ESTIMATION OF THE POTENTIAL FOR REDUCING CARBON DIOXIDE EMISSIONS IN THE TRANSPORTATION SECTOR THROUGH THE INTRODUCTION OF REDEPLOYMENT BICYCLE SHARING SYSTEM

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The advancement of bicycle-sharing systems is crucial for reducing CO_2 emissions from the transport sector in urban areas. The present study aims to estimate the potential reduction in CO_2 emission and the associated benefits of introducing a bicycle-sharing system with bicycle repositioning for everyday travel in the Yuanhui District of Luohe City in China.

The results revealed an 8.3% daily CO_2 emission reduction after transitioning from electric cars, buses, private vehicles, and taxis to bicycle sharing in Luohe City. Additionally, the monetary benefit of a 1% reduction in CO_2 emissions through bicycle sharing was estimated to be 0.23 yen.

Keywords: *Bicycle-sharing; Redeployment track; CO_2 reduction*

1. INTRODUCTION

Advancements in bicycle-sharing systems have become crucial for reducing CO_2 emissions in the urban transport sector. Although bicycles have been shared for approximately 50 years, their low utilization is primarily due to inconvenience-related factors.

Widespread internet and smartphone use have developed bicycle-sharing systems by enhancing their accessibility. Additionally, advanced technology has enabled the mass production of cheap bicycles. Technological advances that support shared-transport platforms increase bicycle usage, improving human health and environmental preservation in residential areas. The proliferation of bicycle sharing can contribute to the fast and sustainable development of shared transport and create more habitable and sustainable urban environments[1)].

In 2021, the shared bicycles in the Chinese bicycle-sharing market were approximately 4 million, with a revenue scale of 936.6 million yuan, and is expected to exceed 1 billion yuan by 2022. As the deployment of shared bicycles increases, the daily usage of bicycles continues to increase, and the revenue generated is expected to be >20 billion yuan by 2025. According to a survey from a consulting firm[2)], 46.0% of Chinese shared-bicycle users use them three to five times a week, and over 50% use this service owing to environmental concerns.

Japan is among the top countries using shared-bicycle systems globally. Furthermore, by the end of December 2019 and 225 cities were using this system globally. Generally, developing a bicycle-sharing system involves setting up stations around supermarkets for convenience to customers and employees[3)].

Fishman et al. evaluated the characteristics of shared-bicycle systems considering four perspectives and revealed that bicycle users consider convenience and availability when using this system, members are more likely to own private bicycles, and users of shared bicycles dislike wearing helmets compared with those using personal bicycles. Furthermore, they revealed that many users are changing from using automobiles to using sustainable modes of transport[4)].

The Ministry of Environment in Japan conducted a comprehensive evaluation of bicycle-sharing systems to assess the reduction in CO_2 emissions due to bicycle sharing using basic data analysis of bicycle-sharing usage patterns, surveys, and interviewing users and bicycle-sharing operators considering user

behaviors and system relocations. Considering the results of evaluating the state of bicycle-sharing systems in Japan, the Ministry proposed innovative assessment methodologies and estimated the effects of reduced CO_2 emissions within the respective regions. The Ministry found that distance to bicycle stations, and the probability of finding available bicycles influence user behavior[5].

Kabra et al. demonstrated that as the distance to a station increased by 1 m, the probability of users utilizing the bicycle-sharing system decreased by 0.19% (± 0.069%), decreasing further for distances exceeding 300 m. Additionally, they found that a 10% increase in the availability of a shared bicycle increases the number of users by 12.21% (± 1.10%)[6]. Therefore, there is a need to construct a dense station network[6].

Zhu demonstrated that younger people generally use shared-cycling services. Furthermore, the utilization of shared-bicycle services could increase with increased bicycle quality and reduced bicycle malfunction[7].

The present study utilizes a bicycle-sharing system involving the repositioning of bicycles in the Yuanhui District of Luohe City in China to assess the potential reduction in CO_2 emissions and estimate the monetary value of this reduction. Furthermore, it aims to reduce the CO_2 emissions associated with daily travel for sustainable urban transport.

2. REALLOCATED TRACK SYSTEM

In bicycle-sharing services, bicycle redistribution between stations often uses trucks to adjust bicycle availability. Using trucks to redistribute bicycles is essential for enhancing availability; however, it increases CO_2 emissions and operational costs.

3. EVALUATED AREA

The present study was conducted in the Yuanhui District, Luohe City, Henan Province, People's Republic of China. Yuanhui District is a municipal district within Luohe City, covering 230.3 km^2, with 322,334 permanent residents (as of November 1, 2020).

As a central transport hub, Yuanhui District has convenient transport options, including walking, cycling, and using electric vehicles and buses. However, the district is suitable for bicycle-sharing services, owing to the limited range of daily travel for residents and the absence of subways or trains.

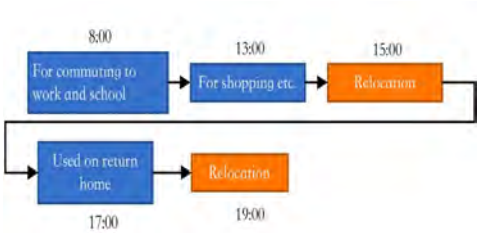

Fig. 1 Bicycle sharing scenarios



Fig. 2 Distribution map of stations on Google My Maps

4. Research Methods

(1) Survey on daily transport patterns in the Genkai District

Using conjoint analysis, we investigated the movement patterns between blocks (number of people, transport mode, and purpose), willingness to use bicycle-sharing services based on distance traveled, and the monetary benefit of reducing CO_2 emissions due to bicycle sharing.

(2) Estimation of CO_2 emissions due to implementing a bicycle-sharing system

a) Bicycle-sharing scenarios

Fig. 1 illustrates a scenario for shared bicycle usage designed for weekday commuting.

First, we assume that some people use shared bicycles for commuting or going to school and shopping at 8:00 am and 11:00 pm, respectively. Next, we rearranged the shared bicycles at 3:00 pm to accommodate people returning from school at 3:00 pm.

After returning home at 6:00 pm, the shared bicycles were rearranged at 7:00 pm to accommodate commuters or pupils going to school the following day.

b) Block division of Yuanhui District

We marked the stations on Google Maps using data from the Share Cycle Ports in the Yuanhui District and established 13 blocks centered around the intersections (**Fig. 2**). Subsequently, we estimated the distances between the centers of these blocks using the Google Maps route search feature.

c) Conditions for simulating the bicycle-sharing systems

Preconditions:

- The percentage of commuters at 8:00 am in each block was considered utilizing our survey results.
- The percentages of people who traveled for shopping or other activities at 1:00 pm in each block were 100, 75, and 50%.
- Bicycle usage based on travel distance was considered based on our survey results.
- Purpose-specific distribution of movements to each block was considered utilizing our survey results.
- Interblock distances between the centers of each block were estimated using Google Maps.
- Each redeployed truck had 20 bicycles.

Constraints:

- At 1:00 pm, the inventory at each block exceeded the demand for shopping and similar usage.
- At 4:00 p.m., the inventory in each block exceeded the combined demand for commuting, school attendance, shopping, and similar usage.
- Bicycles were redistributed at 3:00 pm to meet the demand at 4:00 pm.
- Bicycles were redistributed at 7:00 pm to meet the demands of users commuting to work or school the following day.
- Repositioning within the same block was not conducted.

Optimization Conditions:

- Minimize the increase in CO_2 emissions associated with system implementation.

(Minimizing the total increase in CO_2 emissions from bicycle reallocating trucks, manufacturing of bicycle reallocating trucks, and the production of new bicycles)

CO_2 Emission Source Unit:

- The CO_2 emissions per 1 km traveled by truck and per manufacturing of a 2-ton truck and a bicycle were 0.31 kg/km[8], 8,000 kg/truck[9], and 168 kg/bicycle[8], respectively
- The lifespans of a truck and a bicycle were 10 and 5 years, respectively.

(3) Estimation of CO_2 Emission reduction considering shared bicycle usage

The reduction in CO_2 emissions due to changing from using automobiles (private cars and taxis), buses, and electric motorcycles to shared bicycles was estimated under the following preconditions and methods.

Preconditions:

- Percentage of commuters at 8:00 am: Utilizing our survey results.
- Percentages of people who shop or travel at 1:00 pm were 100%, 75%, and 50%.
- Bicycle usage based on travel distance: Utilizing our survey results.
- Proportions of individuals transported to each block: utilizing our survey results

Estimation method:

- We estimated the total travel distance of automobile, bus, and electric motorcycle users switched to shared cycling based on the interblock distance, travel distance segments, and mode of transport between blocks.
- Reduced CO_2 emissions were estimated by multiplying the per capita CO_2 emission factors for each mode of transportation by the number of kilometers traveled per person, assuming a transition to bicycle sharing by automobile, bus, and electric bicycle users, resulting in zero CO_2 emissions during travel.

CO_2 Emission Source Unit:

- CO_2 emissions per person per kilometer traveled using automobiles, buses, and electric motorcycles were 133.46, 42.36, and 7.02 kg/km/person, respectively.[10]

(4) Estimation of willingness to pay for shared cycling usage

a) Conjoint analysis evaluation model[11]

To evaluate the benefits (V) of shared cycling usage, we consider the distance to the shared cycling port (POR), the percentage reduction in CO_2 emissions from using shared cycling (CO2), and the cost per shared cycling usage per case (FEE), and assume the following linear model:

$$V = \beta_{POR} POR + \beta_{CO2} CO2 + \beta_{FEE} FEE \qquad (1)$$

where β_{POR}, β_{CO2}, β_{FEE} are parameters for each evaluation attribute.

b) Creating question cards for conjoint analysis

We established the levels for the three evaluation attributes listed in Table 1 and extracted 23 combinations (profiles) using an orthogonal design. We created eight sets of profiles (cards) where trade-offs occurred and presented them in choice-based conjoint analysis questions. An example is presented in **Fig. 3**. We assigned four questions to each respondent for the conjoint analysis.

Parameter β was estimated using a conditional logit model based on random utility theory. The marginal willingness-to-pay amount ($MWTP_m$) for a one-unit increase in attribute m was obtained using the following equation[11].

$$MWTP_m = -\beta_m / \beta_{FEE} \qquad (2)$$

Table 1 Attributes and levels for conjoint analysis evaluation

evaluation attributes	level
POR：Distance to the port (m)	10, 50, 100, 300, 500
CO_2：CO_2 emission reduction percentage	10%, 30%, 50%, 70%
FEE：One-time usage fee per instance (yuan (yen))	0.5, 2.5, 5, 10, 25 yuan (10, 50, 100, 200, 500 yen)

Q. Please choose the most desirable one among the following three bicycle-sharing systems.

	port distance	CO_2 reduction ratio	charge
(1)	10m	10%	10 yuan
(2)	100m	30%	5 yuan
(3)	300m	70%	0.5 yuan

Fig. 3 Examples of conjoint analysis questions

Table 2 Composition of sample by gender and age group (unit: person)

Age	0-20	21-30	31-40	41-50
man	182	522	290	118
woman	307	810	608	221
total	489	1332	898	339

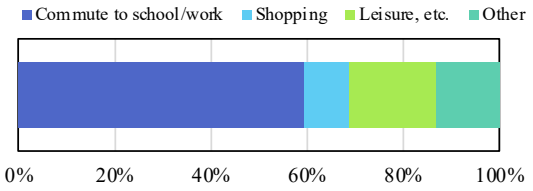

Fig. 4 Distance traveled and bicycle usage percentage

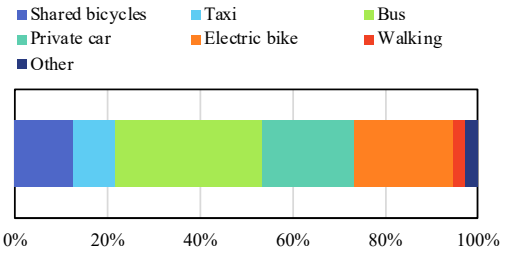

Fig. 5 Proportion of main transportation choices

5. RESULTS AND DISCUSSION

(1) Overview of the survey

The survey was conducted online, using the 'Wenjuanxing' platform (a specialized web page for collecting responses) by Chengdu Beiyan Tong Data Technology Co., Ltd, Chengdu, China. The survey was conducted from May 16 –20, 2023, and received 2,215 valid responses from residents of the Yuanhui District. The compositions of the samples obtained considering sex and age groups are presented in **Table 2**.

The proportion of primary travel purposes is presented in **Fig.4**, with commuting and school-related travel accounting for 59.4% of the total.

The distribution of the principal modes of transportation is illustrated in **Fig. 5**, and usage of buses, electric automobiles, and shared bicycles was 31.6, 21.5, and 12.4%, respectively.

Fig. 6 presents the selection percentages of the reasons for using or wanting to use shared bicycles among those currently using or considering their use.

Table 3 presents shared bicycle utilization rates considering travel distances. The top preferences are driven primarily by convenience, with options such as 'Having a bicycle parking area near a home or along the route home,' 'need to use the bicycle for distances not requiring using a bus,' and 'need to reduce travel time' ranked highest. The choice of 'having a bicycle parking area near home or along the route home' was the highest (35.5%) considering preferences, indicating that with a well-established network of bicycle parking areas, bicycle-sharing is expected to increase.

Reasons	utilization rate
There is a bicycle port near the house or along the travel route	35.5%
I would like to use it when the ports aren't so far	35.1%
I want to shorten the required time	33.6%
I want to use it in a place with inconvenient transportation	24.4%
I want to reduce transportation expenses	22.0%
I want to use when the road is congested	20.4%
Using bicycle is environmentally friendly	12.7%
I am interested in health issues.	7.3%
For the prevention of the novel coronavirus	4.3%
That sounds stylish	2.6%
Other	2.6%

Fig. 6 Reasons for using bicycle-sharing (multiple answers)

Table 3 Distance traveled and bicycle usage rate

Travel Distance (m)	bicycle usage rate
0-500	14.9%
500-1000	42.5%
1000-3000	25.8%
3000-5000	5.8%
5000-10000	5.8%
10000-	5.1%

Contrastingly, the percentages of those concerned about health and the environment were relatively low (12.7% and 7.3%, respectively), indicating a low intent to use bicycles considering the environment.

(2) Estimation of the reduction in CO_2 emission due to shared bicycle usage

The results of the estimation of the number of shared bicycle users and CO_2 emissions after implementing the shared bicycle system, with 100% of the non-commuters' traveling rates, are presented in Table 4, based on the data presented in Table 3.

After system configuration, the proportion of shared bicycle users during the non-commuting period is expected to increase from 11.8% to 26.7% and from 8.8% to 23.6% for work/school travel, respectively. However, the reductions in CO_2 emissions remained at 13.9% and 13.0%, respectively, indicating that many shared-bicycle users covered ≤1 km.

Table 5 presents the estimated results for the number of bicycles and trucks in use and the CO_2 emissions when satisfying the demand for shared bicycles, while minimizing the emissions of the overall system. **Table 6** presents the breakdown of CO_2 emissions before and after system implementation.

Transitioning from using automobiles and buses to a bicycle-sharing system resulted in a 13.5% (1- (37,447 + 22,083)/ (43,479 + 25,377)) reduction in CO_2 emissions during transportation (Table 4). However, the overall CO_2 emission reduction of the system was 8.3% (5,591/ 67,716) owing to the increased CO_2 emissions from the manufacturing of bicycles and trucks and truck operations (Table 6). The proportion of CO_2 emission increase attributed to truck manufacturing and operations was 22.0% ((263 + 610)/ (263 + 610 + 310)), which was relatively lower than that of bicycle manufacturing. Therefore, the utilization of repositioned trucks promotes bicycle sharing.

Table 7 presents the breakdown of CO_2 emissions before and after the introduction of the system when the movement rates of non-commuters were 75% and 50%, respectively. When the non-commuting travel rate was 75% and 50%, the overall CO_2 emissions reduction for the system was 8.5 and 10.4%, respectively, indicating that reducing non-commuting travel can effectively decrease the overall CO_2 emissions of the system, increasing the operational efficiency within the range of non-commuting travel rates by up to 50%.

3) Monetary benefit of reducing CO_2 emissions due to bicycle sharing

The parameter estimation results of the model based on the responses to the conjoint analysis are presented in **Table 8**. All parameters were significant at a 1% level of significance. The estimated marginal

Table 4 User distribution and CO_2 emissions before and after repositioning of the track system

Number of people in transit (person) per day

Modes of Transportation	Current		After System optimization	
	Commuting and School	Other	Commuting and School	Other
Car	45,371	29,314	37,969	24,963
Bus	36,057	27,491	29,946	22,883
Electric Bike	25,801	16,700	21,153	13,807
Shared Bicycle	14,688	7,334	33,294	19,603
Walking	2,736	2,195	2,291	1,778
Total	124,653	8,3034	124,653	83,034
Shared Bicycle Usage Rate	11.8%	8.8%	26.7%	23.6%

CO_2 Emissions from daily transportation (kg/day)

Modes of Transportation	Current		After system optimization	
	Commuting and School	Other	Commuting and School	Other
Car	34,942	18,807	30,124	16,401
Bus	7,700	6,001	6,612	5,195
Electric Bike	838	569	711	487
Shared Bicycle	0	0	0	0
Walking	0	0	0	0
Total	43,479	25,377	37447	22,083
CO_2 reduction ratio	–	–	13.9%	13.0%

Automobiles include private cars, taxis, and others.

Shared bicycles include privately owned bikes.

Table 5 Number of bicycle and truck utilization and CO_2 emissions in the case of minimizing CO_2 emissions

Bicycle and truck utilization (units)

	Current	After system optimization
Bicycle	5,878	31,355
Truck	0	142

Daily redeployment truck travel distance (km)

	Current	After system optimization
day	0	399
night	0	206

CO_2 emissions from bicycle and truck manufacturing (kg/day)

	Current	After system optimization
Bicycle	541	2,902
Truck	0	389

CO_2 emissions from daily redeployment truck operations (kg)

	Current	After system optimization
day	0	123
night	0	63

Table 6 Breakdown of daily CO_2 emissions before and after system optimization

	Current (A)	After (B)	B-A
Movement	67,175	58,142	-9,033
Truck Operation	0	263	263
Bicycle Manufacturing	541	3,110	2,569
Truck Manufacturing	0	610	610
Total	67,716	62,125	-5,591

Table 7 Breakdown of daily CO_2 emissions before and after system optimization (by proportion of non-commute travel)

Percentage of non-commuting travel	Current	After	Reduction Rate
100%	67,716	62,125	8.3%
75%	61,064	55,855	8.5%
50%	54,410	48,774	10.4%

Table 8 Results of conjoint analysis

	PORT	CO2	PRI
Parameter Estimates (β)	-0.002	-0.005	-0.021
Standard Error	0.000	0.001	0.000
t-value	-11.046	-5.521	-50.296
p-value	0.000	0.000	0.000
MWTP (yen)	-0.097	-0.228	—
(yuan)	-0.005	-0.011	—
Log-Likelihood		-2311.377	
AIC		4630.754	
Number of samples		5,412	

willingness-to-pay for each attribute revealed a monetary value of 0.097 yen (0.006 yuan) for a port distance reduction of approximately 1 m and a weight of 0.228 yen (0.011 yuan) for a 1% reduction in CO_2 emissions.

6. Conclusion

The present study estimated the potential reduction in CO_2 emissions associated with daily travel by introducing a bicycle-sharing system using the Yuanhui District of Raohe City, Henan Province, China as a model. Furthermore, we calculated the monetary value of implementing a bicycle-sharing system to reduce CO_2 emissions. The results revealed that by transitioning from electric cars, buses, personal vehicles, and taxis to bicycle sharing, following bicycle sharing considering travel distance, CO_2 emissions from daily travel in Yuánhuì District could be reduced by up to 8.3%. Additionally, a monetary value of 0.23 yen (0.01 yuan) was estimated for a 1% reduction in CO_2 emissions through bicycle sharing.

The current usage fee for shared bicycles in the Yuanhui District is approximately 40 yen (2 yuan). Currently, users use shared bicycles mainly for convenience. Therefore, an additional fee of 1.9 yen (0.1 yuan) (approximately 5% increase) could be accepted by users under a shared-bicycle system considering it reduces CO_2 emissions.

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