), DSB operation (e.g., benchmarking and regulating on redistribution and use efficiency), end-of-life management (e.g., pre-charge a deposit for cleaning up scrapped bikes before inputting new DSBs), and write-off lifetime would be important. In

the end, they should correspondingly invest in proper cycling infrastructure (e.g., bike lanes and parks) to keep pace with the increasing DSBs and propagandize the civilized behavior for DSB use.

Acknowledgements

This work is funded by the National Natural Science Foundation of China (71991484) and the China Scholarship Council (201708510095). We thank Yu Dou and Xiaodong Huang for valuable research assistance and Hao Qin from Mobike company for helpful discussion.

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