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THE URBAN METRO TRANSIT'S PERFORMANCE EVALUATION USING SUPER-DEA

Summary. Urban metro transit systems are essential for socio-economic growth and to the achievement of sustainable urban development. To continuously raise the caliber of services, infrastructure performance must be monitored and evaluated on a regular basis. The effectiveness and efficiency of Delhi's urban public transit system, i.e., Delhi Metro is investigated using Data Envelopment Analysis (DEA) and Super-DEA approaches. DEA is a non-parametric technique used in the estimation of production functions and has been used extensively to estimate measures of technical efficiency. Super-DEA is a linear optimization technique that calculates the relative efficacy of its decision-making units (DMUs) for a wide range of inputs and outputs. The Delhi Metro's "BLUE" line is studied in the present research considering various demographics factors. The relative rankings of the DMUs were assessed taking into account super-DEA after 630 valid responses to commuter-based questionnaires about demographic, travel time components and quality perception parameters were gathered. Each station along the BLUE line is treated as a DMU when analyzing efficiency. Results

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revealed efficiency, relative rankings and scores for which improvement strategies are suggested.

Keywords: performance evaluation, performance efficiency, DEA, Super-DEA, interconnectivity ratio, Delhi Metro, operational, spatial, proximal, access distance, egress distance, IVTT

1. INTRODUCTION

The public transport (PT) system is considered an essential means of transport, especially for captive riders in urban and connected satellite suburban areas. The periodic performance evaluation (PE) is essential for the growth and successful operation of any PT system. The PE of any PT system is a momentous process for operators. The PE facilitates the verification of the efficiency and effectiveness of the system and the identification of the scope of performance improvement in its operations. One of the objectives of PE is to measure and compare PT performance with acceptable standards (Sheth et al., 2007). The authors of a study report that, the PE of a transit system is quantified at four levels, i.e., system, corridor, route, and metro station (TCRP Report 165 "Transit Capacity and Quality of Service Manual," 2013). However, the operators of PT systems are generally interested in PE of the route only due to better control of the variables affecting the system. The authors noted that access time, waiting time, main haul time and the number of transfers are the factors influencing the PT users' decisions about the suitability of PT system and these factors need to be investigated before initiating PE of the PT system (Eluru et al., 2012).

For the PE of Urban Metro Transit System (UMTS), it is important to identify output factors that a UMTS produces and the corresponding input factors it uses in producing these outputs. The various performance attributes based on users and operator perspective considered in this research includes access-egress distance, access-egress modes, main haul time (MHT), out-vehicle travel time (OVTT), in-vehicle travel time (IVTT), total travel time (TTT), running index (RI), interconnectivity ratio (IR).

In the present study, "Blue Line" (line 3) of Delhi Metro (DM) being the longest origin-destination route between NOIDA electronic city to Dwarka Sector-21 is considered for PE. The uniqueness of this study is that 34 metro stations of Blue line situated in Delhi are evaluated for their relative and respective performance efficiencies, unlike relative efficiencies evaluated in past studies. The PE of each station is quantified through three absolute performance efficiencies, viz. operational, proximal and spatial. The above-mentioned relative and respective efficiencies are quantified using a linear programming-based model known as Data Envelopment Analysis (DEA) and super-DEA respectively. The DEA is a performance evaluation method that utilizes a comparative analysis methodology. The method is a nonparametric technique used for computing productivity efficiency by comparing different Decision-making units (DMUs), which are usually the allocated resource units for that system. The methodology and variables used to identify measures for increasing metro system efficiencies can be used in contexts in both developed and developing countries, even though the analysis was done for the Indian context.

2. LITERATURE REVIEW

A performance measurement method that employs comparative analysis is called DEA. To help with the evaluation of various organizations, Charnes, Cooper, and Rhodes created it in 1978 the CCR model, which is a well-known model. In order to validly compare the various efficiencies of the DMUs in a transportation system, it is challenging to assign weights in an objective manner. The DEA provides a novel solution to this problem. The resource units for a system are frequently the different DMUs that the DEA compares. An output unit is typically a performance attribute that needs to be evaluated, and the inputs and outputs are decided upon based on their correlation in terms of how inputs affect outputs. Then, the units that represent best practices are identified by comparing their relative efficiences. The resource and output units' projected values are also identified and calculated by DEA. When figuring out why a metro station is performing well or poorly, the slack values can be useful. The relative efficiency (ŋ) typically is represented in the mathematical form in Equation 1. In this case, the unit is the metro station and in place of weight of inputs, we used the values of the input parameters. y_{rj} and X_{ij} are the projected values obtained for various Metro stations from the analysis for different sets.

$$n_j = \frac{\Sigma_r u_r y_{rj}}{\Sigma_i v_i x_{ij_j}} \tag{1}$$

Where:
η_j – relative efficiency of unit *j*;
v_i – weight of Input *i*;
u_r – weight of Output *r*;
y_{rj} – the quantity of Output r for unit *j*;
x_{ij} – the quantity of Input i for unit *j*;
j – 1, 2, 3 … *n*;
n – number of units.

(Epstein and Henderson, 1989) concluded that all variables that are included in the model have an equal opportunity to influence the calculated efficiency. The authors report that the suitability of a PT system depends on its efficiency and effectiveness, along with the ease of the mode choice for last miles' connectivity (Krygsman and Dijst, 2001). In a study, the authors measure the efficiency and productivity of transit organizations through DEA efficiency analysis (Karlaftis, 2003). The authors reported that PE is quantified through multimodal efficiency while considering operating expenses, capacity of bus, number of staff, transfer time, transfer area and total number of passengers etc. (Sun et al., 2007). The efficiencies of public transportation subunits were calculated for the Chicago Transit Authority (Barnum et al., 2007). The authors evaluate the efficiency and effectiveness of railways based on DEA method considering passenger technical and freight technical efficiencies and, service and technical effectiveness (Yu and Lin, 2008). The author explores number of passenger cars, number of freight cars, length of route length, freight-train km and ton-km as input and output variables respectively for evaluating and comparing technical and service effectiveness using Network Data Envelopment Analysis (NDEA) (Yu, 2008). (Saxena and Saxena, 2010) conducted a study to measure the efficiencies of Indian public road transit using DEA with input variables such as fleet size, total staff, and fuel consumption and output parameters such as passenger kilometers and seat kilometers for 26 DMUs. The authors report that network plays a deciding role in the PT system along with coverage area, synchronized transit routes, speed, schedule and operational capacity (Mishra et al., 2012). The author considers network length, fleet size, available seats, ridership, and traffic volume for evaluating performance and efficiency of high-speed rail systems using NDEA (Doomernik, 2015).

The authors conducted corridor-level research, wherein the performance of DM's two corridors based on the basic CCR model of the DEA approach is evaluated (Swami and Parida, 2015). The authors explore the technical efficiency of European Metro systems considering network length, number of employees, cars and stations, population density, household size, gross domestic product (GDP) using the DEA approach (Lobo and Couto, 2016). The authors explore railway freight stations for efficiency evaluation using the DEA approach (Haghighi and Babazadeh, 2020). The authors evaluate the efficiency of Thailand Metro systems considering railway network length, number of operating employees, cars and stations as input parameters and passengers per year and annual car kilometers considering super-SBM (Slacks Based Measure) DEA approach (Suriyamart and Liangrokapart, 2020). The authors explore the efficiency and sustainability of Urban Rail Transit using Exploratory Data Analysis (EDA) and DEA while considering travel distance, time and cost, CO2 emissions and overall cost as input variables whereas total number of passengers as output variable (Taboada and Han, 2020). One shortcoming in the basic DEA model is its inefficiency in evaluating dynamically the performance efficiency of DMUs over time. The authors in their research explore DEA window analysis to address the above flaw, which offers a reasonable solution to dynamic efficiency monitoring on time series (Asmild et al., 2004). The authors report one of shortcomings of the basic DEA model is that the approach ignores the relationship or links of DMU's internal subunits (Chen et al., 2021). The authors evaluate the comprehensive performance efficiency evaluation of the Beijing intelligent traffic management system based on super-DEA that used 15 inputs and 23 outputs for 10 DMUs for a macro level study correlating the influence of various urban transport indicators (Wei et al., 2012). The input variables in the above study include vehicle ownership, road length and area, employees, energy consumption infrastructure and urban fixed investment etc. whereas the output variables include number of traffic signs and lights, traffic congestion index, average travel time and cost per day etc. The authors evaluate bus rapid transit routes efficiencies i.e. "route design", cost, service and delivery, comfort and safety considering population density, service proximity, ridership/route, average waiting time rate, seat availability rate, cost per route, safety score, punctuality score etc. based on super-DEA approach (Kathuria et al., 2017). The authors of a study came to the conclusion that because there are different evaluation standards in different cities, it is impossible to group all the influencing factors into a single fixed group. Instead, they found that the weight of each factor varies depending on the city (Aboul-Atta and Elmaraghy, 2022). The parking facility provided by DM is observed to be significant in access trips, according to the authors, as some commuters feel that it has "less parking space and unaffordable" and other commuters feel that it has "less parking space but affordable." The authors in a study reveals that post-COVID-19 the performance indicators exhibit the unsatisfactory performance of DM and there is further scope to improve the UMTS performance. The authors noted that the parking options provided by DM are a significant factor for select riders and have room for improvement in terms of parking rates and available parking space. According to the authors of a study, in order to make DM more feasible and to limit the associated total expense of entrance and egress journeys per metro ride, the current metro fee needs to be reduced.

Several other studies, in addition to the ones mentioned above, were carried out prior to COVID-19 for various socioeconomic and demographic contexts. Only a few large-scale studies on the performance efficiency of UMTS were conducted before COVID-19. There is still room for research in the micro level study of commuters' and operators' perspectives on the performance efficiency of the DM after COVID-19. As far as we are aware, there is no other study that compares the relative and respective efficacy of different DMs in an objective manner. Therefore, based on the above-mentioned scope of the research, this post COVID-19 micro level study is conducted on BLUE line to evaluate performance efficiency based on DEA and super-DEA approaches. Three relative performance efficiencies, viz. operational, proximal and spatial considering access-egress distance, in vehicle travel time, frequency of metro, seating-standing space, access-egress mode, number of interchanges, parking facilities offered by DM as input factors are considered. To determine which stations are the most and least efficient, a sensitivity analysis of the stations that are taken into account as DMUs is performed. Finding the gaps between productivity and efficiency in order to increase ridership is the goal of the super-DEA analysis.

The super-DEA (Data Envelopment Analysis) model is used to evaluate the efficiency of decision-making units (DMUs) by allowing for the incorporation of undesirable outputs and giving a more comprehensive measure of performance. The equation you provided represents a formulation for a super-DEA model.

The super-DEA efficiency measurement can be expressed as follows:

$$\theta^* = min_{\theta,\leftthreetimes,s^-,s^+}(\theta - \epsilon e\; s^+) \tag{2}$$

Where:
θ* – is the efficiency score of the DMU under evaluation;
θ – is a variable representing the efficiency level that is being minimized;
$\leftthreetimes$ – represents the weights assigned to the DMUs in the analysis;
s^- – denotes the slack variable for undesirable outputs (indicating excess inputs or outputs);
s^+ – denotes the slack variable for desirable outputs (indicating shortfalls);
ϵ – is a small positive number to ensure that the solution is feasible and allows for some tolerance in the evaluation;
e – is a vector of ones, ensuring that the slack variable is appropriately scaled in the model;

The objective of this model is to find the optimal efficiency score (θ*) while considering the slacks for both undesirable and desirable outputs, thereby allowing for a more nuanced assessment of efficiency.

3. RESEARCH METHODOLOGY

In the current study, information on access-egress trips, such as access-egress distance, main haul distance (MHD), access-egress mode, metro frequency, travel time components, such as in vehicle transfer and transit time, users' approval indicators, such as seating/standing capacity in metro coaches, number of station interchanges, parking facilities offered by DM, etc., is needed to assess the performance efficiency of DM. It takes a sizable amount of precise commuter travel data to collect this kind of information. In the weeks of February and March 2021, following the COVID-19 period, a physical on-board survey was carried out using a thorough and appropriate survey proforma. The above-mentioned data was gathered by the survey proforma.

A total of 742 randomly selected passengers boarded at 34 stations along the BLUE line, and after data was cleaned, 630 passengers, including 364 men and 266 women, were selected for analysis. The completion rate for this survey was found to be around 84.9%. The information derived from the survey proforma was tabulated in a logical manner and statistically examined.

In order to conduct a DEA-based benchmarking, 34 stations on Delhi's "BLUE" line were used as DMU. To enable a more disaggregated understanding of their performance, the analysis was carried out separately for the three output categories of interconnectivity ratio, the best alternative to DM, and (access+egress) time. The following sections provide explanations of the variables used in the analysis, DEA formulation, and data collection.

4. RESULTS AND DISCUSSIONS

The respondents were questioned about their preferred mode of access-egress travel during the data collection process. In a metro transit system, the access trip is defined from the origin to the nearest metro station, while the egress trip is from the metro station to the destination. Access-egress time and distance correspond to these segments' travel time and distance, respectively. They are prompted to identify the most popular access-egress method based on accessibility and practicality following the COVID-19 period. Table 1 displays their responses.

Tab. 1

Access and Egress Mode Share (Source: Authors)

Items	Category	Frequency	%	Items	Category	Frequency	%
Access Mode	Walking	244	38.7	Egress Mode	Walking	271	43
	E-Rickshaw	226	35.9		E-Rickshaw	212	33.6
	Auto-Rickshaw	97	15.4		Auto-Rickshaw	100	15.9
	Feeder Bus	16	2.5		Feeder Bus	9	1.4
	DTC Bus	10	1.6		DTC Bus	16	2.5
	Personal Vehicle	37	5.9		Personal Vehicle	9	3.5

As shown in table 1, walking accounts for a sizeable 38.7% and 43% of access-egress trips, respectively. It suggests that walking may be the most preferred mode due to its flexibility and lack of associated costs. Additionally, other considerations for this decision might include the health and precautions against COVID-19 infection. However, this percentage may change depending on several additional factors, including age, gender, the temperature of the outside environment, the distance, and how easy it is to walk. E-rickshaw is the second most popular mode, accounting for 35.9% and 33.6% of access-egress trips, respectively. It indicates that its use in shorter access-egress distances is due to its ease of accessibility, availability, and route flexibility. The authors noted that the average combined access and egress share of Bicycle and Cycle-rickshaw is 10.5% (Goel & Tiwari, 2016). The average access-egress mode share for E-Rickshaw in the current study is reported to be 34.75%. It has been noted that in Delhi, the E-rickshaw has largely supplanted the cycle rickshaw.

In addition, it is noted that auto-rickshaws have a larger mode share than feeder buses, DTC buses, and private vehicles. In the access-egress trip, it has a mode share of 15.4% and 15.9%, respectively. The results of a study by (Goel and Tiwari 2016) substantiated these findings with minor variations.

In a metro transit system, the main haul distance is the actual distance travelled within the system, and the main haul time is the corresponding travel time. Along with their main haul distance (MHD), DM users were also asked about their access-egress distance from the closest metro stations at their points of origin and destination. The standard deviation and average distance for the various access-egress modes are shown in table 2. The average distance travelled by foot for access and egress is (0.81±0.32/0.35 km, respectively).

Tab. 2

Access-Main Haul-Egress distance per trip (Source: Authors)

Serial Number	Mode Choice	Access Distance	Egress Distance	Main Haul Distance per Trip (km)	(Access+Egress) Distance/Main Haul Distance
1	Walking	0.81±0.32	0.81±0.35	18.81±11.74	0.086
2	E-Rickshaw	2.02±0.69	1.87±0.49	19.94±10.64	0.195
3	Auto-Rickshaw	2.85±0.66	2.66±0.74	22.11±11.96	0.249
4	Feeder Bus	3.29±0.75	3.04±0.69	18.75±6.67	0.337
5	DTC Bus	3.82±0.96	3.23±0.94	13.08±6.23	0.538
6	Personal Vehicle	3.61±1.02	2.45±0.79	19.65±9.91	0.308
	Average/Mean	1.84±1.12	1.61±0.93	19.69±11.19	0.175

The ratio of the mean (access+egress) trip distance to the average MHD ranges from 0.086 to 0.538, with walking and DTC bus having the lowest and highest ratios, respectively. Across all research modes, the aforementioned ratio is found to be 0.175. The outcome points to a high average (access+egress) distance of 17.5% of the MHD. Average MHD is noted to be a nonlinear function of average (access+egress) distance. The average MHD for each trip varies across all modes of transportation, ranging from (13.08±6.23) to (22.11±11.96) km, with DM riders using DTC buses having the lowest MHD and DM riders using auto rickshaws having the highest MHD. The present research reveals that the average MHD across all access-egress modes is observed to be (19.69±11.19) km. The findings of a study confirm the above results, with the average MHD observed as (20.3±0.5) km (Goel & Tiwari, 2016).

The respondents were questioned about their preferred mode of access-egress travel along with the number of station interchange between their origin-destination trips following the COVID-19 period. The table 3 displays the cross tabulation considering mode choice and number of station interchange in their main haul trip (MHP) which is defined as traveling between primary origin and destination stations in a metro transit system, usually covering significant distances and connecting key areas within the transit network. The optimization of MHP enhances network efficiency, reduces operational costs, and improves service reliability, ultimately aligning transit systems with passenger demand and stakeholder objectives (Nnene et al., 2023).

Tab. 3

Access Mode Share vs. Number of Station Interchange (Source: Authors)

Sr. No.	Mode Choice	No of station Interchange (%)	Only 1 (%)	Only 2 (%)	Only 3 (%)	More than 3 (%)
1	Walking	87 (44.9)	91 (39.4)	41 (28.9)	17 (42.5)	8 (34.8)
2	E-Rickshaw	60 (30.9)	84 (36.4)	60 (42.3)	14 (35)	8 (34.8)
3	Auto-Rickshaw	20 (10.3)	35 (15.2)	32 (22.5)	7 (17.5)	3 (13)
4	Feeder Bus	8 (4.1)	5 (2.1)	2 (1.4)	1 (2.5)	0 (0)
5	DTC Bus	4 (2)	3 (1.3)	2 (1.4)	1 (2.5)	0 (0)
6	Personal Vehicle	15 (7.8)	13 (5.6)	5 (3.5)	0 (0)	4 (17.4)
	Mean	194 (30.8)	231 (36.7)	142 (22.5)	40 (6.35)	23 (3.65)

As shown in table 3, a sizeable proportion of 30.8% and 36.7% reports to have either no station interchange or only 1 station interchange respectively in MHP. A fewer proportion of 22.5% and 6.35% reports to have only 2 or 3 station interchange, respectively. A very small proportion of 3.65% reports having more than 3 station interchange during their journey between origin-destination. It is further noted that users who opted for walking as their access mode have sizeable proportion of 44.9% and 39.4% with no station interchange or only 1 station interchange, respectively. Whereas, 28.9% and 42.5% of the population opting for walking as their access mode report having only 2 or 3 station interchanges in their MHP. It is interested to note that user preferring personal vehicle as their access mode have less proportion of 7.8% and 5.6% of no station interchange or only 1 station interchange respectively. Whereas 3.5% and 17.4% of population opting for personal vehicle as access mode, reports to have only 3 or more than 3 station interchanges in their MHP. The MHP impacts metro design by determining capacity and frequency, while optimization enhances efficiency, reduces waiting times, and improves passenger satisfaction, ultimately lowering operational costs (Yang, 2022).

4.1. DEA and Super-DEA parameters

Comfort, commuter service, route features, service characteristics, service consistency were the factors measured for the operational, proximal and spatial efficiencies evaluated by using DEA and Super-DEA study. The Table 4 shows that input and output variables considered for operational, proximal and spatial efficiency, respectively.

Tab. 4

DEA and Super-DEA parameters (Source: Authors)

Input/ Output Variables	Operational Efficiency	Proximal Efficiency	Spatial Efficiency
Input Variables	Access Distance (AD)	Access Distance (AD)	Access Mode (AM)
	Egress Distance (ED)	Egress Distance (ED)	Standing Space (SS1)

	In Vehicle Travel Time (IVTT)	In Vehicle Travel Time (IVTT)	Seating Space (SS2)
	Metro Frequency (MF)	No. of Station Interchange (Ic)	Parking Facility (PF)
		Total Travel Time (TTT)	
Output Variable	Interconnectivity Ratio (IR)	(Access Time + Egress Time) (AT+ET)	Second Best Alternative to DM (BA)

The total travel time (TTT) in the Delhi Metro includes access to the station, waiting for the train, in-train travel, transfers between lines, egress from the station, and any additional delays from origin to destination. TTT can be expressed as: *TTT=Access Time+Waiting Time+In-Train Travel Time+Transfer Time+Egress Time+ Additional Delays*. In the context of a metro, IVTT (In-Vehicle Travel Time) is the time duration a passenger spends traveling inside the metro train from boarding to alighting. The frequency of the Delhi Metro trains varies depending on the line and the time of day. During peak hours, the Delhi Metro trains frequency varies from 2-5 minutes, while during non-peak hours, the frequency ranges from 5-10 minutes depending on the operating line and network.

The interconnectivity ratio (IR), calculated as (Taccess+Tegress)/TTT, and the second-best alternative to DM were factors considered for operational, proximal, and spatial efficiencies in both DEA and Super-DEA. The IR ranges from 0 to 1, with 0 being ideal and 1 being unviable. For most multimodal trips, IR typically falls between 0.2 and 0.5 (Krygsman et al., 2004).

4.2. Operational performance efficiency:

Operational performance efficiency in a metro transit system evaluates how access-egress distance, in-vehicle travel time, and metro frequency impact the interconnectivity ratio, measuring the system's effectiveness in providing timely, reliable, and well-connected travel across the network. The input parameters include access-egress distance, IVTT and metro frequency whereas output parameters include travel time components (IR). The table 5 shows the objective data and the efficiency results of the variables set, which measure the operational efficiency of the four corridors of BLUE line. The interconnectivity ratio (IR) is taken as the performance output. IR is the collective terminology used for describing proximity and connectivity. It is seen that the input variables are statistically significant.

Tab. 5

Operational performance efficiency of BLUE line (Source: Authors)

DMUs	INPUT				OUTPUT	DEA Efficiency Score	Super-DEA Efficiency Score	Rank
	AD	ED	IVTT	MF	IR			
Dwarka Sector 21	1.5	1	30	4.1	0.33	1.00	1.24	1
Dwarka Sector 8	1.8	1.2	30	4.1	0.31	0.90	0.90	6
Dwarka Sector 9	1.7	1.4	40	4.1	0.3	0.79	0.79	15
Dwarka Sector 10	1.7	1.5	35	4.1	0.28	0.74	0.74	19

Dwarka Sector 11	1.7	1.7	30	4.1	0.32	0.90	0.90	6
Dwarka Sector 12	1.5	1.5	31	4.1	0.31	0.92	0.92	5
Dwarka Sector 13	1.6	1.6	32.5	4.1	0.3	0.85	0.85	10
Dwarka Sector 14	2	1.2	40	4.1	0.29	0.75	0.75	18
Dwarka	2.3	2	54	4.1	0.3	0.70	0.70	20
Dwarka Mor	1.5	1.8	45	2.7	0.33	0.98	0.98	3
Nawada	2.2	1.4	40	2.7	0.34	0.83	0.83	12
Uttam Nagar West	1.9	1.7	35	2.7	0.33	0.80	0.80	14
Uttam Nagar East	1.8	1.6	27	2.7	0.36	1.00	1.19	2
Janakpuri West	1.9	1.9	45	2.7	0.3	0.70	0.70	20
Janakpuri East	1.9	1.6	40	2.7	0.33	0.92	0.92	5
Tilak Nagar	1.6	1.4	40	2.7	0.32	0.90	0.90	6
Subhash Nagar	1.7	1.6	39.22	2.7	0.28	0.75	0.75	18
Tagore Garden	1.7	1.5	35	2.7	0.33	0.97	0.97	4
Rajouri Garden	1.7	1.8	35	2.7	0.31	0.81	0.81	13
Ramesh Nagar	1.8	1.3	37	2.7	0.32	0.81	0.81	13
Moti Nagar	1.7	1.2	35	2.7	0.34	0.89	0.89	7
Kirti Nagar	2.1	2.1	41	2.7	0.35	0.76	0.76	17
Shadipur	1.9	1.8	40	2.7	0.31	0.74	0.74	19
Patel Nagar	1.7	1.8	38.5	2.7	0.33	0.87	0.87	8
Rajendra Palace	2	1.9	35	2.7	0.32	0.89	0.89	7
Karol Bagh	1.7	2	40	2.7	0.32	0.84	0.84	11
Jhandewalan	1.5	1.4	42	2.7	0.29	0.86	0.86	9
Ramakrishna Ashram	1.7	1.9	43.5	2.7	0.28	0.74	0.74	19
Rajiv Chowk	2.2	1.7	42	2.7	0.29	0.80	0.80	14
Barakhamba Road	2	1.8	47	2.7	0.28	0.78	0.78	16
Mandi House	1.7	1.9	41	2.7	0.28	0.81	0.81	13
Pragati Maidan	2	2	40	2.7	0.31	0.76	0.76	17
Indraprastha	2.1	1.2	42	2.7	0.26	0.66	0.66	21
Yamuna Bank	2.2	1.8	45	2.7	0.27	0.54	0.54	22

<table>
<tr><th>Coefficients:</th><th>Estimate</th><th>Std. Error</th><th>t value</th><th>Pr(>|t|)</th></tr>
<tr><td>Intercept</td><td>0.227137</td><td>0.0249024</td><td>9.121</td><td>5.10e-10 ***</td></tr>
<tr><td>Access Distance (AD)</td><td>0.007596</td><td>0.0013257</td><td>5.73</td><td>3.35e-06 ***</td></tr>
<tr><td>Egress Distance (ED)</td><td>0.010622</td><td>0.0013221</td><td>8.034</td><td>7.35e-09 ***</td></tr>
<tr><td>IVTT</td><td>-0.00408</td><td>0.0002876</td><td>-14.205</td><td>1.36e-14 ***</td></tr>
<tr><td>Metro Frequency (MF)</td><td>0.00714</td><td>0.0030324</td><td>2.355</td><td>0.0255 **</td></tr>
</table>

The Super-DEA analysis evaluates the operational performance efficiency of various stations along the BLUE line of the Delhi Metro by examining input and output parameters that significantly influence the overall efficiency of metro operations (Kumar & Sharma, 2022), (Bhargava & Singh, 2021). The key inputs considered in this analysis include Access Distance (AD), Egress Distance (ED), In-Vehicle Travel Time (IVTT), and Metro Frequency (MF). The output is quantified in terms of efficiency scores for each station. The followings are the key findings of the analysis.

1. Efficiency Scores:

The DEA Efficiency Score indicates how well each station utilizes its resources to achieve desired outputs. Stations with scores closer to 1 are considered efficient, while those below 1 indicate inefficiencies. For example, Dwarka Sector 21 achieved an efficiency score of 0.33, indicating that it is significantly below optimal performance. In contrast, Dwarka Mor has a higher efficiency score of 0.98, suggesting it operates close to maximum efficiency.

2. Operational Characteristics:

The distances for access (AD) and egress (ED) vary across stations, with Dwarka having the highest access distance of 2.3 km and Dwarka Sector 21 having the lowest at 1.5 km. Longer distances may lead to increased travel times and reduced operational efficiency. The IVTT, which represents the time spent traveling on the train, also varies, affecting overall commuter experience and operational efficiency. For instance, Dwarka Sector 10 shows an IVTT of 35 minutes, which is relatively moderate compared to other stations.

3. Metro Frequency (MF):

Metro frequency is another critical factor influencing operational efficiency, with a frequency range of 2.7 to 4.1 minutes across the analyzed stations. Higher frequencies generally lead to better service levels and can improve efficiency as they reduce waiting times for passengers. For example, Dwarka Sector 21 the metro operates at 4.1 minutes, which is beneficial for reducing passenger wait times despite its lower efficiency score.

4. Statistical Significance:

The coefficients for AD, ED, IVTT, and MF provide insights into their respective impacts on efficiency scores. For instance, the coefficient for Metro Frequency is statistically significant ($p < 0.01$), suggesting a strong positive relationship between increased train frequency and operational efficiency.

5. Ranking:

The stations have been ranked based on their efficiency scores. This ranking can guide management decisions regarding where to focus improvement efforts. For example, Dwarka Sector 21 ranks the lowest, indicating a need for operational improvements.

The operational efficiency scores for the stations along the BLUE line are shown in Fig. 1, along with a ranking of each station's efficiency. An important finding is that the adjacent stations are different operating characteristics and have different efficiency scores. Efficiency's trend in relation to rank is non-uniform. Despite their close proximity, it turns out that no two stations behave similarly. This suggests that in order to increase overall stretch/line efficiency, it is necessary to address each station's unique challenges, issues, and characteristics.

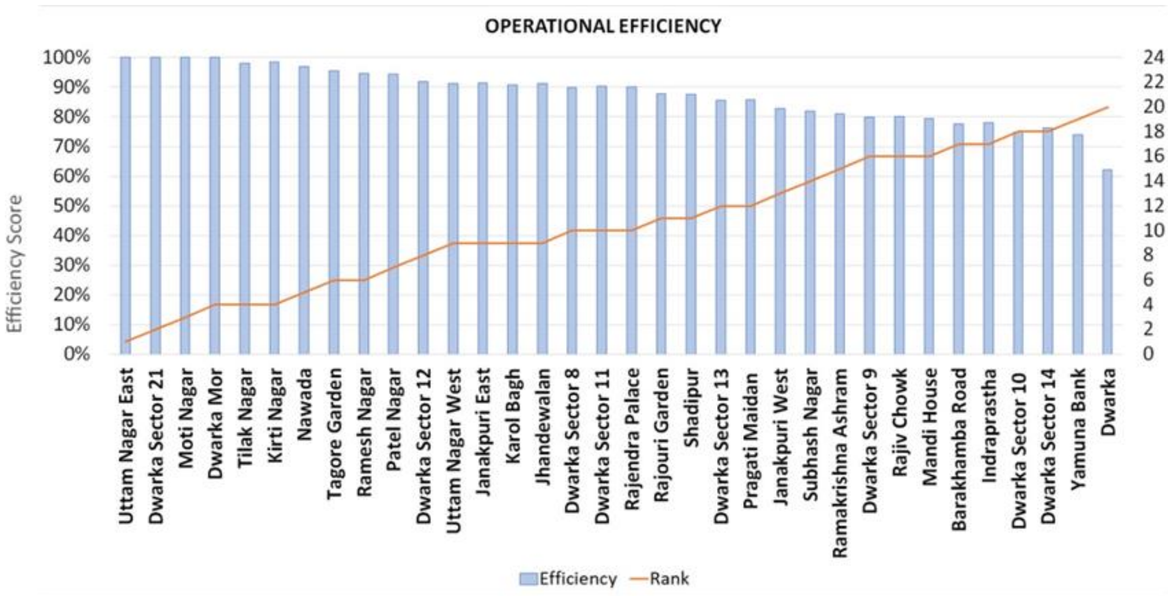

Fig. 1 Operational Efficiency and Ranking of DMU's (BLUE line)

4.3. Proximal performance efficiency

Proximal performance efficiency in a metro transit system measures how access-egress distance, in-vehicle travel time, number of station interchanges, and total travel time influence the combined access and egress time, indicating the system's effectiveness in minimizing user travel time for proximity-based trips. The station's accessibility within the catchment region will be evaluated using the proximate efficiency. To compare the various stations, the proximate efficiency will assess each station's accessibility within its own catchment area. The output parameter from the input variables of access & egress distance, IVTT, number of station interchange, and total travel time is the access & egress trip time sum. The variable set that examines the short-term efficiency of the four corridors of the BLUE line is shown in Table 6 along with the objective data and efficiency findings. The performance output is calculated by adding the access and egress times. The input variables clearly have statistical significance.

Tab. 6

Proximal performance efficiency of BLUE line (Source: Authors)

DMU/Stations	Input Variables					Output	DEA Efficiency Score	Super-DEA Efficiency Score	Rank
	AD	ED	IVTT	Ic	TTT	AT+ET			
Dwarka Sector 21	1.5	1	30	1	14	24	1.00	1.09	5
Dwarka Sector 8	1.4	0.8	30	1	12	22	1.00	1.14	2
Dwarka Sector 9	1.2	1.4	40	2	18	23	0.92	0.92	16
Dwarka Sector 10	1.55	1.5	35	1.5	15.5	22	0.81	0.81	24

Dwarka Sector 11	1.2	1.1	30	1	15	20	0.98	0.98	11
Dwarka Sector 12	1.6	1.55	31	1.5	13	22	0.91	0.91	19
Dwarka Sector 13	1.45	0.85	32.5	2	14.5	21	0.91	0.91	18
Dwarka Sector 14	2	1	40	2	11	20	0.93	0.93	15
Dwarka	2	2	54	2	13	26	0.89	0.89	21
Dwarka Mor	1.2	1.5	45	2	14	25	1.00	1.00	8
Nawada	2.2	1.35	40	2	16.5	22.5	0.74	0.74	28
Uttam Nagar West	1.75	1.65	35	2	14.5	23	0.85	0.85	23
Uttam Nagar East	2	1.5	27	2	16.5	24.5	1.00	1.13	3
Janakpuri West	2	1.8	45	3	17	24	0.72	0.72	32
Janakpuri East	2	1.5	40	2.5	13.5	26	0.94	0.94	13
Tilak Nagar	1.6	1.5	40	2	16	22	0.74	0.74	30
Subhash Nagar	1.7	1.6	39.2	2	15.81	22	0.74	0.74	29
Tagore Garden	1.35	1.5	35	2	14.5	24	0.92	0.92	17
Rajouri Garden	1.8	1.7	35	1	12	24	1.00	1.06	6
Ramesh Nagar	1.6	1	37	1	12	23	1.00	1.02	7
Moti Nagar	1.8	1.1	35	2	13	25	1.00	1.00	10
Kirti Nagar	1.95	2.15	41	2	13	30	1.00	1.15	1
Shadipur	2	1.9	40	2	15	24	0.79	0.79	26
Patel Nagar	1.7	1.9	38.5	2	19	28.5	0.96	0.96	12
Rajendra Palace	1.8	1.8	35	2	18.5	25	0.89	0.89	22
Karol Bagh	1.4	1.6	40	2	14.5	29	1.00	1.13	4
Jhandewalan	1.35	1.1	42	2	16	22.5	0.93	0.93	14
Ramakrishna Ashram	1.3	1.75	43.5	2	17	24	0.89	0.89	20
Rajiv Chowk	2	1.8	42	3	18	24	0.73	0.73	31
Barakhamba Road	2.25	1.95	47	3	17.5	25	0.71	0.71	33
Mandi House	1.2	1.9	41	2	16	25	1.00	1.00	9
Pragati Maidan	2.1	1.8	40	3	16	24	0.78	0.78	27
Indraprastha	2.2	1	42	2	20	22	0.80	0.80	25
Yamuna Bank	2.45	1.95	45	2	15	22	0.69	0.69	34

Coefficients:	Estimate	Std. Error	t value	Pr(>|t|)
Intercept	21.18096	3.525437	6.008	1.79e-06 ***
Access Distance (AD)	-1.065086	1.130905	-0.942	0.35435
Egress Distance (ED)	3.893484	1.140404	3.414	0.00197 ***
IVTT	-0.009377	0.078268	-0.12	0.90549

No. of Station Interchange (Ic)	0.410288	0.933666	0.439	0.66372
Total Travel Time (TTT)	-0.122343	0.180841	-0.677	0.50426

Confidence Level: * = P<0.1, ** = P<0.05, *** = P<0.01

The Super-DEA analysis aims to evaluate the proximal performance efficiency of various stations along the BLUE line of the Delhi Metro. This analysis considers several key performance indicators, including Access Distance (AD), Egress Distance (ED), In-Vehicle Travel Time (IVTT), Interchange Count (IcTTT), and Total Travel Time (TTT). The results provide insights into how efficiently each station operates, which can inform decisions for improvements in metro services. Followings are the key findings of the analysis.

1. Performance Efficiency Scores:

The efficiency scores calculated show how well each station utilizes its resources to provide transit services. Scores closer to 1 indicate a higher level of efficiency, while values below 1 suggest inefficiencies. For instance, Dwarka Sector 21 has an efficiency score of 1.095, indicating it operates relatively efficiently. Conversely, Yamuna Bank has a lower score of 0.690, suggesting areas for improvement.

2. Access and Egress Distances:

Access Distance (AD) and Egress Distance (ED) are crucial indicators of the convenience offered by metro stations. The distances vary across stations, with Dwarka Sector 21 having an AD of 1.51 km and Dwarka station having the highest access distance of 2.25 km. Stations like Nawada and Rajendra Palace have egress distances of 2.1 km and 1.8 km, respectively, which can affect passenger satisfaction and overall efficiency.

3. Travel Times:

In-Vehicle Travel Time (IVTT) and Total Travel Time (TTT) are vital for assessing the efficiency of transit operations. For example, Dwarka Sector 10 has an IVTT of 1.51 minutes, suggesting a relatively quick journey for passengers, while Janakpuri East displays a longer total travel time of 11.13 minutes. The inter-station travel times are critical for determining the quality of service provided to passengers and can be a focal point for improvements.

4. No. of station interchanges:

The number of interchanges available at each station impacts overall accessibility and convenience for users. For instance, Yamuna Bank has a high interchange count of 2 along with higher IVTT, which may limit connectivity for passengers compared to stations with higher interchange counts.

5. Statistical Significance:

The coefficients for the various inputs indicate their impact on efficiency scores. The Egress Distance shows a statistically significant relationship ($p < 0.01$), suggesting that longer egress distances negatively affect performance efficiency. Other variables like Access Distance and IVTT did not show significant effects, indicating that they may not be as critical to overall efficiency.

4.4. Spatial performance efficiency:

Spatial performance efficiency in a metro transit system evaluates how effectively access modes, standing and seating spaces, and parking facilities enable passengers' movement. It considers the spatial and environmental context of the catchment area, highlighting interconnectedness. This assessment identifies the Second-Best Alternative to Delhi Metro as the output, while the input variables include access mode, standing space, seating space, and parking facilities. Table 7 illustrates the objective information and efficiency findings across the four corridors of the BLUE line, demonstrating that these input variables hold statistical significance in evaluating spatial efficiency.

Tab. 7

Spatial performance efficiency of BLUE line (Source: Authors)

DMU/Stations	Input Variables				Output	DEA Efficiency Score	Super-DEA Efficiency Score	Rank
	AM	SS1	SS2	PF	BA			
Dwarka Sector 21	2	4	4	1	2	0.67	0.67	12
Dwarka Sector 8	2	4	4	1	2	0.67	0.67	12
Dwarka Sector 9	2	4	3	1	2	0.67	0.67	12
Dwarka Sector 10	2	4	2.5	1	2	0.67	0.67	12
Dwarka Sector 11	2	4	3	1	2	0.67	0.67	12
Dwarka Sector 12	2	5	4	1	2	0.67	0.67	12
Dwarka Sector 13	2	5	3	1	2	0.67	0.67	12
Dwarka Sector 14	2	5	3	1	2	0.67	0.67	12
Dwarka	2	5	4	1	2	0.67	0.67	12
Dwarka Mor	2	3	3	1	2	0.75	0.75	6
Nawada	2	4	2.5	1	2	0.67	0.67	12
Uttam Nagar West	2	4	4	1	2	0.67	0.67	12
Uttam Nagar East	2	4	3	1	2	0.67	0.67	12
Janakpuri West	2	3.5	2.5	1	2	0.71	0.71	10
Janakpuri East	2	4	3	1	2	0.67	0.67	12
Tilak Nagar	2	4	3	1	2	0.67	0.67	12
Subhash Nagar	2	3.61	2.72	1	2	0.70	0.70	11
Tagore Garden	1.5	4	3	1	2	0.80	0.80	5
Rajouri Garden	2	4	3	1	2	0.67	0.67	12
Ramesh Nagar	2	4	3	1	2	0.67	0.67	12
Moti Nagar	2	4	4	1	1	0.33	0.33	17
Kirti Nagar	2	4	4	1	1	0.33	0.33	17
Shadipur	2	4	4	1	1.5	0.50	0.50	14
Patel Nagar	2	4	3	1	2	0.67	0.67	12
Rajendra Palace	2	3	2	1	2	0.75	0.75	7
Karol Bagh	1	1	1	1	2	1.00	2.20	1
Jhandewalan	1	2.5	1	1	2	1.00	1.00	3

Ramakrishna Ashram	1.5	3	2	1	1	0.40	0.40	15
Rajiv Chowk	2	3	2	1	2	0.75	0.75	8
Barakhamba Road	2.5	3	2	2	2.5	0.63	0.63	13
Mandi House	2	4	2	1	3	1.00	1.50	2
Pragati Maidan	2	3	2	1	1	0.38	0.38	16
Indraprastha	3	2	2	1	2	0.86	0.86	4
Yamuna Bank	2	3	2	1	2	0.75	0.75	9

Coefficients:	Estimate	Std. Error	t value	Pr(>|t|)
Intercept	1.0473	0.5571	2.088	0.0492**
Access mode (AM)	0.1873	0.2173	0.862	0.3958
Standing Space (SS1)	0.235	0.1149	2.045	0.0500**
Seating Space (SS2)	-0.2854	0.1181	-2.416	0.0222**
Parking Facilty (PF)	0.4251	0.4111	1.034	0.3096

Confidence Level: * = P<0.1, ** = P<0.05, *** = P<0.01

The Super-DEA analysis evaluates the spatial performance efficiency of the BLUE line of the Delhi Metro, focusing on factors such as Access Mode (AM), Standing Space (SS1), Seating Space (SS2), and Parking Facility (PF). These metrics are essential for understanding how effectively the metro stations utilize their spatial resources to enhance service delivery and user satisfaction. The followings are the key findings of the analysis.

1. Spatial Efficiency Scores:

The spatial efficiency scores indicate how well each station is utilizing its available space for various functions. Efficiency scores near or above 1 suggest optimal use of space, while values below 1 indicate inefficiencies. For instance, Dwarka Sector 21 has a spatial efficiency score of 0.67, which suggests it is underperforming in terms of space utilization compared to the potential capacity. Similar scores are observed for several other stations, such as Dwarka Sector 8 and Dwarka Sector 9, indicating a consistent pattern across these stations.

2. Access Mode (AM):

The Access Mode (AM) across stations is relatively consistent, with values predominantly around 24. This implies that access to the stations is similarly structured, which could influence passenger flow and overall station usage. However, stations like Indraprastha show a higher score of 32, indicating potentially better access modes that may facilitate higher passenger throughput.

3. Parking Facility (PF):

Parking Facility metrics vary among stations, with some stations like Rajendra Palace having lower scores (0.75) indicating insufficient parking facilities. In contrast, Indraprastha has a higher parking facility score of 0.86, suggesting better provision for passenger vehicles.

Since parking availability can significantly impact the usage of metro services, these metrics are crucial for planning future expansions or improvements.

4. Statistical Significance:

The coefficients for the various inputs indicate their impact on spatial efficiency scores. The coefficients for Access Mode and Parking Facility are statistically significant ($p < 0.05$), suggesting that improvements in these areas could enhance overall spatial efficiency.

The negative coefficient for Standing Space (SS1) implies that increased standing space may not necessarily correlate with improved efficiency, possibly due to overcrowding in some stations.

5. CONCLUSIONS

The present research offers significant contributions to the understanding of urban transit systems, particularly in the context of the Delhi Metro. The analysis highlights that a substantial 38.7% and 43% of access and egress trips involve walking, indicating that walking is the most preferred mode of transit due to its adaptability and cost-effectiveness. The average distances for access and egress are approximately 1.84 km and 1.61 km, respectively, revealing the reliance on pedestrian access to metro stations. Additionally, the study uncovers that auto-rickshaws dominate the mode share for access and egress trips, accounting for 15.4% and 15.9%, respectively, outperforming feeder buses, DTC buses, and private vehicles. The mean haul distance (MHD) for trips utilizing all access methods averages 19.69 km, reinforcing the metro's role as a crucial mode of transport for longer distances. These findings align with previous research conducted in the Delhi-NCR region, confirming the trends observed in user behavior (Goel & Tiwari, 2016; Swami & Parida, 2015).

One of the novel aspects of this research lies in its application of Data Envelopment Analysis (DEA) and Super-DEA methodologies to evaluate the performance of Decision-Making Units (DMUs) in a multimodal transport context. While previous studies have employed similar methodologies, this research enriches the literature by demonstrating their effectiveness in identifying both systemic and individual performance characteristics across different metro stations. The analysis not only provides insights into technical efficiencies but also generates target values for inputs and outputs, enabling less efficient DMUs to align with the performance of the best-performing stations. This aspect is particularly valuable for urban planners and transit authorities seeking to enhance operational effectiveness.

Furthermore, the study identifies critical performance gaps in access and egress trips, particularly at connecting/terminal stations where long distances to access services are prevalent. This issue highlights the need for improved interconnectivity through either the extension of metro lines or the establishment of reliable feeder services. The findings emphasize that each station's unique attributes necessitate tailored strategies for enhancement, which can significantly improve the metro system's integration within the broader multimodal transport fabric.

The research also contributes to international literature by addressing the interplay between operational, spatial, and proximal efficiency attributes in urban transit systems. The insights gained from the Delhi Metro can inform similar evaluations in other metropolitan areas globally, particularly in developing regions where public transport infrastructure is rapidly evolving. By highlighting the importance of organized routes and improved connectivity, the study underscores the need for comprehensive urban transport planning that considers various modes of transportation and their interrelationships.

In conclusion, this research not only advances our understanding of the operational dynamics of the Delhi Metro but also offers a framework for evaluating urban transit systems worldwide. The findings and recommendations serve as a guide for policymakers and transit authorities aiming to enhance the efficiency and effectiveness of urban public transport systems, ultimately contributing to more sustainable and accessible urban mobility.

6. RECOMMENDATIONS

To address the identified inefficiencies and enhance the overall user experience, the following recommendations are proposed:

1. Enhance Access and Egress Facilities: Improving the quality and safety of walking paths, installing signage, and providing adequate lighting can significantly enhance access and egress journeys.
2. Optimize Feeder Services: Given that a substantial proportion of commuters rely on walking, bolstering feeder services to connect residential areas with metro stations is critical. Implementing a well-coordinated feeder bus schedule can help reduce waiting times and improve overall connectivity.
3. Improve Transfer Facilities: Reducing the out-of-vehicle travel time (OVTT) and transfer times through better-designed transfer facilities and streamlined card access at public transport systems will encourage more users to choose metro transit.
4. Expand Network Length and Coverage: Extending metro lines into underserved areas and enhancing the frequency of services can attract more users, thus improving the system's reach.
5. Conduct Regular Performance Audits: Continuous monitoring and evaluation of station performance using DEA methodologies will help identify weak links and facilitate timely interventions.

By implementing these measures, the Delhi Metro can significantly improve its operational efficiency, enhance user satisfaction, and ultimately contribute to a more integrated urban transport system.

7. LIMITATIONS AND FUTURE SCOPE OF WORK

Sample size is one of the study's limitations. The on-board commuters are the only subjects of the study. For further research, a survey of non-metro commuters is required. The user's behavior in other weather conditions may be influenced by this survey, which is conducted in the winter. Future research will examine the impact of comfort factors, intercity metro impact and fare factors on the performance efficiency of DM.

Abbreviations Used:
DEA: Data Envelopment Analysis;
Su-DEA: Super- Data Envelopment Analysis;
DMU: decision-making units;

UMTS: Urban Metro Transit System;
MHT: Main Haul Time;
MHD: Main Haul Distance;
OVTT: Out-Vehicle Travel Time;
IVTT: In-Vehicle Travel Time;
TTT: Total Travel Time;
RI: Running Index;
IR: interconnectivity ratio.

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