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Analyzing Efficiency of Railway Transportation by Considering Quality of Services: New Data Envelopment Analysis Models

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Many studies have been conducted to analyze efficiency of railways for different countries. However, these studies have mainly focused on quantitative aspects of railway transportation and quality has been neglected. In this paper three new data envelopment analysis (DEA) models are presented. The first model is solved for assessing quality of passenger railway services in 71 countries of the world by including perceived quality of railways among outputs of DEA models for the first time in the literature. For the second model which is applied to 27 railways in Europe, a safety index is defined based on number of fatalities and serious injuries and is added as another output. Both models are solved for constant return to scale (CRS) as well as variable return to scale (VRS) setting with output orientation. The follow-up Tobit regression for the first model shows that efficiency results are positively correlated with quality of road and for the second model negatively correlated with the number of level crossings. In the third model which is applied to 19 train operating companies in the UK, passenger-km is the input and stated passenger satisfaction derived from questionnaires together with punctuality level are outputs which proved to be helpful for ranking companies based on quality of their services.

1. Introduction

Railway transportation faces fierce competition from other modes and quality of services is a defining factor for inducing modal shift or at least retaining its current share. Transport quality of service is easy to comprehend but difficult to evaluate due to complex relationship between variables affecting it. Previous approaches such as the highly-cited multi criteria framework presented by Nathanail [1] need weights of different criteria to be determined. In these situations, DEA can be helpful as it provides new possibilities for performance evaluation when there are intricate relationships between outputs and inputs [2]. In this paper innovative application of DEA are presented which can help transportation practitioners and policy makers for determining efficiency of railways while considering quality of services.

2. Literature Review

DEA has been used extensively in different disciplines as surveyed by Emrouznejad and Yang [3] and Liu, Lu [4]. Estimates by Liu, Lu

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[5] shows that about 8 percent of all the published DEA papers in the Web of Science database from 1978 to 2010 are in the field of transportation (the fourth highest after banking, health care and agriculture). In the transportation field, from 461 published papers on DEA from 1989 to 2016, 40% were related to air transportation, 26% maritime, 19% transit, 8% rail and 7% road [6]. DEA models used in railways are summarized in Table 1.

Table 1. Application of DEA in railways as reviewed by Merkert, Smith [7] and updated by the authors

Study	Sample	Inputs	Outputs
[8]	19 railways in Europe and Japan	Staff; energy consumption; rolling stock	Passenger-km; freight-tonne-km
[9, 10]	17 European railways 1988-1993	Staff; rolling stock; track length	Passenger-km; freight-tonne-km
[11]	17 European railways 1970-1995	Operating cost; track-km	Passenger-km; freight-tonne-km
[12]	54 railways in 27 countries 2000-2004	Staff; rolling stock; track-km; operating expenditure	Train-km; passenger-km; freight-tonne-km
[13]	14 European railways 1990-2001	Staff; track length; rolling stock	Passenger-km; freight-tonne-km
[14]	16 European rail systems 1985-2004	Staff; rolling stock (Passenger vs. freight); network length	Passenger-km; freight-tonne-km
[7]	43 Swedish, German and British train operating firms	Material (Annual amount spent on operation including depreciation and rolling stock lease costs but excluding all staff costs); total staff	Train-km
		Material; managerial and administrative staff; the remaining production staff	Train-km; passenger-km
		Material; managerial and administrative staff; the remaining production staff	Train-km; Tonne-km
[15]	31 railway companies of the world	Operating costs Number of employees Length of lines Number of traction vehicles Number of passenger cars Number of freight cars	Total revenue Number of passengers Number of passengers per km Tonnes transported Tonnes per km transported
[16]	17 urban rail transit systems in China	Length of lines Number of employees Number of Rail Cars Car-km Average trip length Population Density	Car-km Number of passengers
[17]	20 urban rail systems of the world	Number of employees Number of cars	Car-km Patronage
[18]	23 European railway companies	Length of lines Number of employees Number of passenger cars Number of freight wagons	Passenger-km Tonne-km
[19]	218 rail enterprises	Number of employees Length of lines Number of locomotives Number of passenger cars Number of freight wagons Length of electrified lines	Passenger-km Tonne-km

None of the models reflect quality of services and they are merely focused on quantitative aspects of transportation. The concept of efficiency in transport has many facets some of which are shown in Figure 1. For instance safety and reliability hugely affect quality of services but have been neglected in the abovementioned literature.

Perceived service quality is a function of the difference between perceptions and expectations of the customer for five dimensions of tangibles, reliability, responsiveness, assurance and empathy as SERVQUAL model suggests [20]. Assessing service quality by SERVQUAL model and DEA (Figure 2) have been done successfully for automobile repair [21] and comparing hotels services [22].

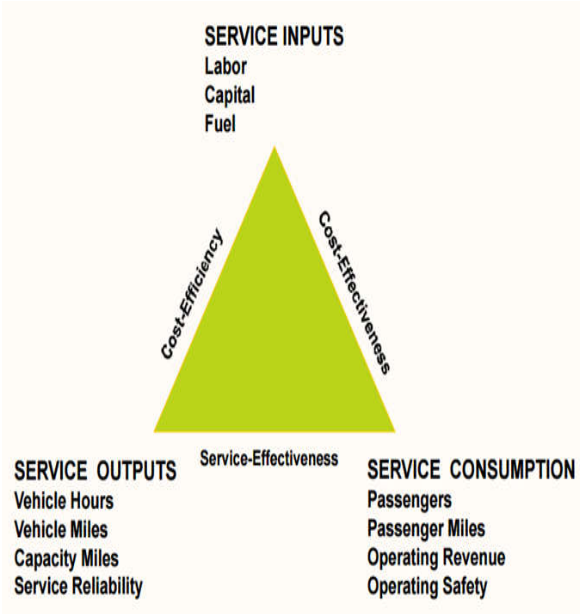

Figure 1. Efficiency and effectiveness in transportation [23]

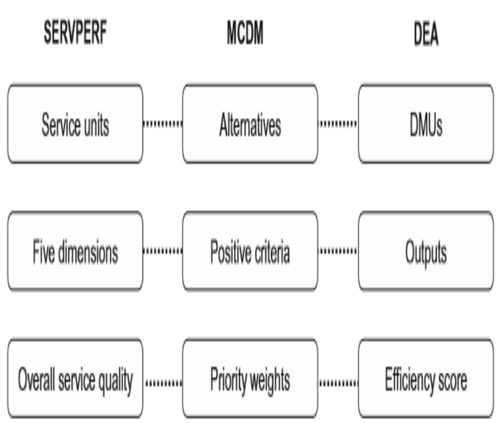

Figure 2. How DEA can be used for SERVPERF [21]

3. Method

DEA is a nonparametric model that can analyze how efficient decision making units (DMUs) produce outputs by the inputs they receive as well as ranking them. DEA is based on a linear programming formulation, it can be easily solved and the results provide useful insights for practitioners and managers. The model presented by Charnes et al. [24] in linear format is:

y_{ro} = amount of output r for unit under assessment
v_i = weight given to input i
x_{io} = amount of input i for unit under assessment
g_o = efficiency of the unit under assessment
ω_i = weight given to input i in the linear model
μ_r = weight given to output r in the linear model

$$\min g_o = \sum_{i=1}^{m} \omega_i x_{io} \tag{1}$$

$$\sum_{i=1}^{m} \omega_i x_{ij} - \sum_{r=1}^{s} \mu_r y_{rj} \geq 0$$

$$\sum_{r=1}^{s} \mu_r y_{ro} = 1$$

$$\mu_r, \omega_i \geq 0$$

Steps needed to do DEA are presented in Figure 3. Many important points to be considered for defining purpose of study, inputs and outputs as well as orientation of DEA models are also summarized by Cook et al.[25].

4. Results

In this paper three different DEA models for analyzing railway efficiency are proposed that consider service quality.

4.1. First model: Quantity of services and perceived quality- worldwide

The inputs of the first model include length of railway lines, population and GDP and the outputs are passenger kilometers and "quality of railroad" (Figure 4). The last item is extracted from Global Competitiveness Report and it's "Executive Opinion Survey'. This survey is "the longest-running and most extensive survey of its kind (over 13 thousand participants), capturing the opinions of business leaders around the world on a broad range of topics" and the question used for measuring this item is "In your country, how efficient (i.e., frequency, punctuality, speed, price) are the train services" [26].

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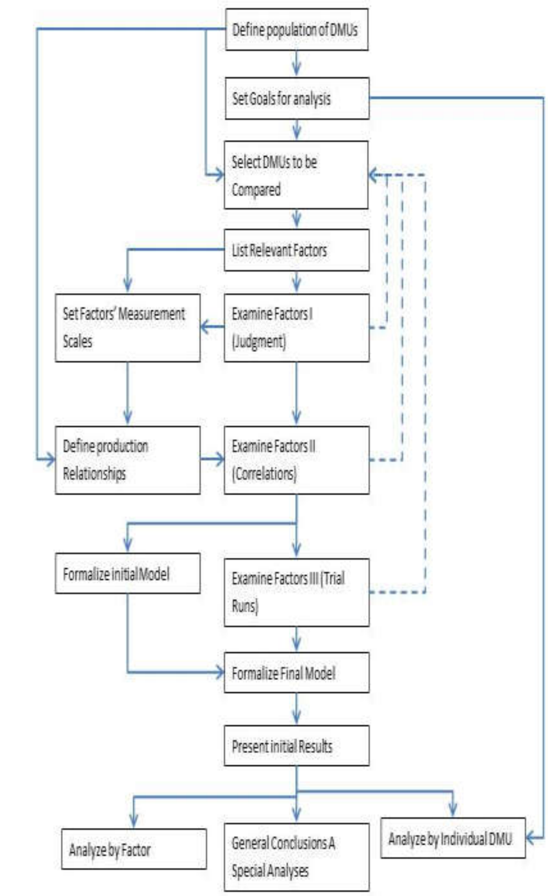

Figure 3. Overall DEA Procedure [27]

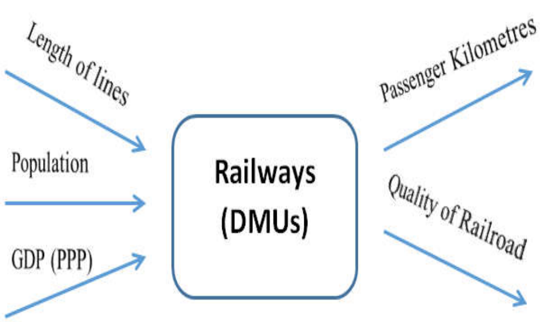

Figure 4. Inputs and Outputs of Model 1

72 countries from 5 continents were chosen as DMUs in the first model (after removing countries with missing data). Table 2 presents some key statistics of the inputs and outputs.

Table 2. Descriptive Statistics of Model 1

	Length of lines (Km) [28]	GDP [29]	Population (thousands) [29]	Passenger Km [28]	Quality of Railroad Infrastructure [26]
Mean	10975	897	83732	36900	3.7
Median	3116	182	14096	3190	3.7
Standard Dev	27780	2537	226618	151626	1.3
Min.	239	5	569	10	1.4
Max.	228218	17947	1371220	1147190	6.7

The model was solved for constant return to scale (CRS) and variable return to scale (VRS) with output orientation (Table 3 and 4). Efficient countries were Estonia, India, Japan, Luxemburg, Mauritania, Switzerland and Tajikistan (CRS model) and Albania, Estonia, India, Japan, Kyrgyzstan, Luxembourg, Mauritania, Mongolia and Switzerland and Tajikistan (VRS model).

Table 3. Summary of Results for Model 1

	CRS Model	VRS Model
	Amount	**Amount**
Mean	0.597	0.68
Median	0.588	0.69
Standard Dev	0.264	0.21
Minimum	0.015	0.21
Maximum	1	1

As a follow-up analysis authors were interested in whether and how quality of other modes of transportation affects the results of the model. Hence a Tobit regression was done to assess the relationship between quality of road, air and marine transportation on VRS efficiency scores (Table 5). The results show

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that only quality of road infrastructure is correlated with results (significant at 0.01).

Table 4. Results of Model 1- Top Efficient and bottom inefficient railways

CRS Model			VRS Model		
Country	**State**	**Score**	**Country**	**State**	**Score**
Estonia India Japan Luxembourg Mauritania Switzerland Tajikistan	Efficient	1	Albania Estonia India Japan Kyrgyzstan Luxembourg Mauritania Mongolia Switzerland Tajikistan	Efficient	1
. . .	. . .	. . .	. . .	. . .	. . .
Canada	Inefficient	0.039	D.R. of the Congo	Inefficient	0.292
USA	Inefficient	0.015	Brazil	Inefficient	0.285

Table 5. Tobit Regression for Quality of other modes

Efficiency	Coef.	Std. Err.	t	P > |t|	[95% Conf. Interval]
Quality of Road Infrastructure	0.12	0.04	2.65	0.01	0.029 0.204
Quality of Air Transportation Infrastructure	0.02	0.06	0.34	0.73	-0.094 0.132
Quality of Port Infrastructure	-0.07	0.04	-1.63	0.11	-0.152 0.016
/ sigma	0.20	0.02			0.179 0.262

This can be due to complementary nature of road and railway transportation as railways cannot offer door-to-door transport. Therefore, the higher quality of road transportation can help railways to attract more passengers to the railways (access and egress of station) and offer higher quality services.

4.2. Second model: Quantity of services, perceived quality and safety- Europe

In the second model it is intended to include a safety index in the outputs to reflect how safe passenger railway services are offered. The number of incidents is not a good measure as there may be a several fatalities in one and none in another. Therefore suggested index considers both fatalities as well as serious injuries. According to UIC's suggested standard, every 10 serious injuries is considered as 1 fatality. This is a negative outcome and to be able to use it as an output in the model we invert the summation hence the safety index is defined as:

$$\frac{1}{Number\ of\ fatalities+0.1\times Number\ of\ Serious\ injuries} \qquad (2)$$

Railway incidents which have fatalities and serious injuries often make headlines in newspapers, television and social media having long-term impact on public opinion. Therefore, mean of fatalities and serious injuries during 3 years and not just 1 year is used. These statistics are only available online at the website of UIC for Europe hence the second model is solved for 27 countries (Cypress could not be included due to several missing data) which is schematically shown in Figure 5.

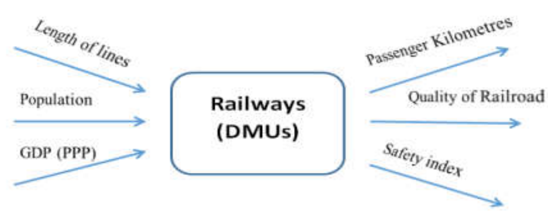

Figure 5. Inputs and Outputs of Model 2

Key descriptive statistics of inputs and outputs are presented in Table 6.

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Table 6. Descriptive statistics of the second model

	Length of lines (Km) [28]	GDP [29]	Population [29]	Passenger Kilometers [28]	Quality of Railroad [26]	Safety index [30]
Mean	7993	608	19005	14623.8	4.3	5.9
Median	4023	229	9799	4911	4.2	0.18
Standard Dev	8724	916	23626	24057.8	0.9	28.80
Minimum	275	22.7	569	273	2.4	0.02
Maximum	33331	3357	81679	83242	5.8	150

Table 7. Summary of Results for Model 2

	CRS Model	VRS Model
	Amount	Amount
Mean	0.642	0.654
Median	0.656	0.666
Standard Dev	0.258	0.260
Minimum	0.015	0.015
Maximum	1	1

The CRS and VRS alternates of this model were solved with output orientation. Countries that were efficient in CRS model were Austria, Estonia, France, Hungry, Latvia, Luxemburg, Netherlands, and Slovakia and in VRS model were Austria, Czech Republic, Estonia, France, Hungry, Latvia, Luxembourg, Netherlands, Slovakia, and the United Kingdom. A summary of results are presented in Table 7 and 8.

Table 8. Results of Model 2- Top Efficicent and Bottom Inefficient Railways

CRS Model			VRS Model		
Country	State	Score	Country	State	Score
Austria Estonia France Hungry Latvia Luxembourg Netherlands Slovakia	Efficient	1	Austria Czech Republic Estonia Finland France Hungry Latvia Luxembourg Netherlands Slovakia UK	Efficient	1
. . .	. . .	. . .	. . .	. . .	. . .
Ireland	Inefficient	0.423	Croatia	Inefficient	0.631
Poland	Inefficient	0.391	Poland	Inefficient	0.578
Greece	Inefficient	0.316	Greece	Inefficient	0.525

The follow-up Tobit regression (Table 9) shows that VRS efficiency scores of countries are negatively correlated with the number of level crossing (significant at 0.05) but it is not correlated with signals passed at danger. This can be due to the fact that accidents at level crossing which is between trains and pedestrians results usually in death or serious injury. Signals passed at danger just sometimes result in collision between trains (as most of the time train stops in short distance after the red signal). Therefore, if countries can reduce the number of level crossing (by building bridges for instance) they can improve their efficiency.

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Table 9. Tobit Regression for the second model

Efficiency	Coef.	Std. Err.	t	P>|t|	[95% Conf. Interval]
Level-Crossing	-0.0000401	0.0000169	-2.36	0.026	-0.000075 -5.09e-06
Signal Passed at danger	0.0006844	0.0003513	1.95	0.063	-0.000041 0.00141
_cons	0.8113235	0.0543132	14.94	0.000	0.69923 0.923421
/ sigma	0.2027743	0.028903			0.143121 0.26243

Table 10. Descriptive statistics of the third model

	Passenger Kilometers [28]	Satisfaction with Station [31]	Public Performance Measure [31]	Satisfaction with Train [31]
Mean	3.36	83.53	89.79	82.53
Median	2.61	83	89.5	82
Standard Dev	2.42	4.09	3.91	5.79
Minimum	0.50	75	81.5	72
Maximum	8.93	91	96.7	91

Table 11. Summary of Results for Model 3

	Amount for **CRS Model**	Amount for **VRS Model**
Mean	0.29	0.96
Median	0.20	0.95
Standard Dev.	0.26	0.03
Maximum	0.05	0.88
Minimum	1	1

Table 12. Results of Model 3- Top Efficient and Bottom Inefficient Operators

CRS Model			VRS Model		
Operator	State	Score	Operator	State	Score
TfL Rail	Efficient	1	TfL Rail Merseyrail c2c Virgin Trains East Coast	Efficient	1
Merseyrail	Inefficient	0.833			
c2c	Inefficient	0.513			
. . .	. . .	. . .	. . .	. . .	. . .
South West Trains	Inefficient	0.081	London Midland	Inefficient	0.924
Virgin Trains West Coast	Inefficient	0.08	Southeastern	Inefficient	0.904
Govia Thameslink Railway	Inefficient	0.054	Govia Thameslink Railway	Inefficient	0.879

4.3. Third model: Stated satisfaction of passengers and punctuality – UK

In many cases, results of passenger surveys are available for transport operators. In the third model a method for comparing and ranking train operating companies based on passenger evaluations is presented. 19 train operating companies from the UK were selected as DMUs. Satisfaction with station and satisfaction with train which are the average of many question on different aspects of quality of service such as cleanliness, safety, security, value for money, staff behavior, and availability of facilities [31] were chosen for two of outputs. The third output is public performance measure (PPM) which is calculated based on punctuality of train services; Higher PPM indicates less delays and cancelation of trains. Figure 6 shows schematic representation of the model and descriptive statistics of data are presented in Table 10.

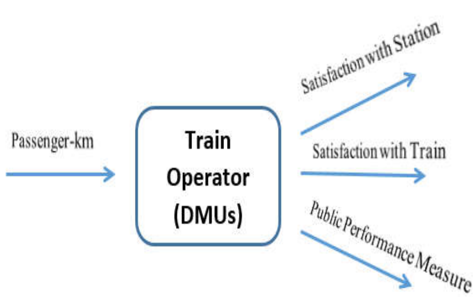

Figure 6. Inputs and Outputs of Model 3

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The model was solved for both CRS and VRS and some interesting results were found. The model is very sensitive to returns to scale that is the CRS efficiency results are very low (mean=0.29) and VRS efficiency results are very high (mean=0.96) as shown in Table 11. The ranking of DMUs is not affected considerably with TfL Rail, Merseyrail and C2C as top three and Govia Thameslink Railway at the bottom (Table 12).

5. Conclusions

Transportation field is rich in research on efficiency based on quantitative measures. Considering quality of service which is extremely important for the passengers have been neglected in the literature. If comparing and ranking DMUs is intended, measuring indices and weighting them can be challenging too. DEA has proven to be a useful tool in these cases for multi criteria decision making and comparison. In this model three different DEA models are presented that use perceived quality of services, punctuality level as well as safety index into consideration for efficiency analysis. It is hoped that a new avenue of research is opened for evaluating quality of transport.

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