IATSS Research 38 (2015) 142–148

Contents lists available at ScienceDirect

IATSS Research

A factor decomposition analysis of transportation energy consumption and related policy implications

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ARTICLE INFO

Available online 14 October 2014

Keywords:
Factor decomposition analysis
Transportation energy consumption
Indicator selection
Energy policy

ABSTRACT

This paper introduces a method of factor decomposition analysis for analyzing the importance of the factors that affect the volume of transportation energy consumption. In choosing the influencing factors from the many possibilities, the paper introduces an indicator analysis to evaluate and select the most important affecting factors. Based on the decomposition results, the paper helps interpret the underlying causes of transportation energy consumption. At the same time, the paper also suggests corresponding policy implications for the improvement of transportation energy efficiency.

1. Introduction

As the social economy continues its rapid development, the topic of sustainable development is an important issue for the world. Sustainability refers to meeting the needs of the present without compromising the ability of future generations to meet their own needs. For humans, in particular, sustainability corresponds to the long-term maintenance of responsibility and has three dimensions: environmental sustainability, economic sustainability, and social sustainability. In this paper, we aim to treat the problem of sustainability in all its dimensions. Energy, one of the issues that play a major role in sustainable development, involves all the three dimensions of sustainability. Statistics indicate that rapid economic growth around the world is driving the volume of energy consumption up on a yearly basis. Especially considering the fact that some developing regions are growing at a staggering rate, the world will likely exhaust several types of energy in several decades if this pace of consumption continues unchecked. This paper concentrates on energy consumption from the transportation sector, which amounts to 20 to 30% of the total, and discusses related policy implications.

In order to control the consumption of energy, it is crucial to determine the underlying causes of energy consumption in transportation—factors that are sophisticated and hard to distinguish at first glance. This is because traffic volume, energy efficiency, and distances in both the passenger and freight transportation sectors are in constant flux. Furthermore, differentiation among the various means of transportation has changed continuously, as well, complicating the issue further. Of all the factors that can affect energy consumption in the transportation sector, those that wield positive and negative effects remain problematic. Moreover, the proportion each of these factors actually accounts for on an individual basis demands attention. In this case, the effective analysis off actors and corresponding policy suggestions hinges on solid input from quantitative research. The next chapter introduces the methodology for calculating the contributing proportions of the factors in question.

2. Methodology

As stated above, the volume of energy consumption in the transportation sector is affected by many factors, including the energy intensity of vehicles, travel distance, and so on. Therefore, there is a certain relationship between changes in energy consumption and mathematical changes in the contributing factors: the degree of change in each factor determines the volume of total change. Decomposition analysis mainly focuses on the decomposition of change in total and distributes the change among the effects of its factors according to certain rules. Decomposition analysis thus decomposes and distributes the changes in an energy-related aggregate indicator of interest among a number of pre-defined factors [3]. This chapter decomposes energy consumption changes in the Japanese transportation sector into several factors. The results illuminate the contribution of each factor to overall energy consumption. Based on these findings, policymakers can locate the key factors and emphasize improvement in the corresponding areas, thereby providing a foundation for a better balance between energy conservation and economic development.

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Peer review under responsibility of International Association of Traffic and Safety Sciences.

Production and hosting by Elsevier

http://dx.doi.org/10.1016/j.iatssr.2014.10.001

Originally an approach for studying the impact of changes in product mix on industrial energy demand, index decomposition methodology is now a common tool in not only industrial fields but also environmental fields in general. Tracing its development back to not long after the world oil crises in the 1970s, the methodology has remained a target of study to this day, with more and more related papers presented every year [4]. The methodology mainly focuses on issues whose total amounts can be expressed as mathematical products of the factors. Considering the number of studies reported, index decomposition analysis is now a widely accepted analytical tool for policymaking on national energy and environmental issues [2]. Over the course of its development, the methodology has applied numerous mathematics algorithms toward decomposition calculation. A survey of studies by various researchers in recent years reveals that the most common decomposition methods are apparently the Laspeyres and Divisia methods, which produce decomposition results easily and reasonably. However, the issue that can interfere with the results of the two methods is that there is always the possibility of an unexplained factor lying beyond the scope of the researchers' imagination. Consequently, researchers developed two other methods—the Refined Laspeyres index method and the Logarithmic Mean Divisia index method—to achieve perfect decomposition that leaves no factors unexplained. Currently, most decomposition studies use these improved methods. This section shows the results of decomposing a three-factor case, for the sake of simplicity, with the two methods discussed by [3]. Using the principles of these methods, one can perform decomposition on more factors in a similar way.

Assume that V represents the aggregate of interest and depends on three independent factors x_1, x_2, and x_3, where $V = x_1 * x_2 * x_3$. Considering the problem at hand temporally and discretely, we assume that the absolute change in V from year 0 to T, ΔV, will be decomposed to determine the effects associated with factors x_1, x_2, and x_3. We have:

$$V^0 = x_1^0 * x_2^0 * x_3^0, V^T = x_1^T * x_2^T * x_3^T,$$
$$\Delta V = V^T - V^0 = x_1^T * x_2^T * x_3^T - x_1^0 * x_2^0 * x_3^0.$$

The purpose of this decomposition is to evaluate the effects imposed on V by each factor. In other words, the goal is to calculate ΔV_{x_1}, ΔV_{x_2}, and ΔV_{x_3} in order to describe the changes in V caused by factors x_1, x_2, and x_3, respectively.

Note that $\Delta x_1 = x_1^T - x_1^0$, $\Delta x_2 = x_2^T - x_2^0$, and $\Delta x_3 = x_3^T - x_3^0$.

Therefore,

$$\begin{aligned}\Delta V &= \left(\Delta x_1 + x_1^0\right) * \left(\Delta x_2 + x_2^0\right) * \left(\Delta x_3 + x_3^0\right) - x_1^0 * x_2^0 * x_3^0 \\ &= \Delta x_1 * \Delta x_2 * \Delta x3 + \Delta x1 * \Delta x2 * x30 + \Delta x1 * x20 * \Delta x3 \\ &\quad + x10 * \Delta x2 * \Delta x3 + \Delta x1 * x20 * x30 + x10 * \Delta x_2 * x_3^0 \\ &\quad + x_1^0 * x_2^0 * \Delta x_3.\end{aligned}$$

According to the rules of the Refined Laspeyres index method, changes in an item with only one changing factor are obviously caused by the changing factor alone. Changes in an item with two changing factors are divided into two equal parts, and the effect is distributed evenly between the changing factors. In the same manner, the item $\Delta x_1 * \Delta x_2 * \Delta x_3$ is divided into three equal parts, and the effect is distributed evenly among all three factors.

The decomposition result of this three-factor case is as follows:

$$\begin{aligned}\Delta V_{x_1} &= \Delta x_1 * x_2^0 * x_3^0 + \frac{1}{2}\Delta x_1 * \Delta x_2 * x_3^0 + \frac{1}{2}\Delta x_1 * x_2^0 * \Delta x_3 \\ &\quad + \frac{1}{3}\Delta x_1 * \Delta x_2 * \Delta x_3 \\ \Delta V_{x_2} &= x_1^0 * \Delta x_2 * x_3^0 + \frac{1}{2}\Delta x_1 * \Delta x_2 * x_3^0 + \frac{1}{2}x_1^0 * \Delta x_2 * \Delta x_3 \\ &\quad + \frac{1}{3}\Delta x_1 * \Delta x_2 * \Delta x_3 \\ \Delta V_{x_3} &= x_1^0 * x_2^0 * \Delta x_3 + \frac{1}{2}x_1^0 * \Delta x_2 * \Delta x_3 + \frac{1}{2}\Delta x_1 * x_2^0 * \Delta x_3 \\ &\quad + \frac{1}{3}\Delta x_1 * \Delta x_2 * \Delta x_3.\end{aligned}$$

Here, we obtain the universal solution of the decomposition result for this problem in the same way for more than three factors [8]:

For year 0 to year T, the effect of each factor is calculated using the equation summarized below:

$$E_x = \sum_{s=1}^{4} \frac{(s-1)!(4-s)!}{4!} \sum_{\substack{S\,:\,x \in S \\ |S| = s}} [E(S) - E(S-x)]$$

where **S** is a set of some four factors and x is one element of the set. E(**S**) is a function where the factor included in **S** uses the data for year T and all the other factors use the data for year 0.**|S|** stands for the number of elements in set S. **S** − **x** stands for set **S** with element **x** gone.

Decomposition results can also be interpreted in two ways: as multiplicative decomposition and as additive decomposition. In multiplicative decomposition, the change in an aggregate is decomposed into a ratio, while in additive decomposition, the change in an aggregate is decomposed into absolute changes [3]. These two approaches have the same essential meaning, but additive decomposition can calculate the ratio of each factor in the gross.

Using this approach, one can decompose the change in transportation energy consumption into the effects of its factors. However, there are so many ways to decompose the transportation energy consumption that the optimal choice is a difficult one to make. We believe that the factors chosen for the energy consumption decomposition should fulfill the following conditions. First, the energy consumption must be decomposable by all the factors multiplied together; this is a basic requirement, as the methodology itself rests on this foundation. Second, all the factors must be available for mathematical calculation. Third, the factors must make sense in the scope of the analysis and the context of using calculation results for policymaking purposes.

Therefore, we introduce indicators for choosing factors that affect transportation energy consumption. In order to find the variables that properly explain the phenomenon of transportation energy consumption, it is important to explore the theory of indicator analysis. In the last decade, the development of research on indicators at the national, regional, local, and field levels has become a common approach to meeting the crucial need for assessment tools, which represent a prerequisite to the implementation of the sustainability concept, especially its environmental component [10]. In order to validate the necessity of applying an indicator-related analysis, we must first discuss the concept of the “indicator”. The following review of the literature concerning the indicator concept provides a brief explanation of indicators and establishes a practical definition for use in this paper.

The word “indicator” is defined as something that indicates a phenomenon. Generally speaking, there are ten criteria for the selection of indicators. It should be kept in mind, however, that the criteria here simply constitute a list of criteria and do not yet merit consideration in the context of a procedure for application [5].

1. *Validity.* A valid indicator must actually measure the issue or factor it is supposed to measure [11]. A valid indicator must be based on a conceptual model that justifies how the indicator and the issue