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The sustainable transport planning index: A tool for the sustainable implementation of public transportation

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Abstract

The transportation sector contributes significantly to global greenhouse gas emissions, so it is crucial to assess and measure the sustainability of transportation systems. In this context, this study was conducted to develop an integrated index through the use of the multi-criteria decision analysis method. The method combines existing discrete indexes into one comprehensive evaluation of public transportation, resulting in the sustainable transport planning index (STPI). In the STPI model, sustainability of transportation systems is assessed based on social, economic, and environmental factors that support the implementation of zero emission busses. The weight of each indicator is determined through the analytical hierarchy process, where expert judgment is used to assess the relative importance of each indicator. Normalization of indicators is performed to ensure comparability and consistency. The final STPI index is calculated as the weighted average of the normalized indicators. The STPI model reduces bias in the decision-making process by considering multiple aspects and utilizing a structured approach to transport planning. The results of this method can provide valuable insights for decision-makers, public transport agencies, government ministries, the private sector, and other stakeholders. As case study model, the STPI model was applied to the public transport system of the United Kingdom from 2007 to 2019, however; the methodology and lessons learned are applicable to all countries that are in the process of assembling data sets to weigh trade-offs and inclusions in relation to sustainable transit such as accessibility and health impacts.

KEYWORDS

analytical hierarchy process, economy, environment, multi criteria decision making, public transportation, social, sustainable transport planning index, zero emission busses

1 | INTRODUCTION

The transportation sector is one of the primary contributors to greenhouse gas emissions (GHG) globally. It is crucial to accurately assess the sustainability of transportation systems to develop effective and practical solutions and drive progress in improving cities. To achieve this, this study endeavors to create an integrating index using a multi-criteria decision analysis method, which will combine existing discrete indexes to ensure a dependable implementation of new technology in the public transportation system. A sustainable system requires creative thinking about a future framework that is within the realm of possibility, is desirable to its users, and addresses the important role of transportation in the sustainable city (Zito & Salvo, 2011). The most common definition of a sustainable development system is provided by the Bruntland Commission (1987): "Sustainable development fulfills the needs of the present without compromising the ability of future generations to meet their own needs." This implies that a sustainable transportation system must consider the possible impacts of transportation on environmental considerations, stable economic growth and employment, and societal dimensions such as affordable access (Sara et al., 2022; Jeremy et al., 2021; Tanguay et al. 2010; Litman, 2008). The impacts of transport on climate action are reiterated in the Paris Agreement, since almost 25 percent of energy related to global GHG are emitted by transport systems (Jeremy et al., 2021). In response to these data world leaders agreed to deploy greener technology such as electric vehicles for transport (High-level Advisory Group on Sustainable Transport, 2016). According to the definition of the Centre for Sustainable Transportation (CST, 2003), a sustainable public transportation system is one that:

1. "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;
2. Is affordable, operates efficiently, offers choice of transport mode, and supports a vibrant economy;
3. Limits emissions and waste within the planet's ability to absorb them, minimizes consumption of non-renewable resources, reuses, and recycles its components, and minimizes the use of land and the production of noise."

However, realizing a sustainable transport system is a challenge. For decades, city planners have struggled to find the correct balance between providing convenient mobility for residents and the need to address the economic, social, and environmental implications of transportation systems since it requires the consistent collaboration of many disciplines including engineers, environmentalists, biologists, transport experts, sociologists, and many more. Although sustainability is about the future of society, it must also consider the current success of industries and businesses. Most countries continue to focus on sustainable development, even though clearly measuring it's progress is required in order to assess improvement. Therefore, it is important to quantify and accurately measure the sustainability of transportation systems to develop innovative and practical approaches and make progress in improving cities. If achieved its impacts are far-reaching: reduction of emissions and particulates, improved quality of urban life through less pollution and noise, improved health of residents, more equitable and affordable reach and choice of transport, industry growth, and green job creation. Secondary benefits include densification and cost reduction of pollution induced disease.

Studies which used different indicators to consider social, environment, and economic aspects to assess the sustainable development of transportation systems. Zito and Salvo (2011) proposed a set of transportation performance indicators (TPIs) to assess the progress toward goals and objectives in urban mobility planning. They chose these TPIs based on standard methodologies for data measures and considered factors such as comprehensiveness, data quality, comparability, ease of understanding, and accessibility and transparency. The TPIs were classified into several categories such as budget, planning and land-use, safety, time, health, and environment, and social. The choice of TPIs was based on a trade-off between available data sources and the defined criteria. Examples of TPIs include GDP per inhabitant, infrastructure expenditure per capita, length of reserved public transport routes, number of deaths in road accidents, energy consumption per private motorized passenger kilometer, and employment/population ratio. The aim was to ensure comparability of different city contexts and assess the effects of policy pathways. Mameli and Marletto (2009) also reinforce the primacy of the same three dimensions for measuring progress toward sustainable public transport by examining citizens' opinions to assess the effectiveness of policies for public transport mobility.

In this study, we present a groundbreaking approach to assess the sustainability of public transport systems through the development of the sustainable transport planning index (STPI). This model integrates the three dimensions of sustainability, which are environmental quality, economic growth, and social development, to provide a comprehensive evaluation of the sustainability of transport systems.

The methodology involves selecting relevant indicators that measure progress toward sustainability and using a multi-criteria decision-making approach to evaluate the public transport system. This allows us to capture the impact of new technologies, such as Zero Emissions busses, on the environment, economy, and society. Additionally, the use of the analytical hierarchy process (AHP) to assign weights to the indicators provides a more nuanced and informed assessment of the sustainability of the public transport system.

This study offers several novel contributions to the field. First, it provides a flexible framework that can be adapted to different contexts and locations, rather than a one-size-fits-all approach. Second, it demonstrates the practicality and usefulness of the STPI as a tool for promoting sustainable public transport planning and development, as well as for monitoring the sustainability of existing systems over time. Lastly, it provides valuable information for decision-makers and practitioners, who can use the STPI to make informed decisions about the sustainability of public transport systems and monitor their progress toward sustainability over time. Overall, this study offers a significant contribution to the field of sustainable transport planning and development and provides a valuable tool for practitioners and decision-makers to promote and achieve sustainability in this critical area.

2 | TRANSPORTATION AND HEALTH CONSEQUENCES

Diesel engines are one of the most significant contributors to environmental pollution caused by exhaust emissions and are a source of various health issues (Resitoglu et al., 2014). The key exhaust pollutants from diesel engines are carbon monoxide (CO), Nitrogen oxides (NOx), hydrocarbons (HC), particle matter (PM), and sulfur dioxide (SO2). It was estimated that air pollution caused 4.2 million premature deaths in 2016 due to exposure to small particulate matter with a diameter of 2.5 microns (PM2.5) or less, which causes cardiovascular stroke,

TABLE 1 Health impacts of diesel exhaust emissions

Emission type	Description	Health impacts
Carbon monoxide (CO)	CO is a colorless, odorless gas that can be harmful when inhaled in large amounts.	• Reduces the amount of oxygen to the heart accompanied by chest pain (also known as angina) • Dizziness • Confusion • Unconsciousness • Death
Nitrogen oxides (NOx)	NOx is referred as nitrogen oxide (NO) and nitrogen dioxide (NO2).	• Damage lung tissue • Lowering the body's resistance to respiratory infection • Worsen chronic lung diseases, such as asthma • More effects on children and the elderly
Particulate matter (PM)	PM stands for particulate matter (also called particle pollution): the term for a mixture of solid particles and liquid droplets found in the air.	• PM < 10 micrometers in diameter can get deep into lungs or bloodstream. • PM < 2.5 pose the greatest risk to health like cardiovascular, stroke, and respiratory disease, including asthma as well as cancers.
Hydrocarbons (HC)	HC is produces as the consequence of incomplete combustion of the hydrocarbon fuel (mostly exhaust gasses of gasoline fueled)	• Potential to respiratory tract irritation • Cancer
Sulfur dioxide (SO2)	Sulfur dioxide (SO2), a colorless, bad-smelling, toxic gas, is part of a larger group of chemicals referred to as sulfur oxides (SOx).	• Harm the human respiratory system • Difficulty breathing. • Contribute to respiratory illness especially for people with asthma, children, and the elderly. • Aggravate existing heart and lung conditions • Eye irritation

respiratory disease, and asthma as well as cancers (WHO, 2018). The results of the study by Crouse et al. (2010) in Montreal, Canada, found evidence of an association between exposure to outdoor concentrations of Nitrous Oxides, (NO_x) and the incidence of postmenopausal breast cancer. Although the (size of effect) results varied using estimates of exposure from different periods, they concluded that there was an increased risk of approximately 25% for every increase of 5 ppb (parts per billion) in exposure. Similar results were reported by Bonner et al. (2005) and Nie et al. (2007).

In another study, Perera (2017) emphasized the effects of fossil-fuel pollution on children's health. Children have higher exposure to air pollution because children inhale more air per kilogram of body weight than adults and require three to four times the amount of food on a body-weight basis than adults (WHO, 2006). The World Health Organization (WHO) estimates that more than 40% of the burden of environmentally associated disease falls on the young, demonstrating their unique vulnerability. Furthermore, particulate matter exposure has a negative impact specifically on children's lung functions, resulting in lower peak expiratory flow and forced expiratory volume, especially in children with asthma, leading to an increase in emergency room visits, hospital admissions, and deaths in children (Hellden et al., 2021). Xie and Xu (2017) stated that particle matter (PM) is more prone to form deposits on the lungs, respiratory bronchioles, and alveoli, resulting in respiratory and lung illnesses. In London, United Kingdom, air pollution by Nitrogen Dioxide (NO2), was identified to have caused heart and lung problems for the whole of year 2017 (Anon, 2017). Moreover, in the UK, PM in air pollution is responsible for 30,000 deaths and NO2 for 10,000 annually (Le Page, 2016). In Table 1, the health impacts of air pollution by diesel engines are listed. In addition, it was reported that exposure to PM2.5 is implicated in increased risk of dementia and Alzheimer's disease (Underwood, 2017) because of progressive gray matter atrophy.

Similar to air pollution, noise pollution is now generally accepted as a health hazard (Wang & Moriarty, 2018a). According to the study by WHO (2011) road traffic noise increases the risk of heart disease and high blood pressure, cognitive impairment in schoolchildren, and annoyance and sleep disturbance are discovered as side effects of noise pollution (Wang & Moriarty, 2018b).

3 | COMPARISON OF AIR POLLUTION EMISSIONS OF CNG, DIESEL, AND HYBRID BUSSES

Air pollution emissions and GHG are known to have negative impacts on the environment as well as human health (Crouse et al., 2010; Hung et al., 2011; Perera, 2017; Varga et al., 2020). Compressed natural gas (CNG) busses consistently have lower NOx emissions and greater CO emissions than diesel and hybrid busses throughout all duty cycles, according to Lowell (2013). Hybrid busses, on the other hand, emit slightly less NOx than diesel busses, while hybrid NOx emissions were higher in several tests than the diesel version of the identical bus. Finally, both diesel and hybrid busses emit very low PM levels, around one-third or less of the maximum allowed by the Environmental Protection Agency Environmental Protection Agency (USA) EPA standard and The CNG busses did not have their PM levels assessed. All three systems produce very low non-methane hydrocarbon (NMHC) HC emissions, which are around one-fourth or less of the EPA's permitted limit.

TABLE 2 Comparison of emission for CNG, diesel, and hybrid busses (refer to Callaghan & Lynch, 2005)

Emissions (gram per mile)	CO	NOx	PM	HC
Diesel	0.12	2.79	0.2	0.02
CNG	2.12	1.89	0.2	1.9
Hybrid	0.03	0.94	0.2	0.02

Callaghan and Lynch (2005) examined the emissions of hybrid, electric, and fuel cell busses, concluding that hybrids lack the zero-emission benefits of battery and fuel cell busses. Nonetheless, laboratory testing on hybrid busses has shown that they provide emissions benefits comparable to or better than clean diesel and CNG busses, as well as a significant improvement over older diesel? busses. (Table 2). Comparison emissions for CNG, diesel, and hybrid busses (refer to Callaghan & Lynch, 2005).

The study conducted by Varga et al. (2020) in Cluj-Napoca City showed the direct emissions reduction that resulted from replacing 41 diesel busses with electric busses. Their results showed the reduction of 668.45 tons of CO2 and 6.41 tons of NOx per year by replacing 41 diesel busses with electric busses. The deployment of 41 electric busses (in the traffic conditions of Cluj-Napoca city) managed to reduce global pollution emissions by 509.95 tons of CO2 and 5.618 tons of NOx each year. However, the results of the study by Song et al. (2018) in Macau's urban transport system by conducting a comparative life cycle assessment between electric busses and diesel busses showed that although ZEB is a viable option to reducing GHG emission by replacing diesel busses, its efficiency highly depends on the local road condition and transport fleet operation. Their results showed that the mean GHG emissions per 100 km of the electric busses supported by current electricity mixes exceeded the emissions due to the charging loss and electricity distribution loss compared to diesel busses. However, they identified the potential to significantly mitigate the GHG emissions from public busses, especially with clean electricity mixes (like solar energy) was used.

Xie and Xu (2017) concluded that PM less than 2.5 μm on average contribute to around 98% in the particle emissions for both hybrid and fuel busses. In addition, hybrid busses reduce 33% of the HC emissions, 44% of the NOx emission, and 51% of the particle emissions compared to the fuel busses. Lowell (2013) concluded that total GHG emissions from hybrid busses are considerably lower than from diesel or CNG busses due to their higher fuel economy, and the reduction in total annual GHG emissions from operating new hybrid busses instead of new CNG busses could be as high as 54.5 tons of CO2-e per bus. In terms of CO2, diesel and CNG busses exhaust almost the same level of CO2, although CNG has lower carbon emissions compared to diesel fuel busses, but this advantage is mitigated by the fact that diesels have a higher fuel economy.

4 | ENERGY DEMAND CONSUMPTION OF ELECTRIC BUSSES

The energy consumption of electric busses has been widely studied and reported by various authors. Erkkilae et al. (2013) found the energy consumption to range from 0.66–1.23 kWh/km for a low duty cycle and 0.7–1.45 kWh/km for a high duty cycle. Vepsalainen et al. (2019) used a computationally efficient model to study the energy efficiency of an electric bus and obtained simulation results of 0.43–2.30 kWh/km for a light duty cycle bus. Lajunen and Tammi (2019) reported energy consumption of 0.9–1.42 kWh/km for light duty cycle and Gao et al. (2017) reported 1.24–2.48 kWh/km for heavy duty cycle.

Varga et al. (2020) conducted a study using real data from an electric bus fleet in Cluj-Napoca City and found that the average energy consumption was 0.96 kWh/km over 530,944 kilometers traveled, with an average monthly load of 3089 passengers per bus. The study revealed that 0.38 kWh/km of energy was recovered/generated. This highlights the importance of considering real-world bus behavior, rather than relying solely on simulations.

Zhou et al. (2016) compared the real-world energy consumption of three different electric busses and found that energy consumption increased by 21%–27% when air-conditioning and passenger load were at their highest levels, with air-conditioning usage having a greater impact than passenger load. When compared to a diesel bus, electric busses use 85%–87% less fuel and emit 19%–35% fewer CO2 emissions, as well as 32%–46% fewer fossil fuels over their lifecycle.

5 | ISO 14001: A PATH TO ENVIRONMENTAL RESPONSIBILITY AND SUSTAINABILITY IN THE TRANSPORTATION INDUSTRY

ISO 14001 is an international standard for environmental management systems that helps organizations minimize their environmental impact and comply with relevant legislation (Camilleri, 2022). It is applicable to organizations of all sizes and sectors and can be used to promote sustainable transportation. Sustainable community-based tourism (CBT) practices can also enhance the benefits of tourism for local communities and businesses (Mtapuri et al., 2021). However, Murillo-Avalos et al. (2021) found that many large companies and multinational enterprises (MNEs) have deficiencies in their corporate social responsibility (CSR) practices related to environmental indicators such as biodiversity and waste. Meanwhile, Camilleri (2021) found that stakeholders in the tourism and hospitality sector are driving businesses to adopt ethical, responsible, and environmentally friendly initiatives, which can lead to long-term growth and competitiveness.

6 | ZERO EMISSION BUS TECHNOLOGIES AS A SUSTAINABLE TRANSPORT SOLUTION

The World Bank (2019) has reported several advantages and disadvantages of zero emission busses (ZEBs) compared to other types of busses in terms of costs, feasibility, performance, and environmental impact. Table 3 provides a summary of the key advantages and disadvantages of the major bus technologies.

TABLE 3 Advantages and disadvantages of different bus technologies (refer to Table 1.1 of World Bank, 2019)

Technology	Advantages	Disadvantages
Diesel	• Existing technology • Lowest purchase costs • No need for new infrastructure	• High GHG emissions • Subject to availability of ultra-low sulfur diesel
Hybrid diesel electric (HBD)	• 20%–30% GHG reduction • Relatively mature technology • Lower operation costs • No new infrastructure needed	• Emission benefits depend strongly on duty cycle and driver efficiency • Higher acquisition cost than diesel
Battery electric bus (BEB)	• Zero tailpipe emissions • 50%–100% GHG savings (depends on electricity source) • Lower maintenance and operation costs • Starting to become commercially available • Battery costs declining rapidly • BEBs expected to have same upfront cost as diesel by 2030	• Very high bus purchase price • Secondary market value uncertain • Evolving technology with limited commercial application • Electricity distribution infrastructure upgrades needed for rapid charging • Range limitations for some BEB

7 | TRANSPORT IN THE UNITED KINGDOM: THE CASE STUDY

Transportation is a rapidly expanding source of GHG emissions globally, with the UK's transportation sector alone contributing to 24% of the country's total GHG in 2020, making it the largest contributor (Department for Business, Energy, & Industrial Strategy, 2022). To address this issue, it is imperative to adopt and promote electric technologies and zero-emission standards, which can significantly decrease local pollution and GHG from the transportation sector. Using public transportation is one effective way to achieve this reduction, and replacing diesel busses with electric ones is expected to have a major impact on mitigating climate change. Furthermore, air pollution has serious implications for both the environment and human health, and reducing emissions from fossil fuels could reduce health impacts caused by illnesses.

The UK government has taken significant steps toward promoting sustainable transportation with the release of the "low carbon fuel strategy" report by the department for transport. This report lays out the government's plan for reducing carbon emissions from the transportation sector and promoting the adoption of low-carbon fuels, public transport, active travel modes such as cycling and walking, and electric vehicles (Department for Transport, 2022). Reducing emissions from fossil fuels can also help to reduce the negative health impacts associated with air pollution, which has been linked to a range of serious illnesses, including cardiovascular and respiratory diseases.

Unfortunately, the majority of public transportation systems in the UK are still reliant on busses that operate on fossil fuels, which contribute to GHG emissions and air pollution. This underscores the urgent need for investment in the electrification of vehicles, especially in the public transportation sector. By investing in electric busses and other zero-emission technologies, not only can we help reduce GHG emissions and improve public health, but we can also make public transportation a more environmentally sustainable mode of transport. Therefore, it is crucial to consider a comprehensive and integrated approach to reduce GHG emissions in the transportation sector. This includes electrifying the public transportation sector, improving infrastructure, increasing the availability of charging and refueling stations, and promoting public transportation through incentives and education programs. With a focus on sustainability, the UK can create a cleaner, healthier, and more sustainable future.

The study conducted by Akgün et al. (2019) identified policy goals and measures for urban freight transportation (UFT) across 11 cities in the UK. The goals were similar: environmental protection, economic growth, reducing congestion, and creating safe and attractive city centers. The most common policy measures were restrictions, such as congestion charges and low-emission zones. The level of involvement in UFT projects, integration of UFT in local transport policy documents, and intervention in UFT policy measures were found to be interrelated. Collaboration between public authorities and private stakeholders was considered essential for policy learning and achieving transport goals.

8 | METHODS FOR SUSTAINABLE TRANSPORT PLANNING INDEXES

The development of a framework for sustainable analysis requires a comprehensive approach that incorporates multiple criteria to assess the environmental, social, and economic impacts of different decisions. Several methods can be used to achieve this, including cost–benefit analysis (CBA), life-cycle sustainability assessment (LCSA), and multi-criteria analysis (MCA). Cost–benefit analysis (CBA) is a widely used method for calculating the economic benefits and costs of different actions. It assesses the negative outcomes (costs) and positive outcomes (benefits) of a particular decision (Baum, 2012; Prokofieva et al., 2011). Life-cycle sustainability assessment (LCSA) is a method that considers the three dimensions of sustainability—social, economic, and environmental analysis—and gives equal weighting to the indicators within each dimension (Klopffer, 2008; Jeon, 2010; Finkbeiner et al., 2010).

Multi-criteria analysis (MCA) allows different stakeholders to assign their own weightings to the indicators, depending on their priorities and preferences (Karvonen et al., 2017). This method can help prioritize the most important indicators based on the stakeholders' perspectives. In the following section, the process of obtaining a sustainable public transport planning rating from different groups of indicators will be discussed in further detail. The method used to analyze and prioritize these indicators will also be explained in depth.

9 | SUSTAINABLE TRANSPORT PLANNING INDEXES MODEL

In this section, we present a comprehensive mathematical model for evaluating the sustainability of public transport planning using a combination of discrete indicators and as one. The STPI is designed to integrate multiple sustainability indicators from various domains over consecutive years to provide an overall assessment of the sustainability of transport. The following is a step-by-step explanation of the procedure for calculating the STPI index:

9.1 | Selection of the main indicators

First, indexes for environment, social and economic aspects are selected, and the index matrix will be constructed. Assume there are n years, and m indexes, then the original matrix is:

$$X = \{X_{ij}\}_{n*m}(1 \le i \le n, 1 \le j \le m), \tag{1}$$

where, X_{ij} defines the index j in in year i.

9.2 | Normalizing the indicators

There is some inconsistency in units among different indices. It is necessary to transform indexes to dimensionless numbers to have a reasonable comparison between them. This process is called Normalization (Nardo et al., 2005). Normalization of indexes means that each value for each index will be converted to the same unit so that different indexes can be compared (Gjolberg, 2009). The procedure for normalization of each index is explained in Equation (2) for a positive index and (3) for a negative index (Cherchye et al., 2004). N_{ij} is the resulting normalized index and lies between 0 and 1, and N_{ij}^{+} is a normalized indicator for indexes where its increasing value has a positive impact on sustainability, and N_{ij}^{-} is a normalized indicator for value which its increasing has a negative impact on sustainability.

$$N_{ij}^{+} = \frac{X_{ij} - X_{min}}{X_{max} - X_{min}}. \tag{2}$$

$$N_{ij}^{-} = 1 - \frac{X_{ij} - X_{min}}{X_{max} - X_{min}}. \tag{3}$$

9.3 | Judgment on indicators' impact and creating the pair-wise comparison matrix

There are different methods for weighting and combining indicators of each of the triple group of indicators to a composite index; like equal weighting, statistical models, and AHP. Among them, AHP (Ishizaka & Labib, 2011; Saaty, 1980) is the most common method for weighting which is based on experts' judgments. Therefore, to combine indices, the same weights (equal importance) are applied to the groups of indicators to simplify the computations (Jeon et al., 2010; Lee & Huang, 2007). In our study the main STPI indicators are selected and categorized into three main categories of environmental, social, and economic categories, and the different weights of each group of indicators computed and integrated to a combined STPI.

Then, the normalized matrix is weighted according to the relative importance of each group of indicators to the main domain of sustainability using the AHP method (Saaty, 1980). AHP is a widely used technique for Multi-criteria analysis (MCA) analysis and has implemented as weighting method of indicators in this study. This technique of decision-making around index weighting has been successfully implemented using the AHP method (Javanbarg et al., 2012). In AHP, criteria weights are determined using expert judgment around the relative importance of different attributes with respect to the goals through the pairwise comparison matrix. The consistency of the judgment is determined to reduce the bias during the decision-making process (Buenk et al., 2019; Saaty, 1980). The procedure of the AHP weighting method is summarized as follows:

Step 1: Estimate the importance of each indicator in a group of categories against the ideal value using Saaty's ratio system allocated by agencies or experts (Table 4).

Step 2: Create a pair-wise comparison matrix.

Step 3: Derive the normalized pair-wise comparison matrix.

Step 4: Determine the criteria weight vector by averaging all entries per row from the step 3.

The comparison matrix is weighted according to the relative importance of each of the main domains of sustainability using the AHP method. The ranking technique of decision-making problems is successfully implemented using the AHP method. In AHP, criteria weights are determined using expert judgments in terms of the relative importance of different indicators with respect to the goals through the pairwise comparison matrix. This supports the estimation of the importance of each indicator in a group of categories against

TABLE 4 The Saaty's nine-point ratio system (Saaty, 1980)

Intensity of importance	Ratio	Reciprocal
Equally preferred	1	1
Moderately preferred	3	1/3
Strongly preferred	5	1/5
Very strongly preferred	7	1/7
Extremely preferred	9	1/9

the ideal value using Saaty's ratio system allocated by agencies or experts' opinion. Pair-wise comparisons are made between pairs of indicators, asking experts which of the two indicators is more important, and by how much. The preference is expressed on a scale of 1–9, in which 1 indicates equal importance between two indicators, while 9 indicates that one indicator is nine times more important than another.

The AHP has been used to derive the weights of indicators by comparison between which of the two indicators are more important with respect to the overall goal of sustainability. The experts are asked to judge the importance of each indicator with respect to other indicators. The experts' judgments are ranked according to the indicators' importance using the scale of 1 to 9 (Table 4). These comparisons between indicators result in $A = N \times N$ matrix, in which N is the number of indicators. In this matrix, the diagonal value (aii) is equal to 1, and other places in the matrix (aij =1/aji) are ranged between minimum 1/9 (≈0.111) to maximum 9. The Rows in this matrix are labeled as the indicators of each group of sustainability indicators within economic, environmental, social, and the columns are also labeled similarly to the rows.

This matrix shows the relative importance of the row item to the column. If the row is greater than a column (or column is lower than a row), it means that the row is more important than the column. The level of importance defined by the Satty's ratio system (Table 4). The pair-wise comparison matrix A is shown as:

$$A = (a_{ij}), i = j = 1, 2, \ldots, n, \tag{4}$$

$$A = \begin{pmatrix} 1 & a_{12} & a_{13} & \ldots & a_{1n} \\ 1/a_{12} & 1 & \ldots & \ldots & \ldots \\ 1/a_{13} & \ldots & \ddots & a_{ij} & \ldots \\ \ldots & \ldots & a_{ji} = 1/a_{ij} & 1 & \ldots \\ 1/a_{1n} & \ldots & \ldots & \ldots & 1 \end{pmatrix}, \tag{5}$$

where, aij is the relative weight of each indicator and shows how much indicator i is more important than indicator j, and n is the number of indicators.

In this matrix, each entry in the main diagonal is always equal to 1, since aii indicates the importance of indicator i compared to itself. If aij = 1, the importance of indicator i and j is the same. If aij >1, the importance of indicator i is considered higher than the importance of indicator j. If aij <1, the importance of indicator i is considered lower than that of indicator j.

9.4 | Identify the weight of indicators

In the previous Section 9.3, the matrix was filled by the relative weight of each indicator. In this step, the relative weight is standardized to determine the weight vector of each indicator. The weight of each indicator is obtained by dividing the relative weight of each indicator by the sum of relative weights of each column in the pair-wise comparison matrix. The weight vector is calculated by averaging the standardized weight of each indicator of each row (Wi). In this step the sum of the weight of indicators would be equal to 1.

$$\sum_{i=1}^{n} W_i = 1. \tag{6}$$

9.5 | Computing the sustainability of each domain of sustainability indicators

The calculation of sustainability for each group of sustainability categories means environment sustainability (S_{En}), economic sustainability (S_{Ec}), and social sustainability (S_{Sc}) is calculated using Equation (7), where:

$$S_{jk} = \sum_{i=1}^{n} W_{i,k}.N_{ij,k}{}^{+} + \sum_{i=1}^{n} W_{i,k}.N_{ij,k}{}^{-}. \tag{7}$$

k = 1 defines environment sustainability (S_{En}),
k = 2 defines economic sustainability (S_{Ec}),
and k = 3 defines social sustainability (S_{Sc}),
j shows time in year from 2007 to 2019,
$W_{i,k}$ is the weight of indicator i for group k of sustainability,
and, n is the number of indicators in each group of sustainability.

9.6 | Computing sustainability of each domain of sustainability

In the final step, the composite sustainability of STPI is computed by the Equation (8). In this Equation, equal weight (1/3) is considered for each group of sustainability, which means that each group has the same importance for the goal of transport sustainability.

$$STPI_j = \frac{1}{3}.S_{En,j} + \frac{1}{3}.S_{Ec,j} + \frac{1}{3}.S_{Sc,j}. \tag{8}$$

10 | CASE STUDY: SUSTAINABLE TRANSPORT SYSTEM IN THE UINTED KINGDOM

The research program "design and implementation support tools for integrated local land use, transport and the environment (DISTILLATE)" was conducted in the United Kingdom over a period of 4 years with the purpose of improving sustainability in urban transportation and land-use systems (May et al., 2008). The program addressed the institutional, financial, regulatory, information, process, and acceptability barriers to sustainability. It was funded under the Sustainable Urban Environment initiative of the UK Engineering and Physical Sciences Research Council and involved 16 local authority partners. Through surveys and case studies, the program developed guidelines on selecting and prioritizing indicators for sustainable

TABLE 5 Time series of environment indicators from 2007 to 2019

Indicator	Abb	Unit	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Volume of fossil fuels- Diesel	vfDIES	Million liters equivalent	–	24309.00	24370.97	24958.15	25256.29	25832.96	26333.36	27168.09	28412.23	29246.49	29346.41	21063.99	28434.67
Volume of fossil fuels- Petrol	vfPETR	Million liters equivalent	–	22104.00	21216.22	19875.63	18776.10	17465.90	17086.98	16689.78	16433.29	16228.19	15744.53	11512.27	15974.24
Vehicle miles on local bus services	vehMile	Million	1646.28	1646.81	1627.90	1609.81	1588.81	1571.68	1566.90	1550.85	1531.68	1508.90	1467.26	1443.01	1413.37
Ultra-low emission vehicles (ULEVs)–busses & coaches	nULEV	–	–	–	–	5	2	16	23	47	25	59	40	90	121
Greenhouse gas emissions by busses and coaches	eGHG	Million tonnes of CO2 equivalent	4.77	4.22	4.21	4.32	3.99	3.82	3.89	3.89	3.77	3.59	3.43	3.26	3.06
Carbon dioxide emissions by busses and coaches	eCO2	Million tonnes of CO2 equivalent	4.74	4.20	4.19	4.29	3.96	3.79	3.86	3.85	3.73	3.55	3.38	3.22	3.02
Number of busses and coaches–Petrol	nPETR	Thousand	0.15	0.10	0.06	0.04	0.05	0.03	0.05	0.04	0.09	0.09	0.07	0.06	0.07
Number of busses and coaches–Diesel	nDIES	Thousand	11.95	11.57	9.49	8.87	8.47	9.77	8.94	8.17	9.43	9.86	8.56	7.71	6.74
Number of busses and coaches–Gas	nGAS	Thousand	0.00	0.00	0.00	0.01	0.00	0.00	0.05	0.07	0.00	0.00	0.05	0.06	0.08
Number of busses and coaches–Battery electric	nBE	Thousand	0.00	0.00	0.00	0.01	0.01	0.02	0.02	0.05	0.05	0.08	0.06	0.15	0.12
Number of busses and coaches–Other	nOTHER	Thousand	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.06
Total number of busses and coaches–Total	nTOT	Thousand	12.11	11.67	9.54	8.92	8.53	9.82	9.06	8.33	9.57	10.04	8.74	7.97	7.06
Air pollutant emissions by busses and coaches-carbon monoxide (CO)	eCO	Thousand tonnes	7.66	6.64	6.71	6.96	6.60	6.46	6.57	6.13	5.33	4.56	3.87	3.28	2.81

TABLE 5 (Continued)

Indicator	Abb	Unit	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Air pollutant emissions by busses and coaches–Nitrogen oxides (NOx)	eNOx	Thousand tonnes	42.14	37.53	35.73	34.89	31.23	28.31	27.08	24.38	20.44	16.06	13.19	10.81	8.92
Air pollutant emissions by busses and coaches-particulates (PM10)	ePM10	Thousand tonnes	0.68	0.55	0.50	0.47	0.40	0.35	0.33	0.30	0.24	0.19	0.15	0.12	0.10
Air pollutant emissions by busses and coaches-particulates (PM2.5)	ePM2.5	Thousand tonnes	0.68	0.55	0.50	0.47	0.40	0.35	0.33	0.30	0.24	0.19	0.15	0.12	0.10
Air pollutant emissions by busses and coaches-sulfur dioxide (SO2)	eSO2	Thousand tonnes	0.05	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.01	0.01

TABLE 6 Time series of economic indicators from 2007 to 2019

Indicator	Abb	Unit	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Road traffic (vehicle miles) by busses & coaches	Traf	Billion vehicle miles	3.40	3.10	3.10	3.20	3.00	2.80	2.90	2.90	2.80	2.60	2.60	2.50	2.40
Petrol prices per liter in April	prPETR	Pence per liter	91.92	107.56	93.61	119.80	134.74	141.74	136.81	128.79	112.55	106.44	117.30	120.57	124.10
Diesel prices per liter in April	prDIES	Pence per liter	94.73	116.55	101.93	120.99	141.12	147.78	141.27	135.87	119.09	106.94	119.89	124.16	132.85
Operating revenue per vehicle kilometer	revBUS	Pence	214.70	229.67	237.15	239.20	245.70	249.57	255.60	256.13	260.88	263.83	273.37	274.82	266.93
Operating revenue per passenger journey on local bus	revPASG	Pence	110.61	115.94	119.75	120.00	121.03	123.79	123.93	124.31	128.03	129.94	133.54	133.48	134.14
Operating revenue on local bus	revTOT	£ Million	5688.40	6086.89	6212.86	6196.91	6282.39	6312.44	6445.30	6392.52	6430.68	6406.69	6455.09	6382.07	6071.65
Operating cost per vehicle kilometer	oprCOST	Pence	151.48	161.59	168.88	171.49	181.12	185.08	189.68	192.89	196.02	200.20	203.95	214.08	220.79
Local bus fares index	Fare	March 2005 = 100	110.40	113.36	123.08	128.95	135.19	143.15	149.64	153.94	158.58	161.12	163.58	168.45	173.28
Hours worked per week	HRdriv	Hours	43.60	43.00	41.80	42.70	41.20	41.90	41.50	41.60	43.10	42.70	42.10	40.40	40.40
Gross weekly earnings-bus and coach drivers	wGr	£	402.20	402.80	420.60	442.70	430.10	437.00	444.40	443.70	475.70	476.90	489.10	509.60	492.90
Employee jobs in transport industries, staff employed by local bus operators	nEMP	Thousand	133.13	135.88	134.38	132.52	131.63	123.79	123.46	124.18	123.88	122.65	121.10	118.69	117.66
Average age of the bus fleet used as public service vehicles	agFLEET	Year	7.82	7.76	7.58	7.77	7.80	7.72	7.77	7.75	7.67	7.65	7.80	7.72	8.02

TABLE 7 Time series of social indicators from 2007 to 2019

Indicator	Symbol	Unit	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Passenger kilometers on local bus services	kmPASG	Billion	29.66	30.66	30.39	29.90	29.51	28.78	29.69	29.84	29.27	28.63	27.95	27.76	26.47
Passenger journeys on local bus services	jourPASG	Million	5142.79	5249.87	5188.19	5164.27	5190.87	5099.16	5200.56	5142.34	5022.92	4930.54	4833.73	4781.27	4526.39
Passenger journeys on local bus services by region per head of population	netPASG	Journeys per head of population	86.35	87.43	85.80	84.72	84.44	82.40	83.51	81.94	79.40	77.30	75.33	74.07	69.74
Number of disability accessible or low-floor busses used as public service vehicles	disACC	Thousand	29.45	32.45	34.57	35.94	37.13	38.17	39.43	39.68	39.36	39.76	39.62	38.83	38.10
Total concessionary passenger journeys	jourTOT	Million	1642.66	1739.81	1772.05	1771.50	1802.79	1763.93	1794.06	1758.61	1715.17	1692.14	1637.12	1633.52	1553.54
Elderly and disabled concessionary passenger journeys	jourELD	Million	1135.18	1214.88	1249.30	1235.93	1258.31	1214.74	1235.78	1222.12	1190.97	1171.66	1135.27	1136.88	1078.38
Average bus occupancy on local bus services–calculated as passenger miles divided by vehicle miles	busOCU	Number	11.00	11.30	11.30	11.10	11.20	11.30	11.60	11.60	11.30	11.30	11.50	11.70	11.70

TABLE 8 Normalized comparison matrix for assessment of environment indicators

Indicator	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
vfDIES	…	0.61	0.60	0.53	0.49	0.42	0.36	0.26	0.11	0.01	0.00	1.00	0.11
vfPETR	…	0.00	0.08	0.21	0.31	0.44	0.47	0.51	0.54	0.55	0.60	1.00	0.58
vehMile	0.00	0.00	0.08	0.16	0.25	0.32	0.34	0.41	0.49	0.59	0.77	0.87	1.00
nULEV	…	…	…	0.97	1.00	0.88	0.82	0.62	0.81	0.52	0.68	0.26	0.00
eGHG	0.00	0.32	0.33	0.26	0.46	0.56	0.52	0.52	0.59	0.69	0.79	0.88	1.00
eCO2	0.00	0.31	0.32	0.26	0.46	0.55	0.52	0.52	0.59	0.69	0.79	0.88	1.00
nPETR	0.00	0.42	0.80	0.91	0.88	1.00	0.86	0.92	0.52	0.48	0.68	0.78	0.71
nDIES	0.00	0.07	0.47	0.59	0.67	0.42	0.58	0.72	0.48	0.40	0.65	0.81	1.00
nGAS	0.95	1.00	1.00	0.92	0.97	1.00	0.38	0.09	1.00	0.96	0.42	0.26	0.00
nBE	0.02	0.00	0.01	0.03	0.07	0.11	0.15	0.31	0.31	0.52	0.43	1.00	0.79
nOTHER	1.00	1.00	1.00	0.98	0.98	1.00	1.00	1.00	0.98	0.95	0.97	0.98	0.00
nTOT	0.00	0.09	0.51	0.63	0.71	0.45	0.60	0.75	0.50	0.41	0.67	0.82	1.00
eCO	0.00	0.21	0.20	0.14	0.22	0.25	0.22	0.32	0.48	0.64	0.78	0.90	1.00
eNOx	0.00	0.14	0.19	0.22	0.33	0.42	0.45	0.53	0.65	0.79	0.87	0.94	1.00
ePM10	0.00	0.23	0.32	0.37	0.48	0.56	0.59	0.66	0.75	0.84	0.90	0.96	1.00
ePM2.5	0.00	0.23	0.32	0.37	0.48	0.56	0.59	0.66	0.75	0.84	0.90	0.96	1.00
eSO2	0.00	0.87	0.83	0.82	0.84	0.90	0.91	0.92	0.91	0.91	0.95	0.98	1.00

TABLE 9 Normalized comparison matrix for assessment of economic indicators

Indicator	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Traf	0.00	0.30	0.30	0.20	0.40	0.60	0.50	0.50	0.60	0.80	0.80	0.90	1.00
prPETR	0.00	0.31	0.03	0.56	0.86	1.00	0.90	0.74	0.41	0.29	0.51	0.58	0.65
prDIES	0.00	0.41	0.14	0.49	0.87	1.00	0.88	0.78	0.46	0.23	0.47	0.55	0.72
revBUS	0.00	0.25	0.37	0.41	0.52	0.58	0.68	0.69	0.77	0.82	0.98	1.00	0.87
revPASG	0.00	0.23	0.39	0.40	0.44	0.56	0.57	0.58	0.74	0.82	0.97	0.97	1.00
revTOT	0.00	0.52	0.68	0.66	0.77	0.81	0.99	0.92	0.97	0.94	1.00	0.90	0.50
oprCOST	1.00	0.85	0.75	0.71	0.57	0.52	0.45	0.40	0.36	0.30	0.24	0.10	0.00
Fare	1.00	0.95	0.80	0.70	0.61	0.48	0.38	0.31	0.23	0.19	0.15	0.08	0.00
HRdriv	1.00	0.81	0.44	0.72	0.25	0.47	0.34	0.38	0.84	0.72	0.53	0.00	0.00
wGr	0.00	0.01	0.17	0.38	0.26	0.32	0.39	0.39	0.68	0.70	0.81	1.00	0.84
nEMP	0.85	1.00	0.92	0.82	0.77	0.34	0.32	0.36	0.34	0.27	0.19	0.06	0.00
agFLEET	0.46	0.58	1.00	0.56	0.50	0.68	0.57	0.60	0.79	0.84	0.50	0.68	0.00

TABLE 10 Normalized comparison matrix for assessment of social indicators

Indicator	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
kmPASG	0.24	0.00	0.06	0.18	0.27	0.45	0.23	0.19	0.33	0.48	0.65	0.69	1.00
jourPASG	0.15	0.00	0.09	0.12	0.08	0.21	0.07	0.15	0.31	0.44	0.58	0.65	1.00
netPASG	0.06	0.00	0.09	0.15	0.17	0.28	0.22	0.31	0.45	0.57	0.68	0.76	1.00
disACC	0.00	0.29	0.50	0.63	0.74	0.85	0.97	0.99	0.96	1.00	0.99	0.91	0.84
jourTOT	0.36	0.75	0.88	0.87	1.00	0.84	0.96	0.82	0.65	0.56	0.34	0.32	0.00
jourELD	0.32	0.76	0.95	0.88	1.00	0.76	0.87	0.80	0.63	0.52	0.32	0.33	0.00
busOCU	0.00	0.43	0.43	0.14	0.29	0.43	0.86	0.86	0.43	0.43	0.71	1.00	1.00

TABLE 11 Pair-Wise comparison matrix for assessment of environment indicators

Indicators	vfDIES	vfPETR	vehMile	nULEV	eGHG	eCO2	nPETR	nDIES	nGAS	nBE	nOTHER	nTOT	eCO	eNOx	ePM10	ePM2.5	eSO2
vfDIES	1	1	1	1/9	1/9	1/9	1/3	1/3	1/3	1/9	1/3	1/3	1/7	1/7	1/7	1/7	1/7
vfPETR	1	1	1	1/9	1/9	1/9	1/3	1/3	1/3	1/9	1/3	1/3	1/7	1/7	1/7	1/7	1/7
vehMile	1	1	1	1/3	1/5	1/5	1	1	1	1/3	1	1	1/7	1/7	1/7	1/7	1/7
nULEV	9	9	3	1	1/9	1/9	3	3	3	1	5	5	1/7	1/7	1/7	1/7	1/7
eGHG	9	9	5	9	1	1	5	5	5	5	5	5	1	1	1	1	1
eCO2	9	9	5	9	1	1	5	5	5	5	5	5	1	1	1	1	1
nPETR	3	3	1	1/3	1/5	1/5	1	1	1	1/9	1	1	1/5	1/5	1/5	1/5	1/5
nDIES	3	3	1	1/3	1/5	1/5	1	1	1	1/9	1	1	1/5	1/5	1/5	1/5	1/5
nGAS	3	3	1	1/3	1/5	1/5	1	1	1	1/9	1	1	1/5	1/5	1/5	1/5	1/5
nBE	9	9	3	1	1/5	1/5	9	9	9	1	9	9	1/5	1/5	1/5	1/5	1/5
nOTHER	3	3	1	1/5	1/5	1/5	1	1	1	1/9	1	1	1/5	1/5	1/5	1/5	1/5
nTOT	3	3	1	1/5	1/5	1/5	1	1	1	1/9	1	1	1/5	1/5	1/5	1/5	1/5
eCO	7	7	7	7	1	1	5	5	5	5	5	5	1	1	1	1	1
eNOx	7	7	7	7	1	1	5	5	5	5	5	5	1	1	1	1	1
ePM10	7	7	7	7	1	1	5	5	5	5	5	5	1	1	1	1	1
ePM2.5	7	7	7	7	1	1	5	5	5	5	5	5	1	1	1	1	1
eSO2	7	7	7	7	1	1	5	5	5	5	5	5	1	1	1	1	1

TABLE 12 Pair-Wise comparison matrix for assessment of economic indicators

Indicators	Traf	prPETR	prDIES	revBUS	revPASG	revTOT	oprCOST	Fare	HRdriv	wGr	nEMP	agFLEET
Traf	1	7	7	7	7	7	7	7	7	1/5	7	7
prPETR	1/7	1	1	3	3	3	3	3	2	1/3	2	3
prDIES	1/7	1	1	3	3	3	3	3	2	1/3	2	3
revBUS	1/7	1/3	1/3	1	1	1	1	1/5	2	1/3	2	1
revPASG	1/7	1/3	1/3	1	1	1	1	1/5	2	1/3	2	1
revTOT	1/7	1/3	1/3	1	1	1	1	1/5	2	1/3	2	1
oprCOST	1/7	1/3	1/3	1	1	1	1	2	2	1/3	2	1/2
Fare	1/7	1/3	1/3	5	5	5	1/2	1	1/3	1/3	3	1
HRdriv	1/7	1/2	1/2	1/2	1/2	1/2	1/2	1	1	1/7	1	1
wGr	5	3	3	3	3	3	3	3	7	1	3	1
nEMP	1/7	1/2	1/2	1/2	1/2	1/2	1/2	1/3	1	1/3	1	1
agFLEET	1/7	1/3	1/3	1	1	1	2	1	1	1	1	1

TABLE 13 Pair-Wise comparison matrix for assessment of social indicators

Indicators	kmPASG	jourPASG	netPASG	disACC	jourTOT	jourELD	busOCU
kmPASG	1	1	1/7	1/6	1	1	1/5
jourPASG	1	1	7	1/5	1	1	1/3
netPASG	7	1/7	1	1/5	1	1	1/3
disACC	6	5	5	1	1	1	1
jourTOT	1	1	1	1	1	1	1
jourELD	1	1	1	1	1	1	1
busOCU	5	3	3	1	1	1	1

development in transportation and created an audit tool to assess the quality of proposed indicators. The program also addressed the inconsistency in monitoring progress toward sustainable transport policy objectives between policy sectors and layers of government. The findings from the program were useful for decision-making and helped in selecting appropriate indicators for decision-support tools. The paper concludes by outlining the approach for implementing the products developed through the program. In another study conducted in the United Kingdom, Castillo and Pitfield (2010) utilized the analytic hierarchy process (AHP) to determine the significance of sustainable transport indicators based on the views of transport planners and academics. The study introduced the evaluative and logical approach to sustainable transport indicator compilation (ELASTIC) as a framework for identifying and selecting appropriate indicators to monitor and report progress toward sustainable transport. ELASTIC considers five crucial criteria, including measurability, ease of availability, speed of availability, interpretability, and the ability to isolate transport's impact. The framework is designed to meet the principles of stakeholder participation and context specificity in sustainability, but there is a possibility of bias toward one or more sustainability dimensions.

In this study, we analyzed the sustainability of the United Kingdom's public transit system using the STPI methodology. Statistical data for environmental, economic, and social indicators were obtained from the www.gov.uk website for the period from 2007 to 2019. The selection of indicators is a crucial step in sustainability analysis, and indicators for the environment, social, and economic aspects were chosen and extracted from the UK website. The results are obtained by using a comprehensive and systematic approach, which involves normalizing and weighting sustainability indicators, and combining them into a composite index that captures the environmental, economic, and social dimensions of sustainability.

The original matrix for economic, environment and social indicators including abbreviations (Abb) and units are presented for 13 years from 2007 to 2019. The first step in the development of the STPI is the selection of indicators for each aspect of sustainability, such as environment, economic, and social indicators. Table 5 shows environmental indicators; Table 6 shows economic indicators, and Table 7 shows social indicators used in this study. In the following steps, the notated Abb were used to define each indicator. These indicators should be chosen based on the local context and specific sustainability goals of the public transport system. A matrix is then constructed to represent the selected indicators over multiple years, enabling a comprehensive analysis of the system's sustainability over time.

The next step involves normalizing the selected indicators to transform them into dimensionless numbers, making it possible to compare them in a meaningful way and determine their relative importance. Normalization is performed to transform the indexes into dimensionless numbers for comparison purposes. This involves converting each value for each index into the same unit using positive and negative normalization procedures. This step is done using

TABLE 14 Standardized pair-wise comparison matrix to derive the weight of the environment indicators

Indicators	vfDIES	vfPETR	vehMile	nULEV	eGHG	eCO2	nPETR	nDIES	nGAS	nBE	nOTHER	nTOT	eCO	eNOx	ePM10	ePM2.5	eSO2	Weight
vfDIES	1	1	1	1/9	1/9	1/9	1/3	1/3	1/3	1/9	1/3	1/3	1/7	1/7	1/7	1/7	1/7	
vfPETR	1	1	1	1/9	1/9	1/9	1/3	1/3	1/3	1/9	1/3	1/3	1/7	1/7	1/7	1/7	1/7	
vehMile	1	1	1	1/3	1/5	1/5	1	1	1	1/3	1	1	1/7	1/7	1/7	1/7	1/7	
nULEV	9	9	3	1	1/9	1/9	3	3	3	1	5	5	1/7	1/7	1/7	1/7	1/7	
eGHG	9	9	5	9	1	1	5	5	5	5	5	5	1	1	1	1	1	
eCO2	9	9	5	9	1	1	5	5	5	5	5	5	1	1	1	1	1	
nPETR	3	3	1	1/3	1/5	1/5	1	1	1	1/9	1	1	1/5	1/5	1/5	1/5	1/5	
nDIES	3	3	1	1/3	1/5	1/5	1	1	1	1/9	1	1	1/5	1/5	1/5	1/5	1/5	
nGAS	3	3	1	1/3	1/5	1/5	1	1	1	1/9	1	1	1/5	1/5	1/5	1/5	1/5	
nBE	9	9	3	1	1/5	1/5	9	9	9	1	9	9	1/5	1/5	1/5	1/5	1/5	
nOTHER	3	3	1	1/5	1/5	1/5	1	1	1	1/9	1	1	1/5	1/5	1/5	1/5	1/5	
nTOT	3	3	1	1/5	1/5	1/5	1	1	1	1/9	1	1	1/5	1/5	1/5	1/5	1/5	
eCO	7	7	7	7	1	1	5	5	5	5	5	5	1	1	1	1	1	
eNOx	7	7	7	7	1	1	5	5	5	5	5	5	1	1	1	1	1	
ePM10	7	7	7	7	1	1	5	5	5	5	5	5	1	1	1	1	1	
ePM2.5	7	7	7	7	1	1	5	5	5	5	5	5	1	1	1	1	1	
eSO2	7	7	7	7	1	1	5	5	5	5	5	5	1	1	1	1	1	
SUM	89.00	89.00	59.00	56.96	8.73	8.73	53.67	53.67	53.67	38.11	55.67	55.67	8.77	8.77	8.77	8.77	8.77	
vfDIES	0.01	0.01	0.02	0.00	0.01	0.01	0.01	0.01	0.01	0.00	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.01
vfPETR	0.01	0.01	0.02	0.00	0.01	0.01	0.01	0.01	0.01	0.00	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.01
vehMile	0.01	0.01	0.02	0.01	0.02	0.02	0.02	0.02	0.02	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
nULEV	0.10	0.10	0.05	0.02	0.01	0.01	0.06	0.06	0.06	0.03	0.09	0.09	0.02	0.02	0.02	0.02	0.02	0.04
eGHG	0.10	0.10	0.08	0.16	0.11	0.11	0.09	0.09	0.09	0.13	0.09	0.09	0.11	0.11	0.11	0.11	0.11	0.11
eCO2	0.10	0.10	0.08	0.16	0.11	0.11	0.09	0.09	0.09	0.13	0.09	0.09	0.11	0.11	0.11	0.11	0.11	0.11
nPETR	0.03	0.03	0.02	0.01	0.02	0.02	0.02	0.02	0.02	0.00	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
nDIES	0.03	0.03	0.02	0.01	0.02	0.02	0.02	0.02	0.02	0.00	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
nGAS	0.03	0.03	0.02	0.01	0.02	0.02	0.02	0.02	0.02	0.00	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
nBE	0.10	0.10	0.05	0.02	0.02	0.02	0.17	0.17	0.17	0.03	0.16	0.16	0.02	0.02	0.02	0.02	0.02	0.08
nOTHER	0.03	0.03	0.02	0.00	0.02	0.02	0.02	0.02	0.02	0.00	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
nTOT	0.03	0.03	0.02	0.00	0.02	0.02	0.02	0.02	0.02	0.00	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
eCO	0.08	0.08	0.12	0.12	0.11	0.11	0.09	0.09	0.09	0.13	0.09	0.09	0.11	0.11	0.11	0.11	0.11	0.11
eNOx	0.08	0.08	0.12	0.12	0.11	0.11	0.09	0.09	0.09	0.13	0.09	0.09	0.11	0.11	0.11	0.11	0.11	0.11

(Continues)

TABLE 14 (Continued)

Indicators	vfDIES	vfPETR	vehMile	nULEV	eGHG	eCO2	nPETR	nDIES	nGAS	nBE	nOTHER	nTOT	eCO	eNOx	ePM10	ePM2.5	eSO2	Weight
ePM10	0.08	0.08	0.12	0.12	0.11	0.11	0.09	0.09	0.09	0.13	0.09	0.09	0.11	0.11	0.11	0.11	0.11	0.11
ePM2.5	0.08	0.08	0.12	0.12	0.11	0.11	0.09	0.09	0.09	0.13	0.09	0.09	0.11	0.11	0.11	0.11	0.11	0.11
eSO2	0.08	0.08	0.12	0.12	0.11	0.11	0.09	0.09	0.09	0.13	0.09	0.09	0.11	0.11	0.11	0.11	0.11	0.11

Equations (2) and (3), depending on whether the increasing value of the indicators has a positive or negative impact on the overall goal of sustainability. The results of normalized indicators for different measurements of sustainability are listed in Tables 8–10.

The next step is to design the pair-wise comparison matrix. As explained in Section 3, the comparison matrix is weighted according to the relative importance of on each of the main domains of sustainability using the AHP method. To combine the indices, the AHP method is used to weight the normalized matrix based on the relative importance of each group of indicators. This involves estimating the importance of each indicator using Saaty's ratio system and creating a pair-wise comparison matrix. The criteria weight vector is then determined by averaging all entries per row. Tables 11–13 show the pair-comparison matrix for environment, economic, and social dimension.

In Table 11, experts believed that GHG by busses and coaches (eGHG) in the row was extremely important (nine times more important) than the volume of fossil fuels in the column (vfDIES). However, importance of vfDIES is nine times lower than the number of ultra-low emission busses and coaches (ULEVs) (or number od low emission busses and coaches nine times are more important than vfDIES).

To derive the weight of each indicator, the pair-wise comparison matrix standardized to obtain the weight of each indicator as explained in Section 9.4. The pair-wise comparison matrix is standardized by dividing into the sum of ratios of each column. The weight of each indicator is calculated by averaging the pair-wise comparison matrix of each row. The procedure to compute the weight of each indicator are listed in Tables 14–16.

Next, the sustainability of each group of sustainability is defined using Equation (7), by multiplying the weight of each indicator (vector weight of Tables 6–14) by the normalized indicators of Tables 8–10 to obtain environmental sustainability (Table 17), economic sustainability (Table 18), and social sustainability (Table 19).

Tables 17–19 show the results of environmental sustainability of 17 indicators, 12 economic indicators, and 7 social indicators in order. The results of sustainability for each category shows the increasing trend for each domain of sustainability. It is difficult to interpret the results of each group, and these should be integrated to a composite index to have a meaningful comparison of the sustainability over these years. Therefore, the last step is weighting and combining indices is to create the STPI for sustainable development of the public transportation system in the United Kingdom. An equal weight of 1/3 was used to three dimensions of sustainability to derive STPI as explained in Equation (8).

The higher values of STPI (close to 1) indicates a positive improvement for sustainability. The results show that the STPI is high in the specific year if the results of sustainability of that group of indicators is high. This method enables us to interpret the relative impact of each domain of sustainability by providing discrete indicators with different values and units. Table 20 and Figure 1 show the results of STPI for public transport in the UK from 2007 to 2019. Environmental factors outweighed economic factors with social factors showing a peak in 2013–14. These patterns are drawn from assessments of data and expert weightings and can be further connected to policy initiatives.

TABLE 15 Standardized pair-wise comparison matrix for assessment of economic indicators

Indicator	Traf	prPETR	prDIES	revBUS	revPASG	revTOT	oprCOST	Fare	HRdriv	wGr	nEMP	agFLEET	Weight
Traf	1	7	7	7	7	7	7	7	7	1/5	7	7	
prPETR	1/7	1	1	3	3	3	3	3	2	1/3	2	3	
prDIES	1/7	1	1	3	3	3	3	3	2	1/3	2	3	
revBUS	1/7	1/3	1/3	1	1	1	1	1/5	2	1/3	2	1	
revPASG	1/7	1/3	1/3	1	1	1	1	1/5	2	1/3	2	1	
revTOT	1/7	1/3	1/3	1	1	1	1	1/5	2	1/3	2	1	
oprCOST	1/7	1/3	1/3	1	1	1	1	2	2	1/3	2	1/2	
Fare	1/7	1/3	1/3	5	5	5	1/2	1	1/3	1/3	3	1	
HRdriv	1/7	1/2	1/2	1/2	1/2	1/2	1/2	1	1	1/7	1	1	
wGr	5	3	3	3	3	3	3	3	7	1	3	1	
nEMP	1/7	1/2	1/2	1/2	1/2	1/2	1/2	1/3	1	1/3	1	1	
agFLEET	1/7	1/3	1/3	1	1	1	2	1	1	1	1	1	
SUM	7.43	15.00	15.00	27.00	27.00	27.00	23.50	21.93	29.33	5.01	28.00	21.50	
Traf	0.13	0.47	0.47	0.26	0.26	0.26	0.30	0.32	0.24	0.04	0.25	0.33	0.28
prPETR	0.02	0.07	0.07	0.11	0.11	0.11	0.13	0.14	0.07	0.07	0.07	0.14	0.09
prDIES	0.02	0.07	0.07	0.11	0.11	0.11	0.13	0.14	0.07	0.07	0.07	0.14	0.09
revBUS	0.02	0.02	0.02	0.04	0.04	0.04	0.04	0.01	0.07	0.07	0.07	0.05	0.04
revPASG	0.02	0.02	0.02	0.04	0.04	0.04	0.04	0.01	0.07	0.07	0.07	0.05	0.04
revTOT	0.02	0.02	0.02	0.04	0.04	0.04	0.04	0.01	0.07	0.07	0.07	0.05	0.04
oprCOST	0.02	0.02	0.02	0.04	0.04	0.04	0.04	0.09	0.07	0.07	0.07	0.02	0.04
Fare	0.02	0.02	0.02	0.19	0.19	0.19	0.02	0.05	0.01	0.07	0.11	0.05	0.08
HRdriv	0.02	0.03	0.03	0.02	0.02	0.02	0.02	0.05	0.03	0.03	0.04	0.05	0.03
wGR	0.67	0.20	0.20	0.11	0.11	0.11	0.13	0.14	0.24	0.20	0.11	0.05	0.19
nEMP	0.02	0.03	0.03	0.02	0.02	0.02	0.02	0.02	0.03	0.07	0.04	0.05	0.03
agFLEET	0.02	0.02	0.02	0.04	0.04	0.04	0.09	0.05	0.03	0.20	0.04	0.05	0.05

TABLE 16 Standardized pair-wise comparison matrix for assessment of social indicators

Indicator	kmPASG	jourPASG	netPASG	disACC	jourTOT	jourELD	busOCU	Weight
kmPASG	1	1	1/7	1/6	1	1	1/5	
jourPASG	1	1	7	1/5	1	1	1/3	
netPASG	7	1/7	1	1/5	1	1	1/3	
disACC	6	5	5	1	1	1	1	
jourTOT	1	1	1	1	1	1	1	
jourELD	1	1	1	1	1	1	1	
busOCU	5	3	3	1	1	1	1	
SUM	22.00	12.14	18.14	4.57	7.00	7.00	4.87	
kmPASG	0.05	0.08	0.01	0.04	0.14	0.14	0.04	0.07
jourPASG	0.05	0.08	0.39	0.04	0.14	0.14	0.07	0.13
netPASG	0.32	0.01	0.06	0.04	0.14	0.14	0.07	0.11
disACC	0.27	0.41	0.28	0.22	0.14	0.14	0.21	0.24
jourTOT	0.05	0.08	0.06	0.22	0.14	0.14	0.21	0.13
jourELD	0.05	0.08	0.06	0.22	0.14	0.14	0.21	0.13
busOCU	0.23	0.25	0.17	0.22	0.14	0.14	0.21	0.19

TABLE 17 Environmental sustainability from 2007 to 2019

Year	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
vfDIES	…	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00
vfPETR	…	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.01
vehMile	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02
nULEV	…	…	…	0.04	0.04	0.04	0.04	0.03	0.04	0.02	0.03	0.01	0.00
eGHG	0.00	0.03	0.04	0.03	0.05	0.06	0.06	0.06	0.06	0.07	0.08	0.10	0.11
eCO2	0.00	0.03	0.03	0.03	0.05	0.06	0.06	0.06	0.06	0.07	0.09	0.10	0.11
nPETR	0.00	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.01	0.01	0.01	0.02	0.01
nDIES	0.00	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02
nGAS	0.02	0.02	0.02	0.02	0.02	0.02	0.01	0.00	0.02	0.02	0.01	0.01	0.00
nBE	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.02	0.02	0.04	0.03	0.08	0.06
nOTHER	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.00
nTOT	0.00	0.00	0.01	0.01	0.01	0.01	0.01	0.02	0.01	0.01	0.01	0.02	0.02
eCO	0.00	0.02	0.02	0.02	0.02	0.03	0.02	0.03	0.05	0.07	0.08	0.10	0.11
eNOx	0.00	0.01	0.02	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09	0.10	0.11
ePM10	0.00	0.02	0.03	0.04	0.05	0.06	0.06	0.07	0.08	0.09	0.09	0.10	0.11
ePM2.5	0.00	0.02	0.03	0.04	0.05	0.06	0.06	0.07	0.08	0.09	0.09	0.10	0.11
eSO2	0.00	0.09	0.09	0.09	0.09	0.09	0.10	0.10	0.10	0.10	0.10	0.10	0.11
Environmental sustainability	0.04	0.30	0.35	0.40	0.49	0.54	0.53	0.57	0.64	0.71	0.78	0.89	0.88

The results of the STPI show an increasing trend in the sustainability of public transportation in the United Kingdom from 2007 to 2019. The higher values of the STPI indicate a positive improvement in sustainability, with a peak in 2013–14 for social factors. These patterns are based on assessments of data and expert weightings and can be linked to policy initiatives that may have contributed to the improvement in sustainability.

The study highlights the importance of using a comprehensive and systematic approach to measure sustainability and provides a useful tool for policy makers, transportation planners, and researchers to understand the sustainability of public transportation systems. The results of the study can also be used to inform future policy decisions and initiatives aimed at improving the sustainability of public transportation systems.

TABLE 18 Economic sustainability from 2007 to 2019

Year	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Traf	0.00	0.08	0.08	0.06	0.11	0.17	0.14	0.14	0.17	0.22	0.22	0.25	0.28
prPETR	0.00	0.03	0.00	0.05	0.08	0.09	0.08	0.07	0.04	0.03	0.05	0.05	0.06
prDIES	0.00	0.04	0.01	0.05	0.08	0.09	0.08	0.07	0.04	0.02	0.04	0.05	0.07
revBUS	0.00	0.01	0.01	0.02	0.02	0.02	0.03	0.03	0.03	0.03	0.04	0.04	0.03
revPASG	0.00	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.03	0.04	0.04	0.04
revTOT	0.00	0.02	0.03	0.03	0.03	0.03	0.04	0.04	0.04	0.04	0.04	0.04	0.02
oprCOST	0.04	0.04	0.03	0.03	0.03	0.02	0.02	0.02	0.02	0.01	0.01	0.00	0.00
Fare	0.08	0.07	0.06	0.05	0.05	0.04	0.03	0.02	0.02	0.01	0.01	0.01	0.00
HRdriv	0.03	0.02	0.01	0.02	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.00	0.00
wGR	0.00	0.00	0.03	0.07	0.05	0.06	0.07	0.07	0.13	0.13	0.15	0.19	0.16
nEMP	0.03	0.03	0.03	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.00
agFLEET	0.02	0.03	0.05	0.03	0.03	0.04	0.03	0.03	0.04	0.04	0.03	0.04	0.00
Economic sustainability	0.20	0.33	0.30	0.39	0.47	0.56	0.52	0.49	0.53	0.55	0.62	0.67	0.65

TABLE 19 Social sustainability from 2007 to 2019

Year	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
kmPASG	0.02	0.00	0.00	0.01	0.02	0.03	0.02	0.01	0.02	0.03	0.05	0.05	0.07
jourPASG	0.02	0.00	0.01	0.02	0.01	0.03	0.01	0.02	0.04	0.06	0.07	0.08	0.13
netPASG	0.01	0.00	0.01	0.02	0.02	0.03	0.02	0.03	0.05	0.06	0.08	0.08	0.11
disACC	0.00	0.07	0.12	0.15	0.18	0.20	0.23	0.24	0.23	0.24	0.24	0.22	0.20
jourTOT	0.05	0.10	0.11	0.11	0.13	0.11	0.12	0.10	0.08	0.07	0.04	0.04	0.00
jourELD	0.04	0.10	0.12	0.11	0.13	0.10	0.11	0.10	0.08	0.07	0.04	0.04	0.00
busOCU	0.00	0.08	0.08	0.03	0.06	0.08	0.17	0.17	0.08	0.08	0.14	0.19	0.19
Social sustainability	0.13	0.34	0.46	0.45	0.54	0.58	0.68	0.68	0.59	0.61	0.65	0.71	0.71

TABLE 20 Time series of the environment sustainability, economic sustainability, social sustainability, and STPI

Sustainability dimension	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
S_{En}	0.04	0.30	0.35	0.40	0.49	0.54	0.53	0.57	0.64	0.71	0.78	0.89	0.88
S_{Ec}	0.20	0.37	0.36	0.43	0.50	0.59	0.54	0.51	0.57	0.59	0.63	0.70	0.66
S_{Sc}	0.13	0.34	0.46	0.45	0.54	0.58	0.68	0.68	0.59	0.61	0.65	0.71	0.71
STPI	0.12	0.34	0.39	0.42	0.51	0.57	0.59	0.59	0.60	0.64	0.69	0.76	0.75

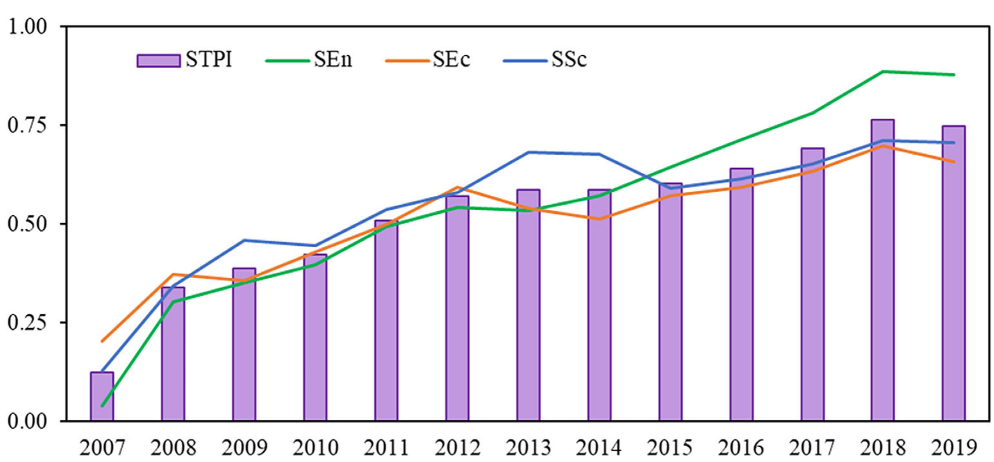

FIGURE 1 Time series of sustainability including environment, economic, social, and STPI for the UK public transport development [Colour figure can be viewed at wileyonlinelibrary.com]

11 | CONCLUSION

This study presents a methodology for developing the STPI which provides a comprehensive assessment of the sustainability of a public transport system by considering its environmental, social, and economic impacts. The methodology has been tested in a case study using data from the UK and provides valuable information for promoting sustainable public transport planning and development.

Theoretically, the STPI offers a useful framework for understanding the interplay between environmental, social, and economic factors in public transport systems, which is crucial for promoting sustainability. By providing a comprehensive assessment of sustainability over time, the STPI can help decision-makers make informed choices about public transport development, and provide insights into the sustainability of existing systems.

For practitioners, the STPI offers a valuable tool for promoting sustainable public transport planning and development. It can be applied to a wide range of transit and transportation challenges. By using the methodology, practitioners can gather comprehensive data on the sustainability of public transport systems, analyze the data to understand trends and patterns, and make informed decisions about public transport planning and development. The results of the case study in the United Kingdom demonstrate the potential of the STPI as a tool for promoting sustainable public transport.

This methodology was tested in a case study using data from the United Kingdom to assess the growth of green public transport. The results show that the STPI provides a valuable tool for promoting sustainable public transport planning and development, and can be used to monitor the sustainability of existing systems over time. The same categories of data can be used for other countries, regions, or cities, providing a means for analysts to consider the factors driving and resulting from the electrification of public transport. In conclusion, the STPI offers a useful and practical framework for assessing the sustainability of public transport systems, taking into account the interplay between environmental, social, and economic factors.

Future research in this area can focus on a number of important aspects. One avenue of research could be to expand the methodology to consider more aspects of sustainability, such as environmental justice, land-use planning, and intermodal connectivity. Additionally, the methodology could be further developed to enable the integration of life cycle assessments (LCAs) and environmental impact assessments (EIAs) into the STPI. Future research can build on the comparison of the sustainability of different types of public transport systems, such as rail-based systems and bus-based systems. This would provide valuable information to decision-makers in choosing the most sustainable transportation options for their communities.

In conclusion, the development of the STPI presents a valuable opportunity for promoting sustainable public transport, and for reducing the environmental impact of transportation. The STPI provides a useful framework for understanding the interplay between environmental, social, and economic factors in public transport systems, and offers a valuable tool for promoting sustainable public transport planning and development.

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CONFLICT OF INTEREST STATEMENT

The authors had full access to all of the data in this study and take complete responsibility for the integrity of the data and the accuracy of the data analysis.

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