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Service equilibrium of urban transportation energy supply station based on cooperative game

Xian-long Ge, MuShun Xu, Bo Wang and Zuo-fa Yin
Chongqing Jiaotong University, Chongqing, China

Abstract

Purpose – As of December 2022, there were 119,000 gas stations, 10,800 gas stations and 4,488,000 charging piles nationwide, while the number of vehicles reached 312 million, including 11.49 million new energy vehicles. The imbalance between transportation energy supply and energy replenishment demand leads to crowded queues of vehicles at some stations and idle resources in others. How to reduce the phenomenon of large queues and improve the utilization rate of idle resources is the key to alleviating the imbalance between supply and demand.

Design/methodology/approach – Therefore, from the perspective of spatio-temporal equilibrium of urban transportation energy supply stations, multi-energy supply station cooperation is established in view of the phenomenon of large spatio-temporal differences among different energy supply stations, and corresponding inducing strategies are adopted for energy supplement vehicles in the road network, so that part of queued users go to energy supply stations with fewer vehicles, so as to balance the supply and demand of transportation energy in the region. On this basis, the income distribution of urban transportation energy supply station is discussed.

Findings – The total revenue after the cooperation was 13,095, an increase of 22.9%. Secondly, in terms of distribution rationality, three impact factors are selected and Shapley correction value is used to distribute the total income. Compared with independent operation, both sites have a certain degree of increase.

Originality/value – Traffic congestion at energy supply stations is closely related to the number, location and number of vehicles at energy supply stations. Therefore, using a cooperative approach of energy trading cannot solve the queuing problem. In addition, there are a few research results on the equalization of energy supply station services considering time-of-use pricing. However, these studies do not consider the vehicular grooming at congested stations. As far as the authors know, there are no relevant research results in the research on the service equilibrium of energy supply stations based on cooperative games.

Keywords Energy supply stations, Services balance, Cooperative game, Shapley value

Paper type Research paper

1. Introduction

With the steady economic growth, private car ownership has increased year by year. According to data released by the Traffic Management Bureau of the Ministry of Public Security, car ownership reached 312 million by August 2022, of which 11.49 million were new-energy vehicles. However, there are 119,000 gas stations, 10,800 filling stations and 4.488 million charging piles in China to supplement energy for these vehicles. In addition, In addition, the service capacity of energy supply stations is limited, and the following phenomena may occur during the service process: in peak traffic hours, some energy supply stations have long queues, and the vehicles at some stations even extend to the main line, which not only increases the time consumption of users, aggravates environmental pollution, but also causes traffic congestion. The other part of the station is idle, resulting in a waste of resources. Therefore, how to reduce the long queues and improve the utilization rate of idle resources is the key to alleviate the imbalance between supply and demand.

This paper's contributions include proposing a cooperative model for energy supply stations based on multiple agents, providing a new approach to solving the spatial-temporal balance of urban traffic energy. We allocate profits to the alliance using an improved Shapley value and validate the effectiveness and applicability of the model through case studies.

The organizational structure of this article is as follows: Section 2 reviews the research on queuing congestion of energy supply stations. Section 3 introduces the existing problems of energy supply stations and proposes a cooperative approach to address them. Section 4 presents a model for maximizing alliance benefits, and uses an improved Shapley value to allocate the benefits of the alliance. Section 5 describes a case analysis and obtains corresponding results. We conclude in Section 6.

2. Literature review

Aiming at the queuing congestion problem of energy supply station, many scholars have studied from many aspects and tried to put forward solutions. In terms of station research, considering the location problem of EV charging queue delay, the two-layer simulation optimization scheme is used to calculate the shortest travel time and queue time of taxi (Jung *et al.*, 2014). For the relationship between refueling demand and station service capability, the set coverage model is adopted to solve the balance between refueling demand and service capability (Sun *et al.*, 2018). In terms of vehicle flow, considering the randomness of vehicle replenishment demand, a cellular automata model was constructed to simulate vehicle replenishment behavior, and the boundary conditions of congestion induced by replenishment behavior were obtained (Lv *et al.*, 2017). Of course, too long waiting time for charging will increase the cost of the vehicle. A partial charging strategy can be adopted to reduce the cost of the vehicle (Ge *et al.*, 2022). In addition, in order to reduce the negative effect of electric vehicle charging, a two-layer charging induction model is proposed to solve the problem of electric vehicle charging queue. Whether it is station selection or vehicle, it is optimized by algorithm. Although it can be effectively solved from a single station, it involves competition and cooperation between stations for multiple stations, so it is not enough to use algorithm optimization only.

In order to explore the service balance of different stations, some scholars use the knowledge of game theory to conduct research. We can trade electricity between electric vehicles and between charging stations to reduce dependence on the grid and ensure stable charging stations (Rana *et al.*, 2019). Based on cooperative game and time-sharing pricing, an EV scheduling optimization model is established to ensure the orderly charging of EV (Cheng *et al.*, 2020). We can also use the virtual charging system for electric vehicles to form an alliance of charging stations with different ownership and coordinate charging vehicles at the stations through the virtual system to improve customer satisfaction (Mokhtar *et al.*, 2022). If public charging stations cannot meet the charging demand, private charging stations can be used to reduce the charging cost of electric vehicles. In addition, a bilateral bargaining model can be used to share idle private charging piles with other charging users to reduce the charging cost of electric vehicles (Zhao *et al.*, 2020). Considering that all charging stations will use price to compete, a multi-agent deep reinforcement learning is proposed to simulate the pricing process. This method can obtain the optimal pricing strategy and reduce the charging cost of users (Qian *et al.*, 2022). For EV users, charging decisions will be made according to the remaining power and charging distance. Therefore, a three-stage Stackelberg game model is proposed to finally get the optimal pricing and charging quantity of charging stations (Yuan *et al.*, 2015). The pricing of charging stations will affect the selection of charging stations for electric vehicles, so the Stackelberg game model can be used to maximize the profit of charging stations (Lewis, 2008). Most of these studies consider the minimum cost of the vehicle or the maximum profit of the charging station from the perspective of price, instead of the allocation of unsatisfied customers to other energy supply stations to obtain part of the profit, so as to coordinate with each other to obtain more benefits. Therefore, these results can only provide ideas for reference, not directly improve the application.

To sum up, the current research on the service equilibrium of energy supply stations focuses on station selection and traffic flow on the road network. Although some scholars have conducted researches in recent years using the game theory, they mainly guide users from the perspective of price, and there is no more discussion on the queuing congestion of the stations. Therefore, from the perspective of spatio-temporal equilibrium of energy supply stations in urban transportation, multi-energy supply station cooperation is established in view of the phenomenon of large spatio-temporal differences among different energy supply stations, and corresponding inducing strategies are adopted for energy supplement vehicles in the road network, so that some queued users can go to energy supply stations with fewer vehicles, which can not only alleviate the operating pressure of some energy supply stations. It can also balance the supply and demand of transportation energy in the region. On this basis, the income distribution of urban transportation energy supply station is discussed.

3. Problem description

In the road network, there is a demand for energy replenishment at every time period. Due to the fixed location and limited number of energy supply stations in the road network, if the demand for energy replenishment is not fixed in time and space, the energy replenishment vehicles at some stations in a specific period of time will exceed the service capacity of the stations. Meanwhile, the other part of the energy supply stations in the road network may be in a remote location with fewer vehicles entering the station. Therefore, how to balance transportation and energy supply through cooperative means has become an urgent problem to be solved.

Based on the above phenomenon, we propose the game model of energy supply station cooperation. As shown in Figure 1, there are two energy supply stations in a region. Assuming that the maximum number of vehicles that can be accommodated at the station is

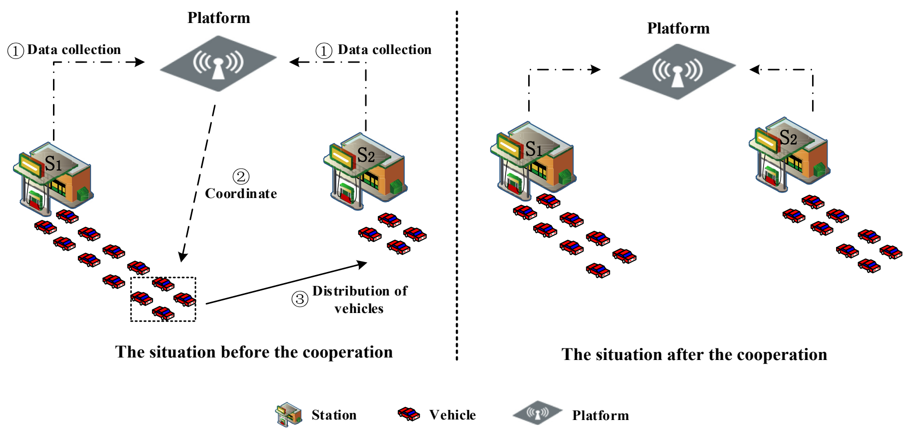

Figure 1.
Game model of energy supply station cooperation

Source(s): Figure created by authors

P, vehicles go to station S_1 for energy replenishment and m vehicles go to station S_2 for energy replenishment at a certain time, and $n > P > m > 0$, at this time, the station S_1 will have queue congestion due to the excess of energy replenishment vehicles. Therefore, we propose that the two stations cooperate to divert part of the queuing vehicles from S_1 to S_2 and compensate them for the benefits, so as to alleviate the queuing congestion of S_1, reduce the queuing time of users and realize the service balance of the stations.

4. Methodology

4.1 Problem assumptions

The factors to be considered in the cooperation of transportation energy supply station include station operation cost, additional cost of cooperation, station income, etc. among which, the calculation of income includes many aspects. To simplify the problem, make the following assumptions:

(1) The station only considers the average revenue per vehicle.

(2) Vehicles beyond the service capacity will be induced to the cooperative station.

(3) The station has the same service capability.

(4) The cooperative sites have an information sharing platform

Hypothesis (a) uses the average value to represent the revenue of vehicles serviced by the site, and since different vehicles have different energy demands, the revenues obtained by the site are also different. To facilitate calculation, the average value is used to represent the revenue of vehicles serviced by the site while ensuring the controllability of calculation time. Hypothesis (b) ensures the revenue of crowded sites which need energy supplement, the alliance provides a small amount of economic compensation for these vehicles. When the cost of changing stations is lower than the time cost generated by the current queuing, users will obey the station's dispatch. Hypothesis (c) ensures the simplicity of the model, which can be relaxed in future research without affecting the rigor of the model. Hypothesis (d) ensures that real-time information of the station can be obtained. When a station generates a queue, the platform will release the corresponding dispatch information. At the same time, vehicle owners can obtain real-time information of the station through the information platform. When vehicle owners obey the dispatch, they can get a small compensation from the platform.

Hypothesis (a) The average value is used to represent the benefits of the station service vehicles. Due to the different energy demands of the vehicles, the benefits of the stations are also different. In order to facilitate calculation, the average value is used to represent the benefits of the station service vehicles and ensure the controllability of the calculation time. Assuming (b) that the benefits of replenishing crowded stations are ensured, the alliance provides a small amount of economic compensation f for these vehicles. When the cost of changing stations is lower than the time cost generated by the current queuing, users will obey station scheduling; Hypothesis (c) ensures the simplicity of the model, which can be relaxed in future studies without affecting the rigor of the model.

Based on the above analysis, the following symbols are involved in the problem as shown in Table 1:

4.2 Main formulation

In order to ensure that the stations work together, the total revenue of the alliance is greater than the original revenue of not working together. Therefore, the characteristic function $V(S)$ is defined as the total revenue of the alliance. According to the above symbol expression, the

Table 1. Definition of notations and parameters

C_1, C_2	The operating costs of the station
Q	The additional cost of setting up an information platform when stations collaborate
R_1, R_2	Revenue from the station after cooperation
T	The computing period is divided into n periods on average, and each interval is divided into N periods, each interval is $\Delta t = T/n$
p	The average profit that each car brings to the station
f	Revenue compensation for vehicles changing stations
η	Maximum service capacity of the station (vehicle/hour)
x_t^1, x_t^2	The number of vehicles at a station in each period of time, and $x_{st}^2 < \eta$, $\forall t \in T$
ε, γ	Compensation coefficients of S_1 and S_2 for vehicles, and $\varepsilon + \gamma = 1$
λ_i^k, μ_i^k	Determine the number of vehicles and service capacity of each time period

Source(s): Table created by authors

mathematical model of the maximum revenue of the energy supply station alliance is established as follows:

$$\max V(S) = R_1 + R_2 - Q \tag{1}$$

$$R_1 = \Delta t \sum_{i=1}^{m} \lambda_i^k p - \Delta t \sum_{i=1}^{m} \alpha f\left(\lambda_i^k - \eta\right) - C_1 \tag{2}$$

$$R_2 = r_2 - C_2 \tag{3}$$

$$r_2 = \Delta t \sum_{i=1}^{n} x_t^2 p + \Delta t \sum_{i=1}^{n} \mu_i^k \left(x_t^1 - \eta\right) p - \Delta t \sum_{i=1}^{n} \beta \mu_i^k f\left(x_t^1 - \eta\right) \tag{4}$$

$$T = \{[0, \Delta t], \ldots, [(i-1)\Delta t, i\Delta t], \ldots, [(n-1)\Delta t, n\Delta t]\} \tag{5}$$

$$\lambda_i^k = \begin{cases} x_t^1, x_t^1 < \eta \\ \eta, x_t^1 \geq \eta \end{cases} \tag{6}$$

$$\mu_i^k = \begin{cases} 0, x_t^1 \leq \eta \\ 1, x_t^1 > \eta \end{cases} \tag{7}$$

$$x_t^2 < \eta\ ,\ \forall t \in T \tag{8}$$

Eq.(1) maximizes the total revenue of the two supply stations. Eq.(2) and Eq.(3) represent the respective revenue after the cooperation between the stations. Eq.(4) is the sales revenue of station S_2. Eq.(5) represents the time period. Eq.(6) represents the number of vehicles entering station S_1 at every moment. Eq.(7) is the variable 0–1. When the number of vehicles entering the station S_1 at time i exceeds the service limit, $\lambda_i^k = 1$; otherwise, $\lambda_i^k = 0$.

4.3 Shapley value

After determining the benefits of the energy supply station alliance, reasonable and fair distribution methods should be considered. Shapley value is a classical method of profit distribution in cooperative games. It is distributed according to the contribution of each member side set and avoids the equal distribution to some extent.

We assume that $I = \{1, 2, \ldots, n\}$ is n energy supply station participants. If any subset $s \in I$ has an eigenfunction, the following preconditions need to be met:

$$v(\varnothing) = 0 \tag{9}$$

$$v(s_1 \cup s_2) \geq v(s_1) + v(s_2)\ s_1 \cap_2 s = \varnothing \tag{10}$$

Obviously, Eq.(9) satisfies the conditions. As for Eq.(10), according to the previous model, the stations after cooperation can absorb more vehicles, and the benefits of the alliance are greater than the sum of the benefits of independent operation of the stations. Therefore, the cooperation of energy supply stations can meet the requirements of Eq.(10). The calculation method of Shapley value alliance allocation is given as follows:

$$\varphi_i(v) = \sum_{|s \subseteq S_i|} \frac{(|s|-1)!(|n|-|s|)!}{|n|!}(v(s \cup i) - v(s)) \tag{11}$$

where, S_i represents the alliance of all members i, $|s|$ is the number of alliance members, and $(|s|-1)!(n-|s|)!/n!$ is the probability of each situation after cooperation. $v(s \cup i) - v(s)$ is the contribution made by Member g in the cooperation process.

4.4 Income distribution model

The Shapley value considers the schemes of all alliances in which participants are involved and calculates the marginal contributions of each participant in the scheme. However, when there are only two energy supply stations forming an alliance, as illustrated in Figure 2, there are three possible paths for forming an alliance, denoted by $\{S_1\}$、 $\{S_2\}$、 $\{S_1, S_2\}$, respectively. Each arrow represents a member joining the alliance, and the weight of each arrow is equal. The difference between the ends of each arrow represents the contribution value of the member joining the alliance. When calculating the profit distribution of S_1 using the Shapley value, it is assumed that the possibilities of all alliances are equal, and thus the contribution values of the two $+V(S_1)$ arrows need to be averaged. However, this allocation method does not consider the influence of other factors, so the Shapley value needs to be improved.

On the basis of Shapley value, the influential factor $\theta_j(0 < \theta_j < 1), j = 1, 2, \ldots, n$ of income distribution is introduced. Analyze the factors influencing the income distribution of the energy supply station alliance, and select three indexes: brand influence (Liu *et al.*, 2022), contribution (Li *et al.*, 2019) and risk bearing (Shalit, 2020).

(1) Brand influence θ_1

Most consumers are more familiar with PetroChina and Sinopec than with other private brands. In the list of domestic energy supply station brands in 2022, Sinopec and PetroChina ranked the top two, and shell ranked the third, indicating that consumers recognized these three brands more. In the cooperation, the station with high brand can improve the trust of consumers and have a greater influence on customers' decisions. Therefore, brand effect plays an important role in station cooperation.

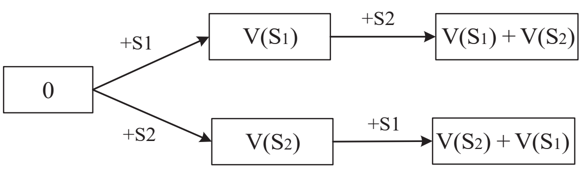

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Figure 2. Formation of the station alliance

(2) Degree of contribution θ_2

In the alliance process, the induction of the vehicle is crucial. For the congestion station, it is necessary to arrange facilitators to facilitate the transfer of vehicles, which will increase the extra cost of the congestion station. At the same time, the stations need to compensate for the revenue of these vehicles, and the compensation will be shared by the alliance. Therefore, the larger the proportion of sharing, the greater the impact of contribution.

(3) Degree of contribution θ_3

Benefits and risks are co-existing, the higher the risk of the station, it will be a greater proportion of income. In the station alliance, the risks mainly come from the operation data of the station, the performance assessment of the staff, the loss of the customer and so on. The Alliance shall distribute the benefits in accordance with the principle of consistent risk and return.

Therefore, the influencing factors of income distribution of alliance building are shown in Table 2:

The table was normalized to calculate the values of different influencing factors j and set as b_{ij}.

$$b_{ij} = \frac{p_{ij}}{\sum_{1}^{n} p_{ij}} \text{且} \sum_{1}^{n} b_{ij} = 1, (j = 1, 2, 3) \tag{12}$$

After normalization, a new matrix is obtained:

$$B = \begin{Bmatrix} b_{11} & b_{12} & b_{13} \\ b_{21} & b_{22} & b_{23} \\ \vdots & \vdots & \vdots \\ b_{n1} & b_{n2} & b_{n3} \end{Bmatrix} \tag{13}$$

As different factors have different degrees of influence, AHP method is used to determine the final weight factors. Let $\beta_j (0 \le \beta_j \le 1)$ be the weight coefficient of factor j, then the weight vector is:

$$\beta = (\beta_1, \beta_2, \beta_3)^T \tag{14}$$

After adjustment, the synthetic vector is λ

$$\lambda = (\lambda_1, \lambda_2, \lambda_3)^T = B * \beta \tag{15}$$

Then the model of the improved Shapley value is:

$$\varphi_i'(V) = \varphi_i(V) + V(I) * (\lambda_i - 1/n)\ ,\ i = 1, 2, ..., I \tag{16}$$

Influencing factors	Brand influence (θ_1)	Degree of contribution (θ_2)	Degree of contribution (θ_3)
Station 1	p_{11}	p_{12}	p_{13}
Station 2	p_{21}	p_{22}	p_{23}
...	...	...	...
Station n	p_{n1}	p_{n2}	p_{n3}

Source(s): Table created by authors

Table 2.
Influencing factors of income distribution

The improved Shapley value fully considers the influence factors of the cooperation between different stations and improves the rationality and objectivity of the allocation.

5. Numerical analysis

5.1 Parameter of example

Without loss of generality, given a transport network, there are two energy supply stations. Relevant data are referenced from references (Ge *et al.*, 2022). Among them, there is often queuing phenomenon at station S_1 during peak hours, and station S_2 is idle all day. Divide the day into 24 periods, $t = 1$ hour. The maximum service quantity of the energy supply station is 50 vehicles/hour. Based on the vehicles entering the station, it can be concluded that the peak hours of the energy supply station S_1 are from 8:00 to 10:00, 12:00 to 14:00, and 18:00 to 20:00. Therefore, the alliance can be reached in these three periods.

Assume that each car can make a profit of 30 yuan, the operation cost of the station is 600 yuan/day, and the operation cost of the station is 400 yuan/day. After the alliance between the two parties, the additional cost of the information platform is 130 yuan/day, and the compensation for the changing vehicles is 5 yuan/vehicle. The traffic flow during peak hours is given in Table 3. The number of vehicles at the gas station within a day is shown in Figure 3.

In the road network, when the traffic flow exceeds the service level, the vehicles entering the station later choose to leave due to the long service waiting time. In the cooperative game, the station has two alternative strategies, operating alone or working in pairs. The various benefits are shown in the table. It can be found that the cooperation between stations can

Time	Number of vehicles at station S_1	Number of vehicles at station S_2	Maximum service vehicle/hour	Vehicle of changing station
8:00~9:00	78	18	50	28
9:00~10:00	63	22	50	13
12:00~13:00	66	30	50	16
13:00~14:00	74	28	50	24
18:00~19:00	56	28	50	6
19:00~20:00	58	30	50	8

Source(s): Table created by authors

Table 3. Traffic flow at some stations during certain periods (vehicles per hour)

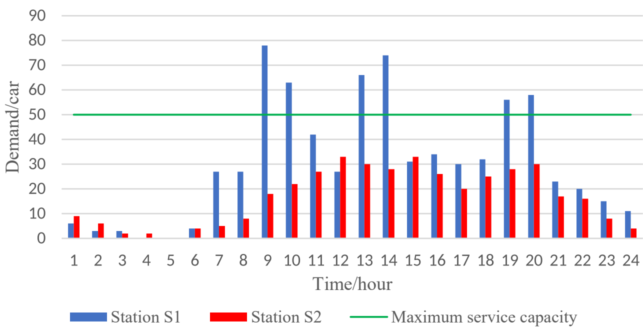

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Figure 3. Vehicle demand per hour

increase the revenue in Table 4. This cooperation is a convex game, and the Shapley value is in the kernel.

5.2 Distribution of profits

Through the previous revenue calculation, we can know that the revenue of cooperation between the two parties is greater than that of independent operation, so the stations are more willing to reach cooperation. Next is the issue of revenue sharing, and the specific distribution process is as follows.

Step 1: According to the evaluation of experts and relevant station personnel, give the correction parameters and weights.

$$(\theta_1,\theta_2,\theta_3)_{S_1}=(0.686,0.367,0.573)\ ,\ (\theta_1,\theta_2,\theta_3)_{S_2}=(0.314,0.633,0.427);$$

The weight coefficient of the three influencing factors is $\beta=(0.5,0.3,0.2)^T$,

from which the correction factor $\lambda_1=0.57,\lambda_2=0.43$ can be obtained.

For the vehicle, the compensation coefficients $\varepsilon=\lambda_1$ and $\gamma=\lambda_2$.

Step 2: Calculate the revenue distribution of the station after the collaboration.

After the cooperation, the additional revenue generated includes the revenue brought by vehicle exchange and government subsidies. Meanwhile, the additional cost generated includes the cost of information platform and the compensation for vehicle exchange, so it can be concluded that the increased revenue after the cooperation is 2,720 yuan. Therefore, the initial distribution of the alliance can be calculated according toEquation (10), and then the Shapley correction value can be obtained according to Equation (16). As shown in Table 5, the total revenue of station S_1 is 9950.4 yuan, and that of station S_2 is 3619.6 yuan.

5.3 Analysis of results

Energy supply station cooperation should first satisfy the increase of income, and then the rationality of income distribution. As can be seen from Table 3, the total revenue after

Time	R_1/yuan	R_2/yuan	R_1+R_2/yuan	$V(S)$ yuan
8:00~9:00	1,500	840	2,340	3,040
9:00~10:00	1,500	390	1,890	2,215
12:00~13:00	1,500	480	1,980	2,380
13:00~14:00	1,500	720	2,220	2,820
18:00~19:00	1,500	180	1,680	1,830
19:00~20:00	1,500	240	1,740	1,940
Total	8,400	2,450	10,650	13,095

Source(s): Table created by authors

Table 4. Benefits of different strategies in cooperative games

Method of allocation	Station S_1	Station S_2
Independent operation	8,400	2,450
Shapley	9,760	3,810
Shapley modified	9950.4	3619.6

Source(s): Table created by authors

Table 5. Comparison of two allocation methods (yuan)

cooperation is 13,095, an increase of 22.9%. Secondly, in terms of distribution rationality, three impact factors are selected and Shapley correction is used to distribute the total revenue. Among them, the revenue of station S_1 increases by 18.4%, and that of station S_2 increases by 47.7%. Compared with independent operation, both stations have a certain degree of increase, especially the increase of station S_2 is nearly half of that before the cooperation. It indicates that cooperation can increase the profits of each party and therefore meets the requirements of cooperation.

From the actual situation, the correction factor depends on the impact factor and its weight coefficient, and the size of the correction factor will affect the income of alliance members. Therefore, it is more reasonable for both parties to jointly formulate the impact factor and weight.

6. Conclusions

With the increase of urban car ownership per capita, the imbalance between supply and demand of energy supply stations occurs from time to time. Previous studies rarely balance the contradiction between supply and demand of vehicle energy supply from the perspective of cooperative game of energy stations. Considering the cooperation of multiple energy supply stations, we induced some vehicles from congested stations to idle stations, proposed a revenue maximization model of energy station alliance, and designed an improved Shapley correction value to distribute the total revenue. The results of the example show that the total revenue generated by cooperation is higher than the sum of the separate operations of the stations, and the revenue obtained by each station is also higher than that of independent operations. As station cooperation transfers the demand of some vehicles to idle stations, which requires the active participation of vehicles, the next step will be to study the impact of vehicle participation degree on energy supply station cooperation.

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Corresponding author
Xian-long Ge can be contacted at: gexianlong@cqjtu.edu.cn