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REGULAR PAPER

Transportation Sustainability and Relevant Ranking of European Countries

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Abstract

The role of transportation in the economic process is central. Transportation's benefits, however, can be dampened because of its environmental and social cost. A central question then arises as to the degree of sustainability of a national transportation system. In the present paper we develop a mathematical model to define and assess national transportation sustainability. The model relies on a number of indicators encompassing environmental impact, efficiency, safety, and economic contributions. Statistical data manipulations and fuzzy multistage reasoning result in an overall sustainability index over [0, 1]. A sensitivity analysis uncovers those indicators with the highest potential for improving transportation sustainability. Thirty European countries are ranked and the most important indicators for each country are pinpointed. It is demonstrated that greatest improvement will be achieved with the reduction of passenger car use, road freight transportation, and fatal accidents. Counterintuitively, Norway, Austria, Denmark, and Luxembourg rank at the bottom of the list together with Bulgaria, Greece, and Malta. This is due to their poor environmental performance and their small sustainability progress over 2010–2020.

Keywords Transportation sustainability · Indicators · Fuzzy evaluation · Sensitivity analysis

1 Introduction

The economic and social importance of transportation systems cannot be overstated. Transportation provides access to different locations for raw materials, finished goods, and individuals, thus contributing to the generation of wealth, the creation of jobs, and leisure. Transportation, on the other hand, does bear an environmental and social cost due to its contribution to global warming, environmental pollution, noise, traffic accidents, and congestion, to name but a few [1].

According to the United Nations Environment Programme (UNEP), about 25% of energy related GHG emissions are due to transportation. Moreover, transportation uses mostly fossil fuels and is responsible for a large share of outdoor air pollution which kills 3.2 million people annually worldwide [2]. It thus becomes very important to devise metrics that assess the viability of transportation systems and point to directions for improvement. Such a metric should incorporate socio-economic and environmental aspects and provide an overall measure of sustainability, augmented by a sensitivity analysis, which unveils those parameters that ought to be given priority to achieve higher transportation sustainability.

A widely used definition of sustainable transportation has been proposed in [3] and adopted as a working definition by the Council of the European Union [4]. A sustainable transportation system is one that:

- 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 promotes equity within and between successive generations;
- is affordable, operates fairly and efficiently, offers choice of transportation 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

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Categories.
Decision Support Systems and applications to management and economics (9).
Transportation systems (Other).

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> rates of generation, and, uses non-renewable resources at or below the rates of development of renewable substitutes, while minimizing the impact on the use of land and the generation of noise.

Sustainable transportation is one of the seven key challenges of European Union's Sustainable Development Strategy (EU SDS), which were adopted by the EU Council [5]. The EU SDS declaration defined sustainable transportation systems to be those that "meet society's economic, social and environmental needs whilst minimizing their undesirable impacts on the economy, society and the environment." The EU has set out a number of relevant objectives and actions focusing on energy efficiency, minimization of greenhouse gases (GHG) and pollutant emissions, environment friendly transportation modes, health impacts, safety, and public transportation services. Similar transportation targets for 2030 have been designated by the Organisation for Economic Co-operation and Development (OECD) regarding emissions of nitrogen oxides (NO_x), volatile organic compounds (VOC), particulates and carbon dioxide, land surface used for transportation, and noise [6].

Interestingly, all the goals above highlight the environmental, social and economic dimensions of sustainable transportation. In contrast, conventional approaches of transportation improvement focus on the optimization of traffic flows and the expansion of transportation infrastructures [7].

Gilbert et al. [3] have proposed fourteen indicators comprising the so called Sustainable Transportation Performance Indicators framework. These indicators, shown below, are chosen to examine transportation sustainability in Canada.

- use of fossil fuel energy for all transport
- GHG emissions from all transport
- emissions of air pollutants from road transport
- incidence of injuries and fatalities from road transport
- total motorized movement of people
- total motorized movement of freight
- share of passenger travel not held by land-based public transport
- movement of light-duty passenger vehicles
- rate of use of urban land
- length of paved roads
- household transport costs
- cost of urban transit
- energy intensity of the road vehicle fleet
- emissions intensity of the road vehicle fleet

Data about each indicator are examined over time and observations are made about the indicator getting closer to or away from sustainability. No aggregation or sensitivity analysis are carried out and no other insights about the data are sought.

Several papers provide alternative approaches to measure sustainable transportation. For example, the triple bottom line approach proposed in [1] considers three main sustainability dimensions: Environmental (air pollution and GHG emissions, energy, land used, and environmental efficiency of vehicles); Social (safety, accessibility, and diversity); and Economical (expenditure, benefit, and revenue of transportation systems). Weights to indicators are derived using principal component analysis/factor analysis techniques, while aggregation is performed via a weighted linear combination. Similar frameworks are proposed in [8–10].

A detailed review of a large number of papers and various approaches of transportation sustainability can be found in [11]. All reviewed papers start with a selection of indicators, followed by choices of appropriate weights and aggregation schemes culminating in the development of composite sustainability indices. Weighting methods are classified in three major categories: equal weighting, weighting based on opinions, and weighting based on statistical models. However, all these methods have limitations, as analytically discussed in [1] and [12].

In this paper we depart from the typical algebraic aggregation approaches such as weighted linear combination, root mean square, geometric aggregation, etc., and use fuzzy reasoning. We present an integrated framework that defines and measures sustainability via 22 indicators capturing environmental, social, and economic aspects of transportation. First we perform smoothing of data to introduce memory which we then normalize over [0, 1] and proceed with a fuzzy approach of aggregation. The model is reminiscent of SAFE (Sustainability Assessment by Fuzzy Evaluation) which has been used to assess national and corporate sustainability [13, 14]. However, the two models differ fundamentally in both their structure and logic due to the disparate nature and dynamics of the systems under examination. By its essence, sustainability is fraught with subjectivity and uncertainty which elude precise mathematical analysis and synthesis. Fuzzy logic provides a convenient framework for dealing with problems of imprecision, uncertainty and nonlinearity of knowledge representation and becomes the tool of choice in our sustainability assessment.

Our main aim is to rank countries according to the sustainability of their transportation systems and identify, by means of a sensitivity analysis, the most important indicators affecting sustainability the most. Those are the indicators where attention should be paid by decision makers to achieve the greatest improvement. Due to lack of systematic data for most countries we focus on ranking European countries but the model can be applied universally when numbers are available.

The remainder of this paper is organized as follows. Section 2 presents the dimensions and indicators of national transportation systems. The methodology and all the technical details are described in Sect. 3. Section 4 provides sustainability assessments and rankings for the transportation systems of 30 European countries and pinpoints critical indicators. Concluding remarks are given in Sect. 5.

2 Dimensions and Indicators of Transportation Sustainability

Transportation sustainability is about meeting the basic mobility needs of the society with the least possible adverse impacts on human health, safety, and the environment. It, therefore, encompasses two broad dimensions, the environmental dimension (ENV) and the social dimension (SOC). We evaluate each dimension by means of three specialized components as we shall soon see. Furthermore, each component is a function of a number of indicator time series from 2000 up to 2020, depending on the availability of data for each country.

The process of computing an overall transportation sustainability index, is carried out through the following steps:

1) Each indicator time series is reduced to a single value via exponential smoothing.
2) Smoothed data are normalized over 0 and 1 by linear interpolation between unsustainable and sustainable indicator values.
3) The normalized inputs are converted to fuzzy sets.
4) A multistage inference process uses fuzzy "if–then" rules to successively aggregate the fuzzy indicators of each country into components, dimensions, and an overall index.
5) Finally, a sensitivity analysis pinpoints the contribution of each indicator to the overall sustainability and can aid national policy-making.

Table 1 shows the components and indicators of the model and the corresponding normalization parameters.

Next we describe in detail the indicators of transportation sustainability. Unless otherwise noted, the main source of data is [15].

2.1 Environmental Dimension (ENV)

Transportation activities and infrastructure have negative impacts on climate and cause air pollution and land degradation. The environmental indicators of transportation outlined below are measured on a per capita, unit of benefit generated (efficiency), or percentage basis.

2.1.1 Emissions

1. GHG emissions

CO_2 and the other greenhouse gases emitted by human activities are the main causes of global warming. In September 2020, the European Commission proposed an emissions reduction target of at least 55% by 2030, compared to 1990 levels [16]. Unlike GHG emissions, which in 2019 were about 24% lower than the 1990 levels, including land use, land use change and forestry (LULUCF), the total emissions of domestic transportation, international aviation, and international shipping rose by more than 33%. Assuming that the shares of GHG emissions are kept at the 2019 values, which are the most recent available ones for all economic sectors in the EU, an emissions target for transportation can be computed as follows:

$$E = 0.45\left(\begin{array}{l}\text{Net GHG}\\ \text{emissions in 1990}\end{array}\right)\frac{\left(\begin{array}{l}\text{Transportation sector}\\ \text{GHG emissions in 2019}\end{array}\right)}{(\text{Net GHG emissions in 2019})} \tag{1}$$

The ratio of E to the total EU population provides a benchmark for the emissions of the transportation sector per capita. Using gross rather than net GHG emissions in (1) (gross emissions are higher than net emissions because they exclude the contribution of LULUCF which is negative) would result in a 2.3% more stringent target.

2. NO_x emissions

Combustion of fossil fuels and biofuels generates poisonous NO_x gases, responsible for acid rain, smog, and respiratory diseases.

3. NMVOC emissions

Benzene, ethanol, and formaldehyde are emitted mainly by road transportation, paints, and solvents. These gases have various effects on health as they are known to cause cancer and contribute to the formation of ground-level ozone, which causes respiratory and cardiovascular problems.

4. $PM_{2.5}$

Fine inhalable particles generated by burning fossil fuels cause severe cardiopulmonary diseases, as they can enter the blood stream and penetrate deep into the lungs. Road transportation accounts for up to 30% of $PM_{2.5}$ in urban areas.

2.1.2 Efficiency

Efficient energy use and emissions intensities are measures of efficiency usually expressed as relative to the value of transportation services provided.

Table 1 Composite variables, indicators, and normalization parameters

Dimension	Component	Basic indicator[a] (raw data; years)	Type[b]	Thresholds[c] (u, τ) and/or (T, U)
ENV	Emissions	GHG emissions (tons of CO_2 equivalent per capita; 2000–2019)	SB	$T=2.18$ (45% of total net EU[d] 1990 emissions scaled by current share of transportation emissions and divided by the current EU population) $U=7.92$ (97.5th percentile)
		NO_x emissions (kg per capita; 2000–2019)	SB	$T=2.26$ (2.5th percentile) $U=91.66$ (97.5th percentile)
		NMVOC emissions (kg per capita; 2000–2019)	SB	$T=0.14$ (2.5th percentile) $U=4.43$ (97.5th percentile)
		$PM_{2.5}$ emissions (kg per capita; 2000–2019)	SB	$T=0.06$ (2.5th percentile) $U=5.89$ (97.5th percentile)
	Efficiency	Energy consumption (oil equivalent tons per capita; 2008–2019)	SB	$T=0.63$ (median of all countries) $U=3.75$ (97.5th percentile)
		Energy from electricity and biofuels (% of total; 2008–2019)	LB	$u=2.79\%$ (2.5th percentile) $\tau=13.94\%$ (average of Scandinavia[d])
		GHG emissions intensity (grams per euro of gross value at current prices added from transportation and storage; 2000–2019)	SB	$T=352$ (2.5th percentile) $U=3{,}865$ (97.5th percentile)
		NO_x emissions intensity (g/€ as above; 2000–2019)	SB	$T=1.44$ (2.5th percentile) $U=37.01$ (97.5th percentile)
		NMVOC emissions intensity (g/€ as above; 2000–2019)	SB	$T=0.06$ (2.5th percentile) $U=2.13$ (97.5th percentile)
		$PM_{2.5}$ emissions intensity (g/€ as above; 2000–2019)	SB	$T=0.03$ (2.5th percentile) $U=2.31$ (97.5th percentile)
	Waste and Vulnerability	Landscape fragmentation (% of total area which is strongly fragmented due to roads and railways; 2009, 2012, 2015)	SB	$T=4.75\%$ (2.5th percentile) $U=86.19\%$ (97.5th percentile)
		Reuse and recycling of ELV (% ELV by weight; 2005–2018)	LB	$u=55.5\%$ (2.5th percentile) $\tau=100\%$ (max possible)
		Rail accidents involving hazardous materials (number of accidents per billion ton-km; 2004–2016)	SB	$T=0$ (min possible) $U=0.36$ (97.5th percentile)
SOC	Modal split	Road freight transportation (% goods by weight; 2009–2016)	SB	$T=36.41\%$ (2.5th percentile) $U=86.53\%$ (97.5th percentile)
		Passenger transportation by car (% total inland passenger-km); 2000–2019)	SB	$T=73.17\%$ (2.5th percentile) $U=89.51\%$ (97.5th percentile)
		Railways satisfaction index (0–45 point scale based on survey responses on satisfaction from rail services and rail travel; 2018)	LB	$u=20.8$ (min of all countries) $\tau=29.6$ (max of all countries)
	Safety	People killed in accidents (per million population; 2006–2019)	SB	$T=0$ (min possible) $U=94.47$ (97.5th percentile)
		People injured in accidents (per million population; 2006–2019)	SB	$T=0$ (min possible) $U=4708$ (97.5th percentile)
		Number of accidents (per million population; 2000–2019)	SB	$T=0$ (min possible) $U=11\ 737$ (97.5th percentile)
	Economic aspects	Employment in transportation (fraction of unemployment avoided; 2010–2019)	LB	$u=0.18$ (2.5th percentile) $\tau=0.61$ (97.5th percentile)
		Age of vehicles (average years; 2019)	NB	$u=6.5$ (min of all countries) $\tau=10$ and $T=11$ (≈average of Scandinavia) $U=20$ (max of all countries)

Table 1 (continued)

Dimension	Component	Basic indicator[a] (raw data; years)	Type[b]	Thresholds[c] (u, τ) and/or (T, U)
		Affordability of urban mass transit (average one-way fare as a percentage of daily GDP per capita; 2019)	SB	$T = 1.5\%$ (5th percentile) $U = 3.8\%$ (max of all countries)

[a] NMVOC: non-methane VOC; $PM_{2.5}$: particulate matter of aerodynamic diameter 2.5 μm or less; ELV: end-of-life vehicles; GDP: gross domestic product.

[b] Type of normalization: SB (smaller is better); LB (larger is better); NB (nominal is best).

[c] υ, τ, T, and U are thresholds of target and unsustainable values. Indicator values in [τ, T] are assigned the sustainability index 1. Values $\le \upsilon$ or $\ge U$ indicate poor performance and are assigned the sustainability index 0; values in (υ, τ) or (T, U) are scaled in (0, 1) by linear interpolation (see Sect. 3.2).

[d] EU: the 27 European Union member countries; Scandinavia: Denmark, Finland, Norway, and Sweden (Iceland not included).

5. Energy consumption

Energy consumption in transportation includes road traffic (cars, buses, trucks, etc.), rail (trains, metro, and trams), domestic aviation, domestic navigation, and pipeline transport. The energy used in international aviation, international marine bunkers, fishing ships, airports, train stations, ports, bus stations, and off-road activities related to agriculture and forestry is excluded [15].

6. Energy from electricity and biofuels

Biofuels and electricity are currently the most important energy sources used in transportation with lower environmental impacts than fossil fuels.

7–10. GHG, NO_x, NMVOC, and $PM_{2.5}$ emissions intensities

Low emission intensities imply that less pollution is being created per unit of value added from transportation services.

2.1.3 Waste and Vulnerability

11. Landscape fragmentation

Land fragmentation is a direct consequence of transportation networks. A measure of land fragmentation called the *effective mesh density* estimates the number of continuous land elements per unit area. Impervious surfaces related to transportation infrastructure including medium sized roads, break up continuous ecosystems, thus diminishing their ability to function properly. Landscape fragmentation is a major threat to wildlife resulting in habitat degradation and loss of species and ecosystem services. The negative effects of landscape fragmentation do not leave human communities untouched. Non-fragmented areas have a mesh density 1. The European Environment Agency (EEA, 2019) classifies landscapes as strongly fragmented if they have over 50 meshes per 1000 km^2 [17].

12. Reuse and recycling of ELV

End-of-life vehicles are dismantled to take out components which can be reused as spare parts, to be recycled or used to generate energy, to be shredded, or otherwise disposed of. Directive 2000/53/EC of the European Parliament and the European Council laid a target of 85% on the reuse and recycling for all ELV.

13. Rail accidents involving hazardous materials

Millions of tons of products containing dangerous substances are transported every day. Accidents involving the release of dangerous goods are harmful to humans and the environment. Of all modes of transportation, complete data are available only for train accidents.

2.2 Social Dimension (SOC)

The social dimension involves infrastructure utilization, safety, and economic aspects. A transportation system must be safe, affordable, and capable of providing high quality services together with a balanced contribution to employment.

2.2.1 Modal split

Passenger cars and aviation are the most emitting modes of passenger and freight transportation [18]. However, aviation contributes to less than 10% of total transportation, except for Greece, Spain and Norway, while international aviation is to a good extent inelastic. Therefore, we choose only the most emissions intensive mode per transportation activity in indicators 14 and 15:

14. Road freight transportation
15. Passenger transportation by car

Additionally we choose indicator 16 which focuses on efficiency.

16. Railways satisfaction index

Rail provides the most emissions efficient and economic mode of transportation. Knowledge of the public's level of satisfaction with rail services and stations, quality of travel, and accessibility can help improve service quality and increase the modal share of rail transportation. Source: [19], Fig. C1b (overall population satisfaction index with railway transportation); zero values are introduced for Cyprus and Malta because they do not have railway systems.

2.2.2 Safety

Safety is a key component for the assessment of transportation sustainability. According to the World Health Organization, about 1.3 million people are killed every year and 20 to 50 million suffer non-fatal injuries because of road accidents. In this paper transportation safety is expressed via three indicators:

17. People killed in accidents
18. People injured in accidents
19. Number of accidents

Sources: [15]; [20], Transport-Transport Safety; [21].

2.2.3 Economic Aspects

20. Employment in transportation

Employment is an important aspect in every economy, therefore, the employment rate in transportation would be a key indicator regarding the economic contribution of transportation to a national economy [10, 22]. Given that economies and job distributions vary from country to country, the use of this indicator would favor economies in which the transportation sector plays a dominant role. To overcome this, we introduce a proxy for the employment opportunities transportation contributes. In dual terms, such a proxy could be viewed as the additional unemployment pressure had the transportation sector not been developed at all. The corresponding indicator is given by

$$z_{20} = \frac{\begin{pmatrix}\text{Employment rate}\\ \text{in transportation}\end{pmatrix}}{\begin{pmatrix}\text{Employment rate}\\ \text{in transportation}\end{pmatrix} + \begin{pmatrix}\text{Total unemployment}\\ \text{rate}\end{pmatrix}} \tag{2}$$

A maximum value $z_{20} = 1$ is attained when there is no unemployment, regardless of the employment rate in transportation, otherwise z_{20} is less than 1. The value $1-z_{20}$ represents a gap which the transportation sector could fill with additional jobs. The employment rate in (2) is estimated from

$$\begin{pmatrix}\text{Employment rate}\\ \text{in transportation}\end{pmatrix} = \begin{pmatrix}\text{Share of employment}\\ \text{in transportation}\end{pmatrix}\begin{pmatrix}\text{Labor force}\\ \text{participation rate}\end{pmatrix}$$

Source: [20] (a) Transport-Performance Indicators-Indicators-Economic and social-Share of employment in the transport sector; (b) Labour force statistics-LFS by sex and age-Indicators-Labour force participation rate; (c) Labour force statistics-LFS by sex and age-Indicators-Unemployment rate.

21. Age of vehicles

Aged vehicles on the road are harmful to public health and the environment because of higher emissions than new cars. They are also costly to operate, requiring more frequent and expensive repairs. On the other hand, replacing vehicles before the end of their useful life creates unnecessary waste and economic stress. Therefore, sustainable values for this indicator lie within a range of intermediate values. Sources: [23]; Bulgaria [24], age > 20; Cyprus [25], age = 14; Malta [26], age = 14.87.

22. Affordability of urban mass transit

Transportation affordability is the ability to pay for mobility services. For public transport, affordability depends on ticket prices, travel pattern (frequency, distance), and household income. The most common measure of affordability is the proportion of household income spent on a certain number of trips over a fixed period of time [27]. Similarly we define

$$z_{22} = \frac{(\text{One - way fare})}{\left(\frac{\text{GDP per capita}}{365}\right)} 100\% \tag{3}$$

where, for a given country, the numerator is calculated by averaging out bus, metro, and trolley fares, whichever apply, for all major cities. Fare-free public transportation programs operate in nearly 100 cities worldwide to make mass transit more accessible for the poor and reduce traffic congestion and emissions. Luxemburg is a case in point with $z_{22} = 0\%$. Yet, such programs have also been criticized for being economically non-viable and for reducing the numbers of cyclists and pedestrians [28]. For these reasons, any value of z_{22} less than or equal to 1.5% (5th percentile of the data), rather than just 0%, is assumed to be affordable.

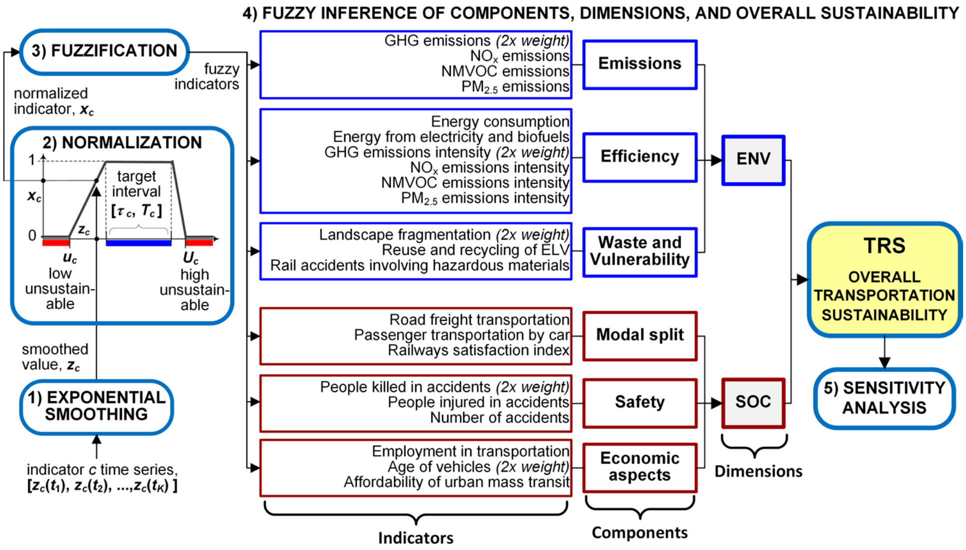


Fig. 1 Data processing, fuzzy inference, and assessment of transportation sustainability

3 Methodology

The steps of the model, shown in Fig. 1, are outlined in the next sections.

3.1 Exponential smoothing

Indicator time series contain a lot of information which might be redundant or contain gaps due to missing data in consecutive years. Each time series is reduced to a single value using Holt's exponential smoothing linear trend model [29]. Two variations of the method are employed, both capable of handling nonconsecutive data modified to account for varying time steps [30]; detailed smoothing algorithms are given in the supplement of [31]. For each country and indicator we use the method that generates values with the smallest sum of squared deviations from the actual data.

3.2 Normalization

The indicators of national transportation have different units, value ranges, and effects on sustainability. For example, higher sustainability is achieved from lower values of air emissions (smaller is better, SB), but higher values of the share of electricity and biofuels (larger is better, LB). In the case of the age of vehicles, however, the sustainable values are neither too low nor too high but a range of intermediate ones (nominal is best, NB).

To enable mathematical manipulation leading to an aggregate sustainability measure, we normalize all smoothed indicators from their physical domains onto a common interval [0, 1]. The value 0 corresponds to a range of values deemed unsustainable and 1 to sustainable ones determined by expert knowledge, standards, or broadly accepted principles.

Four thresholds are defined: $u < \tau \leq T < U$. The interval $[\tau, T]$ comprises the sustainable or target values, which are normalized to 1. Indicator values lower than u or larger than U are deemed unsustainable and are normalized to 0. Intervals (u, τ) and (T, U) correspond to intermediate sustainability levels determined by linear interpolation. Examples of interpolating lines are plotted in Fig. 2. The normalization type and thresholds for each indicator are registered in Table 1.

3.3 Fuzzification

The normalized interval [0, 1] is divided into a number of overlapping fuzzy sets. Four such fuzzy partitions are shown in Fig. 3.

Each normalized indicator x is assigned to one or more fuzzy sets A_0, A_1, A_2 with membership grades shown in Fig. 3a. For example, about 86.57% of the total inland passenger-km in Slovenia are traveled by passenger cars. The corresponding normalized value is $(86.57–U)/(T–U)=0.18$, where $T=73.17\%$ and $U=89.51\%$ from Table 1. From Fig. 3a we see that 0.18 is A_0 with membership grade $\mu_{A_0}(0.18)=(0.6–0.18)/(0.6–0)=0.7$, A_1 with grade $\mu_{A_1}(0.18)=(0.18–0)/(0.6–0)=0.3$, and A_2 with grade $\mu_{A_2}(0.18)=0$.

Components are described by five fuzzy sets, $B_0, \ldots, B_4$, dimensions by seven, $C_0, \ldots, C_6$, and overall sustainability by nine, $D_0, \ldots, D_8$.

3.4 Rule bases

The model aggregates fuzzy inputs (indicators, components, and dimensions) into composite fuzzy outputs using fuzzy

Fig. 2 Normalization types

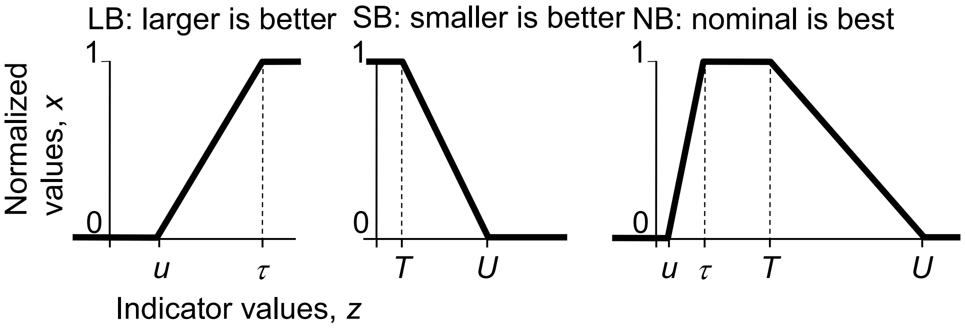
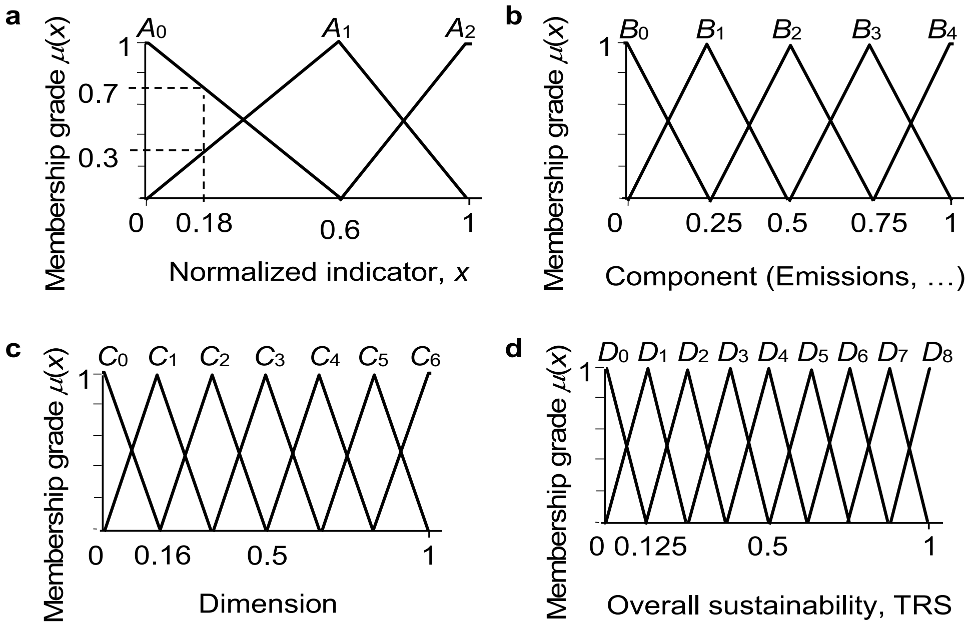


Fig. 3 Fuzzy sets and membership functions $\mu(x)$



inference and fuzzy "if–then" rules. The following are examples of rules corresponding to different output types:

Rule A:**IF** *GHG emissions* is A_2 **AND** *NO$_x$ emissions* is A_1 **AND** *NMVOC emissions* is A_0 **AND** *PM$_{2.5}$ emissions* is A_1, **THEN** ***Emissions*** is B_2

Rule B:**IF** ***Emissions*** is B_2 **AND** ***Efficiency*** is B_2 **AND** ***Waste and Vulnerability*** is B_3, **THEN** ***ENV*** is C_3

Rule C:**IF** ***ENV*** is C_3 **AND** ***SOC*** is C_1, **THEN TRS** is D_2

For each composite output there are as many rules as the number of combinations of its input fuzzy sets. The Emissions component, for example, has four inputs, each with three fuzzy sets (A_0, A_1, A_2) and hence a total of $3^4 = 81$ rules. For TRS there are $7^2 = 49$ rules. The total number of rules used in the model is 900. In general, rules grow exponentially with the number of inputs. To avoid brute force development of all possible rules we apply the following approach first proposed in [32].

Each fuzzy set A_k, B_k or C_k is completely defined by its index k. Fuzzy sets A_0, B_0, and C_0, all indexed $k = 0$, correspond to the lowest sustainability level among the fuzzy sets of the same type. Moreover, to each rule input i we assign a subjective weight of importance w_i relative to the other inputs. Most indicators have unit weights. In Fig. 1, only the weights greater than 1 are shown next to the corresponding indicators.

Consider a rule with n inputs and let k_i be the index of the fuzzy set assigned to input i, $i = 1, \ldots, n$. The weighted sum of the rule inputs is given by

$$\sigma = \sum_{i=1}^{n} w_i k_i \tag{4}$$

We assign σ to the rule output fuzzy set by means of some monotonic function. When all input fuzzy indices are 0, σ is 0 and the output fuzzy set is indexed $k = 0$ as well. The largest σ is attained when all inputs have the highest sustainability levels and so does the output fuzzy set.

As an illustration consider Rule C whose input indices are $k_{\mathrm{ENV}} = 3$ and $k_{\mathrm{SOC}} = 1$. Dimensions ENV and SOC are equally important. From (4) we get $\sigma = k_{\mathrm{ENV}} + k_{\mathrm{SOC}} = 4$. We use the following mapping for the fuzzy set of TRS:

$$k_{\mathrm{TRS}} = \begin{cases} 0 & \sigma = 0 \\ \sigma - 1 & \sigma = 1, 2, 3 \\ \sigma - 2 & \sigma = 4, 5, 6 \\ \sigma - 3 & \sigma = 7, 8, 9 \\ \sigma - 4 & \sigma = 10, 11, 12 \end{cases} \tag{5}$$

From this we obtain $k_{\mathrm{TRS}} = \sigma - 2 = 2$; therefore, if Rule C premise is true, then TRS is D_2.

The other rule bases of the model are given below:

$$\begin{Bmatrix} k_{\mathrm{ENV}} \\ k_{\mathrm{SOC}} \end{Bmatrix} = \left\lfloor \frac{\sigma}{2} \right\rfloor = \begin{cases} 0 & \sigma = 0, 1 \\ \vdots & \\ 5 & \sigma = 10, 11 \\ 6 & \sigma = 12 \end{cases} \tag{6}$$

where x is the largest integer $\leq x$ and

$$\sigma = \begin{cases} k_{\mathrm{Emissions}} + k_{\mathrm{Efficiency}} + k_{\begin{pmatrix} \text{Waste} \\ \text{and Vulnerability} \end{pmatrix}} & \text{for ENV} \\ k_{\begin{pmatrix} \text{Model} \\ \text{split} \end{pmatrix}} + k_{\mathrm{Safety}} + k_{\begin{pmatrix} \text{Economic} \\ \text{aspects} \end{pmatrix}} & \text{for SOC} \end{cases} . \tag{7}$$

$$k_{\mathrm{Emissions}} = \begin{cases} 0 & \sigma = 0, 1, 2 \\ \left\lfloor \frac{\sigma - 1}{2} \right\rfloor & \sigma = 3, \ldots, 10, \end{cases}$$

where

$$\sigma = 2k_{\begin{pmatrix} \text{GHG} \\ \text{emissions} \end{pmatrix}} + k_{\begin{pmatrix} \mathrm{NO}_x \\ \text{emissions} \end{pmatrix}} + k_{\begin{pmatrix} \text{NMVOC} \\ \text{emissions} \end{pmatrix}} + k_{\begin{pmatrix} \mathrm{PM}_{2.5} \\ \text{emissions} \end{pmatrix}} \tag{8}$$

$$k_{\mathrm{Efficiency}} = \left\lfloor \frac{\sigma}{2} \right\rfloor - 1$$

where

$$\sigma = k_{\begin{pmatrix} \text{GHG} \\ \text{emissions} \end{pmatrix}} + k_{\begin{pmatrix} \text{Energy from} \\ \text{electricity} \\ \text{and biofuels} \end{pmatrix}} + 2k_{\begin{pmatrix} \text{GHG} \\ \text{emissions} \\ \text{intensity} \end{pmatrix}} \sum_{\substack{i = \mathrm{NMVOC}, \\ \mathrm{NO_x}, \mathrm{PM}_{2.5}}} k_{\begin{pmatrix} \text{Gas } i \\ \text{emissions} \\ \text{intensity} \end{pmatrix}} .$$

$$\begin{Bmatrix} k_{\begin{pmatrix} \text{Waste and} \\ \text{Vulnerability} \end{pmatrix}} \\ k_{\mathrm{Safety}} \\ k_{\begin{pmatrix} \text{Economic} \\ \text{aspects} \end{pmatrix}} \end{Bmatrix} = \left\lfloor \frac{\sigma}{2} \right\rfloor , \tag{9}$$

where

$$\sigma = \begin{cases} 2k_{\begin{pmatrix} \text{Land} \\ \text{fragmentation} \end{pmatrix}} + k_{\begin{pmatrix} \text{Recycling} \\ \text{and reuse} \\ \text{of ELV} \end{pmatrix}} + k_{\begin{pmatrix} \text{Rail accidents} \\ \text{involving} \\ \text{hazardous} \\ \text{material} \end{pmatrix}} & \text{for} \begin{pmatrix} \text{Waste and} \\ \text{Vulnerability} \end{pmatrix} \\ 2k_{\begin{pmatrix} \text{People} \\ \text{killed in} \\ \text{accidents} \end{pmatrix}} + k_{\begin{pmatrix} \text{People} \\ \text{injured in} \\ \text{accidents} \end{pmatrix}} + k_{\begin{pmatrix} \text{Number of} \\ \text{accidents} \end{pmatrix}} & \text{for Safety} \\ k_{\begin{pmatrix} \text{Employment in} \\ \text{transportation} \end{pmatrix}} + 2k_{\begin{pmatrix} \text{Age of} \\ \text{vehicles} \end{pmatrix}} + k_{\begin{pmatrix} \text{Affordability} \\ \text{of urban} \\ \text{mass transit} \end{pmatrix}} & \text{for} \begin{pmatrix} \text{Economic} \\ \text{aspects} \end{pmatrix} \end{cases} \tag{10}$$

$$k_{\begin{pmatrix} \text{Model} \\ \text{split} \end{pmatrix}} = \begin{cases} 0 & \sigma = 0 \\ \sigma - 1 & \sigma = 0, \ldots, 6' \end{cases}$$

where

$$\sigma = {}^{k}\begin{pmatrix}\text{Road freight}\\ \text{transport}\end{pmatrix} + {}^{k}\begin{pmatrix}\text{Passenger transport}\\ \text{by passenger cars}\end{pmatrix} + {}^{k}\begin{pmatrix}\text{Satisfaction}\\ \text{with railways}\end{pmatrix}$$

We assign double weights to GHG emissions, Land fragmentation, and People killed in accidents because of their relative importance compared to the other indicators. GHG emissions contribute to climate warming, Land fragmentation enhances biodiversity vulnerability, and the indicator People killed in accidents is a lot more important than Numbers of accidents or People injured in accidents.

3.5 Fuzzy inference and defuzzification

For a rule base with inputs $i = 1, 2, \ldots, n$ and output 0, the rules have the form

Rule j: **IF** (input 1 is $L_{1,j}$) **AND** … **AND** (input n is $L_{n,j}$), **THEN** (output 0 is $L_{0,j}$)
where $L_{i,j}$ is the fuzzy set of input i in rule j and $L_{0,j}$ the corresponding fuzzy set of the output. Here we use a different notation for fuzzy sets, $L_{i,j}$, with reference to rule indices j. $L_{i,j}$ is to be understood as one of the fuzzy sets of Fig. 3 to which the variable $i = 0, \ldots, n$ of Rule j belongs. Also $\mu_{i,j}$ denotes the membership grade of variable i to the fuzzy set $L_{i,j}$. The membership grade of the output equals the product of inputs

$$\mu_{0,j} = \mu_{1,j}\mu_{2,j} \cdots \mu_{n,j} \tag{11}$$

If one or more inputs are missing, then we fill in their fuzzy sets with the average of the fuzzy sets of available inputs rounded to the smallest integer. Next, we apply the procedure of Sect. 3.4 to find the weighted sum σ and the corresponding output fuzzy set, $L_{0,j}$, and, finally, we set equal to the product of $\mu_{i,j}$ taken over the available inputs i.

If several rules have the same output fuzzy set Λ, i.e., $L_{0,j} = \Lambda$, then the overall membership grade $\mu_\Lambda(x_0)$ of the output to Λ is given by the sum of the individual membership grades:

$$\mu_\Lambda(x_0) = \sum_{j:L_{0,j}=\Lambda} \mu_{0,j} \tag{12}$$

If the output is used as an input to another rule base, then a similar inference process is applied. Finally, we use height defuzzification to find a crisp value x_0 for the output:

$$x_0 = \frac{\sum\limits_{\substack{\text{all fuzzy sets } \Lambda\\ \text{of the output}}} y_\Lambda \mu_\Lambda(x_0)}{\sum\limits_{\substack{\text{all fuzzy sets } \Lambda\\ \text{of the output}}} \mu_\Lambda(x_0)} \tag{13}$$

where y_Λ is the *peak value* of the output fuzzy set Λ, i.e., the sustainability value with the highest membership grade in Λ. Thus, for the fuzzy sets $D_0, D_1, \ldots, D_8$ shown in Fig. 3d we have $y_{D_0} = 0$, $y_{D_1} = 0.125$, …, $y_{D_8} = 1$.

3.6 Sensitivity analysis

The assessment of composite variables provides information about those components of national transportation that need to be improved. This information is complemented by sensitivity analysis, which quantifies the rate of improvement of the overall sustainability, TRS, with respect to each indicator. In this paper we use first-order differences

$$\Delta_c = \text{TRS}\left(x_1, x_2, \ldots x_c^+, \ldots\right) - \text{TRS}(x_1, x_2, \ldots x_c, \ldots),$$

where $x^+ \equiv \min(1, x + \varepsilon)$ and ε is a fixed positive increment. An important property of the model is that TRS is increasing in x_c, i.e., $\Delta_c \geq 0$ for all c and $\varepsilon > 0$. This follows from Theorem 2 in [33]. Output monotonicity ensures that improving an indicator leads to an improvement of the overall index.

A ranking of indicators by largest Δ_c appears to be a natural choice of the most promising directions for improving transportation sustainability. Yet, this criterion favors indicators with large weights of importance and is biased against those used in inference engines with many inputs. Moreover, such ranking ignores the cost of improvement of indicator c, which is usually increasing in x_c. A better ranking approach proposed in [34] is based on *scaled gradients*,

$$S_c = \Delta_c(1 - x_c)$$

where 1–*xc* is the distance from the target and also a measure of the ease for improvement of indicator c.

Second-order scaled gradients with respect to indicators c and v are similarly defined by differencing and scaling, i.e.,

$$\Delta_{cv} = \text{TRS}\left(x_1, \ldots x_c^+, \ldots x_v^+, \ldots\right) - \text{TRS}(x_1, \ldots x_c, \ldots x_v, \ldots),$$
$$S_{cv} = \Delta_{cv}(1 - x_c)(1 - x_v)$$

This approach can easily be extended to higher order gradients. The maximum scaled gradient corresponds to the combination of indicators having the greatest potential to improve the transportation sustainability of a country.

4 Results

Table 2 shows the ranking of European countries by overall transportation sustainability. Our aim initially was to rank as many countries worldwide as possible, but only

Table 2 Country rankings, assessments, and most important indicators

	Country	TRS	SOC	ENV	Indicator with the largest scaled gradient	Pair of indicators having the largest second-order scaled gradient
1	Sweden	0.648	0.487	0.840	Reuse and recycling of ELV	Railways satisfaction index; Affordability of urban mass transit
2	Slovakia	0.644	0.490	0.828	Vehicle age	Road freight transportation; Vehicle age
3	Netherlands	0.633	0.640	0.647	People killed in accidents	Passenger transportation by car; People killed in accidents
4	Switzerland	0.620	0.486	0.737	Road freight transportation	Energy from electricity and biofuels; Road freight transportation
5	Finland	0.618	0.489	0.740	Passenger transportation by car	Road freight transportation; Passenger transportation by car
6	Hungary	0.616	0.397	0.820	Road freight transportation	Road freight transportation; Railways satisfaction index
7	Ireland	0.611	0.495	0.687	Passenger transportation by car	Road freight transportation; Passenger transportation by car
8	Czechia	0.603	0.479	0.712	People killed in accidents	Road freight transportation; People killed in accidents
9	Latvia	0.602	0.440	0.754	People killed in accidents	People killed in accidents; Affordability of urban mass transit
10	Estonia	0.593	0.478	0.684	Vehicle age	Railways satisfaction index; Vehicle age
11	Belgium	0.574	0.465	0.651	Landscape fragmentation	Landscape fragmentation; People injured in accidents
12	Poland	0.570	0.362	0.752	Road freight transportation	Road freight transportation; People killed in accidents
13	France	0.567	0.430	0.682	Road freight transportation	Landscape fragmentation; Road freight transportation
14	Cyprus	0.563	0.359	0.742	Railways satisfaction index	Energy from electricity and biofuels; Railways satisfaction index
15	Spain	0.558	0.351	0.746	Road freight transportation	Road freight transportation; Employment in transportation
16	UK	0.537	0.311	0.748	Passenger transportation by car	Passenger transportation by car; Affordability of urban mass transit
17	Slovenia	0.535	0.383	0.666	Passenger transportation by car	Passenger transportation by car; People injured in accidents
18	Italy	0.533	0.356	0.696	Railways satisfaction index	Railways satisfaction index; People injured in accidents
19	Portugal	0.514	0.312	0.714	Passenger transportation by car	Passenger transportation by car; People injured in accidents
20	Germany	0.514	0.389	0.633	Road freight transportation	Landscape fragmentation; Road freight transportation
21	Romania	0.507	0.288	0.726	Reuse and recycling of ELV	Railways satisfaction index; People killed in accidents
22	Lithuania	0.496	0.338	0.656	Passenger transportation by car	Passenger transportation by car; Railways satisfaction index
23	Croatia	0.490	0.203	0.780	People killed in accidents	People killed in accidents; Affordability of urban mass transit
24	Norway	0.478	0.494	0.471	Passenger transportation by car	$PM_{2.5}$ emissions; Passenger transportation by car
25	Austria	0.475	0.408	0.557	Rail accidents involving hazardous materials	Rail accidents involving hazardous materials; People injured in accidents
26	Greece	0.464	0.239	0.702	People killed in accidents	People killed in accidents; Employment in transportation
27	Bulgaria	0.429	0.150	0.737	Vehicle age	People killed in accidents; Vehicle age
28	Denmark	0.365	0.481	0.238	NO_x emissions	NOx emissions; NMVOC emissions
29	Luxembourg	0.364	0.317	0.393	Vehicle age	Road freight transportation; Vehicle age
30	Malta	0.361	0.193	0.483	Landscape fragmentation	GHG emissions intensity; Landscape fragmentation

European countries publish consistent data regarding their state of transportation. Sweden, Slovakia, the Netherlands, and Switzerland occupy the top places, followed by Finland, Hungary, Ireland, and Czechia. The low rankings of Luxemburg, Denmark, Norway and Austria as counterintuitive as they may seem will be justified later.

Table 2 also shows the indicators with the maximum first and second-order scaled gradients for each country,

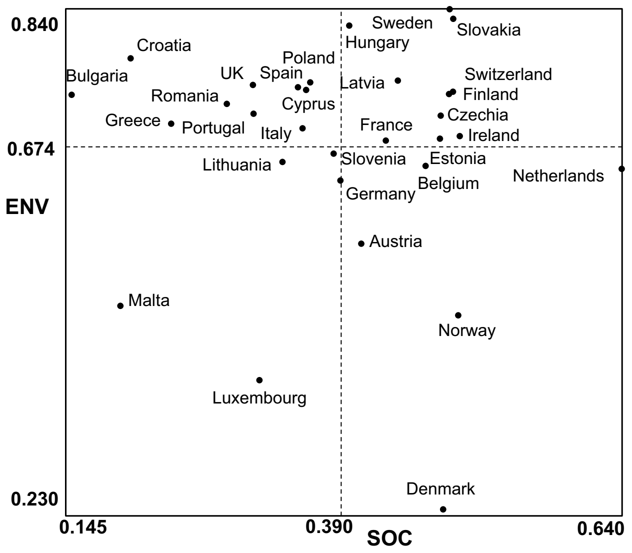


Fig. 4 Scatter plot of countries based on ENV and SOC

Table 3 Probability of each indicator having a top 5 highest potential to improve transportation sustainability

Indicator	Probability
People killed in accidents	73%
Passenger transportation by car	67%
Road freight transportation	63%
Railways satisfaction index	57%
Vehicle age	50%
Landscape fragmentation	40%
Reuse and recycling of ELV	27%
People injured in accidents	27%
Employment in transportation	20%
Affordability of urban mass transit	20%
GHG emissions	17%
Energy from electricity and biofuels	13%
NO_x emissions	7%
$PM_{2.5}$ emissions	7%
GHG emissions intensity	7%
NMVOC emissions	3%
Accidents involving hazardous materials	3%
Energy consumption	0%
NO_x emissions intensity	0%
NMVOC emissions intensity	0%
$PM_{2.5}$ emissions intensity	0%
Number of accidents	0%

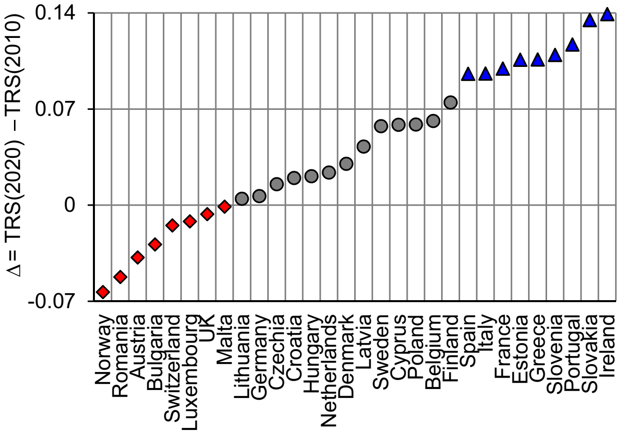


Fig. 5 Change (Δ) in TRS from 2010 to 2020

S_c and S_{cv}, which were computed using $\varepsilon = 0.01$. In general, the indicator with the largest first-order scaled gradient also shows up in the pair with the largest second-order scaled gradient. For Sweden and Romania, reuse and recycling of ELV has the largest scaled gradient. Yet, a second-order analysis pinpoints *railways satisfaction index* and either *affordability of urban mass transit* or *people killed in accidents* as the most crucial indicators for simultaneous improvement. This is clearly a manifestation of the nonlinear nature of the sustainability function and the scaled gradients.

Figure 4 shows an arrangement of countries on the SOC-ENV plane. The broken lines intersect at the point defined by sample means, i.e., 0.390 for SOC and 0.674 for ENV. All but one top-ranking countries of Table 2 score highly in both dimensions. For the Netherlands, the social dimension is the highest of all countries but the environmental dimension is average. Denmark, Luxembourg, Norway, Malta, and Austria have the lowest environmental performance of all European countries. In particular, Denmark's NO_x, NMVOC, and $PM_{2.5}$ emissions and emissions intensities are the highest among all examined countries with corresponding normalized scores 0.

Table 3 summarizes the percentage probabilities of an indicator being among the top five most influential ones for a country. The statistics are obtained via a first-order sensitivity analysis. The most frequently observed indicators belong to SOC: accident fatalities (73%), passenger transportation by car (67%), road freight transportation (63%), satisfaction from railways (57%), and vehicle age (50%).

We compared the TRS indexes using the 2000–2010 and the 2000–2020 datasets; the change of transportation sustainability over the last decade is shown in Fig. 5. For Ireland, Slovakia, Portugal, and Slovenia, Greece, Estonia, France, Italy, and Spain the sustainability score has increased by at least 0.1. Norway, Romania, Austria, Bulgaria, Switzerland, Luxembourg, UK, Malta exhibit a decline.

5 Conclusions

Transportation sustainability was defined and measured mathematically over a scale [0, 1]. The model ranked 30 European countries using 22 indicators and uncovered those indicators with the highest potential for improving transportation sustainability. We focused on European countries because data for the remaining world are scant and often contradictory, depending on the source. To no surprise, Sweden, Slovakia, the Netherlands, Switzerland, and Finland ranked at the very top. However, the model revealed surprisingly that Norway, Austria, Denmark, and Luxembourg ranked at the bottom of the list. Interestingly, those countries exhibit a low transportation environmental performance. The model demonstrated that this negative performance has not improved over the last decade.

A sensitivity analysis showed that the indicators *people killed in accidents, transportation using passenger cars, road freight transportation, vehicle age,* and *satisfaction from railways* need improvement to raise overall sustainability.

A shortcoming of the model is that it uses in its core fuzzy logic which generates results that, to some degree, are subjective. However, given that no rigorous mathematical definition of transportation sustainability exists, subjectivity is unavoidable. Moreover, like any kind of sustainability, transportation sustainability has several sides, primarily amenable to linguistic descriptions instead of precise equations. It is then natural to perform linguistic reasoning which is done exceptionally well using fuzzy logic.

Finally, the model has a dual purpose. First, it derives an aggregate measure of sustainability or, metaphorically, it looks at the forest ignoring the trees. Second, it performs sensitivity analysis which uncovers the indicators with the highest potential to improve this aggregate measure, thus, returns to trees, that is, individual indicators. Of course, the model just flags indicators. It is up to the decision maker to devise specific strategies to reduce, say, the number of traffic fatalities.

Other models using linear weighted averages with fixed weights assigned to indicators can in principle perform sensitivity analysis, but their derivatives will simply yield the weights by linearity. Our model by its nonlinearity avoids such simplistic results. Additionally, it views transportation sustainability macroscopically as well as microscopically and can easily be modified to capture new knowledge as reality and data change.

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Declarations

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