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Measuring and improving the efficiency and effectiveness of bus public transport systems

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A B S T R A C T

In this paper, Data Envelopment Analysis (DEA) is used to evaluate the performance of individual bus lines composing the public transport network in Thessaloniki, Greece. Results showed that efficiency of local bus lines is slightly better than operational effectiveness without indicating a clear positive or negative relationship between the two performance components. Traffic conditions and population density seem to be important exogenous factors influencing performance. We employed bootstrapping techniques to check robustness of DEA results and we explain that performance assessment is more reliable when correcting for bias. We found that production models we developed for evaluating performance do not always exhibit the same technology of returns to scale, indicating that comparison across ratings pertaining to different performance dimensions should be made with caution. DEA results enabled us to perform clustering of bus lines based on the derived piecewise production functions. We defined the variables of these functions so as to allow performance improvement monitoring over service design changes in any given bus public transport network. It is found that for most of the bus lines in Thessaloniki, scheduling of buses with fewer seats would be a more successful performance improvement measure than reducing their span of service.

1. Introduction

Performance measurement in the Public Transport (PT) industry is gaining significant momentum nowadays, since organizations need to continuously improve their performance in order to attract more users while designing and delivering services in an increasingly competitive environment with tight financial constraints. PT actors have to come up with tools that help to monitor progress and detect aspects of delivered service where performance does not meet organisational goals. Benchmarking is regarded as one of the most effective methods for this action and provides agencies with the opportunity to compare performance against other agencies operating different networks or across the sub-units of their own systems (Georgiadis, 2012). Data Envelopment Analysis (DEA) has been extensively used as a comparison tool for benchmarking exercises in the sector (Barnum, 2009).

DEA is a non-parametric method for measuring the relative efficiency of a set of units able to convert multiple inputs into multiple outputs. Application of DEA informs on the best performing units as well as on the improvement which is required by all the other entities in order to reach them. In this paper, we use DEA to evaluate performance of individual bus lines, considering them as sub-units of a PT system. The DEA exercise is based on the bus PT network of Thessaloniki, Greece and examines the relative efficiency and effectiveness of the city's bus routes.

The remainder of the paper is organised as follows. DEA applications in the PT sector and usefulness for Thessaloniki's system are presented in the following section. Section 3 gives the basic mathematic formulae for performing DEA. The data and the models developed for evaluating performance are described in Section 4. Results are reported and discussed in Section 5 and conclusions are summarised in Section 6.

2. Background

2.1. DEA applications in the public transport sector

Performance of a given production unit can be distinguished into two dimensions; namely, efficiency and effectiveness. Efficiency represents the process through which service inputs are transformed into produced outputs while effectiveness has two components. The first one explores the relationship between

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service inputs and consumed services (operational effectiveness) and the second one examines the relationship between produced services and consumed services (service effectiveness). Hensher (2007) recognizes that these interrelationships also hold for the bus PT sector and refers to labour, energy and capital as typical examples of service inputs along with vehicle-kms and patronage levels as typical examples of produced and consumed services, respectively.

In previous DEA applications on bus PT sector, performance evaluation followed this consideration in general terms. Chu, Fielding, and Lamar (1992) used DEA to develop a single measure for efficiency and effectiveness of bus PT agencies and concluded that, for a public agency, measures of efficiency should be kept distinct from measures of effectiveness. Karlaftis (2004) investigated the relationship between efficiency and effectiveness of 256 US transit systems over a five-year period and explained that the two performance dimensions are positively correlated. More recently, DEA exercises are accompanied with bootstrapping techniques so as the necessary sensitivity analysis of results is performed. Boame (2004) used a bootstrap DEA method to estimate technical efficiency for Canadian urban transit systems and identified the sources of efficiency change. De Borger, Kerstens, and Staat (2008) explored a selection of bootstrapping techniques to estimate non-parametric convex (DEA) cost frontiers and efficiency scores for a sample of Norwegian bus operators and found that the bias implied in original result is important. Von Hirschhausen and Cullmann (2010) applied bootstrapping methods to test the robustness of efficiency estimates as well as the technology of returns to scale for 179 bus PT companies in Germany and found that their average technical efficiency is relatively low.

The majority of the existing DEA literature on the field is devoted to comparing PT agencies and very few applications on individual bus lines exist. Sheth, Triantis, and Teodorović (2007) combined DEA and goal programming to evaluate performance of bus routes and investigated both passenger's and operator's points of view using simulated data. Barnum, Tandon, and McNeil (2008) compared the performance of 46 bus routes in a US urban transit agency by investigating the relationship between consumed outputs and produced services. In order to remove environmental influences, they adjusted ridership and on-time performance values before being used as output variables. Lao and Liu (2009) combined DEA and GIS to measure operational efficiency and spatial effectiveness of 24 fixed bus routes of a US bus operator. They found that no clear positive or negative associations exist between performance dimensions they examined.

Typical examples of variables appeared for DEA evaluations on bus lines include vehicle or seat-miles along with passenger or passenger-miles as indicators of produced and consumed services, respectively. We observed a greater variety for service input variables depending, as expected, on the objective of the exercise performed. We may refer to Sheth et al. (2007) approach where both service design and quality indicators, such as headway, service duration and number of priority lanes along with cost indicators are explored as input variables. Previous DEA exercises on bus lines also highlight the influence of exogenous factors on performance. Population densities, types of routes and accessibility factors provide some examples of environmental variables that have been investigated by not necessarily adopting the same methodologies (Barnum et al., 2008; Sheth et al., 2007).

2.2. DEA usefulness in the case of Thessaloniki, Greece

Thessaloniki is the second largest city in Greece with a population of approximately 1 million inhabitants in its metropolitan area (official 2011 census data). PT in Thessaloniki is operated by the Urban Transport Organisation of Thessaloniki (UTOT (OASTH)) and supervised by Thessaloniki's PT Authority (ThePTA). PT system is composed by a network of bus lines and an underground metro line will be added in mid-2017. Improvement of delivered quality, rationalization of resources' allocation and identification of weaknesses in everyday service constitute the main challenges currently faced by Thessaloniki's authorities. The introduction of Automatic Vehicle Location (AVL) equipment for the bus fleet taken place in 2005 and the subsequent launch of real time passenger information system in 2007 can be regarded as investments aiming to improve performance and also to attract more PT travellers (Politis, Papaioannou, Basbas, & Dimitriadis, 2010).

Local PT agencies currently rely on a set of simple performance indicators (ratios) to assess performance of bus lines. However, it is likely that indicator values do not always follow a consistent trend between lines preventing the identification of those who outperform the others. Table 1 shows such an example where the highest values (indicated with bold) for three key service effectiveness indicators appear each time for a different line. Moreover, performance comparisons by using such indicators are fair only if the same technology of returns to scale occurs in all lines, something that is not always correct and needs prior investigation.

In this paper, we apply DEA to evaluate the performance of bus lines in the PT system of Thessaloniki. DEA analysis evaluates performance by examining, at the same time, multiple inputs and outputs for each line and gives the opportunity to identify the cases where different technology of returns to scale may apply. In this context, DEA can serve as a tool for pointing out the bus lines and the corresponding conditions where targeted performance levels are not met as well as the relative effort that is required for their performance improvement.

3. Methodology

In this section we present the basic mathematic formulae for performing DEA. We give the equations for calculating efficiency scores and we discuss the method for sensitivity analysis of DEA results along with a recently proposed DEA-based clustering algorithm.

3.1. DEA efficiency scores

DEA is a non-parametric approach for measuring the relative efficiency of entities called Decision- Making Units (DMUs) being responsible for converting multiple inputs into multiple outputs. DEA was designed by Charnes, Cooper, and Rhodes (1978) who provided the basic CCR (Charnes, Cooper and Rhodes) model extending Farell's original work (1957). Relative efficiency of DMUs is measured against the DEA efficient frontier that is formed as the piecewise linear combinations that connect the set of best practice observations of the sample examined.

Let us consider we have $j = 1,2,\ldots,n$ DMUs with m input items ($x_{1j},x_{2j},\ldots,x_{mj}$) and s output items ($y_{1j},y_{2j},\ldots y_{sj}$). We measure the

Table 1
Key service effectiveness indicator values for 3 urban bus lines of Thessaloniki (2011).

Bus lines	Passengers/Vehicle hour	Passengers/Vehicle km	Passengers/100 seat-kms
Line A	60.51	6.79	**7.01**
Line B	**96.54**	7.45	4.64
Line C	93.37	**9.96**	5.46