



Article

Optimizing the Location of Park-and-Ride Facilities in Suburban and Urban Areas Considering the Characteristics of Coverage Requirements

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Abstract: Within the scope of sustainability, the development of park-and-ride (P&R) facilities can reduce the exhaust emissions of motor vehicles and help build an environmentally friendly society. The location of P&R facilities is the primary consideration in planning, and it plays a decisive role in their transportation, environmental and economic benefits. Given the difficulty of obtaining full data information of traffic network attributes and travel demand characteristics, in this study the P&R facilities in the outer suburbs and cities as were taken as the research object, with a simplified transportation network, improving the principle of nearby selection and 0–1 demand coverage in existing research. By analyzing the P&R facility coverage and demand intensity characteristics, a P&R facility location model considering the coverage demand characteristics was constructed, and a solution algorithm is proposed. The validity of the established model was verified by comparing the existing location model and conducting sensitivity analysis.

Keywords: park-and-ride facility; location planning; coverage model; closure location model



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1. Introduction

With the acceleration of the urbanization process in China, the size of cities and towns is continuously expanding, and residents' travel is gradually transitioning from single-mode to multi-mode [1,2]. As an measure of traffic demand management, P&R is an important way to guide the conversion of individual travel modes to public transport modes, increase the urban public transport ratio, alleviate road traffic congestion, and reduce vehicle exhaust emissions [3–5].

The concept of park and ride was first proposed by Austin MacDonald [6]. The related research on P&R facility planning is mainly divided into the P&R facility location problem, P&R facility parking charge problem [7–9], and P&R facility evaluation problem [10]. Wiseman et al. [11] conducted a study on P&R facilities at the edge of the Adelaide Central Business District in Australia and studied the uncertainty of the impact of P&R on travel behavior. Duncan and Christensen [12] conducted a study on whether government departments need to build P&R facilities considering the new rail transit system. The results show that due to the development trend of public transportation, government departments will be more inclined to deploy P&R facilities. Domestic and foreign scholars mainly use the P median location model, coverage location model, and closure location model to optimize the location of P&R facilities.

Combined with the P median location model, using the P-hub location method, Aros-Vera et al. [13] established a hybrid linear programming model to maximize the users of P&R facilities. The model assumes that travelers can choose to travel by P&R or use a private vehicle to go to the destination, and the travel mode selection behavior follows the logit model. Cavadas et al. [14]. Considered the conventional bus travel mode on the

basis of Aros-Vera et al., distinguished the driving area of urban and suburban sections, and optimized the location model of P&R facilities with the goal of minimizing the driving distance of private vehicles in the city. He et al. [15] applied the P median location model to the location scenario of P&R facilities in the outer suburbs and established a multi-objective location model by minimizing the total weighted distance between P&R facilities and demand points in the outer suburbs and maximizing the existing P&R facilities. Taking the generalized travel cost as the quantitative index, Fang et al. [16] constructed the P&R facility selection behavior model, aiming at the maximum P&R travel demand for travelers, and constructed the location model with P&R travel attraction rate and P&R facility capacity as constraints.

Combined with the coverage model, Bilal and Alan [17] proposed a multi-objective P&R facility location optimization model, with the goal of maximizing the potential demand for P&R facility coverage, minimizing the total distance between P&R facilities and main roads, and maximizing utilization of existing P&R facilities. Lu and Guo [18] based on the criteria of maximizing the coverage of P&R facilities and minimizing the number of P&R facilities added spatial fairness constraints to avoid spatial aggregation, establishing a dual-objective P&R facility location model under spatial fairness constraints. He [15], Chen [19], and Zhang [20] applied the set coverage model to the edge P&R facility location model and constructed the P&R facility location model from the point of view of saving investment costs with the goal of maximizing the utilization of existing P&R facilities. Lu et al. [21] assumed that there is a non-linear relationship between the potential P&R travel demand and the distance between the demand point and the P&R facility, used the distance attenuation function to modify the P&R travel demand, and constructed the P&R facility location model with the goal of maximizing the transfer passenger flow and minimizing the construction cost.

Combined with the closure location model, Horner and Groves [22] constructed a P&R facility location model from the perspective of the road network with the goal of maximizing the mileage of the P&R travelers removed from the network. Both He [15] and Chen [19] set up a network closure location model under uncertain scenarios based on highway network and introduced the concept of regret degree as the objective function of the model to optimize P&R facilities with the goal of minimizing the maximum absolute regret degree in all cases. Based on the location model of P&R facilities in rail transit network, Wang [23] aimed to minimize the total travel time between the newly added P&R facilities and major roads and set the weight coefficient according to different objectives based on the greedy algorithm to solve the problem. Based on the analysis of the influence of the attraction range of adjacent P&R facilities, Cheng [24] constructed a P&R facility location model aiming at the maximum vehicle mileage on the closure network, the minimum cost-effectiveness ratio of the network, and the maximum total surplus of P&R users in the network. Gong [25] believed that in the case of the same mileage of closure, the driving time of vehicles in congested sections is smaller than that of unobstructed sections, so the maximum time cost of intercepted vehicles was taken as the horizontal index of closure to build a location model. Considering the influence of groups on the attraction intensity of travelers near rail transit stations, Zhang [20] analyzed the interaction between groups according to the gravity model, calculated the potential demand for transfer in the service area covered by stations on rail transit lines and then constructed a P&R facility location model with the goal of maximizing the mileage and minimizing the total construction cost on the whole rail network. Yang et al. [26] and Yang [27] considered that when it takes longer for travelers to travel by private vehicle than by P&R, there are penalty fees for being late to work and road congestion fees. Therefore, a closure location model was constructed by comprehensively considering P&R travel cost, vehicle depreciation fee, exhaust emission cost, and penalty cost.

Based on the current situation and trend of urbanization, this study combined the characteristics of transit network, the characteristics of facility supply and the difference of travel demand with the existing location methods, and further research was carried

out. The research results of domestic and foreign scholars on the location of P&R facilities provide a detailed theoretical basis for this study, but there are still some deficiencies.

There are few studies on the level of P&R facilities and information acquisition [15,19]. The regional development of urbanization and the characteristics of inter-regional travel demand make P&R facilities hierarchical. The hierarchical structure of P&R facilities should be focused on the outer suburbs and urban P&R facilities, and then targeted research should be carried out. P&R facilities in the outer suburbs serve the travel demand between satellite towns and central towns. Generally, they are located separately along intercity rail transit lines, connecting with intercity railways, intercity rail transit, commuter railways, etc., such as the American “bus community” that relies on the revival of rail transit stations. The P&R facilities in the urban area serve the travel demand of the urban area and are generally arranged in a ring on the outer ring of the urban area, connecting with the urban rail transit, mainly for the purpose of closing the vehicles going to the center of the urban area. For example, Cambridge has set up surrounding P&R facilities at the five major entrances and exits in the urban center, supplemented by dedicated bus lines, so as to ensure a travel time of about 15 min between the P&R facilities and the urban center. In addition, in the process of urbanization, it is difficult to fully obtain the data information of traffic network attributes and travel demand characteristics. In this case, it is necessary to build a simplified network for modeling and analysis.

In terms of P&R facility coverage, most of the existing studies [19,24] involve the application of traditional facility locations such as factories, hospitals, stores, and warehouses, without taking into account the characteristics of P&R facility coverage requirements. In terms of P&R facility coverage demand, based on the set coverage location model, the maximum coverage location model, and the closure location model, it is assumed that the P&R coverage demand range is 0–1 coverage within a fixed distance and does not take into account the P&R facility coverage demand characteristics. Since passengers need to walk to the transit station to transfer after parking their vehicles at the P&R facility during the trip, the alternative points of the P&R facility are often located near the transit station. Therefore, the coverage demand of P&R facilities should be comprehensively considered according to the layout of transit stations, combined with the accessibility of P&R facilities and travel choice behavior. For example, when the demand point is near the transit station, compared with the transit station, within the acceptable walking range of the transit station, travelers often choose to walk directly to the transit station to transfer to transit. At the same time, with the increase in the distance between the demand point and the P&R facility, the demand for P&R coverage will decrease. Therefore, on the basis of determining the coverage demand range of P&R facilities, the demand intensity within the coverage demand range should be analyzed according to the distance between the demand point and P&R facilities.

In terms of travel choice behavior, existing studies [21,28] often assume that the service model of P&R facilities is a single facility serving a single demand, that is, assuming that the distance between P&R facilities should be greater than the radius of facility coverage or that the travel demand is the nearest choice and does not take into account the scenario of multiple P&R facilities for travelers to choose. However, when travelers are faced with multiple choices of P&R facilities, the nearest P&R facilities may be abandoned due to higher fees, poor surrounding traffic conditions, or low parking success ratio due to the small size of the parking lot. In addition, according to the geographical location and capacity limitation of P&R facilities, more P&R facilities are needed in the areas with high potential demand. Therefore, in a simplified traffic network with incomplete information of road section attributes and travel demand characteristics, the P&R facility location model should be optimized by comprehensively considering P&R facility coverage demand characteristics and travel choice behavior characteristics.

Based on the above analysis, the research contribution is as follows: Assuming that the data information of traffic network attributes and travel demand characteristics is incomplete, combined with the spatial layout of rail transit stations, the coverage of P&R

facilities was analyzed, and the nearest selection principle and demand coverage principle in the existing research [15,18] were improved. Considering the influence of travel distance on P&R facility coverage demand, with the goal of truncating the maximum mileage of private vehicles and the maximum P&R facility coverage demand, this study constructed P&R facility location models in the outer suburbs based on travel choice behavior and in the urban area based on the progressive cooperative coverage model.

2. Problem Formulation

With the acceleration of urbanization, P&R facilities in the outer suburbs and urban areas play different roles, forming a multi-level P&R facility layout model.

Figure 1 illustrates P&R facility hierarchies. The P&R facilities in the outer suburbs are located in various clusters or satellite cities and mainly serve the travel needs of the outer suburbs to the urban center, enabling travelers to move from the whole journey by private vehicles to P&R. Maximizing the truncated mileage of private vehicles is the main goal of P&R facility location in the outer suburbs. The P&R facilities in the city are located outside the city center and mainly serve the travel needs within the urban area. How to meet the P&R travel demand to most effectively maximize the potential P&R demand for coverage is the main consideration for the location of P&R facilities in the city.

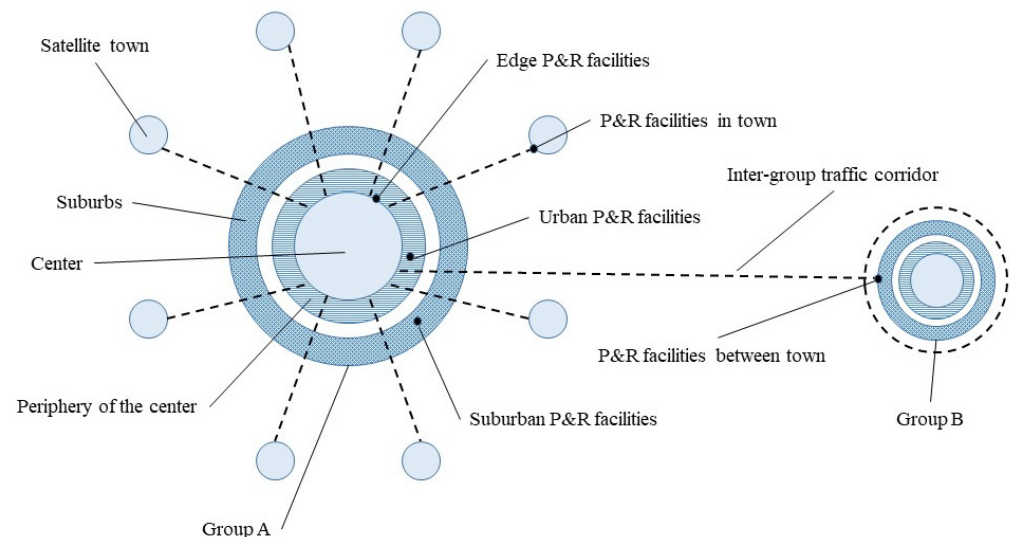


Figure 1. P&R facility hierarchies.

The existing research models are based on two basic assumptions, namely the principle of nearest selection and the principle of 0–1 demand coverage. In terms of the principle of nearby selection, existing studies have not fully considered the characteristics of travelers' choice of P&R facilities. It is assumed that travelers choose the nearest P&R facility within the scope of P&R facility coverage requirements. In actual situations, travelers will face a variety of travel modes, such as private vehicle travel, combined walking and rail transit, and P&R travel. Travelers will choose P&R facilities or abandon P&R trips after comprehensively considering factors such as travel distance, parking fees, parking lot capacity restrictions, and road service levels. Therefore, the location of P&R facilities should be modeled with the characteristics of travel choice behavior.

In terms of the principle of demand 0–1 coverage, existing studies have not fully considered the characteristics of P&R facility coverage requirements. Assume that the P&R coverage area is a binary coverage mode (0–1 coverage) with only “completely covered” and “not covered at all” within a fixed-distance coverage radius. When the distance between the demand point and the P&R facility is within the acceptable distance range, the P&R potential demand point (the source of private vehicle travel) within the range is regarded as the actual P&R travel demand. However, P&R travel should comprehensively

consider the accessibility of P&R facilities and the accessibility of rail transit lines; that is, when travelers are close to rail transit transfer stations, travelers often choose to walk directly to rail transit stations. When the demand point and the rail transit station are beyond the acceptable range of walking and are within the maximum coverage demand of the P&R facility, the potential P&R travel demand will not be fully covered, but it decreases as the distance between the demand point and the facility increases.

In addition, when there are multiple P&R facilities for travelers to choose from, existing studies often assume that a single P&R facility serves the potential demand or that the distance between P&R facilities should be greater than the coverage demand radius of a single facility. However, when the potential demand for P&R is large, a single P&R facility cannot meet the P&R travel demand in the area, and more P&R facilities are often needed to serve travel in areas with greater potential demand. Therefore, the P&R facility location model should comprehensively consider the P&R facility coverage demand characteristics and the scenario where multiple P&R facilities serve multiple demand points.

In summary, according to the functional characteristics of P&R facilities, travel choice behavior characteristics, and P&R facility coverage demand characteristics, this study explored the location of P&R facilities in remote suburbs and urban areas with simplified transportation networks.

Regarding the issue of facility location, it is necessary to consider two factors, the characteristics of facility coverage and travel behavior.

Facility coverage is the primary issue that needs to be resolved in the location of P&R facilities. In the existing studies, it is often assumed that the distance cost or time cost borne by travelers with P&R facilities is not acceptable, which leads to abandonment of the choice of P&R facilities or even P&R travel. Based on the analysis of P&R facility coverage using the P median location model, coverage location model and closure location model, this paper proposes a P&R facility coverage based on rail transit connection, as shown in Figure 2. P&R facilities are set up near rail transit stations, and there are two types of coverage areas and three types of demand points in the area. The first type of coverage area has the rail transit station as the center and the acceptable walking distance (the walked by the traveler from home to the rail transit station) as the radius. The demand points in the area are the blue demand points in Figure 2. Because of their proximity to rail transit stations, blue demand points are more likely to be used to walk to rail transit stations and transfer. The second type of coverage area is centered on the P&R facility and the acceptable range of driving to the P&R facility as the radius, excluding the pedestrian coverage area of the rail transit station. The demand points in the area are the green demand points in Figure 2, and the demand in this area is for P&R travel or private vehicle travel. The third type of coverage area is outside the first and second types of coverage area. The demand points in the area are the gray demand points in Figure 2. The demand in this area is for private vehicle travel.

In terms of travel behavior, on the basis of determining the coverage, this study improved the nearest selection principle in the existing research and analyzed the demand intensity in the coverage. In terms of the demand intensity of P&R facility coverage, an existing study has conducted a survey of P&R facility users in the metropolis of Seattle, USA [29], the results of which are shown in Figure 3.

As can be seen from Figure 3, the demand for P&R facility coverage is unevenly distributed and mostly concentrated around P&R facilities and in the opposite direction of the urban center. The main reason is that travelers are more likely to choose P&R facilities within an acceptable range, and the proportion of P&R trips decreases with the increase in the distance between P&R facilities. Therefore, it is not in line with the actual situation to define the P&R coverage as a binary coverage mode with only “completely covered” and “completely uncovered” within a fixed coverage radius. Based on this, this paper puts forward a method to measure the demand intensity of P&R facility coverage for outer suburb travel and urban travel. In the outer suburb travel scene, the travelers who use the P&R facilities in the outer suburbs often form the commuter flow from the group or the

satellite city to the urban center. When the OD of outer suburb travel is relatively fixed and the complete travel OD is easily obtained, the logit model is used to determine the P&R travel ratio and potential travel demand. In the urban travel scene, the demand for P&R travel in the urban area is not limited to commuter traffic to the urban center but also includes other parts of the urban area through the transfer of rail transit through P&R facilities. In view of the complexity of the travel OD, in the case of not obtaining complete travel OD, the P&R facility coverage demand is determined according to the attenuation function of the travel demand with the distance.

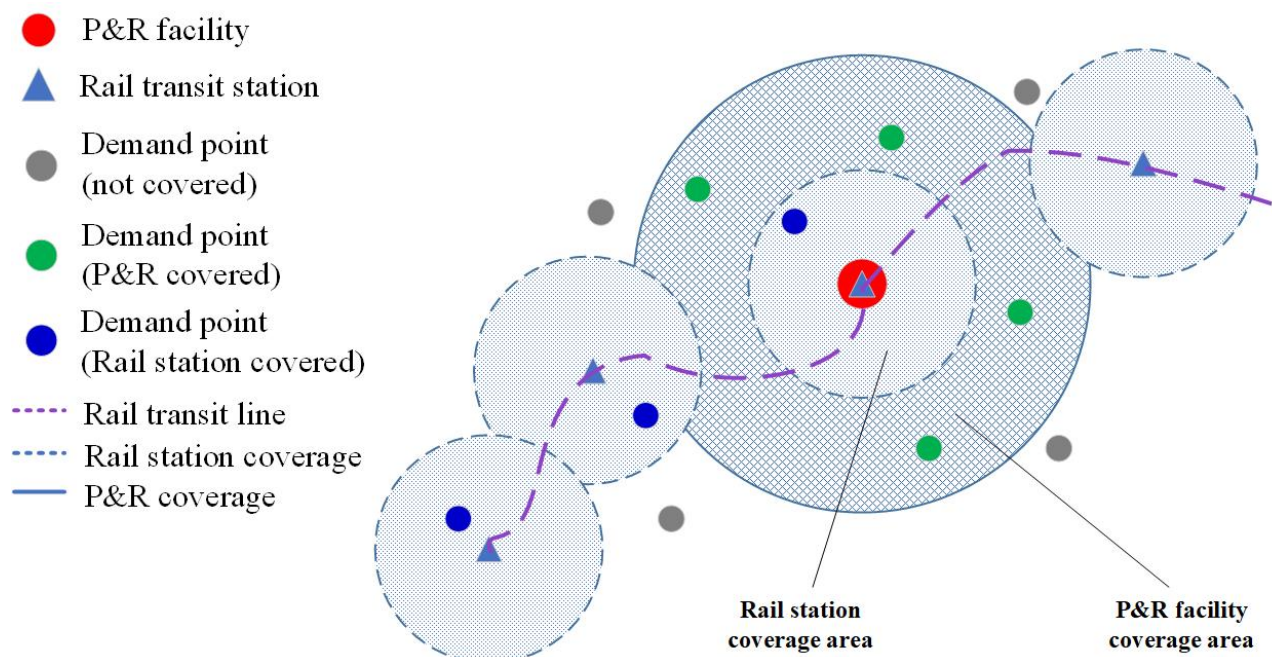


Figure 2. P&R facility coverage based on rail transit connection.

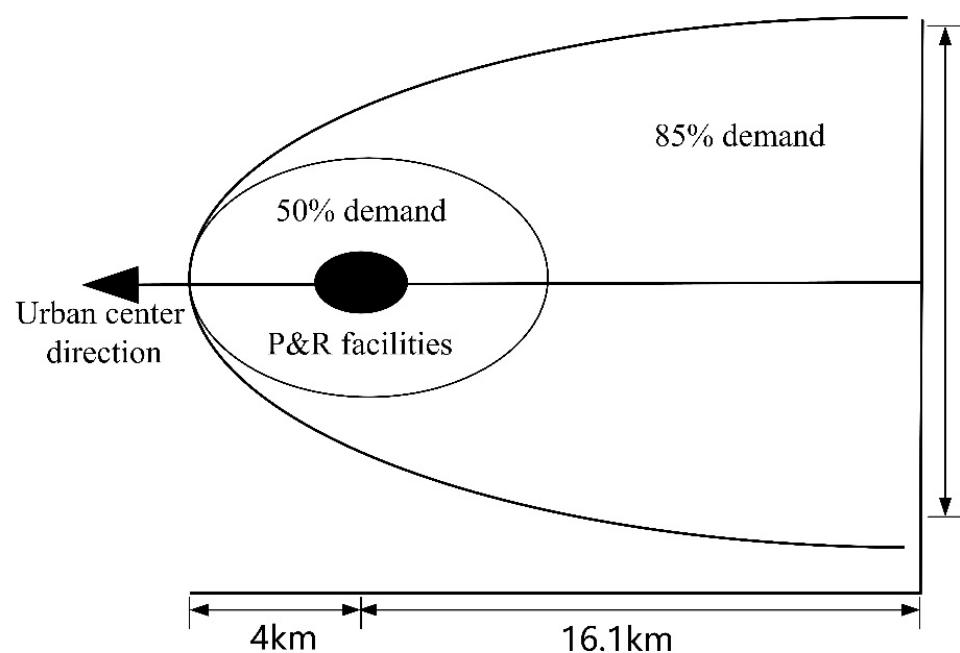


Figure 3. Schematic diagram of P&R coverage area and demand.

3. Model Building

3.1. Location Model of P&R Facilities in Outer Suburbs Based on Travel Choice Behavior

Figure 4 illustrates coverage characteristics of P&R facilities in outer suburbs. In terms of location of P&R facilities in the outer suburbs, it is difficult to obtain a complete travel OD, so it is assumed that all travelers go from the suburban demand point i to the fixed destination z in the city center. I represents the set of potential P&R travel demand points $i, i \in I$. K represents the set of rail transit stations $k, k \in K$. $d_{iz}, d_{ij}, d_{ik}, d_{jz}$ respectively represent the distance from demand point i to the city center z , the distance from demand point i to P&R facility j , the distance from the demand point i to the rail transit station k , and the distance from the P&R facility j to the city center z . P&R facilities j_1 and j_2 are set up near rail transit stations k_{n-1} and k_n to facilitate transfer. Defining the acceptable walking distance radius for transfer to rail transit as D_w , the demand point collection is $I_k = \{i | d_{ik} \leq D_w, \exists k \in K\}$, and travelers who gather at I_k choose to walk to the rail transit station to complete their trip. $I_w = \{i | i \notin I_k, i \in I\}$ is a demand point outside the coverage area of D_w of the rail transit station, the acceptable driving distance radius for a private vehicle traveling to a rail transit station is D_c , and the collection of demand points covered by P&R facilities is $I_p = \{i | d_{ij} \leq D_c, \exists j \in J, i \in I_w\}$. Travelers in the assembly can choose P&R travel or private vehicle travel. The remaining demand points are defined as $I_n = \{i | i \notin I_j, i \in I_w\}$, and all travelers in the assembly choose private vehicles to travel to the destination (city center z).

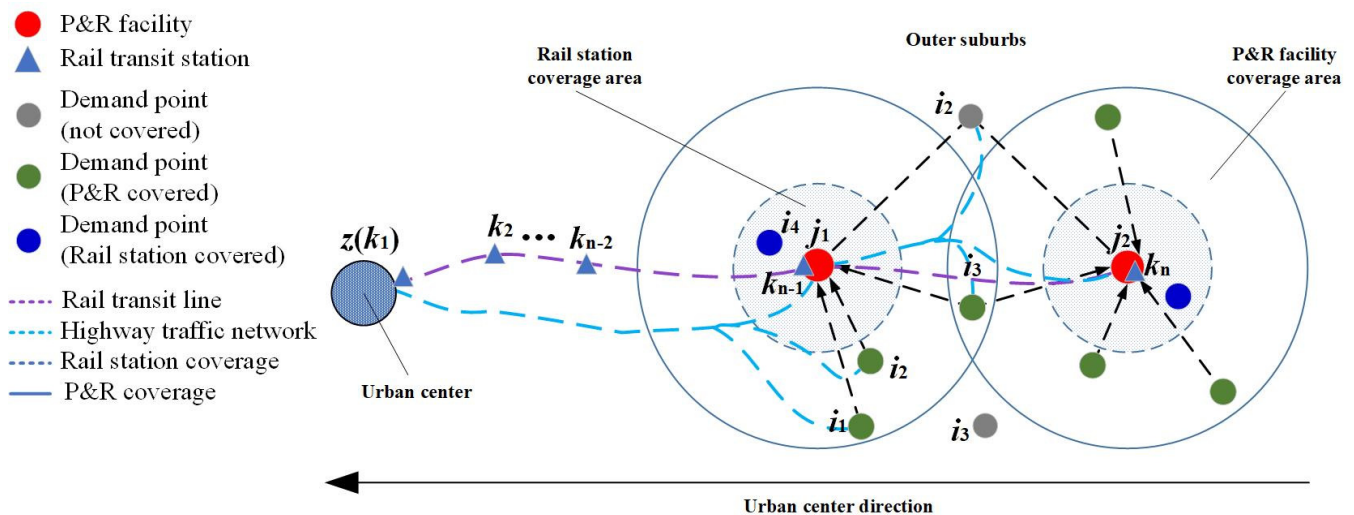


Figure 4. Coverage characteristics of P&R facilities in outer suburbs.

In terms of travel behavior, considering the impact of travel distance on travel choice behavior, the 0–1 coverage demand constraint is improved to a gradual coverage demand. The set of demand points in the set I_p and the set of P&R facilities that can be selected for i is $J_i = \{j | d_{ij} \leq D_c, \forall i \in I_p\}$. The travel time of travelers using the P&R method at demand point i is composed of the travel time of the private vehicle driving to the P&R facility, the travel time of walking to the rail transit station, the waiting time, and the time of taking the rail transit to the destination as defined in (Equation (1)):

$$t_{ij}^p = \frac{d_{ij}}{v_c} + \frac{d_{jz}}{v_{tr}} + \frac{1}{F_{tr}} + t_p \quad \forall i \in I, j \in J \quad (1)$$

The waiting time of travelers can be calculated according to the departure frequency of the rail transit lines. The traveler's choice of private vehicle travel time at demand point i can be expressed as follows (Equation (2)):

$$t_i^c = \frac{d_{iz}}{v_c} \quad \forall i \in I, j \in J \quad (2)$$

The constraint of single P&R facilities covering single demand is improved to multiple P&R facilities for multiple demand point selection, and a P&R facility selection model based on logit selection behavior is constructed as follows (Equation (3)):

$$p_{ij} = \frac{e^{-\theta t_{ij}^p}}{\sum_{j \in J_i} e^{-\theta t_{ij}^p} + e^{-\theta t_i^c}} \quad \forall i \in I, j \in J_i \quad (3)$$

where t_{ij}^p is the travel time from the demand point i to the city center z from the P&R facility j (including private vehicle travel time, rail transit travel time, average rail transit waiting time, parking search time); v_c is the average speed of the private vehicle; v_{tr} is the average speed of rail transit; F_{tr} is the average departure frequency of the rail transit lines; t_p is the parking search time in the P&R facility; t_i^c is the travel time for the demand point i to choose a private vehicle to travel to the city center z ; p_{ij} is the probability that demand point i chooses P&R facility j ; and θ is the user's sensitivity to travel time.

According to the above analysis, the P&R facility location model based on travel choice behavior in the outer suburbs (model 1) is established as follows (Equation (4)):

$$\max F_1 = \sum_{i \in I} \sum_{j \in J} q_i \hat{p}_{ij} (d_{iz} - d_{ij}) \quad (4)$$

Subject to (Equations (5)–(9)):

$$\sum_{j \in J} x_j \leq C \quad (5)$$

$$\alpha_i = \begin{cases} 0 & \exists k \in K, d_{ik} \leq D_w \\ 1 & \text{else} \end{cases} \quad \forall i \in I \quad (6)$$

$$\beta_{ij} = \begin{cases} 1 & d_{ij} \leq D_c \\ 0 & d_{ij} > D_c \end{cases} \quad \forall i \in I, j \in J \quad (7)$$

$$\hat{p}_{ij} = \frac{\alpha_i \beta_{ij} x_j e^{-\theta t_{ij}^p}}{\sum_{j \in J} \beta_{ij} x_j e^{-\theta t_{ij}^p} + e^{-\theta t_i^c}} \quad \forall i \in I, j \in J \quad (8)$$

$$x_j \in \{0, 1\} \quad \forall j \in J \quad (9)$$

where x_j indicates whether to build P&R facilities in the 0–1 variable at candidate point j ; q_i is the travel demand of demand point i ; C is the maximum number of P&R facilities to be constructed; d_{ij} is the distance from demand point i to P&R facility j ; d_{ik} is the distance from demand point i to rail transit station k ; and d_{iz} is the distance from demand point i to destination z in the city center.

Equation (4) maximizes the closure private vehicle mileage under the constraint of the number of P&R facilities, and $d_{iz} - d_{ij}$ represents closure mileage of a unit vehicle. Equation (5) is the quantity constraint for the construction of P&R facilities and can also be expressed in the form of constraints such as construction cost constraints or land use constraints. Equation (6) indicates whether the demand point i is covered by rail transit station k , that is, whether the potential P&R travel demand is for travel by rail transit. If there is a rail transit station k covering demand point i , it is 0; otherwise, it is 1. Equation (7) indicates whether demand point i is within the coverage of P&R facility j . When demand point i is within the coverage of P&R facility j , that is $d_{ij} \leq D_c$, β_{ij} is 1; otherwise, β_{ij} is 0. That is, when there are many P&R facilities built in the network, not every P&R facility will be considered by travelers. If the traveler is not covered by the P&R facility j at the demand point i , they will choose other optional P&R facilities to travel or choose a private vehicle to travel. Equation (8) is the probability that demand point i chooses P&R facility j to travel, which is an improvement in Equation (3) based on the decision variables x_j and parameters

α_i, β_{ij} . When P&R facilities are not set at candidate point j , $x_j = 0$, the probability of demand point i selecting point j is also 0. When P&R facilities are set at the candidate point j , $x_j = 1$, and the ratio of the demand point i to point j is allocated according to Equation (3). At the same time, the pumped P&R facility j for demand point i should be within the range of acceptable mileage D_w to D_c , that is, $d_{ij} \leq D_c$ and $d_{ik} > D_w$. Equation (9) is the 0–1 constraint of decision variables.

3.2. Location Model of Urban P&R Facilities Based on Progressive Cooperative Coverage

Figure 5 illustrates coverage characteristics of urban P&R facilities. In terms of the location of P&R facilities in the urban area, it is difficult to apply the travel choice behavior model to analyze P&R demand in the scenario where travel OD distribution is not easy to obtain. It can be seen from Figure 5 that there are four types of demand points in the P&R coverage area. Aiming at the green demand points in the Figure (type A and B demand points), this study improved the 0–1 coverage constraint into a progressive coverage function that varies with travel distance. The type B demand point is far away from the P&R facility, resulting in a lower level of coverage demand, such as demand point i_1 . The demand intensity of type A demand points is higher than that of type B demand points. One of the reasons is that the closer the demand point is to the P&R facility, the higher the possibility that travelers will choose the P&R method, such as demand point i_2 . In addition, when multiple P&R facilities cover a certain demand point at the same time, the possibility of choosing P&R travel for type A is greater than that for type B demand points, such as demand point i_3 .

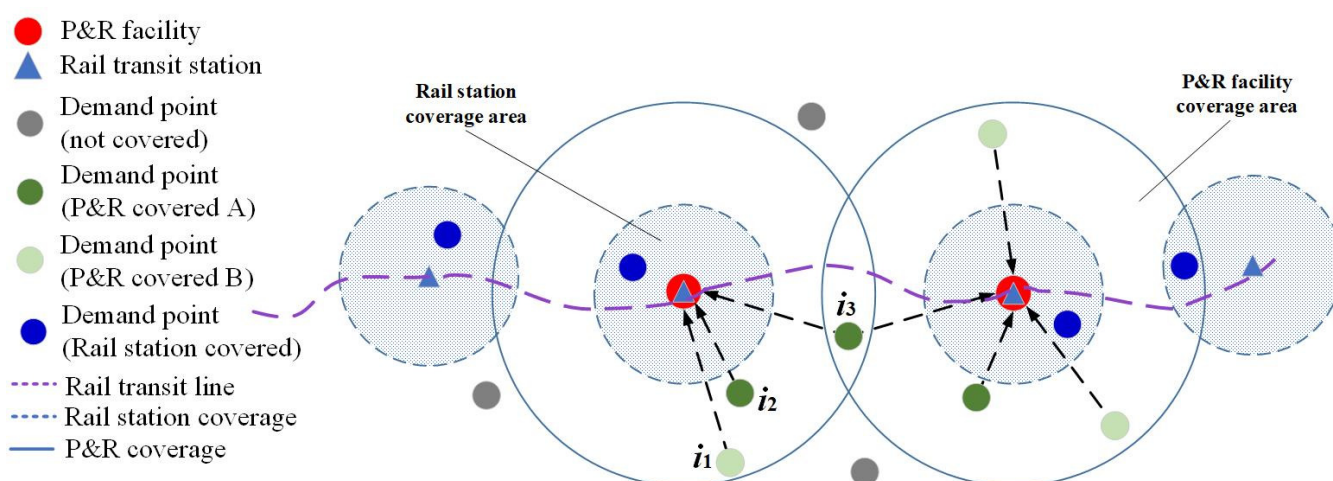


Figure 5. Coverage characteristics of urban P&R facilities.

According to the above analysis, the establishment of the urban P&R facility location model based on progressive cooperative coverage (model 2) is as follows (Equation (10)):

$$\max F_2 = \sum_{i \in I} \left[\min \left\{ \sum_{j \in J} f(d_{ij}) x_j \alpha_i q_i, q_i \right\} \right] \quad (10)$$

Subject to (Equations (11)–(14)):

$$\sum_{j \in J} x_j \leq C \quad (11)$$

$$f(d_{ij}) = \begin{cases} e^{-\beta d_{ij}} & d_{ij} \leq D_c \\ 0 & d_{ij} > D_c \end{cases} \quad \forall i \in I, j \in J \quad (12)$$

$$\alpha_i = \begin{cases} 0 & \exists k \in K, d_{ik} \leq D_w \\ 1 & \text{else} \end{cases} \quad \forall i \in I \quad (13)$$

$$x_j \in \{0, 1\} \quad \forall j \in J \quad (14)$$

where $f(d_{ij})$ is the coverage intensity of P&R facility j to demand point i with distance; q_i is the travel demand of demand point i ; β is the distance attenuation coefficient; and β is greater than 0. As the distance d_{ij} decreases, the greater the distance attenuation coefficient β , the faster the coverage demand attenuates.

Equation (10) maximizes the potential P&R demand under the constraint of the construction quantity of P&R facilities. When multiple P&R facilities cover demand point i and the coverage intensity of facility j to demand point i varying with distance is $f(d_{ij})$, then the parking and transfer supply capacity of facility j to demand point i is $\sum f(d_{ij})x_j\alpha_iq_i$. If it is greater than the q_i of demand point, it is considered that demand point i is completely covered and the potential demand covered is q_i . Otherwise, it is considered that the demand point i is partially covered; that is, part of the potential P&R travel demand is transformed into the actual P&R travel demand, and the potential demand covered is $\sum f(d_{ij})x_j\alpha_iq_i$. Equation (11) is a constraint on the number of P&R facilities. Equation (12) is a function of the demand intensity of P&R facilities in the coverage area, and the attenuation function of the coverage level of P&R facilities with distance is expressed in exponential form. Equation (13) determines whether the demand point i is covered by rail transit station k , that is, whether the potential P&R travel demand will directly choose to travel by rail transit. If there is a rail transit station k covering demand point i , it is 0; otherwise, it is 1. Equation (14) is 0–1 constraints on decision variables.

4. Model Solving

Since the P&R facility location plan is a nonlinear programming problem with 0–1 decision variables, in view of the fact that genetic algorithm is a common tool for solving nonlinear programming problems, a genetic algorithm was selected in this study to solve the P&R facility location plan. In terms of chromosome coding in genetic algorithms, chromosomes are composed of 0 and 1; that is, each gene is a binary variable. Each gene indicates whether the candidate P&R facility is selected: “1” means to build a new P&R facility at the candidate point, and “0” means not to build a new P&R facility at the candidate point. Therefore, the chromosome in the population with the P&R facility location scheme can be expressed as $[x_1, x_2, \dots, x_N]$, that is, the setting of number N P&R facility candidate points. The steps to solve the genetic algorithm are as follows:

1. Parameter initialization. The number of iterations, crossover probability, mutation probability, and population size are determined.
2. The potential P&R travel demand distribution is entered, simplifying the transportation network structure and related parameters.
3. An initial population is randomly generated. The chromosomes in the population contain the initial P&R facility location plan.
4. According to the coverage of rail transit stations and the coverage of P&R facilities, the demand point set I_k covered by the rail transit site, the P&R facility coverage demand set I_p , and the demand point i which can choose the P&R facility set J_i are determined.
5. In the P&R facility location model in the outer suburbs, the ratio of demand points to the selection of P&R facilities is calculated. In the urban P&R facility location model, the demand for incremental cooperation coverage is calculated where demand points are covered by P&R facilities.
6. The fitness of the chromosomes in the population is calculated. Since the models constructed in this study all aim at the maximum target value, the objective function value is set to 0 when the location plan does not meet the constraints, and the fitness of the chromosome is set to the objective function value.
7. The chromosomes in the population are selected, crossed, and mutated to generate a new population.

8. The elite retention strategy is adopted to replace a chromosome in the new population with the chromosome with the highest fitness in Step 7, thereby improving the search speed and accuracy of the algorithm.
9. The number of iterations is verified. If the maximum number of iterations is not reached, the process returns to Step 4; if the number of iterations is reached, the algorithm is terminated and the P&R facility location plan is output.

5. Model Verification

5.1. Location of P&R Facilities in Outer Suburbs

A two-dimensional coordinate system is used to represent the urban area and the suburban area. There is an intercity rail transit line between the urban area and the suburban area to connect the two areas. Travelers can drive a private vehicle to a rail transit station, park the private vehicle at the P&R facility in the outer suburbs, and then take the rail transit to the city center. Potential P&R travel demand points are randomly generated in the outer suburbs, and a simplified transportation network is constructed in the outskirts scenario, as shown in Figure 6.

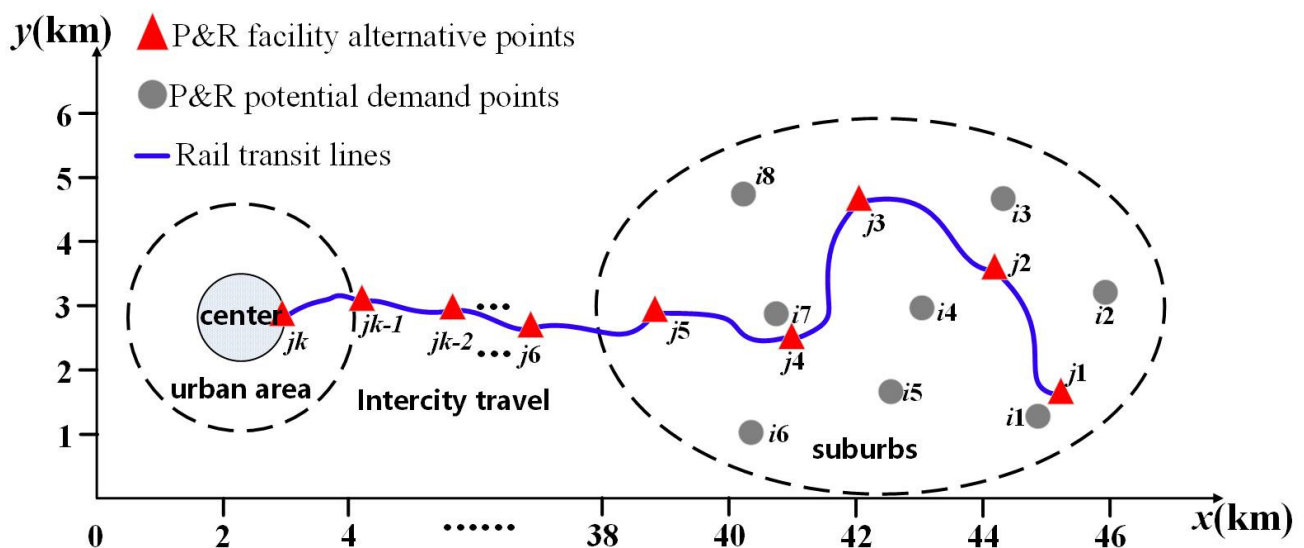


Figure 6. Simplified transportation network topology in the remote suburban scenario.

There are eight demand points (i_1 to i_8) and five P&R facility alternative points (j_1 to j_5) distributed in the outer suburbs. The travel destination of the demand points is the initial city center. P&R facility options, potential P&R travel demand distribution, and demand are shown in Table 1. The Euclidean distance between the P&R facility alternative point and the demand point is taken as the travel distance by rail transit in the P&R travel mode. The rail transit frequency is set to five vehicles per hour; the average speed of rail transit trains and private vehicles are 150 and 60 km/h, respectively; the parking search time in P&R facilities is 3 min; and the travel choice behavior model parameter θ is 0.05. Taking into account the characteristics of outskirts travel, the acceptable distance D_w from walking to the rail transit station is 0.5 km, the acceptable distance radius for driving to P&R facilities is 5 km, and the upper limit of the number of P&R facilities in the outer suburbs is 2.

Table 1. P&R facility alternative points and demand point distribution.

Rail Station	<i>x</i> Axis (m)	<i>y</i> Axis (m)	Demand Points	<i>x</i> Axis (m)	<i>y</i> Axis (m)	Demand (veh)
j_1	45,517	1654	i_1	45,147	1318	762
j_2	44,449	3654	i_2	46,232	3308	581
j_3	42,267	4755	i_3	44,588	4813	367
j_4	41,182	2538	i_4	43,280	3058	287
j_5	38,983	2972	i_5	42,780	1712	814
j_k	2983	3221	i_6	40,531	1058	432
–	–	–	i_7	40,934	2962	673
–	–	–	i_8	40,408	4885	768

MATLAB R2016a was used to solve the P&R facility location plan in the suburban scenario. The maximum number of iterations in the genetic algorithm is 500, the crossover probability is 0.5, the mutation probability is 0.05, and the population size is 500. In order to prove the effectiveness of the model built in this study, on the basis of model 1, Equations (6) and (7) were removed, while α_i and β_{ij} in Equation (8) took constant 1, other formulas remained unchanged, and a location model 3 was established without considering the coverage characteristics. Model 1 was compared with model 3. The optimization results of P&R facility location scheme and the results of conventional location scheme are shown in Table 2.

Table 2. Analysis of the results of P&R facility location in the outer suburbs.

Index	Model 1	Model 3
P&R facility location plan	2, 3	2, 4
Demand points within coverage	2, 3, 4, 5, 6, 8	1–8
Closure number of private vehicles (veh)	2339	3759
Closure private vehicle mileage (km)	8.4×10^3	12.3×10^3

The influence of P&R facility coverage characteristics on the results: The calculation results of model 1 and model 3 both select j_2 , the location scheme of model 1 does not take j_4 as the location scheme, the demand points i_1 and i_7 are not included in the coverage, and the driving mileage of the closure private vehicle is less than that of model 3. The main reason for this result is that model 3 regards the demand point within the 500 meter coverage radius of the rail transit station as the P&R facility coverage demand, while model 1 does not count it as the actual demand point, so this part of the demand is not included in the closure mileage. Although the domestic demand points i_1 and i_7 of the 500 m coverage radius of the rail transit station are the source demand points for private vehicles, it is more reasonable to walk to the rail transit station than to travel. At the same time, if the coverage characteristics are not taken into account, assuming that all the demand is covered, it will lead to an increase in the size of the planned parking lot (the number of private vehicles truncated by model 3 is 1420 more than that of model 2). Part of the demand ($d_{ik} \leq D_w$ or $d_{ij} > D_c$) will not use private vehicles to travel to rail transit transfer points but rather walking or shared bicycles. Therefore, although the driving mileage of the closure private car of model 1 is less than that of model 3, it seems that the result of model 3 is better, but it may lead to excessive waste of space resources. Therefore, the P&R facility location scheme obtained by model 1 is more in line with the actual situation and more reasonable.

The impact of travel choice behavior on the results: In the case of j_2 and j_3 , as the demand points i_5 , i_6 , and i_8 are closer to the urban center and farther from P&R facilities, the proportion of private vehicles chosen by i_5 , i_6 , and i_8 is higher than that of i_2 , i_3 , and i_4 . In line with the conclusion of the literature [29], a survey was conducted on the users of

P&R facilities in the metropolis of Seattle, WA, USA. According to Figure 7, the probability of selecting j_3 for demand points i_5 , i_6 , and i_8 is greater than that of j_2 , mainly because the demand point near the urban center is closer to j_3 . Similarly, the probability of choosing j_2 at demand points i_2 , i_3 , and i_4 is greater than that of j_3 . In addition, there is no significant difference in the selection probability of the demand point for different P&R facilities. The main reason is that there are overlapping road sections in the process of long-distance intercity travel, which accounts for a large proportion of the total travel distance; that is, the radius of the area formed by the demand point is much smaller than that of the urban area, resulting in a small difference in travel time between the demand point i and the P&R facility j to the urban center z . As a result, the difference of selection probability is not statistically significant. In addition, the logit model assumes that the selection behaviors are independent and uncorrelated (independence of irrelevant alternatives, IIA), which leads to no significant difference in facility selection. The P&R behavior is analyzed in the literature [30–33]. The results show that although the logit is independent from irrelevant alternatives, it still has a certain applicability. When there are multiple rail transit lines leading to the urban center, the overlap of paths can be avoided, which is reflected in the layout of P&R facilities in Shanghai [34].

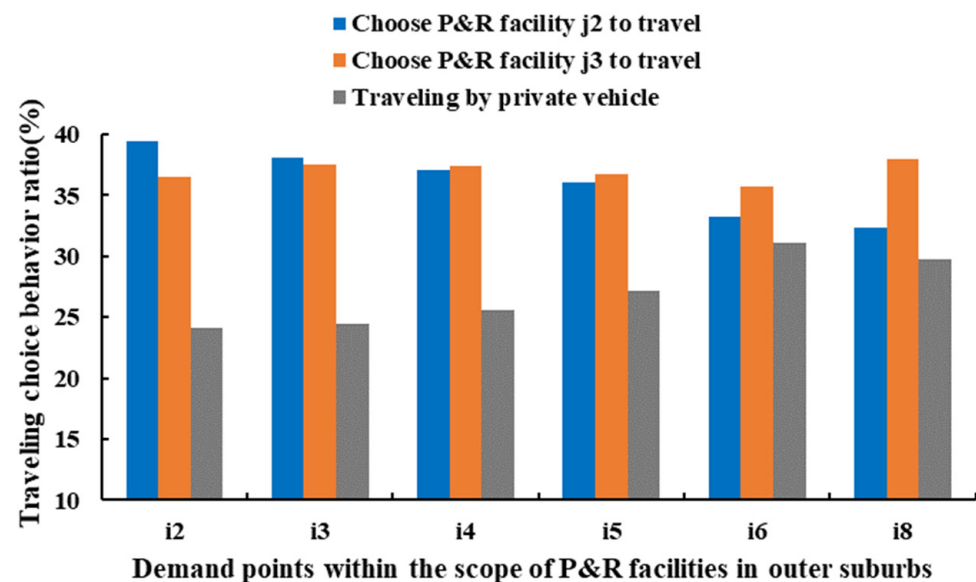


Figure 7. Analysis of the selection behavior of P&R facilities by demand points.

The influence of the quantity constraint of P&R facility construction on the result: The sensitivity analysis of model 1 and model 3 was carried out with different P&R facility construction quantity constraints, as shown in Figure 8. With the increase in the upper limit of the number of constructions, P&R facilities, closure private vehicle mileage, and P&R travel ratio gradually increase. In addition, with the further increase in the number of P&R facilities constructed, the growth ratio of closing the mileage of private vehicles and the P&R travel ratio gradually decreases; that is, the construction of excessive P&R facilities will not achieve better profit effects.

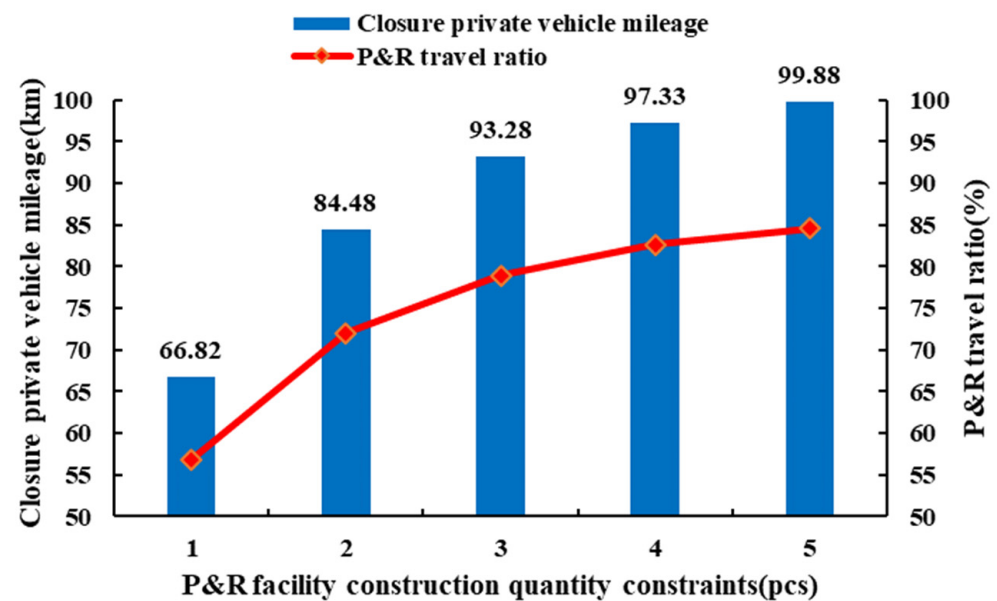


Figure 8. Analysis of location results under the constraints of the construction quantity of different P&R facilities.

5.2. Location of Urban P&R Facilities

Potential P&R travel demand points were randomly generated within the urban area, and a simplified transportation network was constructed in the urban scenario, as shown in Figure 9.

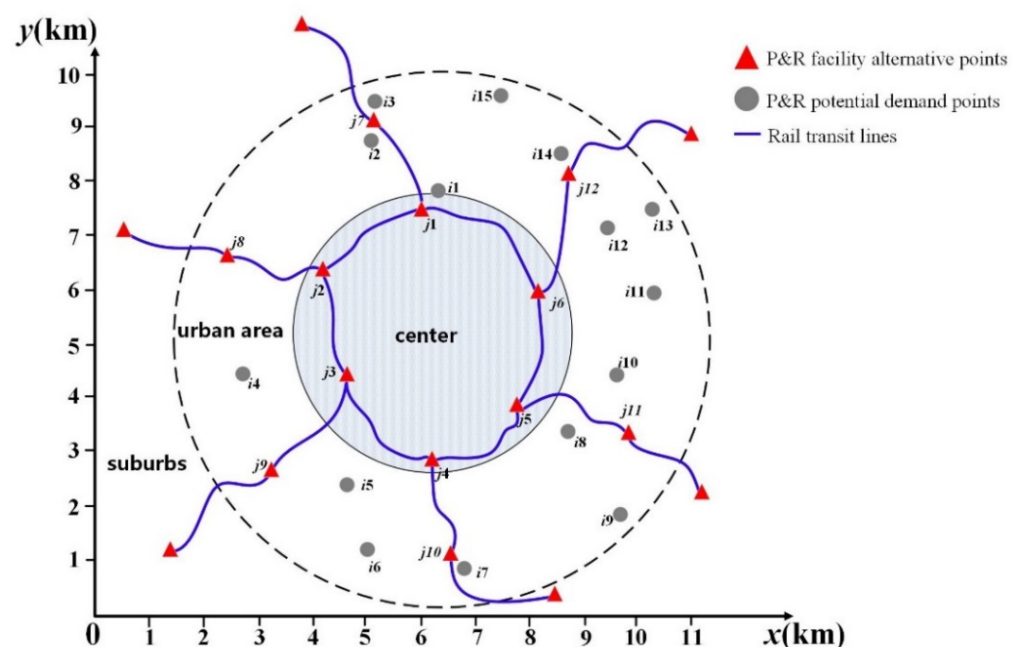


Figure 9. Simplified traffic network topology map in the urban scenario.

Each station in the rail network serves as an initial candidate point for P&R facilities (j_1 to j_{12}). The number of P&R facilities is restricted to 4, and 15 demand points (i_1 to i_{15}) are distributed in the area. P&R facility options, potential P&R travel demand distribution, and demand are shown in Table 3. Euclidean distance is used as the travel distance between two points. Due to the short travel distance in the urban area, the acceptable distance to walk to the rail transit station is set to 0.5 km, and the acceptable distance radius D_c for

driving to the P&R facility is 3 km. The parameter β of the asymptotic cover function model is 0.2. MATLAB R2016a was used to solve the P&R facility location plan under the urban scenario. The maximum number of iterations in the genetic algorithm is 500, the crossover probability is 0.5, the mutation probability is 0.05, and the population size is 500.

Table 3. P&R facility alternative points and demand point distribution.

P&R Facility Alternatives	x Axis (m)	y Axis (m)	Demand Points	x Axis (m)	y Axis (m)	Demand (veh)
j_1	5967	7398	i_1	6274	7777	942
j_2	4165	6306	i_2	5049	8692	658
j_3	4607	4384	i_3	5117	9409	741
j_4	6160	2831	i_4	2704	4428	871
j_5	7712	3828	i_5	4607	2402	278
j_6	8098	5901	i_6	4980	1219	517
j_7	5094	9030	i_7	6749	872	781
j_8	2420	6560	i_8	8645	3376	347
j_9	3224	2638	i_9	9602	1860	456
j_{10}	6500	1108	i_{10}	9537	4410	343
j_{11}	9752	3318	i_{11}	10,217	5907	182
j_{12}	8653	8056	i_{12}	9367	7097	477
–	–	–	i_{13}	10,184	7437	329
–	–	–	i_{14}	8517	8457	687
–	–	–	i_{15}	7417	9517	531

In order to prove the effectiveness of the model built in this study, on the basis of model 2, the constraint condition (12) was changed to $f(d_{ij}) = \begin{cases} 1 & d_{ij} \leq D_c \\ 0 & d_{ij} > D_c \end{cases} \forall i \in I, j \in J$, and a complete coverage location model 4 considering coverage characteristics was established. At the same time, on the basis of model 2, constraint conditions (12) and (13) were changed to $f(d_{ij}) = \begin{cases} e^{-\beta d_{ij}} & \forall i \in I, j \in J \text{ and } \alpha_i = 1, \text{ respectively,} \\ 0 & \end{cases}$ and a progressive coverage location model 5 was established without considering the coverage characteristics. Model 2 was compared with model 4 and model 5. The optimization results of the P&R facility location scheme and the results of the conventional location scheme are shown in Table 4.

Table 4. Comparison of results of urban P&R facility location.

Index			
Considering			
Coverage Characteristics	Model 2	Model 4	Model 5
P&R facility location plan	3, 9, 11, 12	2, 5, 9, 12 (or other solutions)	7, 10, 11, 12
Demand that is not covered by P&R facilities	1, 2, 3, 7, 14	1, 2, 3, 7, 14	4
Potential coverage of P&R travel demand (veh)	4331	4331	7269
Actual coverage of P&R demand (veh)	3527	4331	6379

The influence of P&R facility coverage characteristics on the results: Due to the consideration of the progressive coverage principle, under the constraint of the number of facilities, both model 2 and model 5 can obtain the optimal solution, while model 4 has multiple solutions (other solutions in Table 4). The main reason is that when the D_c is 3 km, because the progressive coverage principle is not taken into account, different P&R facility location schemes can cover all the demand of the urban area. Because the coverage characteristics are taken into account, model 2 is the same as the uncovered demand points and potential requirements of model 4 and are much smaller than model 5. Compared with the three models, the actual coverage requirement of model 2 is the smallest. The main reason is that the domestic demand point in the 500 m coverage radius of the rail transit station is regarded as the coverage demand of P&R facilities. Although the domestic demand points i_1, i_2, i_3, i_7 , and i_{14} are the source demand points of private vehicles in the 500 m coverage radius of rail transit stations, it is more reasonable to choose to walk to rail transit stations to transfer to rail transit. In addition, with the increase in the distance between the demand point and P&R facilities, the demand for the conversion of potential P&R travel demand into actual P&R travel demand will gradually decrease. If model 4 and model 5 are adopted, the calculated demand will be 804 and 2825 more than that of model 2 because the principle of gradual progress and the principle of demand range characteristics are not taken into account. These requirements may involve travel to the rail transit station by walking or bicycle. Using these requirements for the construction of P&R facilities will greatly improve the construction scale and capital investment, which may lead to waste. Therefore, the P&R facility location scheme of model 2 is more in line with the actual situation.

The influence of P&R facility coverage radius on the results: In order to analyze the influence of the coverage radius of P&R facilities on the location results, the sensitivity analysis of the built model was carried out in combination with the coverage radius of different P&R facilities, as shown in Figure 10. As the coverage radius of P&R facilities increases, the potential P&R travel demand and P&R travel demand coverage gradually increase, and P&R facilities have more opportunities to cover the travel demand within the urban area. At the same time, when the P&R facility coverage radius is greater than 4.5 km, it is able to cover all the travel needs within the urban area; that is, when the coverage radius of P&R facilities is large, planning a small number of P&R facilities can meet the demand of points. Therefore, in practical applications, the coverage radius of P&R facilities should be determined based on the actual travel situation in the urban area.

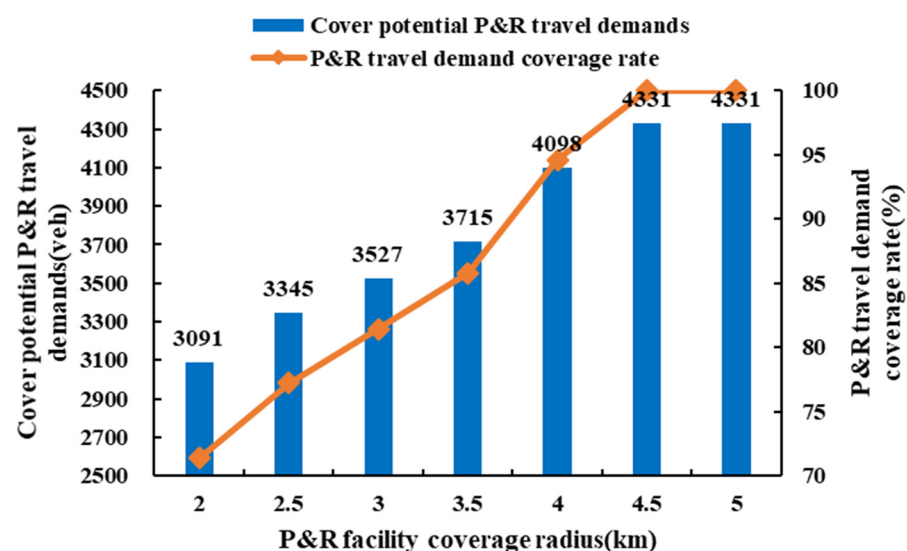


Figure 10. Analysis of location results with different coverage radius of P&R facilities.

The influence of the quantity constraint of P&R facility construction on the result: In order to analyze the influence of P&R facility construction quantity constraints on the location results, sensitivity analysis was carried out in combination with different P&R facility construction quantity constraints. MATLAB R2016a was used to obtain the coverage potential P&R travel demand and P&R travel demand coverage rate under the constraints of different P&R facility construction quantities, as shown in Figure 11.

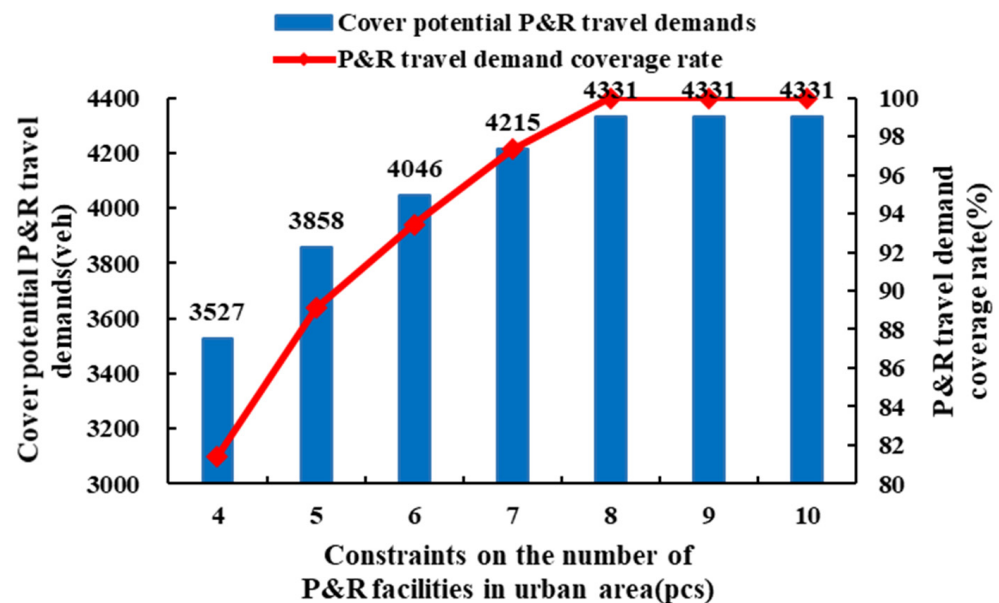


Figure 11. Analysis of location results under the constraints of the construction quantity of different P&R facilities.

With the increase in the upper limit of the number of constructions, the potential P&R travel demand covered by P&R facilities and the coverage rate of P&R travel demand gradually increase. At the same time, when the number of P&R facilities is more than eight, the travel demand within the urban area is fully covered, indicating that excessive P&R facilities do not lead to further benefits. In addition, the construction capacity of P&R facilities should also be considered; when the potential P&R travel demand is greater than the number of parking spaces provided by the P&R facility, it is not possible to achieve full coverage of the travel demand within the urban area.

6. Empirical Analysis

In order to test the effectiveness of the model in practical application, this study used Changchun City, Jilin Province, as an example for empirical analysis. Rail transit line 8 was used as an example to select P&R facilities in the suburbs and rail transit lines 1, 2, 3, and 4 as examples to select P&R facilities in urban areas, as shown in Figure 12.

One hour of the morning peak on a certain day was selected as the data, and in the location of P&R facilities in the suburbs, there are nine demand points (i_1 to i_9) and five alternative points of P&R facilities (j_1 to j_5). The travel destination of the demand point is the initial destination of the urban center. In the location of P&R facilities in the urban area, there are 11 alternative points (j_6 to j_{16}), and 18 demand points (i_{10} to i_{27}) are distributed in the region. The optional locations of P&R facilities, the distribution of potential P&R travel demand, and the demand are shown in Tables 5 and 6.

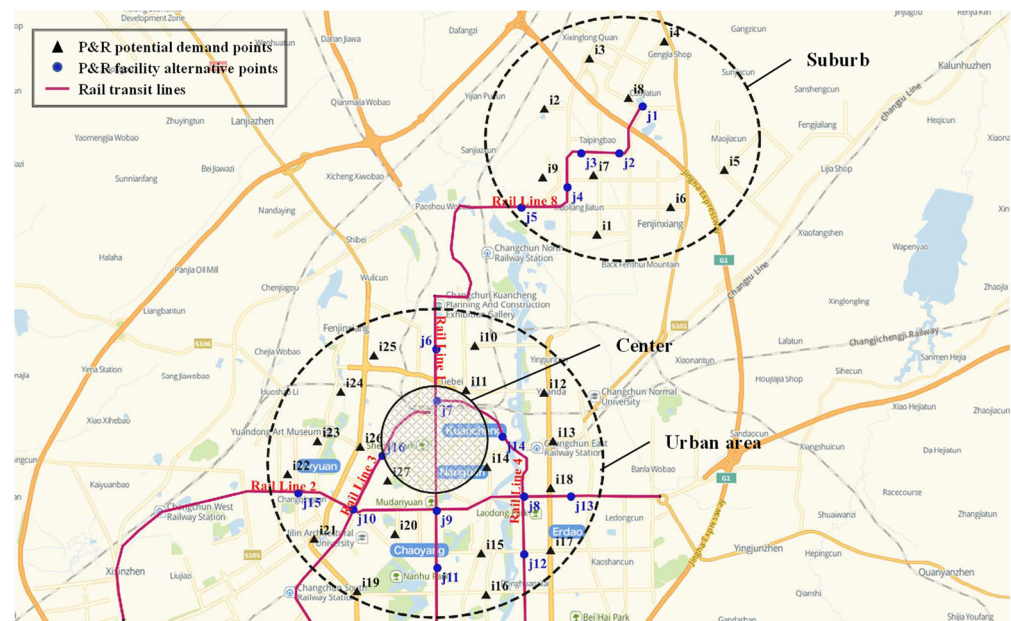


Figure 12. Schematic diagram of location of P&R facilities in the suburbs and urban area of Changchun.

Table 5. Distribution of alternative points and demand points of P&R facilities in the suburbs of Changchun.

P&R Facility Alternative Points	Longitude	Latitude	Demand Points	Longitude	Latitude	Demand (veh)
j_1	125.4478	43.9949	i_1	125.4190	43.9570	154
j_2	125.4344	43.9813	i_2	125.4049	43.9992	67
j_3	125.4178	43.9832	i_3	125.4281	44.0127	79
j_4	125.4095	43.9733	i_4	125.4618	44.0143	55
j_5	125.3880	43.9693	i_5	125.4789	43.9709	47
—	—	—	i_6	125.4530	43.9619	177
—	—	—	i_7	125.4216	43.9759	134
—	—	—	i_8	125.4422	43.9984	88
—	—	—	i_9	125.3994	43.9777	96

In the location of the suburban P&R facility, the departure frequency of suburban rail transit line 8 is six vehicles per hour; the average speed of rail transit trains and private vehicles is 40 and 60 km/h, respectively; the parking search time in the facility is set to 3 min; the travel choice behavior model parameter θ is 0.05; and the acceptable distance radius of driving to the P&R facility is set to 5 km. In the location of urban P&R facilities, the acceptable distance from walking to the rail transit station is 0.5 km, the acceptable distance radius D_c is 3 km, and the parameter β of progressive coverage function model is set to 0.2 km. The genetic algorithm was used to solve the problem. The maximum number of iterations is 500, the crossover probability is 0.5, the mutation probability is 0.05, and the population size is 500. The final location results are shown in Table 7.

Table 6. Distribution of alternative points and demand points of P&R facilities in the urban area of Changchun.

P&R Facility Alternative Points	Longitude	Latitude	Demand Points	Longitude	Latitude	Demand (veh)
j_6	125.3411	43.9291	i_{10}	125.3580	43.9283	287
j_7	125.3378	43.9128	i_{11}	125.3511	43.9147	193
j_8	125.3691	43.8783	i_{12}	125.3850	43.9100	511
j_9	125.3300	43.8782	i_{13}	125.3855	43.8944	332
j_{10}	125.2938	43.8828	i_{14}	125.3549	43.8896	307
j_{11}	125.3263	43.8602	i_{15}	125.3464	43.8627	289
j_{12}	125.3651	43.8601	i_{16}	125.3457	43.8495	143
j_{13}	125.3895	43.8759	i_{17}	125.3768	43.8602	197
j_{14}	125.3638	43.8982	i_{18}	125.3812	43.8797	226
j_{15}	125.2710	43.8907	i_{19}	125.2897	43.8570	251
j_{16}	125.3102	43.8982	i_{20}	125.3102	43.8731	334
–	–	–	i_{21}	125.2747	43.8756	421
–	–	–	i_{22}	125.2676	43.8973	262
–	–	–	i_{23}	125.2829	43.9062	187
–	–	–	i_{24}	125.2965	43.9205	179
–	–	–	i_{25}	125.3134	43.9303	225
–	–	–	i_{26}	125.3011	43.9023	358
–	–	–	i_{27}	125.3107	43.8902	270

Table 7. Results of location of P&R facilities in the suburbs and urban area of Changchun.

Index	Location of P&R Facilities in the Suburbs	Location of P&R Facilities in the Urban Area
P&R facility location scheme	2	7, 8, 11, 16
Covered demand points	1, 2, 3, 4, 5, 6	10, 12, 13, 14, 15, 16, 19, 20, 23, 24, 25
Uncovered demand points	7, 8, 9	11, 17, 18, 21, 22, 26, 27

The P&R facility in the suburbs is located at j_2 , while the P&R facility in the urban area is located at j_7, j_8, j_{11} , and j_{16} . As a result, most of the demand points can be covered, and $i_7, i_8, i_9, i_{11}, i_{17}, i_{18}, i_{21}, i_{22}$, and i_{27} , which are not covered by P&R facilities, have walking access to the rail transit station, which is more in line with the actual situation.

7. Conclusions

Given the difficulty of obtaining data information of traffic network attributes and travel demand characteristics, this study considered the impact of the spatial layout of rail transit stations on the coverage demand range of P&R facilities and improved the principle of nearest selection and demand coverage in the existing research. Based on the analysis of P&R facility coverage demand range and coverage demand intensity characteristics, this paper proposes a method for selecting the location of P&R facilities in the outer suburbs and in the urban area considering the coverage demand characteristics, with the goal of maximizing the mileage of truncated private vehicles and maximizing the demand for P&R facility coverage. A P&R facility location model based on the travel choice behavior model and the progressive cooperation coverage model was constructed. The genetic algorithm

was used to solve the location model, and combined with the simplified transportation network, the model built in this study was compared with the existing P&R facility location model. The results show that when the demand coverage characteristics are not taken into account, the outer suburb P&R closed private vehicle mileage and urban P&R facility coverage demand is larger than that considering the demand coverage characteristics, so the parking scale of planning and construction is larger than the actual P&R demand, resulting in a waste of resources (in the example of this study, the number of private vehicles closed by the traditional model in the outer suburbs is 1420 higher than that of the optimization model, and the demand of the two traditional models in the urban area is 804 and 2825 higher than the optimization model, respectively, which will lead to a larger construction scale of P&R facilities and a waste of resources). In addition, whether in the outer suburbs or urban areas, the construction of excessive P&R facilities does not lead to further benefits; that is, the optimal number of P&R facilities can be obtained through the model. The location model established in this study can more accurately reflect the requirements of closed private vehicle mileage and P&R facility coverage, and the P&R facility location scheme obtained is more reasonable, which verifies the effectiveness of the model built in this study.

The method proposed in this paper addresses the difficulty of obtaining detailed data, has strong adaptability, and is a practical method for hierarchical location of P&R facilities in the outer suburbs and urban areas. However, due to the assumption that the data are not detailed, it is mostly used in the preliminary location stage of P&R facilities. Further research will be carried out in the future based on the nested logit and cross-nested logit model to develop a P&R NL–CNL combined travel behavior model suitable for suburban and urban areas and to develop a P&R location model considering multi-objectives, such as carbon emissions and construction costs.

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