PERFORMANCE EVALUATION OF SUBWAY LINES WITH DATA ENVELOPMENT ANALYSIS AND GEOGRAPHIC INFORMATION SYSTEMS, A CASE STUDY OF BEIJING*

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1. Introduction

Transit system plays an important role in reducing the private vehicle dependence and mitigating the congestion and environmental pressure，and the performance evaluation of transit system is very necessary. However, mainly from management perspective[1)] and little attention has been given to the spatial aspects, especially at the scale of the individual lines within a public transit agency.

China witnessed a major boom in rail transit development in the past ten years, especially for some megacities. This study will take Beijing as case study to evaluate the individual subway lines in two dimensions: operational efficiency and spatial effectiveness.

Beijing has the second largest subway system in mainland China, and the entire network will expand to 420 km by 2012. The subway's first line opened in 1971, and there are 8 lines, 123 stations and about 200 km of tracks in operation by the beginning of 2009 (Figure 1).

Figure 1: Beijing subway map (http://www.johomaps.com/)

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2. Methodology

In this research, we use Data Envelopment Analysis (DEA) to measure operational efficiency and spatial effectiveness. DEA is a non-parametric approach for estimating the relative efficiency of Decision Making Units (DMUs) that perform the same or similar tasks in a production system. The underlying assumption is that each DMU requires certain resources (inputs) to produce its goods or services (outputs). In a relatively short period of time DEA has grown into a powerful quantitative, analytical tool for measuring and evaluating performance. Since it was first developed by Farrell's[2] and later popularized by Charnes et al.[3], various DEA approaches have been widely applied for the efficiency evaluation throughout different industries.

In our case, each subway line is treated as a DMU. The DEA model we employed is the output-oriented super efficiency model[4], as the overall objective of a subway line is to serve as many passengers as possible. Another reason we chose the super efficiency model is that it is particularly useful when the number of DMUs are small and it can easily discriminate between DMUs with full efficiency. The model was solved by the MAXDEA solver.

Variables definition:

The input and output matrices are $\mathrm{X} |= (x_{ij}) \in \mathrm{R}^{\mathrm{m}\times\mathrm{n}}$ and $\mathrm{Y} = (\mathrm{y}_{\mathrm{ij}}) \in \mathrm{R}^{\mathrm{s}\times\mathrm{n}}$ respectively, $\mathrm{X} > 0, Y > 0$; $\mathrm{P} \setminus (\mathrm{x}_0, \mathrm{y}_0) = \{(\bar{\mathrm{x}}, \bar{\mathrm{y}})\ \bar{\mathrm{x}} \geqq \sum_{j=1,\neq 0}^{n} \lambda_j x_j, \bar{\mathrm{y}} \leq \sum_{j=1,\neq 0}^{n} \lambda_j y_j, \bar{\mathrm{y}} \geq 0, \lambda \geq 0\}$; $\bar{\mathrm{P}} \setminus (\mathrm{x}_0, \mathrm{y}_0) = \mathrm{P} \setminus (\mathrm{x}_0, \mathrm{y}_0) \cap \{\bar{\mathrm{x}} \geq \mathrm{x}_0 \text{ and } \bar{\mathrm{y}} \leq \mathrm{y}_0\}$.

Super efficiency model can be written as:

$$\delta^* = \min\delta = \frac{\frac{1}{\mathrm{m}} \sum_{\mathrm{i}=1}^{\mathrm{m}} \frac{\bar{\mathrm{x}}_{\mathrm{i}}}{\mathrm{x}_{\mathrm{i}0}}}{\frac{1}{\mathrm{s}} \sum_{\mathrm{r}=1}^{\mathrm{s}} \frac{\bar{\mathrm{y}}_{\mathrm{r}}}{\mathrm{y}_{\mathrm{r}0}}}$$

$$st \quad \bar{x} \geq \sum_{j=1,\neq 0}^{n} \lambda_j x_j, \qquad \bar{\mathrm{y}} \leq \sum_{j=1,\neq 0}^{n} \lambda_j y_j,$$

$$\bar{x} \geq x_0 \text{ and } \bar{y} \leq y_0, \quad \bar{y} \geq 0, \lambda \geq 0.$$

3. Data

Table 1 displays the input-output specifications for the model. We use operational efficiency to measure the productivity of supply, and spatial effectiveness to measure the benefits of demand for individual subway lines.

Table 1 The input and output indicators for the super efficiency DEA model

	Input data	Output data
Operational Efficiency	Operation time	Daily average passengers transported
	Trip distance	
	Numbers of subway stations	A single fare
Spatial Effectiveness	Potential commuters	Daily average passengers transported
	Average bus lines pass through buffer area	
	Number of transferring station	

We generated data needed for the modeling of individual subway lines with the assistance of Geographic Information Systems (GIS). Table 2 lists the main components of the GIS spatial database.

It contains spatial and attribute information in two categories: transit data and census data. Spatial data are digital map layers with attribute data which are descriptive information associated with each map feature (point, line, or polygon).

Table 2 GIS spatial database

Map feature	Categories	Spatial data	Attribute data
Point data	Transit data	Bus stop	Name, latitude and longitude, bus lines passed by
		Subway station	Name, latitude and longitude, subway lines pass by
Line data	Transit data	Bus line	Name, trip distance, number of stops
		Subway line	Name, trip distance, operation time, number of subway stations, potential passengers, single fare
Polygon data	Census data	Population density	Populations and bus lines in buffer areas for each subway line

4. Evaluation of operational efficiency and spatial effectiveness

The better way to obtain a comprehensive evaluation of subway line performance is to compare operational efficiency with spatial effectiveness. We calculated the differences between operational efficiency and spatial effectiveness scores for each subway line (Table 3), and applied the K-Means clustering algorithm to classify the 8 subway lines into four groups (Figure 2). We also carefully checked the spatial environment of subway lines using GIS.

Table 3 Results by DEA

DMU	Operational efficiency	Spatial effectiveness	Difference((A)-(B))
	Super Efficiency(A)	Super Efficiency(B)	
Line 1	1.08	2.57	-1.49
Line 2	1.06	1.03	0.03
Line 5	0.28	0.83	-0.56
Line 8	1.00	1.00	0.00
Line 10	0.26	0.56	-0.30
Line 13	0.23	0.91	-0.68
Batong Line	0.26	0.58	-0.32
Airport Express	1.85	0.10	1.75

Group 1: the best performing subway lines (Line1, line2, and line8) have very high scores in both operational efficiency and spatial effectiveness. They provide benchmarks for performance evaluation. Specifically, line1 connects major commercial centers, Xidan, Wangfujing, Dongdan and the Beijing CBD, and line2 surrounds the inner city, and stops at 11 of the wall's former gates (ending in men), now busy intersections, as well as the Beijing Railway Station, and line8 is with three stops in the Olympic Green.

Group 2: the subway lines (Line1, line13) that are spatially effective but operationally inefficient should be supported and subsidized to maintain their current operations. These subway lines captured a reasonably large percentage of potential demand, while only a very small portion of the target population is being served. The most likely reason is that certain aspects of subway line services, such as schedules, frequencies, subway station locations, or transfer convenience are not adequate to meet the demand. The second possibility is that part of the target population may not be interested in subway services as they are already well served by other means of transportation. For example, the people with low income will be likely to travel by bus because of the relatively cheaper fare of bus.

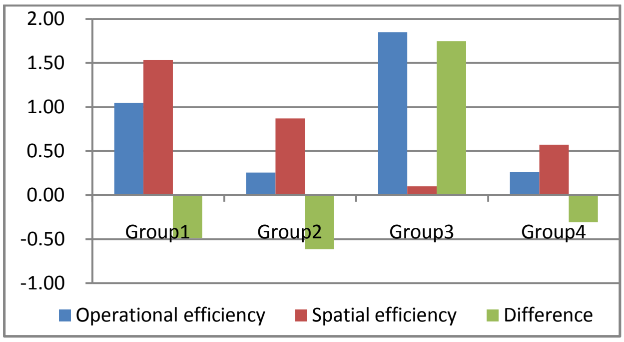

Figure 2: Comparison between operational efficiency and spatial effectiveness

Group 3: efficient performers is airport express, which is mainly served for the airport and operated by the different company from other 7 lines, and the single fare is 12.5 times of other lines.

Group 4: the worst performers (Line10, Batong line) are the subway lines with very low efficiency and effectiveness scores that should be carefully re-planned and adjusted. Strategies to improve usually involve changing subway station or bus stop locations, improving transfer convenience and modifying existing service frequencies and schedules. It requires further analysis of demographics and commuting patterns at neighborhood level, plus comparisons of ridership at individual subway station.

5. Conclusion

The spatial characteristics and distribution of transit system can strongly affect the two basic dimensions of performance: efficiency and effectiveness. Effective spatial layout, coupled with efficient operations and management will promote a better performance of subway lines. For different groups, Group 1and 2 should be operationally improved to increase the spatial attractiveness, while group 4 needs to further consider its spatial layout and operational management. Further improvement strategy requires analysis of demographics and commuting patterns at city scale and neighborhood level, with comparisons of ridership at individual subway station.

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