Proceedings of the World Congress on Engineering 2016 Vol I
WCE 2016, June 29 - July 1, 2016, London, U.K.

Sustainability Performance Evaluation of Transportation Networks Using MCDM Analysis

Orhan İlker Kolak and Orhan Feyzioğlu

Abstract—**Transportation is an important part of modern society and like other economic activities, it has many adverse effects on the environment and the society. One of the top priorities of the nations is the concept of sustainability, thus the evaluation of transportation systems with respect to sustainability performance has received a growing interest in recent years. In this study, we propose an approach to both determine appropriate sustainability indicators and to evaluate the performances of transportation networks with respect to the sustainability criteria. We provide a case study with the proposed methods applied to a set of selected European countries.**

Index Terms—**sustainable transportation, multicriteria decision making, TOPSIS, Choquet integral, MACBETH.**

I. Introduction

SUSTAINABLE development presents a huge challenge for sectors of society, and the need for new analytical tools to deal with this challenge is tremendous [1]. Having immense economic, social and environmental effects, the management of transportation systems plays a significant role in supporting the sustainable development. Even though, the amount of studies that deal with sustainable development in general is abundant, the applications in the transport sector are rather limited. This paper aims to contribute to the relatively scarce literature, particularly related to sustainable transport, by introducing two alternative methods for evaluating the sustainability of the country-wide transport systems.

Various definitions are proposed for sustainable transportation. The most cited and globally recognized definition is given in the Brundtland Commission's Report [2]: satisfying current transport and mobility needs without compromising the ability of future generations to meet these needs. In 2001, the Council of the European Union proposed a more comprehensive definition: "a sustainable transport system allows the basic access and development needs of individuals, companies and societies to be met safely and in a manner consistent with human and ecosystem health, and promises equity within and between successive generations; is affordable, operates fairly and efficiently, offers choice of transport mode, and supports a competitive economy as well as balanced regional development; limits emissions and waste within the planet's ability to absorb them, uses renewable resources at or below their rates of generation, and uses nonrenewable resources at or below the rates of development of renewable substitutes while minimizing the impact on land and the generation of noise". Along these lines, we can state that the central idea is to build a transportation system, that supports a balanced development by integrating the economic, social and environmental objectives while considering the needs of different interest groups.

In order to quantify the progress towards the objectives of sustainable transportation, it is crucial to define the proper indicators. These indicators can be defined as selected, targeted, and compressed variables that reflect public concerns and are of use to the decision makers [3]. It is then possible to construct a composite index by aggregating a selected set of indicators. Such indices to evaluate sustainable development are abundant in the literature [4]–[8]. While there are no well-defined selection rules to identify the appropriate indicator sets associated with the specified sustainability objectives, there are several lists of indicators proposed in the literature [5], [9]–[11]. Several review articles classify and present commonly the used sustainability indicators [12]–[14]. It can be argued that the sets that are constructed according to the available data and have smaller sizes are more convenient to use but may fail to include the important impacts. In contrast, larger sets can be more comprehensive but the costs associated with the data-collection process can be prohibitive [15].

The contributions of this study are (i) developing a framework to assess the sustainability of the transport networks in a multidimensional setting, (ii) specifying a set of sustainability indicators for transport systems, (iii) proposing two methods to aggregate the sustainable transportation indicators, (iv) constructing a detailed case study. The rest of the paper is organized as follows: Section II presents the proposed evaluation framework. Section III contains the details of the proposed assessment methodology and discusses how the aggregate results can be systematically interpreted. The method is then applied to evaluate the transport networks of selected European countries, and the outcomes are briefly discussed in Section IV. Finally, Section V presents concluding remarks and perspectives.

II. Evaluation Framework

It is crucial to select appropriate indicators in order to measure the sustainability of a transportation system accurately. The set of indicators selected in this study captures the economic, social and environmental objectives, it relies mostly on the existing data from the European statistical databases, and is easy to understand by potential users. The selected indicators are related to most transportation sectors, but they concentrate mainly on the road transport, most responsible for unsustainable trends. We have expressed indicators in units that would allow comparing countries objectively; for example, some indicators are expressed relative to the Gross Domestic Product (GDP) or the population size. The GDP

Manuscript received March 03, 2016. This work was supported by the Galatasaray University Research Fund under Grant 15.402.008.

O.I. Kolak and O. Feyzioğlu are with the Department of Industrial Engineering, Galatasaray University, Istanbul, Turkey e-mail: oikolak@gsu.edu.tr

TABLE I
INDICATORS SELECTED TO EVALUATE THE TRANSPORTATION NETWORK SUSTAINABILITY

EC Economic Dimension	
EC1 Use of alternative modes of transport	
EC11	Road share of inland freight transport
EC12	Car share of inland passenger transport
EC13	Share of non-motorized individual transport
EC2 Economic support of transport to the economy	
EC21	Volume of freight transport relative to GDP
EC22	Volume of passenger transport relative to GDP
EC23	Contribution of transport sector to GDP
EC24	Contribution of transport sector to employment
EC3 Efficiency of operations	
EC31	Share of non-road transport infrastructure investments
EC32	Logistics performance index
SC Social dimension	
SC1 Safety	
SC11	People killed in road accidents
SC12	Number of deaths per million inhabitants
SC2 Affordability	
SC21	Price indices for transport (All Items)
SC22	Price indices for transport - Railways
SC23	Price indices for transport Sea and inland waterways
SC24	Total household consumption for transport
SC3 Ease of use	
SC31	% of people taking $\leq$ 20 min to get to work/training place
SC32	Rural Access Index
SC4 Quality of use	
SC41	Satisfaction with public transport
SC42	Quality of roads
SC43	Quality of rail infrastructure
SC44	Quality of port infrastructure
SC45	Quality of air transport infrastructure
EN Environment dimension	
EN 1Use of energy	
EN11	Energy consumption of transport relative to GDP
EN12	Energy consumption of transport per capita
EN13	Energy consumption of road transport
EN14	Share of renewable energy in fuel consumption of transport
EN2 Reuse and Recycling	
EN21	End of life vehicles : Total waste per capita
EN22	End of life vehicles : Reuse and recovery rate
EN23	End of life vehicles : Reuse and recycle rate
EN3 Impacts on ecosystem	
EN31	GHG emission from all transport modes
EN32	GHG emission from all transport modes per capita
EN33	GHG emission from road transport
EN34	Average CO2 emissions per km from new passenger cars
EN4 Impacts on human health	
EN41	Emissions of carbon monoxide (CO)
EN42	Emissions of nitrogen oxides (NOx)
EN43	Emissions of particulate matter from transport

is the best known measure of macro-economic activity and a standard benchmark used by policy makers. For some indicators, we have taken into account their change towards sustainability over a certain time period. Some indicators are based on the statistical data and some are based on the survey results and the perception of network users. In summary, we have identified eight economic, thirteen social and fourteen environmental indicators as given in Table I. The environmental indicators are related to energy usage and emission data, the economic indicators are more related to transportation habits and consumption, and social indicators reflect accidents (with injuries or fatalities), quality of transport or time spend for transportation.

In Table II, important details about each indicator are provided. The first column refers to the code of the indicators. The second column indicates the year(s) when the data are acquired. The third column shows the corresponding units. The forth column indicates the improving directions, i.e. if higher values are prefereble an upward arrow otherwise a downward arrow is used. The last column shows the source of the acquired data. All data are provided by trustworthy international organizations.

III. METHODOLOGY

Let us consider a finite set of alternatives $\mathcal{A} = \{a_1, \ldots, a_m\}$ and a finite set of criteria $\mathcal{N} = \{c_1, \ldots, c_n\}$ for

TABLE II
DETAILS ABOUT THE INDICATORS

Indicator	Year(s)	Unit	Imp. Dir.	Source
EC11	2000-2010	av. % change	⇓	Eurostat
EC12	2000-2010	av. % change	⇓	Eurostat
EC13	2009	av. %	⇑	Eurobarometer
EC21	2000-2010	av. % change	⇓	Eurostat
EC22	2000-2010	av. % change	⇓	Eurostat
EC23	2000-2010	av. %	⇑	Eurostat, WIOD*
EC24	2008-2011	av. %	⇑	Eurostat
EC31	2000-2009	av. %	⇑	OECD
EC32	2007, 2010	av. %	⇑	World Bank
SC11	2000-2009	av. % change	⇓	Eurostat
SC12	2000-2008	average	⇓	Eurostat
SC21	2000-2011	av. % change	⇓	Eurostat
SC22	2000-2011	av. % change	⇓	Eurostat
SC23	2000-2011	av. % change	⇓	Eurostat
SC24	2000-2010	av. %	⇓	Eurostat
SC31	2009	av. %	⇑	Eurobarometer
SC32	1999-2003	%	⇑	World Bank
SC41	2009	av. %	⇑	Eurobarometer
SC42	2009-2010	%	⇑	WEF
SC43	2009-2010	%	⇑	WEF
SC44	2009-2010	%	⇑	WEF
SC45	2009-2010	%	⇑	WEF
EN11	2000-2010	av. % change	⇓	Eurostat
EN12	2000-2010	av. % change	⇓	Eurostat
EN13	2000-2010	av. % change	⇓	Eurostat
EN14	2006-2010	av. %	⇑	Eurostat
EN21	2009	kg	⇓	Eurostat
EN22	2006-2009	av. %	⇑	Eurostat
EN23	2006-2009	av. %	⇑	Eurostat
EN31	2000-2010	av. % change	⇓	Eurostat
EN32	2000-2010	kg (average)	⇓	Eurostat
EN33	2000-2010	av. % change	⇓	Eurostat
EN34	2000-2009	av. % change	⇓	Eurostat
EN41	2000-2010	av. % change	⇓	EEA
EN42	2000-2010	av. % change	⇓	EEA
EN43	2000-2010	av. % change	⇓	EEA

a multicriteria decision problem. In our setup, an alternative represents the transport system of a country, and a criterion corresponds to a sustainability indicator. Each alternative $a_j \in \mathcal{A}$ is associated with a profile $\mathbf{x}^j = \left(x_1^j, \ldots, x_n^j\right) \in [0,1]^n$, where x_i^j denotes the partial score of a_j associated with the criterion c_i. Defining the scores on the interval $[0,1]$ does not detract from the generality of our analysis; it is only required to define all the partial scores on the same interval scale; i.e., using same linear transformation [16].

An aggregate score associated with each profile can be computed by using an aggregation operator which takes into account the importance weights of criteria. The alternatives can then be ranked and the best alternative is selected according to the aggregate scores. If the criteria are independent, then the most often used aggregation operators are the weighted arithmetic mean [17]. The aggregate score associated with the profile $\mathbf{x}^j$ is then given by $C_{\mathbf{w}}(\mathbf{x}^j) = \sum_{i=1}^n w_i x_i^j$, where $w_i \geq 0$ is the weight of the criterion c_i , $i = 1, \ldots, n$, and $\sum_{i=1}^n w_i = 1$. However, the assumption of criteria independence is rarely justified. To model the interaction between multiple criteria, weight vector $\mathbf{w}$ is substituted with a monotonic set function μ on $\mathcal{N}$. This approach allows us to model not only the importance of each criterion but also the importance of coalitions of criteria [16]–[18]. Such a monotonic set function μ is called the Choquet capacity [19] or a fuzzy measure [20]. A suitable aggregation operator that generalizes the weighted arithmetic mean, when the interactions between the criteria exist, is the discrete Choquet integral with respect to the fuzzy measure μ [17], [21]. Indeed, the aggregation operations based on the family of fuzzy integrals include many operators such as weighted mean, min, max, median, or ordered weighted average. These operations express a variety of decision maker behaviors (severity, compromise, tolerance) and various ef-

ISBN: 978-988-19253-0-5
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

fects of interaction between criteria [18]. In section III-B, we briefly present the definition of the Choquet integral and its principal properties as a multicriteria aggregation operator.

A. TOPSIS

The Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS) method is presented in [22]. The basic principle is that the chosen alternative should have the shortest distance from the ideal solution and the farthest distance from the negative-ideal solution. The TOPSIS procedure consists of the following steps:

1) Assuming that x_i^j values are normalized, the weighted normalized value v_i^j is calculated as

$$v_i^j = w_i x_i^j \quad i = 1, \ldots, n, \ j = 1, \ldots, m. \tag{1}$$

2) Let us denote the set of benefit type of criteria and the set of cost type of criteria by $\mathcal{N}'$ and $\mathcal{N}''$, respectively. Basically, $\mathcal{N}'$ and $\mathcal{N}''$ form a partition of the set of criteria $\mathcal{N}$, i.e., $\mathcal{N}' \cup \mathcal{N}'' = \mathcal{N}$ and $\mathcal{N}' \cap \mathcal{N}'' = \emptyset$. Without loss of generality, we assume that the first $|\mathcal{N}'|$ indicators are of benefit type, where $|\mathcal{N}'|$ denotes the cardinality of $\mathcal{N}'$. Then the ideal and negative-ideal solutions are defined as

$$\begin{aligned} \mathbf{v}^+ = & \ (v_1^+, \ldots, v_n^+) \\ = & \ \big(\max_j v_1^j, \max_j v_2^j, \ldots, \max_j v_{|\mathcal{N}'|}^j, \\ & \min_j v_{|\mathcal{N}'|+1}^j, \ldots, \min_j v_n^j \big) \end{aligned} \tag{2}$$

and

$$\begin{aligned} \mathbf{v}^- = & \ \{v_1^-, \ldots, v_n^-\} \\ = & \ \big(\min_j v_1^j, \min_j v_2^j, \ldots, \min_j v_{|\mathcal{N}'|}^j, \\ & \max_j v_{|\mathcal{N}'|+1}^j, \ldots, \max_j v_n^j \big). \end{aligned} \tag{3}$$

3) The distances of each alternative to the ideal and the negative-ideal solutions are calculated using the Euclidean norm

$$d_+^j = \sqrt{\textstyle\sum_{i=1}^n (v_i^j - v_i^+)^2}, \quad j = 1, \ldots, m \tag{4}$$

and

$$d_-^j = \sqrt{\textstyle\sum_{i=1}^n (v_i^j - v_i^-)^2}, \quad j = 1, \ldots, m. \tag{5}$$

4) The relative closeness of each alternative to the negative-ideal solution is given by

$$C^j = d_-^j / (d_+^j + d_-^j), \quad j = 1, \ldots, m. \tag{6}$$

The best alternative is considered to be the one with the highest C^j value.

B. 2-Additive Choquet Integral

In real-life applications, it is really hard to estimate higher than order two interactions between the multiple sustainability indicators. Therefore, we focus only on the pairwise interactions and use a special case of the Choquet integral, which is known as the 2-additive Choquet integral [18] and expressed in the following interpretable form:

$$\begin{aligned} C_\mu^j &= \sum_{i=1}^n \Big(w_i - \frac{1}{2} \sum_{k \neq i} |u_{ik}| \Big) x_i^j \\ &+ \sum_{u_{ik}>0} u_{ik} \min\{x_i^j, x_k^j\} + \sum_{u_{ik}<0} |u_{ik}| \max\{x_i^j, x_k^j\}. \end{aligned} \tag{7}$$

Here, u_{ik} represents the interaction between the criteria c_i and c_k that takes values in the interval $[-1, 1]$. The u_{ik} parameters satisfy the condition that $w_i - (1/2) \sum_{k \neq i} |u_{ik}| \geq 0$ for all $i = 1, \ldots, n$. This condition ensures that the overall importance of interactions associated with a specific criterion is always smaller than the weight of that criterion. The interpretations of the interaction terms can be summarized as follows:

- u_{ik} takes a positive value for a pair of criteria (c_i, c_k), if the alternative with better scores for both criteria is preferable by the decision maker. To reflect the importance of having better scores on both criteria, the overall performance is calculated based on the worse score and the level of importance is quantified by specifying the value of u_{ik}.
- u_{ik} takes a negative value, if the decision maker is satisfied with the alternative, which has a reasonably good score in at least one of the criteria c_i and c_k. When u_{ik} takes a larger negative value, the effect of the lower score gets less significant.
- the value of zero implies that there is no interaction between the two criteria considered, and it leads to the classical weighted sum based on the w_i parameters.

The normalized scores x_i^j and the coefficients of importance w_i and u_{ik} are specified using a special evaluation method named as MACBETH which is described in section III-C.

C. The MACBETH Procedure

The Measuring Attractiveness by a Categorical Based Evaluation TecHnique (MACBETH), is a Multi-Attribute Utility Theory (MAUT) method, which is based on the comparisons between different situations (which identify the context) made by the decision-makers. MACBETH describes these situations with, on one hand, elementary performance expressions, and on the other hand the aggregated ones. The principle is to translate the qualitative information generally obtained from the experts, into quantitative information [23]. In this study, we use MACBETH to determine the criteria weights and interactions and in order to obtain the normalized performance values of alternatives with respect to attributes.

1) Elementary Performance Expression Step: The first decision is the preference determination between available options. Once the preference determination is made, the preference strengths are determined by the experts. Let a_j and a_l denote alternative (or situation) j and alternative l respectively. Let x_i^j and x_i^l be partial scores (or performance values) for criterion i of alternative j and alternative l, respectively. Let h be the preference strength where the strength can take value between 0 and 6 (*null, very weak, weak, moderate, strong, very strong, extreme*). Then, if the experts for criterion i prefers a_j to a_l with strength h then

ISBN: 978-988-19253-0-5
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

$a_j \succ^h a_l \Leftrightarrow x_i^j - x_i^l = h\alpha$ where α is a coefficient necessary to meet the condition $x_i^j, x_i^l \in [0,1]$. If the decision maker is indifferent (*null*) between the situations, then $a_j \approx a_l \Leftrightarrow x_i^j = x_i^l$.

By this procedure, the elementary performance scores are defined along the interval $[0,1]$ in a commensurate way.

As the number of alternatives increases, pairwise comparisons become a cumbersome task. In that case, if the alternatives are evaluated with quantitative values, a simpler method to obtain the elementary performance scores is advised [24]. First, good and neutral values are identified for a given criterion. Then, a few number of intermediate threshold values between the good and the neutral values are selected. All these good, neutral and intermediate values form the dummy alternatives. At the next step, the preference strengths among the dummy alternatives are evaluated using pairwise comparison and their elementary performance scores are obtained by solving the equation system as previously described in this section. Finally, the performance score of each real alternative is determined using linear interpolation in the interval of corresponding dummy alternatives.

2) Extension of MACBETH to the 2-Additive Choquet Integral: A method is proposed to incorporate the MACBETH to the 2-Additive Choquet Integral procedure. Let x_{Ag}^j denote the aggregate score of alternative j [24]. The 2-additive Choquet Integral formulation given in Eq. (7) can be expressed alternatively as [25]:

$$x_{\text{Ag}}^j = \sum_{i=1}^{n} w_i x_i^j - \frac{1}{2}\sum_{i=1}^{n} u_{ik}|x_i^j - x_k^j| \qquad \forall j. \tag{8}$$

This procedure involves the comparison of extreme cases of possible scores that the alternatives can take ie. the alternative takes a perfect value of 1 on one criterion and 0 on all other criteria. In that case it is possible to determine the weights of criteria with the help of expert opinions. Let $x_{\text{Ag}}^{[i]}$ and $x_{\text{Ag}}^{[k]}$ denote the hypothetical alternatives with the scores of ith and kth criteria equal to 1, respectively and all other criteria scores equal to 0. In that case, if the experts state that criterion i is preferable to criterion k with a strength of h (ie. $x_{\text{Ag}}^{[i]} \succ^h x_{\text{Ag}}^{[k]}$) then we can construct our system of equations as $x_{\text{Ag}}^{[i]} - x_{\text{Ag}}^{[k]} = h\alpha$. We can extend this reasoning to interactions setting the values of interacting criteria to 1 and all others to 0. Also, we should state that the sum of all weights are equal to 1 (ie. $\sum_i w_i = 1$).

IV. Case Study

Country-based data collection on the indicators is a demanding task that requires a considerable amount of resources and the involvement of many local agencies. Moreover, a cross comparison is meaningful only if the definitions of the indicators accepted by countries authorities are consistent. It is possible to extract data regarding the transportation industry within Europe from some public databases such as Eurostat. Unfortunately, not all of the local agencies collect data on all transport indicators. Due to the limited available data, seventeen indicators are considered in this study and the data sources used are mentioned in Table II.

We then construct a case to apply the described methods for the following selected European countries: Austria (AT), Belgium (BE), Bulgaria (BL), Denmark (DK), Estonia (EE), Finland (FI), France (FR), Germany (DE), Ireland (IE), Italy (IT), Latvia (LV), Lithuania (LT), Netherlands (NL), Poland (PL), Portugal (PT), Romania (RO), Slovakia (SK), Slovenia (SI), Spain (ES), Sweden (SE) and United Kingdom (UK). The idea behind selecting this set of countries is to contrast the countries with large and small economic activities, and to assure a geographic dispersion.

To transform the values of the indicators into scores for the mentioned countries, the MACBETH method that is discussed in section III-C is utilized. Determining the weights to quantify the relative importance of the sustainability indicators is an integral part of the analysis. The sustainability dimensions and also the indicators within each dimension are also evaluated in a pairwise fashion using the MACBETH method based on consultations with a group of experts in the field. We believe that the interaction parameters reflect the level of conservativeness of the decision makers' preferences. That is, a pessimistic (conservative) decision maker prefers that the scores of all (or most) of the criteria are satisfactory, while an optimistic one is satisfied when a satisfactory performance is observed for at least one criterion. In fact, when dealing with sustainability evaluation, the conservative approach is more suitable, since attaining reasonable scores in most of the sustainability criteria is preferable. This discussion explains why the specified values of the interaction parameters are in general positive.

The weights and interactions between sustainability dimensions are presented in Table III. The scaled values of the derived statistics are given in Tables IV-VI.

TABLE III
Weights and interactions for the sustainability dimensions

ALL	ECO	SOC	ENV	Weight
ECO	0	0.1154	0.1154	0.2692
SOC	0.1154	0	0.1923	0.3462
ENV	0.1154	0.1923	0	0.3846

We observe in Table VII that the developed Western European countries are ranked better than the Eastern European countries using both methods as expected. The differences of orders determined by the two methods clearly indicate that interactions between sustainability indicators and dimensions play an important role on ranking.

Germany is ranked first with TOPSIS, and third with Choquet integral. On the other hand Belgium is ranked third with Choquet integral but first with TOPSIS. This clearly shows that Germany has very high scores on some indicators but fails on others. Belgium, on the other hand may not have very high scores but has good scores on most indicators. As a result, due to interactions between all good indicators Belgium obtains a higher score. Having high scores on most indicators is preferable to having very high scores on some indicators but poor scores on others. Another good example is Denmark and United Kingdom. Denmark is ranked second with TOPSIS but sixth with Choquet integral while United Kingdom is ranked sixth with TOPSIS but second with Choquet integral. This clearly shows that United Kingdom has above average scores on most indicators. France is near the top of the ranking with TOPSIS (4th) but is in the middle with Choquet integral (8th). Sweden also has a drastic difference between both methods, with TOPSIS

ISBN: 978-988-19253-0-5
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

TABLE IV
ECONOMIC INDICATORS AND ASSOCIATED SCALED SCORES FOR THE SELECTED COUNTRIES

	EC11	EC12	EC13	EC21	EC22	EC23	EC24	EC31	EC32
AT	0.91	0.41	0.51	0.75	0.39	0.33	0.69	0.97	0.86
BE	0.87	0.51	0.41	0.91	0.36	0.48	0.78	0.80	0.87
BL	0.17	0.13	0.40	0.25	0.51	0.61	0.76	0.66	0.36
DK	0.69	0.37	0.88	0.96	0.38	0.59	0.68	0.69	0.84
EE	0.16	0.23	0.03	0.88	0.38	0.71	0.89	0.76	0.48
FI	0.45	0.37	0.65	0.77	0.36	0.43	0.78	0.71	0.84
FR	0.34	0.45	0.34	0.79	0.37	0.29	0.72	0.63	0.82
DE	0.43	0.38	0.45	0.57	0.35	0.21	0.67	0.70	0.94
IE	0.38	0.38	0.38	0.84	0.33	0.12	0.68	0.40	0.86
IT	0.39	0.41	0.31	0.65	0.38	0.36	0.67	0.76	0.74
LV	0.02	0.33	0.33	0.53	0.71	0.84	0.94	0.81	0.53
LT	0.20	0.29	0.23	0.39	0.10	0.81	0.83	0.61	0.42
NL	0.47	0.38	0.78	0.70	0.42	0.33	0.68	0.66	0.95
PL	0.11	0.23	0.20	0.34	0.19	0.37	0.74	0.35	0.59
PT	0.39	0.35	0.58	0.38	0.23	0.24	0.51	0.64	0.64
RO	0.24	0.29	0.41	0.49	0.48	0.64	0.70	0.37	0.38
SK	0.11	0.23	0.32	0.70	0.92	0.56	0.80	0.60	0.50
SI	0.29	0.35	0.52	0.23	0.40	0.39	0.75	0.29	0.45
ES	0.37	0.38	0.49	0.50	0.42	0.26	0.68	0.67	0.73
SE	0.66	0.40	0.55	0.68	0.46	0.50	0.71	0.77	0.93
UK	0.47	0.38	0.35	0.80	0.48	0.29	0.70	0.84	0.89

TABLE V
SOCIAL INDICATORS AND ASSOCIATED SCALED SCORES FOR THE SELECTED COUNTRIES

	SC11	SC12	SC21	SC22	SC23	SC24	SC31	SC32	SC41	SC42	SC43	SC44	SC45
AT	0.83	0.83	0.92	0.94	0.64	0.42	0.57	0.86	0.88	0.3	0.51	0.61	0.36
BE	0.83	0.79	0.90	0.97	0.66	0.48	0.57	1.00	0.68	0.47	0.47	0.26	0.32
BL	0.54	0.76	0.53	0.71	0.67	0.27	0.61	0.95	0.23	1.00	0.86	0.76	0.71
DK	0.80	0.92	0.91	0.93	0.57	0.47	0.68	0.97	0.81	0.32	0.49	0.34	0.26
EE	0.89	0.74	0.67	0.70	0.54	0.47	0.54	0.58	0.70	0.66	0.77	0.45	0.64
FI	0.74	0.92	0.93	0.92	0.62	0.48	0.68	0.44	0.82	0.39	0.41	0.26	0.32
FR	0.90	0.83	0.93	0.94	0.69	0.35	0.58	0.97	0.86	0.17	0.21	0.39	0.30
DE	0.89	0.93	0.94	0.93	0.67	0.36	0.54	0.69	0.82	0.26	0.32	0.26	0.17
IE	0.87	0.86	0.90	0.88	0.64	0.48	0.29	0.81	0.67	0.69	0.80	0.6	0.54
IT	0.86	0.82	0.89	0.88	0.46	0.39	0.72	0.95	0.01	0.70	0.79	0.74	0.69
LV	0.98	0.56	0.56	0.77	0.58	0.55	0.40	0.73	0.56	0.86	0.74	0.63	0.49
LT	0.84	0.58	0.81	0.77	0.58	0.28	0.53	0.92	0.22	0.51	0.69	0.63	0.79
NL	0.87	0.99	0.90	0.91	0.73	0.50	0.38	1.00	0.87	0.49	0.43	0.17	0.30
PL	0.73	0.71	0.84	0.87	0.61	0.70	0.47	0.86	0.70	1.00	0.91	0.83	0.79
PT	0.95	0.76	0.87	0.80	0.57	0.33	0.78	0.65	0.39	0.32	0.66	0.6	0.51
RO	0.11	0.79	0.16	0.24	0.26	0.37	0.53	0.69	0.46	1.00	0.94	0.87	0.74
SK	0.87	0.80	0.70	0.84	0.59	0.80	0.61	0.92	0.37	0.74	0.63	0.73	0.83
SI	0.88	0.75	0.70	0.79	0.54	0.29	0.53	0.86	0.62	0.61	0.84	0.51	0.61
ES	0.95	0.80	0.85	0.89	0.56	0.49	0.60	0.86	0.77	0.43	0.49	0.45	0.41
SE	0.87	0.98	0.93	0.94	0.63	0.39	0.43	0.58	0.90	0.43	0.49	0.32	0.32
UK	0.82	0.98	0.89	0.86	0.58	0.30	0.42	0.89	0.77	0.56	0.63	0.47	0.43

it is in the middle of the ranking (10th) but is ranked near the top with Choquet integral (5th). Poland is in the middle with TOPSIS (14th) but near the bottom with Choquet integral (19th). Some countries are ranked the same with both methods like Italy (7th), Portugal (12th) and Slovenia (18th) or are ranked similarly like Bulgaria, Estonia, Ireland, Latvia, Netherlands, Slovakia, and Spain. On the bottom of both rankings, we observe Romania (21st) and Lithuania (20th). These countries clearly need to improve significantly their networks in order to meet sustainability requirements.

TABLE VII
AGGREGATE SCORES AND RANKINGS

	TOPSIS		Choquet Integral	
	C	Rank	C_μ	Rank
Austria	0.3584	8	0.5619	9
Belgium	0.3144	3	0.6043	1
Bulgaria	0.4890	15	0.4538	16
Denmark	0.3087	2	0.5704	6
Estonia	0.5448	17	0.4665	15
Finland	0.3671	9	0.5553	10
France	0.3284	4	0.5671	8
Germany	0.2932	1	0.5916	3
Ireland	0.3801	11	0.5185	13
Italy	0.3535	7	0.5704	7
Latvia	0.6035	19	0.4380	17
Lithuania	0.6229	20	0.4283	20
Netherlands	0.3295	5	0.5876	4
Poland	0.4862	14	0.4355	19
Portugal	0.3988	12	0.5239	12
Romania	0.7175	21	0.3238	21
Slovakia	0.4950	16	0.4997	14
Slovenia	0.5643	18	0.4362	18
Spain	0.4329	13	0.5305	11
Sweden	0.3778	10	0.5874	5
United Kingdom	0.3385	6	0.5945	2

TABLE VI
ENVIRONMENTAL INDICATORS AND ASSOCIATED SCALED SCORES FOR THE SELECTED COUNTRIES

	EN11	EN12	EN13	EN14	EN21	EN22	EN23	EN31	EN32	EN33	EN34	EN41	EN42	EN43
AT	0.25	0.48	0.44	0.74	0.62	0.87	0.42	0.38	0.35	0.50	0.68	0.78	0.53	0.72
BE	0.64	0.57	0.53	0.28	0.73	0.84	0.73	0.48	0.44	0.64	0.77	0.67	0.65	0.83
BL	0.34	0.31	0.32	0.08	0.61	0.78	0.53	0.30	0.80	0.35	0.31	0.76	0.54	0.71
DK	0.34	0.56	0.53	0.03	0.48	0.41	0.40	0.43	0.45	0.58	0.91	0.74	0.74	0.95
EE	0.46	0.37	0.38	0.03	0.51	0.64	0.64	0.31	0.66	0.39	0.63	0.79	0.29	0.30
FI	0.59	0.52	0.51	0.31	0.69	0.41	0.40	0.43	0.41	0.57	0.73	0.65	0.93	0.69
FR	0.85	0.91	0.60	0.64	0.47	0.41	0.32	0.71	0.51	0.72	0.86	0.85	0.72	0.77
DE	0.91	0.86	0.98	0.80	0.60	0.83	0.67	0.95	0.57	0.93	0.79	0.75	0.75	0.78
IE	0.75	0.58	0.49	0.17	0.84	0.38	0.28	0.42	0.28	0.57	0.67	0.75	0.70	0.79
IT	0.65	0.90	0.70	0.35	0.69	0.43	0.32	0.60	0.53	0.68	0.71	0.82	0.64	0.72
LV	0.16	0.24	0.29	0.20	0.08	0.73	0.66	0.26	0.72	0.29	0.76	0.91	0.01	0.01
LT	0.63	0.30	0.33	0.47	0.39	0.70	0.65	0.31	0.73	0.35	0.85	0.49	0.65	0.13
NL	0.75	0.58	0.53	0.36	0.84	0.60	0.51	0.43	0.53	0.59	0.79	0.56	0.64	0.79
PL	0.07	0.22	0.20	0.43	0.66	0.47	0.39	0.20	0.80	0.22	0.45	0.40	0.34	0.70
PT	0.28	0.54	0.53	0.43	0.45	0.66	0.45	0.58	0.60	0.69	0.81	0.81	0.53	0.75
RO	0.32	0.31	0.26	0.25	0.86	0.55	0.39	0.30	0.89	0.33	0.11	0.11	0.18	0.06
SK	0.36	0.18	0.27	0.87	0.96	0.72	0.68	0.24	0.77	0.26	0.77	0.70	0.26	0.39
SI	0.18	0.36	0.33	0.22	0.73	0.65	0.53	0.29	0.49	0.36	0.39	0.81	0.32	0.39
ES	0.73	0.62	0.50	0.33	0.40	0.59	0.37	0.42	0.51	0.58	0.68	0.91	0.35	0.55
SE	0.89	0.57	0.52	0.91	0.94	0.78	0.53	0.44	0.49	0.60	0.84	0.73	0.36	0.53
UK	0.91	0.82	0.62	0.25	0.46	0.49	0.43	0.62	0.55	0.70	0.88	0.92	0.68	0.69

V. CONCLUSION

In this study, we propose a multicriteria decision making framework to evaluate the sustainability of transport networks of countries and a methodology that takes into account criteria dependencies. Sustainability is based on the balanced development concept and therefore, the non-compromise alternatives are of special importance. We show that the proposed technique enables us to identify such preferred alternatives as opposed to the classical weighted mean based approaches.

There exist some indicators for which there is no available data for several countries. There are also other indicators for which the data is available but the collection methods differ for some countries. Therefore, such indicators are not included in our analysis. When appropriate data on additional sustainability indicators are made available, one can apply the proposed methods considering a larger set of indicators. We also plan on identifying indicators on which a country should focus in order to improve its score.

REFERENCES

[1] H. Gudmundsson and M. Hojer, "Sustainable development principles and their implications for transport," *Ecological Economics*, vol. 19, pp. 249–260, 1996.

[2] World Commission on Environment and Development, *Our Common Future*. Oxford, UK: Oxford University Press, 1987.

[3] H. Gudmundsson, "Indicators for environmentally sustainable transport," in *Social Change and a Sustainable Transport*. European Science Foundation and the U.S. National Research FoundationEuropean Science Foundation and the U.S. National Research Foundation, 1999.

[4] R. Hueting and L. Reijnders, "Broad sustainability contra sustainability: the proper construction of sustainability indicators," *Ecological Economics*, vol. 50, pp. 249–260, 2004.

[5] A. Dobranskyte-Niskota, A. Perujo, and M. Pregl, "Indicators to assess sustainability of transport activities," European Comission, Joint Research Centre, Tech. Rep., 2007.

[6] J. Siche, F. Agostinho, E. Ortega, and A. Romeiro, "Sustainability of nations by indices: comparative study between environment sustainability index, ecological footprint and the emergy performance indices," *Ecological Economics*, vol. 66, pp. 28–637, 2008.

[7] G. Van de Kerk and A. Manuel, "A comprehensive index for a sustainable society: the ssi – the sustainable society index," *Ecological Economics*, vol. 66, pp. 228–242, 2008.

[8] S. Shmelev and B. Rodríguez-Labajos, "Dynamic multidimensional assessment of sustainability at macro level: the case of austria," *Ecological Economics*, vol. 68, pp. 2560–2573, 2009.

[9] P. Bickel, S. Ahvenharju, T. Könnölä, M. Hjelt, R. De Tommasi, M. Arend, W. Röhling, and R. Burg, "Setting the context for defining sustainable transport and mobility," SUMMA, Tech. Rep., 2003.

[10] C. Jeon and A. Amekudzi, "Addressing sustainability in transportation systems: definitions, indicators, and metrics," *Journal of Infrastructure Systems*, vol. 11, no. 1, pp. 31–50, 2005.

[11] T. Litman, "A good example of bad transportation performance evaluation," Victoria Transport Policy Institute, Tech. Rep., 2008.

[12] J. Zhou, "Sustainable transportation in the us: A review of proposals, policies, and programs since 2000," *Frontiers of Architectural Research*, vol. 1, pp. 150–165, 2012.

[13] R. B. Hiremath, P. Balachandra, B. Kumar, S. S. Bansode, and J. Murali, "Indicator-based urban sustainability—a review," *Energy for Sustainable Development*, vol. 17, pp. 555–563, 2013.

[14] J. Camargo Pérez, M. H. Carrillo, and J. R. Montoya-Torres, "Multi-criteria approaches for urban passenger transport systems: a literature review," *Annals of Operations Research*, vol. 226, pp. 69–87, 2015.

[15] T. Litman and D. Burwell, "Issues in sustainable transportation," *International Journal of Global Environmental Issues*, vol. 6, no. 4, pp. 331–347, 2006.

[16] J.-L. Marichal and M. Roubens, "Determination of weights of interacting criteria from a reference set," *European Journal of Operational Research*, vol. 124, pp. 641–650, 2000.

[17] J.-L. Marichal, "An axiomatic approach of the discrete choquet integral as a tool to aggregate interacting criteria," *IEEE Transactions on Fuzzy Systems*, vol. 8, no. 6, pp. 800–807, 2000.

[18] M. Grabisch, "K-order additive discrete fuzzy measures and their representation," *Fuzzy Sets & Systems*, vol. 92, pp. 167–189, 1997.

[19] G. Choquet, "Theory of capacities," *Annales de l'Institut Fourier*, vol. 5, pp. 131–295, 1953.

[20] M. Sugeno, "Fuzzy measures and fuzzy integrals: a survey," in *Fuzzy Automata and Decision Processes*, M. Gupta, G. Saridis, and B. Gaines, Eds. Amsterdam: North-Holland, 1977, pp. 89–102.

[21] M. Grabisch, "The application of fuzzy integrals in multi-criteria decision-making," *European Journal of Operational Research*, vol. 89, pp. 445–456, 1996.

[22] C. L. Hwang and K. Yoon, *Multiple Attribute Decision Making-Methods and Applications*. New York: Springer, 1981.

[23] C. Bana e Costa, J. De Corte, and J. Vansnick, "On the mathematical foundation of MACBETH," in *Multiple Criteria Decision Analysis: State of the Art Surveys*, J. Figueira, S. Greco, and M. Ehrgott, Eds. Boston, Dordrecht, London: Springer Verlag, 2005, pp. 409–443.

[24] V. Clivillé, L. Berrah, and G. Mauris, "Quantitative expression and aggregation of performance measurements based on the {MACBETH} multi-criteria method," *International Journal of Production Economics*, vol. 105, no. 1, pp. 171 – 189, 2007.

[25] M. Grabisch and C. Labreuche, "A decade of application of the choquet and sugeno integrals in multi-criteria decision aid," *4OR*, vol. 6, no. 1, pp. 1–44, 2008.