Analysis of Energy Consumption Level and Influencing Factors of Highway Service Area

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Abstract: Highway service area has the characteristics of large passenger flow, complex system equipment, diversified operation management, centralized energy use and complex influence mechanism, which results in the difference of energy consumption between service area and conventional public buildings, but the existing facilities and operation management mode of service area have not reached the optimal state, so it still has high energy-saving potential. Based on the analysis of the principal component analysis, the influencing factors of energy consumption of highway service area are analyzed, the main influencing factors of energy consumption of highway service area are selected, and the close relationship between the annual total energy consumption of highway service area and the influencing factors such as building scale, traffic flow and human flow is determined. Finally, by means of multiple regression analysis, the low-impact factors are further eliminated, and the functional relationship between the total energy consumption and the influencing factors is determined and verified, which is helpful to provide the basis for the service area to adopt the corresponding energy-saving measures.

1. Introduction
The highway service area and parking area are mainly built along the highways, including gas stations, toilets, restaurants, supermarkets, rest rooms, maintenance stations, medical rooms, and parking lots. This article focuses on sixteen service areas in Gaocheng, Xushui, Baoding West, Fuping, Dingxing West, Yixian, Quyang, Shunping, Tangxian, Mancheng, Laiyuan, Baoji, Cuizhuang, Xiongxian, Nanjing, Hengshui of Zhangshi, Baojin, and Deheng highways near Xiongan New District and three parking areas in Tangxian, Quyang, and Wangtong. The main content of the survey is the general situation of the building and energy consumption.

Based on actual energy consumption and related information, the influencing factors of building energy consumption and its level are analyzed.
2. The Influencing Factors and Related Analysis of Energy Consumption of Highway service area

The highway service area of 8 service areas and 2 parking areas with complete research information are selected from the four highways of Zhangshi, Baojin, and Deheng. The total energy consumption and influencing factors of typical service areas and parking areas are shown in Table 1. The table mainly lists two main forms of energy consumption: electricity consumption and coal consumption. In addition, the total energy consumption also includes water consumption\[2\].

| Name       | Bazhou | Cuizhuang | Hengshui | Wangtong | Quyang | Tangxian |
|------------|--------|-----------|----------|----------|--------|----------|
| BC         | 14346  | 7000      | 7045     | 2800     | 3663   | 5330     |
| NOOS       | 17     | 13        | 22       | 20       | 43     | 52       |
| TF         | 24.6   | 19.8      | 16       | 12.4     | 8.4    | 16.8     |
| HT         | 47     | 41        | 37       | 26       | 21     | 40       |
| CSC        | 548    | 109.9     | 484.7    | 112      | 100    | 146.6    |
| HSC        | 1025.7 | 1395.8    | 2093.8   | 697.8    | 698.2  | 1395.9   |
| LP         | 18.6   | 14        | 31       | 19.9     | 20.1   | 15.9     |
| WHP        | 60.3   | 67.9      | 88       | 48       | 45.1   | 99.1     |
| EC         | 1454362| 594447    | 989433   | 90118    | 395392 | 447060   |
| CC         | 375    | 431       | 162      | 140      | 260    | 366      |
| TEC        | 448.6  | 382.9     | 249      | 112.4    | 234.5  | 316.4    |

Table 2. Correlation analysis of energy consumption influencing factors in Baojin, Deheng and Zhangshi highways

| PC | 1    | 0.773 | -0.119 | 0.786 | 0.761 | 0.384 | 0.041 | -0.145 | 0.157 |
| BS | 0.772 | 0.072 | 0.823 | 0.064 | 0.079 | 0.452 | 0.929 | 0.784 | 0.766 |
| NOOS | 0.773 | -0.42 | -0.42 | -0.477 | -0.311 | -0.305 | -0.117 | -0.325 | -0.321 |
| PC | 0.072 | 0.047 | 0.019 | 0.049 | 0.04 | 0.696 | 0.599 | 0.824 |
| BS | 0.782 | 0.407 | 0.338 | 0.548 | 0.557 | 0.825 | 0.53 | 0.535 |
| PC | 0.786 | 0.855 | -0.477 | 1 | 0.695 | 0.629 | 0.333 | -0.014 | 0.333 |
| Sig | 0.064 | 0.019 | 0.338 | 0.002 | 0.181 | 0.519 | 0.979 | 0.518 |
| PC | 0.761 | 0.815 | -0.311 | 0.965 | 1 | 0.63 | 0.511 | -0.011 | 0.564 |

Note: BS [m2] refers to Building Scale; NOOS [people] refers to Number of Office Staff; TF [ten thousand] refers to Traffic Flow; HT [ten thousand] refers to Human Traffic; CSC [kW] refers to Cold Source Capacity; HSC [kW] refers to Heat Source Capacity; LP[kW] refers to Lighting Power; WHP [kW] refers to Water Heater Power; EC [kWh] refers to Energy Consumption; CC [t] refers to Coal Consumption; TEC [Tons of standard coal] refers to Total Energy Consumption.

Compared with Table 1, we can see that the energy consumption per unit area of the service area in the Jingshi Highway is significantly less than that of the service areas and parking areas in the other three highways.

Correlation analysis is used to study whether there is a certain dependence relationship with two random variables which mainly displays the correlation direction and the degree of correlation of two variables by calculating the correlation coefficient. And it is a kind of statistics to study the linear correlation of random variables. From the relevant analysis, it can be concluded that the total annual energy consumption of the highway service area is different from the building scale, the number of office staff, the traffic flow, the human traffic, the cold source capacity, the heat source capacity, the lighting power, and the water heater power\[3\]. The relevant analysis results of the energy consumption influencing factors of typical highway service area are shown in Table 2.
It can be seen from Table 2 that the total energy consumption of highway service areas in Baojin, Deheng, and Zhangshi is positively correlated with the building scale, the traffic flow, the human flow, the cold source capacity, the heat source capacity, and the water heater power, while it has a negative correlation with the number of office staff and the lighting power \(^4\).

3. Construction and verification of energy consumption analysis model based on principal component and multiple regression

There are many influencing factors of energy consumption indicators in each highway service area, and the correlation of variables will cause multiple collinearity problems, so it is not suitable to perform regression analysis directly. This paper uses principal component analysis to select the main influencing factors and reduce the multiple collinearity problems.

3.1 Fundamental principle

Principal component analysis can use the idea of dimensionality reduction to convert multiple indicators into a few comprehensive indicators (principal components), and each principal component can reflect most of the information of the original variable and contains different information \(^5,6\). This method introduces multiple variables and reduces the complex factors into several principal components at the same time, which simplifies the problems and obtains more scientific and effective results.

The basic steps of principal component analysis are as follows:

- The \(p\)-dimensional random vector of the original statistical collection of standardized sample data is \(X = (X_1, X_2, \ldots, X_p)^T\) of \(n\) samples \(x = (x_1, x_2, \ldots, x_p)^T\), \(i = 1, 2, \ldots, n\), \(n > p\). Now construct a sample matrix for the original random vector and perform a standardized transformation

\[
Z_{ij} = \frac{x_{ij} - \bar{X}_i}{S_j} \quad (i = 1, 2, \ldots, n ; j = 1, 2, \ldots, p)
\]  

(1)

- \(Z_{ij}\) is Original sample variables; \(X_{ij}\) is corresponding to standardized variables in formula.

\[
X_i = \frac{\sum x_i}{n}
\]  

(2)

\[
S_j = \sqrt{\frac{\sum (x_{ij} - \bar{X}_i)^2}{n - 1}}
\]  

(3)

(2) Calculate matrix \(R\) based on standardized sample data, and calculate the correlation matrix \(R\) of the evaluation index coefficient which has been standardized. The coefficient correlation matrix of \(Z = (Z_{ij}, Z_{ij}, \ldots, Z_{ij})^T\) is \(R\), we use \(r_{ij}\) represents the correlation coefficient between the element
Calculate eigenvector and eigenroot of matrix $R$ and determine principal component factors and number. By solving the characteristic equation $|R - \lambda I| = 0$, get p relevant characteristic roots, the main component factors are determined according to $\lambda_j$ $(j=1,2,...,m_i)$ denote $\lambda_j$ is the i-th eigenvalue of the matrix $R$; $P_j$ is a standardized variable $Z_1, Z_2, ..., Z_p$ constructed on the j-th principal factor.

### 3.2 Analysis of Main Energy Consumption Influencing Factors of highway service area

#### Table 3. Contribution rate of variable explanation of energy consumption influencing factors of the service areas in Baojin, Deheng and Zhangshi highways

| ingredient | Initial value | Extracted sum of squares |
|------------|---------------|----------------------------|
|            | variance      | Grand variance             | total | variance | Grand variance |
| total      | 4.14          | 51.746                    | 51.746 | 4.14     | 51.746         |
| 1          | 1.719         | 21.484                    | 73.23  | 1.719    | 21.484         |
| 2          | 1.443         | 18.043                    | 91.273 | 1.443    | 18.043         |
| 3          | 0.652         | 8.148                     | 99.421 |          |                |
| 4          | 0.046         | 0.579                     | 100    |          |                |
| 5          | 5.00E-16      | 6.25E-15                  | 100    |          |                |
| 6          | 1.41E-16      | 1.77E-15                  | 100    |          |                |
| 7          | -1.83E-16     | -2.29E-15                 | 100    |          |                |

It can be seen from Table 3 that the variance of the first principal component is 4.14, the variance of the second principal component is 1.719, and the variance of the third principal component is 1.443. The variances of the three eigenvalues are all greater than 1, and the cumulative contribution rate of the variances reaches 91.273%. This shows that the selected principal components basically meet the requirements, and the analysis results are available, so we can just select three principal components[7].

It can be seen from Table 4 that in the first principal component, the absolute value of the coefficients of the four indicators: the building scale, the traffic flow, the human traffic flow, and the cold source capacity exceed 0.8, which indicate these four indicators in the first principal component have a higher degree of influence; In the second principal component, the absolute value of the coefficient of one indicator of water heater power exceeds 0.8, which indicate this indicator has a relatively high degree of influence; In the third principal component, the absolute value of the coefficient of one indicator of the lighting power indicator exceeds 0.8, which indicate this indicator has a relatively high degree of
influence\(^8\). Let \(X_1\sim X_8\) represent the 8 original variables in Table 4, and the function expressions of principal component 1, principal component 2, and principal component 3 are as follows:

\[
F_1 = 0.428X_1 - 0.216X_2 + 0.435X_3 + 0.447X_4 + 0.428X_5 + 0.318X_6 + 0.195X_7 + 0.244X_8 \tag{5}
\]

\[
F_2 = -0.268X_1 + 0.510X_2 - 0.218X_3 + 0.070X_4 - 0.076X_5 + 0.447X_6 - 0.104X_7 + 0.655X_8 \tag{6}
\]

\[
F_3 = -0.140X_1 - 0.110X_2 - 0.357X_3 - 0.333X_4 + 0.216X_5 + 0.313X_6 + 0.748X_7 - 0.070X_8 \tag{7}
\]

### 3.3 Multiple regression energy consumption analysis model

Regression analysis refers to the analysis of the relationship between the dependent variable and the independent variable. Although there is no strict and deterministic functional relationship between them, but we can try to find the mathematical expression that can best represents the relationship between them. On the basis of correlation analysis, a regression model is established by analysis to further determine the specific functional relationship between energy consumption and various influencing factors\(^9\). There are many factors influencing building energy consumption in the expressway service area, so we choose multiple regression analysis when fitting the model, and determine the main building energy consumption factors by principal component analysis. Before that, the redundant variables of the model and the multiple collinear problems between variables are eliminated, and improve the accuracy of the model built.

The total energy consumption \(Y\) of 10 typical service areas in 3 expressways near Xiongan New Area for two consecutive years was analyzed by multiple regression analysis on the main energy consumption factors to further eliminate influencing factors with lower relevance. So we obtain the quantitative relationship expressions between the total annual energy consumption of the service area and various influencing factors. The quantitative expressions of Baojin, Deheng, and Zhangshi highways are as formula (8)

\[
Y = 3.767 \times 10^1 + 2.735X_1 - 0.339X_2 - 0.220X_3 - 2.082X_4 + 0.506X_5 + 0.681X_6 \tag{8}
\]

Model fits good (\(R^2 = 1.00\)), and the linear relationship is significant.

Through the principal component analysis method, it can be known that the total annual energy consumption of the three highway service area of Baojin, Deheng, and Zhangshi has a strong correlation with building scale, vehicle flow, passenger flow, cooling source capacity, lighting power, and water heater power. The three highways adopt a relatively backward conventional electric refrigeration and boiler heating to increase the capacity of the energy contribution rate.

### 4. Conclusions

Through the regression model, it can be concluded that the total energy consumption of service areas on Baojin, Deheng, and Zhangshi highways is positively correlated with building scale, lighting power, and water heater power, and negatively correlated with vehicle flow, passenger flow, and cold source capacity\(^10\). It is found that the expressway service area has the characteristics of large passenger flow, complex system equipment and diverse operation management. Energy consumption is concentrated and has a complex impact mechanism, as a result, the energy consumption of the service area is much higher than that of conventional public buildings. However, the existing service area facilities and operation management models have not reached the optimal state, so they still have high energy-saving potential. The functional relationship between the total annual energy consumption of the service area and various influencing factors made by multiple linear regression is helpful to provide a basis for the service area to adopt corresponding energy-saving measures.

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