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Planning and Layout Method for Community Bus Stops Based on Carbon Reduction Benefits

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ABSTRACT

Regarding "carbon peaking and carbon neutrality goals", with the transportation sector as a key area of carbon emissions, the development of low-carbon transportation is imminent. Urban bus route scheduling is pivotal in realizing carbon emission reduction in transportation, and this paper focuses on the achievement of optimal bus-stop layouts for increased convenience for residents. To realise carbon reduction benefits, this paper focuses on achieving the minimum personal bus trip average carbon emission, passenger trip costs and bus operation costs, while reducing the impact on other bus stops and routes by proposing bus stop planning and layout method under the micro-community scale. Through the simulated annealing algorithm, the optimised bus stop can optimise the average carbon emission of the residents' personal trip by 36.87%, while the probability of residents choosing low-carbon trip increased by 4.94%, choosing medium-carbon trip increased by 1.48% and choosing high-carbon trip decreased by 10.84%, realising a substantial carbon reduction benefit. Furthermore, this paper introduces the emotional coefficient of the residents' public transport trip to determine the effect of travel, waiting and connecting times thereof. Accordingly, new methods and ideas are presented for urban bus stop planning, and the process toward 'carbon neutrality' and 'carbon peaking' is accelerated.

KEYWORDS

community; carbon reduction benefit; public transport stop; planning and layout; simulated annealing algorithm.

1. INTRODUCTION

Entering the 21st century, the contradiction between urban construction and population, society, resources and the environment is increasing, and community, as the main place of human activities and energy consumption, are the key to controlling carbon emissions. Chinese President Xi Jinping announced at the seventy-fifth session of the United Nations General Assembly that China is striving to peak its carbon dioxide emissions by 2030 and to achieve carbon neutrality by 2060. Community, as a carbon reduction unit in the micro-scale of urban and rural construction, is of great significance to the process of realising 'carbon neutrality' and 'carbon peaking'.

The transportation sector, as a key area of carbon emissions, is the fastest growing with regard to urban carbon emissions, and the development of low-carbon urban transportation is imminent [1]. On the one hand, there is a year-on-year surge in the number of motorised and non-motorised vehicles; on the other hand, there is a rapid advancement in the construction of urban roads and other infrastructures. However, the speed of the latter is obviously lagging behind the development of vehicles, which has resulted in the prevalence of traffic congestion, traffic accidents and environmental pollution and other problems in the city.

Public transportation system is an inevitable product of urban development and one of the important infrastructures on which cities depend, and bus priority has become the goal and direction of urban transportation development. As an important part of the urban dynamic human system, the public transportation system has the advantages of meeting diversified trip needs and saving road resources, and plays a vital role in low-carbon urban transportation.

As the nodes of public transportation operation, bus stops undertake the task of meeting the requirements of stopping public transportation vehicles and boarding and alighting passengers. Therefore, planning the layout of bus stops is particularly important for the decarbonisation of urban transportation. A reasonable layout of bus stops can improve the operating efficiency of the corresponding lines and ease traffic pressure; an unreasonable bus stop layout will not only aggravate the road congestion phenomenon but also waste public transportation resources.

As the construction and planning of bus stops involves the land outside the road, the relationship between road conditions, between stops and the relationship between the stop and other modes of transportation, as well as the form of stop layout is affected by a number of factors. In the smallest scale of the city – the community, determine the layout of bus stops is basic of the station layout and create conditions for efficient implementation of traffic management. In the smallest scale of the city – the community, determining the layout of bus stops is the basis of the station layout and creates conditions for efficient implementation of traffic management.

However, the academic research results regarding the bus system focus mostly on the bus network, passenger flow distribution and intelligent scheduling, lacking systematic and in-depth research of optimal bus stops planning, which is mostly based on experience, resulting in bus stops set up to be very non-standardised in many communities in our country, which seriously affects the efficiency of public transport operations, road accessibility, as well as traffic safety and the city's environment. At the same time, there is a lack of bus stop layout solutions under the goal of carbon reduction, so it is necessary to carry out optimisation planning research regarding bus stops in order to balance the resources of the stops, reduce the carbon emission of public transportation and minimise the negative impacts of bus stops on the normal operation of urban road traffic.

Therefore, the purpose of this paper is to determine the layout of bus stops at the micro-community scale under the goal of carbon reduction, in order to make the community bus stop more convenient to serve the residents and at the same time provide new ideas for urban bus stop planning, accelerating the process towards 'carbon neutrality' and 'carbon peaking'.

2. LITERATURE REVIEW

Reasonable bus stop layout is enough to be a condition for sustainable development of a public transportation system, which has a significant impact on passenger service quality. Bus stop planning and layout research is divided into the evaluation and optimisation of bus stop site selection, and the research topics can be divided into the following three categories: (1) Achieving the maximum coverage of bus stops; (2) Mathematical model that considers bus operating costs, passenger trip costs and other factors to optimise the bus stop layout; (3) On the basis of layout of bus stops, further optimise the bus scheduling and dispatching.

The goal of the first category of research topic is realising the maximum coverage of bus stops, using the Geographic Information System and other geographic data platforms, in order to achieve the calculation and visual expression of the coverage rate via graphical recognition analysis function and demand coverage model to intuitively express the fairness and reasonableness of the planning and layout of bus stops [2–4]. This type of research is in the initial stage of planning and laying out bus stops, and today's research is demanding more than improved coverage for bus stop planning and laying out.

The second category of research topic is to optimise the planning and layout of bus stops and improve the overall service level with the goal of reducing the operating costs of bus companies and the passenger trip costs. As we all know, the original intention of the bus design is to solve the basic needs of residents' trip, so the current aim is to improve the quality of service for passengers, based on the fees or time spent, to achieve the optimal layout of bus stops [5–7]. This type of research is one of the more extensive studies conducted in the field of the bus stop layout research and has yielded notable results.

The third category of research topic is based on the planning of bus stops, conducted to improve the accessibility of the bus system, which provides a decision-making basis for the planning and layout of bus stops. It is worth noting that this category of research covers a wide range of studies, including electric bus technology and integrated electric bus planning approaches [8], comprehensive assessment methods for the performance of public passenger transport timetable performances [9], evaluation models for bus route optimisation schemes [10], optimisation of bus stop spacing to minimise bus operating costs, and so on. This type of research is currently the most popular research direction of bus stop planning and layout, and has a wide range of development space.

In this paper, we need to scientifically monitor and evaluate the carbon footprint of personal trip of community residents through personal trip chain, which provides basic data for bus stop planning research. Personal trip chain, also known as activity-based trip mode research, mainly includes the following information: trip origin and destination, and trip transportation mode. Trip in this paper refers specifically to daily trips from that community.

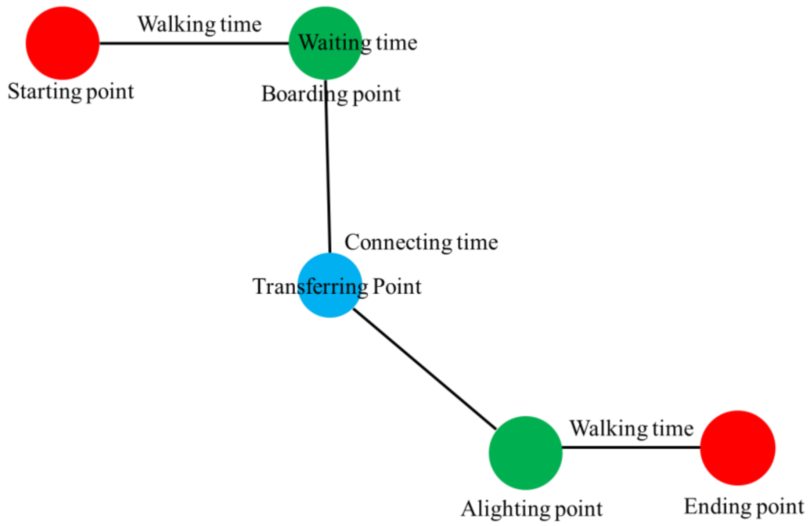

Figure 1 – Public transportation personal trip chain

It is worth noting that scholars mainly acquire personal trip chain data in two ways: (1) Extracting personal trip characteristics through mobile Internet location data such as cell phone signalling data and *GPS* data; (2) Sharing urban transportation resources and managing transportation-related services through electronic interactive interfaces.

For the former, scholars have mainly obtained trip data through *GPS* and other positioning devices, and have studied the residents' personal trip purposes and transportation modes [11–12]; for the latter, due to the development of science and technology, scholars can directly integrate the trip services of multiple modes of transportation through trip and service platforms, obtaining complete personal trip data and providing a data base for the study [13].

The study in this paper takes into account the environmental factors missing in previous studies, and fully explores the rational layout of bus stops under the goal of 'carbon neutrality' and 'carbon peaking', providing guidance for optimising the layout of bus stops and realising the benefits of carbon reduction. Accordingly, this paper obtains the probability of the selection of each trip mode and individual trip carbon emissions based on the existing bus stops in the community by extracting the trip chain data of 572 volunteers in the time period of one week. At the same time, in order to minimise individual bus trip carbon emissions, passenger trip costs and bus operation costs, while reducing the impact on other bus stops and routes, the planning of community bus stops is proposed as the objective layout plan to attain the average carbon emissions of the residents' personal trip, as well as the community residents' trip mode of transportation, so as to evaluate the reasonableness of the layout of the bus stops.

3. DATA AND METHODS

3.1 Site selection and profile of the community

Through the government service platform, we obtained the most suitable community size of 0.5k–1.2w population. Furthermore, we found the resident population, the land area of all the communities in Shenyang City, and we used the Baidu Map Path Planning API to confirm the size of the community and the situation of the peripheral bus stops, thereby selecting Ideal New City as the final selection for case study.

This is a community case study for No 6, Baita Street, Ideal New City, a community located in Shenyang City, Hunnan District. The red serial numbers indicate the existing bus stops and the green serial numbers indicate alternative bus stops. *Figure 2* depicts the overview of the bus stops in the Ideal New City community.

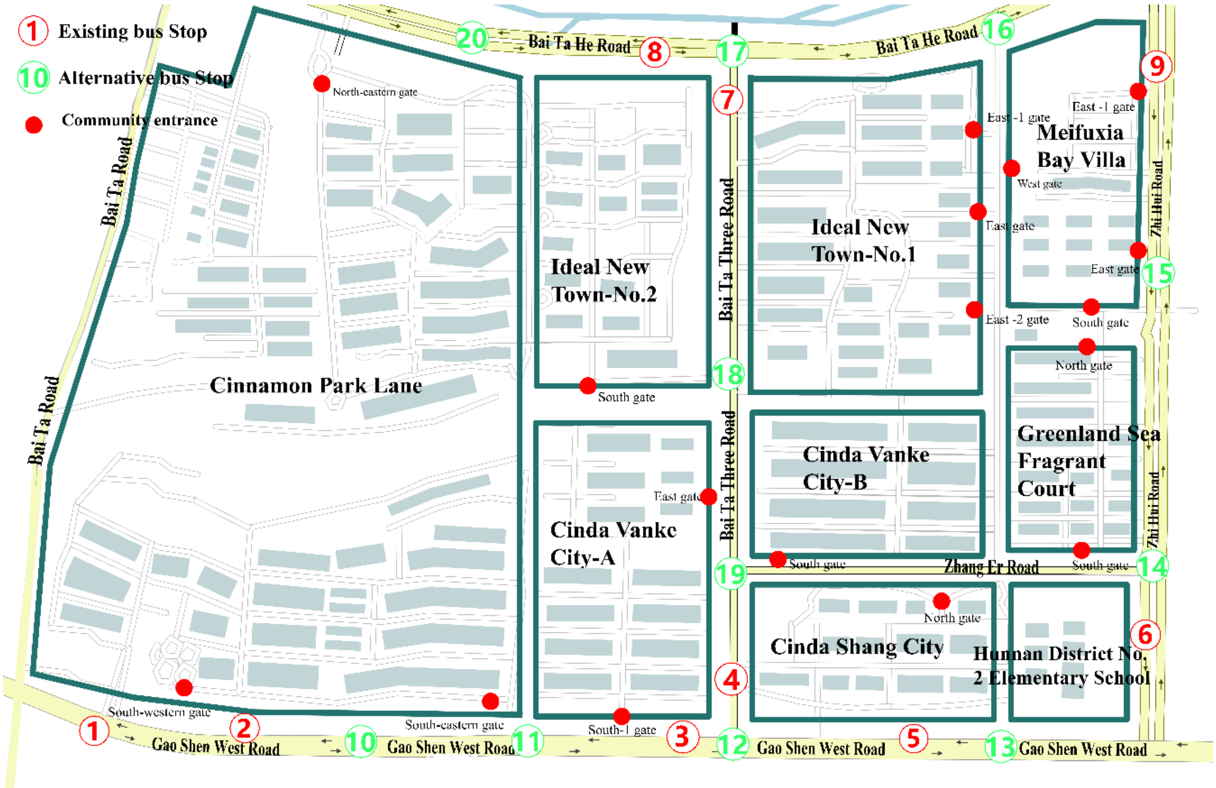

Figure 2 – Map of public transport stops in the Ideal New City community (Author's own drawing)

3.2 Data sources and data processing

Road data

The road data come from the OpenStreetMap, which are the vector data of different levels of roads. In addition, the actual path distances from each neighbourhood entrance to the bus stops are obtained using the Baidu Map Path Planning API. To ensure the accuracy of the data, we conducted manual ranging in the Ideal New City community. The results are described in *Table 1*.

Table 1 – Neighbourhood demand point to public transport stop paths and schedules

Bus stop *ID*	**Community entrance**	**Actual path distance /*m***
1-GaoShen Road Baita Road	Cinnamon Park Lane-South-western gate	87
1-GaoShen Road Baita Road	Cinnamon Park Lane-South-eastern gate	665
1-GaoShen Road Baita Road	Cinda Vanke City A-South-1 gate	815
……	……	……
9-Zhihui Road Baita He Road	Meifuxia Bay Villa East gate	244

Personal trip data

In the survey organisation and implementation stage, the authors recruited 572 volunteers in the Ideal New City community, comprising commuters, students and the elderly, and the mode of trip includes a variety of modes, including bus, subway and car trip. After installing the mobile data collection software for the volunteers, individual *GPS* trip chain traffic data in a week are obtained and recorded in *Table 2*.

In this paper, we use the path navigation data obtained based on the Baidu Map open platform for the collection of trip chain data, where the data refers to each completed trip, involving the mode of transportation, trip time, waiting time, connecting time, boarding stops and alighting stops. Finally, we collected the trip sentiment scores of the completed trips to get all the data of the trips here. The Baidu Map Path Planning API (Application Programming Interface) is a tool that allows us to query the corresponding trip route, trip time, distance, cost, transfer information and walking time by entering the latitude and longitude information of the starting point and ending point, as well as the type of trip mode (walking, public transportation and driving). By combining the origin and destination points of trips uploaded by residents without completing a trip, as well as inbound and outbound station data, complete trip behaviour data of residents can be obtained.

Table 2 – Personal trip data

Carbon source	Non-motorised trips	Public transport trips	Subway trips	Fuel vehicle trips
Personal trip data	*GPS* Tracks	GPS Tracks	GPS Tracks	GPS Tracks
	Travel distance	Boarding point	Boarding point	Boarding point
	Travel time	Alighting point	Alighting point	Alighting point
	Waiting time	Travel distance	Travel distance	Travel distance
	Connecting time	Travel fee	Travel fee	Travel fee
		Travel time	Travel time	Travel time
		Waiting time	Waiting time	Waiting time
		Connecting time	Connecting time	Connecting time

Data on public transportation operations

Public transportation operation data relating to fixed costs and variable costs were provided by the Shenyang City Bus Group, as shown in *Table 3*.

Table 3 – Neighbourhood demand point to public transport stop paths and schedules

Data sources		
Public transportation operations data	Personnel costs	Bus depreciation costs
	Acquisition of bus	Fuel consumption costs
	Maintenance costs	Useful life of the vehicle

3.3 RESIDENTS' TRIP MODE AND CARBON EMISSION ACCOUNTING

Residents' trip mode

This paper reclassifies trip modes into three levels based on the personal carbon intensity of each type of transportation, with a carbon intensity of 0 ~ 10 g/(person-km) as low-carbon trip modes, including walking, bicycles and electric powered vehicles; 10 ~ 100 g/(person-km) as medium-carbon trip modes, including motorcycles, bus, subways and shuttle bus; and 100 g/(person-km) or more as high-carbon trip modes, including private car, rental car and distribution car. The specific divisions are as follows.

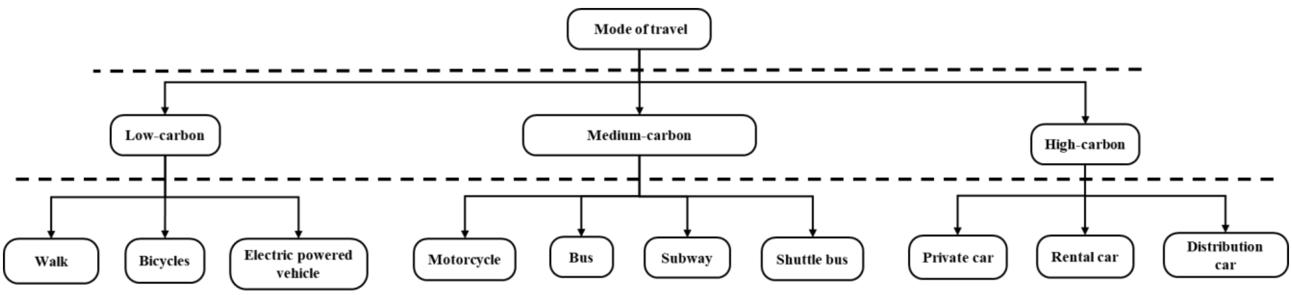

Figure 3 – Residents' trip mode

In this paper, travel times, waiting times and connecting times were the factors affecting the choice of the residents' trip plan [14]. In the survey implementation and organisation stage, 2381 valid sample data were obtained, and after data collation and post-testing, the probability of choice of each trip mode of the community residents was obtained.

Accounting for carbon emissions from residential trip

Owing to the temporary lack of official public large-scale statistics on carbon emissions from the main body of transportation in China, as well as the lack of official authoritative standards for the carbon emission intensity of various modes of transportation, based on existing relevant research and actual situation of the relatively reliable standards, the author obtained the carbon emission intensity of the various types of transportation modes generated by person-kilometre trip [15], the unit of $g\cdot(person\cdot km)^{-1}$, and the specific values are presented in *Table 4*.

Table 4 – Carbon intensity of person-kilometre trips generated by various modes of transportation F_{PKM}

Transportation category	Transportation mode	Carbon intensity of individual trips
Low carbon	Walk, Bicycles	0
	Electric vehicle	8
Middle carbon	Motorcycle	45
	Bus, Shuttle bus	35
	Subway	40
High carbon	Rental car	110
	Private car, Distribution car	135

For trip carbon emissions generated by various modes of transportation in the city, the carbon intensity of the trip per person-kilometre is calculated using the product of the carbon intensity of trip per person-kilometre and the mileage travelled, i.e.:

$$E_{i,k}=F_{PKM,k}\cdot D_{i,k} \quad (1)$$

where $E_{i,k}$ denotes the carbon emissions in trip segment *k* of the i^{th} resident, $D_{i,k}$ is the trip distance of the k^{th} trip segment of the i^{th} resident, the trip mileage of the i^{th} resident is obtained based on the *GPS* trajectory data and $F_{PKM,k}$ is the intensity of carbon emissions per person-kilometre of the k^{th} trip segment [16].

4. SELECTION OF BUS STOP INDICATORS BASED ON CARBON REDUCTION BENEFITS

4.1 Carbon emissions per capita from public transportation

Full load factor refers to the average full load factor of transportation vehicles carrying passengers. The lower the full load factor of vehicles, the higher the per capita energy consumption and emissions. From the perspective of energy saving and emission reduction, improving the full load factor of vehicles is an effective way to save energy in public transportation systems.

For a certain public transportation vehicle, *M* is the actual load factor and M_{max} indicates the upper limit value of the load factor [17], which can be expressed as follows:

$$M\leqslant M_{\max} \quad (2)$$

Achieving higher fill rates is directly related to patronage. For a given public transport trip, the carbon intensity of the trip per capita generated is as follows:

$$E_{ave} = \frac{\sum E_{i,k}}{N} \tag{3}$$

where *N* represents the number of transported passengers.

4.2 Passenger trip costs

Passenger trip costs C_t , including passenger travel cost C_f , passenger waiting cost C_w and fare P_b are related as follows [18–19]:

$$C_t = C_f + C_w + P_b \tag{4}$$

Passenger travel costs are those incurred by travel time and passenger waiting costs are those incurred by waiting time. Waiting time in this context is the time a passenger spends waiting at the platform in public transport during a trip. Assuming that the departure intervals are uniform for one route, the expected waiting time for a passenger is half the departure interval [9]. Thus, it follows that:

$$C_f = U_f \cdot T_f \tag{5}$$

$$C_w = U_w \cdot T_w \tag{6}$$

$$T_w = \frac{H}{2} \tag{7}$$

$$H = \frac{1}{f} \tag{8}$$

$$f_{min} \leqslant f \leqslant f_{max} \tag{9}$$

where U_f and U_w denote the values of travel and waiting times, respectively; yuan/min; T_f denotes the travel time to the stop; T_w denotes the waiting time, since the time for a passenger to arrive at a bus stop is Poisson distributed, we simplify the waiting time of a passenger here as *H/2*, which is set as half of the departure time interval [20], *min*; *H* denotes the departure time interval, *min*; *f* denotes the frequency of the bus line; and f_{min} and f_{min} denote the minimum and maximum frequencies of the bus, respectively [21].

In summary, the passenger trip costs is as follows:

$$C_t = \sum_{i=1}^{I} U_f T_f + \frac{U_w H}{2} + P_b \tag{10}$$

4.3 Public transportation operating costs

Bus-operating companies are responsible for the operation and management of community buses [22]. The cost of public transport operations C_o includes fixed costs C_u *(yuan)* and variable costs C_f *(yuan).*

The fixed costs are the sum of the personnel cost, bus acquisition, maintenance cost, bus depreciation cost C_k (*yuan*). The variable costs are the sum of the fuel consumption cost C_r *(yuan)*, etc. [23].

The amount of fuel consumed by a bus travelling at a constant speed is different from the amount of fuel consumed at stops; the more the bus stops frequently, the more fuel it consumes. In this paper, we assume that the stopping time during bus operation is about 10% of the constant speed time and the fuel cost C_r is as follows:

$$C_r = F_p \times \left(F_i \cdot L + 0.1 \times F_i \cdot L \cdot \sum y_i\right) \tag{11}$$

where F_p is the unit price of fuel for type *i*, *yuan/L*; F_i is the energy consumption when the bus travels at a constant speed; *L* is the distance travelled by the bus at a constant speed, km; y_i is the stop that the bus stops.

Buses that have exceeded their useful life need to be scrapped according to the requirements, so when calculating the depreciation cost of bus, it is spread evenly into the hourly operating cost, then the bus depreciation cost can be expressed as follows:

$$C_k = \frac{(1-5\%)P}{S \times 365 \times 24} \times 10^4 \tag{12}$$

where *P* is acquisition of bus; *S* is the useful life of the vehicle; 5% is the residual value of the vehicle. Different countries have different requirements for the depreciation rate of buses, so the actual study needs to be adjusted according to the national norms. This paper takes the depreciation rate of the author's country as 5%.

Based on the above-stated analysis, the operating cost of the company is as follows:

$$C_o = C_u + C_f \tag{13}$$

4.4 Impact of sites and routes

The location of bus stops needs to consider the distance between two stops and the impact of other routes. Longer distances between stops are likely to cause inconvenience to passengers and reduce their willingness to travel by public transportation; shorter distances between stops are likely to raise the cost of public transportation operations and increase carbon emissions. The bus stop spacing was introduced to ensure that newly planned bus stops in the community would create reasonable connections to the next or previous bus stop, i.e.:

$$l_{\min} \leqslant l_{j,\, j+1} \leqslant l_{\max} \tag{14}$$

where $l_{j,\, j+1}$ denotes the distance between bus stops, and $l_{\min}$, $l_{\max}$ denote the minimum and maximum bus stop spacing, respectively.

Bus stops are generally set up in a little more than one line; when too many bus lines pass through the site, it is easy to cause raw bus vehicles queuing to enter the stop, passenger disorder and even the phenomenon of buses parked in other lanes. Accordingly, the location of bus stops needs to consider the impact of other bus lines; [24]. Therefore, passenger walking access time T_j leads to a passenger access trip costs C_j as follows:

$$C_j = U_f \cdot T_j \tag{15}$$

where T_j denotes passenger walking time to connect and U_f denotes the value of walking time, *yuan/mi*n.

5. CONSTRUCTION OF THE SITE SELECTION MODEL

5.1 Description of the problem

The assumptions that need to be met for the modelling are as follows:

1) Each neighbourhood entrance and bus stop is viewed as a geometric point at its geometric centre.
2) The distance from each neighbourhood entrance to the bus stop is calculated as the actual roadway distance.
3) Each bus stop can meet the trip demands of residents.

5.2 Objective function and constraints

Based on the above-stated analysis, the objective function of this model should be as follows:

Set the optimisation objectives as follows:

Minimum personal bus trip carbon emissions:

$$\min\ E_{ave} \tag{16}$$

Minimum passenger trip costs:

$$\min\ C_t \tag{17}$$

Minimum public transport operating costs:

$$\min\ C_o \tag{19}$$

Minimise impacts on other stops and routes:

$$\min\ C_j \tag{20}$$

The aforementioned optimisation objectives are integrated, all influencing factors are dimensionless and the processing equation is given as follow [25]:

$$S_j = \max - S'_j \tag{21}$$

$$S'_j = \frac{D_j^-}{D_j^+ + D_j^-} \tag{22}$$

where D_i^- denotes the distance between the j^{th} influence factor and its minimum value, and D_j^+ denotes the distance between the j^{th} influence factor and its maximum value.

Establish the objective function:

$$f = \min \sum_{i=1} (\lambda_1 E_{ave} + \lambda_2 C_t + \lambda_3 C_o + \lambda_4 C_j) \tag{23}$$

The constraints should also be satisfied, see *Equation 24*:

$$\begin{cases} \sum_{j=1}^{n} y_j = p \\ \sum_{j=1}^{n} x_{ij} \leqslant 1 \\ x_{ij} \leqslant y_j;\ \forall i,\ j \\ x_{ij} = 0,1;\ y_j = 0,1 \\ M \leqslant M_{\max} \\ D_f \leqslant D_e \\ f_{\min} \leqslant f \leqslant f_{\max} \\ l_{\min} \leqslant l_{j,\ j+1} \leqslant l_{\max} \end{cases} \tag{24}$$

where $\lambda_1,\ \lambda_2,\ \lambda_3,\ \lambda_4$ represent the weight coefficients of the four objectives, and $\lambda_1 + \lambda_2 + \lambda_3 + \lambda_4 = 1$, set in this paper as $\lambda_1 = \lambda_2 = \lambda_3 = \lambda_4$; *p* is the number of constructions of the actual bus stops (which $p \leqslant n$); when $x_{ij} = 1$, it indicates that the public transportation demand of the cell entrance and exit *i* is served by the actual bus stop *j*, otherwise it is 0; when $y_j = 1$, it indicates that bus stop *j* has been selected, otherwise it is 0; the meaning of all the parameters in the equation is the same as the previous case.

In a systematic review, Norgate et al. reported the relationship of trip emotions among commuters, with commuters experiencing higher levels of emotions in active modes (e.g. biking and walking) [26]; Friman, M , et al. suggested that among all daily activities and modes of transportation, the lowest levels of emotions were found in public transportation and car commuting [27]; Morris and Guerra concluded that people traveling by bus had the lowest trip emotions [28]. Therefore, we introduced the coefficient of residential public transport trip sentiment and defined it as the cost of the trip experience due to an individual's choice of public transport trip [29–30]. As mentioned earlier, travel, waiting and connecting times are the three major factors affecting the choice of the residents' trip options, and all of them are inversely proportional to the probability of the residents' choice of public transport trip, i.e. the longer the travel time, the longer the waiting time, the longer the transportation connecting time, the smaller the probability of residents' choice of green public transport trip; and the worse the trip experience of the residents, the lower the coefficient of trip sentiment. In this paper, P_1, P_2, P_3 are introduced to denote the impact of travel time, waiting time and connecting time on the emotional coefficient of the residents' public transportation trip.

Partial regression analysis was used to study the influence on the overall public transport service perception of the sample [13]. Travel time, waiting time and connecting time were taken as independent variables, and the comprehensive index of trip happiness was taken as dependent variable for partial analysis [31–32], the relationship between travel time, waiting time, connecting time and the comprehensive index of trip happiness can be studied, i.e. P_1. P_2, P_3.

6. RESULTS AND DISCUSSION

Simulated annealing is a general-purpose stochastic intelligent optimisation algorithm. It was first proposed by N. Metropolis et al. in 1953, and then, S. Kirkpatrick et al. successfully introduced the idea of annealing into the field of combinatorial optimisation in 1983. When solving combinatorial optimisation problems, the simulated annealing algorithm can probabilistically jump out of the local optimal solution and eventually converge to the global optimum [33].

As can be seen from *Figure 4*, in the simulated annealing process of the algorithmic program, as the t overall number of iterations increases, the value of the objective function gradually decreases and eventually stabilises. When the number of iterations reaches 900 times, the result tends to stabilise, realise the optimal layout of the bus stops in the ideal new city community.

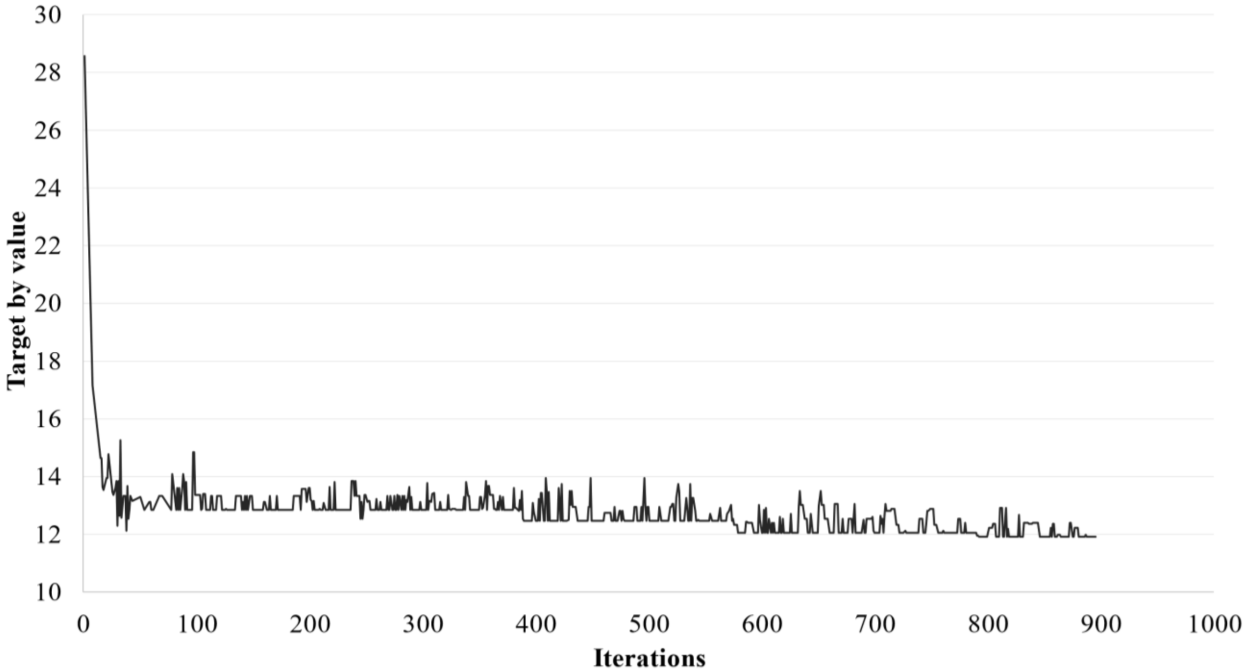

Figure 4 – Simulated annealing iteration curve (Author's own drawing)

In the process of bus stop planning, the number and the location of stops is constantly changing, so we change the number of optimised bus stops, respectively. The number of bus stops set to 4, 5, 6, 7, 8, 9. When the number of bus stops is 7, the minimum objective function can be achieved and the optimisation objective is achieved, $f_{min} = 11.9071$. The following *Figure 5* shows the optimised bus stop map. The symbol of star represents the optimised bus stops and the line segment from the entrance and exit of the district to the bus stop indicates the shortest distance from the passenger's point of view. It can achieve the minimum connecting time based on walking, so it reduces the walking time of the passengers.

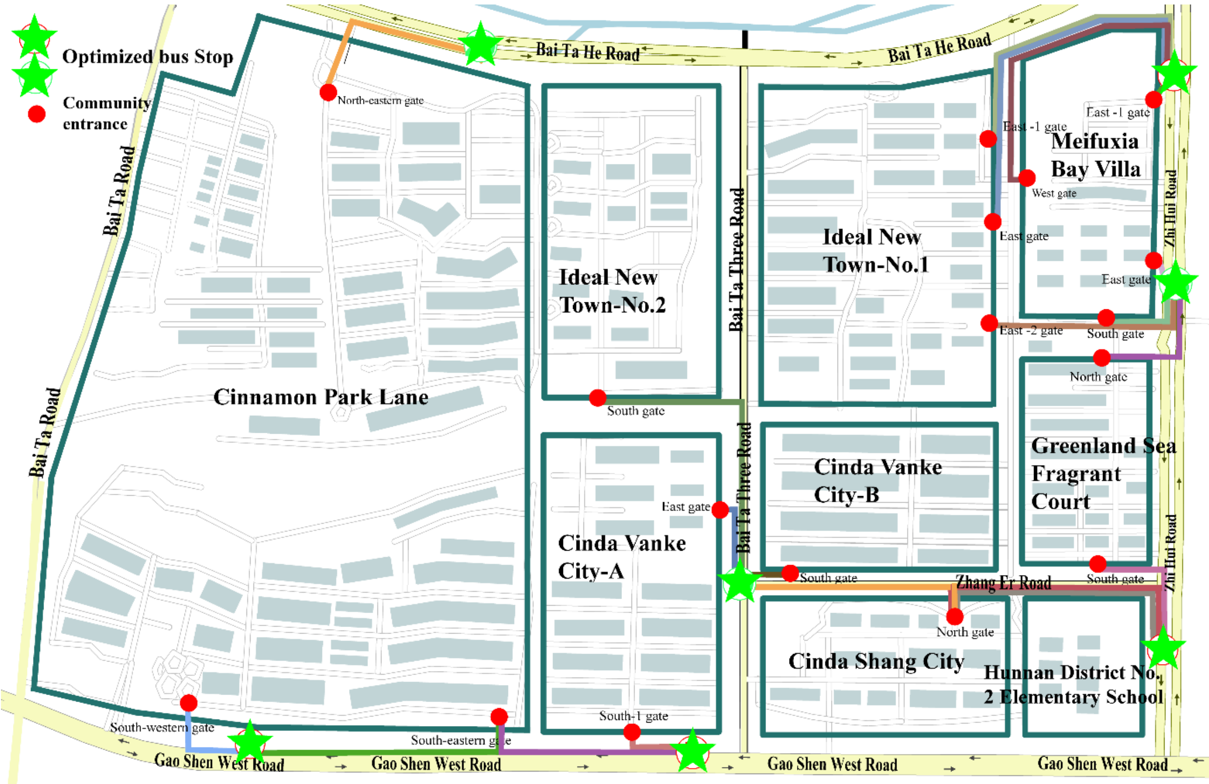

Figure 5 – Optimised bus stop overview map of the Ideal New Town community (Author's own drawing)

It is evident from *Figure 5* that the number of bus stops in the community has been optimised from nine to seven. In Gao Shen West Road, the existing bus stop #2 and #3 were selected as the optimised bus stops, and the existing bus stops #1, # 5, as well as the alternative bus stops #10, #11 #12 and #13 were deleted; in Zhi Hui Road, the existing bus stops #6 and # 9, and the alternative bus stop #15 were selected as the optimised bus stop, the alternative #14 was deleted; in Bai Ta He Road, the alternative #20 was selected as the optimised bus stop, the existing #8 and the alternative #16, #17 were deleted; and in Bai Ta Three Road, the alternative #19 was selected as the optimised bus stop, the existing #4 and the alternative #18 were deleted. In summary, four existing bus stops and three alternative bus stops were selected as optimised bus stops, and the remaining existing and alternative stops were deleted.

In addition, we get the figure of choosing each type of transportation mode before and after optimisation as follows:

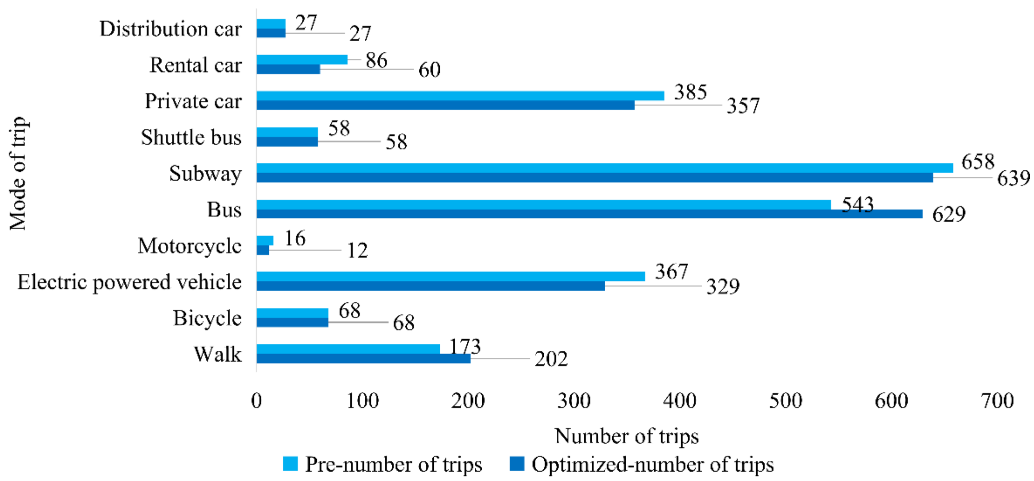

Figure 6 – The figure of choosing each type of transportation mode before and after optimisation

The probability of residents choosing low-carbon trip has increased by 4.94%, the probability of choosing medium-carbon trip has increased by 1.48%, and the probability of choosing high-carbon trip has decreased by 10.84%, and the optimisation of the community residents' trip modes to 17.26%. These changes have led to an optimization rate of 17.26% in the travel modes of community residents.

We get individual travel carbon emission by multiplying the carbon intensity of individual trips with the distance travelled. By calculating the carbon emissions of residential trips after optimisation and comparing them with the carbon emissions of residential trips before optimisation, we get the figure of average carbon emissions of personal trips by each type of transportation mode before and after optimisation as follow:

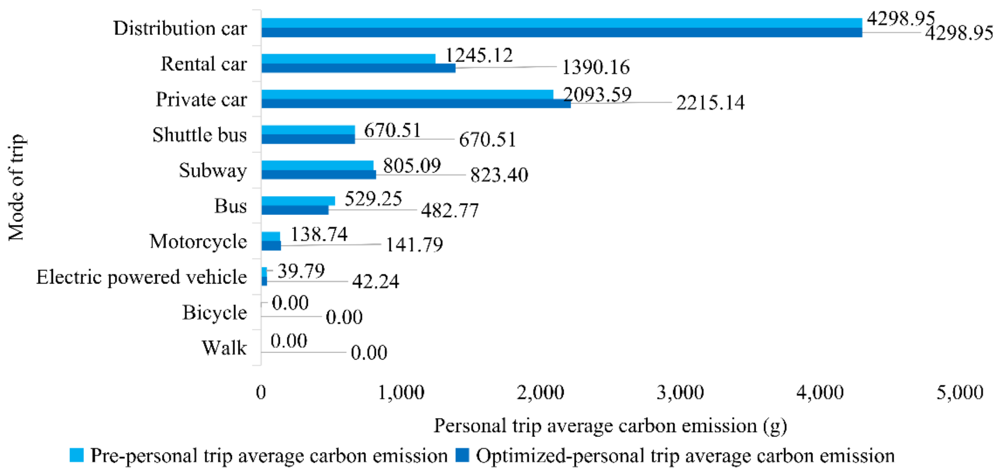

Figure 7 – The figure of average carbon emissions of personal trips by each type of transportation mode before and after optimisation

The average carbon emission of personal trips calculated under the existing bus stops is 1006.49g, while the average carbon emission of personal trips after optimisation is 982.10g, and the optimisation of the average carbon emission of personal trips is 36.87%, which achieves substantial carbon reduction benefits.

In addition, the relationship between travel time, waiting time, connecting time and the comprehensive index of trip happiness is presented in *Figure 8*:

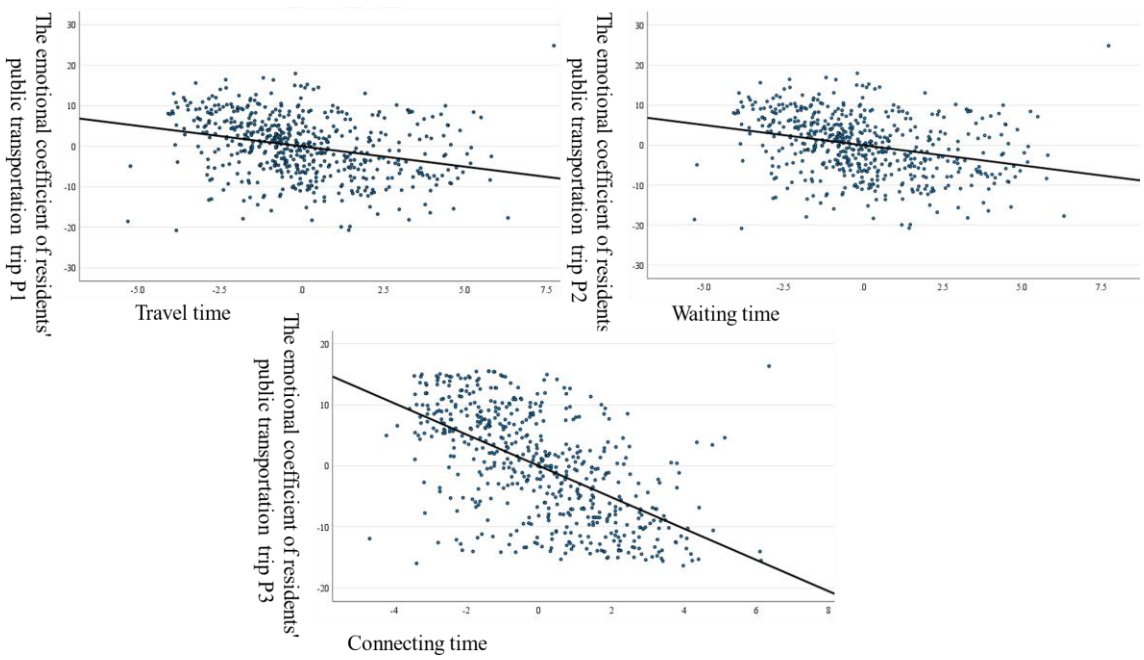

Figure 8 – Relationship between travel time, waiting time, connecting time and public transport trip probability

The results of the survey show that when the travel time is within the interval of 0–6 minutes, the residents' acceptance of public transportation is very high, but when the travel time is 10 minutes and above, the residents' acceptance of public transportation is very low; when the waiting and connecting times are within the interval of 0–10 minutes, the residents' acceptance of public transportation is very high, but when the waiting and connecting times are 20 minutes and above, the residents' acceptance of public transportation is very low [32–34]. By calculating the emotion coefficient of public transport trip after optimisation, it is found that the optimisation of the emotion coefficient of public transport trip is not obvious. As mentioned above, the residents' trip emotion coefficient is affected by travel time, waiting time and connecting time. We can reduce the residents' travel time by optimising bus stops and planning trip routes, but waiting time is affected by the frequency of the bus route scheduling and the residents' arrival at the stop, while connecting time is affected by whether other modes of transportation can reasonably connect with the bus route. In summary, improving the level of bus service and realising the accessibility of bus stops to reduce the waiting time and connecting time are particularly important for increasing the emotion coefficient of public transport, in order to realise the carbon reduction benefits of the community.

7. CONCLUSION

This paper proposes a community bus stop planning and layout scheme based on carbon reduction benefits, with the goal of realising the minimum individual bus trip carbon emissions, passenger trip costs and bus operating costs, while minimising the impact on other sites and routes at bus stops. It establishes a simulated annealing model to obtain the optimal bus stop location in the Ideal New City community, and the optimisation of the average carbon emission of personal trip is 36.87%, with the optimisation of the community residents' trip modes to 17.26%, which realises a substantial carbon reduction benefit and provides a theoretical basis and decision-making reference for the relevant governmental departments to formulate the carbon emission reduction target of urban transportation.

The innovation of this paper lies in the following: 1) The results of the study are more valuable and can be widely applied to the planning and layout of bus stops and other public infrastructure in other areas; 2) The emotional coefficient of public transport is introduced to obtain the emotional impact coefficients of travel, waiting and connecting times on the public transport travellers' bus trips, providing suggestion for the optimisation of bus stops; 3) Based on the cell phone application, the GPS and the carbon footprint of the residents' trips based on the GPS data are collected, with a high degree of credibility.

Future research should focus on the following: First, in this paper, the influencing factors of carbon emissions of public transportation vehicles only consider passenger capacity; in fact, there are many factors affecting the carbon emissions of public transportation vehicles, such as vehicle type, vehicle manufacturing and driver behaviour. However, it is difficult to obtain the relevant information and conditions for accurate calculations using GPS data. In future research, more detailed data can be used to conduct accurate emissions analysis. Second, the residents' stop selection behaviour is related to a variety of factors, and this paper assumes that all stops can meet the residents' trip needs, so an in-depth discussion of their internal logic will significantly improve the efficiency of the bus stop selection model. Third, the methodology in this paper is to recommend the planning and layout of bus stops, and this does not include bus scheduling and dispatching. Therefore, future research can establish a scheduling model for calculating the carbon emissions of buses from the actual operation of buses.

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基于减碳效益的社区公交站点规划布局方法

摘要：
"双碳"背景下，交通部门作为碳排放的重点领域，交通低碳化发展迫在眉睫。城市公交线路规划对于实现交通碳减排有着举足轻重的作用，如何实现公交站点的优化布局，使其更加便捷地为居民服务，是本文研究的关键问题。在实现最大减碳效益的目标下，本文以实现公交站点的最小个人公交出行碳排放、最小乘客时间成本、最小公交运营成本、最小化对其他站点和线路的影响为目标，提出微观社区尺度下的公交站点规划布局方案，通过模拟退火算法，得到优化后的公交站点对居民个人出行平均碳排放的优化程度为 36.87%，居民选择低碳出行概率增加了 4.94%，选择中碳出行概率增加了 1.48%，选择高碳出行概率减少了 10.84%，实现了大幅度的减碳效益，此外，本文引入居民公交出行情绪系数，得到出行时间、候车时间、接驳时间对于居民公交出行情绪的影响。通过本文的研究，能够在"碳中和""碳达峰"目标下，为城市公交站点规划提供新方法与新思路，加快"双碳"目标实现进程。

关键词：
社区；减碳效益；公交站点；规划布局；模拟退火算法