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A Method for Assessment of Optimum Transport Sustainability Index of an Indian City

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The estimated Transport Sustainability Index (TSI) of a city is dependent upon the weighted performance of several indicators that can be grouped into environmental, social, economic, or other pillars and signifies the extent to which the city is live-able without creating any adverse future impact. Several researchers have estimated TSI in their own regions using varying indicators, weighting techniques, and aggregation methods for Pillar Sustainability Indices (PSIs). After studying a total of 354 indicators used by different researchers, this study identifies a set of 34 indicators under four pillars of sustainability, following 10-point selection criteria. The identified indicators have been appropriately grouped and attributed to three separate categories of million plus Indian cities. The study proposes to generalize a certain group of indicators for all the cities in a particular category. This study also validates the relevance of proposed set of indicators, their grouping under four pillars and their allocation as per city categories by conducting an Expert Opinion Survey. Studies on estimation of optimum value of TSI at holistic level have not been found readily in literature, though some researchers have considered optimization at indicator level such as network congestion, cost of multimodal travelling, etc. This study proposes a method for arriving at an optimum value of TSI of a typical city, deploying Principal Component Analysis (PCA) method for assigning weights to utility value of indicators and fuzzy logic technique for aggregation of PSIs. The optimum value of TSI is a valuable estimate to the policy planners since it helps them to deploy just adequate resources for improving the city's transport sustainability, minimizing wastage and maximizing savings in resources.

Keywords: Expert opinion survey, Fuzzy logic, Indicator weightages, Pillars of sustainability, Utility values

Introduction

Transport sustainability traditionally impinges upon three pillars[1,2] viz. (a) *environment* because of emissions and energy consumption by vehicles and land use by transport infrastructure etc., (b) *social* as it involves safety, security, mobility and accessibility issues pertaining to users, and (c) *economy* as it involves costs and time spent by commuters on travel, generation of employment opportunities for people from public transportation, etc. However, the impact of some important and relevant parameters such as, alternate fuel vehicles, clean transport fuels and the related R&D investments therein on transport sustainability have not been adequately focused by the researchers. Besides, deployment of Intelligent Transport Systems (ITS) technologies related to infrastructure, pricing, vehicle detection, congestion, etc. affects transport sustainability significantly and therefore, it is essential to assess their impact too. These features are best captured by non-traditional sustainability pillars like organizational, institutional or technological ones.[3,4] This study proposes to consider these additional pillars for a holistic assessment of transport sustainability.

The choice of appropriate indicators which are truly reflective of the region or the city being studied are also important for estimation of sustainability index. The indicators must neither be too few to miss out important features nor too many to make the study complex that consumes a higher amount of time and resources.[1] The indicators must also be chosen as per an appropriate and suitable criterion, that is tailored according to specific needs of the study at hand. As reported by Tanquay *et al.*[5] an indicator must be SMART, i.e. "Specific – be clear and concise and avoid vague terms; Measurable – quantifiable indicators to measure progress; Achievable (Assignable) – someone must be able to complete the objective; Relevant (Realistic) – able to be interpreted

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within budget and time frame; and Time-related – measured and completed by a certain date." Computation of the realistic utility values of chosen indicators is the key to a reliable estimate of sustainability index. These values are generally computed through primary and secondary data collection followed by assigning limiting values to the indicators based upon practical considerations or by using a 'Likert scale', where inputs are qualitative or linguistic in nature.[6,7] Researchers have also developed expressions or equations for estimation of utility value of an indicator, e.g. Sayyadi & Awasthi[8] evolved a regression equation between the indicator (viz. congestion level), taken as the dependent variable and the parameters that influence the indicator (such as trip rate, average Km travelled, length of road network in Km/lane, etc.), taken as independent variables to compute its utility value; Sinha[9] have developed regression equations between several independent and dependent variables; Reisi *et al.*[10] has described three land use/transport interaction models, where 'car ownership', 'Vehicle Kilometres Travelled (VKT)' and 'percentage of trips by car or modal split' have been considered as dependent variables and socio-economic factors, viz. 'household income' & 'proportion of couples with children' and land use factors such as 'population density', 'access to public transport', 'distance to CBD', 'walk ability' and 'land area' have been considered as independent variables.

The utility values of indicators are usually normalized and weighted for computation of sustainability index. Normalization is essentially required to convert the utility values of indicators into dimensionless numbers.[11] For this, re-scaling method or min-max method is generally adopted since it normalizes the indicators between 0 and 1 corresponding to worst or best performance depending upon, whether an indicator has a positive or negative impact on sustainability. Illahi & Mir[12] have studied transport sustainability index of four metropolitan cities of India and critically reviewed different methods for weighting of indicators, viz. equal weighting, expert opinion, Delphi method, AHP (Analytical Hierarchy Process), DEA (Data Envelopment Analysis) and PCA (Principal Component Analysis) or FA (Factor Analysis). While 'equal weighing' approach does not consider the relative impact of indicators, 'expert opinion' method is subjective and suffers from pair-wise inconsistent rankings.[13] The PCA and FA are statistical methods and avoid any bias due to personal choice as demonstrated by Mahdinia *et al.*[14]

Finally, the sustainability indices computed for each pillar needs to be aggregated to compute a composite index called the Transport Sustainability Index (TSI). Aggregation is generally performed by equal weighting method[6,15] though there exist other methods, wherein varying weights can be assigned to sustainability indices of different pillars.[12]

Studies on optimization of TSI at holistic level are not available readily in literature although Song *et al.*[16] have proposed a genetic algorithm-based model to minimize the cost of multi-modal travelling through optimal combination of congestion pricing for private cars and bus & rail fares. Considering the above discussion, the objectives of this paper are: to describe a method for estimating the optimum transport sustainability index of a typical Indian city; to suggest most suitable indicators that will appropriately consider the impact of deployment of Intelligent Transport Systems (ITS) as well as R&D in alternative fuel vehicles and fuels on sustainability index; and to allocate the indicators to different categories of cities, which can be used to estimate sustainability index of any other Indian city.

Methodology

The methodology adopted in this study is given in Fig. 1. To begin with, an appropriate Indicator Selection Criterion is proposed by examining various criteria considered in several studies in the literature. This is followed by proposing the most suitable indicators grouped into appropriate pillars by analysing the studies in literature as well as keeping in mind the objectives of this study. Next, the indicators are allocated to different categories of Indian cities based upon population and availability of public transportation facilities, therein. Proceeding further, Expert Opinion Survey is undertaken to validate the proposed parameters in the previous steps. After this, the Pillar Sustainability Indices are computed for which the utility values of indicators are normalized and weighted. This leads to computation of Transport Sustainability Index, wherein the various pillar indices are aggregated. Finally, optimization of TSI is done after selection of independent variables; evolving regression equations with indicator as dependent variable; formulation of TSI objective function as a multi-variable non-linear expression;

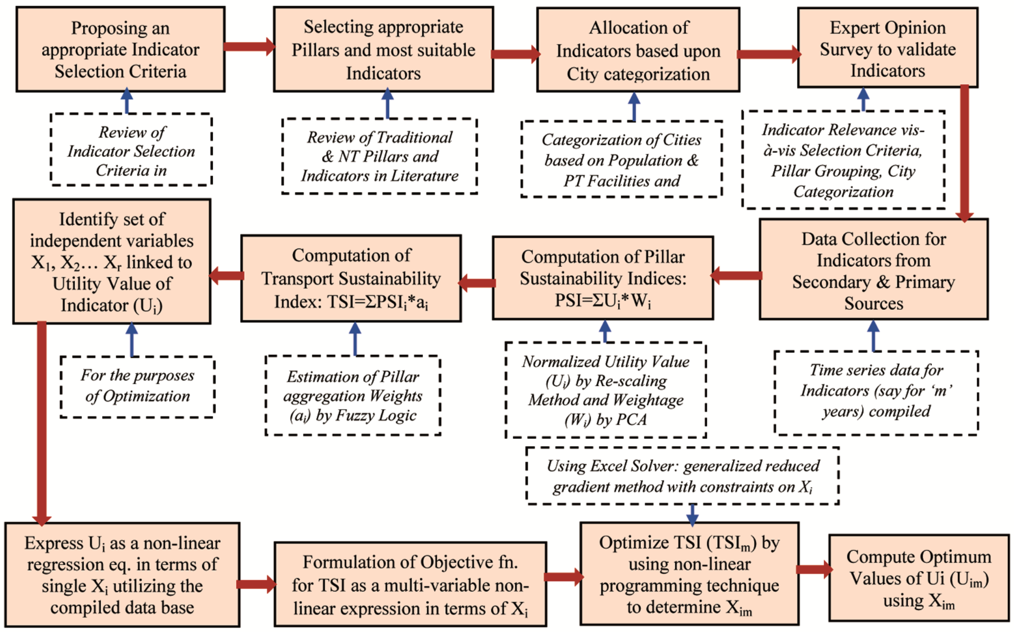

Fig. 1 — Methodology for optimization of TSI

Table 1 — Probable set of indicators for sustainable transportation

Economic		Social	Environment
A. Accessibility	E. Accidents,	A. Equity	A. Air Pollution
B. Traffic Congestion	F. Reduction of non-renewable resources	B. Human health	B. Noise Pollution
C. Infrastructure costs		C. Aesthetics	C. Effect on natural resources
D. User Costs		D. Affordability	

and solving for the values of independent variables that maximize TSI.

Assessment of TSI

Assessment of TSI of a city involves finalization of pillars, indicator selection criteria and suitable indicators including their validation through survey before computation of PSI and TSI.

Pillar Selection

Most of the researchers[1,2,10,17] have considered three traditional pillars of sustainability, viz. economic, social and environment for estimation of transport sustainability index. Comprehensive sustainable transportation indicators[18] under the traditional pillars are given in Table 1.

On the other hand, some researchers have considered non-traditional pillars in addition to the traditional pillars, e.g. System Effectiveness[19], Transport System Effectiveness[20] and Technical[21] although the indicators used under these Non-Traditional Pillars (NTPs) such as, mobility, congestion, modal split, travel time, reliability, vehicle occupancy etc. can be easily included under the traditional pillars itself. Another group of researchers have considered NTPs, e.g. Technical & Operational and Organizational[22], Technological[3], Process and Organization & Innovation[4] that include new indicators, not hitherto considered under traditional pillars and are capable of adding incremental value to sustainability index. These NTPs as well as indicators under these pillars are listed in Table 2. It includes inference on the uniqueness of these NTPs based on whether the indicators considered under these pillars can be covered under traditional pillars or not.

Since this study attempts to include the impact of R&D in alternate fuel vehicles and use of clean transport fuels as well as deployment of ITS technologies, it is proposed to consider 'Technological' as the fourth pillar out of various NTPs listed in Table 2 in addition to the three traditional pillars. Furthermore, the following studies reinforce the inclusion of Technological pillar in this study. Jiang & Huan[23] use a fourth technological dimension as an important pillar to add to the index given by the three traditional pillars. They

Table 2 — Non-traditional pillars (NTPs) and indicators considered by researchers

S. No.	Non-traditional Pillar (NTP)	Indicators under the Pillar	Inference on Uniqueness of NTP
1.	System Effectiveness[19]	a. Average occupancy rate of passenger vehicles b. Reliability c. Annual Trips per capita d. Modal split	Indicators (a), (b), (c), (d) can be considered under Social Pillar. *Hence, NTP* is *Not Unique*
2.	Transport System Effectiveness[20]	a. Mobility b. Congestion (Avg. freeway speed) c. Vehicles Km travelled d. Public Transit share (Transit passenger Km travelled	Indicators (a), (b), (d) can be considered under Social Pillar. Indicator (c) is essentially an influencing parameter for quantifying the indicators such as Energy Consumption and Emissions under Environmental pillar. *Hence, NTP* is *Not Unique*
3.	Technical[21]	a. Travel time b. Reachability c. Service reliability d. Spatial accessibility e. Frequency of transport f. Service area network g. Connectivity to multi-modal transport h. Park and ride facility i. Safety and security j. Vehicle occupancy k. Staff service quality l. Suitability to disabled customers m. Modern & clean facilities n. Possibility of network expansion o. Integration with IT	Indicators (b) to (m) and (o) can be considered under Social Pillar. Indicators (a) and (n) can be considered under Economic Pillar. *Hence, NTP* is *Not Unique*
4.	Technical & Operational[22]	a. Occupancy rate of passenger vehicles b. Load factors for freight transport (LDV, HDV) c. Average age of vehicle fleet d. Size of vehicle fleet (vehicle/ million inhabitants) e. Proportion of vehicle fleet meeting certain air emission standards (Euro IV, Euro V etc.)	Indicator (a) can be considered under Social pillar. Indicators (b), (c) and (e) are essentially the influencing parameters to quantify the indicator - vehicular pollution under Environmental pillar. Indicator (d) can be considered under Economic pillar. *Hence, NTP* is *Not Unique*
5.	Institutional[22]	a. R&D expenditure on “eco vehicles” and clean transport fuels b. Total expenditure on pollution prevention and clean-up c. Measures taken to improve public transport d. Uptake of strategic environmental assessment in the transport sector	Indicator (a) new. Indicators (b) and (c) can be considered under Economic pillar. Indicator (d) can be considered under Environmental pillar. *Hence, NTP* is *Partially Unique*
6.	Technological[3]	a. Technological maturity of alternative-fuel vehicles b. Energy density or embodied energy per unit volume c. Availability or current production and retail availability for vehicles d. Distribution infrastructure for alternative fuel vehicles	All the indicators are new *Hence, NTP is Unique*
7.	Process[4] (Operational Efficiency)	a. Smart infrastructure technologies b. Smart vehicle technologies c. Smart road pricing d. Smart fare collection e. Advanced traveller and goods information f. Smart congestion and incident management g. Operator capability h. Supplier capability	All the indicators are new *Hence, NTP is Unique*
8.	Organization & Innovation[4] (Learning and Innovation)	a. Local and global feedback b. Innovations and good practices c. Research and development	All the indicators are new *Hence, NTP is Unique*

demonstrate that technological pillar can capture the attributes of (a) innovation which encompasses the advanced alternate fuel vehicles, an essential requirement of modern urban mobility system and (b) intelligence which encompasses newer forms of rail-road transit systems, a feature of emerging smart cities. Ayadi & Hamani[24] reviewed 47 studies carried out between 2002 and 2022 that assessed sustainability of transport systems through composite indicators and found that 32% of the studies used dimensions other than the traditional dimensions such as political, spatial, efficiency and advanced technology. They state that it is essential to consider additional dimensions for a comprehensive assessment of transport sustainability index.

Selection Criterion for Choice of Indicators

A good selection criterion is not only useful in pruning extraneous indicators that are either ambiguous or difficult to measure, but also assists in choice of indicators that are simple and targeted for the study, quite often necessitating re-phrasing of indicators to suit the selected criterion. In order to assess the sustainability of a city, researchers have used varying number of indicator selection criteria and indicators since there does not exist a universal set. Tanguay *et al.*[5] examined 17 studies that deployed a total of 68 different indicator selection criteria, having parameters ranging from 3 to 14. They found that parameters, viz. 'credible', 'universality', 'data requirements & availability' and 'comprehensible' were most used in all the criteria studied. Apart from these, the present study further considered 10 parameter criterion by Joumard *et al.*[25], 7 parameter criterion by Haghshenas & Vaziri[17], 8 parameter criterion by Reisi *et al.*[10], 5 parameter criterion by Castillo[26] and 6 parameter criterion by Shiddiqi *et al.*[27]. Similar meaning parameters under different criteria adopted by these researchers were replaced by a single representative parameter. Furthermore, parameters not relevant for this study in the context of India were dropped, e.g. 'Ethical concerns' parameter by Joumard *et al.*[25] has not been considered since the present study is not targeting any data for an indicator that violates human rights. Similarly, the 'Transport Impact Isolatable' parameter by Castillo[26] has also not been considered since the present study is not considering to isolate the impact of an indicator on transport sector. Further, since, this study proposes to consider different categories of Indian cities, a parameter viz. 'Applicability' that signifies suitability of the indicator for a particular Indian city category has been added. The selection criterion that emerges as a result of this exercise is given in Table 3.

Choice of Indicators

A total of 2396 indicators were identified in 99 articles shortlisted out of 728 articles (related to urban transport, mobility and sustainability) extracted from Web of Knowledge, Scopus and Google Scholar search engines.[28] Around 50 indicators, which were cited from 10 to 45 times in these articles were compiled in 24 thematic groups such as, accidents and fatalities, GHG & air pollutants, energy, land use, modal split, congestion rates, travel times, accessibility, safety and security. A systematically conducted review led to the conclusion that though a variety of methods are

Table 3 — Selection criterion for indicators

S.No.	Parameter	Description
1	Validity / Quantifiable	Must be able to directly measure – what the indicator is supposed to measure
2	Reliability / Predictability	Must reproduce a similar measure if another similar population is measured around the same time
3	Sensitivity	Must be able to capture the changes in the parameters that influence the indicator
4	Data availability	Secondary sources must be known from where data can be made available or carrying out primary survey must be cost effective
5	Measurability	Techniques for measurement must be simple and inexpensive, equipment required for measurement should be readily available
6	Transparency / Understandable /Interpretability	Meaning of the indicator and what it is measuring must be understandable in unambiguous terms to the users
7	Target relevance / Goal orientation	Indicators must be directed towards one of the goals, objectives and targets of sustainability i.e. must contribute towards one of pillars of sustainability
8	Independent	Each indicator must be distinct from another indicator and must not yield values that point to a similar target as by another indicator.
9	Standardized	It should be possible to normalize the indicator values to facilitate computation of sustainability index
10	Applicability	The indicator must be applicable for the category of Indian city selected

available to identify indicators, the chosen set of indicators in various studies is incomparable and inconsistent. In order to choose appropriate indicators for this study, certain studies were critically reviewed that focused on a variety of indicators under the traditional as well as non-traditional pillars, as described in subsequent paragraphs.

Rajak *et al.*[29] used 60 transport sustainability attributes or indicators grouped under 20 categories, which were assigned to four pillars of sustainability. Most of the transport sustainability indicators, used by them under the traditional pillars can be either assimilated or conveniently grouped into a set of similar meaning indicators, viz. energy and fuel consumption, land use, accessibility, mobility, trip length, modal split, congestion, road accidents, safety & health hazards, noise pollution, equity, travel cost & time, fare subsidy in public transport, vehicle ownership & occupancy, revenue generation, employment generation and productivity. These are designated as the 'universal set of indicators' in our study. However, few other indicators, such as Stakeholder involvement, Cultural preservation, and Hydrologic impact, used by them are not relevant for our study and hence, not included. Similarly, varying no. of indicators used in several papers studies[1–4,10,17,22,30–33] were examined and it was found that the universal set of indicators are mostly representative of indicators used under the traditional pillars except that additional indicators used under NTPs are relevant for inclusion in our study under the 'Technological' pillar. Such indicators are: 'R&D expenditure on eco vehicles and clean transport fuels' by Dobranskyte-Niskota *et al.*[22]; 'smart vehicle technologies' & 'research and development' by Karjalainen & Juhola[2]; and 'technological maturity of alternative-fuel vehicles' & 'distribution infrastructure for such vehicles' by Liang *et al.*[3]

Thus, a critical review of a total of 354 indicators in above mentioned papers led to short-listing of thirty-four indicators, viz. eight indicators under the 'Environmental' pillar (En-1 to En-8), twelve indicators under the 'Social' pillar (So-1 to So-12), nine indicators under the 'Economic' pillar (Ec-1 to Ec-9) and five indicators under the 'Technological' pillar (T-1 to T-5). A description of these indicators is given in Table 4.

Since the objective of this study is to assess the sustainability of different categories of Indian cities, the categorization of Indian cities is discussed in next section.

City Categorization for Indicator Allocation

Population is an important characteristic for studying transport sustainability of cities and since Indian cities have vastly varying population, this becomes an important characteristic according to which they can be categorized. According to UN World Population Prospects (UNWPP)[34], 63 Indian cities were having population in excess of 1 million as of 2021, of which 54 cities were having population up to 5 million, 3 cities were having population between 5 and 10 million and 6 cities were having population exceeding 10 million. The availability of Public Transportation (PT) and types of Intermediate Public Transportation (IPT) facilities in cities also form another significant characteristic for studying transport sustainability. Since Indian cities with less than 1 million population generally lack these facilities, this study excludes such cities. Therefore, this study proposes to consider only those: Category I cities that have Shared Auto Rickshaws & Bus as PT & IPT facilities; Category II cities that additionally have Bus Rapid Transit System (BRTS)/Metro facility; and Category III cities that have all the facilities for Category II cities plus Mass Rapid Transit System (MRTS), e.g., sub-urban rail. Thus, the suggested three categories of Indian cities are shown in Table 5.

Further, it is necessary to allocate the indicators according to different categories of cities. Zito & Salvo[35] argued that developing a standardized set of indicators for a set of cities is very complex since homogenized data for indicators from various cities is not readily available. Therefore, indicator values or transport sustainability indices across cities are not comparable. In view of this, a set of 24 transport performance indicators have been identified by Zito & Salvo[35] in several categories such as budget, planning & land-use, safety, time, health & environment and social for comparing the transport sustainability indices of 36 European cities. However, while assessing TSI they used only 13 indicators, since uniform data was only available for these, across the cities.

This study however, attempts to allocate the indicators among the city categories based on population, size, and availability of PT facilities and status of cities in terms of their economic, industrial & technological advancement. Since, Category III cities with more than 10 million population, have all forms of PT facilities and are most advanced, all the

Table 4 — Proposed indicators under four pillars for TSI assessment

S. No.	Proposed Indicators under four Pillars i.e. Environmental (En), Social (So), Economic (Ec) & Technological (T)
1	En-1: Transportation energy consumption annually
2	En-2: GHG emissions (CO_2-e) annually
3	En-3: Emission of other Air pollutants (CO, SOx NOx, VOCs, O_3, CH_4, PM10, PM2.5) annually
4	En-4: Percent share of alternate fuels in total fuel consumption
5	En-5: Percentage of Land devoted for transport facilities
6	En-6: Transportation waste generated annually
7	En-7: Noise pollution i.e. peak noise level exceeding a threshold level
8	En-8: Depletion of upper atmosphere or stratospheric Ozone layer annually
9	So-1: Accessibility to public transport
10	So-2: Persons killed in traffic accidents annually
11	So-3: Personal mobility or trips undertaken by persons annually
12	So-4: Safety and Security in public transport (PubT)
13	So-5: Equity/Fairness i.e. percentage of PubT facilities equipped with special features for disadvantaged
14	So-6: Average Additional travel time due to Congestion
15	So-7: Average annual occupancy rates of passenger vehicles, pvt or public
16	So-8: Average annual Level of Service of a busy urban road network
17	So-9: Scheduled PubT frequency and its average reliability
18	So-10: Modal Share or percentage of trips by Non-Motorized Transport (NMT) and Public Transport (PubT)
19	So-11: Availability of printed journey planners & service frequency tables in respect of PubT on a periodic basis
20	So-12: Premature deaths due to chronic respiratory diseases, cancer, etc. because of motor vehicle pollution annually
21	Ec-1: Affordability i.e. percentage of annual income of commuters allocated for transportation
22	Ec-2: Costs incurred on travel by public and pvt. mode annually
23	Ec-3: Pvt vehicle ownership and annual maintenance costs
24	Ec-4: Fare subsidy in PubT provided annually by the City/State
25	Ec-5: Revenue generation from transport infrastructure annually
26	Ec-6: Contribution of transport sector to employment generation
27	Ec-7: Fund availability to expand or add new transport infrastructure
28	Ec-8: Fund availability to expand productivity or improve efficiency of existing transport infrastructure
29	Ec-9: Contribution of transport sector to GDP
30	T-1: Deployment of smart technologies i.e. no. of smart technologies deployed annually
31	T-2: Demand/Sales of alternate fuel vehicles (e.g. CNG, Electric, Hybrid Electric)
32	T-3: Service Infrastructure for alternative fuel vehicles (e.g. CNG filling and Electric Charging stations)
33	T-4: Industrial projects on building advanced alternative-fuel vehicles (e.g. biofuels, hydrogen, fuel cells)
34	T-5: R&D budget on development of advanced alternate fuel vehicles and related clean transport fuels

Table 5 — Suggested categorization of Indian cities

Category	Population	Type of Transportation System
I	1 – 5 million	Shared Autorickshaws, Bus
II	5 – 10 million	Shared Autorickshaws, Bus, Bus Rapid Transit System (BRTS) and/or Metro
III	> 10 million	Shared Autorickshaws, Bus, Bus Rapid Transit System (BRTS), Metro, Mass Rapid Transit System (MRTS e.g. Sub-urban Rail)

34 indicators are considered to be applicable. For the moderately advanced Category II cities with 5–10 million populations and having lesser PT facilities compared to category III, only 29 indicators are considered to be applicable. For example, En-8 (Depletion of Ozone layer) and So-12 (Premature deaths due chronic respiratory diseases) is believed to be negligible because of smaller size and population in category II cities. Also, measurement of Ec-9 (Contribution of transport sector to GDP) cannot be done because of unavailability of GDP values for these cities. Furthermore, T-4 and T-5 are not relevant, since neither of these cities have any industrial projects on building advanced alternative-fuel vehicles nor do they allocate any R&D budget for advanced alternate fuel vehicles. For the least advanced Category I cities with 1–5 million population and having bare minimum PT facilities, only 23 indicators out of 29 indicators for category II are considered to be applicable. For instance, En-7 (noise pollution) is insignificant in view of less vehicle ownership and PT facilities. So-11

(printed journey planners & service frequency tables) is not relevant in view of skeletal bus services in these cities; Ec-7 and Ec-8 indicators are of no consequence since the authorities in these smaller cities lack funds for expansion or efficiency improvement of transport infrastructure. Further, T-2 and T-3 indicators are irrelevant since these cities hardly have any production, retail, or service infrastructure for alternate fuel vehicles. Thus, the indicators applicable for the three categories of cities are given in Table 6.

Expert Opinion Survey

The survey proforma was designed comprising of all the 34 proposed indicators, which were allocated as per city categories and the proposed indicator selection criteria was mentioned alongside. The expert opinion survey was conducted to verify if the proposed indicators satisfy the indicator selection criteria and are relevant for the study. Further, the opinion of the experts was sought on, whether the allocation of indicators as per city categories is alright. The experts included faculty from the Civil Engineering/Transportation Engineering departments of universities and key educational institutions, working scientists from road and transportation related research institutions, officials from the Central Government Ministries and Departments and professionals from foundations/associations operating in this area. The experts were required to assess, whether the indicators broadly fit into the criterion given in Table 3 as well as opine on the relevance of each of the 34 indicators, proposed for the study. The experts expressed their opinion on a 5-point Likert scale and indicated a rating ranging from 1 to 5 [(1) Strongly disagree; (2) Disagree; (3) Neither Agree nor Disagree; (4) Agree; (5) Strongly agree)]. The survey format was circulated to around 70 experts and 21 responses were received. The composition of responses received are: 52% from senior scientists of road and transportation research institutes; 24% from senior Transportation Engineering faculty; 14% from senior Civil Engineering faculty and research associates; and 5% each from senior officers from Government Ministry and Foundation related to Sustainable Energy.

Since the experts indicated responses to all the proposed indicators, it is inferred that they agreed with the proposed selection criteria. All the responses indicated by the experts were compiled and average rating and standard deviation for each indicator is presented in Table 7. It can be seen that the average rating values of the indicators are ranging from 3.38 to 4.67 for Environmental, 3.29 to 4.24 for Social, 3.33 to 4.10 for Economic and 3.38 to 4.14 for Technological Pillars.

Thereafter, the average ratings of the responses were analysed. As observed from Table 7, none of the indicators have an average rating below 3.0. If any indicator obtained such a rating, it would have been outrightly dropped from the study since the experts do not agree with the proposed choice of indicator. Ten indicators, viz. En-1, En-2, En-3, So-1, So2, So6, So9,

Table 6 — Allocation of indicators as per city categories

City Category	Total no. of Indicators	Symbols of Allocated Indicators
I	23	En-1 to En-6; So-1 to So-10; Ec-1 to Ec-6; T-1
II	29	En-1 to En-7; So-1 to So-11; Ec-1 to Ec-8; T-1 to T-3
III	34	En-1 to En-8; So-1 to So-12; Ec-1 to Ec-9; T-1 to T-5

Table 7 — Average and Standard Deviation (S.D.) of Ratings for Indicators from Expert Survey

S. No.	*Indicator*	*Avg.*	*S.D.*	S. No.	*Indicator*	*Avg.*	*S.D.*	S. No.	*Indicator*	*Avg.*	*S.D.*	S. No.	*Indicator*	*Avg.*	*S.D.*
1	En-1	4.67	0.73	9	So-1	4.24	0.94	21	Ec-1	3.86	1.01	30	T-1	3.71	1.01
2	En-2	4.33	0.91	10	So-2	4.10	1.18	22	Ec-2	3.90	1.00	31	T-2	3.95	0.97
3	En-3	4.05	0.92	11	So-3	3.29	1.15	23	Ec-3	3.33	1.32	32	T-3	4.14	0.79
4	En-4	3.62	1.02	12	So-4	3.90	1.00	24	Ec-4	3.71	1.19	33	T-4	3.38	1.16
5	En-5	3.90	1.09	13	So-5	3.76	1.00	25	Ec-5	3.52	1.29	34	T-5	3.90	1.26
6	En-6	3.48	1.21	14	So-6	4.05	0.74	26	Ec-6	3.57	1.03				
7	En-7	3.81	0.98	15	So-7	3.57	1.08	27	Ec-7	3.71	1.01				
8	En-8	3.38	1.07	16	So-8	3.86	0.96	28	Ec-8	4.10	1.00				
				17	So-9	4.10	0.83	29	Ec-9	4.05	0.97				
				18	So-10	3.95	0.97								
				19	So-11	3.67	1.24								
				20	So-12	3.71	1.10								

Ec-8, Ec-9 and T-3 have an average rating of 4.0 or above implying that majority of experts 'agree' or 'strongly agree' with the proposed choice and thus, these indicators are relevant for inclusion in the study. The remaining 24 indicators have an average rating between 3.0 and 4.0 implying that the experts are not sure about their relevance for inclusion in the study. The percentage distribution of ratings [Strongly Disagree (1), Disagree (2), Neither Agree nor Disagree (3), Agree (4), Strongly Agree (5)] in respect of these indicators is given in Table 8. The percentage of experts giving ratings of 4 & above (agree category) and 3 & below (disagree & not sure category) has also been given in the same. An indicator is proposed to be included in the study only if 'agree category' percentage is greater than 'disagree & not sure category'.

It is observed from Table 8 that percentage of expert ratings greater than or equal to 4 are higher than expert ratings less than or equal to 3 in respect of all the remaining 24 indicators. In view of this, it is inferred that these indicators are relevant and good for inclusion in the study.

Moreover, since none of the experts suggested any shuffling of the indicators among the city categories, the proposed allocation i.e. 23, 29 and 34 indicators for categories I, II and III cities respectively are considered valid.

Computation of Pillar Sustainability Indices (PSI) and Transport Sustainability Index (TSI)

The pillar sustainability index is computed as per Eq. 1 given below:

$$PSI_P = \sum_{i=1}^{n_P} W_i * U_i \quad \ldots (1)$$

where, PSI_P, is Pillar Sustainability Index of Pillar 'P'; Wi, weight of i^{th} indicator; Ui, utility value of i^{th} indicator; and n_p, total number of indicators in Pillar 'P'.

Since various indicators have different units, the utility value of an indicator, U_i is normalized so that it becomes dimensionless and can be compared with utility values of other indicators. As mentioned in previous section, re-scaling method[11] or min-max method is proposed to be used in this study for normalization. As regards, estimation of indicator weightages, PCA (Principal Component Analysis)

Table 8 — Analysis for Inclusion of Indicators having average ratings between 3 & 4

Indicator	% of Experts Rating as (1)	% of Experts Rating as (2)	% of Experts Rating as (3)	% of Experts Rating as (4)	% of Experts Rating as (5)	Avg. Rating	% of Experts Rating ≥ 4 (a)	% of Expert Rating ≤3 (b)	Inclusion (Y/N) of indicator in Study if (a)>(b)
En-4	0.0%	19.0%	19.1%	42.9%	19.0%	3.62	61.9%	38.1%	Y
En-5	4.8%	4.8%	19.0%	38.1%	33.3%	3.90	71.4%	28.6%	Y
En-6	4.8%	23.8%	9.5%	42.9%	19.0%	3.48	61.9%	38.1%	Y
En-7	4.8%	0.0%	28.6%	42.9%	23.8%	3.81	66.7%	33.3%	Y
En-8	0.0%	28.6%	19.0%	38.1%	14.3%	3.38	52.4%	47.6%	Y
So-3	9.5%	19.0%	9.5%	57.1%	4.8%	3.29	61.9%	38.1%	Y
So-4	4.8%	4.8%	9.5%	57.1%	23.8%	3.90	81.0%	19.0%	Y
So-5	0.0%	19.0%	4.8%	57.1%	19.0%	3.76	76.2%	23.8%	Y
So-7	4.8%	14.3%	14.3%	52.4%	14.3%	3.57	66.7%	33.3%	Y
So-8	0.0%	14.3%	9.5%	52.4%	23.8%	3.86	76.2%	23.8%	Y
So-10	0.0%	9.5%	19.0%	38.1%	33.3%	3.95	71.4%	28.6%	Y
So-11	4.8%	19.0%	9.5%	38.1%	28.6%	3.67	66.7%	33.3%	Y
So-12	4.8%	9.5%	19.0%	42.9%	23.8%	3.71	66.7%	33.3%	Y
Ec-1	0.0%	14.3%	14.3%	42.9%	28.6%	3.86	71.4%	28.6%	Y
Ec-2	0.0%	14.3%	9.5%	47.6%	28.6%	3.90	76.2%	23.8%	Y
Ec-3	9.5%	23.8%	9.5%	38.1%	19.0%	3.33	57.1%	42.9%	Y
Ec-4	4.8%	14.3%	14.3%	38.1%	28.6%	3.71	66.7%	33.3%	Y
Ec-5	4.8%	23.8%	14.3%	28.6%	28.6%	3.52	57.1%	42.9%	Y
Ec-6	0.0%	19.0%	23.8%	38.1%	19.0%	3.57	57.1%	42.9%	Y
Ec-7	0.0%	14.3%	23.8%	38.1%	23.8%	3.71	61.9%	38.1%	Y
T-1	0.0%	19.0%	9.5%	52.4%	19.0%	3.71	71.4%	28.6%	Y
T-2	0.0%	9.5%	19.0%	38.1%	33.3%	3.95	71.4%	28.6%	Y
T-4	9.5%	9.5%	28.6%	38.1%	14.3%	3.38	52.4%	47.6%	Y
T-5	9.5%	4.8%	9.5%	38.1%	38.1%	3.90	76.2%	23.8%	Y

will be used in this study, as done by other researchers.[12,14,15] SPSS software will be used for carrying out PCA, which yields a reduced no. of factors say 'j' that will mostly represent the variance in 'n_P' No. of indicators in any pillar of sustainability. In order to carry out PCA, certain no. of samples, say 'm' for the set of 'n_P' indicators is required. The minimum no. of samples (m) required is five times the No. of indicators.[36] This study proposes to generate 'm' samples by considering utility values of 'n_P' indicators over a time series or under different scenarios in any particular year. The different scenarios could emerge as a result of regulatory policies and planning & investment policies.[37] This exercise yields a data matrix of size m × n_P. PCA also requires that the correlation coefficient of the data matrix should be between 0.3 and 1. To illustrate computation of PSI_P, let's consider 'm' samples of 8 indicators under the Environmental pillar. Let's assume that PCA from 'm' samples yields two factors, j_1 & j_2 that explain more than 80% of the variance in n_P indicators and the corresponding factor loadings, FL_{jk} over 'k' No. of indicators, are A_i and B_i. Estimation of PSI_P for a typical sample of utility values of indicators is done, as illustrated in Table 9.

From Table 9, $PSI_P = \sum_{j=1}^{2} SI_j \times a_j$ … (2)

PSI_P computed by Eq. (2) above is identical to PSI_P computed by Eq. (1), such that

$$W_i = \sum_{j=1}^{n_f} FL_{ji} * a_j \quad \text{… (3)}$$

wherein 'n_f' is the No. of factor loadings; and

$$a_j = \sum_{i=1}^{n_P} FL_{ji}^2 / \sum_{j=1}^{n_f} \left(\sum_{i=1}^{n_P} FL_{ji}^2 \right) \quad \text{... (4)}$$

Similarly, sustainability indices for other pillars, i.e. social, economic and technological are computed. The Transport Sustainability Index (TSI) is computed by aggregating all the pillar sustainability indices, as in Eq. 5).

$$TSI = \sum_{P=1}^{q} \propto_P \times PSI_P \quad \text{… (5)}$$

where, TSI, is Transport Sustainability Index; PSI_P, Sustainability Index of p[th] pillar; q, total no. of pillars; and $\propto_P$, aggregating weight of p[th] pillar.

Assigning equal weightages[6,15,17,20] to all the pillar indices is the simplest way of aggregating. If we adopt equal weighting technique in our study, $\propto_P$ will be 0.25 since 'q' or no. of pillars are 4. However, it is proposed to adopt fuzzy weighting technique in our study, as demonstrated by Illahi & Mir (2021).[12] The computed sustainability indices for each pillar, i.e. environment (PSI_{En}), social (PSI_{So}), economic (PSI_{Ec}) and technological (PSI_T) shall lie between 0.0 to 1.0. Based on the range of values of indices from various samples, they will be defined by triangular fuzzy sets, viz. Very High (VH), High (H), Medium (M), Low (L) or Very Low (VL). A Fuzzy Logic Designer (FLD) shall be developed with Mamdani type of fuzzy inference system.[38] Expert opinion survey shall be used to develop rules for interaction among various indices denoted by fuzzy numbers. Now, consider a 'rule', where fuzzy sets for two or more indices are interacting with 'AND' connector, then 'minimum' of the 'consequences' are taken, else, if the fuzzy sets are interacting with 'OR' connector, then 'maximum' of the 'consequences' are taken to arrive at a conclusion. The conclusions drawn from various rules shall be aggregated to yield the TSI, which shall also be in fuzzy terms, defined by triangular fuzzy sets viz. Extremely Sustainable (E), Very Sustainable (D), Sustainable (C), Fairly Sustainable (B), or Barely Sustainable (A). Finally, this will be de-fuzzified using the centroid method to obtain a discrete value of TSI between 0.0 and 1.0.

Optimization of TSI and Discussion

Optimization involves constructing an objective function, whose value depends upon the values of

Table 9 — Illustration for estimation of PSI_p

Indicator	NI_i	Factor loading FL_{ji}		Weights $W_{ji} = FL_{ji}^2/EV_j$				
i		j=1	j=2	j=1	j=2			
En-1	N_1	A_1	B_1	W_{11}	W_{21}	NI_i	:	Normalized utility value: Indicator i
En-2	N_2	A_2	B_2	W_{12}	W_{22}	Eigen value$_1$	:	$EV_1 = \sum_{i=1}^{8} FL_{1i}^2 = \sum_{i=1}^{8} A_i^2$
En-3	N_3	A_3	B_3	W_{13}	W_{23}	Eigen value$_2$	:	$EV_2 = \sum_{i=1}^{8} FL_{2i}^2 = \sum_{i=1}^{8} B_i^2$
En-4	N_4	A_4	B_4	W_{14}	W_{24}	EV ratio$_1$	:	$a_1 = EV_1/(EV_1 + EV_2)$
En-5	N_5	A_5	B_5	W_{15}	W_{25}	EV ratio$_2$	:	$a_2 = EV_2/(EV_1 + EV_2)$
En-6	N_6	A_6	B_6	W_{16}	W_{26}	PSI (Factor 1)	:	$PSI_1 = \sum_{i=1}^{8}(NI_i \times W_{1i})$
En-7	N_7	A_7	B_7	W_{17}	W_{27}	PSI (Factor 2)	:	$PSI_2 = \sum_{i=1}^{8}(NI_i \times W_{2i})$
En-8	N_8	A_8	B_8	W_{18}	W_{28}	Pillar SI	:	$PSI_P = \sum_{j=1}^{2} SI_j \times a_j$

certain decision variables. The decision variables are varied, subject to certain constraints on their values and an optimum combination of values of all the variables is determined that maximizes or minimizes the objective function. In general, optimization problems fall into one of two categories: linear and nonlinear. Classical optimization algorithms use the first and second derivative of the objective function. Setting first derivative as zero gives the inflexion point and examination of the second derivative at the inflexion point, viz. negative confirms a maxima and positive confirms a minima. There are many different optimization methods, some better suited to different types of problems than others. The gradient descent method is the most popular optimisation method.

Considering PSI_P expression (Eq. 1) itself as the Objective Function, in which the normalized utility values of indicators (U_i) are the decision variables and the weightages (W_i) are constants. Since the objective function is a linear equation in terms of U_i, the first partial derivative with respect to any of the U_i is W_i itself and the second partial derivative zero. This objective function neither yields any information on the value of U_i at which inflexion point occurs nor indicates if it is a maxima or minima. Moreover, since sum of W_i's is 1.0, the optimum value of the objective function is 1.0 with all U_i's as 1.0. However, this is a theoretical maximum, which cannot be targeted by authorities in practical terms. Alternately, the following methodology is proposed. Independent variables, X_i's (i = 1 to r) are identified such that various U_i's can be represented in terms of polynomials of one of the identified X_i or in other words, U_i is represented as a single variable non-linear expression, given below:

$U_i = f\left(X_i, X_i^2, \dots, X_i^k\right)$ such that X_i *is either* X_1 or $X_2, \dots\dots, or\ X_r$ ... (6)

The expressions for U_i are evolved as regression equations based upon the compiled data set ('m' samples) for U_i as well as for X_i. Since Wi's are constant, substituting Eq. (6) into Eq. (1) and finally into Eq. (5), yields an expression for TSI Objective Function, which is a multi-variable non-linear expression in terms of X_i. Now, this objective function can be optimized (maximized) to determine the values of X_i subject to constraints on X_i as given below:

***Objective Function*:**

$Max.TSI = Max.f\left(X_i, X_i^2, \dots, X_i^k\right)$ for I = 1 to r, subject to constraints on X_i … (7)

The Excel Solver - GRG Nonlinear algorithm[39] is used to solve for X_i that optimizes (maximizes) TSI. Substituting the values of X_{im} as determined after optimization in Eq. (6) yields the optimum indicator values, U_{im}. These optimum values i.e. U_{im} can be targeted by policy planners to improve the efficiency of city's transportation system.

Utility of the Study

The assessment of optimum Transport Sustainability Index (TSI_m) of a typical Indian city, as proposed will allow the authorities and the transport planners to announce varying incentive packages and schemes for different cities. Knowledge of optimum TSI will guide the city planners in setting aside only as much physical and financial resources for a city to implement policy measures that will enhance the TSI, just up to the optimum level. It will thus, prevent excess allocation of funds to any one city and give planners an opportunity to re-direct the resources for another city and pave the way for equitable and sustainable development of all cities.

Conclusions

The present study has attempted to propose a method to optimize Transport Sustainability Index (TSI) for a typical Indian city. In doing so, it has highlighted the necessity of one additional pillar of sustainability, viz. 'Technological' that intends to adequately capture the impact of deployment of ITS as well as the rising demand for development and use of electric and alternate fuel vehicles on TSI. The study has used an expert opinion survey to validate a 10-point selection criterion and a set of 34 indicators for Indian cities with over 10 million population and goes on to suggest a reduced no. of indicators for Indian cities with population between 1–10 million. The study has proposed statistical based PCA technique for weighting of indicators and assessment of Pillar Sustainability Index (PSI_P). Fuzzy weighting technique has been proposed to aggregate various PSI_P into TSI. In order to assess the optimum TSI (TSI_m), the study has proposed non-linear programming optimization technique, which is simple to use and can be conveniently accomplished by using Excel solver's generalized reduced gradient method.

Limitation of the study is smaller sample size for the expert opinion survey, not having adequate number of professionals from the traditional sustainability dimensions. There is scope for future research in allocating indicators to different categories of cities based on case study oriented quantitative assessment of indicators and exploring more sophisticated methods to compute the optimum value of TSI.

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Declarations

The authors have no conflict of interest to report. All participants were consented prior to participation.

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