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

Iman Mahdinia[a], Meeghat Habibian[a,*], Yaser Hatamzadeh[a], Henrik Gudmundsson[b]

[a] Department of Civil and Environmental Engineering, Amirkabir University of Technology, Hafez St., Tehran 15875-4413, Iran
[b] CONCITO, Kattesundet 4, 3. Sal 1458 Copenhagen K, Denmark

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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

* Corresponding author.
*E-mail address:* Habibian@aut.ac.ir (M. Habibian).

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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

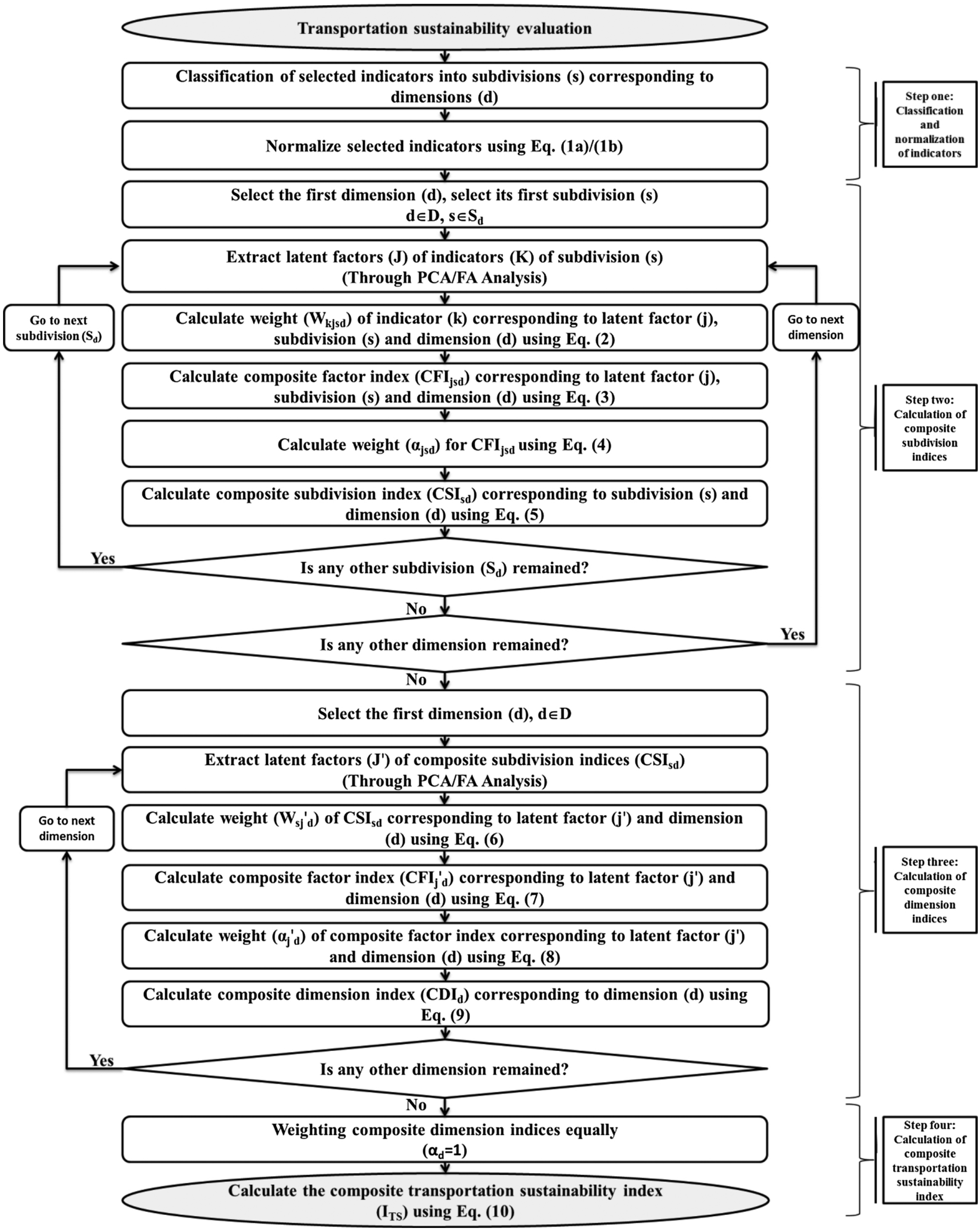


**Fig. 1.** Proposed algorithm for evaluating sustainability of a transportation system.

environmental, social and economical. They suggested a composite index by combination of nine standardized indicators using equal weighting method (Haghshenas and Vaziri, 2012). Ahangari et al. used equal weighting method to aggregate 10 indicators to introduce a cost-oriented national transportation sustainability index (NTSI) and use it to compare the sustainability of transportation in national scale of the US with 27 selected European countries for two years of 2005 and 2011 (Ahangari et al., 2016). Based on 15 indicators, De Gruyter et al. developed an aggregate measure to assess sustainability of urban public transit systems using equal weighting method. It covers several cities of

**Table 1**
Selected sustainable transportation subdivision and objectives.

| Dimension | Subdivision | Objective |
|---|---|---|
| Environmental | 1. Air pollution and greenhouse gases emission | 1. Reduce emissions of air pollutants and greenhouse gases |
| | 2. Energy | 2. Reduce petroleum-dependence; use renewable energy and energy with lower air pollutants and greenhouse gases emissions |
| | 3. Land used | 3. Reduce land used by transportation |
| | 4. Environmental efficiency of vehicle | 4. Improve the environmental efficiency of vehicles |
| Social | 5. Safety | 5. Enhance safety and minimize risk of crashes |
| | 6. Accessibility | 6. Enhance accessibility of transportation systems |
| | 7. Diversity | 7. Increase diversity of transportation modes |
| Economical | 8. Expenditure and benefit of transportation systems users | 8. Increase benefit and decrease expenditure of users of transportation systems |
| | 9. Expenditure and revenue of transportation systems operators | 9. Increase revenue and decrease expenditure of local governments and operators of transportation systems |

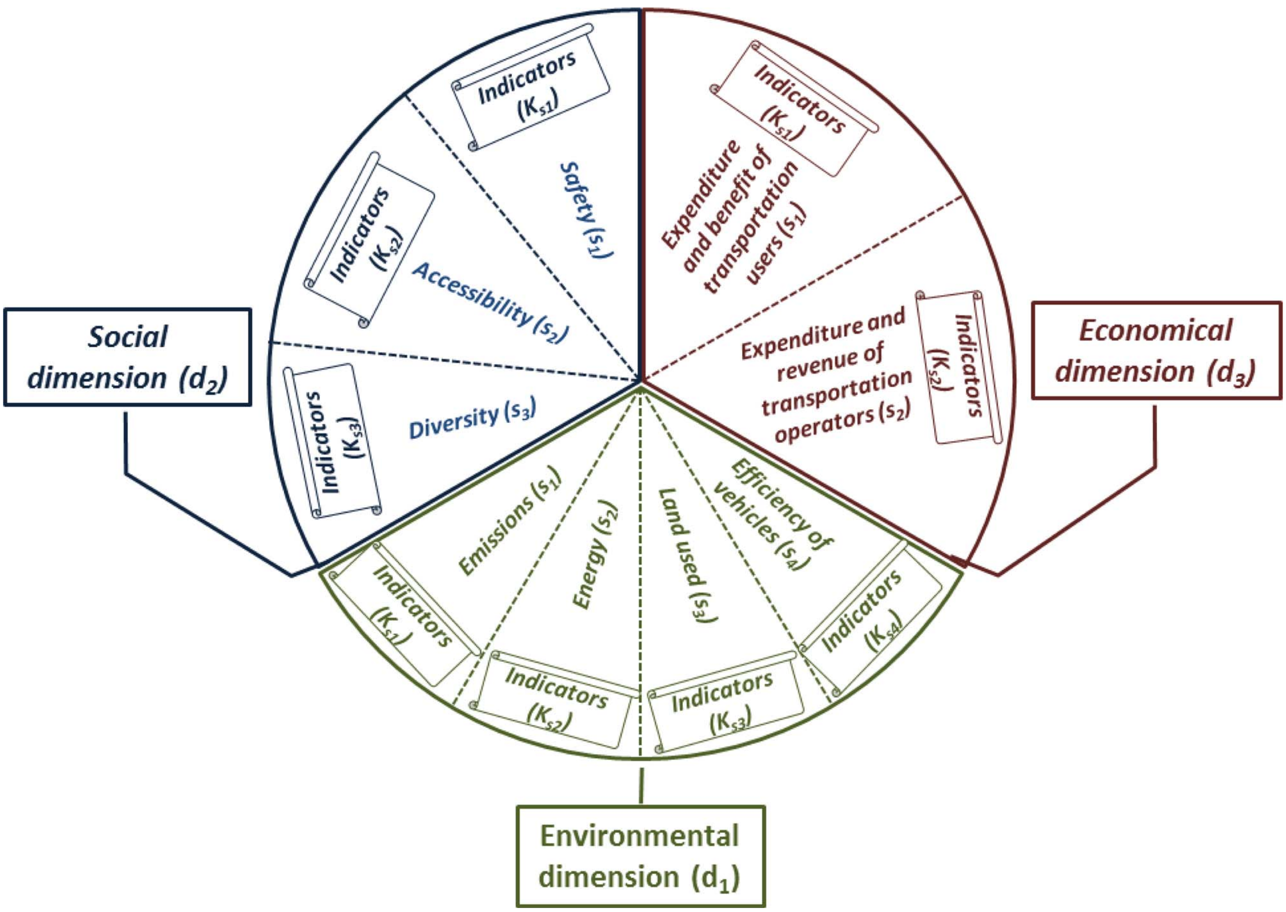


**Fig. 2.** Classification of indicators into dimensions and subdivisions (step 1 of the algorithm).

developing countries located in the Asia and Middle East region (De Gruyter et al., 2017). Jeon et al. evaluated and discussed 15 performance measures in Atlanta metropolitan region and aggregated them along with equal weighting into four indices representing four parameters that they proposed for sustainability: system effectiveness, environmental, social and economical (Jeon et al., 2013). Alonso et al. proposed an analysis of sustainability of urban passenger transportation systems based on available indicators in 23 European cities (Alonso et al., 2015). They used nine indicators and aggregated them along with equal weighting to three composite indices representing the three sustainability dimensions. Zito and Salvo proposed a specific set of sustainable and transportation performance indicators to evaluate effects of policy measures at the urban level in Europe. The indicators are aggregated using equal weighting along with the Euclidean distance between a city and the worst city based on the Normalized Transport Sustainability Index (NTSI) value. The NTSI is defined to compare the sustainability of adopted transportation policies in different European cities (Zito and Salvo, 2011).

Black used principal component analysis on nine transportation sustainability and potential mobility variables to select the strongest variable based on its component. Using the selected variable, he defined an index to measure transportation sustainability taking into account the potential mobility of a country. The index was demonstrated for U.S. states and 28 nations (Black, 2002). Reisi et al. developed a method for obtaining a composite transportation sustainability index for Melbourne (Reisi et al., 2014). Nine sustainability indicators relevant to urban transportation which deal with environmental, social and economical dimensions were selected based on available data for Melbourne. The indicators were integrated to a composite index, along with weighting based on statistical models using the Principal Component

**Table 2**
Environmental indicators (based on the studied data).

| Subdivision | Indicator | Sign |
|---|---|---|
| Air pollution and greenhouse gases emission ($s_1$) | 1. Annual air pollution[a] emissions by transportation per capita | − |
| | 2. Annual air pollution emissions by transportation per area | − |
| | 3. Annual air pollution emissions by transportation per total energy used by transportation | − |
| | 4. Annual greenhouse gases[a] by transportation per capita | − |
| | 5. Annual greenhouse gases by transportation per area | − |
| | 6. Annual greenhouse gases by transportation per total energy used by transportation | − |
| | 7. Annual on-road air pollution emission per total annual Vehicle Kilometers Traveled (VKT) | − |
| | 8. Annual on-road greenhouse gases per total annual VKT | − |
| Energy ($s_2$) | 9. Annual transportation energy[b] consumption per capita | − |
| | 10. Annual transportation energy consumption per total annual VKT | − |
| | 11. Annual motor fuel used by transportation per total annual VKT | − |
| | 12. Annual transportation energy consumption per Gross Domestic Product (GDP) | − |
| | 13. Annual motor fuel[b] used by transportation per capita | − |
| | 14. Annual motor fuel used by transportation per total vehicles | − |
| | 15. Annual renewable energy (ethanol) consumption by transportation per capita[c] | + |
| | 16. Annual renewable energy (ethanol) consumption per total transportation energy consumption[c] | + |
| | 17. Annual Compressed Natural Gas (CNG) consumption per total transportation energy consumption[c] | + |
| | 18. Annual electricity used per total energy consumption by transportation[c] | + |
| | 19. Annual motor fuel used in public transportation per capita | − |
| | 20. Annual motor fuel used in public transportation per annual unlinked passenger trips by public transportation | − |
| | 21. Annual motor fuel used in public transportation per total motor fuel used by transportation | + |
| | 22. Annual motor fuel used in public transportation per motor fuel used in private transportation | + |
| | 23. Percentage of motor fuel used in highway (high mobility) per total motor fuel used by vehicles[d] | + |
| Land used ($s_3$) | 24. Total roads length per capita | − |
| | 25. Total roads length per area | − |
| | 26. Total roads length per Annual total VKT | − |
| | 27. Percentage of highways length per total roads length | − |
| | 28. Total highways length per capita | − |
| | 29. Total highways length per area | − |
| | 30. Total highways length per Annual total VKT | − |
| | 31. Percentage of urban roads length per total roads length | − |
| | 32. Total urban roads length per capita | − |
| | 33. Urban roads length per area | − |
| Environmental efficiency of vehicles ($s_4$) | 34. Percentage of vehicles with alternative fuels[b] per total number of vehicles | + |
| | 35. Percentage of vehicles with renewable fuels per total number of vehicles | + |
| | 36. Number of alternative fuel station per number of alternative fuel vehicle | + |

[a] Air pollution including: $SO_2$, $PM_{10}$, $PM_{2.5}$, CO, $NO_X$, VOC. Greenhouse gas including: $CO_2$, $CH_4$, $N_2O$.
[b] Transportation energy including: CNG, diesel, jet fuel, motor gasoline, residual fuel, aviation gasoline, LPG, lubricants, ethanol, electricity. Motor fuel including: Gasoline and Diesel. Alternative fuels including: LPG, CNG, ethanol, electricity, hydrogen, propane, biodiesel.
[c] Biofuel (ethanol) and alternative fuels such as LPG, CNG and electricity have some benefits over petroleum and have been regarded as sustainable options for reducing petroleum-dependence and GHG emissions in transportation sector (Chang et al., 2017).
[d] High mobility in highways leads to lower fuel use per kilometer traveled and, therefore, more kilometers per gallon.

Analysis/Factor Analysis (PCA/FA) method.

Shiau and Liu selected ten indicators to measure the sustainable transportation in Taipei metropolitan area (Shiau and Liu, 2013). They used the Analytical Hierarchy Process (AHP) to weight the indicators and to evaluate sustainable transportation strategies.

Regarding the sustainability measurement at state level, the Federal Highway Administration's (FHWA) Highway Performance Monitoring System (HPMS) provided guidelines for transportation system performance and sustainability measures at state level (FHWA, 2012). Furthermore, Black viewed sustainable transportation in terms of 14 variables on over-reliance on petroleum, excessive emissions harmful to environment, excessive injuries and fatalities, congestion, use of alternate fuel vehicles, gasohol, and transit vehicles and derived an indicator to measure sustainable transportation for the U.S. states (Black, 2000).

Reviewing the studies in the literature elucidate two major limitations. First, various indicators were given equal weighting, (i.e., equal importance) in most studies (Haghshenas and Vaziri, 2012), (Jeon et al., 2013), (Alonso et al., 2015; Ahangari et al., 2016) or using AHP for weighting (Shiau and Liu, 2013) which both weighting methods have some limitations as mentioned before. Second, few number of indicators had been used to evaluate different aspects of sustainable transportation (Haghshenas and Vaziri, 2012), (Jeon et al., 2013), (Alonso et al., 2015; Shiau and Liu, 2013; Reisi et al., 2014), (Black, 2000), (Black, 2002), (Ahangari et al., 2016). Therefore, there is a lack of studies which use a diverse range of indicators to cover the broad and complex goal of sustainable transportation through using different weights for more than a few number of indicators. In order to surmount the limitation of previous studies, this paper aims to use a statistical weighting method to design an algorithm as a framework that has no limitation in the number of indicators for evaluating transportation sustainability. This approach can provide a more comprehensive basis for assessment and also utilize potentially rich sources of statistical data which may be available.

## 3. Methodology

As mentioned before, the intention of this paper is to propose an algorithm as a framework. In the proposed framework, the PCA/FA method was used for correlated indicators aggregation (Gomez-Limon and Riesgo, 2008). The method of PCA/FA has superiority over the other weighting methods (i.e., equal weighting method and weighting based on experts' judgments) used in the literature (Reisi et al., 2014). The PCA/FA is based on identifying a certain number of unobserved variables. In other words, the observed correlated variables in terms of a potentially lower number of unobserved variables called latent factors which should be fewer than the number of individual indicators, representing the data (OECD, 2008). Each latent factor depends on a set of coefficients (loadings), where each coefficient measures the correlation between an individual indicator and the latent factor. Latent factor extraction using PCA/FA requires two sets of values: an

**Table 3**
Social indicators (based on the U.S. data).

| Subdivision | Indicator | Sign |
|---|---|---|
| Safety ($s_1$) | 1. Annual traffic fatalities per capita | − |
| | 2. Annual traffic fatalities per annual total VKT | − |
| | 3. Annual traffic fatalities per total roads length | − |
| | 4. Annual traffic fatalities per total number of vehicles | − |
| | 5. Annual traffic fatalities per total number of licensed drivers | − |
| | 6. Annual public transportation fatalities per annual unlinked passenger trips by public transit | − |
| | 7. Annual public transportation injuries per annual unlinked passenger trips by public transit | − |
| | 8. Annual public transportation incidents per annual unlinked passenger trips by public transit | − |
| | 9. Percentage of annual bus passenger fatalities per total traffic fatalities | − |
| | 10. Annual bus passenger fatalities per annual unlinked passenger trips by bus | − |
| | 11. Annual number of bus passenger fatalities per total number of buses | − |
| | 12. Annual number of vehicle involving in fatal crashes per total number of vehicles | − |
| | 13. Annual number of bus involving in fatal crashes per total buses | − |
| | 14. Percentage of annual bus involving in fatal crashes per total annual number of vehicle involving in fatal crashes | − |
| | 15. Annual vulnerable traffic fatalities include pedestrian and bicyclist per total traffic fatalities | − |
| Accessibility ($s_2$) | 16. Annual unlinked passenger trips by bus per capita | + |
| | 17. Annual unlinked passenger trips by bus per total number of buses | + |
| | 18. Annual unlinked passenger trips by public transportation per capita | + |
| | 19. Annual aircraft hours flown per total number of active aircraft | + |
| | 20. Annual public transportation unlinked passenger trip except bus per total annual public transportation unlinked passenger trips | + |
| | 21. Percentage of annual work trips by public transportation per total annual work trips | + |
| | 22. Percentage of annual non motorize work trips per total annual work trips | + |
| | 23. Total number of vehicles per total number of households | + |
| | 24. Total number of vehicles per capita | + |
| | 25. Total number of vehicles per total number of licensed drivers | + |
| | 26. Percentage of exclusive and controlled right-of-way motor bus transit route per total motor bus transit route length | + |
| | 27. Percentage of total motor bus transit route length per total roads length | + |
| | 28. Total motor bus route length per area | + |
| | 29. Annual work trips (transit, walk, bicycle, motorcycle, taxicab, carpooled, etc.) except drive alone per total annual work trips | + |
| Diversity ($s_3$) | 30. Sum of squared of differences between modes with equal contributions in four modes: public, private, carpool and taxi, walking; in annual work trips[a] | − |
| | 31. Number of available transit mode | + |

[a] NOTE: Calculated using the following equation (For more information see (Haghshenas and Vaziri, 2012)): $\sqrt{(\text{Drivealone}-0.25)^2+(\text{Transit}-0.25)^2+(\text{CarpoolandTaxicab}-0.25)^2+(\text{Walk}-0.25)^2}$.

**Table 4**
Economical indicators (based on the studied data).

| Subdivision | Indicator | Sign |
|---|---|---|
| Expenditure and benefit of transportation systems users ($s_1$) | 1. Annual total cost spend for gasoline price including taxes per total annual VKT | − |
| | 2. Annual total cost spend for gasoline price including taxes per capita | − |
| | 3. Average travel time to work | − |
| Expenditure and revenue of transportation systems operators ($s_2$) | 4. Annual transportation expenditures per capita | − |
| | 5. Annual transportation expenditures per GDP per capita | − |
| | 6. Annual public transportation expenditures per capita | − |
| | 7. Annual transportation revenues per transportation expenditures | + |
| | 8. Annual public transportation revenues per public transportation expenditures | + |
| | 9. Annual public transportation expenditures per public transportation funds | − |
| | 10. Annual public transportation revenues per public transportation funds | + |
| | 11. Annual public transportation funds per total unlinked passenger trips by public transportation | − |
| | 12. Annual public transportation expenditures per total unlinked passenger trips by public transportation | − |
| | 13. Annual public transportation fund per capita | − |
| | 14. Annual public transportation funds per GDP | − |
| | 15. Annual public transportation fund per GDP per capita | − |
| | 16. Annual public transportation property damage by public transportation incidents per annual unlinked passenger trips by transit | − |
| | 17. Annual transportation payroll per number of paid employees | − |
| | 18. Annual public transportation payroll per number of paid employees | − |
| | 19. Number of transportation employments per capita | − |
| | 20. Number of public transportation employments per capita | − |
| | 21. Number of public transportation employees per annual unlinked passenger trips by public transportation | − |
| | 22. Annual freight shipment by rail per capita | + |

eigenvector which is simply a column or row of numbers in a correlation matrix of data and an eigenvalue which is the sum of squares of factor loadings of each latent factor (Reisi et al., 2014). Usually, a few latent factors will account for most of the variation and these latent factors can be used to replace the original indicators. Normally, latent factors that have eigenvalues larger than 1.0 are selected. The simplest justification for this rule is that it does not make sense to add a latent factor that explains less variance than is contained in one individual indicator (OECD, 2008). SPSS20 software was used to carry out PCA/FA analysis in this study.

To compose an individual composite index for the purpose of evaluation and comparison of transportation sustainability, the PCA/FA

**Table 5**
Sustainability Indices across the U.S States.

| State | Subdivision index | | | | | | | | | Dimension index | | | $I_{TS}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Environmental | | | | Social | | | Economical | | | | | |
| | $I_{Emission}$ | $I_{Energy}$ | $I_{LandUse}$ | $I_{Vehicle}$ | $I_{Safety}$ | $I_{Accessibility}$ | $I_{Diversity}$ | $I_{User}$ | $I_{Operator}$ | $I_{En.}$ | $I_{So.}$ | $I_{Ec.}$ | |
| Alabama | 0.684 | 0.489 | 0.894 | 0.028 | 0.621 | 0.190 | 0.000 | 0.394 | 0.556 | 0.471 | 0.234 | 0.475 | 0.394 |
| Alaska | 0.623 | 0.210 | 0.793 | 0.066 | 0.749 | 0.171 | 0.376 | 0.488 | 0.346 | 0.366 | 0.389 | 0.417 | 0.391 |
| Arizona | 0.737 | 0.578 | 0.923 | 0.117 | 0.642 | 0.194 | 0.266 | 0.496 | 0.552 | 0.541 | 0.334 | 0.524 | 0.466 |
| Arkansas | 0.689 | 0.440 | 0.838 | 0.012 | 0.586 | 0.108 | 0.196 | 0.520 | 0.594 | 0.444 | 0.261 | 0.557 | 0.421 |
| California | 0.878 | 0.571 | 0.924 | 0.039 | 0.786 | 0.250 | 0.644 | 0.415 | 0.625 | 0.553 | 0.524 | 0.520 | 0.532 |
| Colorado | 0.760 | 0.536 | 0.918 | 0.056 | 0.846 | 0.183 | 0.282 | 0.508 | 0.609 | 0.517 | 0.386 | 0.559 | 0.487 |
| Connecticut | 0.823 | 0.624 | 0.768 | 0.012 | 0.845 | 0.233 | 0.231 | 0.453 | 0.510 | 0.522 | 0.389 | 0.482 | 0.464 |
| Delaware | 0.762 | 0.563 | 0.794 | 0.087 | 0.787 | 0.257 | 0.054 | 0.410 | 0.589 | 0.514 | 0.322 | 0.500 | 0.445 |
| District of Columbia | 0.416 | 0.828 | 0.664 | 0.968 | 0.832 | 0.820 | 0.667 | 0.640 | 0.604 | 0.738 | 0.770 | 0.622 | 0.710 |
| Florida | 0.730 | 0.578 | 0.925 | 0.019 | 0.608 | 0.185 | 0.558 | 0.466 | 0.623 | 0.512 | 0.423 | 0.545 | 0.493 |
| Georgia | 0.728 | 0.534 | 0.917 | 0.037 | 0.767 | 0.181 | 0.232 | 0.389 | 0.601 | 0.502 | 0.348 | 0.496 | 0.449 |
| Hawaii | 0.880 | 0.576 | 0.974 | 0.086 | 0.558 | 0.291 | 0.225 | 0.440 | 0.535 | 0.576 | 0.336 | 0.488 | 0.467 |
| Idaho | 0.586 | 0.468 | 0.888 | 0.053 | 0.877 | 0.168 | 0.084 | 0.558 | 0.567 | 0.447 | 0.320 | 0.563 | 0.443 |
| Illinois | 0.778 | 0.573 | 0.808 | 0.034 | 0.814 | 0.253 | 0.474 | 0.445 | 0.612 | 0.508 | 0.473 | 0.529 | 0.503 |
| Indiana | 0.704 | 0.514 | 0.908 | 0.013 | 0.774 | 0.163 | 0.176 | 0.493 | 0.607 | 0.482 | 0.323 | 0.550 | 0.452 |
| Iowa | 0.711 | 0.416 | 0.868 | 0.018 | 0.776 | 0.253 | 0.065 | 0.468 | 0.615 | 0.449 | 0.321 | 0.542 | 0.438 |
| Kansas | 0.712 | 0.535 | 0.845 | 0.028 | 0.788 | 0.152 | 0.030 | 0.610 | 0.543 | 0.484 | 0.272 | 0.577 | 0.444 |
| Kentucky | 0.754 | 0.491 | 0.839 | 0.048 | 0.655 | 0.157 | 0.029 | 0.442 | 0.554 | 0.487 | 0.240 | 0.498 | 0.408 |
| Louisiana | 0.785 | 0.469 | 0.883 | 0.044 | 0.649 | 0.200 | 0.201 | 0.389 | 0.525 | 0.493 | 0.315 | 0.457 | 0.422 |
| Maine | 0.755 | 0.516 | 0.784 | 0.017 | 0.775 | 0.164 | 0.217 | 0.381 | 0.617 | 0.476 | 0.339 | 0.500 | 0.438 |
| Maryland | 0.788 | 0.572 | 0.936 | 0.055 | 0.735 | 0.144 | 0.649 | 0.232 | 0.613 | 0.537 | 0.470 | 0.423 | 0.477 |
| Massachusetts | 0.830 | 0.598 | 0.781 | 0.003 | 0.891 | 0.304 | 0.653 | 0.374 | 0.671 | 0.516 | 0.575 | 0.523 | 0.538 |
| Michigan | 0.673 | 0.587 | 0.939 | 0.021 | 0.768 | 0.201 | 0.016 | 0.467 | 0.566 | 0.503 | 0.282 | 0.517 | 0.434 |
| Minnesota | 0.656 | 0.546 | 0.826 | 0.031 | 0.903 | 0.235 | 0.416 | 0.461 | 0.587 | 0.471 | 0.468 | 0.524 | 0.488 |
| Mississippi | 0.764 | 0.388 | 0.886 | 0.080 | 0.356 | 0.117 | 0.004 | 0.401 | 0.495 | 0.475 | 0.139 | 0.448 | 0.354 |
| Missouri | 0.649 | 0.493 | 0.846 | 0.051 | 0.773 | 0.168 | 0.203 | 0.441 | 0.552 | 0.463 | 0.334 | 0.497 | 0.431 |
| Montana | 0.631 | 0.450 | 0.739 | 0.046 | 0.702 | 0.195 | 0.110 | 0.533 | 0.529 | 0.426 | 0.295 | 0.531 | 0.417 |
| Nebraska | 0.664 | 0.472 | 0.797 | 0.030 | 0.826 | 0.168 | 0.039 | 0.609 | 0.550 | 0.446 | 0.291 | 0.580 | 0.439 |
| Nevada | 0.732 | 0.550 | 0.930 | 0.094 | 0.702 | 0.182 | 0.079 | 0.513 | 0.547 | 0.526 | 0.279 | 0.530 | 0.445 |
| New Hampshire | 0.789 | 0.541 | 0.794 | 0.004 | 0.779 | 0.195 | 0.038 | 0.286 | 0.562 | 0.490 | 0.289 | 0.424 | 0.401 |
| New Jersey | 0.879 | 0.526 | 0.797 | 0.040 | 0.738 | 0.314 | 0.658 | 0.259 | 0.645 | 0.519 | 0.542 | 0.452 | 0.504 |
| New Mexico | 0.705 | 0.484 | 0.868 | 0.183 | 0.704 | 0.128 | 0.226 | 0.510 | 0.562 | 0.515 | 0.309 | 0.537 | 0.454 |
| New York | 0.815 | 0.630 | 0.846 | 0.025 | 0.746 | 0.311 | 0.857 | 0.439 | 0.679 | 0.538 | 0.611 | 0.559 | 0.570 |
| North Carolina | 0.672 | 0.548 | 0.769 | 0.086 | 0.642 | 0.119 | 0.200 | 0.464 | 0.604 | 0.483 | 0.281 | 0.534 | 0.432 |
| North Dakota | 0.561 | 0.395 | 0.480 | 0.073 | 0.716 | 0.242 | 0.056 | 0.479 | 0.517 | 0.358 | 0.299 | 0.498 | 0.385 |
| Ohio | 0.612 | 0.555 | 0.826 | 0.021 | 0.825 | 0.200 | 0.344 | 0.512 | 0.582 | 0.460 | 0.410 | 0.547 | 0.472 |
| Oklahoma | 0.722 | 0.482 | 0.880 | 0.027 | 0.647 | 0.179 | 0.042 | 0.551 | 0.547 | 0.476 | 0.251 | 0.550 | 0.425 |
| Oregon | 0.773 | 0.568 | 0.917 | 0.045 | 0.739 | 0.229 | 0.323 | 0.535 | 0.607 | 0.526 | 0.392 | 0.572 | 0.497 |
| Pennsylvania | 0.792 | 0.574 | 0.776 | 0.016 | 0.760 | 0.234 | 0.599 | 0.437 | 0.645 | 0.502 | 0.495 | 0.541 | 0.513 |
| Rhode Island | 0.826 | 0.654 | 0.754 | 0.041 | 0.882 | 0.232 | 0.055 | 0.567 | 0.554 | 0.538 | 0.336 | 0.561 | 0.478 |
| South Carolina | 0.742 | 0.481 | 0.800 | 0.065 | 0.622 | 0.158 | 0.020 | 0.380 | 0.597 | 0.479 | 0.229 | 0.489 | 0.399 |
| South Dakota | 0.644 | 0.451 | 0.614 | 0.098 | 0.852 | 0.231 | 0.078 | 0.540 | 0.517 | 0.425 | 0.337 | 0.529 | 0.430 |
| Tennessee | 0.728 | 0.530 | 0.894 | 0.035 | 0.676 | 0.148 | 0.344 | 0.428 | 0.575 | 0.497 | 0.351 | 0.502 | 0.450 |
| Texas | 0.818 | 0.479 | 0.877 | 0.070 | 0.680 | 0.160 | 0.391 | 0.425 | 0.550 | 0.511 | 0.373 | 0.488 | 0.458 |
| Utah | 0.654 | 0.523 | 0.909 | 0.039 | 0.658 | 0.193 | 0.420 | 0.592 | 0.499 | 0.479 | 0.391 | 0.546 | 0.472 |
| Vermont | 0.762 | 0.564 | 0.763 | 0.052 | 0.727 | 0.212 | 0.119 | 0.434 | 0.461 | 0.499 | 0.311 | 0.448 | 0.420 |
| Virginia | 0.837 | 0.551 | 0.789 | 0.066 | 0.660 | 0.235 | 0.262 | 0.352 | 0.592 | 0.522 | 0.353 | 0.472 | 0.449 |
| Washington | 0.689 | 0.565 | 0.928 | 0.037 | 0.780 | 0.264 | 0.481 | 0.437 | 0.561 | 0.504 | 0.471 | 0.500 | 0.491 |
| West Virginia | 0.806 | 0.553 | 0.640 | 0.019 | 0.536 | 0.110 | 0.020 | 0.400 | 0.605 | 0.478 | 0.188 | 0.503 | 0.390 |
| Wisconsin | 0.651 | 0.555 | 0.805 | 0.021 | 0.780 | 0.174 | 0.218 | 0.524 | 0.602 | 0.466 | 0.344 | 0.563 | 0.458 |
| Wyoming | 0.607 | 0.262 | 0.792 | 0.048 | 0.683 | 0.201 | 0.107 | 0.480 | 0.482 | 0.373 | 0.291 | 0.481 | 0.382 |

analysis is adopted through an algorithm which is shown in Fig. 1. For the sake of clarification the algorithm is divided into four major steps as follows.

### 3.1. Step one: classification and normalization of indicators

In the first step, the three general dimensions which reflect the environmental, social and economical status of a system are divided into subdivisions with specific objectives (Table 1); each of which includes a number of indicators (Fig. 2). Categorizing indicators based on subdivisions could help tracing each of subdivision toward its objectives. Due to several possible categorization, the categorized objectives presented in Table 1 were selected according to the literature (Litman, 2009), (Litman, 2011), (Haghshenas and Vaziri, 2012).

It is necessary to normalize indicators because they contain different types of information which might cause inconsistency in units among indicators. In this study, indicators are normalized to a range between 0 and 1 using the *re-scaling method* (Joumard and Gudmundsson, 2010). As an increase in an indicator will have a positive or negative impact on transportation sustainability, the normalization is done using Eq. (1), respectively.

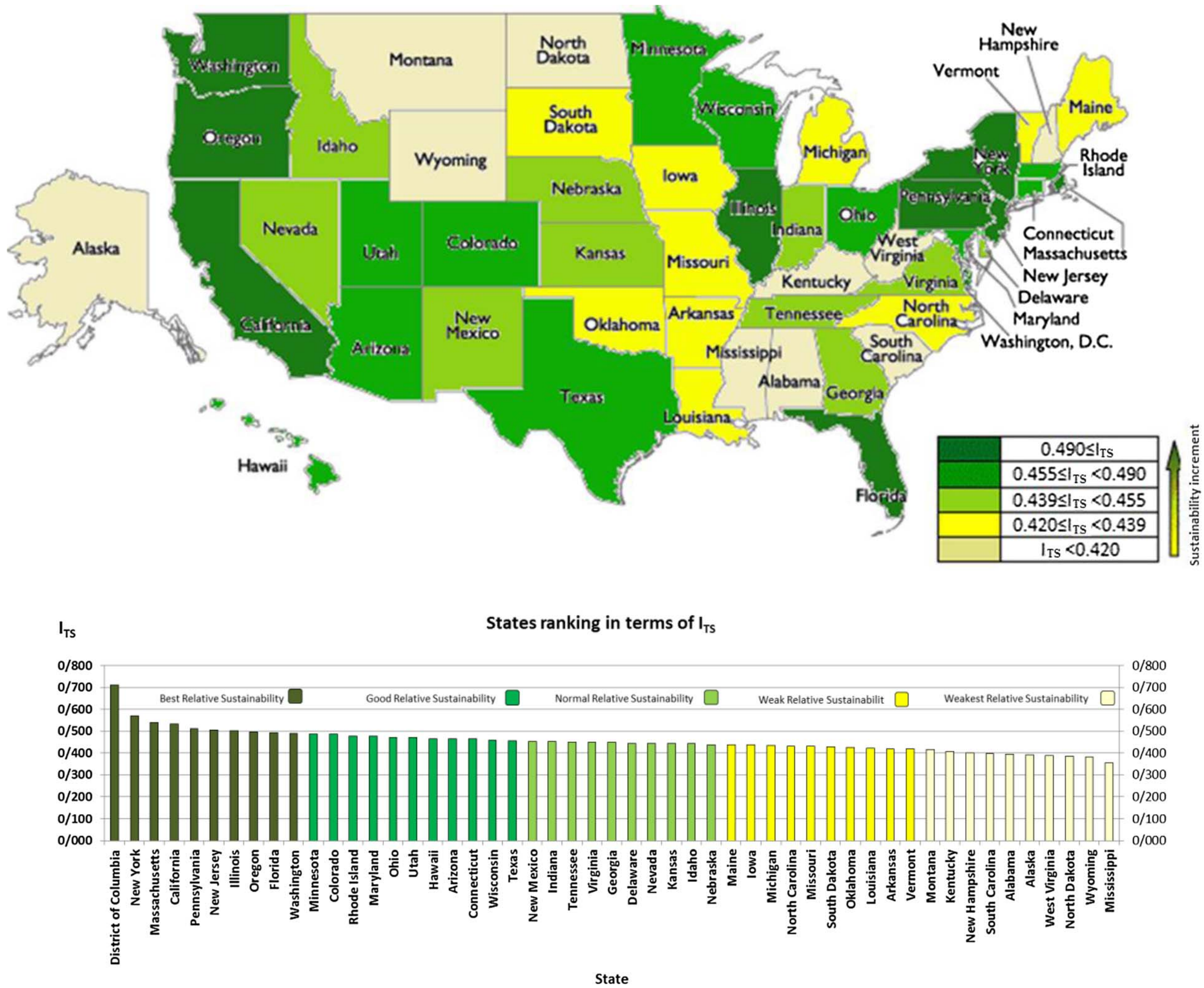


**Fig. 3.** Comparison of U.S States by the calculated Composite Transportation Sustainability Index ($I_{TS}$).

$$NI = \begin{cases} \dfrac{I^{+} - I^{+}_{\min}}{I^{+}_{\max} - I^{+}_{\min}}, & \text{if the effect of I is positive} \\ \dfrac{I^{-}_{\max} - I^{-}}{I^{-}_{\max} - I^{-}_{\min}}, & \text{if the effect of I is negative} \end{cases} \quad (1)$$

Where, *NI* is a normalized indicator; $I^{+}$ in Eq. (1) is the value of indicator whose increasing value has positive impact on sustainability, $I^{-}$ in Eq. (1) is the value of indicator whose increasing value has negative impact on sustainability; $I_{\min}$ is the minimum value of indicator *I* and $I_{\max}$ is the maximum value of indicator *I*.

### 3.2. Step two: calculation of composite subdivision indices

In the second step, indicators are aggregated to form composite indices representing characteristics of each subdivision (CSI) of each dimension. In this line, latent factors (*J*) of indicators (*K*) corresponding to each subdivision (*s*) and dimension (*d*) (as shown in Fig. 2), were extracted by applying the PCA/FA analysis. Then, a composite factor index (*CFI*) corresponding to each of the latent factors (*J*) was calculated. To do this, indicators corresponding to each latent factor (*j*) are weighted by Eq. (2); and then, aggregated by Eq. (3)

$$W_{kjsd} = \frac{(FactorLoading_{kjsd})^2}{Eigenvalue_{jsd}} \quad , k \in K_s,\ j \in J_s,\ s \in S_d,\ d \in D \quad (2)$$

$$CFI_{jsd} = \sum_k W_{kjsd} NI_{kjsd} \quad , k \in K_s,\ j \in J_s,\ s \in S_d,\ d \in D \quad (3)$$

where, $W_{kjsd}$ is the weight of an indicator obtained from the factor loading and eigenvalue; *k*, stands for indicators; *j*, stands for latent factors; *s*, stands for subdivisions; *d*, stands for dimensions; $CFI_{jsd}$, stands for composite index of latent factor *j* corresponding to subdivision *s* and dimension *d* and $NI_{kjsd}$ stands for normalized indicator value.

After calculating the composite factor indices ($CFI_{jsd,}$), they were weighted by Eq. (4) and then aggregated by using Eq. (5) to form the composite indices representing characteristic of each subdivision (CSI)

$$\alpha_{jsd} = \frac{Eigenvalue_{jsd}}{\sum_{J_s} Eigenvalue_{jsd}} \quad , j \in J_s,\ s \in S_d,\ d \in D \quad (4)$$

$$CSI_{sd} = \sum_j \alpha_{jsd} CFI_{jsd} \quad , j \in J_s,\ s \in S_d,\ d \in D \quad (5)$$

Where, $\alpha_{jsd}$ is the weight applied to corresponding composite factor index ($CFI_{jsd}$) and $CSI_{sd}$ stands for composite subdivision index.

### 3.3. Step three: calculation of composite dimension indices

In the third step, indices calculated in previous step (i.e., $CSI_{sd}$) are aggregated to form indices representing characteristics of each dimension ($CDI_d$). The analysis process is somehow similar to the second step. However, the output of this step will be three indices representing three dimensions of sustainability. In this line, the PCA/FA analysis was applied to composite subdivision indices ($CSI_{sd}$) through which latent factors ($J'$) of each dimension ($d$) were extracted. Then, $CFI_{j'd}$ (i.e., a composite factor index corresponding to latent factor ($j'$) and dimension ($d$)) was calculated. To do this, a weight was calculated for the index ($CSI_{sd}$) by Eq. (6). Then, by using Eq. (7) a composite factor index ($CFI_{j'd}$) for a latent factor ($j'$) corresponding to dimension ($d$) was calculated

$$W_{sj'd} = \frac{(FactorLoading_{sj'd})^2}{Eigenvalue_{j'd}} \quad , j' \in J'_d,\ s \in S_d,\ d \in D \tag{6}$$

$$CFI_{j'd} = \sum_s W_{sj'd} CSI_{sd} \quad , j' \in J'_d,\ s \in S_d,\ d \in D \tag{7}$$

Where, $W_{sj'd}$ is the weight applied to a composite subdivision index ($CSI_{sd}$) according to subdivision ($s$), latent factor ($j'$) and dimension ($d$). In Eq. (7), $CFI_{jd}$ stands for a composite factor index corresponding to latent factor ($j'$) and dimension ($d$).

After calculating the composite factor indices ($CFI_{j'sd,}$), they were weighted by Eq. (8) and then aggregated by using Eq. (9) to form the composite indices representing characteristic of each dimension ($CDI_d$)

$$\alpha_{j'd} = \frac{Eigenvalue_{j'd}}{\sum_l Eigenvalue_{ld}} \quad , j' \in J'_d,\ d \in D \tag{8}$$

$$CDI_d = \sum_{j'} \alpha_{j'd} CFI_{j'd} \quad , j' \in J'_d,\ d \in D \tag{9}$$

Where, $\alpha_{j'd}$ is the weight corresponding to composite factor index ($CFI_{j'd}$) and $CDI_d$ stands for a composite dimension index.

### 3.4. Step four: calculation of composite transportation sustainability index

Finally, in the fourth step, all three composite dimension indices ($CDI_d$) calculated in step 3 are aggregated to form the composite transportation sustainability index ($I_{TS}$). In this step, equal weight was applied to the indices because all sustainability concepts clearly affirm that environmental, social and economical dimensions must have an equal relevance for measuring progresses toward a sustainable transportation (Zito and Salvo, 2011). The three composite dimension indices are aggregated by using Eq. (10) (Haghshenas and Vaziri, 2012), (Jeon et al., 2013)

$$I_{TS} = \frac{\sum_d \alpha_d CDI_d}{D} \quad \mathrm{d} \in \mathrm{D} \quad \alpha_d = 1 \tag{10}$$

Where, $\alpha_d$ is the weight applied to corresponding composite dimension index (which equals to one representing the equal weighting) and $I_{TS}$ stands for the composite transportation sustainability index.

## 4. Case study

This paper considers the U.S. as a case study to evaluate sustainability of transportation system in the state level due to the existence of a homogeneous large amount of data that is helpful to show the power of the proposed algorithm for calculation of $I_{TS}$. The algorithm is applied to 50 states and the Federal District of Columbia and the composite transportation sustainability indices are calculated.

### 4.1. Data and indicator description

For the case study, data collected from the U.S. Department of Transportation (U.S.DOT, 2012), U.S. Environment Protection Agency (U.S. EPA, 2011) and U.S. Census Bureau (U.S. Census Bureau, 2010) during 2010 and 2011 for 50 states and the Federal District of Columbia were used. By using the available data and considering the previous studies and guidelines for indicator selection (Haghshenas and Vaziri, 2012), (Alonso et al., 2015), (Litman, 2007), (EPA, 2011) 89 indicators were defined to evaluate transportation sustainability. As the main contribution of the proposed algorithm in which it has no limitation on using too many indicators (to address different aspects of sustainability dimensions), initial selection of the indicators were based on the availability of data through considering the mentioned studies and guidelines for indicator selection. It is worth noting that reaching more data could increase the number of possible adopted indicators.

As described in the methodology, these indicators were normalized and then classified into subdivisions of each of environmental, social and economic dimensions regarding Table 1. Each of the 89 indicators belongs to a specific subdivision as described in Tables 2–4. The column "sign" in each table shows whether an increase in the value of an indicator has a positive or negative effect on the sustainability of a transportation system.

## 5. Results and discussion

Using the proposed algorithm, all 89 indicators were normalized and aggregated into nine composite subdivision indices (step 2). According to the third step, these indices were aggregated to form indices $I_{Environment}$ ($I_{En}$), $I_{Social}$ ($I_{So}$) and $I_{Economical}$ ($I_{Ec}$) regarding the three dimensions of a sustainable transportation system. Finally, in the fourth step these three indices were aggregated to make the composite transportation sustainability index, $I_{TS}$. Values of the mentioned indices were calculated for 50 states and the federal districts of the U.S. and were ranked with respect to $I_{TS}$ as reported in Table 5. The calculated indices are between zero and one which makes it possible to compare the transportation sustainability across different states. Results show that while District of Columbia (0.710), New York (0.570), Massachusetts (0.538), California (0.532) and Pennsylvania (0.513) have the highest values of $I_{TS}$, Mississippi (0.354), Wyoming (0.382), North Dakota (0.385), Vest Virginia (0.390) and Alaska (0.391) have the lowest values.

To better follow the algorithm, a numerical example of New York State and a brief explanation of the algorithm are presented in the Appendix A. Considering the first step of algorithm, Tables A1–A3 in the Appendix A present the values of normalized environmental, social and economical indicators, respectively. According to the second step, Tables A4–A6 in the Appendix A demonstrate the calculation of the composite subdivision index, $CSI_{sd}$, for environmental, social and economical dimensions, respectively. Finally, Table A7 in the Appendix A shows the calculation of the composite dimension index, $CDI_d$, for each of the dimensions in the third step and Table A8 presents the calculation of $I_{TS}$ in the fourth step of the proposed algorithm.

In order to demonstrate the results more clearly, states were categorized into five groups with equal proportion based on highest to least value of $I_{TS}$ to compare the relative transportation sustainability among the U.S. states (Fig. 3). Subsequently, states with values greater than 0.490 are named the best relative transportation sustainability, values between 0.455–0.490 are named good relative sustainability, values between 0.439–0.455 are named normal relative sustainability, values between 0.420–0.439 are named weak relative sustainability and values less than 0.420 are named the weakest sustainability of state's transportation systems (Fig. 3).

By decomposing the indices of the regions to their components, decision makers and transportation planners can recognize and track weaknesses and strengths of transportation systems in concept of sustainability. For instance, among the results, the federal District of Columbia was found with the highest rank. By decomposing the composite index into its components, some reasons of this superiority could be discovered. District of Columbia is a very small area of about 158 square kilometers and is mostly encompassed by the capital Washington DC metropolitan area. This makes this region with high population density in a state scale as a specific geographical and social condition. One reason of the region's significant advantage with respect to other states may be the small area of the federal region. This factor has positive effect in some indicators. For example, a decrease in an area increases the indicator of bus routes length per area (Table 3) and, therefore, the accessibility through which the transportation sustainability improves. Also, a small area of states with urban regions decreases the travel time and energy consumption which in turn improves the transportation sustainability. The observation that a small region with more population causing high population density seems to enhance transportation sustainability is consistent with the Reisi et al. (2014) study which claimed that statistical local areas with high population density show higher sustainability index.

Moreover, New York was found with the second best rank in state's transportation sustainability (Table 5). One reason of this superiority is the New York City. It had the most diverse transit modes among the other U.S. cities which provides high accessibility to transit system. As a result, this feature increases the values of $I_{Diversity}$, $I_{Accessibility}$, $I_{So}$ and $I_{TS}$ as well. Also, New York City encompasses a large part of state's population. As a result, regarding some traffic policies in New York City along with a high accessibility and diversity of public transit modes, give rise to high public transit utilization. Thereby, this provides significant benefits for public transit operators and users (e.g., high revenue for operators and low energy consumption and emission). As a result, these factors provides high values of $I_{Ec}$, $I_{En}$ and $I_{TS}$ as well.

On the other hand, Mississippi was found with the lowest rank. By decomposing the composite indices into their components, some reasons of this inferiority could be discovered. Mississippi State based on the social composite index $I_{So}$ had the least value (Table 5). According to the data, Mississippi State possessed a high rate of traffic fatalities per capita which has negative impacts on many indicators such as traffic fatalities per total vehicles and public transit fatalities and injuries per annual unlinked passenger trips (Table 3). Furthermore, this state had the lowest number of available transit modes and the highest rate of commuting to work by private car which negatively influence on indicators such as percentage of annual work trips by transit per total annual work trips and percentage of annual non-motorized work trips per total annual work trips (Table 3). These factors negatively affect the safety, accessibility and diversity subdivisions of environmental dimension respectively which in turn reduce the values of $I_{So}$ and consequently worsened $I_{TS}$.

## 6. Conclusion

The aim of this paper was to design an algorithm to use several numbers of indicators in sustainable transportation dimensions and their various subdivisions. The method of PCA/FA was used for weighting and aggregating indicators to overcome limitations of other methods used in previous studies. The algorithm was designed through which a new index ($I_{TS}$) is developed to evaluate the sustainability of a transportation system. This algorithm enumerates several sustainable transportation indicators as well as their impact, providing a comprehensive view of the complexity of sustainable transportation dimensions and their several subdivisions as it feeds into different composite indices and the $I_{TS}$. The algorithm could be useful for stakeholders and decision makers to assess their progress compared to other regions. Furthermore, through decomposing the $I_{TS}$ of a region to their components, decision makers and transportation planners can recognize and track weaknesses and strengths of a transportation system toward the concept of sustainability.

In this study, 89 indicators were selected only based on indicators adopted in previous studies and the available data in the U.S. States from the three sources (i.e., U.S. EPA, U.S. Census Bureau and U.S. DOT). As many indicators as possible were defined to demonstrate the utility of the algorithm. It is worth mentioning that different indicators could be adopted based on the data availability. Also, each indicator was assigned to only one of the studied dimensions. However, variation of an indicator may also influence other dimensions. Therefore, it is suggested that future research focus on addressing the effect of indicators on different dimensions simultaneously.

Finally, previous studies have usually evaluated transportation inside urban areas while this study evaluates transportation in the scale of states. Considering a large scale would help planners to rank region's transportation sustainability to identify the condition of regions comparatively. It is worth mentioning that the analysis on the results of the U.S. states was based on some basic information of the states and for more detailed analysis, more information including cultural, geographical and historical may be required. Furthermore, in this study, the indicators are calculated based on a specific time period which could be developed in future studies. It is suggested to collect data over a multi-year period and use the proposed method to consider variations in transportation sustainability.

## Appendix A

The process of calculation of composite transportation sustainability index, $I_{TS}$, of the New York State is shown by the following tables. Tables A1–A3 present the normalized indicators values representing the environmental, social and economical dimensions, respectively (first step).

In the second step of the algorithm, the calculation of Composite Subdivision Indices, $CSI_{sd}$, of environmental, social and economical dimensions are demonstrated by bolded numbers in Tables A4–A6, respectively.

To better follow the process of the algorithm, the procedure of calculating $CSI_{sd}$ for the environmental dimension and one of its subdivisions "air pollution and greenhouse gases emission" (Table A4) is described by the following example:

First, the PCA method was applied to the normalized indicator values of the subdivision "air pollution and greenhouse gases emission" (indicators number 1–8). Therefore, the factor loadings and eigenvalues for the three obtained latent factors (j-1 to j-3) were calculated. Using Eq. (2) the weight of each indicator in each of the three latent factors, $W_{kjsd}$, was calculated. Then, the Composite Factor Index, $CFI_{jsd}$, values were calculated for the three latent factors through using Eq. (3). Finally, using Eq. (4) the weights of each $CFI_{jsd}$ were calculated and the $CSI_{sd}$ for the subdivision of "air pollution and greenhouse gases emission" was calculated by using Eq. (5). Table A4 shows that the calculated $CSI_{sd}$ value is equal to 0.815.

According to the third step, the composite dimension indices representing the environmental, social and economical dimensions are calculated as shown in Table A7.

To demonstrate the process of the algorithm clearer, the procedure of calculating the Composite Dimension Index ($CDI_d$) for the environmental dimension (Table A7) is described by the following example:

First, the PCA was applied to the previously calculated $CSI_{sd}$ values for the environmental dimension. Therefore, the factor loadings and eigenvalues were calculated for the two obtained latent factors (j'-1 and j'-2). Then, using Eq. (6) the weight of each $CSI_{sd}$ was calculated in each latent factor. Then the $CFI_{j'd}$ was calculated for each latent factor using Eq. (7). Adopting Eq. (8) the weight of each $CFI_{j'd}$ which is shown by $\alpha_{j'd}$ was determined. Finally, using Eq. (9) the Composite Dimension Index, $CDI_d$ for the environmental dimension was calculated ($CDI_d = 0.538$).

Finally, Table A8 presents the calculation of $I_{TS}$ for the New York State in the fourth step of the proposed algorithm (Using Eq. (10)).

**Table A1**
Normalized environmental indicators value.

| Step 1 | | |
|---|---|---|
| Subdivision | Environmental Indicator | NI Value |
| Air pollution and greenhouse gases emission ($s_1$) | 1. Annual air pollution emissions by transportation per capita | 0.920 |
| | 2. Annual air pollution emissions by transportation per area | 0.946 |
| | 3. Annual air pollution emissions by transportation per total energy used by transportation | 0.533 |
| | 4. Annual greenhouse gases by transportation per capita | 1.000 |
| | 5. Annual greenhouse gases by transportation per area | 0.962 |
| | 6. Annual greenhouse gases by transportation per total energy used by transportation | 0.497 |
| | 7. Annual on-road air pollution emission per total annual Vehicle Kilometers Traveled (VKT) | 0.920 |
| | 8. Annual on-road greenhouse gases per total annual VKT | 0.647 |
| Energy ($s_2$) | 9. Annual transportation energy consumption per capita | 0.915 |
| | 10. Annual transportation energy consumption per total annual VKT | 0.752 |
| | 11. Annual motor fuel used by transportation per total annual VKT | 0.933 |
| | 12. Annual transportation energy consumption per Gross Domestic Product (GDP) | 0.819 |
| | 13. Annual motor fuel used by transportation per capita | 0.845 |
| | 14. Annual motor fuel used by transportation per total vehicles | 0.781 |
| | 15. Annual renewable energy (ethanol) consumption by transportation per capita | 0.401 |
| | 16. Annual renewable energy (ethanol) consumption per total transportation energy consumption | 0.582 |
| | 17. Annual Compressed Natural Gas (CNG) consumption per total transportation energy consumption | 0.111 |
| | 18. Annual electricity used per total energy consumption by transportation | 0.174 |
| | 19. Annual motor fuel used in public transportation per capita | 0.953 |
| | 20. Annual motor fuel used in public transportation per annual unlinked passenger trips by public transportation | 0.999 |
| | 21. Annual motor fuel used in public transportation per total motor fuel used by transportation | 0.169 |
| | 22. Annual motor fuel used in public transportation per motor fuel used in private transportation | 0.163 |
| | 23. Percentage of motor fuel used in highway (high mobility) per total motor fuel used by vehicles | 0.910 |
| Land used ($s_3$) | 24. Total roads length per capita | 0.972 |
| | 25. Total roads length per area | 0.906 |
| | 26. Total roads length per Annual total VKT | 0.948 |
| | 27. Percentage of highways length per total roads length | 0.916 |
| | 28. Total highways length per capita | 0.972 |
| | 29. Total highways length per area | 0.987 |
| | 30. Total highways length per Annual total VKT | 0.952 |
| | 31. Percentage of urban roads length per total roads length | 0.248 |
| | 32. Total urban roads length per capita | 0.960 |
| | 33. Urban roads length per area | 0.586 |
| Environmental efficiency of vehicles ($s_4$) | 34. Percentage of vehicles with alternative fuels per total number of vehicles | 0.032 |
| | 35. Percentage of vehicles with renewable fuels per total number of vehicles | 0.014 |
| | 36. Number of alternative fuel station per number of alternative fuel vehicle | 0.073 |

**Table A2**
Normalized social indicator values.

| Step 1 | | |
|---|---|---|
| Subdivision | Indicator | Sign |
| Safety ($s_1$) | 1. Annual traffic fatalities per capita | 0.916 |
| | 2. Annual traffic fatalities per annual total VKT | 0.745 |
| | 3. Annual traffic fatalities per total roads length | 0.585 |
| | 4. Annual traffic fatalities per total number of vehicles | 0.802 |
| | 5. Annual traffic fatalities per total number of licensed drivers | 0.870 |
| | 6. Annual public transportation fatalities per annual unlinked passenger trips by public transit | 0.916 |
| | 7. Annual public transportation injuries per annual unlinked passenger trips by public transit | 0.997 |
| | 8. Annual public transportation incidents per annual unlinked passenger trips by public transit | 0.812 |
| | 9. Percentage of annual bus passenger fatalities per total traffic fatalities | 0.358 |
| | 10. Annual bus passenger fatalities per annual unlinked passenger trips by bus | 0.995 |
| | 11. Annual number of bus passenger fatalities per total number of buses | 0.709 |
| | 12. Annual number of vehicle involving in fatal crashes per total number of vehicles | 0.803 |
| | 13. Annual number of bus involving in fatal crashes per total buses | 0.812 |
| | 14. Percentage of annual bus involving in fatal crashes per total annual number of vehicle involving in fatal crashes | 0.673 |
| | 15. Annual vulnerable traffic fatalities include pedestrian and bicyclist per total traffic fatalities | 0.134 |
| Accessibility ($s_2$) | 16. Annual unlinked passenger trips by bus per capita | 0.258 |
| | 17. Annual unlinked passenger trips by bus per total number of buses | 0.078 |
| | 18. Annual unlinked passenger trips by public transportation per capita | 0.286 |
| | 19. Annual aircraft hours flown per total number of active aircraft | 0.338 |
| | 20. Annual public transportation unlinked passenger trip except bus per total annual public transportation unlinked passenger trips | 1.000 |
| | 21. Percentage of annual work trips by public transportation per total annual work trips | 0.680 |
| | 22. Percentage of annual non motorize work trips per total annual work trips | 0.524 |
| | 23. Total number of vehicles per total number of households | 0.381 |
| | 24. Total number of vehicles per capita | 0.015 |
| | 25. Total number of vehicles per total number of licensed drivers | 0.350 |
| | 26. Percentage of exclusive and controlled right-of-way motor bus transit route per total motor bus transit route length | 0.097 |
| | 27. Percentage of total motor bus transit route length per total roads length | 0.077 |
| | 28. Total motor bus route length per area | 0.007 |
| | 29. Annual work trips (transit, walk, bicycle, motorcycle, taxicab, carpooled, etc.) except drive alone per total annual work trips | 0.598 |
| Diversity ($s_3$) | 30. Sum of squared of differences between modes with equal contributions in four modes: public, private, carpool and taxi, walking; in annual work trips | 0.713 |
| | 31. Number of available transit mode | 1.000 |

**Table A3**
Normalized Economical indicator values.

| Step 1 | | |
|---|---|---|
| Subdivision | Economical Indicator | NI Value |
| Expenditure and benefit of transportation systems users ($s_1$) | 1. Annual total cost spend for gasoline price including taxes per total annual VKT | 0.708 |
| | 2. Annual total cost spend for gasoline price including taxes per capita | 0.742 |
| | 3. Average travel time to work | 0.036 |
| Expenditure and revenue of transportation systems operators ($s_2$) | 4. Annual transportation expenditures per capita | 0.681 |
| | 5. Annual transportation expenditures per GDP per capita | 0.982 |
| | 6. Annual public transportation expenditures per capita | 0.706 |
| | 7. Annual transportation revenues per transportation expenditures | 0.586 |
| | 8. Annual public transportation revenues per public transportation expenditures | 0.657 |
| | 9. Annual public transportation expenditures per public transportation funds | 0.535 |
| | 10. Annual public transportation revenues per public transportation funds | 0.532 |
| | 11. Annual public transportation funds per total unlinked passenger trips by public transportation | 0.974 |
| | 12. Annual public transportation expenditures per total unlinked passenger trips by public transportation | 0.877 |
| | 13. Annual public transportation fund per capita | 0.312 |
| | 14. Annual public transportation funds per GDP | 0.918 |
| | 15. Annual public transportation fund per GDP per capita | 1.000 |
| | 16. Annual public transportation property damage by public transportation incidents per annual unlinked passenger trips by transit | 0.974 |
| | 17. Annual transportation payroll per number of paid employees | 0.746 |
| | 18. Annual public transportation payroll per number of paid employees | 0.373 |
| | 19. Number of transportation employments per capita | 0.288 |
| | 20. Number of public transportation employments per capita | 0.686 |
| | 21. Number of public transportation employees per annual unlinked passenger trips by public transportation | 0.987 |
| | 22. Annual freight shipment by rail per capita | 0.002 |

**Table A4**
Calculation of composite subdivision indices of the environmental dimension.

d = Environmental, s = Air pollution and greenhouse gases

| Indicator Number | NI Value | Factor Loading$_{kjsd}$ | | | $W_{kjsd}$ (Eq. (2)) | | | $CFI_{jsd}$ (Eq. (3)) | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | j = 1 | j = 2 | j = 3 | j = 1 | j = 2 | j = 3 | j = 1 | j = 2 | j = 3 |
| 1 | 0.920 | 0.858 | 0.333 | 0.229 | 0.246 | 0.046 | 0.042 | 0.904 | 0.692 | 0.839 |
| 2 | 0.946 | −0.769 | 0.473 | 0.377 | 0.198 | 0.094 | 0.113 | | $\alpha_{jsd}$ (Eq. (4)) | |
| 3 | 0.533 | 0.175 | 0.720 | −0.290 | 0.010 | 0.217 | 0.067 | 0.45 | 0.36 | 0.19 |
| 4 | 1.000 | 0.607 | 0.435 | −0.406 | 0.123 | 0.079 | 0.131 | | Eigenvalue$_{jsd}$ | |
| 5 | 0.962 | −0.745 | 0.504 | 0.381 | 0.186 | 0.106 | 0.115 | 2.987 | 2.388 | 1.261 |
| 6 | 0.497 | −0.405 | 0.778 | −0.439 | 0.055 | 0.253 | 0.153 | | $CSI_{sd}$ (Eq. (5)) | |
| 7 | 0.920 | 0.643 | 0.226 | 0.664 | 0.138 | 0.021 | 0.350 | | **0.815** | |
| 8 | 0.647 | 0.356 | 0.658 | 0.196 | 0.042 | 0.181 | 0.030 | | | |

d = Environmental, s = Energy

| Indicator Number | NI Value | Factor Loading$_{kjsd}$ | | | $W_{kjsd}$ (Eq. (2)) | | | $CFI_{jsd}$ (Eq. (3)) | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | j = 1 | j = 2 | j = 3 | j = 1 | j = 2 | j = 3 | j = 1 | j = 2 | j = 3 |
| 9 | 0.915 | 0.903 | −0.102 | 0.319 | 0.134 | 0.003 | 0.051 | 0.745 | 0.344 | 0.793 |
| 10 | 0.752 | 0.788 | 0.059 | 0.498 | 0.102 | 0.001 | 0.123 | | $\alpha_{jsd}$ (Eq. (4)) | |
| 11 | 0.933 | 0.596 | −0.102 | 0.730 | 0.058 | 0.003 | 0.265 | 0.522 | 0.306 | 0.173 |
| 12 | 0.819 | 0.879 | 0.063 | −0.089 | 0.127 | 0.001 | 0.004 | | Eigenvalue$_{jsd}$ | |
| 13 | 0.845 | 0.879 | 0.035 | −0.314 | 0.127 | 0.000 | 0.049 | 6.082 | 3.568 | 2.012 |
| 14 | 0.781 | 0.550 | 0.088 | −0.511 | 0.050 | 0.002 | 0.130 | | $CSI_{sd}$ (Eq. (5)) | |
| 15 | 0.401 | −0.146 | −0.716 | −0.024 | 0.004 | 0.144 | 0.000 | | **0.630** | |
| 16 | 0.582 | 0.615 | −0.546 | 0.029 | 0.062 | 0.084 | 0.000 | | | |
| 17 | 0.111 | −0.519 | 0.470 | 0.474 | 0.044 | 0.062 | 0.112 | | | |
| 18 | 0.174 | 0.485 | 0.766 | −0.044 | 0.039 | 0.164 | 0.001 | | | |
| 19 | 0.953 | 0.594 | −0.585 | −0.160 | 0.058 | 0.096 | 0.013 | | | |
| 20 | 0.999 | 0.618 | −0.253 | −0.544 | 0.063 | 0.018 | 0.147 | | | |
| 21 | 0.169 | 0.438 | 0.849 | −0.101 | 0.032 | 0.202 | 0.005 | | | |
| 22 | 0.163 | 0.439 | 0.849 | −0.099 | 0.032 | 0.202 | 0.005 | | | |
| 23 | 0.910 | 0.648 | −0.255 | 0.439 | 0.069 | 0.018 | 0.096 | | | |

d = Environmental, s = Land used

| Indicator Number | NI Value | Factor Loadingk$_{jsd}$ | | | | $W_{kjsd}$ (Eq. (2)) | | | | $CFI_{jsd}$ (Eq. (3)) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | j = 1 | j = 2 | j = 3 | j = 4 | j = 1 | j = 2 | j = 3 | j = 4 | j = 1 | j = 2 | j = 3 | j = 4 |
| 24 | 0.972 | 0.883 | −0.295 | 0.211 | −0.260 | 0.215 | 0.030 | 0.024 | 0.059 | 0.931 | 0.816 | 0.765 | 0.789 |
| 25 | 0.906 | −0.326 | 0.546 | 0.706 | −0.280 | 0.029 | 0.104 | 0.270 | 0.068 | | $\alpha_{jsd}$ (Eq. (4)) | | |
| 26 | 0.948 | 0.879 | −0.290 | 0.185 | −0.258 | 0.213 | 0.029 | 0.019 | 0.058 | 0.382 | 0.303 | 0.194 | 0.121 |
| 27 | 0.916 | 0.109 | 0.855 | 0.180 | 0.388 | 0.003 | 0.254 | 0.018 | 0.131 | | Eigenvalue$_{jsd}$ | | |
| 28 | 0.972 | 0.837 | 0.360 | 0.004 | 0.370 | 0.193 | 0.045 | 0.000 | 0.119 | 3.626 | 2.875 | 1.846 | 1.147 |
| 29 | 0.987 | −0.180 | 0.706 | 0.599 | −0.319 | 0.009 | 0.173 | 0.194 | 0.089 | | $CSI_{sd}$ (Eq. (5)) | | |
| 30 | 0.952 | 0.769 | 0.453 | 0.014 | 0.410 | 0.163 | 0.071 | 0.000 | 0.147 | | **0.846** | | |
| 31 | 0.248 | −0.234 | −0.641 | 0.570 | 0.399 | 0.015 | 0.143 | 0.176 | 0.139 | | | | |
| 32 | 0.96 | 0.631 | −0.441 | 0.506 | −0.118 | 0.110 | 0.068 | 0.139 | 0.012 | | | | |
| 33 | 0.586 | −0.424 | −0.487 | 0.545 | 0.453 | 0.050 | 0.082 | 0.161 | 0.179 | | | | |

d = Environmental, s = Environmental efficiency of vehicles

| Indicator Number | NI Value | Factor Loadingk$_{jsd}$ j = 1 | $W_{kjsd}$ (Eq. (2)) j = 1 | Eigenvalue$_{jsd}$ j = 1 | $CFI_{jsd}$(Eq. (3)) j = 1 |
|---|---|---|---|---|---|
| 34 | 0.032 | 0.988 | 0.479 | 0.025 | 2.040 |
| 35 | 0.014 | 0.987 | 0.478 | $\alpha_{jsd}$ (Eq. (4)) | $CSI_{sd}$(Eq. (5)) |
| 36 | 0.073 | 0.298 | 0.044 | 1.000 | **0.025** |

**Table A5**
Calculation of composite subdivision indices of the social dimension.

Step 2

d = Social, s = Safety

| Indicator Number | NI Value | Factor Loading$k_{jsd}$ | | | | | $W_{kjsd}$(Eq. (2)) | | | | | $CFI_{jsd}$ (Eq. (3)) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | j = 1 | j = 2 | j = 3 | j = 4 | j = 5 | j = 1 | j = 2 | j = 3 | j = 4 | j = 5 | j = 1 | j = 2 | j = 3 | j = 4 | j = 5 |
| 1 | 0.916 | 0.955 | 0.043 | −0.028 | 0.132 | −0.097 | 0.155 | 0.001 | 0.000 | 0.016 | 0.009 | 0.775 | 0.710 | 0.501 | 0.917 | 0.899 |
| 2 | 0.745 | 0.883 | 0.058 | 0.166 | 0.258 | −0.093 | 0.133 | 0.001 | 0.017 | 0.059 | 0.008 | | | $\alpha_{jsd}$ (Eq. (4)) | | |
| 3 | 0.585 | −0.283 | 0.262 | 0.850 | −0.046 | 0.028 | 0.014 | 0.021 | 0.438 | 0.002 | 0.001 | 0.453 | 0.254 | 0.127 | 0.086 | 0.079 |
| 4 | 0.802 | 0.914 | 0.230 | 0.223 | 0.064 | −0.012 | 0.142 | 0.016 | 0.030 | 0.004 | 0.000 | | | $Eigenvalue_{jsd}$ | | |
| 5 | 0.870 | 0.960 | 0.096 | 0.002 | 0.142 | −0.086 | 0.157 | 0.003 | 0.000 | 0.018 | 0.007 | 5.866 | 3.292 | 1.650 | 1.120 | 1.030 |
| 6 | 0.916 | −0.105 | 0.073 | −0.100 | 0.268 | 0.928 | 0.002 | 0.002 | 0.006 | 0.064 | 0.836 | | | $CSI_{sd}$ (Eq. (5)) | | |
| 7 | 0.997 | 0.629 | 0.305 | −0.017 | −0.611 | 0.223 | 0.067 | 0.028 | 0.000 | 0.333 | 0.048 | | | **0.746** | | |
| 8 | 0.812 | −0.077 | −0.243 | 0.480 | 0.112 | 0.144 | 0.001 | 0.018 | 0.140 | 0.011 | 0.020 | | | | | |
| 9 | 0.358 | −0.556 | 0.719 | −0.121 | 0.013 | −0.149 | 0.053 | 0.157 | 0.009 | 0.000 | 0.022 | | | | | |
| 10 | 0.995 | 0.450 | 0.539 | −0.074 | −0.617 | 0.149 | 0.035 | 0.088 | 0.003 | 0.340 | 0.022 | | | | | |
| 11 | 0.709 | −0.106 | 0.896 | −0.021 | 0.249 | 0.035 | 0.002 | 0.244 | 0.000 | 0.055 | 0.001 | | | | | |
| 12 | 0.803 | 0.895 | 0.257 | 0.247 | 0.119 | 0.005 | 0.137 | 0.020 | 0.037 | 0.013 | 0.000 | | | | | |
| 13 | 0.812 | −0.105 | 0.915 | −0.007 | 0.257 | 0.019 | 0.002 | 0.254 | 0.000 | 0.059 | 0.000 | | | | | |
| 14 | 0.673 | −0.530 | 0.691 | −0.166 | 0.004 | −0.159 | 0.048 | 0.145 | 0.017 | 0.000 | 0.025 | | | | | |
| 15 | 0.134 | −0.556 | 0.070 | 0.707 | −0.166 | −0.020 | 0.053 | 0.001 | 0.303 | 0.025 | 0.000 | | | | | |

d = Social, s = Accessibility

| Indicator Number | NI Value | Factor Loading$k_{jsd}$ | | | $W_{kjsd}$ (Eq. (2)) | | | $CFI_{jsd}$ (Eq. (3)) | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | j = 1 | j = 2 | j = 3 | j = 1 | j = 2 | j = 3 | j = 1 | j = 2 | j = 3 |
| 16 | 0.258 | 0.982 | 0.105 | −0.049 | 0.123 | 0.006 | 0.002 | 0.329 | 0.196 | 0.371 |
| 17 | 0.078 | 0.955 | 0.113 | −0.078 | 0.117 | 0.007 | 0.006 | | $\alpha_{jsd}$ (Eq. (4)) | |
| 18 | 0.286 | 0.981 | 0.086 | 0.036 | 0.123 | 0.004 | 0.001 | 0.730 | 0.170 | 0.100 |
| 19 | 0.338 | 0.516 | 0.009 | −0.481 | 0.034 | 0.000 | 0.216 | | $Eigenvalue_{jsd}$ | |
| 20 | 1.000 | 0.599 | −0.133 | 0.216 | 0.046 | 0.010 | 0.044 | 7.826 | 1.821 | 1.071 |
| 21 | 0.680 | 0.928 | 0.019 | 0.105 | 0.110 | 0.000 | 0.010 | | $CSI_{sd}$ (Eq. (5)) | |
| 22 | 0.524 | 0.634 | 0.037 | 0.511 | 0.051 | 0.001 | 0.244 | | **0.311** | |
| 23 | 0.381 | −0.261 | 0.897 | −0.104 | 0.009 | 0.442 | 0.010 | | | |
| 24 | 0.015 | −0.248 | 0.927 | 0.035 | 0.008 | 0.472 | 0.001 | | | |
| 25 | 0.350 | −0.553 | 0.143 | 0.461 | 0.039 | 0.011 | 0.198 | | | |
| 26 | 0.097 | 0.236 | −0.085 | −0.491 | 0.007 | 0.004 | 0.225 | | | |
| 27 | 0.077 | 0.940 | 0.221 | −0.051 | 0.113 | 0.027 | 0.002 | | | |
| 28 | 0.007 | 0.921 | 0.163 | −0.008 | 0.108 | 0.015 | 0.000 | | | |
| 29 | 0.598 | 0.935 | −0.060 | 0.204 | 0.112 | 0.002 | 0.039 | | | |

d = Social, s = Diversity

| Indicator Number | NI Value | Factor Loading$k_{jsd}$ j = 1 | $W_{kjsd}$ (Eq. (2)) j = 1 | $CFI_{jsd}$ (Eq. (3)) j = 1 | $\alpha_{jsd}$ (Eq. (4)) j = 1 | $Eigenvalue_{jsd}$ j = 1 | $CSI_{sd}$ (Eq. (5)) |
|---|---|---|---|---|---|---|---|
| 30 | 0.713 | 0.813 | 0.500 | 0.857 | 1.000 | 1.322 | **0.857** |
| 31 | 1.000 | 0.813 | 0.500 | | | | |

**Table A6**
Calculation of composite subdivision indices of the economical dimension.

Step 2

d = Economical, s = Expenditure and benefit of transportation systems users

| Indicator Number | NI Value | Factor Loading$k_{jsd}$ j = 1 | $W_{kjsd}$ (Eq. (2)) j = 1 | $CFI_{jsd}$ (Eq. (3)) j = 1 | $\alpha_{jsd}$ (Eq. (4)) j = 1 | Eigenvalue$_{jsd}$ j = 1 | $CSI_{sd}$(Eq. (5)) |
|---|---|---|---|---|---|---|---|
| 1 | 0.708 | 0.372 | 0.085 | 0.510 | 1.000 | 1.626 | **0.510** |
| 2 | 0.742 | 0.893 | 0.490 | | | | |
| 3 | 0.036 | −0.830 | 0.424 | | | | |

d = Economical, s = Expenditure and revenue of transportation systems operators

| Indicator Number | NI Value | Factor Loading$k_{jsd}$ | | | | | | | $W_{kjsd}$ (Eq. (2)) | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | j = 1 | j = 2 | j = 3 | j = 4 | j = 5 | j = 6 | j = 7 | j = 1 | j = 2 | j = 3 | j = 4 | j = 5 | j = 6 | j = 7 |
| 4 | 0.681 | −0.609 | 0.733 | 0.017 | 0.112 | 0.097 | 0.115 | 0.048 | 0.071 | 0.140 | 0.000 | 0.008 | 0.007 | 0.012 | 0.002 |
| 5 | 0.982 | 0.014 | 0.877 | −0.084 | 0.123 | 0.209 | 0.059 | 0.187 | 0.000 | 0.200 | 0.004 | 0.009 | 0.032 | 0.003 | 0.033 |
| 6 | 0.706 | −0.844 | 0.307 | −0.159 | 0.287 | 0.043 | 0.136 | −0.094 | 0.137 | 0.025 | 0.014 | 0.050 | 0.001 | 0.017 | 0.008 |
| 7 | 0.586 | 0.128 | 0.737 | 0.105 | 0.148 | 0.123 | −0.243 | 0.069 | 0.003 | 0.141 | 0.006 | 0.013 | 0.011 | 0.054 | 0.004 |
| 8 | 0.657 | 0.712 | 0.040 | 0.247 | 0.371 | −0.202 | −0.254 | 0.065 | 0.097 | 0.000 | 0.033 | 0.084 | 0.030 | 0.059 | 0.004 |
| 9 | 0.535 | −0.433 | −0.461 | 0.397 | 0.372 | 0.269 | −0.211 | 0.382 | 0.036 | 0.055 | 0.086 | 0.085 | 0.053 | 0.040 | 0.138 |
| 10 | 0.532 | 0.771 | 0.299 | −0.147 | −0.123 | −0.344 | 0.008 | −0.290 | 0.114 | 0.023 | 0.012 | 0.009 | 0.087 | 0.000 | 0.079 |
| 11 | 0.974 | 0.382 | 0.825 | 0.143 | −0.115 | −0.127 | 0.026 | 0.024 | 0.028 | 0.177 | 0.011 | 0.008 | 0.012 | 0.001 | 0.001 |
| 12 | 0.877 | 0.337 | 0.270 | 0.072 | 0.619 | −0.349 | −0.366 | 0.170 | 0.022 | 0.019 | 0.003 | 0.235 | 0.090 | 0.122 | 0.027 |
| 13 | 0.312 | 0.832 | −0.436 | 0.142 | −0.130 | 0.124 | −0.129 | 0.080 | 0.133 | 0.049 | 0.011 | 0.010 | 0.011 | 0.015 | 0.006 |
| 14 | 0.918 | 0.766 | −0.348 | 0.054 | 0.155 | 0.451 | 0.123 | 0.050 | 0.113 | 0.032 | 0.002 | 0.015 | 0.150 | 0.014 | 0.002 |
| 15 | 1.000 | 0.526 | 0.094 | −0.022 | 0.342 | 0.406 | 0.445 | 0.204 | 0.053 | 0.002 | 0.000 | 0.072 | 0.122 | 0.180 | 0.039 |
| 16 | 0.974 | 0.185 | 0.060 | 0.352 | 0.097 | −0.418 | 0.636 | 0.225 | 0.007 | 0.001 | 0.068 | 0.006 | 0.129 | 0.367 | 0.048 |
| 17 | 0.746 | 0.142 | 0.205 | 0.430 | −0.636 | 0.224 | −0.029 | 0.270 | 0.004 | 0.011 | 0.101 | 0.248 | 0.037 | 0.001 | 0.069 |
| 18 | 0.373 | −0.710 | −0.090 | 0.273 | 0.185 | 0.125 | 0.023 | −0.188 | 0.097 | 0.002 | 0.041 | 0.021 | 0.012 | 0.000 | 0.033 |
| 19 | 0.288 | −0.377 | 0.109 | −0.326 | −0.394 | −0.129 | −0.257 | 0.586 | 0.027 | 0.003 | 0.058 | 0.095 | 0.012 | 0.060 | 0.324 |
| 20 | 0.686 | −0.081 | 0.324 | 0.838 | −0.215 | −0.110 | 0.026 | −0.054 | 0.001 | 0.027 | 0.383 | 0.028 | 0.009 | 0.001 | 0.003 |
| 21 | 0.987 | 0.502 | 0.360 | −0.535 | −0.040 | 0.167 | 0.092 | 0.174 | 0.048 | 0.034 | 0.156 | 0.001 | 0.021 | 0.008 | 0.029 |
| 22 | 0.002 | −0.204 | −0.472 | −0.143 | 0.071 | −0.483 | 0.231 | 0.399 | 0.008 | 0.058 | 0.011 | 0.003 | 0.172 | 0.048 | 0.150 |

| $CFI_{jsd}$ (Eq. (3)) | | | | | | | Eigenvalue$_{jsd}$ | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| j = 1 | j = 2 | j = 3 | j = 4 | j = 5 | j = 6 | j = 7 | j = 1 | j = 2 | j = 3 | j = 4 | j = 5 | j = 6 | j = 7 |
| 0.638 | 0.733 | 0.700 | 0.712 | 0.680 | 0.803 | 0.463 | 5.203 | 3.843 | 1.833 | 1.633 | 1.355 | 1.102 | 1.060 |
| | | | $\alpha_{jsd}$ (Eq. (4)) | | | | | | | $CSI_{sd}$ (Eq. (5)) | | | |
| 0.325 | 0.240 | 0.114 | 0.102 | 0.085 | 0.069 | 0.066 | | | | **0.679** | | | |

**Table A7**
Calculation of composite dimension indices.

Step 3

d = Environmental

| s | $CSI_{sd}$ | Factor $Loading_{sj'd}$ | | $W_{Sj'd}$ (Eq. (6)) | | Eigenvalue | | $CFI_{j'd}$ (Eq. (7)) | |
|---|---|---|---|---|---|---|---|---|---|
| | | j' = 1 | j' = 2 | j' = 1 | j' = 2 | j' = 1 | j' = 2 | j' = 1 | j' = 2 |
| Air pollution and greenhouse gases | 0.815 | 0.767 | 0.407 | 0.338 | 0.131 | 1.738 | 1.262 | 0.48 | 0.619 |
| Energy | 0.63 | −0.252 | 0.917 | 0.037 | 0.666 | $\alpha_{j'd}$ (Eq. (8)) | | $CDI_d$ (Eq. (9)) | |
| Land used | 0.846 | 0.591 | 0.366 | 0.201 | 0.106 | 0.579 | 0.421 | **0.538** | |
| Environmental efficiency of vehicles | 0.025 | −0.858 | 0.347 | 0.424 | 0.095 | | | | |

d = Social

| s | $CSI_{sd}$ | Factor $Loading_{sj'd}$ j' = 1 | $W_{Sj'd}$(Eq. (6)) j' = 1 | $\alpha_{j'd}$ (Eq. (8)) j' = 1 | $CFI^{j'd}$(Eq. (7)) j' = 1 | Eigenvalue j' = 1 |
|---|---|---|---|---|---|---|
| Safety | 0.746 | 0.656 | 0.143 | 1.000 | 0.611 | 1.685 |
| Accessibility | 0.311 | 0.818 | 0.223 | | $CDI_d$ (Eq. (9)) | |
| Diversity | 0.857 | 0.765 | 0.195 | | **0.611** | |

d = Economical

| s | $CSI_{sd}$ | Factor $Loading_{sj'd}$ j' = 1 | $W_{Sj'd}$(Eq. (6)) j' = 1 | $\alpha_{j'd}$ (Eq. (8)) j' = 1 | $CFI^{j'd}$(Eq. (7)) j' = 1 | Eigenvalue j' = 1 |
|---|---|---|---|---|---|---|
| Expenditure and revenue of transportation systems operators | 0.679 | −0.794 | 0.500 | 1.000 | 0.559 | 1.26 |
| Expenditure and benefit of transportation systems users | 0.51 | 0.794 | 0.500 | | $CDI_d$ (Eq. (9)) | |
| | | | | | **0.559** | |

**Table A8**
Calculation of composite transportation sustainability index, $I_{TS}$.

Step 4

| d | $CDI_d$ | $I_{TS}$(Eq. (10)) |
|---|---|---|
| Environmental | 0.538 | **0.570** |
| Social | 0.611 | |
| Economical | 0.559 | |

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