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COMPREHENSIVE EVALUATION OF TRANSPORTATION INFRASTRUCTURE SYSTEMS EFFICIENCY USING DATA ENVELOPMENT ANALYSIS

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Abstract: DEA is adopted for evaluating the efficiency of transportation infrastructure systems of nineteen cities and towns in Japan. The cities can be divided into two groups, which are big cities from the whole Japan and small cities and towns in Hokkaido. The decision-making unit here is not a single infrastructure unit, but the whole transportation infrastructure systems in the city which include the road networks and the railway systems. Transportation modes, which serve people mobility, consist of road-using modes (cars and buses) and rail-using modes (JR, private trains, streetcars, subways, monorails, etc.). For comparison purpose, evaluations using various input-output combinations were performed. Furthermore, to achieve robust evaluation, different DEA concepts, including CCR, Inverse DEA, and BCC models, were performed. This study provides a benchmark for cities to improve their infrastructure system management by identifying weak points of each city and suggesting the way to improve efficiency.

Key Words: Data Envelopment Analysis, Transportation Infrastructure Systems, Efficiency Evaluation

1. INTRODUCTION

Infrastructure systems are built to serve the basic needs of people in a community. Without good infrastructure systems, the development of technology, economic, etc. would be difficult. As the large amount of money is essential for the construction and operation of such systems, a well plan with detailed study is need before starting a project. Furthermore, after a system started the operation, evaluation of efficiency of the system is required as a monitoring process providing the information for the planner to improve or adjust the existing system in order to operate more efficiently. To assess the feasibility or efficiency of a certain project, it is not enough to consider only monetary cost and benefit, such as the benefit from revenue, capital budget and operation cost. The other elements of cost and benefit of the project should be taken into account as well. Thus the evaluation method, which can deal with several inputs and out puts in a unified manner, should be applied to this problem.

Transportation infrastructures serve for moving people and goods from one place to another. Clearly, it is requires the system that can manage the large amount of transported units fast safely, and environmental friendly. To evaluate the efficiency of infrastructure system, the method that can combine various kinds of inputs and outputs in a unity manner should be preferable. For example, we desire to maximize transportation mobility with minimum infrastructure facilities, environmental burden, and accident. All factors should be considered together at the same process. That is the evaluation is made from the viewpoint of various factors. DEA is one of the analytical tools that can handle such problem. DEA has been using for evaluating the efficiency of various kinds of enterprises or decision making units. DEA can deal with multiple inputs and outputs problems, which each item of input or output is not necessary to be in monetary term and can have different unit. This is different from the conventional cost-benefit analysis, which all cost and benefit items have to be converted to be the monetary unit.

Data Envelopment Analysis (DEA) is commonly used to evaluate the efficiency of a number of producers or Decision Making Units (DMUs). It is a nonparametric approach used for the estimation of frontiers in economics. A typical statistical approach, such as the regression analysis, is characterized as a central tendency approach and it evaluates DMUs relative to an average DMU. In contrast, DEA is an extreme point method and compares each DMU with only the best DMUs. DEA determines the efficiency of a certain enterprise or a decision making unit (DMU) as the ratio of the virtual output by the virtual input. The virtual input and output are the weighted sum of all input factors and the weighted sum of all output factors, respectively. Weights in DEA are derived from the data instead of being fixed in advance. Each DMU is allowed to select the best weights for inputs and outputs. Each DMU can assign great weights to its strong factors and assign small weights to its weak factors. The procedure of finding the best virtual DMU can be formulated as a linear program. Analyzing the efficiency of n DMU is then a set of n linear programming problems.

The objective of this study is to examine the efficiency of transportation infrastructure systems of the small cities in Hokkaido, and big cities of Japan. In this study, the Data Envelopment Analysis (DEA) is used for evaluating the efficiency of transportation infrastructure systems of nineteen cities and towns in Japan. The cities can be divided into two groups, which are 1) big cities including Sapporo, Yokohama, Kawasaki, Nagoya, Kyoto, Fukuoka, Kitakyushu, Sendai, Chiba, and Hiroshima; and 2) small cities and towns in Hokkaido including Otaru, Tobetsu, Ebetsu, Kitahiroshima, Eniwa, Chitose, Asahikawa, Hakodate, and Kushiro. The big cities overall Japan, which already have complex transportation systems to fulfill transportation demands, are selected to compare with the small cities in Hokkaido as examples from which the small cities can identify their weak points and find the proper direction for their future development.

The decision-making unit (DMU) here is not a certain company or a single infrastructure unit, but the whole transportation infrastructure systems in the city which include the road network and the railway systems. The profit or output is the mobility of the people in the city (the mobility of goods is not taken into account in this study), while, the costs or inputs are the amount of road and rail systems in city, the environmental burden from transportation activities and the traffic accident.

2. DATA ENVELOPMENT ANALYSIS (DEA)

DEA, which was first developed by Charnes *et al.* (1978), is a method to find the relative efficiency of enterprises or decision making units (DMUs). DEA has been widely used in technical efficiency evaluation over recent years. Some examples of the studies using DEA include evaluation of transit systems (Karlaftis, 2003), site selection for retail stores (Cook and Green, 2003), planning for relocation of government agencies (Takamura and Tone, 2003), airport evaluation (Fernandes and Pacheco, 2002), etc. Various DEA models have been developed as summarized in literatures like Seiford and Thrall (1990) and Seiford (1996). A fundamental concept of DEA is that if a given DMU is able to produce certain units of output with certain units of input, then other DMUs should also be able to do the same if they were efficiently operated. This concept is extended to the case with multiple inputs and multiples outputs. For a certain DMU, inputs and outputs are combined to be composite inputs and outputs, which is so called virtual input and virtual output, using the most preferable weights. The core of the method is to find the best weights for each DMU. The values of the best weights for each DMU may vary from one DMU to other DMU. It is selected so as to make the considering DMU most efficiency, while keeping the other DMUs evaluated with the same weights maintain the constraint that the efficiency value is not more than unity. The DMU is considered to be efficient if the evaluation result is equal to one. The DMU is inefficient if there is at least one DMU that either makes more output with the same input or makes the same output with less input, and the analytical result will be less than one.

For the comparison purpose, three DEA models, which are CCR model, Inverse DEA model, and BCC model, were selected to evaluate the transportation systems.

2.1 CCR Model

The CCR Model (Charnes *et al.*,1978) can be described as:

Objective function: $$\max h_0 = \frac{\sum_{r=1}^{s} u_r y_{r0}}{\sum_{i=1}^{m} v_i x_{i0}}$$

subject to: $$\frac{\sum_{r=1}^{s} u_r y_{rj}}{\sum_{i=1}^{m} v_i x_{ij}} \le 1; \quad j = 1,\ldots,n$$

$$u_r, v_i \ge 0; \quad r = 1,\ldots,s; \quad i = 1,\ldots,m$$

y_{rj},x_{ij} are outputs and inputs of the j^{th} DMU. u_r,v_i are the weights to be determined for each DMU$_0$. The efficiency of each DMU$_0$ is to be evaluated relative to the others. The optimal efficient score of DMU$_0$ caused from the optimal weights (v^* and u^*), the most favorable weighting that the constraints allow, is denoted as h^*. The DMU$_0$ is considered to be relatively efficient if h^* is equal to one, and not efficient if h^* is less than one.

The model can be expressed in the linear programming form as:

Objective function: $\min \theta$

Subject to: $\theta\mathbf{x_0} - \mathbf{X\lambda} \geq 0$

$\mathbf{y_0} - \mathbf{Y\lambda} \leq 0$

$\mathbf{\lambda} \geq 0$

2.2 Inverse DEA

Inverse DEA was developed by Yamada *et al.* (1992). The concept of the model is contrary to the concept of normal DEA model. That is the inverse DEA is use for determining the most disadvantageous weights and the most inefficient DMU. The evaluation index of the inverse DEA is the L-Efficiency value. The inverse DEA model can be formulated as follows:

Objective function: $$\min z_0 = \frac{\sum_{r=1}^{s} u_r y_{r0}}{\sum_{i=1}^{m} v_i x_{i0}}$$

subject to: $$\frac{\sum_{r=1}^{s} u_r y_{rj}}{\sum_{i=1}^{m} v_i x_{ij}} \geq 1; \quad j = 1,\ldots,n$$

$$u_r, v_i \geq 0; \quad r = 1,\ldots,s; \quad i = 1,\ldots,m$$

where the variables in the model are defined as the same as in DEA model.

L-Efficiency: g_0*=1-(1/z_0*) ; (0≤g_0*<1)

If g_0*=0, DMU$_0$ is L-inefficient. If 0<g_0*<1, then DMU$_0$ is L-efficient. * indicates the optimal solution.

The results from inverse DEA together with CCR model can be used to classify DMUs as follows:

- Class A: the DMU has no weak point and has excellent condition in all factors (CCR-Efficient, L-Efficient)
- Class B: the DMU has excellent condition for the most of factors (CCR-Efficient, L-Inefficient)
- Class C: the DMU has small weak points for all factors (CCR-Inefficient, L-Efficient)
- Class D: the DMU has weak points in some factors (CCR-Inefficient, L-Inefficient)

2.3 BCC Model

The Banker-Charnes-Cooper (BBC) model (Banker *et al.*, 1984), which is based on the variable returns to scale assumption in contrast to CCR model which is built on the assumption of constant returns to scale, is capable of estimation of returns to scale (RTS) in DEA. The returns to scale expresses the comparison of the proportional change (marginal change per average change) in input and the proportional change in output. If the rate of changing in input equal to that of output, the DMU is operated under constant returns to scale.

If the rate of changing in input is faster than that of output, it indicates that the DMU is operated under decreasing returns to scale, while the reverse situation indicates increasing returns to scale.

BCC is formulated by adding a convexity constraint to CCR model. It can be expressed by linear programming problem as:

Objective function: $\min \theta$

Subject to:

$$\theta \mathbf{x}_0 - \mathbf{X}\boldsymbol{\lambda} \geq 0$$
$$\mathbf{y}_0 - \mathbf{Y}\boldsymbol{\lambda} \leq 0$$
$$\mathbf{e}\boldsymbol{\lambda} = 1$$
$$\boldsymbol{\lambda} \geq 0$$

3. APPLICATION OF DEA TO INFRASTRUCTURE SYSTEM EVALUATION

3.1 Inputs and outputs definition

The results of the DEA depend on the choice of input and output variables. It is important to select them carefully as to be the best suit for the objective of the analysis. As DEA is a comparative evaluation method not an absolute evaluation method, therefore, negative outputs might be determined as inputs of the model. In this study, the input variables are the resources that the system uses to carry out the transport activities. We defined three models of input-output combination for DEA (IO-I, IO-II, and IO-III) for the comparison purpose. The summary of the input and output indicators of each model is shown in Table 1. The factors, including mobility, extent of infrastructure systems, safety, and environmental impact, are considered for selecting the inputs and outputs of DEA model as follows:

(1) Total length of road network (kilometers): It represents the extent of the road transportation infrastructure systems in the city. It includes national roads, prefecture roads, and city roads. This indicator is treated as one of the inputs for the analysis.

(2) Number of stations of rail transportation systems (stations): It represents the extent of the rail transportation infrastructure systems in the city. The type of rail systems in each city could be different. In small cities, only train might be available, whereas, in big cities, various systems might be available, including train, subway, monorail, streetcar, etc. The number of the stations is an indicator that implies how large of the entire rail systems in the city. Thus, it is used as input in the analysis.

(3) Number of people injured and killed in traffic accident (persons): It represents the safety aspect (i.e., the higher dead and injury the lower safety). The number of people injured and died in accident from rail systems is small comparing to that from roadway system. Therefore, only traffic accident is considered. Actually this item is one of the outputs from transport activities. As a negative effect, we put it in the input side of DEA for IO-I and IO-II, and use its reciprocal for the output side of IO-III.

(4) Amount of CO_2 emitted from transportation activities (units): CO_2, one of the main products from the engine combustion, is selected as the representative of the pollution cause by transportation activities. Like accident, pollution is the negative output from the system; therefore we treat it as one of the input for IO-I and IO-II and, apply its reciprocal in the output side of IO-III. The rates of the CO2 emission for different kinds of

transportation modes (West Japan Railway Company, 2004) are listed in Table 2. The rates listed are the average amounts of CO_2 emission cause by one person-trip compared to that of rail system (i.e., comparative rate based on rail system's emission of 100 units).

(5) Mobility: We define two types of mobility for the sake of comparison purpose. For, the first one (denoted as Mobility-I), speed is included in the mobility index, in which the mobility is defined as the summation of the total number of trips from each transportation mode times the average travel speed of that mode.

Mobility-I (trip-kilometer/hour) =

$$\sum_{l} \{(\text{average speed of transportation mode } l) \times (\text{number of person trips using transportation mode } l)\}$$

However, it is difficult to estimate as well as collect the data of the average speed of each transportation mode in each city, especially the average speed of cars. Some values of average speeds have to be assumed. The deviation of the assumed speeds from the actual ones will cause incorrect analytical results. One might treat this problem as imprecise data envelopment analysis by using the bounded data, ordinal data, or ratio bounded data and solving with scale transformations and variable alternations; or converting imprecise data into exact data and solving with standard DEA model (Zhu, 2003). The second definition of mobility (Mobility-II) does not take speed into account. The mobility is defined as the total number of person-trips in the city.

$$\text{Mobility-II (trips)} = \sum_{l} \{\text{number of person - trips using transportation mode } l\}$$

It is obvious that the first definition is better represent the mobility of the transportation systems but it is also easy to provide misleading results. While, the second definition representing only total number of transportation activities with neglecting speed, is more stable. In the analysis, we apply Mobility-I as an output in IO-I, and Mobility-II as an output in IO-II and IO-III.

One might suspect that the construction cost and operating cost of each infrastructure system should be selected as the input for DEA model. However, it is difficult to acquire that kind of data. Therefore, item (1) and (2) are adopted as they include the aspects of construction and operating costs. This is based on the assumption that the construction and operating costs are proportional to the extent or size of infrastructure system.

Table 1. Inputs and outputs for DEA

Input-output factors	IO-I	IO-II	IO-III
Inputs			
Total length of road network (kilometers)	x	x	x
Number of stations of rail transportation systems (stations)	x	x	x
Number of people injured and killed in traffic accident (persons)	x	x	
Amount of CO_2 emitted from transportation activities (units)	x	x	
Outputs			
1/(Number of people injured and killed in traffic accident) (per person)			x
1/(Amount of CO2 emitted from transportation activities) (per unit)			x
Mobility-I (trip-km/hr)	x		
Mobility-II (trips)		x	x

Table 2. CO_2 emission rate per person-trip (units) compared to 100 units emitted from rail system

Transportation mode	CO_2 emission rate
rail system	100
bus	380
car	900

3.2 Area Studied

Nineteen cities and towns including the cities and towns in Hokkaido and the large cities in Japan, were selected to be the study area. The cities can be divided into two groups:

1) Large cities: Sapporo, Yokohama, Kawasaki, Nagoya, Kyoto, Fukuoka, Kitakyushu, Sendai, Chiba, and Hiroshima;
2) Small cities and towns in Hokkaido: Otaru, Tobetsu, Ebetsu, Kitahiroshima, Eniwa, Chitose, Asahikawa, Hakodate, and Kushiro

The locations of all cities and towns studied are depicted in Figure 1.

Figure 1. Location of the Cities Studied

The analysis is based on data in 1995 because of it is the year when the last person-trip survey in Central Hokkaido was carried out. The data are based on information from statistics books including the person-trip survey of city areas in Central Hokkaido (1996), the person-trip survey of city areas around Japan (1995), the book of the comparison of annual statistics of large cities (1997), and the statistics book of each city. The number of person-trips per day and average operation speed of each transportation mode is presented in Table 3. The average speed of cars in large cities used in the analysis are taken from Liu *et al.* (2001), while the average speed of car in the small cities are assumed to be 30 km/hr. The value of 12.5, 12.5 and 40 km/hr are assumed for the average speeds of buses, streetcars, and trains, respectively, for all cities that they are available.

The values of the inputs and outputs used in the analysis are shown in Table 4.

Table 3. Person-trips per day and average operation speed of each transportation mode

City	Number of Trips per Day (Person Trips)						Average Operation Speed (km/hr)		
	Car	Bus	Train	Subway	Street Car	New System	car	subway	new system
Sapporo	2,238,112	410,095	175,406	628,171	25,628	-	25.1	34.3	
Otaru	223,541	49,969	18,936	-	-	-	30.0		
Tobetsu	46,316	427	6,527	-	-	-	30.0		
Ebetsu	183,618	11,742	27,581	-	-	-	30.0		
Kitahiroshima	107,436	7,527	16,824	-	-	-	30.0		
Eniwa	113,584	1,827	13,760	-	-	-	30.0		
Chitose	164,120	8,885	11,895	-	-	-	30.0		
Asahikawa	478,742	60,198	8,540	-	-	-	30.0		
Hakodate	434,455	47,912	5,700	-	22,397	-	30.0		
Kushiro	366,387	28,653	3,081	-	-	-	30.0		
Sendai	1,123,846	235,057	160,474	167,151	-	-	27.8	30.7	
Yokohama	1,872,871	970,617	3,013,621	320,228	-	47,908	21.1	36.9	24.6
Kawasaki	628,790	318,933	1,230,750	-	-	-	22.1		
Chiba	639,677	199,527	493,697	-	-	42,330	23.5		25.0
Nagoya	2,133,287	838,318	808,612	1,134,020	-	-	20.5	33.4	16.0
Kyoto	1,084,739	610,162	938,982	207,029	-	-	20.6	31.4	
Hiroshima	1,144,241	210,290	170,642	-	179,712	45,543	27.4		30.0
Kitakyushu	998,587	314,625	220,348	-	-	31,299	28.3		27.0
Fukuoka	1,252,586	390,441	394,814	316,838	-	-	19.9	30.0	

Table 4. Values of input and output factors for DEA model

City	Road Length (km)	Number of Rail Transport Stations (stations)	Casualties from Traffic Accident (persons)	CO_2 emission (10^9 units)	Mobility-I (10^7 trip*km/hr)	Mobility-II (10^6 person trips)
Sapporo	5,182.8	93	11,880	822.366	3,291.777	1,269.256
Otaru	640.1	8	870	81.055	295.222	106.743
Tobetsu	565.0	6	130	15.512	60.440	19.444
Ebetsu	806.4	5	558	62.954	246.687	81.373
Kitahiroshima	437.9	1	355	36.951	145.640	48.102
Eniwa	567.8	4	355	38.068	145.298	47.147
Chitose	821.5	5	584	55.580	201.131	67.488
Asahikawa	2,313.8	17	2,320	165.928	564.157	199.830
Hakodate	987.2	3	1,708	150.389	516.129	186.320
Kushiro	1,025.5	6	898	124.445	418.765	145.314
Sendai	3,233.1	42	3,912	413.744	1,669.206	615.583
Yokohama	8,773.6	135	25,904	873.297	6,759.439	2,272.215
Kawasaki	2,404.9	53	7,866	295.716	2,449.621	795.142
Chiba	2,822.9	47	6,305	257.373	1,399.140	501.959
Nagoya	6,144.9	129	17,382	887.965	4,541.426	1,793.696
Kyoto	3,185.8	115	13,451	482.796	2,702.192	1,036.933
Hiroshima	3,761.9	129	8,778	419.501	1,621.300	638.906
Kitakyushu	3,998.1	63	8,700	380.859	1,527.591	571.173
Fukuoka	3,715.5	57	13,465	491.604	2,011.609	859.458

4. ANALYTICAL RESULTS

4.1 Efficiency Evaluation

This study uses input-oriented type DEA for the evaluation. That is we evaluate the efficiency by comparing the amount of input used in each city to produce a certain amount of output. The results of the analysis using CCR model, Inverse DEA model, and BCC model with three scenarios of input-output combination (IO-I, IO-II, and IO-III) are shown in Table 5 and Table 6. Table 5 shows the result of DEA evaluating all cities (pooled evaluation), while Table 6 shows the evaluation result among the small cities.

Table 5. Result of analysis based on nineteen cities

City	IO-I							IO-II							IO-III						
	CCR				BCC			CCR				BCC			CCR				BCC		
	Score	Rank	L-Eff	Class	Score	Rank	RTS	Score	Rank	L-Eff	Class	Score	Rank	RTS	Score	Rank	L-Eff	Class	Score	Rank	RTS
Sapporo	0.814	13	0.143	C	0.925	12		0.927	11	0.207	C	0.964	12		0.816	9	0.020	C	0.857	10	
Otaru	0.843	10	0.067	C	0.933	11		0.852	12	0.095	C	0.998	10		0.727	10	0.411	C	0.925	8	
Tobetsu	1.000	1	0.000	B	1.000	1	CRTS	0.939	9	0.000	D	1.000	1	ICRT	1.000	1	0.000	B	1.000	1	CRTS
Ebetsu	1.000	1	0.134	A	1.000	1	CRTS	0.935	10	0.083	C	0.975	11		0.589	15	0.204	C	0.653	14	
Kitahiroshima	1.000	1	0.141	A	1.000	1	CRTS	1.000	1	0.089	A	1.000	1	CRTS	1.000	1	0.354	A	1.000	1	CRTS
Eniwa	0.945	9	0.104	C	0.964	9		0.843	13	0.036	C	0.935	13		0.691	13	0.148	C	0.771	11	
Chitose	0.837	11	0.055	C	0.846	14		0.799	15	0.015	C	0.843	15		0.508	17	0.035	C	0.595	16	
Asahikawa	0.659	16	0.000	D	0.662	17		0.687	17	0.000	D	0.687	17		0.394	19	0.000	D	0.410	19	
Hakodate	1.000	1	0.013	A	1.000	1	CRTS	1.000	1	0.039	A	1.000	1	CRTS	1.000	1	0.544	A	1.000	1	CRTS
Kushiro	1.000	1	0.000	B	1.000	1	CRTS	1.000	1	0.000	B	1.000	1	CRTS	0.719	12	0.397	C	0.754	13	
Sendai	1.000	1	0.157	A	1.000	1	CRTS	1.000	1	0.201	A	1.000	1	CRTS	0.724	11	0.190	C	0.760	12	
Yokohama	1.000	1	0.405	A	1.000	1	CRTS	1.000	1	0.265	A	1.000	1	CRTS	0.922	6	0.000	D	1.000	1	DRTS
Kawasaki	1.000	1	0.493	A	1.000	1	CRTS	1.000	1	0.354	A	1.000	1	CRTS	1.000	1	0.499	A	1.000	1	CRTS
Chiba	0.700	15	0.249	C	0.700	15		0.767	16	0.173	C	0.769	16		0.612	14	0.213	C	0.613	15	
Nagoya	0.811	14	0.275	C	0.949	10		0.971	8	0.311	C	1.000	1	DRTS	0.904	7	0.000	D	1.000	1	DRTS
Kyoto	0.833	12	0.184	C	0.872	13		0.984	7	0.132	C	1.000	1	DRTS	0.984	5	0.000	D	1.000	1	DRTS
Hiroshima	0.562	18	0.000	D	0.562	18		0.665	18	0.000	D	0.665	18		0.514	16	0.000	D	0.530	17	
Kitakyushu	0.545	19	0.022	C	0.545	19		0.618	19	0.000	D	0.619	19		0.504	18	0.000	D	0.513	18	
Fukuoka	0.643	17	0.000	D	0.667	16		0.826	14	0.000	D	0.866	14		0.824	8	0.143	C	0.866	9	

Table 6. Result of analysis of the small cities

City	IO-I							IO-II							IO-III						
	CCR				BCC			CCR				BCC			CCR				BCC		
	Score	Rank	L-Eff	Class	Score	Rank	RTS	Score	Rank	L-Eff	Class	Score	Rank	RTS	Score	Rank	L-Eff	Class	Score	Rank	RTS
Otaru	1.000	1	0.067	A	1.000	1	CRTS	1.000	1	0.095	A	1.000	1	CRTS	0.980	4	0.167	C	1.000	1	ICRT
Tobetsu	1.000	1	0.000	B	1.000	1	CRTS	0.998	6	0.000	D	1.000	1	ICRT	1.000	1	0.000	B	1.000	1	CRTS
Ebetsu	1.000	1	0.134	A	1.000	1	CRTS	1.000	1	0.083	A	1.000	1	CRTS	0.651	7	0.204	C	0.695	8	
Kitahiroshima	1.000	1	0.141	A	1.000	1	CRTS	1.000	1	0.089	A	1.000	1	CRTS	1.000	1	0.354	A	1.000	1	CRTS
Eniwa	0.971	7	0.104	C	0.971	8		0.954	7	0.036	C	0.956	8		0.753	6	0.148	C	0.771	7	
Chitose	0.918	8	0.055	C	0.922	9		0.924	8	0.015	C	0.927	9		0.572	8	0.035	C	0.616	9	
Asahikawa	0.863	9	0.000	D	1.000	1	DRTS	0.915	9	0.000	D	1.000	1	DRTS	0.458	9	0.000	D	1.000	1	DRTS
Hakodate	1.000	1	0.013	A	1.000	1	CRTS	1.000	1	0.039	A	1.000	1	CRTS	1.000	1	0.544	A	1.000	1	CRTS
Kushiro	1.000	1	0.000	B	1.000	1	CRTS	1.000	1	0.000	B	1.000	1	CRTS	0.790	5	0.397	C	0.798	6	

Using different models and different input-output the evaluation results are different. However, some consistent results can be drawn from the analysis. Comparing among the small-size cities in Hokkaido (Table 6), the results from all models identify Class-A for Kitahiroshima and Hakodata; Class-C: for Eniwa and Chitose; and Class-D for Asahikawa. Almost in all efficient cities, the transportation infrastructure systems are operated under constant returns to scale, except Asahikawa (evaluated by BCC), which operates under decreasing returns to scale (i.e., the size transportation system is too large so that the rate of increasing in output is smaller than the rate of increasing in input.) The result of Tobetsu is increasing returns to scale when IO-II data is used, while the result of Otaru is increasing returns to scale when IO-III data is used.

In the pooled evaluation (Table 5), when the small cities are evaluated together with the large cities, as the high efficient cities are included in the analysis, the evaluation rates of many cities reduce and some change from efficient to inefficient. The agreeable results from all models and input-output data used indicate that:

- For the small cities, all models identify Class-A for Kitahiroshima, and Hakodate; Class-C for Otaru, Eniwa, and Chitose; and Class-D for Asahikawa. Transportation infrastructure systems of Kitahiroshima and Hakodate, the efficient cities, operated under constant returns to scale.
- For the large cities, all models identify Class-A for Kawasaki (operated under constant returns to scale); Class-C for Sapporo and Chiba; and Class-D for Hiroshima.
- Overall, the cities with very low efficiency rate, i.e., CCR-Efficiency, and BCC-Efficiency below 0.70, are Asahikawa, Hiroshima, and Kitakyushu.

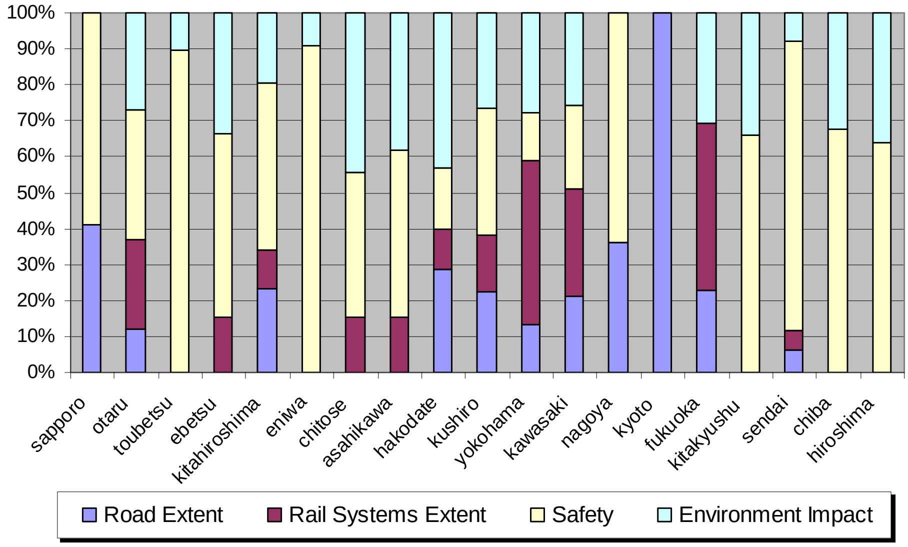

Figure 2. Contributing proportion of each input factor (pooled evaluation)

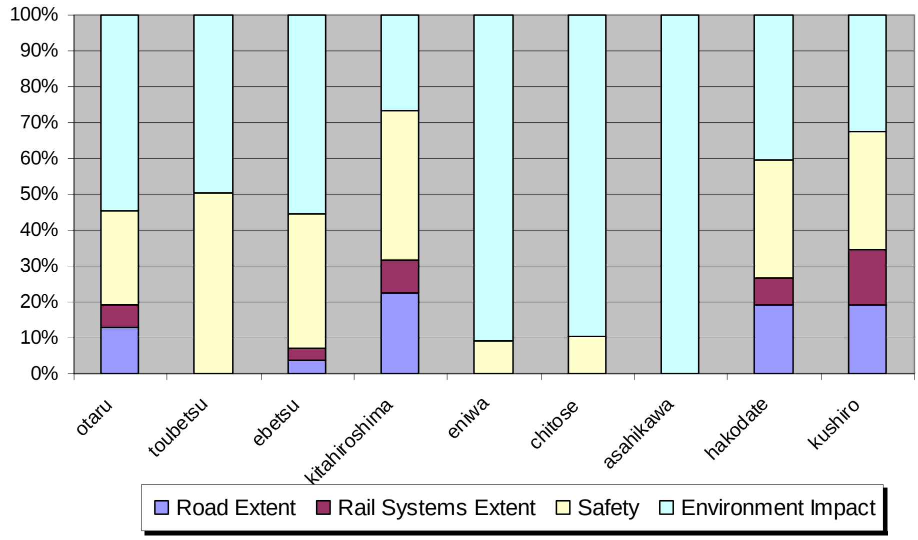

Figure 3. Contributing proportion of each input factor (separate evaluation of small cities)

Figure 2 and Figure 3, respectively, show the contributing proportion (the results are taken from CCR model with IO-II data) of each input factor for pooled evaluation and separate evaluation only small cities. These values are the product of weight for each factor and the value of that factor. Determining the pooled evaluation, input factors contributing in each city are as follows:

- Safety and environmental impact: Tobetsu, Eniwa, Kitakyushu, Chiba, and Hiroshima
- All factors: Otaru, Kitahiroshima, Hakodate, Kushiro, Yokohama, Kawasaki, and Sendai
- Road extent, rail systems extent, and environmental impact: Fukuoka
- Rail systems extent, safety, and environmental impact: Ebetsu, Chitose, and Asahikawa
- Road extent and Safety: Sapporo, and Nagoya
- Road extent: Kyoto

The factor, which is the weak point for each city, is not used in the combined input for DEA. Some interpretation can be drawn from the results, such as all cities are strong in safety except Kyoto and Fukuoka; all cities are strong in environmental impact except Sapporo, Nagoya, and Kyoto; most of the small cities in Central Hokkaido are weak in road network extent.
In the separate evaluation of the small cities, most of them put high priority in environmental impact. The condition changes when all cities are compared in the pooled evaluation. Larger weights are assigned to safety.

However, the interpretation of the Efficient City may not be accurate, because the solutions for the efficient DMUs are not unique. Moreover the strength of factor is the relative strength compared among all factors in each city, therefore its absolute value cannot be directly used for comparing across cities.

4.2 Improvement measures

To approach efficiency, one can do by reducing the input to produce the same amount of out put, or making more output with the same amount of input, or reducing input to produce more output. The ways to improve efficiency can be received from the projection of each DMU's inefficient position in the manner of reducing input to the efficiency frontier by using input-oriented CCR and vice versa. Table 7 presents the projection sizes of each inefficient DMU (evaluated using CCR with IO-II data) to the efficiency envelopment.

Minus sign means that the factor is to be reduced to approach efficiency. However, reducing road network and rail systems does not make sense for the real practice. Instead, other improvements should be done, such as improvement in service of buses, trains, subways, etc. to increase to number of passengers and reduce travel time; and improvement in level of service or road such as reducing congestion by adopting some traffic management measures. Improvement in safety can be achieved through introducing some safety measures or improving roadway geometry at dangerous points in order to reduce the number of people killed and injured in traffic accident. Improvement in environmental impact is to reduce the amount of pollution emitted from transportation activities. It might be achieved by encouraging people to use more public transports instead of personal cars.

Table 7. Projection sizes for approaching efficiency (CCR with input-output IO-II)

city	Road Extent	Rail Systems Extent	Safety	Environmental Impact
Sapporo	-375.77	-7.71	-861.35	-602.31
	-7.25%	-8.29%	-7.25%	-26.73%
Otaru	-94.58	-1.18	-128.55	-32.81
	-14.78%	-14.78%	-14.78%	-14.78%
Tobetsu	-448.18	-4.89	-7.87	-2.57
	-79.32%	-81.56%	-6.05%	-6.05%
Ebetsu	-315.08	-0.32	-36.08	-11.15
	-39.07%	-6.47%	-6.47%	-6.47%
Eniwa	-316.26	-0.84	-55.76	-16.38
	-55.70%	-21.04%	-15.71%	-15.71%
Chitose	-434.48	-1.00	-117.11	-30.53
	-52.89%	-20.05%	-20.05%	-20.05%
Asahikawa	-1294.05	-5.33	-726.79	-142.41
	-55.93%	-31.33%	-31.33%	-31.33%
Chiba	-1224.46	-13.49	-1466.80	-164.04
	-43.38%	-28.69%	-23.26%	-23.26%
Nagoya	-176.82	-9.06	-500.17	-404.65
	-2.88%	-7.02%	-2.88%	-16.63%
Kyoto	-49.61	-45.88	-3193.07	-266.18
	-1.56%	-39.90%	-23.74%	-20.12%
Hiroshima	-1523.64	-86.20	-2943.37	-385.38
	-40.50%	-66.82%	-33.53%	-33.53%
Kitakyushu	-2099.59	-24.81	-3321.20	-398.33
	-52.51%	-39.38%	-38.17%	-38.17%
Fukuoka	-645.57	-9.90	-5070.70	-234.02
	-17.37%	-17.37%	-37.66%	-17.37%

5. CONCLUSIONS

In this study, data envelopment analysis is used to evaluate the efficiency of transportation infrastructure systems in nineteen cities, including the cities in Hokkaido and some large cities of Japan. The decision-making units to be considered are the combination of transportation facilities available in each city, not an individual unit as the other studies. For the sake of comparison purpose, three types of efficiency indices from CCR model, inverse DEA model and BCC model are calculated using three patterns of input-output data. Deviation results between the models and between the types of data used can be observed. However, some results are consistent among all model and data type indicating the robustness of those results. Overall, the efficient cities in term of transportation infrastructure systems found in this study are Kawasaki, Kitahiroshima, and Hakodate. And Asahikawa, Hiroshima, and Kitakyushu are the most inefficient cities. Together with the efficiency scores the ranking and returns to scale are also determined.

The study provides a benchmark for cities to improve their infrastructure systems management. Inefficient cities may look at the efficient cities, which have similar characteristics, then follow them or find the new way to approach the same efficiency level. The study also identifies the weak point of each city, and provides the way to improve efficiency. However, the instability of the results points to the need to improve the model by imposing some constraints adding supplementary algorithm or adjusting the input/output combinations, which will be the topic for further studies.

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REFERENCES

Banker, R.D., Charnes, A., and Cooper, W.W. (1984). Some Models for Estimating Technical and Scale Inefficiencies in Data Envelopment Analysis, **Management Science 30/9**, 1078-1092.

Charnes, A.W., Cooper, W.W., Rhodes, E. (1978) Measuring Efficiency of Decision Making Units, **European Journal of Operational Research 2(6)**, 429-444.

Cook, W.D., and Green, R.H. (2003) Selecting Sites for New Facilities Using Data Envelopment Analysis, **Journal of Productivity Analysis, 19**, 77-91.

Fernandes, E. and Pacheco, R.R. (2002) Efficient Use of Airport Capacity, **Transportation Research Part A 36**, 225-238.

Karlaftis, M.G. (2003) Investigating Transit Production and Performance: A Programming Approach, **Transportation Research Part A 37**, 225-240.

Liu, Z., Kishi, K., and Satoh, K., (2001) Efficiency of Urban Transportation with Regard to Environmental Improvement by Electric Vehicle, **the First Circular of China-Japan Electric Vehicle Joint Conference**, Beijing, P.R. China.

Seiford, L.M. (1996) Data Envelopment Analysis: The Evolution of the State of the Art (1978-1995), **The Journal of Productivity Analysis 7**, 99-137.

Seiford, L.M., and Thrall, R.M. (1990) Recent Developments in DEA: The Mathematical Programming Approach to Frontier Analysis, **Journal of Econometrics 46**, 7-38.

Takamura Y., Tone, K. (2003) A Comparative Site Evaluation Study for Relocating Japanese Government Agencies Out of Tokyo, **Socio-Economic Planning Sciences 37**, 85-102.

Yamada, Y., Sugiyama, M., and Matsui, T. (1992) Analysis of Uniqueness on DMU Management by DEA and Inverse DEA, **The 1992 Fall National Conference of ORSJ Abstracts** [in Japanese]

West Japan Railway Company Website (2004) http://www.westjr.co.jp

Zhu, J. (2003) Imprecise Data Envelopment Analysis (IDEA): A Review and Improvement with An Application, **European Journal of Operational Research 144**, 513-529.

Central Hokkaido Area Transportation Systems Investigation Committee (1996) **City Transportation Systems Survey for Year 1995: The 3rd Person-trip Survey of City Areas in Central Hokkaido**. [in Japanese]

The Large Cities Statistics Survey Committee (1997) **The Comparison Book of Annual Statistics of Japan's Large Cities : Year 1995**. [in Japanese]

Urban Transportation Survey Office, Ministry of Construction (1995) **The Person-trip Survey of City Areas : Year 1995**. [in Japanese]