Comparative evaluation of bus rapid transit routes using super efficiency data envelopment analysis

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Periodical evaluation of the transit system and its subunits is becoming paramount for improving its performance. This article evaluates the performance of 12 routes of the bus rapid transit system operating in Ahmedabad, India. The performance indices considered in the study were divided into five major types of efficiency, viz. route design, scheduled design, cost, service delivery, and comfort and safety efficiency. Super efficiency data envelopment analysis was used to estimate efficiency scores for each type. Further, composite efficiency of routes was estimated based on analytical hierarchy process technique.

Keywords: Analytical hierarchy process, bus rapid transit, data envelopment analysis, route performance.

THE bus rapid transit system (BRTS) has now become an integral part of the urban transportation system in a number of cities in both developed and developing countries. Transit agencies are therefore trying to operate this system efficiently to increase the revenue for balancing the operating cost. The cities in which BRTS is in operation are still in the process of expanding the corridors of this system; therefore, limited research has been carried out to understand the performance of the already existing corridors and routes.

According to the literature, the performance of a transit service can be measured at four levels, viz. bus stop, route, corridor and system[1]. The transit agencies are mainly concerned with evaluating the performance of the route as most of the variables affecting it are under their control. Various route performance attributes based on passenger, operator and community perspective have been studied and presented here.

In the present study we evaluate the route performance of the entire network BRTS in Ahmedabad, India consisting of 12 routes. This evaluation was done using ITS, ticketing, landuse and user perception data. The selected parameters were consolidated to five efficiencies, viz. route design, scheduled design, cost, service delivery, and comfort and safety efficiency. To evaluate the performance of each route, a linear programming-based model, i.e. data envelopment analysis (DEA) was used. DEA is a nonparametric method in operations research which is used to measure productivity efficiency of decision-making units (DMUs) which in the present study are the BRTS routes. DEA was used in the present study as it is capable of handling multiple inputs, and outputs and also because the sources of the inefficiency can be analysed and quantified for every evaluated unit (BRTS route). To evaluate the performance of BRTS routes, two types of DEA models were used, viz. Charles, cooper and Rhodes (CCR) model based on constant return to scale and super efficiency data envelopment analysis (SEDEA) model. SEDEA is an improvement over the conventional DEA model as the unity constraint of efficiency is relaxed in this model; this allows the routes to achieve an efficiency score more than unity. This is important because by the conventional DEA model some routes achieve an efficiency score of ‘1’ and hence finding the best route among them becomes a problem. Therefore, this problem is solved using SEDEA.

After estimating individual efficiency, composite efficiency was estimated based on analytical hierarchy process (AHP) technique. Using this technique, weights were assigned to each individual efficiency to finally estimate the composite efficiency of all 12 routes.

The subsequent sections contain a review of performance attributes and use of CCR DEA and SEDEA to evaluate the performance of BRTS routes. Further, a brief study methodology is proposed to evaluate the performance using the aforesaid models. Then, based on the efficiency scores, improvements to increase the performance of routes are suggested. Composite efficiency of the routes is finally estimated using AHP technique.

Literature review

The past research on measuring transit performance can be categorized into four major levels[1], viz. bus stop, route, corridor and system. DEA approach has been majorly used to evaluate the performance of the transit system and agencies. Limited studies have been reported

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in the past to evaluate the performance of subunits of the transit system such as bus stop and route. At the system level, Tongzon[2] used DEA approach to evaluate the performance of ports in Australia and 12 other international container ports. The basic CCR DEA model was used by which four ports were found to be the most inefficient because they achieved a low efficiency score. In another system level study, Husain *et al.*[3] evaluated the performance of a transit system in Australia using DEA. A group of service units was compared to identify relatively inefficient units. Also, the magnitudes of the inefficiencies were measured using the basic DEA model. Chu *et al.*[4] applied the DEA model to two transit peer groups – one serving large metropolitan areas and the other serving relatively small cities and large towns. This study used a single measure for computing the efficiency as well as for computing the effectiveness of a transit agency relative to other agencies within the same peer group. Tone and Sawada[5], while evaluating the performance of transit agencies analysed the cost, service, income and public service efficiency separately by giving individual efficiency scores to all of them. Obeng[6] measured technical efficiency of 73 US urban transit systems using three inputs and one output. The inputs were labour, fuel and fleet size, while the output was vehicle miles. Two-stage DEA model was used; the second stage included the effect of environmental variables, namely operating and capital subsidies on the efficiency scores. Nolan[7] reported DEA-based performance evaluation of mid-sized transit agencies operating in the US. The study measured agency-level technical efficiency with nonparametric frontier analysis, i.e. DEA. The analysis was supplemented by a second stage regression of agency characteristics on the technical efficiency scores. Carotenuto *et al.*[8] and Boile[9] evaluated the efficiencies of the transit system and observed the inefficiencies in input and output variables after the development of the DEA model. De Borger *et al.*[10] reviewed the production and cost frontiers as a part of the DEA model for public transit system; the study presents a review of transit performance indicators and methods to measure them. Kerstens[11] evaluated the performance of the French Urban Transit Sector (FUTS) for the single bus mode using variable return to scale DEA with either strong or weak disposability in both inputs and outputs using free disposable hull (FDH). A system-level study was presented by Oh *et al.*[12], Oh and Kim[13], wherein they estimated efficiencies of urban bus companies in Korea using the basic DEA model. Karlaftis[14,15] reported a relationship between scale economies and performance of the transit systems, using the concept of scale economies in a broader sense. A system-level study was also presented by Tsamboulas[16], wherein the efficiency scores of 15 European transit systems were estimated using the basic DEA model.

The aforementioned studies were mainly based on estimating efficiency scores of the transit system as a whole using conventional DEA models. Further, DEA-based studies to evaluate the efficiency of the subunits of the transit system have been presented. A corridor-level study was carried out by Mansha and Parida[17], wherein performance of metro rail corridors and stations based on the DEA approach using basic CCR model was evaluated. Seth *et al.*[18] evaluated the performance of bus routes based on goal programming and DEA. The data used in the study were artificially simulated for various input and output variables including environmental and societal variables, i.e. an advanced DEA model was reported in the study. Lao and Liu[19], and Hahn *et al.*[20] evaluated the performance of bus lines, including both operation and operational environment attributes using DEA and geographical information system (GIS). Banker, Chames and Cooper (BCC) model of DEA was used to compute the efficiency scores of the bus lines. In studies based on transit route performance evaluation, Tandon[21] and Barnum[22] presented the effect of exogenous variables on the efficiency of the routes; the outputs in the study were first adjusted for the environmental factors and then a reverse two-stage DEA model was applied using data from a large American bus system. On similar lines, Hagashimoto[23] evaluated bus routes using the DEA approach keeping in mind the social priority (exogenous variables) in terms of access to hospitals and commercial facilities. Sun *et al.*[24] developed a GIS and AHP-based DEA model to evaluate bus routes of Shenzhen city in China.

It can be observed from the above studies that generally the conventional DEA model was applied to evaluate the performance of either the system or its subunits. No study has reported the use SEDEA. As the present study focuses on bus route performance evaluation, Table 1 illustrates various input and output variables used in previous studies to evaluate the performance of bus routes based on the DEA approach. Both the input and output variables are clubbed together in Table 1, because in the literature inputs in some cases have been considered as outputs and vice versa when used in the DEA model. From this table it can be observed that variables like service frequency, duration, schedule reliability, round-trip distance and number of bus stops are widely considered in the development of DEA models.

CCR and SEDEA

The efficiency measurement of a BRTS route and identification of the attributes affecting its efficiency are a prerequisite for improving the performance of any BRTS route. While developing any DEA model, an input and output are required for different DMUs. In this study, DMUs are the BRTS routes. Twelve BRTS routes are presently operating in Ahmedabad, i.e. DMU_1,

Table 1. Input and output variables used in previous studies

Variable	Benn[33]	Seth *et al.*[18]	Barnum *et al.*[22]	Lao and Liu[19]	Hahn *et al.*[20]	Hagashimoto *et al.*[23]	Sun *et al.*[24]
Service frequency	✓	✓	✓	×	✓	×	×
Cost or cost/h	✓	✓	×	×	✓	×	×
Transportation cost		×	×	×	×	✓	×
Service duration	✓	✓	✓	✓	×	✓	×
Number of Intersections	×	✓	×	×	×	×	×
Average travelling time	×	✓	×	×	×	×	×
Operational speed		×	×	×	×	×	✓
Vehicle miles	×	✓	×	×	×	×	×
Schedule reliability	×	✓	✓	✓	×	×	✓
Passenger miles or passenger per miles	✓	✓	×	×	×	×	×
Number of accidents	✓	✓	×	×	×	×	×
Number of transfers	✓	×	×	×	×	×	✓
Emissions	×	✓	×	×	×	×	×
Noise pollution	×	✓	×	×	×	×	×
Round-trip distance	×	✓	×	✓	✓	×	×
Number of bus stops	✓	✓	×	✓	✓	×	×
Maximum number of passengers standing	✓	×	×	×	×	×	✓
Peak hour delay rate	×	×	×	×	×	×	✓
Number of passengers or passengers/h	✓	×	✓	×	✓	×	×
Passengers/trip	✓	×	×	×	×	×	×
Seat kilometres	×	×	×	×	✓	×	✓
Seat hours	×	×	×	×	✓	×	×
Revenue per passenger per route	✓	×	×	×	×	✓	×
Subsidy per passenger per route	✓	×	×	×	×	×	×
Cost: recovery ratio	✓	×	×	×	×	×	×
Population density	✓	×	×	×	✓	✓	×
Employment density	✓	×	×	×	×	×	×
Route coverage	✓	×	×	×	×	×	✓
Route directness	✓	×	×	×	×	×	×
Number of hospitals and commercial facilities along route	×	×	×	×	×	✓	×
Proximity to residences	✓	×	×	×	×	×	×

DMU_2, …, DMU_{12}. The input and output matrices of the DMU are

$$X = \begin{pmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{pmatrix}, \; Y = \begin{pmatrix} y_{11} & y_{12} & \cdots & y_{1n} \\ y_{21} & y_{22} & \cdots & y_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ y_{m1} & y_{m2} & \cdots & y_{mn} \end{pmatrix},$$

where X and Y are the input and output data matrices, including the entire dataset. The basic CCR model used to estimate the route efficiency for each dimension is given in eq (1) as

$$\theta_q = \frac{\sum_{i=1}^{s} u_i y_{iq}}{\sum_{i=1}^{m} v_j \; x_{iq}}, \tag{1}$$

where u_i and v_j are the input and the outputs weights respectively, and θ_q is the efficiency of the qth DMU. The constraint of this model is that θ_q should not exceed unity, but should be maximized to obtain the corresponding weights. Further, all input and output data are considered as positive values. Equation (1) can be replaced by a linear programming problem as

$$\text{Max}\theta_q = u_1 \; y_{1q} + u_2 y_{2q} \ldots u_n y_{n0}, \tag{2}$$

$$\text{Subjected to } v_1 x_{1q} + v_2 \; x_{2q} \ldots v_n \; x_{n0} = 1, \tag{3}$$

$$u_1 y_{1q} + u_2 y_{2q} \ldots u_n \; y_{n0} \leq v_1 x_{1q} + v_2 x_{2q} \ldots v_n x_{n0}, \tag{4}$$

where

$$v_1, v_2, \ldots, v_m \geq 0, \tag{5}$$

$$u_1, u_2, \ldots, u_m \geq 0. \tag{6}$$

The model shown in eq. (2) follows unit invariance, i.e. the efficiency obtained from the model is independent of the units in which the input and outputs are measured. This is the basic CCR model having two types, i.e. input-oriented CCR model (I-CCR) and output-oriented CCR model (O-CCR). The I-CCR model aims at minimizing the inputs to cover up the given output level. On the other hand, the O-CCR model attempts to maximize the output without requiring more of the input values. Here we use the I-CCR model, i.e. the dual linear programming (DLP) model in the first part of the study. This model has a relaxed assumption compared to the previous model; the data in this model are assumed semi-positive. The DLP model can be presented as

$$(\text{DLP})\text{Min}\,\theta, \tag{7}$$

subject to

$$2\theta x_o - X\lambda \geq 0, \tag{8}$$

$$Y\lambda \geq y_0, \tag{9}$$

$$\lambda \geq 0, \tag{10}$$

where θ is a real variable and a scalar value and λ is a non-negative vector of the constants ($N \times 1$). The value of θ obtained will be the efficiency score of the ith route. This has to satisfy $0 < \theta = 1$. The one value of θ shows a point on the production frontier. This DLP problem has to be solved n times, once for each route. In DLP, the input access and output shortfalls can be presented as s^- and s^+ respectively. These are named as slacks and are estimated as

$$s^- = \theta x_o - X\lambda, \tag{11}$$

$$s^+ = Y\lambda - y_0, \tag{12}$$

with $s^- \geq 0$ and $s^+ \geq 0$ for any feasible solution of (θ, λ) of DLP.

The I-CCR model sometimes produces efficiency scores of 1 for two or more DMUs, but with these scores ranking of the DMUs becomes difficult. Therefore, Andersen and Petersen[25], in order to rank these DMUs, allowed them to achieve an efficiency score of more than unity. Therefore, the model which estimates this score is the SEDEA model and the score thus obtained (more than unity) is called the super efficiency score.

The SEDEA model is presented in eq. (13)

$$\theta^* = \min_{\theta,\lambda,s^-,s^+} \theta - \varepsilon e s^+, \tag{13}$$

subject to

$$\theta x_o = \sum_{j=1,\neq 0}^{n} \lambda_j x_j + s^-, \tag{14}$$

$$y_o = \sum_{j=1,\neq 0}^{n} \lambda_j y_j - s^+, \tag{15}$$

where all components of λ, s^- and s^+ are constrained to be non-negative, $\varepsilon > 0$ is the non-Archimedean element, and e is a row vector which is unity for all elements.

Methodology

The route performance is measured based on the variables of concern to the user, operator and community. The present study lists different variables under five different route efficiency categories (Figure 1).

Input and output variables

The literature provides various performance measures to estimate the efficiency of the transit system, based on which route-specific performance attributes were selected as inputs and outputs for the DEA model as shown in Figure 1. The performance measures of the routes were divided into five different efficiencies. The first one being the route design efficiency which gives an idea about its geographical coverage and rationalization. Second, the schedule design efficiency which provides information to the operator about the passengers' demands and the corresponding transit unit supply requirements on a particular route. Third is the cost-efficiency criteria which represents the economic and ridership performance at the route level. The input and output parameters used under this efficiency measure give a comprehensive assessment of the ridership productivity and the financial performance. Fourth is the service delivery efficiency, which is a measure of route reliability in terms of headway adherence and average operating speed. Finally the comfort and safety efficiency is estimated to include the user perception in the performance evaluation of the routes. The parameters used in the present study are briefly explained as under:

Explanation of parameters

Population density: This represents the number of people living in per square km or per hectare in an influence zone. The influence zone here is the walking distance zone of a transit route. The present study considers 400 m as the transit walking zone on either side of the route, and population density is estimated for the same. A 400 m influence zone was marked based on the limit that most people will walk to reach a BRTS station[26].

Service proximity: It is estimated as the percentage of route passing the major residential land use. This is an important parameter because a route should be planned in such a way so as to reach major residential areas for significant ridership. Figure 2 shows a sample influence zone inside the circle as considered for the above two parameters.

Ridership per route: This provides information about the route patronage per day. For this, the average ridership data were computed using the ticketing data.

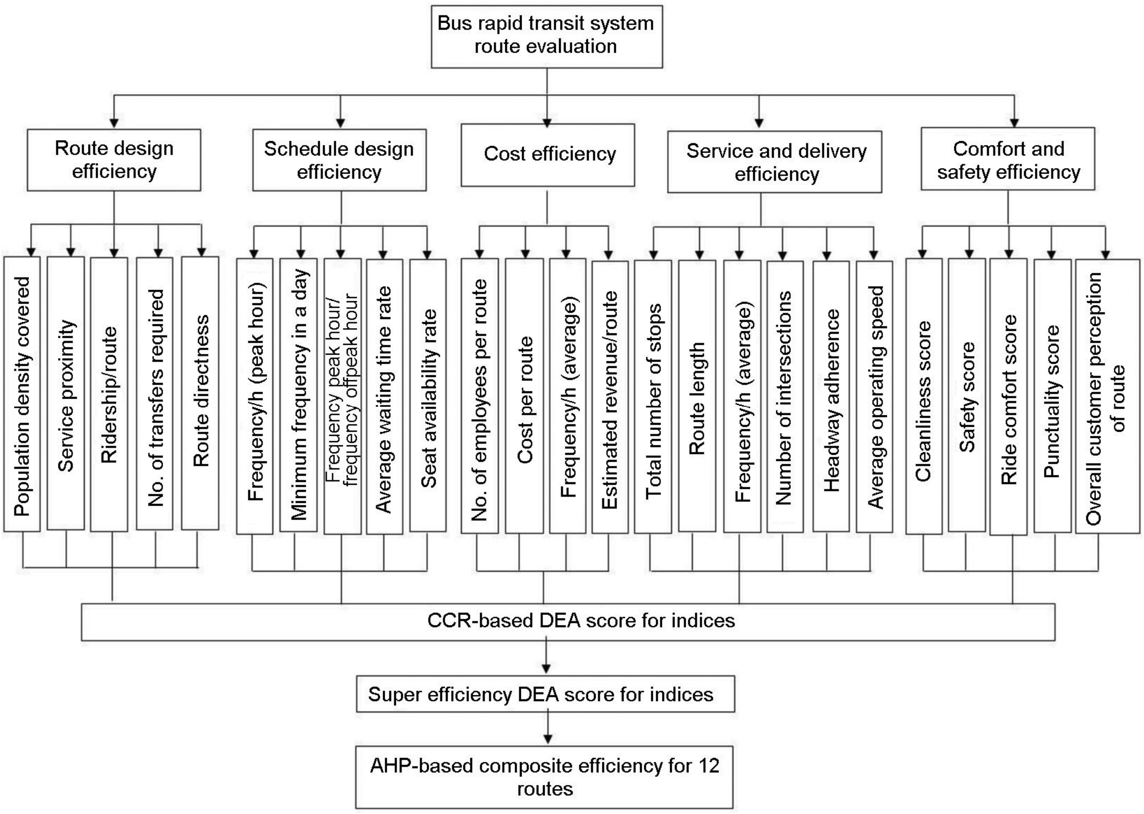

Figure 1. Framework for bus rapid transit system route efficiency.

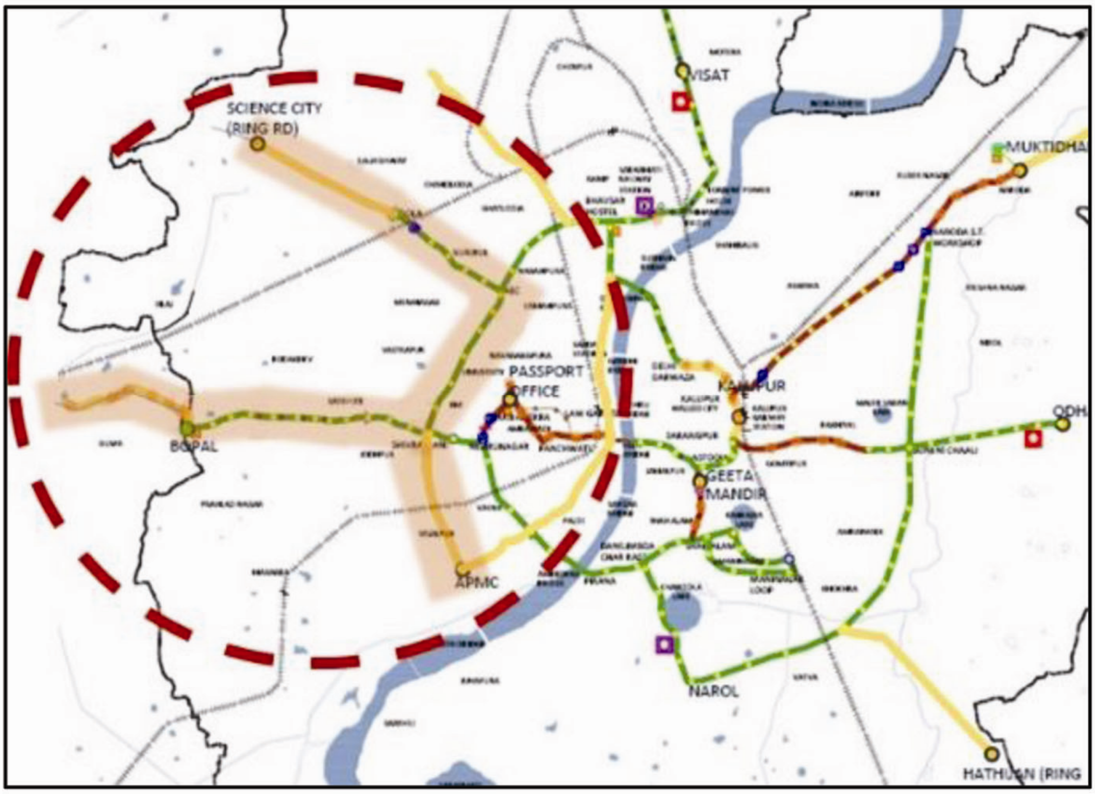

Figure 2. Influence zone representation for estimating population density and service proximity.

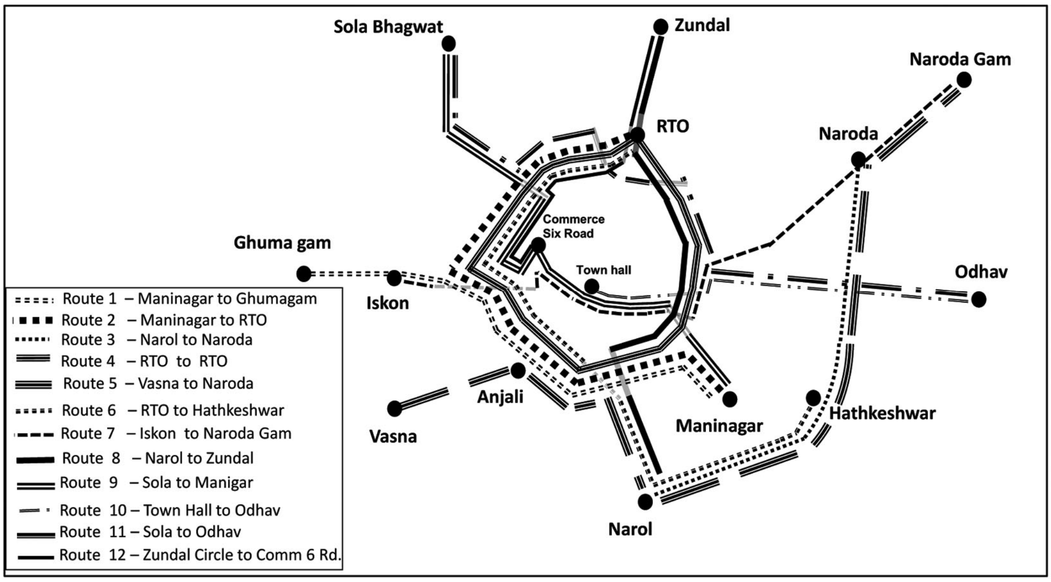

Figure 3. Routes of Ahmedabad BRTS.

Number of transfers: This criterion states the number of transfer that will be required by a passenger travelling in a particular route to complete the entire journey. Less number of transfers means that the route has good connectivity with the residential, commercial and institutional landuses.

Route directness: It is estimated as the ratio of the travel time by BRTS to the travel time for the same route on private mode (automobile). Lesser the ratio better is the BRTS service. However, in the present study inverse of this parameter is used; this has been done to assist the DEA model. Therefore, the value '1/route directness' is used. Hence more this value, better is the performance of BRTS.

Frequency per hour: This is a basic and important parameter for a transit route operation. It is defined as the number of transit units passing through a given point on a transit route in one direction per hour[27]. The present study uses five types of frequency values, viz. the maximum frequency, minimum frequency, average frequency, peak hour frequency and off-peak hour frequency.

Seat availability rate: It is the ratio of total number of seats available to the total number of passengers travelling during peak hour. This will provide information to the transit agencies to schedule additional bus trips to decrease the number of standing passengers, and hence increasing comfort.

Average waiting time rate: It is the ratio of average travel time in the main line haul to the average waiting time at the stop.

Cost per route: This is the cost of operation of the service per day on each route.

Headway adherence: This criterion measures reliability based on 'on time performance' and is calculated as the average percentage of buses arriving more than 4 min late or 3 min early to the scheduled arrival time[28].

Safety score: This is user perception parameter about the safety of a route both at the stop and inside the bus.

Cleanliness score: This parameter evaluates cleanliness both at the stop and inside the bus.

Ride comfort score: This user perception scoring is dependent on the driver. The driver should be careful enough and not speed up after stopping till both sitting and standing passengers settle in their places.

Punctuality score: This is again a user score about their perception of the on-time bus arrival.

After understanding the variables and collecting the relevant data, CCR DEA and SEDEA-based efficiencies were estimated. The following steps were considered in the estimation:

Step 1: List down the variables for the five different efficiencies, viz. route design, schedule design, cost, service delivery, and comfort and safety efficiency.

Step 2: After understanding DEA, categorize the selected variables as input (X) and output (Y). These

Table 2. Customer satisfaction survey

Sample questionnaire	Level customer satisfaction				
	Very satisfied		Neutral	Very unsatisfied	
Is this bus running on time today?	5	4	3	2	1
The number of times you have to transfer	5	4	3	2	1
How clean are the buses and bus stops?	5	4	3	2	1
How comfortable was the ride?	5	4	3	2	1
Safety on the BRTS stops and buses	5	4	3	2	1
Your overall satisfaction with this route of BRTS	5	4	3	2	1

variables are selected in a way that the ratio of output to input provides information about the efficiency.

Step 3: The weights (u_i, v_j) to both inputs and outputs are first assigned using the CCR DEA model. This was done using a tool named DEA Solver LV8 (ref. 29). After calculating the weights further, efficiency of each route is estimated.

Step 4: In this step, the weights to the input and output variables are given using SEDEA approach, after which the efficiency is estimated. The efficiency score by this model can exceed unity. Therefore, the most efficient route can be ranked using this model.

The above four steps were used to estimate the individual efficiency of each route. Further, to estimate the composite efficiency of the routes, AHP technique was considered. The approach for the same is presented later in the text.

Study area and data collection

The Ahmedabad BRTS, considered in the present study, is a model of an efficient public transit system for cities of India and other developing countries[30]. Primary and secondary data for the entire BRT network were collected in the year 2015. During this period, 12 BRTS routes were under operation (Figure 3). These routes act as independent networks, i.e. they are not integrated with any other mode. However, routes of the conventional bus transit system (AMTS buses) might overlap with the BRTS routes, but conventional buses move with mix traffic and are not allowed to move on the segregated bus ways. Table 3 presents the basic details of the routes in terms of route length, number of intersections, number of bus stops, etc. The data collection was done as presented below:

ITS data

Continuous 15 days of archived GPS data were collected from the ITS control centre (BRTS cell) of Ahmedabad Janmarg Limited. The data were received in Excel database, which showed time stamp of arrival and departure at each stop and for each bus. The following data were extracted from the primary data:

- Travel time data.
- Bus frequency data.
- On-time performance data to estimate headway adherence.

GIS-based data

Route-wise population density was estimated using GIS software. A zone-wise population density map was made in GIS environment over which the BRTS routes were layered. The influence zone was then marked. The population density for each route was estimated for the marked buffer zone in person per hectare (ppha). Further, the land-use map of Ahmedabad was imported to GIS over which the same buffer zone was marked as explained above. The percentage of residential land use covered by each route was then estimated.

Smart card and ticketing data

Both smart card and point of scale data of 15 days were used in this study. These data were collected from Ahmedabad Janmarg Limited. The data were used to estimate the ridership per route.

User data

On-board customer satisfaction survey was conducted in the study area. Table 2 presents a sample of the data. On-board survey was conducted as personal interview in which answers for a short series of questions were recorded. Likert scale was used to infer the user perception. The study population is all fixed-route riders, i.e. 1.11 lakh riders (15 weekdays average). The sample size was estimated based on ±3% point[31]; with sampling error for 95% confidence interval for the above study population size. This value turned out to be 1057. The study aimed at collecting 1057 samples on 12 routes of the

Table 3. Evaluation indices used as input in CCR and super efficiency DEA models

Route no.	Route design efficiency		Schedule design efficiency			Cost efficiency			Service delivery efficiency				Comfort and safety efficiency			
	Population density (ppha)	Service proximity (%)	Maximum frequency	Minimum frequency in a day (buses/h)	Peak hour frequency/ off-peak hour frequency (%)	No. of employees per route	Cost per route (INR)	Average frequency per hour (buses/h)	No. of stops	Route length (km)	Frequency/h (buses/h)	Number of inter-sections	Cleanli-ness score	Safety score	Ride comfort score	Punctua-lity score
1	198	78	12	5.5	0.55	60	175,517	8.3	30	18.6	6	33	4.24	2.66	4.21	3.12
2	238.23	67	10	7.5	0.75	60	203,008	9.0	30	18.6	6	47	4.04	3.17	4.08	2.81
3	268.18	61	15	7.5	0.80	48	118,421	12.5	24	15.1	10	19	3.33	2.76	3.65	3.46
4	288.12	42	15	7.5	0.63	80	277,021	10.7	40	25.6	8	57	3.1	3.16	4.11	3.14
5	256.25	64	7.5	7.5	0.63	70	133,224	9.1	35	22.2	10	49	3.13	2.64	4.16	3.91
6	206.66	53	8.6	8.6	0.63	70	124,765	10.3	35	22.4	8	28	3.18	2.39	4.34	3.66
7	271.10	38	12	7.5	0.63	72	266,448	10.0	36	20.3	8	50	3.56	4.12	4.02	3.06
8	254.05	26	12	10	0.83	80	148,027	10.8	40	23.2	10	45	3.1	3.27	4.31	3.66
9	223.33	28	15	10	0.83	76	183,976	10.9	38	16.1	10	60	4.42	4.14	3.76	3.81
10	240.19	28	12	5.5	0.80	38	93,045	8.5	19	12.4	8	19	2.84	4.02	4.11	3.45
11	219.44	38	15	12	0.80	68	141,683	13.2	34	18.5	10	37	2.56	3.81	3.24	3.08
12	210.19	50	10	5.5	0.55	66	249,531	8.2	33	20.9	6	36	3.44	4.18	4.51	2.94

Table 4. Evaluation indices used as output in CCR and super efficiency DEA models

Route no.	Route design efficiency			Schedule design efficiency		Cost efficiency	Service delivery efficiency		Comfort and safety efficiency
	Daily ridership/ route	Route directness	1/Transfers	Total seats/ total no. of passenger(#)	Average travel time/ average waiting time (min)	Revenue per route (INR)	Headway adherence (%)	Average route operating speed (km/h)	Overall customer perception
1	9229	0.55	0.45	0.69	3.9	147,511	25	17.1	3.56
2	10,674	0.57	0.59	0.64	4.6	170,615	23	19.4	3.94
3	6227	0.74	0.43	0.70	6.8	99,525	36	28.6	3.55
4	14,566	0.54	0.56	0.57	4.4	232,818	33	19.4	3.11
5	7005	0.56	0.48	0.66	5.5	111,966	18	21.4	3.41
6	6560	0.68	0.49	0.72	5.6	104,857	30	18.2	3.71
7	14,010	0.63	0.69	0.60	3.6	223,932	35	17.1	3.82
8	7783	0.67	0.41	0.68	7.3	124,406	30	24.0	3.41
9	9673	0.52	0.56	0.61	5.7	154,619	35	14.6	4.22
10	4892	0.49	0.32	0.75	3.2	78,198	33	18.2	3.44
11	7450	0.61	0.67	0.65	6.8	119,075	33	17.6	3.32
12	13,120	0.46	0.71	0.60	2.7	209,714	22	24.0	3.58

Table 5. Route-wise efficiency scores and ranks

	Route design efficiency			Schedule design efficiency			Cost efficiency			Service delivery efficiency			Comfort and safety efficiency		
Route no.	θ_1	θ_2	Rank	θ_1	θ_2	Rank	θ_1	θ_2	Rank	θ_1	θ_2	Rank	θ_1	θ_2	Rank
1	1.00	1.00	7	1.00	1.13	1	1.00	1.00	2	1.00	1.00	2	1.00	0.91	5
2	0.90	0.74	10	0.86	0.83	8	1.00	0.96	5	0.91	0.79	5	0.98	1.08	6
3	0.87	0.79	9	1.00	1.08	3	1.00	0.67	10	1.00	1.34	3	1.00	1.01	1
4	0.97	0.96	8	0.82	0.71	11	1.00	0.99	4	0.94	0.66	10	0.97	0.83	7
5	0.72	0.63	12	1.00	1.08	2	1.00	0.69	8	0.58	0.52	12	0.66	0.9	12
6	1.00	1.09	4	1.00	1.02	5	1.00	0.70	7	0.90	0.64	7	0.91	1.07	8
7	1.00	1.08	6	0.78	0.76	10	1.00	1.00	3	1.00	1.01	4	1.00	0.95	4
8	1.00	1.26	1	1.00	1.00	6	1.00	0.65	11	0.70	0.56	11	0.78	0.86	11
9	1.00	1.10	3	0.78	0.69	12	1.00	0.73	6	0.98	0.63	6	0.85	1.03	10
10	0.76	0.74	11	1.00	1.06	4	1.00	0.67	9	1.00	1.10	1	1.00	0.9	2
11	1.00	1.09	5	0.96	0.79	9	1.00	0.63	12	0.79	0.64	8	0.79	1.07	9
12	1.00	1.18	2	0.95	0.93	7	1.00	1.05	1	0.85	1.08	9	1.00	0.87	3

Ahmedabad BRTS, but among these only 989 were correct based on the responses received and hence were used in the present study. Apart from these, data were also collected from the users regarding waiting time at the BRTS stop and number of transfers required to complete the journey. Other miscellaneous data related to cost, revenue and number of employees were collected directly from Ahmedabad Janmarg Limited.

Route evaluation using CCR and superefficiency DEA models

Five different types of efficiency were estimated for the 12 routes of Ahmedabad BRTS. Tables 3 and 4 present the input and output indices respectively. The five route efficiencies are presented in Table 5, wherein θ_1 is the CCR efficiency and θ_2 is the SEDEA efficiency. Based on the SEDEA efficiency scores, the BRTS routes were classified into five categories as follows:

Routes inefficient in all aspects: Route 4 was found to be inefficient with respect to all five efficiencies because the efficiency score was less than '1'. The efficiency scores of route design and cost efficiency were close to unity; therefore, no improvements were suggested for these aspects. To improve the schedule design efficiency, the average waiting time at the stop should be reduced; this can be done by increasing the frequency of the buses in this route during peak hours. In case of service efficiency, route 4 showed a low super efficiency score, i.e. 0.66. This mainly occurred due to lower operating speed on this route because of the presence of a large number of intersections and BRTS stops. Applying strategies like bus priority signal and skip stop operation will help in improving the operating speed. Further, it can be observed in every route, including route 4 that the headway adherence is less than 35%; this value is too low for a high-quality system like BRTS. Hence, the transit agency should update the scheduled arrival time obtained from GPS based on the travel-time data. The comfort efficiency in case of routes was estimated as 0.8; hence there is a need to increase cleanliness at the stops and inside the buses.

Routes inefficient in four aspects: Routes 2 and 5 were efficient only in comfort and safety, and schedule design efficiency respectively. Route 5 had the lowest route design efficiency amongst all 12 routes. The ridership of this route was low despite having a good population density coverage and service proximity. The route does not get significant patronage as it does not touch the Central Business District (CBD), nor does it connect major terminals like railway station, etc. Hence, this route requires an improvement in terms of good feeder system for an efficient last mile connectivity. Providing a feeder system for route 2 will also help in increasing ridership and subsequently the route design efficiency. Cost efficiency in case of both the routes can be increased either by decreasing the inputs, i.e. reducing cost or number of employees or by increasing the output revenue by increasing advertisements both in bus stops and buses. The service efficiency in both the routes can be increased by increasing the headway adherence, i.e. on-time performance of the buses, or by applying strategies like bus signal priority and skip stop operation to reduce the stop delays on the routes. In route 5 the comfort and safety efficiency is close to '1' hence no adjustment or optimization is suggested for this aspect.

Routes inefficient in three aspects: Routes 8–11 were efficient in two out of five aspects. Except route 10, all other routes were efficient in case of route design efficiency. Route 10 had the lowest daily ridership. Also, this is the smallest route and hence there is scope of extending it to the major residential, institutional and commercial

Expert 1	E1	E2	E3	E4	E5
E1	1	4	7	6	6
E2	1/4	1	3	2	5
E3	1/7	1/3	1	1/3	4
E4	1/6	1/2	3	1	3
E4	1/6	1/5	1/4	1/3	1

Expert 2	E1	E2	E3	E4	E5
E1	1	6	5	4	8
E2	1/6	1	1/2	3	1/3
E3	1/5	2	1	1/2	2
E4	1/4	1/3	2	1	1/6
E4	1/8	3	1/2	6	1

Expert 3	E1	E2	E3	E4	E5
E1	1	3	5	2	7
E2	1/3	1	2	1	1/4
E3	1/5	1/2	1	1/3	6
E4	1/2	1	3	1	3
E4	1/7	4	1/6	1/3	1

Expert 4	E1	E2	E3	E4	E5
E1	1	4	7	6	9
E2	1/4	1	3	3	5
E3	1/7	1/3	1	1/3	3
E4	1/6	1/3	3	1	3
E4	1/9	1/5	1/3	1/3	1

Expert 5	E1	E2	E3	E4	E5
E1	1	2	6	5	3
E2	1/2	1	2	2	2
E3	1/6	1/2	1	1/2	1
E4	1/5	1/2	2	1	1
E4	1/3	1/2	1	1	1

Expert 6	E1	E2	E3	E4	E5
E1	1	5	3	4	6
E2	1/5	1	2	2	3
E3	1/3	1/2	1	1/2	2
E4	1/4	1/2	2	1	3
E4	1/6	1/3	1/2	1/3	1

Expert 7	E1	E2	E3	E4	E5
E1	1	3	6	2	3
E2	1/3	1	2	1	2
E3	1/6	1/2	1	1/3	2
E4	1/2	1	3	1	3
E4	1/3	1/2	1/2	1/3	1

Expert 8	E1	E2	E3	E4	E5
E1	1	3	5	5	1
E2	1/3	1	4	3	1
E3	1/5	1/4	1	1/3	1/2
E4	1/5	1/3	3	1	1
E4	1	1	2	1	1

Expert 9	E1	E2	E3	E4	E5
E1	1	3	5	4	3
E2	1/3	1	3	2	2
E3	1/5	1/3	1	1/2	1
E4	1/4	1/2	2	1	3
E4	1/3	1/2	1	1/3	1

Expert 10	E1	E2	E3	E4	E5
E1	1	7	6	9	2
E2	1/7	1	5	2	2
E3	1/6	1/5	1	1/4	1/2
E4	1/9	1/2	4	1	1
E4	1/2	1/2	2	1	1

Figure 4. Decision matrices as a result of scoring obtained from ten public transport experts.

land-use corridors. Routes 9 and 11 were inefficient in case of schedule design efficiency. Hence, in these routes the minimum frequency can be reduced so that the ratio of output to input increases so as to increase the efficiency. All the four routes were inefficient in case of cost efficiency, which can be increased by increasing advertisements inside the buses and stops to increase the revenue. Routes 8–10 were inefficient in terms of service delivery efficiency. This type of efficiency can be increased by following suggestions similar to that of route 5. Further, only route 8 showed a low efficiency score in case of comfort and safety efficiency. Both cleanliness and safety in the stop and inside bus need to be improved. Extra safety can be provided by illuminating the exit and entry of the BRTS stations.

Routes inefficient in two aspects: Routes 3, 6, 7 and 12 were efficient in three out of five aspects. Only route 3 was inefficient in case of route design efficiency. This route has the same problem as route 10 (Town Hall to Odhav); hence similar suggestions are applicable to this route as well. Route 7 showed a lower schedule design efficiency. The suggestions for routes 9 and 11 mentioned earlier can be applied to this route also. In case of cost efficiency, routes 3 and 6 were inefficient; hence, suggestions, similar to those of routes 8–11 can be applied to these routes. Further, in terms of service delivery efficiency, route 6 showed a low efficiency score. Operating speed of this route needs to be improved; this can be done by applying suggestions mentioned for route 4.

Routes inefficient in one aspect: Route 1 was perceptibly inefficient only in case of comfort and safety efficiency, but the efficiency value was close to 1. Hence, no adjustment or optimization is required to be carried out for route 1 at this stage.

The above results indicate that although the Ahmedabad BRTS is one of the best performing among developing countries, many routes do not perform well in various aspects, suggesting scope for improvement in future.

Composite efficiency

The comprehensive performance of the BRTS routes was evaluated by combining the five different efficiencies using AHP technique. For this, first the importance matrix was filled based on the expert opinion scores of 10 public transport experts. Scores from 1 to 9 were used to represent importance of each efficiency. A score of 1 indicates that two efficiencies contribute equally to route performance, while a score of 9 indicates that one efficiency strongly dominates the other in evaluating route performance. Based on these scores 10 decision matrices were developed (Figure 4). E1–E5 are the five efficiencies considered in this study. After developing the expert matrix, the eigen value ($\lambda_{\max}$) of the matrices was estimated and consequently the consistency index (CI) was calculated as shown in eq. (16)

$$\mathrm{CI} = \frac{\lambda_{\max} - n}{n-1}, \tag{16}$$

where n is the number of comparisons, i.e. 5 in this case. Once this index is estimated, the consistency ratio (CR) can be estimated as shown in eq. (17):

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}}, \tag{17}$$

where RI is the random consistency index which is estimated from the CI table[32]. If the CR value is smaller or equal to 10%, the inconsistency is acceptable. If the CR value is greater than 10%, then there is a need to revise the subjective judgment. In the present study, CR value of the comparison matrix of experts 2 and 3 was more than 10% and hence the judgments were revised by repeating the survey for the two experts. After the consistency test was done, the weights for five efficiencies were estimated as $W = \{0.49, 0.18, 0.09, 0.14, 0.10\}$.

Based on the aforementioned weights, Figure 5 represents a radar diagram to present the composite efficiencies of the 12 routes numbered in clockwise direction. Ranks obtained by the AHP efficiency are also represented in the Figure 5. From Figure 5 it can be observed that route 1 is the most efficient as it obtained an efficiency score of 1.02, while route 5 shows the worst performance at an efficiency score of 0.72.

Conclusion

The previous studies reported in the literature used conventional DEA models for evaluating the performance of the transit systems and subunits. The present study demonstrates the use of SEDEA by relaxing the unity constraint in the basic DEA model. This study also combines DEA and AHP approaches to evaluate the performance of transit routes. It estimated both individual and composite efficiency scores of the 12 BRTS routes based on five aspects, viz. route design, schedule design, cost, service delivery, and comfort and safety efficiency. The study uses GIS spatial analysis tool and a wealth of field data, including GPS data, user perception data, smart card and point of sale data to compute the efficiency scores. Using the results obtained from the SEDEA model, the BRTS routes were classified into five categories. For each category, suggestions were given for future improvement of the BRTS routes. In addition, a composite efficiency score was estimated for each BRTS route. To estimate the same, weights for all five efficiencies were given using AHP technique. By combining route planning, schedule planning, cost management and user perception, the evaluation methodology proposed in this study could better reflect the performance of the BRTS routes. This study is limited to the evaluation of BRTS routes and suggesting strategies to improve them. It can further be extended by carrying out sensitivity analysis of the suggested strategies using simulation software. Also, with advancement in data collection technologies, more transit data such as bluetooth and cell-phone data can be used for the BRTS route evaluation.

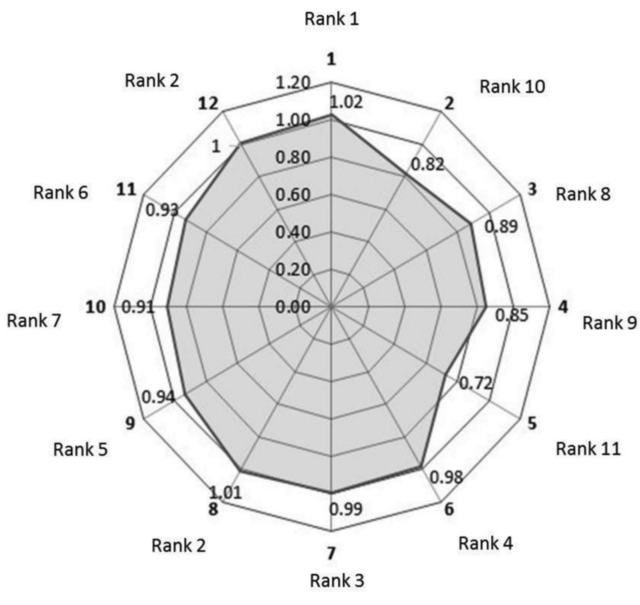

Figure 5. Composite efficiency scores and ranks of the BRTS routes.

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