A Factor-analysis-based Study on the Energy Efficiency Competitiveness Evaluation System for China's Passenger Vehicles

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Abstract. To address the current problems including energy and environmental pressures as well as climbing oil prices, governments and consumers have been increasingly focused on fuel economy. Combined fuel consumption of passenger vehicles (L/100km) is applied as an important indicator in industry management and consumer promotion. Because fuel consumption is affected by various factors such as curb weight, power and space, combined fuel consumption fails to fully reflect vehicle energy efficiency ability. In this article, the problem of how to establish an indicator system to comprehensively reflect vehicle energy efficiency competitiveness will be discussed. With comprehensive consideration of various indicators, China's gasoline-powered passenger vehicles in 2015 will be analysed by the approach of factor analysis, and an indicator system reflecting passenger vehicle energy efficiency competitiveness and comprehensive competitiveness will be proposed.

1. Introduction

China's automotive industry has been developing dramatically since the beginning of 21st century. By 2015, China's automobile production and sales volume both exceeded 21 million, and the car-park reached 136 million. The rapid increase in the car-park lead to gradual exposure of problems in energy, environment and transportation, with the growing energy problem as the top issue to address. In 2014, China's motor gasoline consumption took up 90% of the total social gasoline apparent consumption. Additionally, the climbing gasoline prices make consumers more concerned with fuel economy.

So far, absolute fuel economy indicators commonly used in China include urban fuel consumption, suburban fuel consumption, combined fuel consumption and 90km/h constant-speed fuel consumption. Due to the relatively strong correlativity between passenger vehicle fuel economy and curb weight, power rating and external dimensions, energy efficiency comparison between vehicles with different parameters will be one-sided so that a comprehensive indicator system is required to evaluate vehicle energy efficiency competitiveness.

2. An Overview of the Model

Factor analysis is a widely applied comprehensive evaluation method, which is a statistical model to analyze factor effects behind superficial phenomenon. And then analysis on influencing factors behind vehicle performance data is workable. In this article, the factor analysis model will be employed. The basic structure of the model is as follows:

Assume $\vec{X} = (X_1, X_2, \cdots, X_p)^T$ is an observable random vector, and

$$E(\vec{X}) = \vec{\mu} = (\mu_1, \mu_2, \cdots, \mu_p)^T \tag{1}$$

$$var(\vec{X}) = \vec{\Sigma} = (\sigma_{ij})_{p\times p} \tag{2}$$

Then the basic form of the factor analysis model is

$$\vec{X} = \vec{\mu} + \vec{A}\vec{F} + \vec{\varepsilon} \tag{3}$$

Where $\vec{F} = (f_1, f_2, \cdots, f_m)^T$ （$m < p$） denotes the common factor, $\vec{\varepsilon} = (\varepsilon_1, \varepsilon_2, \cdots, \varepsilon_p)^T$ is the specific factor, $\vec{A} = (a_{ij})_{p\times m}$ represents the factor load matrix, which means $cov(\vec{X}, \vec{F}) = \vec{A}$, i.e. factor loading a_{ij} is the correlation coefficient of the i-th variable and the j-th common factor.

It is generally assumed that

$$E(\vec{F}) = \vec{0}, \tag{4}$$

$$var(\vec{F}) = \overrightarrow{I_m} \tag{5}$$

$$E(\vec{\varepsilon}) = \vec{0} \tag{6}$$

$$var(\vec{\varepsilon}) = \vec{D} = diag(\sigma_1^2, \sigma_2^2, \cdots \sigma_p^2) \tag{7}$$

$$cov(\vec{F}, \vec{\varepsilon}) = \vec{0} \tag{8}$$

This is the basic model structure, and estimations of relevant parameters are required after establishing the basic model.

3. Modeling Process

3.1 Indicator Selection. There are many indicators related to vehicle energy efficiency. In this article, power, economy and practicability, the usual concerns of consumers, will be selected as first class indicators, and second class indicators will be determined accordingly. To prevent unbalanced factor weight caused by the quantitative difference, the number of subordinate second class indicators of every first class indicator should be kept roughly the same.

Table 1 illustrates the chosen evaluation indicator system. Macro indicators of power are maximum vehicle speed, power rating, specific power, torque. Economy indicators include urban fuel consumption, suburban fuel consumption, and combined fuel consumption. Practicability indicators are vehicle length, width, height and space, where height refers to the actual height of the vehicle (hereinafter), equaling to roof height minus ride height. Because of the difficulty in acquiring space data, an approximate value of length * width * height will be applied as a replacement.

In addition, curb weight is highly correlated to all three first class indicators, thus it is treated as an independent second class indicator. There are 12 indicators in total.

Table 1 Selected evaluation indicators of vehicle energy efficiency competitiveness

First Class Indicator	Parameter	Second Class Indicator
	X_1	Curb Weight (Weight)
	X_2	Length
Practicability	X_3	Width
	X_4	Height
	X_5	Length * Width * Height (Space)
	X_6	Combined Fuel Consumption (Combination)
Economy	X_7	Urban Fuel Consumption (Urban Area)
	X_8	Suburban Fuel Consumption (Suburban Area)
	X_9	Maximum Vehicle Speed (Speed)
Power	X_{10}	Torque
	X_{11}	Power Rating
	X_{12}	Specific Power

3.2 Model Building. A sedan, an SUV and a MPV vary greatly in structural functions, for this reason, 708 China's gasoline sedans manufactured in 2015 will be selected as objects to study.

Firstly, 12 parameters of all sedans will be normalized and standardized, and maximum likelihood estimation will be conducted on standardized data to estimate the factor load matrix. Then variance will be maximized by orthogonal rotation and factor scores will obtained by performance comparison on different sedan models.

Maximum Likelihood Estimation (MLE). Maximum likelihood estimation (MLE) results of the factor load matrix can be gained by iteration. MLE results of the factor analysis model is provided by factor analysis on gasoline sedan data in 2015:

Table 2 MLE of the factor load matrix

Indicator	Factor 1	Factor 2	Factor 3
Weight	0.750	0.364	0.482
Length	0.657	0.103	0.650
Width	0.295	0.592	0.385
Height	0.529	-0.315	0.672
Space	0.646	0.061	0.758
Combination	0.951	0.051	0.297
Urban Area	0.933	0.057	0.286
Suburban Area	0.918	0.049	0.314
Vehicle Speed	-0.071	0.797	-0.211
Torque	0.538	0.729	0.275
Power Rating	0.376	0.894	0.233
Specific Power	-0.319	0.862	-0.203

Variance contribution rates obtained by the MLE approach are as follows:

Table 3 Proportion var of MLE

Factor	Factor 1	Factor 2	Factor 3
SS loadings	6.799	2.086	1.158
Proportion Var	0.567	0.174	0.097
Cumulative Var	0.567	0.740	0.837

Orthogonal Rotation. If $\vec{\mathbf{F}}$ is the common factor vector of the factor model, then $\vec{\mathbf{Z}} = \vec{\mathbf{\Gamma}}^{\mathbf{T}}\vec{\mathbf{F}}$ is also the common factor vector of any orthogonal matrix $\vec{\mathbf{\Gamma}}$. Accordingly, the variance of the factor load matrix $\vec{\mathbf{A}}$ can be made as large as possible by conducting post-multiplication of orthogonal matrix $\mathbf{\Gamma}$, so as to simplify the structure of the common factors and indicate more specific meanings.

Orthogonal rotation common factors with maximum variance can be gained by conducting orthogonal rotation.

Table 4 MLE of the factor load matrix after varimax orthogonal rotation

Indicator	Factor 1	Factor 2	Factor 3
Weight	0.810	0.420	0.404
Length	0.694	0.380	0.267
Width	0.785	0.329	0.263
Height	-0.235	-0.058	-0.041
Space	0.733	0.389	0.282
Combination	0.313	0.930	0.179
Urban Area	0.293	0.913	0.174
Suburban Area	0.319	0.877	0.169
Vehicle Speed	0.592	0.179	0.664
Torque	0.571	0.198	0.728
Power Rating	0.498	0.317	0.804
Specific Power	0.077	0.126	0.979

Variance contributions after doing orthogonal rotation are as follows:

Table 5 Proportion var of MLE after varimax orthogonal rotation

Factor	Factor 1	Factor 2	Factor 3
SS loadings	3.562	3.241	3.052
Proportion Var	0.297	0.270	0.254
Cumulative Var	0.297	0.567	0.821

The factor connotations can be identified according to the correlativity of normalized vector $\vec{Y_i}$ and factor f_1.

Based on the correlation coefficient of MLE results, it can be inferred that the first factor correlates highly with curb weight, length, width and space, which can be considered as the practical factor. The second factor can be regarded as the economical factor due to its high correlation with urban fuel consumption, suburban fuel consumption, and combined fuel consumption. The third factor has relatively high correlation with maximum vehicle speed, torque, power rating, and specific power, so it can be treated as the power-related factor.

Factor Scores. Based on identified factor connotations, factor scores need to be calculated to make a general evaluation on the comprehensive performance of vehicles and make a reasonable comparison between vehicles with different weights and of different levels.

Assume $\vec{R} = (r_{ij})_{p\times p}$ represents the correlation matrix, then the score coefficient matrix $\vec{B} = (b_{ij})_{m\times p}$ is:

$$\vec{B} = \vec{A}^{T}\vec{R}^{-1} \tag{9}$$

Accordingly, factor score coefficient matrixes are as follows:

Table 6 coefficient matrix of factor scores

Sedan	Weight	Length	Width	Height	Space	Combination	Urban Area	Suburban Area	Vehicle Speed	Torque	Power Rating	Specific Power
Factor 1	1.456	0.022	0.042	-0.003	0.031	-0.513	-0.056	-0.020	0.017	0.019	-0.150	-0.413
Factor 2	-0.378	-0.005	-0.012	0.001	-0.007	1.124	0.114	0.051	-0.013	-0.020	-0.108	0.039
Factor 3	-0.517	-0.010	-0.019	0.002	-0.014	-0.111	-0.009	-0.007	0.012	0.028	0.881	0.507

factor 1, factor 2, factor 3 (denoted by f_1, f_2, f_3)can be regarded as the practical factor, economical factor and power-related factor, according to the correlation coefficient in Table 4 and regression coefficient in Table 6.

Taking actual physical significance into consideration, we can determine that the higher the practical and power-related factors score, the better the vehicle performance will be; in contrast, the lower the economical factor score, the better vehicle economy will be. In order to maintain uniform monotonicity, the economical factor is negated, i.e.

$$f_2 = 0.378y_1 + 0.005y_2 + 0.012y_3 - 0.001y_4 + 0.007y_5 - 1.124y_6 - 0.114y_7 - 0.051y_8 + 0.013y_9 + 0.020y_{10} + 0.108y_{11} - 0.039y_{12} \quad (10)$$

Based on weights of the factors, a comprehensive evaluation indicator of the vehicle performance can be gained:

$$f = 0.297f_1 + 0.270f_2 + 0.254f_3 \quad (11)$$

4. An Analysis on Evaluation Results

On the basis of factor scores, overall rankings of 708 sedans of different models can be made accordingly. See the economical factor ranking:

Table 7 Top 5 of fuel economical factor score

Common Name	Weight [kg]	Length [mm]	Width [mm]	Height [mm]	Space [m3]	Combination [L/100km]	Urban Area	Suburban Area	Vehicle Speed	Torque	Power Rating	Specific Power	Score
Golf	1280	4255	1799	1346	10.303	5.1	6.2	4.5	190	200	81	63.28	2.034
408	1320	4750	1820	1364	11.792	5.2	6.8	4.3	200	230	100	75.76	2.021
C4	1320	4588	1800	1370	11.314	5.2	6.8	4.3	200	230	100	75.76	2.011
308S	1305	4255	1820	1355	10.493	5.2	6.8	4.3	195	230	100	76.63	1.970
Focus	1314	4534	1823	1363	11.266	5.2	6.9	4.4	195	170	94	71.54	1.955

Overall rankings based on weighted average are as follows:

Table 8 Top 5 of comprehensive evaluation indicator

Common Name	Weight	Length	Width	Height	Space	Combination	Urban Area	Suburban Area	Vehicle Speed	Torque	Power Rating	Specific Power	Score
S60L	1651	4715	1866	1339	11.781	6.5	8.8	5.3	230	350	200	121.14	1.891
BMW 5 Series	1815	5055	1860	1356	12.750	7.2	9.1	6.1	250	350	200	110.19	1.810
Benz E-Class	1769	5024	1854	1334	12.426	6.7	8.6	5.6	243	350	155	87.62	1.662
Audi A6L	1750	5036	1874	1356	12.797	6.5	8	5.7	235	320	140	80.00	1.626
BMW 3 Series	1560	4650	1811	1327	11.175	6.7	8.8	5.5	250	350	200	128.21	1.527

S60L is placed in front because of its outstanding power performance. BMW 5 series, Benz E-class and Audi A6L have larger space than S60L, but short of power performance.

Turbo is widely used in the cars which rank top of the overall rankings. Applying of energy-saving technologies is a great help of improving in the overall rankings.

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