CASE STUDY AND APPLICATION

Sustainable benchmarking of a public transport system using analytic hierarchy process and fuzzy logic: a case study of Hyderabad, India

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Abstract

To achieve a well-balanced sustainable public transport system in an Indian scenario, a thorough performance assessment and benchmarking of existing systems in conventional and sustainable dimensions is necessary. Although institutionalisation of sustainable benchmarking of public transport systems is habituated across the globe, it is not largely practised in India. Based on this, we aim at developing a comprehensive mode-specific benchmarking framework for the urban bus system under Indian conditions with a case study of Hyderabad city. The developed framework consists of 29 evaluators structured into eight indicator groups. As the significance of these indicator groups and evaluators varies in the framework, the same has been determined by an expert opinion survey by applying multi-criteria decision-making techniques such as 'analytic hierarchy process' and 'direct weighting.' The assessment revealed that the overall performance of the urban bus system is approximately 70%. The parameters associated with the sectors of 'passenger information systems' and 'social sustainability' were found to underperform and required improvement. A better performance was observed among the service- and quality-oriented sectors. The associated intangibility in weighting and ranking during the process of benchmarking was addressed through the application of a fuzzy logic technique, and the 'overall normalised rate of performance' of the urban bus system was determined to be 74%. Based on these factors, the present study achieves a successful development and application of mode-specific benchmarking of public transport systems in the Indian context.

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1 Background and introduction

Approximately 190 million motor vehicles have been registered in India as of 31st March, 2016, and the compounded annual growth rate for 2011–2016 was 94.40% (MoRTH 2016). On the other hand, planning authorities and urban local bodies (ULB) have been investing huge amounts of funds for expanding the road infrastructure to manage the prevalent travel demands. The increase in travel demands in conjunction with the increased vehicular ownership is causing negative externalities such as decreased ambient air quality and increased congestion and accidents. This is a frightening call towards sustainable development. Thus, to alleviate this situation, a well-balanced sustainable public transport system should be established by understanding the current performance of the system. Moreover, for the same purpose, a comprehensive performance assessment and subsequent benchmarking with a broad vision towards achieving long-term sustainability is necessary.

The Ministry of Urban Development (MoUD) defines benchmarking as a 'process of comparing performance levels against set targets or best practice cases' (MoUD and CEPT 2013). Benefits associated with benchmarking are as follows:

- Creating a consistent and comparable local and national database
- Providing a platform to identify the critical problems and formulating necessary policies
- Establishing a competitive environment between cities.

Although the benchmarking of public transport (PT) is an institutionalised practice at the global level, it is not largely practised in the Indian scenario. Hence, there is a need for developing a standardised mode-specific framework to evaluate and strengthen the performance of PT systems in the Indian context. The establishment of new PT systems and the implementation of any improvement measures require heavy financial investments. In the present scenario of rapid urbanisation, prioritisation, and wise allocation of funds play a key role in addressing such challenges. Establishing PT benchmarking tools and standardised frameworks at the national level will certainly encourage a competitive environment between different cities and ULBs, thus resulting in an overall improvement in the PT systems in the Indian context.

The MoUD has released guidelines for service level benchmarking (SLB) of urban transport systems (MoUD 2010). These guidelines are broader in nature and not specific towards the comprehensive benchmarking of any PT system in an Indian condition. As PT is multi-modal in nature, a dedicated mode-specific benchmarking framework is necessary to assess the overall performance of any system, such as urban bus, Metro, and Monorail. The objective of the present study was to develop such a mode-specific benchmarking framework for ensuring sustainable benchmarking of urban bus systems, thus capturing all possible attributes that influence the performance of the system in the Indian context. The framework was developed after reviewing the existing global practices, prevailing guidelines, and local policies. The proposed framework was structured with 29 evaluators nested into eight

indicator groups (IGs). Subsequently, prioritisation of these IGs and evaluators was logically derived using multi-criteria decision-making (MCDM) techniques, such as the 'analytic hierarchy process' (AHP) and 'direct weighting' by conducting an expert opinion survey. Moreover, the associated intangibility in the ranking of the benchmarking process was addressed by applying fuzzy logic. As the application of AHP in combination with fuzzy logic is not practised in any institutionalised or standardised benchmarking framework in the Indian system, this study experiments the same to achieve better benchmarking results and making them more reliable.

This article presents a comprehensive overview of various practices in the research area, followed by a case study of Hyderabad city focusing on mode-specific benchmarking of the urban bus system. The MCDM techniques used for benchmarking that are supported by the fuzzy logic approach to nullify the intangibility effect are discussed in detail. The article concludes with a discussion on specific contributions and the lessons learnt.

2 Review of Indian and international benchmarking processes

In this section, a comprehensive overview of the literature affiliated to different aspects of PT benchmarking and sustainability are presented with a summary of performance measures considered by various researchers. Although a considerable number of studies are available on benchmarking in general, only specific studies that are relevant to the objectives and the proposed methodology of this study are covered in this section.

The global practices on performance evaluation and benchmarking can be broadly categorised as either attribute- or framework-based practice. Although the former approach concentrates on evaluating a system based on the key service and quality attributes, the latter approach concentrates on a comprehensive framework-based assessment that includes various aspects of the system. The attributes such as accessibility, mobility, availability, and connectivity are considered as the parts of the service-oriented assessment process. Martens (2015) juxtaposed accessibility and potential mobility to assess a public transport system. Mamun and Lownes (2011) developed a composite index for evaluating accessibility in three dimensions viz. spatial, temporal, and trip coverage. Gahlot et al. (2013) developed numerical indexes such as public transit coverage index, ideal and actual stop accessibility index, and stop coverage ratio index to assess the availability and accessibility of PTs for a specific case of the city of Jaipur, India.

In addition to the service attributes, a predominant focus on quality attributes, such as passenger comfort and overall convenience, was laid towards the assessment and benchmarking of PT systems. Kinsella and Caulfield (2011) conducted importance performance analysis (IPA), a technique for prioritising attributes based on measures of importance and performance, for assessing the service quality of PT of the city of Dublin, Ireland. The perception of tourists and the native public was used during the analysis. The results concluded that the tourists gave greater importance to reliability and passenger information aspects of service.

Moreover, it was observed that the quality-centric assessment studies attract multi-criteria and fuzzy logic approaches to address the subjective nature of these variables and to strengthen the results. Adding strength to this observation, Vaidya (2014) and Patrick and Mulley (2013) adopted data envelopment analysis (DEA) to evaluate the performance of bus and metro systems, respectively. Moreover, the AHP and partial factor productivity were adopted in combination with DEA. Similarly, Kanuganti et al. (2013) calculated an overall level of service rating for public transit routes in the city of Jaipur, India, by using different multi-criteria approaches, such as numerical rating, fuzzy set theory, AHP, and a fuzzy-AHP approach. They found that the fuzzy set theory and fuzzy-AHP approaches perform better as they annihilate fuzziness.

For framework-based assessment, Balachandra and Reddy (2013) developed a framework for benchmarking different dimensions of sustainability such as environmental, economic, social, and governance aspects for the cities of Mumbai and Bangalore, India. These results were compared with those of London, Shanghai, and Singapore to assess the relative performance in terms of sustainability. Amongst the five cities, Singapore has emerged as the most sustainable city, while the two Indian cities occupied the bottom positions. Eboli and Mazzulla (2012) evaluated both subjective and objective measures of performance by setting benchmarks in accordance with the 'Transit Co-operative Research Programme' report 88. Buzási and Csete (2014) offered recommendations to effectively evaluate the sustainability of transport systems with 43 indicators classified under economic, environmental, and social categories.

The SLB guidelines released by MoUD (2013) were exercised on six Indian cities (MoUD and CEPT 2013). This framework was focused on a broader scope of urban transport with its own set of limitations in terms of spatial transferability because the framework was found to be slightly biased towards metropolitan cities. India is currently switching towards the modern PT systems such as Mass Rapid Transit System (Metro and Monorail), Light Rail Transit System, and Bus Rapid Transit System. Such modern PT systems attract huge investments from various bilateral and multilateral funding agencies, and timely repayment of these loans symbolise a nation's pride. Hence, a comprehensive evaluation and benchmarking of the existing PT system in integration with sustainability aspects is mandatory to ensure the right investment at the right time. Thus, a mode-specific sustainable benchmarking framework is developed and exercised on the city of Hyderabad, India, during this study. In addition to the discussed literature, the adopted practices by Paz et al. (2013), Bickford (2013), Buehler and Pucher (2011), Bruun and Vanderschuren (2017), Fu and Xin (2007), Kittelson and Associates (2003), Jasti and Ram (2016, 2018), Mishra et al. (2012), Derrible and Kennedy (2010), Litman (2014, 2018), were also examined while developing the framework.

A summary of the performance measures/evaluators considered by various researchers in both attribute and framework-based benchmarking practices is presented in Table 1.

Table 1 Performance measures/evaluators considered by various researchers

Referred work	Type of PT system	Performance measures/evaluators
Eboli and Mazzulla (2007)	Bus-based	Bus stop availability, route characteristics, frequency, reliability, bus stop furniture, overcrowding, cleanliness, cost, information, promotion, safety on board, personal security, personnel, complaints, environmental protection and bus stop maintenance
Fu and Xin (2007)	Generalized	Transit service index
Derrible and Kennedy (2010)	Rail-based	Coverage, directness and connectivity
Kinsella and Caulfield (2011)	Bus and rail-based	Quality of vehicles, safety, provision of information, proximity of stops, convenience, punctuality, waiting times, frequency, price, night services
Henning, et al. (2011)	Generalized	Travel mode, passenger kilometers travelled, public-transport patronage, speed of journey, travel time, vehicle fuel consumption, reliability departure and arrival time, catchment area-time, catchment area-distance, travel cost, road safety, personal security, comfort
Georgiadis (2012)	Bus-based	Spatial availability, temporal availability, capacity, reliability, travel time, customer satisfaction, availability (DRT), fare structure and policy
Prasertsubpakij and Nitivattananon (2012)	Rail-based	Safety, social usefulness, trust, comfort, activity period, trip purpose, duration, income, occupation, basic needs, market-based, potential connectivity, mixed use, attractiveness of metro utilities, equality to access, opportunity to access, time obtaining, activity location, compact, reducing sprawl
Kanuganti et al. (2013)	Bus-based	Travel cost, total journey time, walking distance, waiting time at bus stop, punctuality and reliability, availability of seat, space available for standing, comfort level of the seats, ease of boarding and alighting, sufficient number of seats for women, ventilation inside bus, quality of bus-stop, safety and security inside bus, bus driver, conductor and co- passenger behaviour, route information, convenience in ticket purchasing, condition and cleanliness of bus, noise level, jerking inside the running bus
Olivková (2015)	Rail-based	Transit time, punctuality, accessibility of stops, waiting for connection, transferability in mass transit network, arrangement of stops, operational information, arrangement of ticket presales, vehicle occupancy, noise level and vibrations, microclimate in vehicles, driving style, layout of interior of vehicles, transportation costs, impact of mass transit system on city environment

3 Development of sustainable benchmarking framework

From literature, it is evident that the practice of mode-specific benchmarking for the existing public transportation systems with an emphasis on sustainability is missing for Indian conditions. Hence, the proposed benchmarking framework of the urban bus system is targeted towards assessing the real-world scenario of the existing system in various conventional and sustainable dimensions with 29 evaluators nested in eight IGs. As the current benchmarking is a framework-based approach, every IG is nested with multiple evaluators, and every evaluator has its own formulation towards a respective performance evaluation. On a broader perspective, the framework is structured based on international practices and guidelines, such as MoUD's framework (MoUD 2010) of the conventional benchmarking of urban transport, European Commission's BESTRANS guidebook (2004), National Center for Transit Research's 'Benchmark Rankings for Transit Systems in United States' (NCTR 2004), and a detailed review publication on various global sustainability practices by Bongardt et al. (2011).

The developed framework is expected to assess and benchmark the performance of urban bus systems in Indian cities. A brief description of the target evaluation of all the IGs is presented with the framework in Table 2. Formulations of the evaluators are further presented under the section titled 'Integrated and Sustainable Benchmarking of the Urban Bus System' in this article.

It is illogical to weigh all the IGs and evaluators equally because their impact on the overall performance varies. Hence, a weight-based ranking system was developed through an expert opinion survey by applying multi-criteria decision-making techniques such as AHP and 'direct weighting.'

4 Determining weights for IGs and evaluators through expert opinion

The perception of significance and weight of IGs and evaluators varies from person to person as this is a subjective judgement. Hence, an expert opinion is sought by using the AHP method for determining the weights of IGs, which offers a pair-wise comparison between the eight IGs. Then, weights of evaluators under the IGs were also determined by expert opinion through the 'direct weighting' technique. AHP was selected over other MCDM techniques due to the convenience in terms of the possible pair-wise comparisons, ability to check inconsistencies, and the intuitive appeal to the decision makers (Gavade 2014). A wide range of experts working in the discipline of urban transport were selected for the expert opinion survey. They include industry practitioners, professionals working in PT agencies, academicians, and young research professionals who have a better understanding of the practical scenario of PT and associated policies. The expert opinion was collected by circulating the developed questionnaire to the experts through an e-mail. The opinions of senior professionals were collected through a direct interview. The experience of the

Table 2 Framework for sustainable benchmarking of the urban bus system

Indicator group (IG)	Evaluators	Target evaluation and description
Service availability (SA)	Public transport (PT) intensity (bus) (% city network covered)	To evaluate the SA attributes of the system and identify the areas of improvement, basic aspects, such as availability, intensity, and frequency, are evaluated. An emphasis was drawn on understanding the number of transfers as it reveals the robustness of connectivity
	Headway (min)	
	Ease of availability (bus stops/10 km along major corridors only)	
	Bus transfers (amount) (No. of bus transfers to reach the destination)	
	The intensity of buses (amount) (buses/1000 population)	
Service reliability (SR)	Presence of organised public transportation (%)	A reliable system would result in a better modal shift from personalised modes. Hence, attributes such as headway regularity, TT ratio, and waiting time are evaluated under this IG
	Average waiting for bus (min) (waiting time at bus stop)	
	Travel time (TT) ratio	
	Headway regularity as per schedule	
Comfort	Passenger comfort load factor (passenger/seat)	Although facilitating low-cost travel yields better ridership, certain passenger groups prefer comfort over cost. Hence, aspects such as passenger load factor, ride quality, and accessibility are assessed in this IG
	Ride quality	
	Accessibility	
Fare	Fare affordability	The target is to evaluate the out-pocket benefits offered to the end user by the PT service and to perceive the user opinion on fare affordability
	Ratio of PT expense to personal transport expense	
Passenger information system (PIS)	% Bus stops/terminals with PIS	PIS is turning out to be a basic component with continuous upgrade in technology. Accordingly, availability and deployment of technologies such as GPS and real-time PIS is evaluated
	% of buses equipped with global positioning system (GPS) for real-time PIS	
	The existence of customer care for intracity travel (toll free)	
Environment sustainability (ES)	CO_2 emission levels (g/km) (in ratio)	The urban bus system is an eco-friendly mode. Thus, the benefits of opting for the bus system over personal modes, such as reduction in pollution levels and fuel consumption, are evaluated in this category. Moreover, the presence of compressed natural gas (CNG) buses is considered
	Fuel consumption/km	
	% of compressed natural gas (CNG) buses	

Table 2 (continued)

Indicator group (IG)	Evaluators	Target evaluation and description
Economic and financial sustainability (EFS)	Extent of non-fare revenue/annum/bus (ratio)	Any PT system is expected to be economically sustainable and advisable to be financially sustainable for achieving longevity. Accordingly, aspects such as dependency on non-fare revenue, operation ratio, occupancy ratio, staff–bus ratio are evaluated
	Staff/bus ratio	
	Operation ratio (operating cost/earnings)	
	Ridership and occupancy ratio	
Social sustainability (SS)	Modal share (%)	This IG plays a key role in achieving the long-term sustainability of any PT system. Factors affecting the same, such as accessibility to the differently-abled, signal and social priority, and modal share, are evaluated with the accident rate
	% of accidents involving buses in the last five years	
	Accessibility of differently-abled (%)	
	Social priority (%)	
	Signal priority (%)	

experts participating in the opinion survey ranged from 25 to 3 years, thus providing the required blend of experience and ingenuity.

4.1 Procedure adopted for determining the weights of IGs by using the AHP method

In AHP, Saaty (1980) indicated that the decision maker (the expert in this case) assigns his or her priority in a pair-wise comparison among the available alternatives. Similarly, in the present case, the pair-wise ranking was obtained for the available eight IGs from the experts on the 'Scale of Relative significance', as shown in Table 3.

The opinions received from an expert are assigned to a group to form a matrix which is named as judgement matrix or decision matrix. In the present case of eight IGs, the experts have to offer 28 judgements through pair-wise comparisons. One such judgement offered by an expert is presented in Table 4 as a sample.

After obtaining a judgement matrix, the consistency of the matrix is checked in this study prior to utilising the sample to assess the degree of randomness in the judgement. Saaty (1980) proposed a measure of consistency that is known as the consistency index (CI). Moreover, to determine the consistency, a normalised relative weight has to be derived, in which the summation of the columns equals 1. Furthermore, the normalised principal eigenvector is obtained by taking an average across the rows. This eigenvector is also called a priority vector. The priority vector shows relative weights among the IGs being compared, as shown in Table 5.

To assess the consistency in the expert opinions, the principal eigenvalue (λmax) is obtained by summing the products between all elements of the eigenvector and the sum of the columns of the reciprocal matrix, as shown in Table 5. Now, as λmax is calculated, the CI can be calculated using Eq. (1) as follows. In the equation, 'n' represents the number of alternatives (IGs in this case):

$$\text{CI} = \frac{\lambda\text{max} - n}{n - 1} = \frac{8.759 - 8}{8 - 1} = 0.108 \tag{1}$$

The CI is then compared with the average CI of randomly generated reciprocal matrices or the random consistency index (RI). The average RI for a sample size of 500 matrices that was proposed by Saaty (1980) is presented in Table 6 for reference.

Saaty (1980) also proposed the consistency ratio (CR) between CI and RI, as shown in Eq. (2):

$$\text{CR} = \frac{CI}{RI} = \frac{0.108}{1.41} = 7.65\% \tag{2}$$

Moreover, Saaty (1980) indicated that an acceptable CR should be less than 10%. However, a CR of less than 20% is considered tolerable (Wedley 1993). Accordingly, the expert opinions within 20% CR are only considered as accepted samples, and the rest are dropped. The CR of the judgement by an expert illustrated above is 7.65%, which is < 20% and thus is acceptable.

Table 3 Illustrative criterion matrix for pair-wise comparison using AHP

Intensity of importance	Definition	Explanation
1	Equal significance	Two IGs contribute equally to the objective
3	Relative significance of one over another	Experience and judgement relatively favour one IG over another
5	Moderate significance of one over another	Experience and judgement moderately favour one IG over another
7	Strong significance	An IG is strongly favoured, and its dominance demonstrated in practice
9	Extreme significance	The evidence favouring one activity over another is of the highest possible order of affirmation
2, 4, 6, 8	Intermediate values between the two adjacent judgements	
Reciprocals of above non-zero values	If option A has a rating of one of the above when compared to option B for a criterion, then option B has the reciprocal rating when compared to option A	

Table 4 judgement matrix of an expert for IGs in AHP

Indicator groups	SA	SR	Comfort	Fare	PIS	ES	EFS	SS
Service availability (SA)	1	3	3	3	3	3	1	1
Service reliability (SR)	1/3	1	3	1	5	1	1	1
Comfort	1/3	1/3	1	1/3	1/3	1/3	1/3	1/3
Fare	1/3	1	3	1	3	1	1	1
PIS	1/3	1/5	3	1/3	1	1	1	1
Environmental sustainability (ES)	1/3	1	3	1	1	1	1	1/3
Economic and financial sustainability (EFS)	1	1	3	1	1	1	1	1/3
Social sustainability (SS)	1	1	3	1	1	3	3	1
SUM	4.67	8.53	22.00	8.67	15.33	11.33	9.33	6.00

With these criteria, only eight out of the 12 expert opinions (66.67% of the total collected samples) were found to be within the 'tolerable' limits and thus were considered for further analysis. The weights were determined by taking the arithmetic mean of the accepted samples and the final resultant weights for the eight IGs are as shown in Table 7.

4.2 Procedure adopted for determining the weights of evaluators

In the 'direct weighting' technique, the experts are requested to offer their judgements or decisions in the form of simple numerical weights for evaluators nested in an IG, which is equivalent to 10. For instance, consider that an IG 'service availability' has five evaluators. Then, the expert shall offer his or her judgement in the form of weights to these five evaluators whose collective sum would be equivalent to 10. Accordingly, the experts have offered their judgements for all the evaluators, and the resultant weights of the same are presented in the section 'Integrated and Sustainable Benchmarking of the Urban Bus System' of this article. The reason for adopting 'direct weighting' over AHP for determining evaluator weights is the associated complexity due to the exhaustive pair-wise comparisons, which are expected to be more than 400 for 29 evaluators. Moreover, as evaluators are the micro-level aspects in such a comprehensive framework, 'direct weighting' within an IG shall suffice.

4.3 Summarising the expert opinion

The expert opinions revealed that 'service availability', 'service reliability', and 'social sustainability' have to be prioritised for achieving a better urban bus system for Indian conditions. On the contrary, quality-oriented IGs such as 'comfort' and 'PIS' are placed. On a broader perspective, experts prioritised the service-oriented IGs, followed by the sustainability-oriented IGs. This behaviour signifies the need for attaining long-term sustainability.

Table 5 Normalised relative weight matrix and priority vector

Indicator groups	SA	SR	Comfort	Fare	PIS	ES	EFS	SS	SUM	Priority vector	λmax
SA	0.214	0.352	0.136	0.346	0.196	0.265	0.107	0.167	1.783	22.28	8.318
SR	0.071	0.117	0.136	0.115	0.326	0.088	0.107	0.167	1.128	14.11	9.630
Comfort	0.071	0.039	0.045	0.038	0.022	0.029	0.036	0.056	0.337	4.21	7.410
Fare	0.071	0.117	0.136	0.115	0.196	0.088	0.107	0.167	0.998	12.48	8.650
PIS	0.071	0.023	0.136	0.038	0.065	0.088	0.107	0.167	0.697	8.71	10.687
ES	0.071	0.117	0.136	0.115	0.065	0.088	0.107	0.056	0.757	9.46	8.574
EFS	0.214	0.117	0.136	0.115	0.065	0.088	0.107	0.056	0.899	11.24	8.394
SS	0.214	0.117	0.136	0.115	0.065	0.265	0.321	0.167	1.401	17.52	8.407
SUM	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	8	100	8.759 (avg)

Table 6 RI proposed by Saaty (1980)

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

Table 7 Resultant weights of IGs by AHP from expert opinion

Indicator groups	Resultant weights
Service availability	18.65
Service reliability	17.56
Comfort	6.61
Fare	10.06
Passenger information system	7.31
Environment sustainability	13.32
Economic and financial sustainability (EFS)	10.01
Social sustainability	16.48
SUM	100

5 Exercising the framework on Hyderabad

Hyderabad is considered as one of the fastest growing metropolitan cities in India. The Hyderabad Metropolitan Region Development Authority (HMDA) in a study indicated that 95% of the PT mode share in Hyderabad belongs to the urban bus system (HMDA 2013). This is one of the reasons for selecting the Hyderabad Metropolitan Area (HMA) as the study area for the current study. This aspect shall serve as an additional objective towards verifying the soundness of the developed framework. HMDA through a recent study indicated that HMA, with a population of 9.5 million as per the 2011 census, is expected to attain the 19 million mark by 2041 in terms of the population when estimated using a very moderate growth rate (HMDA 2013). As per the HMDA (2012), HMA is spread over 7200 km^2 in terms of area, thus forcing longer trip lengths and automobile dependency. The quantum of travel can be understood from the fact that approximately 44,000 intra-city bus trips occur on a daily basis in Hyderabad. The following are the PT carriers within the city as per the HMDA (2012).

- Telangana State Road Transport Corporation (Erstwhile Andhra Pradesh State Road Transport Corporation) is a state transport undertaking holding above 97% of the buses and service coverage.
- Set-win is a private contract carrier with approximately 3% buses and service coverage.

Among the vast bus network of 2400 km, the study routes or corridors are selected in a way that they reflect the overall passenger trip pattern within HMA and cover all major corridors. Thus, a list of 70 routes (to and fro routes) are selected. A map of the selected bus routes with their service numbers and route lengths is shown in Fig. 1.
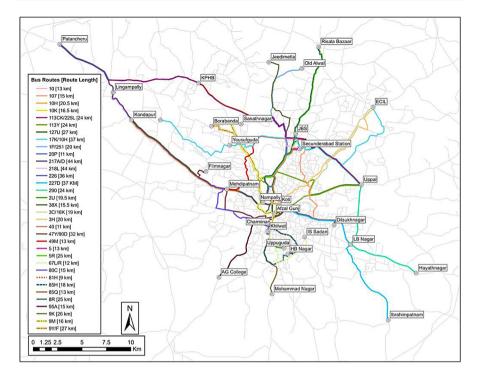
Fig. 1 Map displaying the selected routes and operating service numbers. Source: HMDA (2012)

The sustainable benchmarking based on a comprehensive evaluation with a weight-based ranking system demands extensive data such as vehicle operating costs (VOCs), passenger opinions, CO_2 emission levels, traffic volumes, and speed and delay data. The collection of raw data and its requisite analysis to draw proper conclusion plays a key role in the successful assessment of the system.

A systematic mechanism of data collection was adopted to optimise time and avoid any repetitive exercises. The formulations developed for all the evaluators were closely examined, and the methodology of requisite analysis was finalised. As majority of the formulations attract customised analysis, requisite data for conducting such analysis was collected through primary and secondary data collection.

6 Integrated and sustainable benchmarking of the urban bus system

The developed framework was exercised on the urban bus system of Hyderabad after the completion of necessary data collection and analysis. By post-feeding the data, the trailing procedure is adopted to finally arrive at a conclusion on the overall performance of the urban bus system of Hyderabad.

Evaluator performance was assessed with respective formulations. Moreover, an exclusive quality of service was derived based on the output of 'evaluator quality of service' (EQoS) and ranked on a scale of 1–4 (set target). Most of the EQoS scales

were equally distributed among these four levels on a range of 0–100 or 0–1, whichever is suitable. The evaluators for which the scaling cannot be defined on the said basis, such as 'frequency', 'waiting time', and 'fuel consumption', the scaling (set target) was defined on the basis of the practical situation in the Indian scenario. The respective EQoS achieved by every evaluator is highlighted in Table 8 (Column 4).

The IGs in the framework are also assessed individually and an 'indicator quality of service' (IQoS) is derived using Eq. (3):

$$IQoS = \frac{\sum_{i=1}^{n} WE\, i \times EQoS\, of\, i}{10} \tag{3}$$

WE i represents the weight of Evaluator i (where $i = 1, 2, 3, \ldots n$).

For better convenience and for further application of the fuzzy logic approach, the 'indicator rate of performance' (IRoP) is represented using Eq. (4):

$$IRoP(\%) = \left(\frac{IQoS}{4}\right) \times 100 \tag{4}$$

Similarly, the 'overall quality of service' (OQoS) for the entire urban bus system is represented using Eq. (5):

$$OQoS\, Score = \frac{\sum_{i=1}^{n} WIG\, i \times IQoS\, of\, IG\, i}{400} \tag{5}$$

WIG i represents the weight of IGs i (where $i = 1, 2, 3, \ldots n$) and 400 represents that the scaling set has four intervals. Hence, 400 would be the maximum attainable value.

Finally, the overall rate of performance (ORoP) of a given system is represented using Eq. (6) for an easy resemblance:

$$ORoP\,(\%) = OQoS \times 100 \tag{6}$$

The exercise of the developed framework on Hyderabad's urban bus system is presented in Table 8. In the table, the data/analysis output is fed into the formulations. Based on the result, the evaluator is ranked against EQoS as shown. As aforementioned, the evaluator weights derived from the expert opinion survey are also presented in Table 8 (Column 5).

Now, OQoS of the entire system was computed using Eq. (5) by assigning respective indicator weights derived from expert opinion (Table 7), as shown in Eq. (7):

$$OQoS\, Score = \frac{\begin{array}{c}(18.65 \times 3.37) + (17.56 \times 3.23) + (6.61 \times 3.38) + (10.06 \times 3.49) + \\ (7.31 \times 1.38) + (13.32 \times 1.99) + (10.01 \times 3.20) + (16.48 \times 1.67)\end{array}}{400} = 0.68 \tag{7}$$

Finally, the ORoP of the entire system, expressed in percentage terms, is calculated using Eq. (6), resulting in a value of 68.27%. This clearly indicates that the performance of Hyderabad's urban bus system is moderately satisfactory with almost 68% of the rated performance. However, efforts need to be continued to improve the

Table 8 Integrated and sustainable benchmarking of the urban bus system

Indicator group (IG) (1)	Evaluators (2)	Formulation (3)	EQoS scaling (4)		Evaluator weights (5)
Service availability (SA)	Public transport (PT) intensity (% network covered)	$\left(\dfrac{\text{PT Availability in km}=2400}{\text{Total Road Network in km}=3428}\right) \times 100$	**3**	**50–75**	**2.45**
			4	> 75	
			2	25–49	
			1	<25	
	Headway (min)	Frequency of a service = 10.14 min	4	<5	**2.56**
			3	**06–15**	
			2	15–30	
			1	> 30	
	Ease of availability (bus stops/10 km along major corridors only)	$\left(\dfrac{\text{Average number of bus stops}=18}{\text{Average Route Length}=22.64}\right) \times (100)$	**4**	**> 75**	**2.18**
			3	50–75	
			2	25–49	
			1	< 25	
	Bus transfers (amount)	Number of bus transfers to reach destination = 0.61	**4**	**< 1**	**1.49**
			3	2–3	
			2	3–4	
			1	> 5	
	The intensity of buses (amount)	$\left(\dfrac{\text{Total number of buses}=3628}{\text{Population in } 1000's=6809.97}\right)$	4	> 0.6	**1.31**
			3	**0.4–0.6**	
			2	0.2–0.4	
			1	< 0.2	

IQoS = (2.45×3 + 2.56×3 + 2.18×4 + 1.49×4 + 1.31×3)/10 = 3.37

Table 8 (continued)

Indicator group (IG) (1)	Evaluators (2)	Formulation (3)	EQoS scaling (4)		Evaluator weights (5)
Service reliability (SR)	Presence of organised public transportation (%)	$\left(\dfrac{\text{Buses owned by STU/SPV}=3628}{\text{Total number of buses}=3628} \right) \times 100$	**4**	**>75**	**2.33**
			3	50–75	
			2	25–49	
			1	<25	
	Average waiting for bus (min.)	13 min	**4**	**<5**	**2.75**
			3	**5–15**	
			2	16–20	
			1	>20	
	Travel time (TT) ratio	$\left(\dfrac{\text{Avg.TT of bus/km (min)}=2.94}{\text{Avg.TT of Pvt.Mode/km (min)}=2.61} \right)$	**4**	**<1**	**2.58**
			3	**1–3**	
			2	3–5	
			1	>5	
	Headway regularity in peak hour as per schedule	User rating of bus punctuality = 2.43	**4**	**3–4**	**2.33**
			3	**2–3**	
			2	1–2	
			1	≤1	

IQoS = (2.33×4 + 2.75×3 + 2.58×3 + 2.33×3)/10 = 3.23

Table 8 (continued)

Indicator group (IG) (1)	Evaluators (2)	Formulation (3)	EQoS scaling (4)		Evaluator weights (5)
Comfort	Passenger comfort load factor (passenger/seat)	$\left(\dfrac{\text{Seat kilometers provided} =54{,}885}{\text{Passenger kilometers travelled}=48{,}330} \right)$	**4**	**≤ 1.5**	**3.75**
			3	1.5–2	
			2	2–2.5	
			1	> 2.5	
	Ride quality	User rating = 2.51	4	3–4	**2.53**
			3	**2–3**	
			2	1–2	
			1	≤1	
	Accessibility	User rating = 2.49	4	3–4	**3.72**
			3	**2–3**	
			2	1–2	
			1	≤1	

IQoS = (3.75 × 4 + 2.53 × 3 + 3.72 × 3)/10 = 3.38

Table 8 (continued)

Indicator group (IG) (1)	Evaluators (2)	Formulation (3)	EQoS scaling (4)		Evaluator weights (5)
Fare	Fare affordability	User rating = 2.9	4	3–4	**5.08**
			3	**2–3**	
			2	1–2	
			1	≤ 1	
	Ratio of PT expense to personal transport expense	$\left(\dfrac{\text{Avg.per person/km cost by bus=0.33}}{\text{Avg.per person/km cost by personal mode=1.59}} \right)$	**4**	**< 0.25**	**4.92**
			3	0.25–0.5	
			2	0.5–1.0	
			1	≥ 1	

IQoS = (5.08 × 3 + 4.92 × 4)/10 = 3.49

Table 8 (continued)

Indicator group (IG) (1)	Evaluators (2)	Formulation (3)	EQoS scaling (4)		Evaluator weights (5)
Passenger Information system (PIS)	% bus stops/terminals with PIS	$\left(\dfrac{\text{Number of bus stops equipped with PIS} =100}{\text{Number of bus stops within GHMC} =1970} \right) \times 100$	4	>75	**3.83**
			3	50–75	
			2	25–49	
			1	**<25**	
	% of buses equipped with GPS for real-time PIS	$\left(\dfrac{\text{Number of buses equipped with GPS} =1,193}{\text{Number of buses in service} =3,628} \right) \times 100$	4	>75	**3.78**
			3	50–75	
			2	**25–49**	
			1	<25	
	The existence of customer care for intracity travel (Toll Free)	If No, EQoS = 1 If Yes, % of area covered with the information	4	>50	**2.39**
			3	20–50	
			2	≤20	
			1	**No**	

IQoS = (3.83×1 + 3.78×2 + 2.39×1)/10 = 1.38

Table 8 (continued)

Indicator group (IG) (1)	Evaluators (2)	Formulation (3)	EQoS scaling (4)		Evaluator weights (5)
Environment sustainability (ES)	CO$_2$ emission levels (g/km) (in ratio)	$\left(1 - \dfrac{CO_2 \text{ emissions/person by buses} = 19.72}{CO_2 \text{ emissions/person by personal modes} = 26.30}\right) \times 100$	4	> 75	**3.73**
			3	50–75	
			2	**25–49**	
			1	< 25	
	Fuel consumption/km	Average mileage of buses = 4.45	4	> 6	**3.10**
			3	**4–5**	
			2	3–4	
			1	< 3	
	% of CNG buses	$\left(\dfrac{\text{Number of CNG buses} = 131}{\text{Total number of buses in service} = 3,752}\right) \times 100$	4	> 75	**3.17**
			3	50–75	
			2	25–49	
			1	**< 25**	

IQoS = (3.73 × 2 + 3.10 × 3 + 3.17 × 1)/10 = 1.99

Table 8 (continued)

Indicator group (IG) (1)	Evaluators (2)	Formulation (3)	EQoS scaling (4)		Evaluator weights (5)
Economic and financial sustainability (EFS)	Extent of non-fare revenue/annum/bus (ratio)	$\left(\dfrac{\text{Annual non-fare revenue} = 18,866.61}{\text{Total annual revenue all sources} = 86,005.49}\right) \times 100$	4	> 40	**1.74**
			3	**21–40**	
			2	10–20	
			1	< 10	
	Staff/bus ratio (only TSRTC)	$\left(\dfrac{\text{Total on board \& maintenance staff} = 2467}{\text{Total number of buses} = 3530}\right)$	**4**	**< 5.5**	**1.95**
			3	5.5–8	
			2	8.0–10	
			1	> 10	
	Operation ratio	$\left(\dfrac{\text{Earnings per bus} = 86,005.49}{\text{VOC per bus} = 88,010.2}\right)$	4	> 1.0	**2.40**
			3	**0.75–1.0**	
			2	0.75–0.50	
			1	< 0.50	
	Ridership and occupancy ratio	$\left(\dfrac{\text{Occupancy} = 39}{\text{Design capacity (standing)} = 60}\right) \times 100$	4	> 75	**3.91**
			3	**50.1–75**	
			2	25.1–50	
			1	< 25	

IQoS $= (1.74 \times 3 + 1.95 \times 4 + 2.40 \times 3 + 3.91 \times 3)/10 = 3.20$

Table 8 (continued)

Indicator group (IG) (1)	Evaluators (2)	Formulation (3)	EQoS scaling (4)		Evaluator weights (5)
Social sustainability (SS)	Modal share (%)	Modal share of bus = 34.5%	4	> 50	**2.05**
			3	35–50	
			2	**25–35**	
			1	< 25	
	% of accidents involving buses in last 5 years	$\left(\dfrac{\text{Accidents in which buses are accused} = 791}{\text{Total number of accidents} = 7172}\right) \times 100$	4	< 10	**2.30**
			3	**10–25**	
			2	25–50	
			1	> 50	
	Accessibility of differently-abled (%)	$\left(\dfrac{\text{Number of low floor buses} = 161}{\text{Total number of buses} = 3628}\right) \times 100$	4	> 75	**1.71**
			3	50–75	
			2	25–50	
			1	**< 25**	
	Social priority in km (%)	$\left(\dfrac{\text{Length of dedicated bus lanes} = 0}{\text{Length of PT network} = 2400}\right) \times 100$	4	> 75	**2.27**
			3	50–75	
			2	25–50	
			1	**< 25**	
	Signal priority (%)	$\left(\dfrac{\text{Length of dedicated bus lanes} = 0}{\text{Length of PT network} = 2{,}400}\right) \times 100$	4	> 75	**1.68**
			3	50–75	
			2	25–50	
			1	**< 25**	

IQoS = (2.05×2 + 2.30×3 + 1.71×1 + 2.27×1 + 1.68×1)/10 = 1.67

SPV special purpose vehicle

Table 9 Linguistic ratings of the benchmarking for IRoP

Linguistic variables	IRoP interval (%)
Very good (VG)	> 90
Good (G)	71–90
Fair (F)	51–70
Poor (P)	36–50
Very poor (VP)	≤ 35

performance further. The proposed framework gave a direction towards the logical and realistic evaluation of the existing urban bus system with considering the sustainability aspects.

7 Application of fuzzy logic and linguistic ratings

Although the subjective judgements, such as weights, are assigned logically using the AHP and 'direct weighting' techniques by expert opinion, the proposed scaling and benchmarking in the framework is expected to have some intangibility and vagueness. To address and neutralise the same, the fuzzy logic approach was used with a triangular membership function (TMF). Fuzzy logic operates on membership functions for processing data and facilitates an effective method for arriving at a precise conclusion based on imprecise, vague, or uncertain information. In the present study, several evaluators were assessed and ranked under the criteria of multiple IGs.

The IRoP calculated using Eq. (4) is categorised on a scale of five with linguistic ratings, as shown in Table 9. As these ratings are perceptive and qualitative in nature, the ratings have to be normalised to avoid uncertainty in benchmarking while using fuzzy logic membership functions.

Moreover, TMF is adopted in this study due to its computational simplicity. Only three parameters are required, that is, lower and upper width (a and c) that represent the 'feet' and a nodal point (b) that represents the peak. Note that for the majority of the practical applications, triangular fuzzy numbers are popularly used.

The triangular curve in TMF is based on the three scalar parameters (a, b, and c) and presents a function of the vector X, as shown in Eq. (8):

$$f(x;a,b,c) = \max\left\{\min\left(\frac{x-a}{b-a}, \frac{c-x}{c-b}\right), 0\right\} \tag{8}$$

Based on the realistic scenario of public transport in India, the scalar parameters for all five linguistic variables are perceived as shown in Table 10.

The above scalar parameters are applied using the TMF to the IGs, based on the respective linguistic ratings achieved. After application of the TMF and defuzzification function, the corresponding rating for IGs is as listed in Table 11.

By applying the fuzzy logic approach using TMF and a defuzzification function, the ONRoP of Hyderabad's urban bus system is obtained to be 73.76%.

Table 10 Scalar parameters of linguistic variables

Linguistic variable	Scalar parameters			Defuzzied values $\frac{(a+b+c)}{3}$
	a	b	c	
Very good (VG)	0.90	1.00	1.00	0.97
Good (G)	0.75	0.90	1.00	0.88
Fair (F)	0.50	0.75	0.90	0.72
Poor (P)	0.35	0.50	0.75	0.53
Very poor (VP)	0.10	0.35	0.50	0.32

Table 11 Performance rating after defuzzification

Indicator group	IQoS	IRoP (%)	Linguistic rating	Defuzzied value (DV) (Table 10)	Indicator weights (WPI)
Service availability	3.37	84.19	G	0.88	18.65
Service reliability	3.23	80.83	G	0.88	17.56
Comfort	3.38	84.38	G	0.88	6.61
Fare	3.49	87.30	G	0.88	10.06
Passenger information system (PIS)	1.38	34.44	VP	0.32	7.31
Environmental sustainability	1.99	49.83	P	0.53	13.32
Economic and financial sustainability	3.20	79.88	G	0.88	10.01
Social sustainability	1.67	41.63	P	0.53	16.48
Overall normalised rate of performance (ONRoP) = WPI×DV					73.76

8 Specific contributions

Specific contributions, made from the study involving the development of the framework and its subsequent application for the case study of Hyderabad city, are listed below for reference:

- The attempt towards integrating the conventional and sustainable aspects for PT performance evaluation and benchmarking is a pioneering effort, in particular for the Indian context. The standardisation of this framework for performance comparison across various Indian cities will provide long-term sustainability.
- Application of appropriate MCDM techniques, i.e. AHP and 'direct weighting', through expert opinion has made the results of the weight-based ranking system more reliable.
- Successful application fuzzy logic approach for the framework-based benchmarking to address the built-in intangibility has made the process robust.
- The developed mode-specific framework presents a simplified decision-making tool for the local and central government officials for prioritising the development schemes.

9 Conclusions and discussion

This study was conducted after realising the importance of sustainable benchmarking of PT in general. The lack of a standardisation process for performance evaluation and prioritisation for effective fund allocation in India makes this study more relevant. The major lessons learnt during this study are summarised below for reference:

- The practice of mode-specific benchmarking of urban public transportation systems with an emphasis on sustainability is missing for Indian conditions.
- By considering the upgrade towards modern transport and considering the multimodal nature of PT systems in India, mode-specific PT benchmarking is recommended for accurate performance assessment.
- Application of MCDM techniques such as AHP and 'direct weighting' are found to be suitable for framework-based benchmarking for determining the significance (in terms of weights) of IGs (alternatives) and evaluators, respectively. However, note that the significance varies due to the ever-changing urban transport scenario, thus establishing the need to update the same in accordance with the prevailing conditions.
- Though the present study has taken care of planned delays during peak hours, it does not account the disturbances due to un-expected incidents such as accidents, special events. Addressing this limitation in the future scope shall further strengthen the proposed benchmarking approach.

The study reveals that Hyderabad's urban bus system is performing at an 'ORoP' of 68%. Upon application of fuzzy logic, the resultant 'ONRoP' was calculated to be 74%. Moreover, the specific performance of various IGs was summarised as below for reference.

- The performance of service- and quality-oriented sectors such as 'service availability', 'service reliability', 'comfort' and 'fare' are identified to be satisfactory with an IRoP of over 80%. However, the improvement of 'frequency' and 'average waiting time' of the services shall further uplift the sectoral performance.
- With an 'IRoP' of 49.83%, the performance of 'environmental sustainability' is observed to be poor.
- The sectoral performance of 'social sustainability' is not encouraging with an 'IRoP' of 41.63%. Although the urban bus 'modal share' is observed to be moderately acceptable with a value of 22%, the 'accessibility' facilities for the differently abled appear to be notional. Moreover, there are no initiatives towards 'social priority' and 'signal priority', which is a discouraging fact towards achieving long-term social sustainability.
- The sectoral performance of 'PIS' is observed to be the least with an 'IRoP' of 34.44%. This is because, only 15% of the bus stops are equipped with basic PIS facilities and only 32% of the buses are equipped with GPS, thus leaving huge scope for improvement.

In addition to the above, it can be observed that substantial funding for the development of urban PT systems in India is obtained from multilateral and bilateral funding agencies. Timely repayment of such huge loans is not only a responsibility but also plays a key role in maintaining the respect of the country in the global market. In this regard, it is vital to select and prioritise the funding distribution of PT projects within India. Thus, a perfect assessment of the existing performance of public transportation systems is required. Hence, the developed framework is recommended to be institutionalised and exercised in Indian cities of similar size and scale to keep track and compare the performance of urban bus systems.

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