An indicator-based algorithm to measure transportation sustainability: A case study of the U.S. states

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ABSTRACT

Nowadays, there is a growing interest in applying the concept of sustainable transportation around the world. However, measuring the level of sustainability of transportation for a particular territory is an issue which is not well addressed due to several numbers of various indicators. Sustainable transportation encompasses environmental, social and economical dimensions which each dimension is composed of various subdivisions. To comprehensively address all sustainability dimensions and their subdivisions, several indicators are required. The aim of this paper is proposing an algorithm as a framework to take into account various number of indicators in different dimensions and subdivisions of transportation sustainability. The method of Principal Component Analysis/Factor Analysis (PCA/FA) was used to overcome the limitations of other methods used in previous studies. The proposed algorithm composes composite indices in each of transportation sustainability dimensions as well as their subdivisions and develops the transportation sustainability index (I_{TS}) to measure the sustainability of transportation. To put the algorithm into practice, 89 sustainable transportation indicators are used based on available data. As a case study, transportation sustainability indices were determined for 50 states and the Federal District of Columbia in the U.S. according to the proposed algorithm. Thereby, the relative sustainability of transportation among the U.S. states is demonstrated. Results showed while the District of Columbia, New York and Massachusetts were the most sustainable, Mississippi, Wyoming and North Dakota were the least sustainable states.

1. Introduction

Growing social activities followed by increasing transportation demand has led to several impacts such as traffic congestion, traffic injuries and fatalities, air and noise pollution and global warming. In order to control such impacts on the environment and the quality of human life, sustainability is introduced to transportation planning. Sustainable transportation can be viewed as a major contributor to the bigger picture of sustainability which encompasses a holistic consideration of environmental, social and economical progress − usually referred to as sustainability dimensions (Zietsman, 2011); each of which can be divided into different subdivisions. The Center for Sustainable Transportation (CST) developed a definition of sustainable transportation that is referred to by many studies (Haghshenas and Vaziri, 2012), (Litman, 2007), (Jeon and Amekudzi, 2005): a sustainable transportation system is one that meets the following criteria (Gilbert et al., 2003):

- Limits emissions and waste within the planet's ability to absorb them, minimizes consumption of renewable resource to the sustainable yield level, reuses and recycles its components and minimizes the use of land and the production of noise.
- Allows the basic access needs of individuals and societies to be met safely and in a manner consistent with human and ecosystem health and with equity within and between generations.
- Is affordable, operates efficiently, offers choice of transportation mode and supports a vibrant economy.

Addressing such criteria ensures policymakers to consider environmental, social and economical aspects of sustainability in a transportation system. Recent studies show that achieving sustainability goal through transportation systems has become an important objective of policymakers (e.g., (Zheng et al., 2013)). In order to reach to a sustainable transportation system, decision-makers are increasingly being required to evaluate, monitor and report the sustainability performance of a transportation system (Herb and Pitfield, 2010). Measuring performance of a transportation system allows decision-makers to quickly observe the effects of a proposed transportation plan or project or to

monitor trends in a transportation system performance toward sustainability (EPA, 2011). Monitoring the sustainability level of a transportation system is required to illustrate the impact of some decisions (e.g., specific investment or program) toward sustainability (Habibian and Ostadi Jafari, 2013). In this context, indicators can be used to evaluate progress toward a more sustainable transportation system (EPA, 2011).

The above mentioned criteria issued by Gilbert et al. also show that the sustainable transportation is a broad and complex goal which could not be measured by a single indicator. Therefore, a set of various indicators which reflect different objectives of transportation sustainability should be used (Litman, 2009). Indicators should be clearly defined, accessible and based on data that are available or that can be made available at a reasonable cost and that are of known quality and regularly updated (Santos and Ribeiro, 2013), capable of quantification, standardized for comparison purposes and reflecting dimensions and various subdivisions of the sustainable transportation concept (Santos and Ribeiro, 2013), (Haghshenas and Vaziri, 2012). On the other hand, using too many indicators may contribute to make the results harder to interpret and the decision making process more complex and costly. Nonetheless, as addressing all dimensions and their subdivisions of sustainable transportation in a comprehensive point of view does require several indicators, aggregating different indicators into a composite index is suggested as a useful and practical approach for sustainability evaluation (Reisi et al., 2014; Dur et al., 2010; Saisana, 2011; Zhou et al., 2007; Freudenberg, 2003).

Previous studies have used different methods to weight indicators and aggregate them into a composite index. Available weighting methods can be classified in three categories, equal weighting, weighting based on opinions and weighting based on statistical models (Saisana, 2011). Principal Component Analysis/Factor analysis (PCA/FA) is a popular means for making comparisons between different indicators on several aspects. The equal weighting method and weighting based on expert or stakeholder judgments are two methods which have been widely applied. However, each of these methods has some limitations which should be considered.

With the equal weighting approach, there is a risk that certain topics are double counted (Reisi et al., 2014), which is because two or more indicators may be measuring the same underlying phenomenon (Freudenberg, 2003). Furthermore, equal weighting disregards correlation between indicators. To consider the correlation and decrease the risk of double counting, only one indicator should be selected among a number of indicators which have significant inter-correlations. Thereby however, the number of indicators that can be used for evaluating different aspects of sustainable transportation with the equal weighting method may be limited. It is worth noting that this limitation can make it more difficult to fully incorporate all aspects of sustainable transportation. A common method based on judgment is the Analytical Hierarchy Process (AHP), which also has some drawbacks. One of limitations of this method is that pairwise comparison of alternatives does not always lead to consistent rankings. Another is that weighting based on expert judgment or stakeholder preferences may introduce subjective and arbitrary elements (Saisana, 2011; OECD, 2008).

The main objective of this study is to overcome limitations in previous studies by developing a new index (composite transportation sustainability index, I_{TS}) for evaluating sustainability of transportation systems. In this line, considering the variables' inter-correlations a measuring framework (algorithm) which allows for several numbers of indicators is proposed. Based on I_{TS}, sustainability of transportation system in different regions can be compared. This comparison helps to rank different regions toward sustainable transportation to identify the condition of regions relatively and track weaknesses and strengths of a transportation system. Through using the proposed algorithm, it is also possible to decompose the new index into its components. This helps planners to assess dimensions and their subdivisions of sustainability from a comprehensive point of view as well as to better understand the reasons for which a particular region is ranked low or high among others.

Furthermore, this study focuses on measuring transportation sustainability at state level which has not been well established in previous studies. In fact, it is indispensable to monitor progress toward sustainability in a state/province because many decisions or actions at this level have profound consequences for transportation system development at all levels from local to state/province to national levels. Monitoring performance at state level is also useful for budget allocation problems of federal governments, where transportation budget should allocate to state/province governments considering their transportation performances toward sustainability. Therefore, federal transportation planning administrators should be cognizant about each state transportation system to predict and allocate its budget in order to make best decisions for performance improvement toward sustainability.

The rest of this paper is organized as follows: the next section contains literature review and the research context which is followed by methodology. Then the case study of this research is explained followed by definition and determination of the indicators. The final section comprises the results and discussion of the analysis and conclusions.

2. Literature review

Evaluating the performance of a transportation system is a common approach since many years ago for monitoring and analysis process to determine how well policies, programs and projects perform. Several researchers studied the efficiency aspect of a transportation system performance by applying Data Envelopment Analysis (DEA) method to different case studies (Husain et al., 2000; Nolan, 1996). However, in some studies the performance of a transportation system was evaluated based on more than a single criteria (e.g., efficiency, effectiveness and efficacy) (Fielding et al., 1985; Mahdinia and Habibian, 2017). Considering different criteria in transportation system evaluation has brought about using multi-criteria evaluation techniques in recent studies (e.g., (Mahdinia and Habibian, 2017)). It is worth noting that in recent years the performance of a transportation system is usually assessed through its progress toward sustainability.

Most of the literature has been concerned with evaluating transportation sustainability at the national and city level. They have used diverse indicators and frameworks to measure the sustainability of a transportation system, however, they have used a few number of indicators to evaluate all aspects of transportation sustainability. Jeon and Amekudzi conducted a comprehensive literature review on sustainable transportation indicators from 16 different initiatives around the world (Jeon and Amekudzi, 2005). Their review indicated that there are common themes and dimensions in sustainable transportation while a standard framework for evaluating progress toward sustainability did not exist. Gudmundsson et al. provides a description of different approaches to develop indicators for sustainable transportation planning and how these have been applied in practical cases (Gudmundsson et al., 2016). Cornet and Gudmundsson developed a meta-framework to review other frameworks in terms of how they support sustainability considerations from a conceptual, operational and governing point of view (Cornet and Gudmundsson, 2015). Their study discusses the need for an integrated view for sustainability assessment but does not establish practical indicators or aggregation methods.

More recent studies deal with the challenge of developing a framework to measure transportation sustainability based on long lists of sustainable indicators (Santos and Ribeiro, 2013). However, they have adopted a few number of indicators in each study to cover vast domain and different aspects of sustainable transportation.

Haghshenas and Vaziri ranked 100 world cities based on an urban sustainable transportation composite index. They used nine sustainable transportation indicators, three indicators in each three groups of