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A Perfect Decomposition Model for Analyzing Transportation Energy Consumption in China

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Abstract: Energy consumption in transportation industry is increasing. Transportation has become one of the fastest energy consumption industries. Transportation energy consumption variation and the main influencing factors of decomposition contribute to reduce transportation energy consumption and realize the sustainable development of transportation industry. This paper puts forwards an improved decomposition model according to the factors of change direction on the basis of the existing index decomposition methods. Transportation energy consumption influencing factors are quantitatively decomposed according to the transportation energy consumption decomposition model. The contribution of transportation turnover, transportation structure and transportation energy consumption intensity changes to transportation energy consumption variation is quantitatively calculated. Results show that there exists great energy-conservation potential about transportation structure adjustment, and transportation energy intensity is the main factor of energy conservation. The research achievements enrich the relevant theory of transportation energy consumption, and help to make the transportation energy development planning and carry out related policies.

Keywords: transportation; energy consumption; influencing factors; index decomposition approach

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1. Introduction

Transportation has become one of the fastest growing energy consumption industries worldwide. Quantitative assessment of various factors affecting energy consumption is essential not only for a better understanding of past behaviors of transportation energy consumption, but also for estimating energy requirements of alternative industrialization strategies.

To study the related issues of energy consumption in the transportation system, we should first clarify the composition of the transportation system. The national transportation system divides into the domestic inter-city transportation system composed of railway, highway, waterway, civil aviation, and pipeline, and the urban transportation system formed by urban road and rail transportation. Therefore, waterway transportation does not include ocean transportation. According to the nature of transportation tasks, road transportation can divide into operational transportation completed by operating vehicles, and non-operational transportation completed by non-operating vehicles. According to the different railway transportation systems undertaken, railway transportation can be divided into passenger and freight transportation completed by the national and local railway transportation systems with or without a network, and urban passenger transportation completed by the urban rail transit system. The inter-city transportation system, composed of five modes of transportation, undertakes the road transportation of operational and non-operational vehicles, the same as the transportation tasks of railway, waterway, civil aviation, and pipeline, defined as complex transportation. The transportation system is composed of the domestic inter-city transportation system, and the intra-city transportation system is a total transportation system. To facilitate the analysis and calculation and the availability of data, the scope of the transportation system studied is the operational transportation system, which includes five modes of transportation (highway, railway, waterway, aviation, and pipeline).

Decomposition methodology is an effective method dealing with energy consumption-related issues analysis. Studies can be traced back to the early 1980s. Laspeyres index decomposition was first proposed to analyze the influence factors of industrial energy consumption [1]. Many researchers subsequently applied this method to decompose the energy consumption change [2–4]. However, an important factor, called residual known as the sum of all the interactions of the main effects, was usually ignored, which caused large estimation errors.

Boyd et al. is likely to be the first to analyze energy consumption problems using Divisia index decomposition [5–7]. The same decomposition methods were also directly applied in Howarth et al. [8,9] and Li [10], where the residual was not resolved. Though Sun, J. [11–13] proposed a complete decomposition model, which disposed the residual according to the principle of "common creation, equal distribution", the error will become bigger when the time span of analysis is enlarged.

Among Divisia index decomposition methods, two methods are widely applied: arithmetic mean Divisia index method (AMDI) [14] and logarithmic mean Divisia index decomposition method (LMDI) [15]. In the formulae of AMDI, logarithmic terms were introduced, which might lead to computational problems when zero values appear in the data set (i.e., denominator is zero). A framework for additive and multiplicative decomposition [16,17] was extended based on the two general parametric Divisia index methods, i.e., additive and multiplicative decompositions [14]. The LMDI was proposed with the continuous development of the Divisia Decomposition [18,19]. It is reasonable to replace arithmetic mean weight function by logarithmic mean weight function, because the latter can decompose the residual completely without generating unexplained residual. Ang B.W. [20–27] analyzed many index decomposition approaches and pointed out the advantages of LMDI including eliminating residual term and using time independence. Many researchers analyzed the problems of the LMDI method, which occurred when processing negative numbers and zero values [28–31]. A new decomposition method called the LMDII was introduced [21]. This approach could completely decompose the remaining items and deal with zeros appearing in the data set in the decomposition process. However, it is lack of the consideration of changes of intermediate demand, and it ignores the influence of the energy consumption or consumption structure changes. Another method introduced a 'mean rate-of-change index' (MRCI) [28] to give different weights for decomposed terms. This method provides more plausible and reasonable results, because it ensures residual-free decomposition even when data contain negative values, which cannot be handled by the LMDI method.

In addition, the Shapley decomposition, which calculates the influence of factors on the energy consumption variation according to the total contribution of various factors [24], makes it possible to present a correct and symmetric decomposition without residual [32]. Thus, the residual can be resolved completely.

In summary, every method has its own advantages and disadvantages. The Laspeyres and Divisia index decompositions are the most primitive methods. However, neglecting residual term is their common problem. The complete decomposition model is widely used to solve the residual, the index weight and the change of the positive and negative numbers are neglected. In LMDI decomposition, the residual term can be totally decomposed, while zero and negative values remain as a problem in data processing.

Analyzing energy consumption trends and strength is beneficial to solving the problem of energy distribution imbalance and then to improving energy efficiency [33–36]. The calculation results also have many errors according to different decomposition methods of the residual items. Therefore, it is necessary to seek a more scientific decomposition method to accurately analyze influence factors of energy consumption. The residual term is related to changes in both quantity and direction of influence factors, and is more likely decided by negatively changed factors. To this end, this paper proposes a perfect decomposition method that considers the changes of influence factors and the changing direction. The remainder of this paper is organized as follows: Section 2 proposes the methodology; Sections 3 and 4 describe an empirical case study and discuss the results; Conclusions are made at last.

2. Methodology

2.1. Decomposition Model Construction According to Factor Direction

A perfect decomposition model is proposed according to the different changing directions of factors. This principle can be extended from two factors and three factors to multiple factors.

2.1.1. Two-Factor Decomposition Model

We take a two-factor model as a sample example to describe this principle. Figure 1 illustrated the process of the factor changes in different directions, i.e., x_1 decreases by Δx_1, and then x_2 increases by Δx_2.

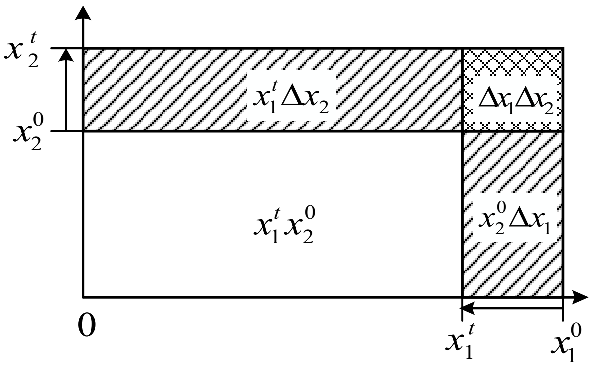

Figure 1. Index change when two factors change at different directions.

Assume that $v = x_1x_2$, i.e., variable v is determined by factors x_1 and x_2, within the time period $[0,t]$, $x_1^t = x_1^0 + \Delta x_1$, $x_2^t = x_2^0 + \Delta x_2$, the change of variable Δv can be represented as:

$$\Delta v = v^t - v^0 = x_1^t x_2^t - x_1^0 x_2^0 = x_2^0 \Delta x_1 + x_1^0 \Delta x_2 + \Delta x_1 \Delta x_2 \quad (1)$$

where $x_2^0\Delta x_1$ and $x_1^0\Delta x_2$ represent the contributions of x_1 and x_2 to the total change of variable v, respectively; $\Delta x_1\Delta x_2$ is the residual term. There are two situations need to be discussed.

The factors change at the same direction;

If x_1 increases by Δx_1, x_2 increases by Δx_2, accordingly. The complete decomposition of two factors is as follows:

$$x_{1-effect} = x_2^0 \Delta x_1 + \frac{1}{2}\Delta x_1 \Delta x_2 \quad (2)$$

$$x_{2-effect} = x_1^0 \Delta x_2 + \frac{1}{2}\Delta x_1 \Delta x_2 \quad (3)$$

The term $\Delta x_1\Delta x_2$ is the residual term in the traditional decomposition method, which can be divided equally to the contributions of x_1 and x_2. Both the changes of x_1 and x_2, i.e., Δx_1 and Δx_2, determines the contributions. If one of Δx_1 and Δx_2 is zero, the other is also zero.

The factors change in different directions;

Figure 1 illustrated the process of the factor changes in different directions, i.e., x_1 decreases by Δx_1, and then x_2 increases by Δx_2.

It can be seen from Figure 1 that when x_2^0 increases by Δx_2, $x_1^0 \Delta x_2$ is the contribution of the change of x_2 to the total change of v that contains two parts, i.e., $x_1^t \Delta x_2$ and $\Delta x_1 \Delta x_2$. When x_1^0 decreases by Δx_1, $x_2^0 \Delta x_1$ is the contribution of the change of x_2 to the total change of v, which counteracts $\Delta x_1 \Delta x_2$ because x_2^0 increase by Δx_2, the contribution of x_1 and x_2 to the total change of variable v can be respectively calculated as follows:

$$x_{1-effect} = x_2^0 \Delta x_1 + \Delta x_1 \Delta x_2 \quad (4)$$

$$x_{2-effect} = x_1^0 \Delta x_2 \quad (5)$$

From Figure 1 and Equations (2)–(5), it can be summarized that for the two-factor model, if the two factors change at same direction, the residual term can be divide equally to the two factors; however, if the two factors change at different directions, the residual term belongs to the factor that changes negatively.

2.1.2. Three-Factor Decomposition Model

Assume that the variable $v = x_1 x_2 x_3$, where the variable v is determined by x_1, x_2 and x_3, within the time period $[0, t]$. The change of variable v, i.e., Δv, can be calculated as:

$$\begin{aligned} \Delta v &= v^t - v^0 = x_1^t x_2^t x_3^t - x_1^0 x_2^0 x_3^0 = (x_1^0 + \Delta x_1)(x_2^0 + \Delta x_2)(x_3^0 + \Delta x_3) - x_1^0 x_2^0 x_3^0 \\ &= \overbrace{x_2^0 x_3^0 \Delta x_1 + x_1^0 x_3^0 \Delta x_2 + x_1^0 x_2^0 \Delta x_3}^{\text{similar items}} + \overbrace{x_3^0 \Delta x_1 \Delta x_2 + x_2^0 \Delta x_1 \Delta x_3 + x_1^0 \Delta x_2 \Delta x_3}^{\text{joint effect items}} + \overbrace{\Delta x_1 \Delta x_2 \Delta x_3}^{\text{residual item}} \end{aligned} \quad (6)$$

where Δv is composed of the following three parts: the first part is the contributions of the change of single factor x_1, x_2, or x_3 to the total change of v, which is the sum of $x_2^0 x_3^0 \Delta x_1$, $x_1^0 x_3^0 \Delta x_2$, and $x_1^0 x_2^0 \Delta x_3$; the second part $x_3^0 \Delta x_1 \Delta x_2$, $x_2^0 \Delta x_1 \Delta x_3$, and $x_1^0 \Delta x_2 \Delta x_3$ are the joint effects of the change of two factors; the third part $\Delta x_1 \Delta x_2 \Delta x_3$ is a residual item produced by the change of the three factors simultaneously.

The factors change at the same direction;

In the three-factor model, when all factors change at the same direction, there are two situations, i.e., all factors increase or decrease simultaneously. The common effect and contribution of the changes of the factors are the same, which can be equally assigned to each factor as follows:

$$x_{1-effect} = x_2^0 x_3^0 \Delta x_1 + \frac{1}{2} \Delta x_1 (x_3^0 \Delta x_2 + x_2^0 \Delta x_3) + \frac{1}{3} \Delta x_1 \Delta x_2 \Delta x_3 \quad (7)$$

$$x_{2-effect} = x_1^0 x_3^0 \Delta x_2 + \frac{1}{2} \Delta x_2 (x_3^0 \Delta x_1 + x_1^0 \Delta x_3) + \frac{1}{3} \Delta x_1 \Delta x_2 \Delta x_3 \quad (8)$$

$$x_{3-effect} = x_1^0 x_2^0 \Delta x_3 + \frac{1}{2} \Delta x_3 (x_2^0 \Delta x_1 + x_1^0 \Delta x_2) + \frac{1}{3} \Delta x_1 \Delta x_2 \Delta x_3 \quad (9)$$

The factors change at different directions;

When the three factors change at different directions, two cases are needed to discuss.

The change of two factors is positive, and one factor is negative;

Assume that the change of x_3 is negative, i.e., x_3 decreases, while the changes of x_1 and x_2 are positive, i.e., both x_1 and x_2 increase. Figure 2 illustrates the changes of the three factors.

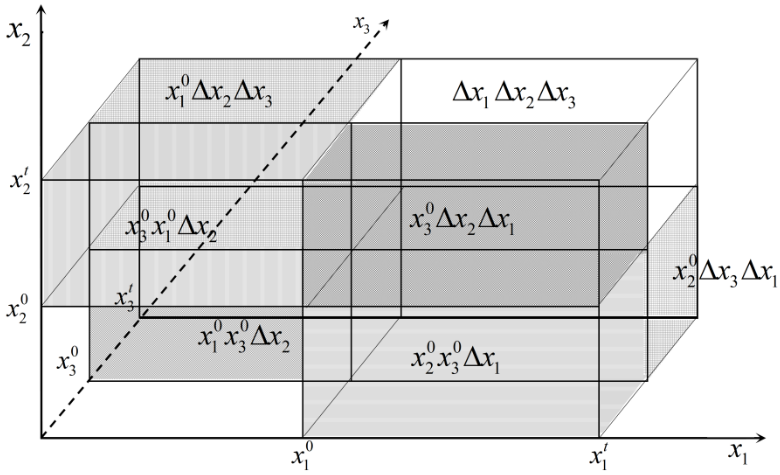

Figure 2. Index change when three factors change at different directions.

It can be seen from Figure 2 that, when x_2 increase by Δx_2, the total change of v increases by $x_1^0 x_3^0 \Delta x_2$, ($x_1^0 x_3^0 \Delta x_2 = x_3^t x_1^0 \Delta x_2 + x_1^0 \Delta x_2 \Delta x_3$); when x_1 increases by Δx_1, the total change of v increases by $x_2^0 x_3^0 \Delta x_1 = x_3^t x_2^0 \Delta x_1 + x_2^0 \Delta x_1 \Delta x_3$; when x_3 decreases by Δx_3, the total change of v decreases by $x_2^0 x_1^0 \Delta x_3$, $x_2^0 \Delta x_1 \Delta x_3$, $x_1^0 \Delta x_2 \Delta x_3$, and $\Delta x_1 \Delta x_2 \Delta x_3$. At the same time, it also cancels out the total change of $x_2^0 \Delta x_1 \Delta x_3$, $x_1^0 \Delta x_2 \Delta x_3$, and $\Delta x_1 \Delta x_2 \Delta x_3$, because x_2 increases by Δx_2 and x_1 increases by Δx_1. Each factor increases or decreases to offset the other. The contribution of x_1, x_2 and x_3 to the total change of v is represented in the following formulas, respectively.

$$x_{1-effect} = \Delta x_1 x_2^0 x_3^0 + \frac{\Delta x_1 x_3^0 \Delta x_2}{2} \tag{10}$$

$$x_{2-effect} = \Delta x_2 x_1^0 x_3^0 + \frac{\Delta x_2 x_3^0 \Delta x_1}{2} \tag{11}$$

$$x_{3-effect} = x_1^0 x_2^0 \Delta x_3 + \Delta x_2 \Delta x_3 x_1^0 + \Delta x_1 \Delta x_3 x_2^0 + \Delta x_1 \Delta x_2 \Delta x_3 \tag{12}$$

It can be seen that, when the factors change at different directions, an amount of changes are negative, such as $x_2^0 x_1^0 \Delta x_3$, $x_2^0 \Delta x_1 \Delta x_3$, $x_1^0 \Delta x_2 \Delta x_3$, the residual $\Delta x_1 \Delta x_2 \Delta x_3$ belongs to the change of the negative factors.

The change of two factors is negative, and one factor is positive;

Assume that the change of x_1 and x_2 are negative, while the change of x_3 is positive. Then, the contribution of x_1, x_2 and x_3 can be respectively calculated as follows:

$$x_{1-effect} = \Delta x_1 x_2^0 x_3^0 + \Delta x_1 x_2^0 \Delta x_3 + \frac{\Delta x_1 \Delta x_2 x_3^0}{2} + \frac{\Delta x_1 \Delta x_2 \Delta x_3}{2} \tag{13}$$

$$x_{2-effect} = \Delta x_2 x_1^0 x_3^0 + \Delta x_2 x_1^0 \Delta x_3 + \frac{\Delta x_1 \Delta x_2 x_3^0}{2} + \frac{\Delta x_1 \Delta x_2 \Delta x_3}{2} \tag{14}$$

$$x_{3-effect} = x_1^0 x_2^0 \Delta x_3 \tag{15}$$

2.1.3. Multi-Factor Decomposition Model According to Factors Changing Direction

In general, if variable v is determined by n factors, denoted by $x_1, x_2, \ldots, x_n$, i.e., $v = x_1 x_2 \ldots x_n = \prod_{i=1}^{n} x_i$, we can analyze the changes as follows.

All factors change at the same direction;

According to the two-factor and three-factor decomposition processes, the common effect of the changes of the factors is the same, when the changing directions of the factors are the same. The influence of the interaction in Δv can be separated into related factors, and the contribution of each factor to the total change of v can be respectively calculated as follows:

$$x_{i-effect} = \frac{v^0}{x_i^0}\Delta x_i + \sum_{j\neq i}\frac{v^0}{2x_i^0x_j^0}\Delta x_i\Delta x_j + \sum_{j\neq r\neq i}\frac{v^0}{3x_i^0x_j^0x_r^0}\Delta x_i\Delta x_j\Delta x_r + \ldots + \frac{1}{n}\Delta x_1\Delta x_2\ldots\Delta x_n \quad (16)$$

Factors change at different directions;

According to the decomposition process of two factors and three factors, whose changing directions are different, the perfect decomposed principles can be generalized. During the decomposition, it is considered that the positive and negative terms offset each other, $x_{i-effect}$ must contain Δx_i, for the negative variable x_i, all the variables x_i and increment Δx_i are needed to consider in the process of decomposition. For the positive variable x_i, only variables x_i are considered, and the increment Δx_i, which is more than 0, cannot contain the variables less than zero. Unified expression of multiple variables can be deduced.

When the changing directions are different, there are $n-1$ cases that need to be discussed, i.e., $\Delta x_k < 0$, where $k = 1, 2, 3\ldots, n-1$.

- One factor changes less than 0, i.e., $k = 1$;

$$x_{1-effect} = \Delta x_1\prod_{j=2}^{n} x_j^t = \Delta x_1\prod_{j=2}^{n}\left(x_j^0 + \Delta x_j\right), \quad \text{if } i = 1 \quad (17)$$

$$\begin{aligned} x_{i-effect} = {} & \tfrac{v^0}{x_i^0}\Delta x_i + \sum_{j\neq i\neq 1}\tfrac{v^0}{2x_i^0x_j^0}\Delta x_i\Delta x_j + \sum_{j\neq r\neq i\neq 1}\tfrac{v^0}{3x_i^0x_j^0x_r^0}\Delta x_i\Delta x_j\Delta x_r \\ & + \ldots + \tfrac{x_1}{n-1}\Delta x_2\ldots\Delta x_n, \qquad \text{if } i > 1 \end{aligned} \quad (18)$$

- More than one factor change less than 0, i.e., $k \geq 2$;

  According to the size of i and k, two cases are needed to discuss.

$$\begin{aligned} x_{i-effect} = {} & \tfrac{v^0}{x_i^0}\Delta x_i + \sum_{j\neq i>k}\tfrac{v^0}{x_i^0x_j^0}\Delta x_i\Delta x_j + \ldots + \sum_{j\neq r\neq i>k}\tfrac{v^0}{x_i^0x_j^0x_r^0}\Delta x_i\Delta x_j\Delta x_r \\ & + \tfrac{v^0}{x_ix_{k+1}\ldots x_n}\Delta x_i\Delta x_{k+1}\ldots\Delta x_n + \sum_{j\neq i<k}\tfrac{x_1^0x_2^0\ldots x_k^0}{2x_i^0x_j^0}\Delta x_i\Delta x_jP(X) \\ & + \sum_{j\neq r\neq i<k}\tfrac{x_1^0x_2^0\ldots x_k^0}{3x_i^0x_j^0x_r^0}\Delta x_i\Delta x_j\Delta x_rP(X) + \ldots + \tfrac{v^0}{kx_1^0x_2^0\ldots x_k^0}\Delta x_1\Delta x_2\ldots\Delta x_k \\ & \text{if } i \leq k \end{aligned} \quad (19)$$

where $P(X)$ is a mixed term that can be expressed as $P(X) = \sum p(x)$, where $p(x) = \prod_{i=k+1}^{n}\tau_i$, $(i \geq k+1)$. τ_i can be uniquely taken from x_i^0 or Δx_i, i.e., from the following $2(n-k)$ variables: x_{k+1}^0, Δx_{k+1}, x_{k+2}^0, Δx_{k+2}, $\ldots$, x_n^0, Δx_n. Thus, the number of $p(x)$ is 2^{n-k}, and $P(X)$ is equal to their sum.

$$\begin{aligned} x_{i-effect} = {} & \tfrac{v^0}{x_i^0}\Delta x_i + \sum_{k<j\neq i}\tfrac{v^0}{2x_i^0x_j^0}\Delta x_i\Delta x_j + \sum_{k<j\neq r\neq i}\tfrac{v^0}{3x_i^0x_j^0x_r^0}\Delta x_i\Delta x_j\Delta x_r \\ & + \ldots + \tfrac{v^0}{(n-k)x_{k+1}^0x_{k+1}^0\ldots x_n^0}\Delta x_{k+1}^0\Delta x_{k+1}^0\ldots\Delta x_n^0, \quad \text{if } k < i \leq n \end{aligned} \quad (20)$$

It should be pointed out that for the influence factors of the decomposition model, the change of dependent variable is caused by several factors, when the factors change at the same direction. The residual term is decomposed according to the principle of "average distribution". When the factors change in different directions, the changing direction that offsets each other must be considered by the residual items decomposition. The more the variables are, the more complex their changing directions are.

2.2. Transportation Energy Consumption Decomposition Model

Transportation energy consumption is connected with transportation turnover volume (the product of transportation volume and average distance), transportation structure (the transport structure usually refers to the transport volume structure. In a certain period, within the scope of a country or region, the proportion of various transport modes in the total passenger and freight transport volume or total turnover. It reflects the status and role of modes of transportation in the whole transportation system. Transportation volume share of mode *i* among all modes) and transportation energy intensity. The perfect complete decomposition model for explaining the change of transportation energy consumption can be written as follows.

$$E = \sum_i E_i^t = \sum_i \frac{E_i^t}{D_i^t} \times D_i^t = \sum_i \frac{E_i^t}{D_i^t} \times \frac{D_i^t}{D^t} \times D^t = \sum_i I_i^t \times S_i^t \times D^t \quad (21)$$

where $i = 1, 2, 3, 4, 5$ presents five transportation modes, namely, highway, railway, aviation, water transportation, pipeline, respectively; E is total energy consumption of the five transportation modes; E_i^t is energy consumption transportation mode i in year t; D_i^t is transportation turnover volume of mode i in year t; $I_i^t = E_i^t / D_i^t$ is transportation energy intensity of mode i in year t; $S_i^t = D_i^t / D^t$ is transportation structure share of mode i in year t.

It can be seen from Equation (21), transportation energy consumption can be decomposed into the common effect of three factors: transportation turnover volume, transportation structure and transportation energy consumption intensity. The impact of each factor on transportation energy consumption not only has a close relationship with the changes of the factors, but is also connected with the initial and final value of the other two factors.

The contribution of each influence factor to transportation energy consumption change can be seen as the product of five "three factors". Transportation energy consumption factor decomposition model can be constructed. $D_i^t = D_i^0 + \Delta D_i$, $S_i^t = S_i^0 + \Delta S_i$, $I_i^t = I_i^0 + \Delta I_i$, according to the three-factor decomposition model, the change of transportation energy consumption in the base year 0 and target year t, ΔE can be calculated as Equations (22) and (23).

$$\Delta E = E^t - E^o = \sum_i I_i^t \times S_i^t \times D^t - \sum_i I_i^0 \times S_i^0 \times D^0 \quad (22)$$

$$\Delta E = \Delta E_t - \Delta E_0 = \Delta E_D + \Delta E_I + \Delta E_S \quad (23)$$

where ΔE_I, ΔE_S and ΔE_D are the contributions of transportation energy consumption intensity, transportation structure, and transport turnover volume, respectively.

Based on the perfect decomposition model, three influence factors of transportation energy consumption changing direction can be divided into two cases.

2.2.1. Change at the Same Direction

Three influence factors change at the same direction, i.e., "the three factor" increase ($\Delta D_i > 0$, $\Delta S_i > 0$, $\Delta I_i > 0$) or decrease ($\Delta D_i < 0$, $\Delta S_i < 0$, $\Delta I_i < 0$) simultaneously. According to the perfect decomposition model, the contribution of three factors to the transportation energy consumption can be determined as follows:

$$\Delta E_D = \sum \Delta D I_i^0 S_i^0 + \frac{\sum \Delta D}{2} (\Delta I S_i^0 + I_i^0 \Delta S) + \frac{\sum \Delta D \Delta I_i \Delta S_i}{3} \quad (24)$$

$$\Delta E_S = \sum \Delta S I_i^0 D_i^0 + \frac{\sum \Delta S}{2} (\Delta I D_i^0 + I_i^0 \Delta D) + \frac{\sum \Delta D \Delta I_i \Delta S_i}{3} \quad (25)$$

$$\Delta E_I = \sum \Delta I S_i^0 D_i^0 + \frac{\sum \Delta I}{2}(\Delta S D_i^0 + S_i^0 \Delta D) + \frac{\sum \Delta D \Delta I_i \Delta S_i}{3} \quad (26)$$

2.2.2. Change at Different Directions

Three influence factors change at different directions, i.e., one factor decreases ($\Delta D_i \times \Delta I_i \times \Delta S_i < 0$) or two-factor decrease ($\Delta D_i \times \Delta I_i \times \Delta S_i > 0$), simultaneously. According to the perfect decomposition model, the contribution of three factors to the transportation energy consumption is as follows.

(i) When $\Delta D_i < 0$, $\Delta S_i > 0$ and $\Delta I_i > 0$ the formulas are as follows:

$$\Delta E_D = \sum \Delta D_i S_i^t I_i^t \quad (27)$$

$$\Delta E_S = \frac{\sum \Delta S_i}{2} D_i^0 (I_i^t + I_i^0) \quad (28)$$

$$\Delta E_I = \frac{\sum \Delta I_i}{2} D_i^0 (S_i^t + S_i^0) \quad (29)$$

When $\Delta D_i > 0$, $\Delta S_i < 0$, $\Delta I_i > 0$ and $\Delta D_i > 0$, $\Delta S_i > 0$, $\Delta I_i < 0$, the formulas can also be obtained just by replacing the corresponding variables of the calculated formula.

(ii) When $\Delta D_i < 0$, $\Delta S_i < 0$ and $\Delta I_i > 0$, the formulas are as follows:

$$\Delta E_D = \frac{\sum \Delta D_i}{2} I_i^0 (S_i^t + S_i^0) \quad (30)$$

$$\Delta E_S = \frac{\sum \Delta S_i}{2} I_i^0 \left(\sum D_i^T + \sum D_i^0\right) \quad (31)$$

$$\Delta E_I = \sum D_i^0 \times S_i^0 \times \Delta I_i \quad (32)$$

The cases $\Delta D_i > 0$, $\Delta S_i < 0$, $\Delta I_i < 0$ and $\Delta D_i < 0$, $\Delta S_i > 0$, $\Delta I_i < 0$ of the formulas can be similarly obtained.

3. Effective Verification and Case Study

3.1. The Effective Verification of the Perfect Decomposition Model

To examine the effectiveness of the proposed decomposition model, transportation energy consumption data based on the transportation sectors in China are decomposed from 1985 to 2012. To illustrate the remaining items and to omit for index, we use period wise decomposition. The change is only analyzed by the validation between the two base years, i.e., setting two different time intervals, 10 years (1985–1995) and 27 years (1985–2012). The results are presented in Table 1.

It can be seen from Table 1 that the total contribution of the perfect model and the complete decomposition model is identical ($\Delta E = \Delta E_D + \Delta E_S + \Delta E_I$), because the residual items are completely decomposed in both models. However, the Laspeyres model neglects the residual, therefore the results ΔE is different from the sum of influence factors change $\Delta E_D + \Delta E_S + \Delta E_I$. Compared with Laspeyres model and the complete decomposition model, the results of the proposed perfect decomposition model are more accurate and the method is more appropriate.

Table 1. The calculation results of the three decomposition model.

Time	1985–1995				1985–2012			
Model	ΔE	ΔE_D	ΔE_S	ΔE_I	ΔE	ΔE_D	ΔE_S	ΔE_I
Laspeyres model	2680.71	3069.77	538.38	−927.44	19,807.90	19,735.56	1442.69	−1370.36
Complete decomposition model	2306.64	2906.42	722.16	−1321.94	23,233.83	20,770.77	6205.35	−3742.29
Errors	—	5.32%	34.14%	42.54%	—	5.25%	330.12%	173.09%
proposed perfect decomposition model	2306.64	3397.81	716.47	−1807.63	23,233.83	26,504.38	5190.34	−8460.89
Errors	—	10.69%	33.08%	94.91%	—	34.30%	259.77%	517.42%

For the influence of each factor, compared with Laspeyres, the errors of three influence factors (transportation turnover volume, transportation structure and transportation energy consumption intensity) are 10.69%, 33.08% and 94.91%, respectively, from 1985 to 1995. When the analysis period is longer (from 1985 to 2012), the errors are larger, i.e., −34.29%, 259.77% and 517.42%, respectively. It can be seen that the errors caused by the negative factors are very obvious, and the perfect decomposition model takes into account the effects of the different factors, when dealing with the remaining items. The weight is more consistent with the actual situation, and the perfect decomposition model is necessary.

Compared to the complete decomposition model, the errors of three influence factors are 16.91%, 0.79% and 36.74% during the period from 1985 to 1995. When the analysis period is enlarged, the error will be greater, which are 27.60%, −17.66% and 126.09%, respectively, during the period from 1985 to 2012. The longer the analysis time is, the larger the error percentage is, because the residual processing, are even greater than the total change of a single factor. Therefore, the Lapsers index and its model of residual term ignore will produce a larger error. The changing directions of the factor are considered in the perfect decomposition model when dealing with the remaining items; therefore, decomposition results are more reasonable.

3.2. Perfect Decomposition Results Analysis

Index decomposition models can be divided into period wise and time series according to research objects. Time series decomposition can reflect energy changes trajectory within a certain period, and better explain the change mechanism of transportation energy consumption. Time series decomposition model is used to study transportation energy consumption, and conversion turnover is used in the decomposition process.

Based on the perfect decomposition model, we analyze the three factors (transportation turnover volume, transportation structure, transportation energy intensity) affecting transportation energy consumption change and calculate the change of related factors and the contribution rate with the analysis time period from 1985 to 2012. The decomposed results are shown in Table 2.

Table 2. The decomposed results.

Years	ΔE_D	ΔE_S	ΔE_I	ΔE	ΔTE	ΔTER
1985–1986	340.21	32.75	−141.23	231.72	108.49	2.56
1986–1987	431.09	181.26	−172.46	439.90	−8.80	−0.19
1987–1988	412.91	170.07	−280.40	302.58	110.33	2.22
1988–1989	196.77	−33.64	−51.38	111.75	85.02	1.68
1989–1990	−63.88	46.12	55.58	37.82	−101.70	−2.07
1990–1991	283.64	−37.40	−159.97	86.28	197.36	3.73
1991–1992	361.64	93.44	−231.47	223.61	138.03	2.53
1992–1993	388.21	50.38	−183.30	255.29	132.92	2.33
1993–1994	414.79	72.13	−63.15	423.77	−8.98	−0.15
1994–1995	167.67	116.10	−89.85	193.92	−26.25	−0.43
1995–1996	241.12	66.81	142.52	450.45	−209.33	−3.25
1996–1997	−376.25	448.84	−18.99	53.61	−429.86	−6.85
1997–1998	−42.96	187.87	195.32	340.23	−383.19	−5.75
1998–1999	209.89	123.32	378.85	712.06	−502.17	−6.93
1999–2000	1139.04	−299.36	−760.84	78.85	1060.19	11.92
2000–2001	−30.15	205.71	528.81	704.36	−734.5 l	−9.41
2001–2002	610.43	75.41	−107.62	578.22	32.20	0.35
2002–2003	552.78	−126.55	24.64	450.87	101.90	1.05
2003–2004	1719.26	−287.88	−184.78	1246.60	472.66	4.19
2004–2005	1225.18	−9.56	343.83	1559.46	−334.27	−2.78
2005–2006	1322.41	208.45	−479.51	1 OS 1.34	271.06	1.98
2006–2007	1794.73	308.25	−291.36	1811.62	−16.89	−0.11
2007–2008	1663.56	612.10	−102.06	2173.60	−510.04	−3.02
2008–2009	698.49	1017.68	−349.13	1367.05	−668.56	−3.69
2009–2010	2985.27	344.51	−526.76	2803.02	182.25	0.84
2010–2011	2759.44	318.17	−644.49	2433.12	326.32	1.34
2011–2012	1650.27	1438.64	23.83	3112.74	−1462.47	−5.70
1985–2012	26,504.38	5190.34	−8460.89	23,233.83	3270.55	30,395.08

From the decomposed results of the perfect model where transportation turnover volume is the main influence factor in determining the main trend of transportation energy consumption, the contribution is gradually strengthened. The transportation volume makes transportation energy consumption increase by 265.044 Mtce from 1985–2012, according to the perfect decomposition model. Except for a few years, the contribution rate of transportation turnover volume to transportation energy consumption growth is more than 80%.

The change in transportation structure, transportation energy, and consumption intensity saves transportation energy consumption by 32.706 (51.903 − 84.609 = −32.706) Mtce, with an energy saving rate of 10.76%. The average annual energy saving rate is 1.06% from 1985 to 2012.

The transportation energy consumption intensity is the main factor of energy saving. From 1985 to 2012, the change in energy intensity saves 84.609 Mtce. Except for 1989–1990, 1995–1996, 1997–1998, 1997–1999, and 2000–2001, 2001–2003, and 2004–2005, most of the other years have energy saving effects.

The change in transportation structures reduces the demand for energy in 1988–1989, 1990–1991, 1999–2000, 2002–2003,2003–2004 and 2004–2005, and the energy demand has been increased in most of the other years. Energy demand increased by 51.903 Mtce due to the change of transportation structure from 1985 to 2012, and thus the transportation structure adjustment is the key to saving energy and has great potential to economize.

According to the above analysis, the structure adjustment has great energy saving potential. It is necessary to analyze the specific contribution of each transportation mode to energy consumption. It is transportation turnover volume, transportation structure and transportation energy consumption intensity of five transportation modes changes on the influence of transportation energy consumption, which are shown in Table 3.

Table 3. The contribution of five transportation modes for irallic mileage.

Years	Highway	Railway	Aviation	Water Transportation	Pipeline	Total
1985–1986	125.42	176.46	8.96	20.47	8.90	340.21
1986–1987	168.10	216.39	12.83	23.22	10.55	431.09
1987–1988	179.10	189.73	12.92	21.67	9.49	412.91
1988–1989	88.76	86.46	6.28	10.84	4.43	196.77
1989–1990	−29.16	−27.47	−2.10	−3.74	−1.41	−63.88
1990–1991	129.17	119.25	10.84	18.01	6.37	286.64
1991–1992	162.18	149.98	15.40	25.64	8.14	361.64
1992–1993	180.05	150.95	19.46	29.47	8.28	388.21
1993–1994	198.96	148.99	23.50	35.10	8.25	414.79
1994–1995	83.26	56.39	10.47	15.00	2.54	167.67
1995–1996	120.99	79.83	15.64	21.20	3.46	241.12
1996–1997	−195.97	−117.09	−25.54	−32.67	−4.98	−376.25
1997–1998	−23.73	−12.61	−3.22	−2.83	−0.57	−42.96
1998–1999	121.91	54.96	16.45	13.93	2.65	209.89
1999–2000	706.40	259.61	82.90	76.28	13.86	1139.04
2000–2001	−18.19	−6.47	−2.51	−2.62	−0.35	−30.15
2001–2002	394.87	123.22	58.37	26.93	7.05	610.43
2002–2003	364.39	102.70	53.19	26.16	6.33	552.78
2003–2004	1127.44	310.14	169.19	92.48	20.00	1719.26
2004–2005	795.29	200.77	129.56	84.43	15.13	1225.18
2005–2006	862.69	196.88	140.16	102.68	19.99	1322.41
2006–2007	1223.53	253.38	199.73	85.96	32.13	1794.73
2007–2008	1160.47	214.18	177.65	81.43	29.83	1663.56
2008–2009	503.70	80.31	70.08	33.05	11.36	698.49
2009–2010	2142.39	343.70	317.42	135.72	46.05	2985.27
2010–2011	1975.57	319.64	285.68	133.43	45.11	2759.44
2011–2012	1233.04	147.62	163.59	76.76	29.25	1650.27
1985–2012	12,016.48	10,303.26	1944.56	1702.93	537.14	26,504.38

From the decomposition results of this perfect method in the share of transport volume contribution, the energy demand is increased with the growth of each mode transportation volume. Railway transportation turnover volume plays a dominant role from the 1985–1987, and contribution rate is more than road transportation rate, at 51.87%, 50.20% and 45.95%, respectively. With the rapid development of highway, road transportation turnover volume increase during 1987–1988, the contribution share of highway is more than rail for the first time. Since 1995–1996, the contribution share is more than 50% and continues to increase. The highest contribution share reached 74.72% from 2010–2011. Certain volatility exists in other modes of transportation.

Highway is the dominant in the changes of the transportation structure, in the total contribution of the transportation structure, and the contribution of highway was more than 30% apart from 1988–1989. Therefore, the adjustment of the transportation structure is the key to reduce energy demand. Railway plays an obvious energy saving role in the transportation structure in two-thirds of the analysis period. The change of air transport structure over a few years has an energy saving effect. Pipeline plays a certain role in energy saving during more than half of the analysis period. The change of water transportation turnover volume saves energy over eight years.

Except for a few years, the five transportation modes play a certain important role in energy saving due to the lower energy intensity. Over the course of 27 years, road energy consumption intensity has an energy saving effect in 15 years, with the highest years saving 6.1414 million tons of standard coal (in 1999–2000). The energy consumption increase was promoted by the change of energy intensity in the rest of the years. The main reason is continuous increasing comfort requirements for highway transportation services, turning out the increase of highway energy intensity. The change of railway energy intensity on energy conservation effects in 23 years, the highest energy saving is in 2010–2011. The main reasons are the implementation of electrification railways instead of steam and diesel locomotives, which prompts the railway transportation energy consumption intensity to decrease. The energy consumption intensity of aviation changes have been saving energy in 18 years, with the highest energy saving is in 2009–2010. The energy consumption intensity of the pipeline has no change in some years without obviously energy saving. The year with the highest energy saving are 1993–1994.

In the long-term development, highway transportation will still account for a large proportion of the total transportation volume, but highway transportation is mainly based on regional short-distance transportation and passenger and freight distribution and plays a role in the connection. The railway will bear a large proportion of inter-regional and intercity transport demand. Civil aviation mainly completes long-distance transportation and transportation of high-value-added products. The waterway undertakes the transportation of medium and long-distance bulk and cheap goods. However, from the analysis of the energy consumption intensity, the energy consumption intensity of railways is the lowest among various transportation modes. China's railway energy consumption accounts for only 8% of the total consumption of the national transportation industry, fully reflecting the comparative advantage of "low energy consumption and high efficiency", therefore, the railway is the best way to adapt to the development direction of China's energy structure in the transportation industry and plays a significant role in adjusting and optimizing the energy consumption structure in transportation.

4. Conclusions

A perfect model that decomposes the residual term is proposed on the basis of the Laspeyres Index Decomposition and complete decomposition method. This paper focuses on the residual terms in the exponential decomposition method. The existing complete decomposition model is improved, the improved decomposition model is summarized and deduced in detail, and the unified expression of the decomposition model is derived. The model is applied to build a complete decomposition model of the impact factors of transportation energy consumption in different directions. The decomposition model not only has the advantages of the existing decomposition methods but also can "perfect" decompose the remaining items, taking into account the direction of the change of the index influencing factors. This technique makes it possible to present symmetric decomposition without residuals. The perfect method decomposes the residual term completely according to the direction of index change. More accurate calculation results are obtained by comparing Laspeyres and the complete decomposition method. The validity of the perfect model is verified. Lastly, this decomposition model to transportation energy consumption is applied in China and the following conclusions have been drawn.

Transportation turnover volume is the main influencing factor that determines the main trend of transportation energy consumption. Except for a few years, the contribution rate of transportation turnover volume to transportation energy consumption growth is more than 80%.

Transportation energy consumption intensity is the main factor for energy savings. From 1985 to 2012, the change of energy intensity saves 84.609 Mtce. Except for a few years, five transportation modes play a key role in energy saving due to their lower energy intensity. Research on energy consumption intensity should focus on reducing energy consumption intensity of highway and aviation.

The transportation structure adjustment is the key to saving energy and has great potential to save energy. Highways account for absolute advantage. Reducing energy demand is mainly decided by the adjustment of highway transportation structures. Railways play an obvious energy saving role in structure share.

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