# Causes of inefficiency in Japanese railways : Application of DEA for managers and policymakers

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# Causes of inefficiency in Japanese railways

*Application of DEA for managers and policymakers*

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**Abstract**

Although railway services have been suffering financially due to modal shifts and aging populations, they have been and will be an essential component of the basic social infrastructure. Since railway firms generate positive externalities and are required to operate in predetermined licensed areas, governmental intervention/support may be justified in some cases. Indeed, there are many types of subsidies offered for railway operation in Japan; while some of these subsidies are meant for covering huge investments, others are used as compensation for regional disparities. However, thus far, there has been no attempt made to analyze the reasons for the underperformance of the railway services; in other words, it is unclear whether this underperformance can be attributed to exogenous and uncontrollable causes or whether it can be understood to be the result of endogenous causes and hence capable of being handled by managers. Therefore, the optimal degree of intervention is not satisfactorily known. In this article, we propose a method based on data envelopment analysis (DEA) to analyze the causes of inefficiency in Japanese railway operations as well as to calculate the optimal subsidy that compensates for the practical lack of discretion for location change. This method was applied to 53 Japanese railway operators; as a result, we derived several characteristics in relation to the inefficiency of Japanese railway operations and found an optimal subsidy for them.

*Keywords:* Data envelopment analysis, Japanese railways, Efficiency, Optimal subsidy

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## 1. INTRODUCTION

Currently, there are 206 firms in Japan that offer railway services. In 2002, these operators used 27,517 kilometers of railway tracks and carried 21.56 billion passengers. Since these firms provide basic transportation for local residents, they have for long been considered as an element of social infrastructure in which both national and municipal governments should be deeply involved. It is true that Japanese railways have recently been losing their relative importance due to changing conditions,[1] especially in relation to freight services where they currently handle only 4% of the country's total freight tonnage; however, they are still expected to play a significant role in passenger services for some time to come. In reality, Japanese railways have continued to carry 27% of all passengers, including 76.1% of mass-transit passengers.[2] In downtown Tokyo or other central business districts where traffic congestion is commonly observed, the railways remain a notably reliable form of transport.[3] Moreover, regarding freight services, the Ministry of Land, Infrastructure and Transport (MLIT) plans to expand the role played by railway services in future freight transport; this is partly because of the railways' positive environmental performance (e.g., reduced $CO_2$ and NOx emissions compared to motor traffic). Thus, it appears that Japanese railways will continue to satisfy the transportation demand and also possibly remain important both for local residents and for the environment.

Even if railway firms are socially desirable, they cannot survive unless they earn consistent operating profits. Since they generate positive externalities and are required to continue operation in predetermined locations through licensing regulation, intervention/support from governments may be justified in some cases. In fact, despite the huge national deficit, in cooperation with Japan Railway Construction, Transportation and Technology Agency

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[1] Exogenous factors such as modal shifts have caused many local Japanese railway firms to suffer significant financial losses. The Local Railway Business Study Group (LRBSG) [1] has cast some doubt on the viability of railway providers in the near future, identifying at least four factors as having a negative impact (modal shifts; acceleration of demographic aging; deflation; and financial deficits of national and municipal governments).

[2] This is based on Asahi Shimbun Publishing Co. [2] and the information provided on the MLIT website (http://toukei.mlit.go.jp/16/handbook/001youran.1-1hyou.pdf).

[3] Various traffic control initiatives, such as off-peak commuting, "no car" days, and working from home, have for long been implemented in Japan; however, the situation has not improved significantly. Mitomo and Jitsuzumi [3] estimate the number of Japanese "teleworkers" and summarize the impact of this activity.

(JRTT),[4] the MLIT spent 224.1 billion yen on railway support in 2004. Table 1 shows examples of railway subsidy schemes. In addition, many municipal governments have extended substantial support to local railway firms in order to keep them from bankruptcy. Some of this support is offered directly in order to ensure that operating deficits are met; other supports, on the other hand, are indirect and offered with the intention of helping firms attract more customers (e.g., via provision of station-front parking lots or short-haul commuter bus services linking neighboring communities).

However, to date, the optimal degree of intervention is not satisfactorily known. We believe that until the degree of influence of the external/uncontrollable causes on the railway's operation is determined, the optimal amount of subsidy will remain unclear. Any support provided to compensate for the financial hardships derived from endogenous or managerially controllable factors will convey a misleading message to railway managers. This paper aims to analyze variations in the causes of inefficiency among Japanese railway firms and to propose a method to calculate the optimal subsidy size for individual railway firms. It is believed that the analysis of variations in the causes of inefficiency and the new method of calculation will be beneficial for managers and policymakers, respectively. At this point, it is important to mention that our proposed subsidy is designed to compensate for the financial burden caused, not by first-best pricing under the diminishing average cost structure, but by regional disparities that may require railway operators in rural areas to bear additional costs.[5] Once a community decides to maintain railways as a key infrastructure for its economic and social activities, offering financial support to a rural firm in order to compensate for the unfavorable operating condition of the community appears to be a sensible decision from the economic perspective.

The remainder of this paper is organized as follows. Section 2 explains our analytical framework. Section 3 details the data used in the study, and Section 4 provides a brief explanation of the DEA method. Section 5 includes our empirical findings, and Section 6 presents the conclusion.

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[4] JRTT is an independent agency that was founded in 2003 by integrating Japan Railway Construction Public Corporation and Corporation for Advanced Transport and Technology; it offers support for new line construction and R&D.

[5] In order to calculate the optimal subsidy as compensation for the decreasing average cost structure, we need to estimate the cost functions of railway operation to determine the efficient amount of expenditures that is not covered by marginal cost pricing. Such estimations have already been made by several researchers, including Mizutani [4]. Thus, if there exists a diminishing average cost structure and if operators employ marginal cost pricing, our optimal subsidy will not be sufficient to cover the total financial loss.

Table 1: Subsidies and assistance offered to Japanese railways

| Name of subsidy | Application/ Type | Enterprise who gets subsidy | Amount of subsidy/Incidence |
|---|---|---|---|
| Subway construction subsidy | Construction of subway/ Capital subsidy (but essentially operating subsidy) | Eidan and public or semi-public subways (local government) <urban area> | 70% of construction cost/ National & local government 35% each |
| New town line subsidy | Construction of new town commuter line/ Capital subsidy (but essentially operating subsidy) | Local government and semi-public sector <urban area> | 36% of construction cost/ National & local government 18% each |
| Interest payment assistance | New lines or expanded lines/ Capital subsidy | Private railways in large metropolitan areas (but lines must be approved by government) | Repayment over 5% interest rate/ National & local government equally/ The year after construction |
| Arterial rail line subsidy | Conversion from freight service to passenger service, lowering truck, and speeding up etc./ Capital subsidy | Semi-public contractor <urban area> | Up to 40% of construction cost/ National & local government 20% each |
| Station vicinities development subsidy | Improvement of railway station facilities/ Capital subsidy | Semi-public contractor <urban area> | A part of cost/ Up to 25% of cost from national government. At least equivalent subsidy from local government. |
| Deficit subsidy (until 1997) | Timeworn local line and necessary to operate for community/ Operating subsidy | Small to medium-sized local railways (mainly rural areas) | Annual operating deficit/ National & local government equally |
| Modernization subsidy | Old-fashioned railways/ Capital (equipment) subsidy | Small to medium-sized local railways | 20% of equipment improvement cost/ National & local government equally or 10% of cost by only national government |
| Grade crossing subsidy | Improvement of crossing facilities/ Capital (facility) subsidy | Small to medium-sized local railways | 83.3% of improvement cost (66.7% for a company which yields profit)/ National 50% (33.3%) & local government 33.3% (33.3%) |
| Subsidy for privatized lines | Privatized line from JNR etc/ Operating subsidy | Small to medium-sized local railways (mainly rural areas) | 40% of ordinary deficit/ National government |
| Equipment subsidy for local new line (until 2001) | Equipment (car etc)/ Capital (equipment) subsidy | Small to medium-sized local railways | A part of equipment cost (10 million yen per route-km limit)/ National government |
| Disaster restoration subsidy | Post-disaster restoration/ Capital subsidy | Railways | 50% of restoration cost/ National & local government 25% each |
| Public transportation subsidy: LRT | Light Rail Transit system/ Capital subsidy | Railways | 50% of equipment cost/ National & local government equally |
| Public transportation subsidy: IC card | LRT car, LRT system, IC card system/ Capital subsidy | IC card consortium | A part of system install cost/ National government pays 33.3% or the equivalent amount of local government, whichever is smaller. |
| Barrier-free facility subsidy | Installation of barrier-free facilities/ Capital subsidy | Railway (except Eidan & other public subway) | Up to 66.6% of equipment cost/ National &local government equally (National government less than equal to local government) |

Source: Adapted from Mizutani [5, pp.31-32, Table 2.6.1], by using the data from ITPS [6, 7] and the MLIT website.

## 2. ANALYTICAL FRAMEWORK

In order to refrain from offering excessive support (and thus hindering private sector incentives) or very little support (and thus jeopardizing the long-term survival of the railways), we need to analyze the current operation to determine the internal and external sources of operational inefficiencies. In order to be optimal, we need to ensure a subsidy level that is just high enough to compensate for the external causes, which include the community's request to continue railway operations in the designated area or the practical lack of discretion for location change to seek more profitable operations. In this study, we propose a DEA approach in order to differentiate internal or intrinsic inefficiency factors from external or environmental-based ones, utilizing the analytical framework originally proposed by Nakamura and Jitsuzumi [8].

Before constructing the analytical model, we need to define an appropriate "outcome" for railway operations.

Hensher et al. [9] identified the three key factors — productivity, profitability, and rate of return on assets (ROA)—that indicate the success of a business. According to Preston [10], since Japanese railway firms are generally involved in both transport and real-estate development, with their profits coming mainly from property development and related commercial development, the sole reliance on profitability figures can be misleading. Therefore, in this analysis, the authors mainly focus on productivity or operational efficiency, not on profitability or ROA.

Moreover, in order to explicitly reflect the social importance of the railways, we include their impact on surrounding communities as an "externality" outcome. This approach is employed in response to that adopted by Nakajima and Fukui [11], who measured the total factor productivity for major Japanese railway firms and pointed out that productivity should be measured by taking into consideration both qualitative aspects and externality issues.

In this article, we employ the following production process of the railway business (Figure 1). Here, it is assumed that railway businesses use fixed asset, staff, and related operating expenditures as inputs, and turn them into two outputs, which are passenger service and externalities on surrounding communities. In addition, the whole process is influenced by environmental or uncontrollable factors. In this article, we employed transportation density as a primary uncontrollable factor; which will be explained later in Section 4.

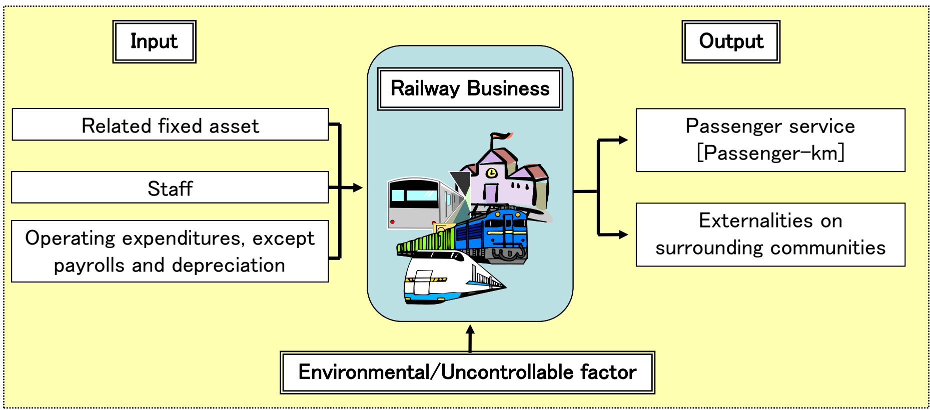



Figure 1: Projected production process of the railway business

## 3. DATA

As research samples for our study, we observed railway enterprises located in the Tokyo metropolitan area (large city), Kyushu (mostly countryside), and Kinki (includes large cities as well as countryside regions). Financial and operational data for 57 firms from 1998 to 2003 were collected from the Annual Statistics of Railway [12], and corresponding geographic and demographic data were gathered from Minryoku CD-ROM [2]. The geographic and demographic data, as well as the passenger transport share of mass transit, of each area are summarized in Table 2. The Tokyo metropolitan area is the most populated region in Japan and includes 7 prefectures (Chiba, Gunma, Ibaraki, Kanagawa, Saitama, Tochigi, and Yamanashi), in addition to Tokyo itself. From the viewpoint of the transportation demand, the Tokyo metropolitan area is the largest region in Japan and most of its transportation demand is satisfied by railway firms, possibly due to the rich availability of public transportation facilities and traffic congestion in city centers. Kinki is the second most populous region and consists of the following 7 prefectures: Hyogo, Kyoto, Mie, Nara, Osaka, Shiga, and Wakayama. The profiles of Kinki's transportation needs are similar to those of transportation needs in the Tokyo metropolitan area. Kyushu is located in the southwest part of Japan and consists of the following 7 prefectures: Fukuoka, Kagoshima, Kumamoto, Miyazaki, Nagasaki, Oita, and Saga. The transportation demand in this region is not as high as that in the Tokyo metropolitan area or Kinki, and less than half of Kyushu's transportation demand is met by the railway sector.

Table 2: Tokyo metropolitan, Kinki, and Kyushu areas

| As of year 2000 | Tokyo Metro. Area | Kinki Area | Kyushu Area | Whole Japan |
|---|---|---|---|---|
| Area (km$^2$) | 36,887 | 33,110 | 42,165 | 377,873 |
| Habitable area | 19,077 (51.7%) | 10,486 (31.7%) | 15,287 (36.3%) | 126,325 (33.4%) |
| Area of DID | 3,956 (10.7%) | 2,212 (6.7%) | 1,225 (2.9%) | 12,457 (3.3%) |
| Population | 41,321,883 | 22,712,924 | 13,445,561 | 126,925,843 |
| Daytime population | 41,250,682 (99.8%) | 22,636,324 (99.7%) | 13,424,955 (99.8%) | |
| Population in DID | 32,396,140 (78.4%) | 17,352,468 (76.4%) | 6,947,789 (51.7%) | 82,809,682 (65.2%) |
| Area GDP (billion yen) | 185,541 | 90,708 | 44,566 | 509,702 |
| Area GDP p.c. (thousand yen) | 4,490 | 3,994 | 3,315 | 4,016 |
| Taxable income (billion yen) | 71,631 | 33,556 | 15,582 | 188,149 |
| Taxable income p.c. (thousand yen) | 1,733 | 1,477 | 1,159 | 1,482 |
| Length of road (km) | 255,138 | 126,744 | 149,997 | 1,159,723 |
| Share of paved road | 73.6% | 83.0% | 86.2% | 76.4% |
| Annual trips of public transportation system (thousands) | 15,798,418 | 6,220,543 | 1,402,578 | 28,181,542 |
| Railroad | 13,337,375 (84.4%) | 5,014,242 (80.6%) | 613,791 (43.8%) | 21,453,359 (76.1%) |
| Bus | 2,433,361 (15.4%) | 1,194,407 (19.2%) | 770,700 (54.9%) | 6,635,255 (23.5%) |
| Air | 27,682 (0.2%) | 11,894 (0.2%) | 18,087 (1.3%) | 92,928 (0.3%) |
| Annual trips per capita | 383.0 | 274.8 | 104.5 | 222.0 |
| Railroad | 323.3 | 221.5 | 45.7 | 169.0 |
| Bus | 59.0 | 52.8 | 57.4 | 52.3 |
| Air | 0.7 | 0.5 | 1.3 | 0.7 |

Note 1: "p.c." = per capita, and "DID" = Densely-Inhabited District
Note 2: "Annual trips per capita" is "annual trips" divided by "daytime population."

Tokyo metropolitan, Kinki, and Kyushu areas have 54, 41, and 18 railway enterprises, respectively. However, these numbers include firms without data as well as firms that adopt different forms of railway services technology, such as monorails, trams, subways, cable cars, and light rail transits (LRTs).[6] While some operators carry only

[6] LRT is a form of tramcar system that generally employs electric rail cars on private rights of way or sometimes on streets.

passengers, some others offer freight services as well. Since the analytical approach adopted in this article is based on a peer comparison between samples, we may not be able to derive any meaningful information by comparing the operational efficiency of different rail technologies. Thus, we consider 53 passenger rail operators as samples for further analysis; of these, 25 are located in the Tokyo metropolitan area; 19, in Kinki; and 9, in Kyushu. The data of "fixed asset" is a year end monetary value of the fixed assets used for railway operation, and the data of "operating expenditure" does not include labor cost, tax, and depreciations. The number of the employees both in the railway operation section and in the headquarters is used as a staff input[7]. With respect to an uncontrollable factor, we propose transportation density, which is calculated as passenger kilometer divided by the length of operating lines. For externalities, we assume that the impact of railway services will be reflected in the general economic activity of the surrounding region; thus, we take into account the relative annual growth rate of per capita taxable income as a proxy for economic activity. We consider the average of the annual growth rate of the per capita taxable income index of the areas with no rail services as a baseline figure and then calculate the externality index for each railway company by comparing the annual growth rate of the service area with the baseline. In other words, when the index is more than 100, the region has more general economic activity than the average of areas with no rail services. On the other hand, an index of less than 100 may indicate a "straw" phenomenon in which railways enable the movement of economic and social activities from small communities to large cities. In order to evaluate inefficiency components in monetary terms, we need the unit cost information for each input factor: unit cost for fixed asset is obtained as depreciation cost divided by the value of fixed assets, unit cost for staff as labor cost divided by the number of staff, and unit cost for operating expenditures is set to unity.

The data for individual samples as of 2003 is presented in Table 3.

[7] The authors understand that this staff input is at most a good proxy of true labor input; however, uniform statistics on labor hours was not available for sample firms.

Table 3: Basic data of sample firms as of 2003

| Area | Control | Company Name | Output | | Input | | | Unit Cost | | Uncontrollable |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Passenger-km (,000km) | Externality | Fixed asset (million yen) | Employee | Operating expenditure (,000yen) | Fixed asset | Employee | Transportation density (,000 person) |
| Tokyo metropolitan area | private | Choshi | 2,393 | 100.8 | 563,177 | 23 | 39,615 | 0.0181 | 4,703.6 | 373.9 |
| | | Enoshima | 49,261 | 99.1 | 5,071,294 | 146 | 473,145 | 0.0699 | 7,783.0 | 4,926.1 |
| | | Fujikyu | 32,636 | 98.8 | 2,810,999 | 72 | 439,525 | 0.0542 | 7,262.7 | 1,226.9 |
| | | Ibaraki | 6,753 | 98.3 | 730,525 | 29 | 56,254 | 0.0777 | 5,057.7 | 472.2 |
| | | Jomo | 20,285 | 100.0 | 374,239 | 64 | 184,436 | 0.0476 | 5,945.6 | 798.6 |
| | | Joshin | 33,878 | 99.8 | 979,610 | 84 | 222,776 | 0.0340 | 5,552.1 | 1,005.3 |
| | | Kanto | 100,780 | 100.0 | 6,496,655 | 226 | 472,116 | 0.0725 | 6,907.7 | 1,812.6 |
| | | Kashima | 6,184 | 102.2 | 440,866 | 31 | 72,219 | 0.0488 | 6,157.7 | 227.4 |
| | | Keihin | 6,212,774 | 101.2 | 247,711,710 | 1,756 | 21,742,655 | 0.0647 | 11,520.3 | 71,411.2 |
| | | Keio | 7,154,930 | 101.3 | 191,518,322 | 2,016 | 20,926,760 | 0.0686 | 12,363.5 | 84,473.8 |
| | | Keisei | 3,461,141 | 101.5 | 194,404,407 | 1,918 | 12,819,606 | 0.0466 | 10,426.1 | 33,800.2 |
| | | Kominato | 22,557 | 100.6 | 653,819 | 81 | 104,832 | 0.0491 | 5,680.0 | 576.9 |
| | | Odakyu | 10,499,579 | 101.0 | 452,892,668 | 3,320 | 22,994,557 | 0.0518 | 11,026.1 | 87,133.4 |
| | | Sagami | 2,620,202 | 100.2 | 121,232,047 | 1,101 | 6,201,876 | 0.0602 | 10,932.4 | 72,986.1 |
| | | Seibu | 8,724,909 | 101.6 | 352,909,676 | 3,224 | 23,264,198 | 0.0635 | 10,272.7 | 49,404.9 |
| | | Shin-Keisei | 724,155 | 100.2 | 17,189,713 | 482 | 2,861,985 | 0.0850 | 10,352.1 | 27,326.6 |
| | | Soubu-Nagareyama | 19,995 | 100.0 | 701,601 | 72 | 125,918 | 0.0360 | 5,670.8 | 3,507.9 |
| | | Tokyu | 9,476,929 | 101.3 | 434,573,395 | 2,671 | 59,153,395 | 0.0582 | 12,072.5 | 94,674.6 |
| | semi-public | Hokusou | 422,082 | 101.6 | 102,262,688 | 280 | 3,463,266 | 0.0223 | 7,517.7 | 13,067.6 |
| | | Isumi | 6,269 | 99.7 | 71,054 | 31 | 88,163 | 0.1366 | 5,234.1 | 233.9 |
| | | Moka | 20,590 | 100.6 | 53,833 | 53 | 191,682 | 0.1431 | 4,032.8 | 491.4 |
| | | Tokyo rinkai | 245,898 | 101.8 | 266,544,418 | 237 | 2,365,362 | 0.0288 | 6,922.6 | 20,155.6 |
| | | Toyo | 406,168 | 100.3 | 278,618,953 | 258 | 1,834,939 | 0.0204 | 6,878.3 | 25,072.1 |
| | | Watarase | 11,257 | 99.5 | 59,049 | 56 | 168,789 | 0.0889 | 4,604.8 | 255.3 |
| | | Yagan | 10,779 | 95.7 | 256,534 | 47 | 209,313 | 0.0673 | 5,968.0 | 351.1 |
| Kinki area | private | Eizan | 28,876 | 100.7 | 3,555,039 | 85 | 262,119 | 0.0492 | 6,780.0 | 2,005.3 |
| | | Hankyu | 8,916,762 | 100.2 | 410,131,740 | 1,855 | 41,821,334 | 0.0313 | 12,887.6 | 60,865.3 |
| | | Hanshin | 1,741,176 | 100.2 | 79,652,652 | 1,155 | 7,326,478 | 0.0590 | 8,486.9 | 38,607.0 |
| | | Hokushin | 68,160 | 100.0 | 15,869,868 | 54 | 1,098,586 | 0.0473 | 2,712.4 | 9,088.0 |
| | | Keihan | 4,365,263 | 99.9 | 214,124,867 | 2,381 | 11,327,368 | 0.0393 | 10,213.0 | 49,549.0 |
| | | Kintetsu | 12,281,160 | 100.1 | 741,718,013 | 5,669 | 57,159,025 | 0.0284 | 9,283.4 | 21,406.9 |
| | | Kisyu | 231 | 101.0 | 40,886 | 5 | 9,563 | 0.0700 | 3,342.2 | 85.6 |
| | | Kita-Osaka | 258,182 | 100.4 | 13,885,963 | 151 | 1,467,193 | 0.0723 | 11,628.0 | 43,759.7 |
| | | Kobe | 524,032 | 100.0 | 80,090,819 | 536 | 2,191,204 | 0.0373 | 6,828.4 | 7,529.2 |
| | | Mizuma | 8,211 | 99.3 | 488,783 | 29 | 81,882 | 0.0461 | 4,782.5 | 1,492.9 |
| | | Nankai | 3,930,025 | 99.9 | 366,213,687 | 2,659 | 16,744,863 | 0.0265 | 7,884.4 | 23,240.8 |
| | | Nose | 170,713 | 99.0 | 27,391,095 | 78 | 1,160,649 | 0.0259 | 7,999.9 | 11,085.3 |
| | | Omi | 30,929 | 99.3 | 3,866,125 | 86 | 359,503 | 0.0495 | 5,302.0 | 519.8 |
| | | San-yo | 789,792 | 99.9 | 31,286,768 | 725 | 3,966,214 | 0.0676 | 8,615.2 | 11,218.6 |
| | semi-public | Hojo | 3,210 | 99.8 | 27,988 | 12 | 30,865 | 0.0771 | 4,969.5 | 236.0 |
| | | Kita-Kinki-Tango | 44,047 | 100.1 | 2,398,889 | 156 | 996,754 | 0.0821 | 5,070.0 | 386.4 |
| | | Miki | 820 | 99.8 | 193,938 | 12 | 21,198 | 0.0878 | 4,911.8 | 124.2 |
| | | Osaka-Toshi | 468,576 | 99.4 | 20,695,922 | 311 | 2,323,887 | 0.0838 | 8,898.7 | 32,767.6 |
| | | Shigaraki | 6,778 | 99.7 | 88,887 | 18 | 55,286 | 0.0942 | 5,681.1 | 461.1 |
| Kyushu area | private | Chikuhou | 42,408 | 98.9 | 1,722,980 | 79 | 495,274 | 0.0672 | 7,283.9 | 2,650.5 |
| | | Kumamoto | 7,399 | 99.8 | 324,485 | 26 | 85,829 | 0.0847 | 4,541.8 | 564.8 |
| | | Nishi-nihon | 1,745,032 | 100.3 | 66,005,323 | 966 | 6,232,303 | 0.0675 | 8,257.6 | 15,056.4 |
| | | Shimabara | 34,476 | 99.8 | 5,074,081 | 136 | 200,021 | 0.0218 | 4,064.4 | 439.2 |
| | semi-public | Amagi | 8,735 | 100.2 | 174,372 | 28 | 72,432 | 0.1258 | 4,792.5 | 637.6 |
| | | Kumagawa | 13,830 | 99.3 | 87,627 | 31 | 84,494 | 0.0850 | 3,654.6 | 557.7 |
| | | Matsuura | 35,603 | 100.2 | 322,894 | 95 | 408,194 | 0.1265 | 3,932.8 | 379.6 |
| | | Minami-Aso | 3,542 | 100.1 | 22,442 | 14 | 39,911 | 0.0944 | 3,914.4 | 200.1 |
| | | Takachiho | 9,833 | 98.5 | 78,211 | 35 | 112,850 | 0.0916 | 3,536.1 | 196.7 |

## 4. DEA APPROACH[8]

The basic concept of DEA is to evaluate the comparative efficiency of a decision-making unit (DMU) by calculating the ratio between output and input. In this article, each observation, i.e., each combination of railway and year, is regarded as an individual DMU. The DEA method measures efficiency by estimating an empirical production frontier, fitting pieces of hyperplanes to envelop the observed input-output data.[9] The inefficiency of a

[8] For further details, refer to Cooper et al. [13].

[9] According to Banker et al. [14], the resulting piecewise linear production frontier of a DEA is more flexible in approximating the true production frontier than the so-called flexible translog parametric functional form.

DMU (i.e., a sample firm at a specific point in time) is measured by the distance from the point representing its observed input-output combination to the corresponding reference point on the production frontier.

Mathematically, DEA can be expressed as the linear programming problems (1) and (2), with inputs ($x_1$, $x_2 \ldots x_m$), outputs ($y_1$, $y_2 \ldots y_s$), a nonnegative vector ( $\lambda = (\lambda_1, \cdots \lambda_n)^T$ ), and $\theta^*$ as the optimal solution for problem (1). Here, the superscript $T$ indicates a vector transpose. If an optimal solution satisfies $\theta^* = 1$ and is zero slack $\left(\mathbf{s}^{-*} = \mathbf{0}, \mathbf{s}^{+*} = \mathbf{0}\right)$, then the particular DMU under study (DMUo) is defined as "efficient." If DMUo is not efficient, then several efficient DMUs are designated as a "reference set" and the $\theta^*$ of DMUo is calculated based on the distance between DMUo and a "projected DMUo," which is a projection of DMUo toward the possibility frontier constructed by the reference set and has an input vector $\theta^* \mathbf{x_o} - \mathbf{s}^{-*}$ and an output vector $\mathbf{y_o} + \mathbf{s}^{+*}$.

$$\min \ \theta \quad \text{subject to} \begin{cases} \theta \mathbf{x_o} - \mathbf{X}\lambda \geq 0, \ \mathbf{Y}\lambda \geq \mathbf{y_o} \\ L \leq \mathbf{e}\lambda \leq U, \ \ \lambda \geq \mathbf{0}, \text{where } \mathbf{e} = (1, \ldots, 1) \end{cases} \tag{1}$$

$$\max_{\lambda, \mathbf{s}^-, \mathbf{s}^+} \ \omega = \mathbf{es}^- + \mathbf{es}^+ \quad \text{subject to} \begin{cases} \mathbf{s}^- = \theta^* \mathbf{x_o} - \mathbf{X}\lambda, \ \mathbf{s}^+ = \mathbf{Y}\lambda - \mathbf{y_o}, \\ \lambda \geq \mathbf{0}, \ \ \mathbf{s}^- \geq \mathbf{0}, \ \ \mathbf{s}^+ \geq \mathbf{0} \end{cases} \tag{2}$$

DEA involves two different approaches: an input-oriented approach and an output-oriented approach. The former yields the optimum input mix that is necessary for attaining a certain output level, and the latter provides the optimal output level that is to be obtained from a given input level. As Oda and Otsubo [15] note, the output level of a railway sector has the characteristic of a "derived" demand; we adopt the input-oriented model. Moreover, because previous studies such as Preston [10] state that scale economies remain important in the railway sector, we employ an input-oriented Banker-Charnes-Cooper (BCC-I) model that assumes variable returns to scale by setting $L = U = 1$ [16]. On the other hand, input-oriented Charnes-Cooper-Rhodes (CCR-I) model assumes constant-returns to scale by setting $L = 0$ and $U = \infty$ [17].

The outcome of the BCC-I model reflects the combined outcome of true managerial efficiency as well as the effects of uncontrollable constraints imposed by external conditions.[10] DEA prepares a variation in order to

[10] According to Oum et al. [18], "It is essential that any comparisons of productive efficiency among firms or over time take into account the differences in the factors beyond managerial control" (p.35). Moreover, Oum and Yu [19] stated, "The productive efficiency measured from observable data is also heavily influenced by the market and operating environments to which the railways are subjected. These include factors largely beyond managerial control such as

explicitly deal with such uncontrollable variables. By modifying the model such that the uncontrollable variables are taken into account, an input-oriented, noncontrollable variable model under a variable returns to scale assumption (NCN-IV) model is obtained. In the railway business, it is sometimes stated that transportation density is negatively correlated with business performance (e.g. LRBSG [1]). Thus, we include transportation density variable as a good proxy for environmental variables that determine the potential profitability of the market[11].

The abovementioned efficiencies focus on the technical-physical aspect of production and do not consider cost information. Since we have the unit cost data for input variables, it is possible to construct cost-based efficiency scores by following the methods suggested by Farrell [21] and Debreu [22]. Cost model, a variation of DEA, can accommodate procedures such as a linear programming problem (3), where $\mathbf{c_o}$ is a vector of the unit input cost of DMUo. Based on an optimal solution of (3), $(\mathbf{x}^*, \boldsymbol{\lambda}^*)$, the cost efficiency of DMUo is defined as $\mathbf{c_o x}^* / \mathbf{c_o x_o}$. Here, by setting $L = 0 \,\&\, U = \infty$, we can assume input-oriented constant returns to scale (COST-IC model); when $L = U = 1$, we have a COST-IV model that assumes variable returns to scale.

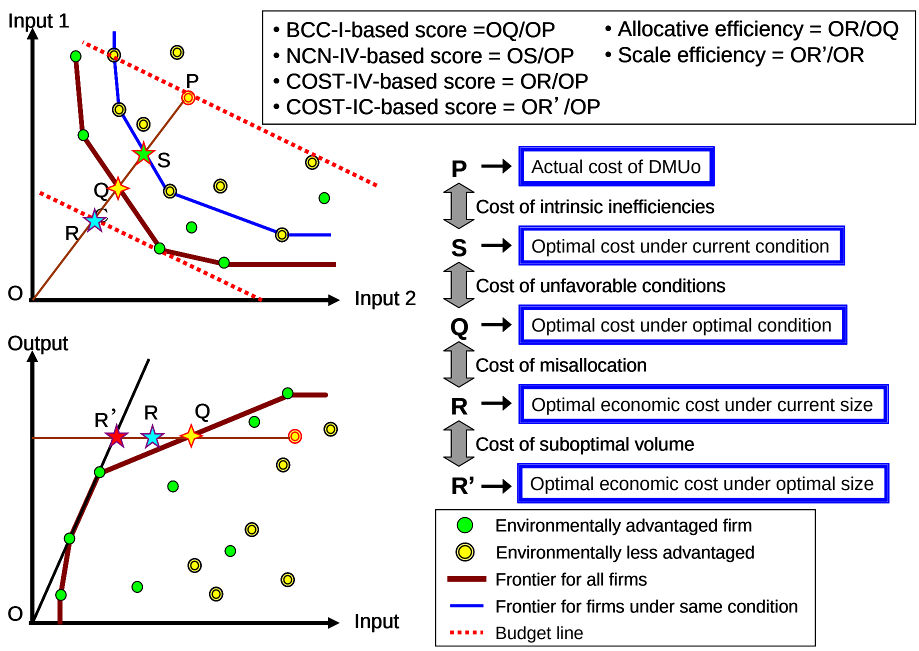
$$\min \ \mathbf{c_o x_o} \ \text{ subject to } \begin{cases} \mathbf{x_o} - \mathbf{X}\lambda \geq 0,\ \mathbf{Y}\lambda \geq \mathbf{y_o} \\ L \leq \mathbf{e}\lambda \leq U,\ \lambda \geq \mathbf{0} \ \text{where } \mathbf{e} = (1, \ldots, 1) \end{cases} \tag{3}$$

When the BCC-based projected DMUo is different from the COST-IV-based projected one, such a difference can be translated into an allocative inefficiency that represents the degree to which the DMUo fails to prepare an optimal input mix ratio. Thus, allocative efficiency scores can be obtained as COST-IV-based scores divided by BCC-I-based scores for each DMU. However, it is important to understand that if a certain DMUo has some extreme input/output values, a certain part of misallocation has already been taken care of as non-radial input slacks,

topography and the climate of the region, the extent of development of other transport modes, traffic density, average load, average distance of haul, the economic development stage of the nation, and so on" (p.121). In addition, by reviewing 211 small rail companies that came into operation from 1970 to 1984, Due [20] presented flexibility in use of labor, general shipper support, and cooperation of major carriers as factors that determine the success of these companies. However, since Due's article addresses railway firms that mainly carry freight, his findings may not be applicable to Japanese railway firms, which are more passenger-oriented.

[11] It is true that transportation density itself is an efficiency index, although it is heavily influenced by surrounding situations that are noncontrollable by individual railway operators.

when estimating the reference point in NCN-IV or BCC-I calculation. Therefore allocation efficiency score can be somewhat biased in this sense. Similarly, scale efficiency is calculated as COST-IC score divided by COST-IV score. We consider the cost-based and BCC-I-based projected DMUo as the overall optimal input mix and the technically optimal input mix, respectively.[12] In addition, NCN-IV-based projected DMUo is representative of the operationally optimal input mix, which shows the target that the DMUo can attain under the surrounding market conditions. Thus, by comparing the corresponding monetary values of each projected input mix, we can evaluate the various inefficiency margins on a comparable scale (Figure 2). For example, an optimal cost corresponding to BCC-I-based projected DMUo, Q, is obtained as $C_o^* = \mathbf{p_o}\left(\theta^* \mathbf{x_o} - \mathbf{s}^{-*}\right)$ where $\mathbf{p_o}$ is a vector of unit costs for original DMUo, P. In our framework, the cost of unfavorable or bad environments should be equal to the incentive-compatible subsidy that aims to compensate for regional disparity. Although independently developed, our proposed approach has some aspects that are similar to the approach employed by Tone and Tsutsui [23]. Apart from an apparent difference in the subject of analysis, there exists a major distinction in that our approach explicitly takes an uncontrollable factor into consideration.




Note: The arrangement of this figure is modified for simplicity. For example, projected points are not necessarily linearly-arranged.

Figure 2: DEA-based analytical framework

[12] Although some railway firms enjoy monopoly in their service area, the overall optimal input derived from cost-based model may still have slacks in the economic sense. Thus, cost-based model figures should be interpreted

## 5. RESULTS AND EVALUATIONS

Table 4 shows the average sample-year results of the DEA evaluation. The estimated monetary value of inefficiency components are presented in Table 5, and its summary is in Table 6, which indicates that, on average, when a railway firm fully rationalizes itself without changing its input mix (except for eliminating non-radial input slacks), the operating cost can become two-thirds. By compensating for unfavorable conditions, the operating cost can be reduced by 9.79%; if a firm can optimize its input mix, it will be further reduced by 9.54%; and by adjusting its size, the cost will be even further reduced by 1.38%. In addition, Table 6 clarifies that our samples have some variations in terms of geography and corporate governance. Firms in the Kyushu area are influenced more heavily by the misallocation of inputs, whereas those in Kinki suffer more through the suboptimal scale, than in the other areas. Private firms are more influenced by an unfavorable environment and the suboptimal scale of operation, whereas semi-public firms suffer more heavily from misallocation. The comparatively smaller impact from the suboptimal scale is similar to a finding of Tone and Tsutsui [23] in the study of electric power firms in Japan and the US; this may imply the appropriateness of market demarcation in utility regulations in the respective industries.

Figure 3 shows the share trend of each inefficiency component value by setting the current cost size as 100%. It shows that poorly managed firms are more influenced by intrinsic inefficiency and less influenced by failure in resource allocation, practical lack of discretion for location change, and suboptimal scale of operation. On the other hand, the Kendall's tau-b statistics of the bivariate rank correlation between the efficiency scores obtained from BCC and NCN models turns out to be 0.757, which is quite high. This implies that the impact of lack of discretion for location change is large for better managed firms, but not large enough to reverse the efficiency ranking.

The optimal amount of subsidy as compensation for regional disparity, or for the practical lack of discretion for location change, must be just equal to the monetary value of the unfavorable environment in Column 6 of Table 5. We can use these figures to judge the appropriateness of the subsidy scheme that is currently being applied. National and municipal governments continue to spend large sums of money on the railway system in Japan; it is possible to evaluate the appropriateness of such public intervention by comparing actual subsidies with our estimated optimal level. For example, Miki railway lost 64 million yen in 2004, which was fully reimbursed by the municipal government. Based on our model, the optimal subsidy as compensation for only regional disparities is estimated at 1.4 million yen, which indicates that the subsidy is extremely high for securing an efficient operation and may be giving an incorrect message to a railway manager, unless the size of the fixed cost can fill the gap.

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cautiously.

Table 4: Efficiency scores of the sample firms

| | | | Technical Efficiency | | Overall Efficiency | | Allocative | Scale |
|---|---|---|---|---|---|---|---|---|
| Area | Control | Company Name | NCN-based | BCC-based | COST-IV-based | COST-IC-based | Efficiency | Efficiency |
| Tokyo metropolitan area | private | Choshi | 0.4475 | 0.3219 | 0.2825 | 0.2669 | 0.8810 | 0.9551 |
| | | Enoshima | 0.4577 | 0.2864 | 0.2022 | 0.2019 | 0.7158 | 0.9986 |
| | | Fujikyu | 0.3009 | 0.2547 | 0.2340 | 0.2332 | 0.9186 | 0.9966 |
| | | Ibaraki | 0.5279 | 0.4238 | 0.3050 | 0.3038 | 0.7253 | 0.9958 |
| | | Jomo | 0.6002 | 0.5560 | 0.2558 | 0.2550 | 0.4603 | 0.9969 |
| | | Joshin | 0.6081 | 0.5733 | 0.2938 | 0.2934 | 0.5129 | 0.9988 |
| | | Kanto | 0.5607 | 0.5324 | 0.2870 | 0.2869 | 0.5426 | 0.9996 |
| | | Kashima | 0.3540 | 0.3384 | 0.2506 | 0.2471 | 0.7417 | 0.9868 |
| | | Keihin | 0.9086 | 0.8998 | 0.8249 | 0.8249 | 0.9176 | 1.0000 |
| | | Keio | 0.9985 | 0.9817 | 0.9729 | 0.9711 | 0.9909 | 0.9982 |
| | | Keisei | 0.6149 | 0.6106 | 0.5780 | 0.5779 | 0.9473 | 0.9999 |
| | | Kominato | 0.7963 | 0.7498 | 0.2858 | 0.2853 | 0.3824 | 0.9982 |
| | | Odakyu | 0.9993 | 0.9990 | 0.9938 | 0.9573 | 0.9948 | 0.9632 |
| | | Sagami | 1.0000 | 0.9151 | 0.7830 | 0.7830 | 0.8557 | 1.0000 |
| | | Seibu | 0.9948 | 0.8799 | 0.8381 | 0.8246 | 0.9541 | 0.9838 |
| | | Shin-Keisei | 0.9730 | 0.8263 | 0.6503 | 0.6503 | 0.7881 | 0.9999 |
| | | Soubu-Nagareyama | 0.9881 | 0.5709 | 0.2762 | 0.2757 | 0.4842 | 0.9981 |
| | | Tokyu | 0.9631 | 0.9356 | 0.7621 | 0.7414 | 0.8199 | 0.9726 |
| | semi-public | Hokusou | 0.4711 | 0.4231 | 0.2990 | 0.2989 | 0.7068 | 0.9995 |
| | | Isumi | 0.6893 | 0.6518 | 0.3380 | 0.3365 | 0.5269 | 0.9957 |
| | | Moka | 0.9881 | 0.9809 | 0.4616 | 0.4609 | 0.4712 | 0.9984 |
| | | Tokyo rinkai | 0.2478 | 0.1494 | 0.0741 | 0.0738 | 0.5388 | 0.9967 |
| | | Toyo | 0.6401 | 0.4680 | 0.2117 | 0.2117 | 0.4529 | 0.9998 |
| | | Watarase | 0.7782 | 0.6334 | 0.2824 | 0.2821 | 0.4447 | 0.9989 |
| | | Yagan | 0.4163 | 0.4137 | 0.2153 | 0.2129 | 0.5206 | 0.9888 |
| Kinki area | private | Eizan | 0.4056 | 0.2961 | 0.2122 | 0.2118 | 0.7218 | 0.9985 |
| | | Hankyu | 0.9713 | 0.9373 | 0.8844 | 0.8708 | 0.9451 | 0.9848 |
| | | Hanshin | 0.6014 | 0.5491 | 0.5406 | 0.5406 | 0.9847 | 1.0000 |
| | | Hokushin | 0.6942 | 0.3988 | 0.1748 | 0.1748 | 0.4402 | 0.9999 |
| | | Keihan | 0.8722 | 0.8589 | 0.6934 | 0.6934 | 0.8076 | 1.0000 |
| | | Kintetsu | 1.0000 | 0.9839 | 0.9568 | 0.5520 | 0.9723 | 0.5784 |
| | | Kisyu | 1.0000 | 0.9993 | 0.9859 | 0.9077 | 0.9865 | 0.9207 |
| | | Kita-Osaka | 0.9917 | 0.5353 | 0.5300 | 0.5298 | 0.9901 | 0.9996 |
| | | Kobe | 0.5322 | 0.5176 | 0.3503 | 0.3503 | 0.6767 | 0.9999 |
| | | Mizuma | 0.7430 | 0.3488 | 0.2934 | 0.2920 | 0.8413 | 0.9953 |
| | | Nankai | 0.6024 | 0.5522 | 0.4927 | 0.4927 | 0.8935 | 1.0000 |
| | | Nose | 0.6869 | 0.4955 | 0.4099 | 0.4096 | 0.8328 | 0.9993 |
| | | Omi | 0.2534 | 0.2452 | 0.2145 | 0.2142 | 0.8771 | 0.9983 |
| | | San-yo | 0.5159 | 0.4934 | 0.4346 | 0.4345 | 0.8810 | 0.9999 |
| | semi-public | Hojo | 0.9589 | 0.9437 | 0.5602 | 0.5580 | 0.5928 | 0.9963 |
| | | Kita-Kinki-Tango | 0.3076 | 0.2634 | 0.1567 | 0.1567 | 0.5957 | 0.9997 |
| | | Miki | 0.4621 | 0.4462 | 0.4302 | 0.4277 | 0.9643 | 0.9943 |
| | | Osaka-Toshi | 0.6962 | 0.5204 | 0.5164 | 0.5163 | 0.9922 | 0.9998 |
| | | Shigaraki | 0.9359 | 0.8246 | 0.4275 | 0.4251 | 0.5171 | 0.9948 |
| Kyushu area | private | Chikuhou | 0.5402 | 0.3989 | 0.2778 | 0.2774 | 0.6965 | 0.9985 |
| | | Kumamoto | 0.6380 | 0.5506 | 0.4490 | 0.3411 | 0.7839 | 0.8876 |
| | | Nishi-nihon | 0.6591 | 0.6581 | 0.6547 | 0.6547 | 0.9947 | 1.0000 |
| | | Shimabara | 0.4385 | 0.4338 | 0.2174 | 0.2172 | 0.5032 | 0.9993 |
| | semi-public | Amagi | 0.7778 | 0.6552 | 0.4278 | 0.4257 | 0.6531 | 0.9951 |
| | | Kumagawa | 0.9910 | 0.9901 | 0.5102 | 0.5097 | 0.5154 | 0.9990 |
| | | Matsuura | 0.9917 | 0.8522 | 0.3502 | 0.3496 | 0.4114 | 0.9983 |
| | | Minami-Aso | 0.9562 | 0.9461 | 0.5666 | 0.5645 | 0.5997 | 0.9963 |
| | | Takachiho | 0.9144 | 0.6904 | 0.3618 | 0.3604 | 0.5253 | 0.9963 |

## Table 5: Value of inefficiencies

| Area | Control | Company Name | Actual cost | Monetary value of inefficiency components | | | | Optimal cost |
|---|---|---|---|---|---|---|---|---|
| | | | | Intrinsic ineffi. | Bad envrnmt. | Misallocation | Subopt. Scale | |
| Tokyo metropolitan area | private | Choshi | 186,170 | 102,989 | 23,889 | 6,632 | 3,061 | 49,600 |
| | | Enoshima | 1,924,135 | 1,095,384 | 432,719 | 7,131 | 529 | 388,371 |
| | | Fujikyu | 1,193,239 | 838,188 | 56,930 | 19,650 | 920 | 277,550 |
| | | Ibaraki | 268,245 | 144,202 | 37,893 | 4,287 | 339 | 81,525 |
| | | Jomo | 677,227 | 300,184 | 44,340 | 159,791 | 539 | 172,373 |
| | | Joshin | 875,343 | 424,528 | 71,048 | 122,168 | 314 | 257,284 |
| | | Kanto | 2,729,481 | 1,815,368 | 113,333 | 17,376 | 282 | 783,121 |
| | | Kashima | 303,295 | 209,201 | 10,020 | 8,486 | 1,019 | 74,568 |
| | | Keihin | 55,122,335 | 7,734,458 | 858,390 | 1,023,814 | 1,046 | 45,504,626 |
| | | Keio | 57,085,270 | 128,668 | 907,137 | 502,604 | 100,242 | 55,446,619 |
| | | Keisei | 42,258,472 | 17,309,756 | 367,641 | 161,610 | 1,395 | 24,418,070 |
| | | Kominato | 700,010 | 430,930 | 49,669 | 18,849 | 390 | 200,171 |
| | | Odakyu | 80,939,964 | 97,903 | 18,116 | 390,437 | 2,979,032 | 77,454,476 |
| | | Sagami | 25,541,724 | 0 | 5,236,582 | 304,712 | 517 | 19,999,913 |
| | | Seibu | 78,090,130 | 544,926 | 11,299,905 | 816,704 | 1,076,779 | 64,351,817 |
| | | Shin-Keisei | 9,388,277 | 435,368 | 2,303,535 | 543,260 | 620 | 6,105,493 |
| | | Soubu-Nagareyama | 565,026 | 9,272 | 369,253 | 29,850 | 305 | 156,347 |
| | | Tokyu | 98,061,211 | 6,991,102 | 2,367,542 | 14,347,721 | 2,074,034 | 72,280,812 |
| | semi-public | Hokusou | 7,504,683 | 4,792,716 | 276,333 | 191,619 | 1,177 | 2,242,838 |
| | | Isumi | 266,989 | 95,617 | 2,534 | 78,626 | 380 | 89,832 |
| | | Moka | 463,163 | 6,978 | 2,533 | 239,669 | 354 | 213,629 |
| | | Tokyo rinkai | 5,887,355 | 5,098,233 | 280,913 | 20,164 | 1,164 | 486,881 |
| | | Toyo | 9,968,322 | 7,096,218 | 735,076 | 35,508 | 424 | 2,101,096 |
| | | Watarase | 417,136 | 115,302 | 53,350 | 130,968 | 126 | 117,390 |
| | | Yagan | 559,847 | 344,543 | -13,738 | 108,305 | 1,325 | 119,412 |
| Kinki area | private | Eizan | 1,080,565 | 657,327 | 188,477 | 6,133 | 348 | 228,280 |
| | | Hankyu | 80,784,210 | 2,312,609 | 2,733,706 | 4,231,871 | 1,103,882 | 70,402,143 |
| | | Hanshin | 23,038,867 | 9,542,318 | 992,292 | 57,458 | 331 | 12,446,468 |
| | | Hokushin | 1,694,157 | 1,161,448 | 156,538 | 81,789 | 28 | 294,354 |
| | | Keihan | 45,290,149 | 12,593,795 | 1,258,720 | 22,577 | 633 | 31,414,423 |
| | | Kintetsu | 148,845,719 | 0 | 2,742,328 | 3,327,550 | 60,651,114 | 82,124,727 |
| | | Kisyu | 32,504 | 0 | 319 | 108 | 2,917 | 29,159 |
| | | Kita-Osaka | 4,300,033 | 74,873 | 1,927,793 | 17,295 | 873 | 2,279,199 |
| | | Kobe | 9,812,599 | 6,102,416 | 247,728 | 4,973 | 398 | 3,457,083 |
| | | Mizuma | 306,550 | 87,581 | 112,515 | 16,759 | 428 | 89,267 |
| | | Nankai | 51,987,877 | 22,359,474 | 3,934,405 | 7,666 | 391 | 25,685,942 |
| | | Nose | 3,058,290 | 1,198,856 | 542,846 | 62,474 | 832 | 1,253,282 |
| | | Omi | 1,014,707 | 770,744 | 21,549 | 4,688 | 366 | 217,360 |
| | | San-yo | 14,097,149 | 7,336,887 | 525,939 | 127,330 | 349 | 6,106,643 |
| | semi-public | Hojo | 94,315 | 6,124 | 177 | 35,430 | 195 | 52,388 |
| | | Kita-Kinki-Tango | 2,039,468 | 1,508,928 | 52,673 | 158,209 | 110 | 319,548 |
| | | Miki | 92,049 | 50,158 | 1,397 | 963 | 225 | 39,305 |
| | | Osaka-Toshi | 7,552,471 | 2,339,536 | 1,291,847 | 31,623 | 662 | 3,888,802 |
| | | Shigaraki | 258,213 | 82,209 | 16,076 | 68,090 | 473 | 91,365 |
| Kyushu area | private | Chikuhou | 1,424,897 | 670,779 | 196,336 | 163,704 | 594 | 393,483 |
| | | Kumamoto | 247,655 | 90,728 | 24,213 | 23,473 | 24,872 | 84,370 |
| | | Nishi-nihon | 20,441,632 | 6,964,183 | 19,635 | 72,907 | 553 | 13,384,355 |
| | | Shimabara | 953,010 | 734,691 | 6,153 | 4,156 | 148 | 207,862 |
| | semi-public | Amagi | 228,302 | 51,608 | 31,951 | 47,141 | 481 | 97,122 |
| | | Kumagawa | 220,212 | 1,925 | 212 | 105,996 | 115 | 111,965 |
| | | Matsuura | 859,911 | 18,380 | 271,168 | 269,086 | 514 | 300,763 |
| | | Minami-Aso | 103,817 | 5,487 | 742 | 38,910 | 220 | 58,459 |
| | | Takachiho | 256,775 | 20,772 | 58,744 | 84,072 | 360 | 92,827 |

Note : All figures are in thousands and sample year average.

## Table 6: Impact of various inefficiencies on operating cost

| | Actual Cost | | Intrinsic inefficiency | | Unfavorable environment | | Misallocation | | Suboptimal Scale | | Optimal Cost |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | − | | − | | − | | − | | = | |
| Overall average | 100.00 | − | 35.46 | − | 9.79 | − | 9.54 | − | 1.38 | = | 43.83 |
| Tokyo metropolitan area | 100.00 | − | 37.75 | − | 9.70 | − | 8.70 | − | 0.41 | = | 43.44 |
| Kinki area | 100.00 | − | 36.95 | − | 9.62 | − | 5.05 | − | 2.74 | = | 45.64 |
| Kyushu area | 100.00 | − | 25.98 | − | 10.39 | − | 21.34 | − | 1.20 | = | 41.09 |
| private | 100.00 | − | 35.96 | − | 10.95 | − | 3.53 | − | 1.98 | = | 47.58 |
| semi-public | 100.00 | − | 34.41 | − | 7.32 | − | 22.27 | − | 0.11 | = | 35.89 |

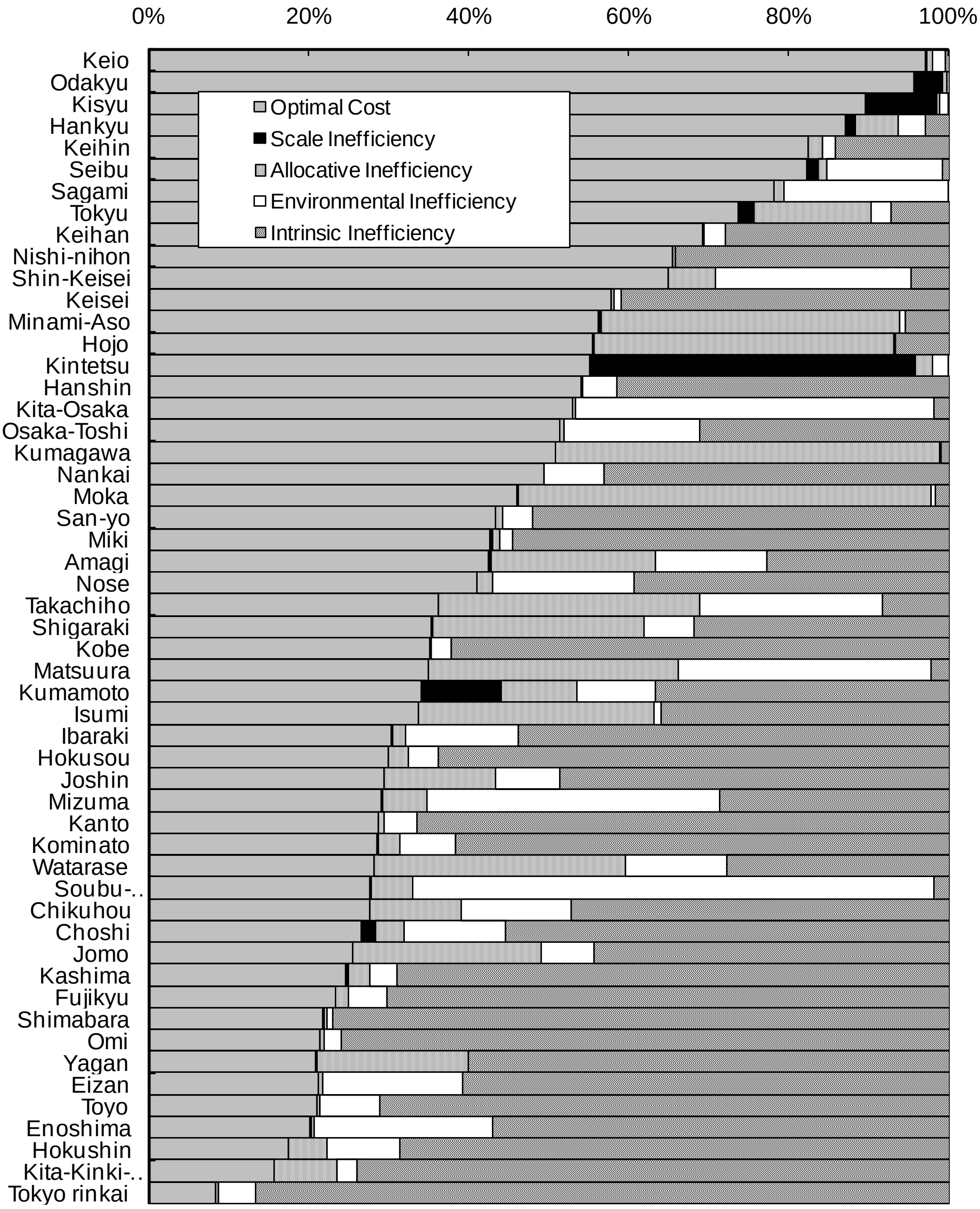


Figure 3: Causes of inefficient operations

Liu and Tone [24] proposed a different approach to single out the impact of environmental factors when measuring DMU's efficiency. Adopting an output-oriented framework, they employed a weighted slack-based measure (SBM) model[13] and measured output-slacks, which include radial and non-radial ones. They then employed stochastic frontier analysis (SFA) in order to attribute such slacks either to management incompetence,

[13] The SBM model was introduced by Tone [25] and weight SBM model, a SBM model that allocate pre-determined weights on input and output variables, was explained in Cooper et al. [26, p.105].

disadvantageous environments, or data noises; adjusted outputs by filtering out an environmental impact as well as a data noise impact; and finally adopted such adjusted outputs for DEA procedure.

In order to compare their methodology with ours, firstly, we ran an input-oriented weighted SBM model, which assumes variable returns to scale, on our DMU set and calculated input slacks ( $s_{rjt}^{-*}$ ) for input r of company j at year t. As for the weight of the model, we employed equal weight among the input variables since we could not find any better alternatives. Then, we practiced SFA estimations, employing SBM-based slack ratio to each input variable as an explained variable, in order to single out an environmental contribution from these slacks and constructed environmentally-optimized input variables. Transportation density was again used as a primary environmental factor. In order to generate variance regressors, we estimated a fixed effects linear model where "Operating Margin Ratio (OMR)" and "Depreciation divided by Operating Income (DOI)" are explained variables and transportation density (TD) as an explaining variable (Equation 4). Then, we singled out group-wise, or company-specific, fixed effects ($\alpha_j$) and error terms ( $\varepsilon_{jt}$ ); these fixed effects, FIXED1 and FIXED2, are used for variance regressors in SFA's symmetric components; whereas the error terms, RES1 and RES2, are for variance regressors in SFA's one-sided components (Equation 5). Table 8 shows the results of SFA estimation.

$$OMR_{jt} \; or \, DOI_{jt} = \alpha_j + \beta TD_{jt} + \varepsilon_{jt} \tag{4}$$

Table 7: Results of fixed effect model estimation

| Explained variable | Operating Margin Ratio | | | Depreciation/Operating Income | | |
|---|---|---|---|---|---|---|
| N | | 305 | | | 305 | |
| F[ 52, 252] | | 88.11 | *** | | 102.64 | *** |
| Log likelihood | | 397.52 | | | 630.83 | |
| Restricted(b=0) | | -52.96 | | | 158.21 | |
| Chi-sq [ 52] | | 900.96 | *** | | 945.26 | *** |
| LogAmemiya Prd. Crt. | | -5.09 | | | -6.62 | |
| Akaike Info. Criter. | | -5.10 | | | -6.63 | |
| Variable | Coefficient | Standard Error | | Coefficient | Standard Error | |
| Transportation Density | 6.84E-06 | 4.01E-06 | ** | -3.90E-06 | 1.87E-06 | *** |

Note: *** indicates p<0.01.

$$
\begin{cases}
\dfrac{s_{rjt}^{-*}}{original\ Y_{rjt}} = \beta_{r0} + \beta_{r1} TD + v_{rjt} + u_{rjt} \\
v_{rjt} \sim N\left[0, \sigma_{vrjt}^2\right] \\
u_{rjt} = \left|U_{rjt}\right| \ and\ U_{rjt} \sim N\left[0, \sigma_{urjt}^2\right] \\
\sigma_{vrjt}^2 = \sigma_v^2 \exp\left(\delta_{r0} + \delta_{r1} FIXED1 + \delta_{r2} FIXED2 + \delta_{r3} D\_AREA1 + \delta_{r4} D\_AREA2\right) \\
\sigma_{urjt}^2 = \sigma_u^2 \exp\left(\gamma_{r0} + \gamma_{r1} RES1 + \gamma_{r2} RES2 + \gamma_{r3} D\_PUBLIC\right)
\end{cases}
\tag{5}
$$

Table 8: Results of SFA estimation (variable returns to scale)

| Dependent variable | | SBM-based slack ratio of operating expenditure | | | SBM-based slack ratio of related fixed asset | | | SBM-based slack ratio of staff | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Weighting variable | | None | | | None | | | None | | |
| Number of observations | | 305 | | | 305 | | | 305 | | |
| Iterations completed | | 20 | | | 55 | | | 28 | | |
| Log likelihood function | | 34.1915 | | | -34.8366 | | | 48.9094 | | |
| Number of parameters | | 11 | | | 11 | | | 11 | | |
| Info. Criterion: AIC | | -0.1521 | | | 0.3006 | | | -0.2486 | | |
| Finite Sample: AIC | | -0.1491 | | | 0.3035 | | | -0.2456 | | |
| Info. Criterion: BIC | | -0.0179 | | | 0.4347 | | | -0.1144 | | |
| Info. Criterion:HQIC | | -0.0984 | | | 0.3542 | | | -0.1949 | | |
| Variances | $s^2(v)$ | 0.0493 | | | 0.0739 | | | 0.0853 | | |
| | $s^2$ (u) | 0.0414 | | | 0.0037 | | | 0.0101 | | |
| | s(v) | 0.2220 | | | 0.2718 | | | 0.2920 | | |
| | s(u) | 0.2035 | | | 0.0605 | | | 0.1006 | | |
| Sigma = Sqr[($s^2$(u)+$s^2$(v)] | | 0.3012 | | | 0.2784 | | | 0.3089 | | |
| Variable | | Coefficient | Standard Error | | Coefficient | Standard Error | | Coefficient | Standard Error | |
| ---------+Primary Index Equation for Model | | | | | | | | | | |
| | Constant | 0.3926 | 0.0285 | *** | 0.5090 | 0.0406 | *** | 0.5880 | 0.0322 | *** |
| | Transportation Density | -5.40E-06 | 4.77E-07 | *** | -3.50E-06 | 9.68E-07 | *** | -7.72E-06 | 3.58E-07 | *** |
| ---------+Parameters in variance of v (symmetric) | | | | | | | | | | |
| | Constant | -3.0683 | 0.2443 | *** | -2.8287 | 0.2439 | *** | -2.4766 | 0.1961 | *** |
| | FIXED1 | -2.6051 | 0.7337 | *** | 0.1206 | 0.4653 | | -2.8744 | 0.4294 | *** |
| | FIXED2 | -6.3455 | 1.3890 | *** | 0.6759 | 0.7032 | | -7.6075 | 1.1387 | *** |
| | D_AREA1 | 0.8807 | 0.4009 | *** | 0.3517 | 0.3070 | | 1.1914 | 0.3997 | *** |
| | D_AREA2 | 1.1500 | 0.3590 | *** | 0.0125 | 0.2823 | | 0.9682 | 0.2909 | *** |
| ---------+Parameters in variance of u (one sided) | | | | | | | | | | |
| | Constant | -3.4708 | 0.3944 | *** | -7.2261 | 4.1104 | * | -5.2310 | 1.1208 | *** |
| | RES1 | -1.3501 | 1.1798 | | 24.1737 | 27.4377 | | -2.4561 | 2.4370 | |
| | RES2 | -1.4829 | 2.1938 | | 66.8660 | 80.2378 | | -0.2943 | 2.0689 | |
| | D_PUBLIC | 0.6873 | 0.3504 | ** | -3.6319 | 7.6441 | | 1.2845 | 0.9002 | |

Note1: D_AREA1, D_AREA2, and D_PUBLIC equal 1 if and only if the sample is in Tokyo metropolitan area, in Kinki area, and operated by semipublicly, respectively; otherwise 0.
Note2: *, **, and *** indicate p<0.1, p<0.05, and p<0.01, respectively.

Then, in the following Equation 6, we calculated environmentally optimized input variables and ran the weighted SBM model to determine the Liu-Tone based efficiency scores.

$$
optimized\ Y_{rjt} = original\ Y_{rjt} \left(1 - \left(\hat{\beta}_{r0} + \hat{\beta}_{r1} TD + \hat{u}_{rjt}\right)\right) \tag{6}
$$

The authors also tried a constant-returns-to-cost-based SBM model and repeated the similar procedure as just explained. Table 9 indicates the SFA results based on constant returns to cost assumption.

Table 9: Results of SFA estimation (constant returns to scale)

| Dependent variable | SBM-based slack ratio of operating expenditure | | | SBM-based slack ratio of related fixed asset | | | SBM-based slack ratio of staff | | |
|---|---|---|---|---|---|---|---|---|---|
| Weighting variable | None | | | None | | | None | | |
| Number of observations | 305 | | | 305 | | | 305 | | |
| Iterations completed | 24 | | | 22 | | | 64 | | |
| Log likelihood function | 47.3849 | | | -14.0770 | | | 72.8719 | | |
| Number of parameters | 11 | | | 11 | | | 11 | | |
| Info. Criterion: AIC | -0.2386 | | | 0.1644 | | | -0.4057 | | |
| Finite Sample: AIC | -0.2356 | | | 0.1674 | | | -0.4028 | | |
| Info. Criterion: BIC | -0.1044 | | | 0.2986 | | | -0.2715 | | |
| Info. Criterion:HQIC | -0.1849 | | | 0.2181 | | | -0.3521 | | |
| Variances $s^2(v)$ | 0.0426 | | | 0.0672 | | | 0.0676 | | |
| $s^2(u)$ | 0.0465 | | | 0.0483 | | | 0.0022 | | |
| s(v) | 0.2065 | | | 0.2593 | | | 0.2600 | | |
| s(u) | 0.2157 | | | 0.2198 | | | 0.0472 | | |
| Sigma = $Sqr[(s^2(u)+s^2(v)]$ | 0.2986 | | | 0.3399 | | | 0.2643 | | |
| Variable | Coefficient | Standard Error | | Coefficient | Standard Error | | Coefficient | Standard Error | |
| ---------+Primary Index Equation for Model | | | | | | | | | |
| Constant | 0.4004 | 0.0238 | *** | 0.5276 | 0.0415 | *** | 0.6428 | 0.0752 | *** |
| Transportation Density | -5.62E-06 | 4.55E-07 | *** | -5.24E-06 | 5.40E-07 | *** | -8.34E-06 | 5.86E-07 | *** |
| ---------+Parameters in variance of v (symmetric) | | | | | | | | | |
| Constant | -3.1477 | 0.2585 | *** | -2.4327 | 0.2644 | *** | -3.1637 | 0.1535 | *** |
| FIXED1 | -3.6118 | 1.1357 | *** | -3.3267 | 0.7828 | *** | -4.0754 | 0.5669 | *** |
| FIXED2 | -6.6504 | 1.3657 | *** | -4.5506 | 1.2111 | *** | -2.7127 | 0.5223 | *** |
| D_AREA1 | 0.8402 | 0.4579 | * | 0.2568 | 0.3279 | | 1.2691 | 0.3616 | *** |
| D_AREA2 | 0.5442 | 0.5097 | | -0.2696 | 0.3942 | | -0.2639 | 0.2469 | |
| ---------+Parameters in variance of u (one sided) | | | | | | | | | |
| Constant | -3.2547 | 0.3148 | *** | -3.4160 | 0.4111 | *** | -5.7045 | 3.2542 | |
| RES1 | -2.0089 | 1.0543 | * | 0.5170 | 0.8727 | | -0.5630 | 5.7701 | |
| RES2 | -0.9644 | 2.2801 | | 0.5685 | 2.8183 | | 0.0190 | 17.5396 | |
| D_PUBLIC | 0.4641 | 0.3150 | | 0.8829 | 0.3142 | *** | -56.3269 | 5.64E+12 | |

Note1: D_AREA1, D_AREA2, and D_PUBLIC equal 1 if and only if the sample is in Tokyo metropolitan area, in Kinki area, and operated by semipublicly, respectively; otherwise 0.
Note2: *, **, and *** indicate p<0.1, p<0.05, and p<0.01, respectively.

By these procedure, we can find the Liu-Tone-based reference points that are equivalent to S, Q, R, and R' of Figure 2; and can generate the table of inefficiency costs (Table 10) which can be comparable to Table 6. This result indicates that, although the estimated optimal costs of each methodology looks similar (the correlation coefficient is 0.829), Liu-Tone methods allocates more inefficiency on environmental factors than ours. Which method is more close to the reality will be the research topic of further analysis.

Table 10: Results of Liu-Tone style inefficiency impacts

| | Actual Cost | − | Intrinsic Inefficiency and Misallocation | − | Unfavorable environment | − | Suboptimal Scale | = | Optimal Cost |
|---|---|---|---|---|---|---|---|---|---|
| Overall average | 100.00 | − | 5.53 | − | 36.81 | − | 2.40 | = | 55.27 |
| Tokyo metropolitan area | 100.00 | − | 3.74 | − | 28.18 | − | 2.96 | = | 65.12 |
| Kink area | 100.00 | − | 6.53 | − | 36.03 | − | 3.46 | = | 53.99 |
| Kyushu area | 100.00 | − | 5.40 | − | 40.70 | − | 1.34 | = | 52.56 |
| private | 100.00 | − | 5.65 | − | 40.66 | − | 2.19 | = | 51.49 |
| semi-public | 100.00 | − | 5.27 | − | 29.02 | − | 2.82 | = | 62.88 |

Finally, through the application of DEA models, we can derive a set of reference and projected DMUs which can be categorized as the most productive scale size or MPSS [27]. The location of MPSS is where DMUos that are judged efficient both from BCC-I model and from CCR-I model exist, or where BCC-I model judges a range of constant returns to scale. On the other hand, following Cooper et al [26, chap.12), degree of scale economies ( $\rho$ ), or more accurately its upper and lower bound, can be measured by the following linear program. The returns to scale is said to be increasing, constant and decreasing if $\rho > 1$, $\rho = 1$ and $\rho < 1$ respectively.

$$\overline{\rho} = 1 + \overline{\omega} \text{ and } \underline{\rho} = 1 + \underline{\omega} \tag{7}$$

$$\text{where } \overline{\omega}(\underline{\omega}) = \max(\min)\omega \quad \text{subject to } \begin{cases} \mathbf{v}\mathbf{x}_\mathbf{o} = 1 \\ \mathbf{v}\mathbf{X} - \mathbf{u}\mathbf{Y} + \mathbf{e}\omega \geq 0 \\ \mathbf{v}\mathbf{x}_\mathbf{0} - \mathbf{u}\mathbf{y}_\mathbf{0} + \omega = 0 \\ \mathbf{v} \geq \mathbf{0}, \mathbf{u} \geq \mathbf{0}, \omega : \text{free in sign} \end{cases} \tag{8}$$

Table 11 shows the ranges of $\rho$ and input variables of increasing, constant, and decreasing returns to scale DMUs; where MPSS corresponds to the middle. Here, for simplicity reason, we use DMUs from 2003's sample only. It shows that DEA-based judgment of the returns to scale generally corresponds to estimated range of $\rho$. Among the 14 "BCC-I efficient" DMUs, Hankyu, Hojo, Keio, Kisyu, Kumagawa, Minami-Aso, Moka, and Odakyu,are within the range of MPSS; whereas Kashima, Kintetsu, Matsuura, Seibu, Shin-Keisei, and Tokyu are beyond the MPSS range, or within the range of decreasing returns to scale.

Table 11: Returns to scale and degree of scale economies

| | Returns to Scale Judgment by BCC-I model | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Increasing | | | Constant | | | Decreasing | | |
| $\overline{\rho}$ (Upper bound of ρ) | 1.000 | ~ | 1.000 | 1.000 | ~ | 2.105E+16 | 1.085 | ~ | 3.602E+16 |
| $\underline{\rho}$ (Lower bound of ρ) | 0.727 | ~ | 0.993 | 0.000 | ~ | 1.000 | 1.005 | ~ | 49.176 |
| Fixed Asset (yen) | 37,638.2 | ~ | 52,552,106.5 | 22,442.0 | ~ | 452,892,668.0 | 41,309.8 | ~ | 741,718,013.0 |
| Employee (person) | 9.7 | ~ | 506.9 | 5.0 | ~ | 3,320.0 | 17.6 | ~ | 5,669.0 |
| Operating expenditure (yen) | 36,769.5 | ~ | 4,885,858.4 | 9,563.0 | ~ | 41,821,334.0 | 50,414.0 | ~ | 59,153,395.0 |

## 6. CONCLUSION AND REMAINING ISSUES

In this article, we proposed a method to measure inefficiency in monetary terms and to differentiate their source by using a DEA framework, and applied the method to 53 railway firms in Japan. We also showed that our proposed DEA approach can be used to generate the optimal size of subsidy as compensation for regional disparities that should be equal to the value of an unfavorable environment for securing incentive compatibility. These estimates, when combined with the size of the fixed cost of railway operation under the diminishing average cost structure, are the target figures that national or municipal governments should subsidize without hampering the efficient operation of railway firms. It is true that, as DEA scores are obtained through peer comparisons, firms may be able to affect the DEA scores by collusion, which may deteriorate the effectiveness of our proposed subsidy. However, according to Armstrong et al. [28], such collusion becomes difficult to arrange when there are too many firms involved. We believe that such collusion is less likely to occur given the large number of Japanese railway firms.

There still remain several drawbacks in our analysis. The most concerning drawback is the robustness of the DEA approach. Since the efficiency index is very vulnerable to model configuration, we may need to employ an alternative configuration in order to verify the robustness of our findings. It may also be important to identify other uncontrollable factors and incorporate them in our analysis. Second the estimated unit cost or optimized operating costs are not based on economic costs. In our analysis, we calculated such figures using the financial statements of the railway firms involved in our study because we could not find any other alternative. Although such accounting figures are convenient, they are not perfectly appropriate for economic analysis because financial statements are based on the historical cost, whereas economic costs need to reflect the opportunity cost. Finally, since the possible disparity between DEA-based and economic-based optimality in the often monopolistic railway industry requires additional attention, it should be included in our future research agenda.

We hope that our proposal will help corporate managers and related policymakers determine proper efficiency-improving strategies and that our efforts here represent a meaningful contribution to the field of DEA application.

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**REFERENCES**

[1] Local Railway Business Study Group (LRBSG). 2003. *Revitalization plan for local railway sector: self-help efforts and government intervention* [Chihou tetsudou fukkatsu no tame no shinario: tetsudou jigyousha no jijodoryoku to kuni chihou no tekisetsuna kan-yo] [online document]. http://www.jterc.or.jp/ chiho_tetudo /chiho_hokoku.pdf [retrieved on May 13, 2006].

[2] Asahi Shimbun Publishing Co. (ed). *Minryoku 1989-2005 CD-ROM for Windows & Macintosh*. Tokyo, Japan: Asahi Shimbun Publishing Co; 2005.

[3] Mitomo, Hitoshi and Toshiya Jitsuzumi. Impact of telecommuting on mass transit congestion: the Tokyo case. *Telecommunications Policy* 1999;23(10/11):741-51.

[4] Mizutani, Fumitoshi. Privately owned railways' cost function, organization size and ownership. *Journal of Regulatory Economics* 2004;25(3):297-322.

[5] Mizutani, Fumitoshi. *Japanese urban railways: a private-public comparison*. Aldershot, UK: Avebury; 1994.

[6] Institution for Transport Policy Studies (ITPS). *Transportation Policy and Regional Development* [Kotsu Seisaku to Chiiki Shinko]. Tokyo, Japan: ITPS; 2004a.

[7] ITPS. *Statistics of Railways 2004* [Suuji de Miru Tetsudo 2004]. Tokyo, Japan: ITPS; 2004b.

[8] Nakamura, Akihiro and Toshiya Jitsuzumi. A DEA-based pricing method for railtrack usage: taking the value of local services into account [Tetsudou jigyo no koukyousei wo kouryosita senro siyouryou no kettei houhou ni kansuru kentou –DEA ni yoru senro fusetsu kanri no yardstick sihyou no keisoku-]. *Annual Report on Transportation Economics* 2004;47:59-68.

[9] Hensher, David A., Rhonda Daniels, and Ian DeMellow. A comparative assessment of the productivity of Australia's public rail systems 1971/72-1991/92. *The Journal of Productivity Analysis* 1995;6:201-23.

[10] Preston, John. The economics of British Rail privatization: an assessment. *Transport Reviews* 1996;16(1):1-21.

[11] Nakajima, Takanobu and Yoshitaka Fukui. Total Factor productivity of Japanese railway enterprises [Nihon no tetsudou jigyou no zen youso seisannsei]. *Transportation and Economy* 1996;56(1):32-40.

[12] Railway Bureau, Ministry of Land, Infrastructure and Transport (MLIT). (ed). *Annual statistics of railway [Tetsudou toukei nenpou]*. Tokyo, Japan: Government Data Research Center of Japan; 2000-2005.

[13] Cooper, William W., Lawrence M. Seiford, and Kaoru Tone. *Data envelopment analysis: a comprehensive text with models, applications, references and DEA-solver software*. Boston, Massachusetts: Kluwer Academic Publishers; 1999.

[14] Banker, Rajiv D., Abraham Charnes, and William W. Cooper. Some models for estimating technical and scale

inefficiencies in data envelopment analysis. *Management Science* 1984;30(9):1078-92.

[15] Oda, Kyoji and Yoshiaki Otsubo. The productivity of all the elements of railway enterprise after privatisation of the Japanese national railways. *Transportation and Economy* 2000;60(2):52-60.

[16] Banker, Rajiv D., Abraham Charnes, William W. Cooper, and Ajay Maindiratta. A comparison of DEA and translog estimates of production frontiers using simulated observations from a known technology. In *Applications Modern Production Theory: Efficiency and Productivity*, edited by Ali Dogramaci and Rolf Färe, 33-55. Boston, Massachusetts: Kluwer Academic Publishers 1988.

[17] Charnes, A., Cooper, W. W., and Rhodes, E. Measuring the efficiency of decision making units. *European Journal of Operational Research*, 1978;2(6): 429-444.

[18] Oum, Tae H., William G. Waters II, and Chunyan Yu. A survey of productivity and efficiency measurement in rail transport. *Journal of Transport Economics and Policy* 1999;33(Part.1):9-42.

[19] Oum, Tae H. and Chunyan Yu. Economic efficiency of railways and implications for public policy: a comparative study of the OECD countries' railways. *Journal of Transport Economics and Policy* 1994;28(2):121-38.

[20] Due, John F. Abandonment of rail lines and the smaller railroad alternative. *Logistics and Transportation Review* 1987;23(1):109-34.

[21] Farrell, Micheal J. The measurement of productive efficiency. *Journal of the Royal Statistical Society* 1957;120(3):253-90.

[22] Debreu, Gerard. The coefficient of resource utilization. *Econometrica* 1951;19(3):273-92.

[23] Tone, Kaoru and Miki Tsutsui. Decomposition of cost efficiency and its application to Japanese-US electric utility comparisons. *Socio-Economic Planning Sciences* 2007;41(2):91-106.

[24] Liu, Junming and Kaoru Tone. A multistage method to measure efficiency and its application to Japanese banking industry. *Socio-Economic Planning Sciences* 2008;42(2):75-91.

[25] Tone, Kaoru. A slacks based-measure of efficiency in data development analysis. *European Journal of Operational Research* 2001;130(3): 498-509.

[26] Cooper, William W., Lawrence M. Seiford, and Kaoru Tone. *Data envelopment analysis: a comprehensive text with models, applications, references and DEA-solver software, Second edition*. Boston, Massachusetts: Kluwer Academic Publishers; 2007.

[27] Banker, Rajiv D. Estimating most productive scale size using data envelopment analysis. *European Journal of*

*Operational Research* 1984;17(1):35-44.

[28] Armstrong Mark, Simon Cowan, and John Vickers. *Regulatory Reform: Economic Analysis and British Experience*. Cambridge, MA: MIT Press; 1994.