European Journal of Operational Research 248 (2016) 1–20

Contents lists available at ScienceDirect

European Journal of Operational Research

journal homepage: www.elsevier.com/locate/ejor

Invited Review

Efficiency and effectiveness in the urban public transport sector: A critical review with directions for future research

Cinzia Daraio [a,*], Marco Diana [b], Flavia Di Costa [a], Claudio Leporelli [a], Giorgio Matteucci [a], Alberto Nastasi [a]

[a] DIAG, University of Rome “La Sapienza”, 00185 Rome, Italy
[b] DIATI, Politecnico di Torino, 10129 Turin, Italy

ARTICLE INFO

Article history:
Received 2 September 2014
Accepted 25 May 2015
Available online 2 June 2015

Keywords:
Translog
DEA
SFA
Transport indicators
Transit scheduling

ABSTRACT

This paper proposes a self-contained reference for both policy makers and scholars who want to address the problem of efficiency and effectiveness of local public transport (LPT), with special emphasis on urban transit, in a sound empirical way. Framing economic efficiency studies into a transport planning perspective, it offers a critical discussion of the existing empirical studies, relating them to the main methodological approaches used. The connection between such perspectives and Operations Research studies dealing with scheduling and tactical design of public transport services is also developed. The comprehensive classification of selected relevant dimensions of the empirical literature, namely inputs, outputs, kind of data analysed, methods adopted and policy relevant questions addressed, and the systematic investigation of their interrelationships allows us to summarise the existing literature and to propose desirable developments and extensions for future studies in the field.

1. Introduction

The operation of public transport services has a significant impact on the budget of most territorial public bodies (central state, regions, provinces and municipalities). Moreover, in many cases only a small fraction of these costs is recovered through end user tickets and subscriptions. This expenditure of public money usually is justified both in terms of welfare efficiency and equity goals, given the pervasive socio-economic and environmental impact of transport. In terms of equity goals, a reasonable level of access to mobility services is unanimously considered an essential right in a democratic society. As far as efficiency goals are concerned, stakeholders are in fact usually interested both in the direct effects (improving the efficiency and the quality of the offer of the public transport system itself), and in the external effects such as reducing pollution and congestion and improving labour supply in urban centres. Most remarkably, these “external effects” often constitute the primary rationale for such interventions, both in the political arena, and in more technical analysis of the transport planning documents. The matter is not how much “output” one is able to produce given some input, but how the intervention impacts the transport system as a whole by modifying environmental footprints, land use patterns or territorial accessibility and more generally, how the intervention affects a vector of social goals given its use of social resources. While this issue is usually considered when implementing strategic decisions, such as the construction of a new transport infrastructure, at the more tactical level this general vision is seldom implemented. Therefore, in the following we focus on such level, which on the other hand absorbs the majority of the resources that public bodies invest in public transport systems.

It should nevertheless be acknowledged that any evaluation method should consider this framework, in order to provide really useful indications to transport policy decision makers. We preliminary observe that at least two radically different approaches are used, both at the research and at the practitioner level, to make such kind of assessment, according to the disciplinary background of the analysts. Civil engineers and transport planners are usually conscious of the different implications that often underlie any investment in a public transport system and are interested in studying also the technical performances of the system itself. This generally leads to the definition of a set of indicators, since this method permits to jointly consider heterogeneous kinds of data (for example, public subsidies, commercial speed and decrease of pollutants emissions) in a rather straightforward way, on an analytical point of view, often involving simple mathematical operations. On the other hand, economists tend to apply efficiency analyses at a more aggregated level, using shadow

* Corresponding author. Tel.: +39 6 77274 068; fax: +39 6 77274 074.
E-mail address: daraio@dis.uniroma1.it (C. Daraio).

http://dx.doi.org/10.1016/j.ejor.2015.05.059
0377-2217/

prices of the social resources and a social welfare function to design intervention policies. Their methodologies are very insightful, allowing one to evaluate how well a Decision Making Unit (DMU) is operating, if, and how much the resources could be better used, and so on. As such, these tools are very useful for a public transport operator, like for any other firm, but from the more general point of view of the stakeholder need to be integrated according to the above described framework.

We believe that a promising avenue of research is to interface the analysis based on transport indicators, whose flexibility allows us to consider a wide range of data, such as cost drivers, output, levels of use and impact measures, with the efficiency analysis literature, a powerful analytical tool that is widely used in different fields both in the public and in the private sector to estimate possible improvements in the amount and mix of used resources and the trade-offs between output attributes. In other words, efficiency models could be enriched by considering as input and output variables some of the indicators that are used in the transport engineering field. For example, outputs could not only represent production amounts but measures of impacts, ranging from a decrease of emission of pollutants to an increase of territorial accessibility. To the best of our knowledge, a unified framework that jointly considers these two research areas is missing, and could provide insightful indications for researchers and policy makers.

To contribute in achieving this goal, our ambition is to provide a systematic analysis of the existing studies and elaborate a taxonomy of the main research questions, the main results and policy implications addressed in the literature by means of a careful study of the data, variables and methods applied in these growing fields of study. The most valuable output of our research will be a self-contained reference to researchers and policy makers interested in modelling and empirically investigating the local public transport (LPT) sector under their different perspectives and needs. We focus in the following on local public transport, since the operation of many long distance services (e.g. high speed trains, airline services or coaches) does not need public money in many countries, at least if we exclude infrastructures construction costs. On the other hand, most of local public transport services are provided in urban areas: therefore, we interchangeably use the two expressions “local public transport” and “urban public transport” in this paper.

The first step that we accomplish here is a critical review of the research carried out so far and dealing with efficiency analysis, in order to underline its common points with the research stream on transport indicators, to analyse in what they differ and to prospect how these two approaches could be improved and then integrated at best. To this purpose we collected and deeply analysed 124 papers, also extending and updating previous reviews examining economic efficiency studies in urban public transit (Brons, Nijkamp, Pels, & Rietveld, 2005).

Secondly, we analyse in detail the research questions, methods applied, input and output variables definitions, main results and policy implications of existing studies in order to present a general structure of the literature. This comprehensive frame will allow us to characterise the state of the art in the assessment of public transport systems efficiency and effectiveness.

The paper ends by enlarging the perspective of the study to another disciplinary field that is of primary interest for this Journal’s readership, namely Operations Research (OR) and its applications to the tactical design of urban public transport services. Such methods can be seen as the counterpart of efficiency studies that are the main focus of the present review, since they are primarily used for the design rather than the evaluation of a service. It is however apparent that both aspects should take similar objectives and viewpoints for consistency reasons: therefore, we deemed it important to make a comparative assessment of the two fields within the framework sketched above.

The paper unfolds as follows. In Section 2 we describe the methodology of the review. In Section 3 we introduce the theoretical background of the analysis, whilst Section 4 discusses in details the main inputs, outputs and other variables used in the surveyed studies. Section 5 offers a schematic view on the main methods used in the empirical works and link them to the main variables analysed. Section 6 outlines the analysed data and Section 7 extends the perspective to the tactical planning of urban transit services. Finally, Section 8 concludes the paper outlining directions for future research.

2. Methodology of the review

Given the ambition of the present research of interfacing different disciplinary fields according to the above described framework, the bibliographic search aimed at retrieving the relevant papers both in the transport engineering and planning literature and among works dealing with efficiency analyses. However, we soon noted a connection between the latter group and an additional set of papers in the economic literature that are also of interest, since they deal with the impact of relevant issues such as deregulation processes on the efficiency of public transport services. The papers of interest for the present review have been therefore classified in the following three (broad and not completely fixed) preliminary categories, or lists:

(A) *Evaluation of urban public transport systems through indicators*. Given the focus of the present research, we do not consider here papers dealing with strategic evaluation processes as explained in Section 1. Papers falling in this first list are mainly taken from the transportation engineering literature. We also privilege the stakeholder rather than the customer viewpoint, therefore not reviewing papers focused on service quality or customer satisfaction, even if indicators have been proposed also to deal with these latter aspects. Public transport quality issues are in fact more integrated in the economic efficiency analysis, and considering them would make this review overwhelmingly long and complex.

(B) *Efficiency analyses of urban public transport systems*, usually found in the economic efficiency analysis literature.

(C) *Other economic analyses* dealing with aspects related to the efficiency of urban public transport systems: *productivity, economic performances, cost structures, cost functions, subsidies, deregulation and privatisation, scale and scope*. Papers dealing with these issues are a lot, but we systematically disregarded those that do not discuss implications on efficiency, such as those merely describing deregulation and competition processes or designing and analysing pricing structures without reporting empirical evidences.

A search of the literature was carried out and a systematic search of the bibliographic references was also done, updated at the end of April 2014, on the Scopus database, by using a list of 33 relevant keywords (see Appendix A). The final number of papers retrieved for the analysis has been of 124, the oldest ones in each list (reported above as A, B and C) having been respectively published in 1974, 1977 and 1970. Each bibliographic item has been classified according to a grid that highlights the main relevant aspects of the analysed work to facilitate the systematic analysis of the different approaches, methods used and the comparison of the obtained results. More in detail, the fields in the grid summarise the information and classify each reference considering the following aspects:

- Paper reference.
- Objectives of the study.
- Method.
- Kind of data—this class includes eight sub-classes regarding the kind of data gathered (cross section, time series, panel) the size of the sample, the nationality and the geographical extension of the analysis.

Table 1
Matching evaluation aspects with viewpoints and with the literature on efficiency.

Evaluation aspect	Relevance for different viewpoints			Relevance for the five identified groups of papers				
	Producer (efficiency)	User (quality)	Community (effectiveness)	I Efficiency productivity	II Determinants of technical efficiency	III Effect of alternative regulatory regimes	IV Public versus private ownership	V Economies of density, scope and scale
Profit/cost analysis	***	*	**	***	***	***	***	***
Service performance	**	***	**	***	***	**	***	**
Road congestion	**	**	***	*	**	*	*	*
Sustainability	*	*	***	**	**	*	*	**
Social inclusion	*	**	***	*	*	*	**	*
Accessibility	*	***	***	*	*	*	**	*

* = little relevant; ** = relevant to some extent; *** = strongly relevant.

- Variables used—this class divides the variables utilised in the analysed papers in three classes: input, output and variables that cannot be classified as input or output such as those that describe the quality of the service or external factors (location, climate, pollution etc.).
- Main results.
- Policy implications.
- Comments.

See Appendix B which contains the outline of the grid used for the analysis of the selected papers and Appendix C where we provide the full list of the journals and the distribution of publications for each journal.

After having classified the relevant papers, the Software tool VosViewer (www.vosviewer.com) was used to analyse the contents of the set of selected articles that were distilled through the above grid. VosViewer provides support for creating term maps based on a corpus of documents. A term map is a two-dimensional map in which terms are located in such a way that the distance between two terms can be interpreted as an indication of the relatedness of the terms. In general, the smaller the distance between two terms, the stronger the terms are related to each other. The relatedness of terms is determined on the basis of the co-occurrences in documents (titles, abstracts or full texts of scientific publications). This technique is therefore similar to Correspondence Analysis, a multivariate statistical analysis method for analysing the relationship between nominal variables, whose use is well attested both in the marketing and in the transport engineering literature (Diana, 2012). Additional technical information about VosViewer and the VosViewer mapping and clustering techniques can be found in Waltman and Van Eck (2013). We used maps for two key components of the summary information in our grid, namely methods used and abstracts of the papers.

3. Framing economic efficiency studies into a transport planning perspective

Before presenting the results of the above described research activity, we think it is necessary to provide a theoretical background to connect transport policy and economic analysis. The goal is to show how evaluation activities carried out in economic studies can be framed within the evaluation perspectives that are most typically encountered in transport planning and decision making processes, and usually tackled through simplified indicators we reviewed through the above list “A” of papers. In doing this, we will identify the gaps that need to be addressed by future research in order to make efficiency analyses a tool that is fully usable also for transport planning activities. The previously identified three lists of papers were useful to conduct the literature review across different disciplines, but a more detailed categorisation of the actual contents of studies in the economic efficiency literature (i.e. the above lists “B” and “C”) is needed to conduct such gap analysis.

In setting a framework for an evaluation exercise, the evaluated activities need first to be characterised in terms of objectives they need to pursuit. This leads to the definition of the goals of the evaluation process, and to understand which issues should be investigated. To perform this task, we have to consider the evaluation perspective of the different stakeholders, since any economic activity involves different parties, whose objectives might be conflicting.

When the analyst deals with economic activities in the private sector under ordinary market laws, setting up such framework is a relatively straightforward task. The activity must maximise profits or minimise costs, the point of view is that of the producer or provider that is making the analysis, therefore an efficiency analysis with input and output from the production process is most appropriate. However, when considering public transport, the evaluation framework can be much more complex. It is therefore important to start our review by looking at how the different evaluation perspectives have originated researches that take different viewpoints and answer different policy questions. We believe that there are three main different perspectives can be traced back to the following three stakeholder groups:

- the providers that have a private economic perspective, possibly affected by the ownership and the regulatory framework;
- the traveller that is sensitive to the service quality (as previously mentioned, we are not focusing here on quality aspects);
- the general population and political and regulatory bodies, which measure the service effectiveness in terms of its compliance with public goals.

Considering the viewpoints of these three groups allows us to set up a more general evaluation framework, that brings together six issues, performance measures and goals, some of which are in fact typically used in public transport analyses:

- economic goals (such as cost minimisation, given suitable output and quality constraints, profit maximisation, or social surplus maximisation);
- operational performances of the transport system;
- its role in relieving road congestion;
- its environmental impacts in terms of sustainability;
- social inclusion issues;
- territorial accessibility.

We believe that the above six dimensions represent a fairly complete set. The first one summarises the economic perspective, the second one the key interest of the travellers, while the last four represent the main benefits that are typically expected by the community when implementing public transport systems (UITP, 2009). In the left half of Table 1, we more systematically match the two dimensions of our framework by indicating which aspects are more or less relevant for a given viewpoint through an ordinal scale (one star = little relevant; two stars = relevant to some extent; three stars = strongly relevant).

We do not discuss in detail our grades that are rather intuitive in most cases. On the other hand, we acknowledge that our assessment is to some extent sketchy. However, what matters here is to propose a general structure useful to classify the existing literature on economic efficiency. Based on such evaluation framework, this review therefore identified five main areas of research in which efficiency studies tried to measure the effect of alternative public policies. As already mentioned, this constitutes a more targeted classification of efficiency papers compared to the distinction between lists "B" and "C" that was proposed in the preceding section to drive the literature search. We label these five groups of papers with roman numerals and we briefly describe them in the following, before trying to understand to what extent these papers can cover the six aspects listed in the rows of Table 1.

First, there are studies aiming simply at identifying the technical efficiency of transit systems, in a more descriptive than interpretative setting. This avenue of research applies tools from the efficiency/productivity literature to the public transport industry and, in this sense, its originality relies more on applying new methods to an old problem than proposing an answer to a policy question. It is then of strict interest of the public transport provider, since it is focusing on the first of the above evaluation aspects (cost minimisation and/or profit maximisation). On the other hand, it is widely acknowledged that there is a close relationship between operational efficiency and service performance, so that these studies are also indirectly useful to study the latter aspect.

Second, part of the literature goes a step further, by asking which factors affect technical efficiency. In particular, in Tables 5 and 6, and mostly in Table 7, we classify as P (external or environmental parameters) the variables added to the estimated input–output frontiers, i.e. both in NFA (nonparametric frontier analysis) and in PFA (parametric frontier analysis). The usual approach, here, is to identify a number of possible explanatory variables that could affect technical efficiency and then incorporate them in the analysis via one of the methods proposed in the literature on efficiency estimation (see Section 5 for more details). Estimating a more precise model of the efficient frontier is of interest both for service providers and for regulators. From the service provider's point of view, there is an obvious interest in understanding how she can improve technical efficiency using the instruments under her control. However it should be noted that the above mentioned factors are also related to broader issues that are not totally under the control of the service provider, and are on the other hand also relevant for different evaluation perspectives. One good example is the role of congestion that affects commercial speed and thus both productivity and efficiency of public transport (Kerstens, 1999).

Third, some authors go to the problem of looking at the effect of alternative regulatory regimes on the efficiency of the operation. In particular, consider two polar regulatory regimes: cost-plus and fixed price schemes. In the first regime the government subsidies public transport by paying the unbalances (deficits) of local transit systems. These systems require a detailed analysis of the service provider's accounts and the regulators can reject, in principle, the reimbursement of incurred costs if they do not consider them relevant and prudently incurred for an efficient service provision. However, these analyses are costly, and the regulator has less information on technology and costs than the provider has. Consequently, the local transit systems have an incentive to operate in deficit or, at least, do not exert enough effort to reduce costs. Moreover, such a system can produce a bias in the allocation of inputs, leading a local transit system to overcapitalise (Averch–Johnson effect) or hire more workers than needed. On the contrary, in a fixed price, or price-cap scheme, the government commits to pay to the local transit system an amount fixed or exogenously indexed. This creates an incentive to reduce costs, because the local transit system retains the surplus resources that derive from cost reduction. Even in this case, the regulator needs information on relevant revenues and costs, but the analysis becomes forward-looking: the regulator forecasts future cash flows of the regulated firms using technology and demand models, in order to set the end-of period constraint on regulated prices. The papers in this group analyse the relative merits of these mechanisms, focusing on aspects such as the scope of deregulation processes, the possible evolution of vertical and horizontal market structure, the allocation of subsidies.

A fourth group of papers enlarges the discussion of regulation and analyses the relative merits of public versus private ownership and/or operation. The recent privatisation wave has been mainly justified on the basis that private, profit-oriented organisations have stronger incentives towards efficiency with respect to public organisations. Franchise bidding implements competition for the market among private firm as a mean of determining the cost of production in asymmetric information setting, and as an exit strategy from public monopolies. However, the dynamics of franchise bidding and tendering does not solve all regulatory problems. In particular, in a transit system, the ownership of the infrastructure and of other durable goods could put the incumbent firm in favourable position when the franchise contract is renewed. Moreover, the franchisee incentives to lower costs could undermine the quality with which the service is provided.

Finally, the fifth group of papers analyses the economies of density, scope and scale which are fundamental in transport economics in that they pertain to the space and time dimension of service provision and to the characterisation of transportation technology (infrastructures, indivisible capacity of transportation means, connections, incidence of fixed costs, and so on). Geographical characteristics of the service area and the spatial and temporal distribution of the travel demand have a major impact over dimensional economies and affect the transit system performance in terms of average levels and distribution of costs and attainable quality. The coordination and dimensional economies also affect the tendering process: an effort should be made to define traffic catchment areas of appropriate size; the synergies associated with the joint use of different public transport modes (bus lines, shuttle and feeder services, tramways, metro) should be preserved even if different technologies are managed by different providers.

We want now to understand to which extent these five groups of papers, focusing on different policy issues, are relevant for an assessment analysis according to any of the above mentioned six evaluation perspectives. We present our proposal on the right half of Table 1, using the previously defined scale (from one to three stars). It is clear from the table that the state of the art of the research dealing with economic efficiency analyses in urban public transport, while spanning over an appreciable range of issues, is nevertheless far from dealing with all the relevant evaluation perspectives that we believe are worth of consideration. In particular, it appears that those aspects that are more relevant to study effectiveness deserve more attention. Therefore, one of the sought methodological developments in this area should focus on issues that are more relevant for those individuals and entities that are not directly involved in public transport production or consumption (e.g. public bodies or communities living in areas where the service is taking place). This review has identified only a handful of papers that take such perspective, i.e. that run efficiency analyses considering both productive efficiency and environmental issues (Chang et al., 2013; Fraquelli, Piacenza, & Abrate, 2004; Karlaftis, 2003; Miller, 1970; Oh, Shon, Kim, & Park, 2011; McMullen and Noh (2007); Yu, 2008a, 2008b; Yu & Fan, 2006) or service quality aspects (Hensher, 2014; Mouwen & Rietveld, 2013).

We finally note that in order to close the gap between different perspectives, the internalisation of external and social costs and benefits is often proposed as an evaluation method (shadow prices) or policy measure (environmental or congestion taxes and subsidies). When such an ideal condition achieved, all the five classes of research would become much more relevant for the social issues that we put in the last four row of Table 1. However, the focus of this review is not to suggest ways to more closely match different evaluation perspectives, but rather to analyse how the current state of the art in efficiency analyses could evolve in order to better fit a more general framework. As discussed in Section 1, a promising research avenue seems to focus on the transport engineering literature on indicators that makes use of a wide range of data (Diana & Daraio, 2014). We therefore focus now our analysis on the variables used in the transport engineering studies we have reviewed.

4. Input, output and external variables

The preliminary review of the literature in the preceding section has shown the interest in enriching the set of variables used in economic analyses to make them relevant for a higher number of evaluation perspectives.

The definitions of the set of inputs and outputs used in a production model are of paramount importance in evaluating efficiency, yet the literature on efficiency analysis in urban public transport is relatively homogeneous with regard to the definition of inputs and outputs. This is consistent with the fairly narrow evaluation perspective of the majority of these papers, as it emerged in the previous section. We report in Table 2 the list of input and output variables that are used in the studies we have reviewed, for each variable we also report its occurrence, both in absolute terms and percentage.

Turning first our attention to input variables, these normally fall in two main categories: "physical" production factors with their own measurement units (number of employees, hours of work etc.) on one side, and costs in monetary units on the other, that are further split into capital expenses (CAPEX) and operating expenses (OPEX)[1] in Table 2. Concerning the first category, the number of employees (or hours of work), fuel consumption, number of vehicles in the fleet are largely the most considered variables since they represent the main inputs in the production process. The other two above mentioned "physical" inputs are a measure of the stock of capital (number of vehicles) and of the variable input associated with the use of the capital stock (fuel). It is worth noting that limiting the analysis to this group of input variables may not capture some relevant drivers of efficiency (or inefficiency) such as the distinction between driving and non-driving staff, our review reveals that only a couple of papers include this distinction in their models. As regards the rolling stock, limiting the analysis to the number of vehicles may not spot out inefficiencies especially when talking about tramways, metro and railways. Usually in these categories of LPT services the heterogeneity in the rolling stock is significant and should be considered by including variables such as the number of seats and the standing room per vehicle. As regards the other clusters of input variables we analogously find that the prices of labour, capital and fuel are the far more utilised while only a limited number of papers, mainly representative of the group II of Table 1, go further and consider a broader set of cost oriented input variables such as maintenance and overhead costs.

On the output side, the range of considered measures, reported in Table 2, is wider. We believe that it is nevertheless possible to categorise the output variables in three groups. In the first group, we put variables that measure the production efficiency of the service under investigation: vehicles by travelled kilometres and seats offered by travelled kilometres are the most frequently used. All these measures are from the supply side. In the second group, we put variables related to the effectiveness of the production process, such as number of passengers and passengers by travelled kilometres. The third group represents the financial counterpart of the second one, since it considers the service revenues. Unlike the preceding one, these two latter groups consider output measures on the demand (service consumption) side. The first group of efficiency variables is therefore reflecting the producer perspective, while the other two groups of effectiveness variables describe the community point of view, according to the framework of the preceding section.

Table 2
Input and output variables.

Class	Variable	Percent	No.
Input			
Physical measure	Number of vehicles	60.5	75
	Number of employees	40.3	50
	Fuel consumption	36.3	45
	Employees * hours of work	10.5	13
	Seat capacity (total seats of the fleet)	1.6	2
	Hours of work during service	8.9	11
	Drivers	3.2	4
	Non-driving employees	1.6	2
	Number of depots	0.8	1
CAPEX	Price of capital	21.0	26
	Capital expenses (CAPEX)/fixed assets//investment	4.0	5
	ICT (soft capital) cost	1.6	2
	Possession costs (generalised price of capital or cost of capital including leasing etc.)	0.8	1
OPEX	Price of labour	38.7	48
	Price of fuel	29.0	36
	Operating expenses (OPEX)	12.1	15
	Materials costs (tyres lubricants etc.)	11.3	14
	Fuel costs	8.9	11
	Operating costs of vehicles	6.5	8
	Maintenance	5.6	7
	Operating labour expenses	4.0	5
	Overhead—general/administrative expenses	4.0	5
	Expenses excluding labour and fuel costs (other operating expenses)	2.4	3
	Non-labour maintenance and repair costs	1.6	2
	Total expenses (OPEX + CAPEX) – Total Cost	2.4	3
Output			
Service supply	Vehicles * travelled kilometres	53.2	66
	Seats offered * travelled kilometres	25.8	32
	Vehicles * hours of operations	4.0	5
	Revenue-vehicle kilometre	4.8	6
	Vehicles* revenue hours of service	3.2	4
	Seats offered* hours of operations	0.8	1
Service consumption	Passengers * travelled kilometres	24.2	30
	Number of passengers	16.9	21
	Number of trips	5.6	7
	Number of bus traffic trips on routes	1.6	2
	Load factor	1.6	2
Revenue	Operating revenues	11.3	14
	Fare revenues per unlinked trips	0.8	1
	Total revenue	0.8	1

Concerning this latter point, it is here interesting to recall the debate in the efficiency analysis literature on the most appropriate kind of output measures (De Borger et al., 2002). For example Berechman (1993) considers supply-side variables more appropriate. We concur with that argument if the evaluation itself is only involving the public transport service supply and the service provider is constrained in its operational choices: in this case, factors not under the control of the firm (such as the level of demand or required quality of service) should not be considered. However, transport policy decision makers need broader evaluation exercises, as shown in Table 1: effectiveness analyses cannot just focus on the supply side. Moreover, in an appropriate regulatory setting where public (i.e. policy makers) and private (i.e. operators) goals are aligned, the providers could benefit from the operational flexibility in planning their services (i.e. vehicles * kilometres offered, network design, pricing, etc.) that make

[1] To avoid excessive proliferation of classes we have inserted in the CAPEX class also the price of capital and in the OPEX class the price of fuel and labour.

them responsible also of the effectiveness of the service, in this case demand oriented measures of output are appropriate.

However, if we consider how the characteristics of demand, the spatial and quality attributes of supply strongly influence an appropriate specification of technology for the purpose of performance evaluation, the debate between demand oriented or supply oriented output measures loses much of its significance. In fact, the surrounding social, political and regulatory environment intimately shape objective functions and constraints of transit firms. For instance, when the regulator or the public owner implicitly stimulates over-hiring labour, then cost minimisation at observed input prices is an inappropriate benchmarking model yielding highly misleading results. It is now also generally recognised that transport outputs are heterogeneous in terms of temporal, spatial and quality characteristics. Transport planners have in fact debated over the past decades about the spatial and temporal transferability of their models (Ortúzar & Willumsen, 2011). A suitable spatial and temporal disaggregation of the evaluation model would help in understanding the meaning and origin of differences between offered capacity measures and satisfied demand measures.

Some of the reviewed studies are considering such issues by taking into account an additional set of variables that are listed in Table 3. These latter are not rigidly considered as inputs or outputs of production models, and in some cases they appear as model parameters, or simply terms of reference that are taken to draw meaningful comparisons across services in different areas and different time periods. In the following, we name such group as “external” variables.

Interestingly enough, the biggest cluster in this list refers to quality and service characteristics aspects, two issues that are often not easily distinguishable through the variables that are shown in the table, since such variables are often relevant for both of them. We see here a reflection of the burgeoning literature dealing with quality aspects in public transport. Variables in this first group are well representing both service performances (e.g. commercial speed, on time performance) and accessibility (e.g. length of network, number of stops), that are the two relevant aspects for end users as shown in the third column of Table 1.

In particular, a number of papers consider the fundamental role played by commercial speed in encompassing a large number of quality aspects of the LPT services. A higher commercial speed may reveal both a higher efficiency and a higher effectiveness. In fact, a higher speed implies lower operating costs but also implies a better service (passengers are transported in less time). Commercial speed also relates to external factors that are often out of the operators’ control (i.e. the presence of preferential lanes or other measures to reduce congestion) that directly refer to policy interventions in order to improve the effectiveness of the service. Some other papers consider in their analysis also the average age of the fleet, also this variable refers contemporarily to efficiency and effectiveness since a younger fleet it usually less expensive both in terms of fuel consumption and maintenance costs, it improves the level of passengers’ perceived quality, reduces the vehicles’ failures the pollutant emissions.

The subsequent three groups listed in Table 3 all refer to situational variables that are typically considered to improve the comparability of results in the analysis of different systems. In particular, one cluster contains variables describing the socioeconomic characteristics of the service patronage, while the other two pertain to management and economic characteristics of the service. It clearly emerges that, despite the wide variety of variables used in single and focused studies, only a few are quite recurrently considered. In particular, the population density and the binary location variable (urban/rural) are quite diffused amongst the considered papers in order to describe accessibility while some other papers consider in their analysis variables related to ownership (public versus private) type of contracts and subsidies in order to describe the effects of alternative regulatory regimes.

Table 3
Variables that are considered as neither input nor output in efficiency models.

	Variable	Percent	No.
Quality and characteristics of service	Length of network	24	30
	Average commercial speed	21	26
	Average fleet age	14.5	18
	Service frequency/headway	6.5	8
	Peak to base ratio	1.6	2
	Number of stops	5.6	7
	Average length of a route	3.2	4
	Average number of stops per route	2.4	3
	Intensity—vehicle miles per route mile	0.8	1
	Spares ratio	2.4	3
	On-time performance (time reliability)	2.4	3
	Dummy for intercity/urban/mixed company	16	2
	Service satisfaction score	16	2
	Percent vehicle-kilometres in urban areas	1.6	2
	Passengers’ perceived quality	1.6	2
	Number of night routes	0.8	1
	Number of routes	0.8	1
	Average distance between stops	0.8	1
	Percent compressed natural gas vehicles	0.8	1
	Overlapped route lengths	0.8	1
	Dummy—alternative public transport	0.8	1
	Proximity to train station/bus stop	0.8	1
	Ratio of bus-kilometres to total vehicle-kilometres	0.8	1
	Transport route in relation to route need	0.8	1
	Departure times in relation to departure need	0.8	1
	Operating cost/kilometre	0.8	1
	Travel time	0.8	1
Socio/ demographic–geographic	Population density	16.1	20
	Dummy for location	12.9	16
	Car ownership	7.3	9
	Population in the service area	6.5	8
	Size of the area where the service is accessible	4.8	6
	Climate	2.4	3
	GDP gross domestic product per inhabitant	1.6	2
	Size of the area where the service is implemented	1.6	2
	Population that has access to service	1.6	2
	Ratio of inhabitants who are unemployed	1.6	2
	Average duration of a private motorised trip	0.8	1
	Number of parking spaces	0.8	1
	Gini index for income inequality	0.8	1
	Percent people with disabilities, percent of elderly people	0.8	1
	Perceived difference between men and women	0.8	1
	Ratio of inhabitants living in urban areas	0.8	1
	Percent of poor households	0.8	1
Managerial/ organisational	Dummy for public company	15.3	19
	Dummy for contract type	10.5	13
	Dummy—size of the company	2.4	3
	Dummy for competitive tendering	0.8	1
	Unionisation rate	0.8	1
	Number of owners	0.8	1
	Size of largest owner (percent)	0.8	1
Subsidies	Subsidies from public funds	9.7	12
	Subsidies to operating expenses	8.1	10
	Local subsidy/total subsidies	2.4	3
	Ratio of subsidy in total revenue	1.6	2
	Dummies for type of subsidy	1.6	2
Externalities	Number of accidents	7.3	9
	Emissions	4.0	5

Finally yet importantly, in a handful of papers some variables represent externalities, an issue of central interest for an effectiveness analysis: the most popular aspect here considered is the number of accidents.

We propose a match of the variables in the above tables against the evaluation framework in Table 1 to summarise the findings of this analysis. It is immediate to see that the variables considered in the literature fully cover the first evaluation aspect and are mainly considering the point of view of the service operator (first column of Table 1). Quality issues are increasingly being included, even if their measures and indicators are not univocally embedded in models as either input or output variables. Finally, effectiveness issues are represented through output variables as far as patronage levels are considered. Output is in turn related to road congestion, sustainability, social inclusion or accessibility (last four lines of Table 1). However, other, more direct, measures of these latter dimensions are seldom considered, as the last two rows of the bottom panel of Table 3 show.

The findings from the classification of the papers presented in the previous section seem therefore largely confirmed here. Considering our detailed review of the variables, we think that one promising research avenue could focus on the integration of a broader set of variables in the analysis itself, thus making it relevant for different evaluation perspectives as reported in Table 1. In other words, input and output variables of models, currently mainly restricted to the sets shown in Table 2, could consider a larger number of variables among the "external" ones listed in Table 3, in addition to others that better represent important issues such as congestion relief, environmental impacts, or social inclusion aspects.

This integration requires wider applications and methodological extensions of economic efficiency analysis. Nevertheless, some papers already take such broader perspective when considering input and output variables. Nolan, Ritchie, and Rowcroft (2002) measure both the technical and the social efficiency of transit agencies through DEA (Data Envelopment Analysis; Charnes, Cooper, & Rhodes, 1978). McMullen and Noh (2007) include the amount of emissions of pollutants into an efficiency analysis of transit agencies. Sheth, Triantis, and Teodorovic (2007) explicitly address both the provider and the passenger perspective when evaluating public transport systems, although their paper does not provide an analysis with real data but only a simulation.

Considering some of the input and output variables, that are routinely used in transport engineering to monitor urban public transport operations, could allow researchers to more systematically extend the above results. These variables were analysed in a previous study (Diana & Daraio, 2014) that focused on the "List A" that was mentioned in Section 2. The interested reader is referred to that paper for more details; here it is sufficient to note that, according to such findings, the indicators already available in the transport engineering literature are related to the following eight aspects:

1. "Operational efficiency",[2] to relate the quantities of produced service with the resources being used (example: expenses/(vehicles * kilometre)).
2. Intensity of use of the service, to relate the quantities of produced service with the patronage (example: (passenger * kilometre)/(vehicles * kilometre)).
3. Service use related to input, to relate the patronage with resources being used (example: expenses/(passenger * kilometre)).
4. Relative service dimension, to relate the used resources with the dimension of the potential market (example: fleet dimension/population of the service area).
5. Service coverage, to relate the produced service with the dimension of the potential market (example: lines length/population of the service area).
6. Market penetration, to relate the patronage with the dimension of the potential market (example: passengers/population of the service area).
7. Revenues generation, to relate the revenues with consumed resources, produced service or patronage (example: revenues/vehicle).
8. Externalities, to relate some key effects of the system operations with consumed resources, produced service or patronage (example: number of accidents/(vehicle * kilometre)).

It can be easily recognised that the above eight groups of indicators can cover most of the evaluation perspectives of Table 1, while only some of them can be found in Tables 2 and 3. Integrating more of such indicators into an efficiency analysis could make the latter a powerful tool for transport policy makers.

5. Main methods and econometric approaches

After the detailed investigation of the input, output and other variables used in the reviewed papers, we concentrate our attention on the methods applied by researchers for their empirical investigations on LPT. The classification of the main econometric approaches used in the LPT literature required a dedicated effort and the combination of an exploratory analysis and a subsequent systematic investigation.

5.1. Initial assessment through density maps

We started by exploring the main methodological terms with the help of the VosViewer software, to have a first approximated picture. Fig. 1 shows the density map of the most relevant terms in the methodological section of the analysed studies. Colours indicate the density of terms, ranging from blue (lowest density) to red (highest density).

As it clearly appears from Fig. 1 there are two well-identified groups of methods that have been applied in the literature on LPT analysed in this study. A predominant parametric approach[3] on the West (W) side of the figure, going from the South-West (SW) of the figure, based on Cobb–Douglas cost functions, to the North-Centre (NC) part of the figure, characterised by the predominance of Translog cost functions. These studies use on the one hand parametric frontier models (the so called Stochastic Frontier Analysis, SFA, see e.g. Kumbhakar & Lovell, 2000). On the other hand, they use multistage analyses ("stage" in Fig. 1) of cost functions, when the model includes parameters to represent the determinants of cost-based performance. Most studies that estimate total cost are located in the SW corner of Fig. 1. A smaller group of studies, located at the CE of the figure, adopt a nonparametric approach based on DEA; this group includes also total factor productivity analysis based on Malmquist indices. Interestingly it seems that the nonparametric approach application originated by the evolution of a part of the literature on the cost function on "average cost function" based analysis (SW corner of the figure). Close to the group of studies that use the Translog cost function we find works that applied a demand analysis, namely estimated the parameters of total demand for travelling by LPT as a function of deregulation measures, fares, and other factors. Of course, within each cluster that identifies a predominant approach less typical methods or variations co-exist.

Widening the perspective, we can see in Fig. 2 a density map of the objectives of the surveyed studies in which also the main used methods are included. Fig. 2, in fact, illustrates the density map of the most relevant terms in the abstracts of the analysed studies.

By inspecting Fig. 2 we observe that nonparametric methods based on DEA and total factor productivity ("factor productivity" in the NC of the map) are entering into the empirical analysis of LPT showing peculiarities with respect to the traditional "economic" analysis based on total cost and average cost function estimates,

[2] In a broad sense, according to a transport planning view; this concept is different from technical efficiency which refers to output–input relations, for more details see Section 5.

[3] In the parametric approach a pre-defined functional form for the relation among variables is specified and the relative parameters are estimated afterwards.

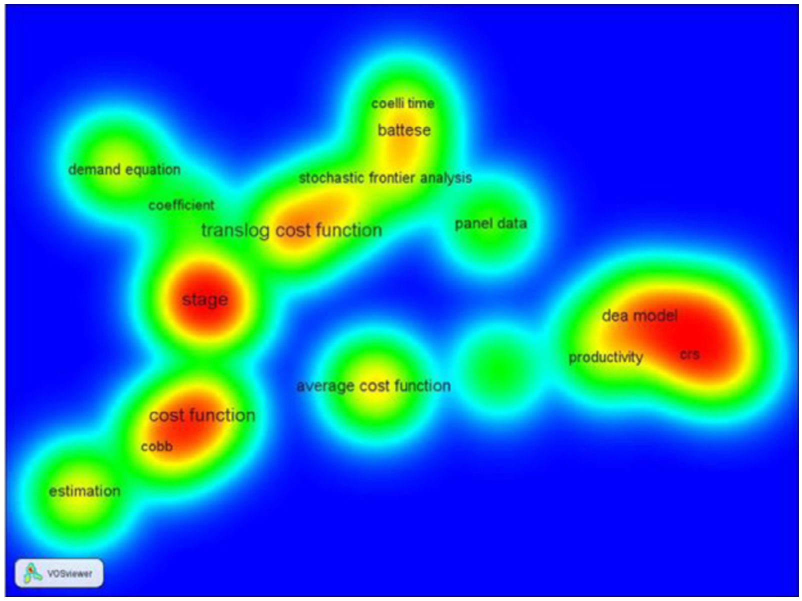

Fig. 1. Density map of the most relevant terms in the methodological section of the analysed studies. (For interpretation of the references to colour in the text, the reader is referred to the web version of this article.)

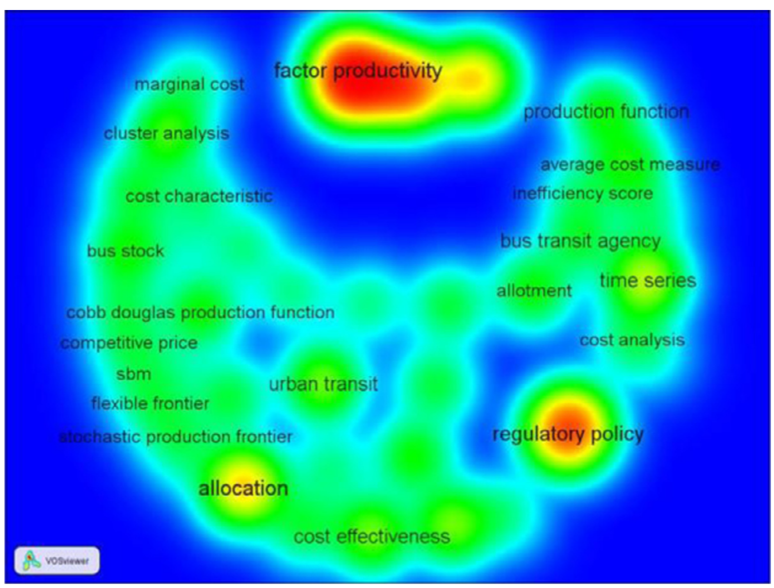

Fig. 2. Density map of the most relevant terms in the abstracts of the analysed studies.

which are based on standard regression methods. On the contrary, SFA seems closer and more integrated with the traditional approach: it looks like a kind of evolution of the standard regression approach keeping as link the functional specification of the relationship between inputs and output of the analysis (very often a Cobb–Douglas, even if also Translog functions are applied).

Regulatory policies (SE corner in Fig. 2) seem closer to traditional cost analysis based on ordinary least squares estimates methods (in CE of Fig. 2). Regulatory policies are linked with “allocations” and “cost effectiveness” (SC of Fig. 2) which are related to parametric production frontiers, which represent a kind of evolution of the traditional cost analysis (“stochastic production frontiers” and “Cobb–Douglas” in Centre-SW part of Fig. 2). Far away are located the nonparametric methods, including DEA (“factor productivity” in NC of Fig. 2), which are more flexible and are characterised by a wider range of used variables, as we shall see in the following of this section. It seems that the nonparametric approach entered later and is growing within this literature.

5.2. Classification of the methods

We will investigate later in the section what are the relationships between inputs/outputs and other variables adopted in the different studies and how the usage of these variables changes according to the methods applied.

Before, to deepen our understanding of the main methods applied in the literature, we carried out a systematic examination of the selected studies that were classified according to an overall methodological framework, summarised in Table 4, whose main dimensions are:

- *Benchmarking.* This dimension relates to the benchmark against which the researchers compare the analysed sample. We find here two main approaches: *average analysis versus frontier analysis*. The main difference relies on the kind of benchmark selected for the analysis. In the *average analysis*, using regression methods, the expected value of the dependent variable, given the independent

Table 4
Taxonomy of the econometric approaches used in the literature.

		Assumption on the DGP	Kind of analysis	
		Parametric (P) versus nonparametric (N)	Input–output (IO)	Cost (C)
Benchmark	Regression (R)	PR		
		NR		
	Frontier analysis (FA)	PFA		
		NFA		

ones, is estimated, pointing to estimate a kind of "average" performance of a representative unit of the analysed sample. Instead, in the *frontier analysis*, the benchmark is set at the most efficient estimated level for the analysed units in the sample that is at the boundary of the production possibility set. Deviations from the best performing behaviour are estimated as the distance of units from the efficient boundary.

- *Assumptions on the Data Generating Process (DGP). Parametric versus nonparametric approach.* This distinction derives from the functional specification of the relationships among variables. We observe two main approaches: a parametric functional specification versus a nonparametric specification of this relationship.
- *Kind of analysis.* This distinction opposes studies that analyse only "physical" (input–output) relationships versus studies that investigate the cost dimension of the analysed units. In a frontier setup, this distinction amounts to the analysis in terms of distance from the efficient boundary of the input–output production possibility set (technical efficiency) against the specification of additional behavioural goal expressed minimising costs, considering also information on prices. In this latter case, we talk about allocative or price efficiency.

It is interesting to note that no surveyed paper, applied a nonparametric regression (NR) framework, and therefore the corresponding cells in Table 4 are shadowed. On the contrary, all empirical studies that investigated the average behaviour of public transport units have used a parametric regression approach: in most cases ordinary least squares (OLS), see e.g. Merewitz (1977) and Alexandersson, Hulten, and Folster (1998); in other cases, seemingly unrelated regressions (SUR; Zellner, 1962), such as Cambini, Piacenza, and Vannoni (2007). While earlier studies (such as Koshal, 1970; Miller, 1970; Pucher, Markstedt, & Hirschman, 1983) consider mainly input–output relations, in more recent studies prevail the estimation of variable and total costs (e.g. Cambini et al., 2007; Fraquelli et al., 2004; Obeng & Sakano, 2002; Ottoz & Di Giacomo, 2012, among others).

On the other hand, the efficiency literature provides a number of alternative ways of measuring the technical efficiency of production. In our sample of papers the main methods used are SFA, DEA and parametric cost functions.

The empirically most used SFA model is the Battese and Coelli (1995) Cobb–Douglas production function specification in a panel setting which allows for the introduction in the estimation of external factors or parameters that affect the inefficiency term (see e.g. Piacenza, 2006). Most SFA literature estimated Cobb–Douglas or Translog frontiers.

DEA in its various forms (i.e. input oriented, output oriented, pooled DEA in which all the observations for all the years are considering together, or Malmquist DEA or simple DEA with different RTS (Returns to Scale) assumptions, such as VRS (Variable Returns to Scale), CRS (Constant Returns to Scale)) provides estimates of technical efficiency for each single observation. Most papers focus exclusively on the identification of those efficiency scores, without neither investigating the statistical precision of the estimates nor analysing the influence of external variables on the obtained estimates. Some notable exceptions which applied the bootstrap are the papers of Boame (2004), De Borger, Kerstens, and Staat (2008) and von Hirschhausen and Cullmannn (2010). Some papers nevertheless tried to identify the effect of a number of external environmental variables onto the efficiency of production. There are several ways for introducing external factors in a nonparametric efficiency analysis (see e.g. Badin, Daraio, & Simar, 2014 for an overview). In the so called "one stage approach" the external factors are included directly in the estimation of the efficient frontier and hence of the efficiency scores. If the external factor has a positive role in the production process it is introduced in the analysis as an additional input freely available; if it has a negative impact it is introduced in the analysis as an extra undesired output to be produced. However, even if simple to implement, this approach shows several weaknesses. Firstly, the analyst should know in advance what the sign of the impact of the external factor is. Secondly, non-linear impacts (such as u-shaped or inverse u-shaped impacts) cannot be included. Thirdly, the free disposability (that broadly speaking means the possibility of destroying goods without costs) of these factors is assumed as well as the free disposability of the extended production set (including the external factors). This approach is not used any more frequently, given the strict assumptions it requires.

The most used approach to include external factors in the analysis is the so-called "two stage approach" in which the efficiency scores are estimated using a nonparametric approach in a first stage and are regressed in a second stage versus external environmental variables. Some papers in our sample have been published in years in which the nonparametric statistical approach in efficiency analysis was less known. We observe in fact that most of those that applied a two stage approach (e.g. Boame, 2004; Cowie, 2002; Kerstens, 1996; Nolan, 1996; Nolan, Ritchie, & Rowcroft 2001; Pina & Torres, 2001; Soderberg, 2009; Tsamboulas, 2006) did not specified a general and correct statistical framework. As a consequence, their estimates could be unreliable and biased. As demonstrated in Simar and Wilson (2007), the efficiency scores estimated in the first stage are biased estimates and if they have to be regressed in a second stage, standard inference does not work and hence a bootstrap procedure is necessary. Also, the Tobit regression that has been applied in other studies is not appropriate: instead, a truncated regression has to be implemented in a two stage semi-parametric approach. [4] However, even if correctly implemented, the two-stage approach relies on a very strong assumption, namely the *separability condition*, on the base of which, it is assumed that the external factors do not influence the "efficient frontier" but only the distribution of the distances of the observations from the efficient frontier. This is a strong assumption because external factors may affect both the efficient boundary and the distribution of inefficiency (Badin, Daraio, & Simar, 2012).

Only very few studies (including Oh et al., 2011; Pestana Barros & Peypoch, 2010; McMullen & Noh 2007)) applied a directional distance framework which allows for a more flexible specification of the direction of movement of an observed unit towards the frontier. None

[4] See the Appendix of Simar and Wilson (2007) for an extensive description of why the Tobit regression cannot be applied in this context and for a clarification of the misunderstanding in the use of terms truncation and censoring.

Table 5
Distribution (percent) of input variables per paper and method.

Input													
		PR (41)				NFA (54)			PFA (29)				
		IO (10)		C (31)		IO (53)		C (1)	IO (10)		C (19)		
Class	Variable	I	P	I	P	I	P	I	I	P	I	P	
Physical measure	Number of vehicles	50		51.6		64.2	3.8		70		57.9		
	Number of employees	10	10	22.6		66.0			50		5.3		
	Fuel consumption		10	19		58.5			40		15.8		
	Employees ∗ hours of work			6.5		15.1			20		5.3		
	Seat capacity (total seats of the fleet)			6.5	6.5	9.4						10.5	
	Hours of work during service			6.5		1.9			10				
	Drivers					3.8							
	Non-driving employees					3.8							
	Number of depots					1.9							
CAPEX	Price of capital	10		45.2		1.9			20		42.1		
	Capital expenses (CAPEX)/fixed assets//Investment	10		3.2	3.2		1.9			10			
	ICT (soft capital) cost			3.2							5.3		
	Possession costs (generalised price of capital or cost of capital including leasing etc.)					1.9							
OPEX	Price of labour	40		77.4		1.9			30		84.2		
	Price of fuel	20		58.1		1.9			20		68.4		
	Operating expenses (OPEX)	30		3.2		17.0			20				
	Materials costs (tires lubricants etc.)	10		19		7.5					15.8		
	Fuel costs			10		9.4		100	20				
	Operating costs of vehicles	10		6.5		5.7			10		5.3		
	Maintenance			10		3.8	1.9		10				
	Operating labour expenses	10		3.2		1.9		100	10				
	Overhead—general/administrative expenses	20		3.2		3.8							
	Expenses excluding labour and fuel costs (other operating expenses)					3.8		100					
	Non-labour maintenance and repair costs	10		3.2									
	Total expenses (OPEX + CAPEX) total cost								20		5.3		

of the analysed studies implemented robust nonparametric methods in efficiency analysis. [5]

5.3. Relationships between kind of I/O variables and method of analysis

Having completed the short description of the main methods applied in the surveyed papers, we can investigate in details the relationships between input, output and external variables, as they were presented in Section 4, and how they vary according to the method empirically applied in the analysed studies.

The following Tables 5–7 are the relative contingency tables (percent of occurrences) respectively of the input, output and external variables (rows of the tables) considered in the 124 reviewed papers, matched against the different methods (columns of the tables). The columns consider the combinations of the following three methodological variants: assumptions, according to the left side of Table 4 (columns PR (parametric regression), NFA (nonparametric frontier analysis) and PFA (parametric frontier analysis) respectively), approaches, according to the right side of Table 4 (columns IO (input–output or technical approach) and C (cost approach)) and ways of considering the variable, according to the discussion in Section 4 (columns I (inputs), O (outputs) and P (parameters)). In such cases, the percent shown in each column for each variable has been calculated with respect to the number of papers classified by method and approach. For example, in Table 5, the variable "number of vehicles" has been used as input variable by the 50 percent of the papers (10) classified as parametric regressions based papers (PR) with an input–output approach and as parameter variable (P) by the 3.8 percent of the papers (53) classified as nonparametric frontier analysis (NFA) with an input–output approach.

Tables 5–7 offer a lot of interesting information that could be useful for applied researchers or policy makers which aim to analyse efficiency and effectiveness of LPT units. Interested readers can focus on the most frequently used variables and see also how the variables used change according to the methods applied. Considering only those cells in the table that are related to a sufficiently high number of papers, the most dramatic changes in relative frequencies of a given variable (row) according to the method could be observed for fuel consumption, price of labour and of fuel for input variables (Table 5); number of passengers and passengers ∗ travelled kilometre for output variables (Table 6) and commercial speed or population density for "external" ones (Table 7). At the other extreme relative frequencies of many other variables are not significantly affected by the used method. Such discrepancies could be an indication that some of the reviewed variables can more or less easily be considered through some methods, whereas for others this is not a real issue.

What immediately emerges from the tables is that parametric models (regression and frontier analysis) are mainly focused on the cost approach while non-parametric models consider, with the exception of a single paper, only the IO approach. Considering the input variables, we see that they are quite homogeneously distributed throughout the different methods. Within the physical measures of input, within the three mainly utilised, the number of vehicles share similar percentage independently of the method or the approach. The number of employees and fuel consumption are largely employed in non-parametric methods while they are more variably utilised

[5] These are methods which estimate the efficient boundary of the units analysed being less influenced by outlying and anomalous observations. For an introduction and an overview, see Daraio and Simar (2007).

Table 6
Distribution (percent) of output variables per paper and method.

Output		PR (41)				NFA (54)			PFA (29)		
		IO (10)		C (31)		IO (53)		C (1)	IO (10)	C (19)	
Class	Variable	O	P	O	P	O	P	O	O	O	P
Service supply	Vehicles * travelled kilometres	36.4	9.1	56.7		52.8	1.9		50	52.6	
	Seats offered * travelled kilometres	18.2		26.7		28.3		100	20	21.1	
	Vehicles * hours of operations	18.2				3.8				5.3	
	Revenue-vehicle kilometre	9.1				7.5					5.3
	Vehicles * revenue hours of service					5.7					5.3
	Seats offered * hours of operations					1.9					
Service consumption	Passengers * travelled kilometres	9.1		16.7	3.3	32.1			10	21.1	5.3
	Number of passengers	9.1		10		26.4	1.9		10	5.3	
	Number of trips	9.1		3.3			3.8		20	5.3	
	Number of bus traffic trips on routes					3.8					
	Load factor					1.9					5.3
Revenue	Operating revenues	9.1	9.1	13.3		9.4			10	10.5	
	Fare revenues per unlinked trips								10		
	Total revenue			3.3							

throughout the parametric methods. On the opposite we find that price of capital, price of labour and price of fuel are blockbuster in parametric cost models (both regression and frontier) while practically neglected in non-parametric methods. The reason of such dichotomy is attributable to the fact that these variables are related to cost analysis while the focus of non-parametric models is on the IO approach.

On the output variables side, we find more interestingly that parametric methods are mainly oriented to supply side measures while non-parametric methods are more keen in extending the analysis also to consumption side measures of output.

Considering the set of external variables, we observe that parametric methods are more compact in the choice of variables focusing on the variables already discussed in Section 4 while non-parametric methods use a larger variety of external variables. For a detailed discussion on the modelling choice for the technology and the input/output specification see also De Borger et al. (2002, Section 3, p. 9 and ff.).

5.4. Temporal evolution of the analytical approaches

To conclude our analysis on the methods, we show in Fig. 3 the evolution over time of the number of papers published for each type of method.

From Fig. 3 it appears that the parametric frontier approach (PFA) has taken the heritage of the traditional parametric regression approach (PR) which is less and less used in the applied works. On the contrary, we observe a deep increase in the use of the nonparametric frontier approach (NFA) and foresee a great potential for future application of recently proposed advancements within this field. In our view, the main advances rely on the overcoming of the traditional limitations of the nonparametric approach based on DEA techniques, namely:

- deterministic nature and impact of extreme or outlying points on the estimates;
- separability condition to be assumed for the estimation of the impact of external factors and hence for taking into account the heterogeneity of the analysed units;
- more flexible specification of the benchmark moving from equi-proportional radial-based efficiency scores based on DEA to more flexible directional distance measures.

As showed by Badin et al. (2012), robust nonparametric conditional efficiency analysis is a more general approach to evaluate the impact of external factors in nonparametric frontier models and to allow for the heterogeneity of units in the performance measurement without relying on the separability condition we recalled above. Moreover, a framework in which the efficient boundary does not envelop all points is more robust to extremes and outliers. The main idea of conditional efficiency analysis is to estimate the probability of being dominated of each unit, according to its inputs and outputs in a multidimensional framework frontier, keeping into account the external factors which might influence its performance, and allowing for a finer comparison of units with other units sharing the same external environmental conditions.

Within this framework, Daraio and Simar (2014) extended Badin et al. (2012) approach to the directional distance framework and propose a bootstrap based test for the estimation of the statistical significance of the impact of external factors on the performance. We see a great potential in the application of robust (to outliers and extreme values) and nonparametric conditional directional distances for running a more general and robust assessment of the LPT performance.

6. Data analysed

This paragraph provides information about the type of dataset used (i.e. cross-section, time-series, pooled cross-section or panel data), sample size (number of operators and years analysed) and the countries in which the transit systems analysed in the selected studies operate. In particular, Table 8 by providing information on the type of data and the sample size shows that panel and cross-sectional studies prevail in the literature. The sample size varies widely both on the number of entities observed (from 1 up to 444, 68 on average) and time span that, excluding cross-sectional studies, ranges from 2 to 33 years (6.43 years on average). Of the 124 papers reviewed, the great majority takes transit operators (95 papers) or municipalities (22 papers) as sample unit. Of the remaining seven papers four utilise wide geographical areas (i.e. counties), two papers collect data at route level and one at passenger level; see Table 9.

Table 10 shows that the majority of the studies deals with EU or USA national data, at country level (73 percent), 13 papers deal with international data, of which only six deals with EU countries. Table 10 also shows that only a very small number of studies have analysed transport systems at regional (6 percent) or city level

Table 7
Distribution (percent) of external variables per paper and method.

		PR (41)			NFA (54)				PFA (29)				
		IO (10)	C (30)		IO (53)			C (1)	IO (10)			C (19)	
	Variable	P	I	P	I	O	P	P	I	O	P	I	P
Quality and characteristics of service	Length of network	10		22.6	18.9		3.8				30		36.8
	Average commercial speed	50		19.4	1.9	3.8	15.1						21.1
	Average fleet age	30		12.9	3.8	1.9	9.4						15.8
	Service frequency/headway	10				7.5	3.8						5.3
	Peak to base ratio	30					5.7						5.3
	Number of stops			9.7	1.9								
	Average length of a route			3.2			1.9						5.3
	Average number of stops per route						5.7						
	Intensity—vehicle miles per route mile	10			1.9								5.3
	Spares ratio	10			1.9								
	On-time performance (time reliability)	10				1.9							
	Dummy for intercity/urban/mixed company			3.2			1.9						
	Service satisfaction score			3.2			1.9						
	Percent vehicle-kilometres in urban areas					1.9					10		
	Passengers' perceived quality	10											
	Number of night routes												5.3
	Number of routes						1.9						
	Average distance between stops						1.9						
	Percent compressed natural gas vehicles						1.9						
	Overlapped route lengths						1.9						
	Dummy—alternative public transport						1.9						
	Proximity to train station/bus stop					1.9							
	Ratio of bus-kilometres to total vehicle-kilometres					1.9							
	Transport route in relation to route need					1.9							
	Departure times in relation to departure need					1.9							
	Operating cost/kilometre				1.9								
	Travel time					1.9							
Socio/demographic–geographic	Population density	20		12.9	5.7		9.4				30		15.8
	Dummy for location	20		6.5	3.8		5.7	100					31.6
	Car ownership	10					13.2				10		
	Population in the service area	10			7.5		1.9		10			5.3	
	Size of the area where the service is accessible			3.2			1.9				30		5.3
	Climate						3.8					5.3	
	GDP gross domestic product per inhabitant	10					1.9						
	Size of the area where the service is implemented			3.2									5.3
	Population that has access to service						1.9				10		
	Ratio of inhabitants who are unemployed						3.8						
	Average duration of a private motorised trip	10											
	Number of parking spaces	10											
	Gini index for income inequality	10											
	Percent people with disabilities, percent of elderly people										10		
	Perceived difference between men and women					1.9							
	Ratio of inhabitants living in urban areas						1.9						
	Percent of poor households										10		
Managerial/organisational	Dummy for public company	20		25.8			3.8	100			20		21.1
	Dummy for contract type			6.5			5.7	100			10		31.6
	Dummy—size of the company			3.2			1.9						5.3
	Dummy for competitive tendering			3.2									
	Unionisation rate											5.3	
	Number of owners						1.9						
	Size of largest owner (percent)						1.9						

(*continued on next page*)

Table 7 (*continued*)

		PR (41)			NFA (54)				PFA (29)				
		IO (10)	C (30)		IO (53)			C (1)	IO (10)			C (19)	
	Variable	P	I	P	I	O	P	P	I	O	P	I	P
Subsidies	Subsidies from public funds	10		12.9	1.9		1.9				20		15.8
	Subsidies to operating expenses	10	3.2				7.5				10		15.8
	Local subsidy/total subsidies	10		3.2									5.3
	Ratio of subsidy in total revenue			3.2								5.3	
	Dummies for type of subsidy			3.2									5.3
Externalities	Number of accidents	10		3.2		3.8	7.5			10			
	Emissions					7.5					10		

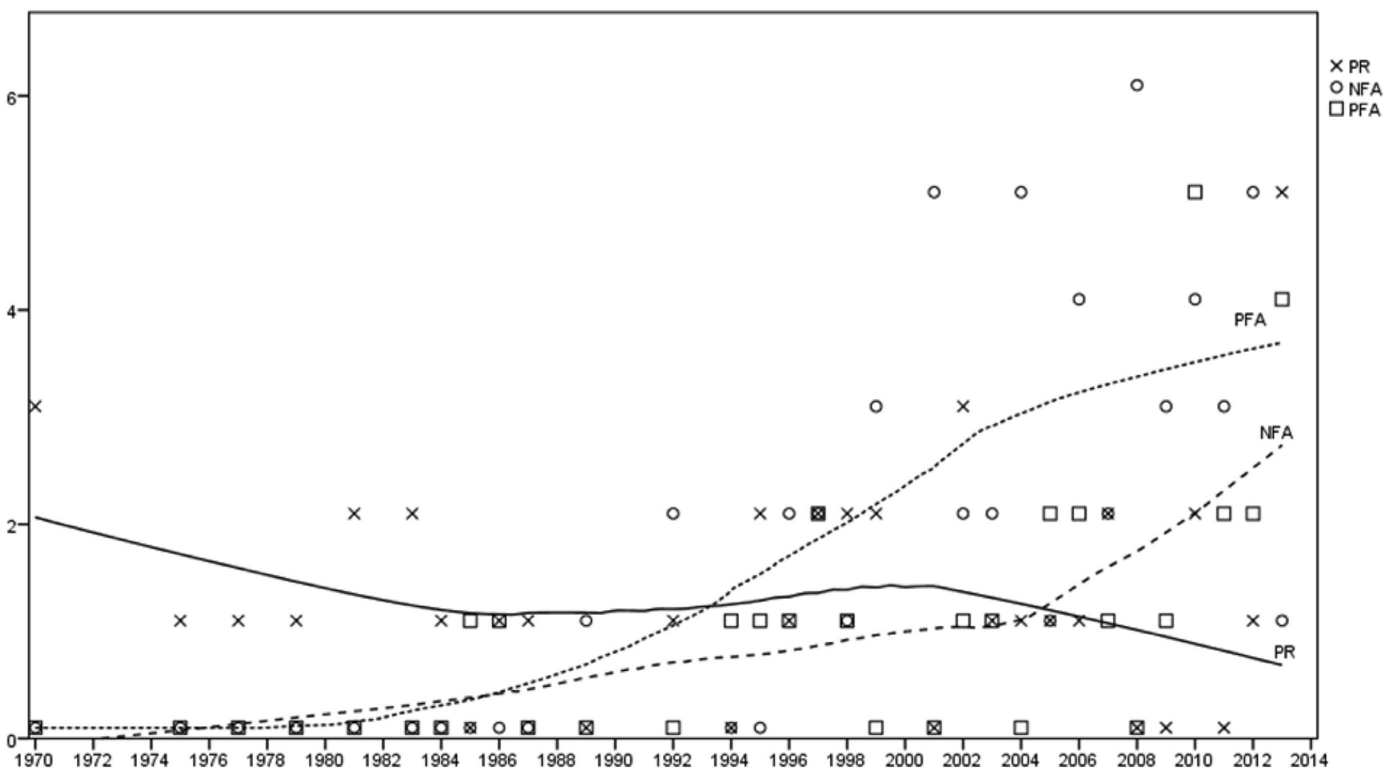

Fig. 3. Evolution of the number of papers per publication, year and method (PR is parametric regression, NFA is nonparametric frontier analysis and PFA stands for parametric frontier analysis). Lines are nonparametric smoothed trends (loess with 65 percent of interpolated points).

Table 8
Distribution of papers by type of data used, sample size and time span.

	No.	Percent	N_firms (entities) Mean	Max	Min.	Time_span Mean	Max	Min.
Time series	8	6.5	31.2	168	1	7.13	16	1
Pooled cross section	9	7.3	132.3	440	3	8.56	20	2
Panel	62	50.0	59.9	444	5	9.85	33	2
Cross section	45	36.3	76.3	261	8	1	1	1
Total	124	100	69.6	444	1	6.37	33	1

(10 percent). Table 10 also provides information on the data source: the data source panel compares the number and percent of papers that make use of official and sometimes publicly available databases ("official data" in the table) with the papers that utilise ad hoc surveys such as questionnaires or interviews with the transit operators. The availability of transport and economic data in this branch of literature is fundamental and the availability of public databases is strictly correlated with the production of quality papers. The majority of the selected papers (78 percent) takes data from official sources such as transport authorities or statistical offices. In particular, 36 of the 124 published papers (29 percent) use data provided by the National Transit Database, a US public databank in which detailed data on transit systems are freely available.

7. The tactical planning of urban transit services through OR techniques and its connections with our evaluation perspectives

This article has reviewed the state of the art of applications of economic efficiency analyses to the operations of urban public transport. Moreover, it has given evidence on how such analyses could broaden their scope by taking into consideration the transport engineering and planning viewpoint. Before coming to our conclusions, we

Table 9
Distribution of papers by unit of analysis.

Sample unit	No.	Percent
Large-scale (national, regional, counties etc.)	4	3.2
City-wide system, transit agency	22	17.7
Operator	95	76.6
Transit line	2	1.6
Passengers	1	0.8

however feel that the review would not be complete without making a connection with another related research sector, namely the design and operation of urban public transport systems through operations research techniques.

A full review of the wealth of scientific production in this latter field is beyond the scope of this paper: here we rather focus on showing the points in common between efficiency analysis and operations research, when both are applied to the study of public transport systems. From our perspective, it is interesting in particular to look at the decision variables, objective functions and constraints that are normally considered in transit-related optimisation tools that are somewhat the counterpart of the input and output variables of efficiency models. Solution methods, usually starting with the solution of a passenger assignment problem, are less relevant in our review and they will not be discussed in the following. The goal is then to understand to which extent it could be possible to make also such tools more relevant under different perspectives by considering different sets of variables, according to the framework developed in Sections 3 and 4. Economic efficiency analyses are often employed to run ex-post evaluations, while operations research methods are normally used as ex-ante design tools. Therefore, it is of interest here to understand to which extent such design process could better take into consideration the different viewpoints shown in the left part of Table 1.

Consistently with the definitions of the three initial bibliographic lists in Section 2, we focus here on the tactical planning level, where the schedule of the urban public transport service (excluding railways and intercity services) has to be determined and decision variables are typically headways, frequencies or timetables. Therefore, we let aside the strategic level involving the design of the network and the definition of the routes. Such distinction between the two levels is quite relevant in practice, since the network (re)-design occurs in real systems not too frequently, whereas service schedules are typically adjusted on a seasonal basis. However, it is sometimes blurred in the scientific literature, since models are often implemented to jointly perform both tasks. In this case, we only considered articles that primarily address tactical design problems (e.g. headways adjustments, routes synchronisation, optimisation of transfers). On the other hand, also the operational level, that is concerned with the scheduling of vehicles and crews, is not relevant here, since it is exclusively related to the production of the service and therefore to the point of view of the service operator. We are also disregarding more specific scheduling problems, such as short-turning, corridor express services, feeder services, or deadheading, along with issues related to dynamic and real-time service management or equilibrium problems involving travel demand assignment to the network.

An overview and definition of the tactical design of a public transport service can be found in Ceder (2002, 2007), whereas Liebchen (2007) provides a mathematical treatment of the timetabling problem. A number of good reviews of the state of the art in this very active research area has appeared, starting from the works of Odoni, Rousseau, and Wilson (1994) and Desaulniers and Hickman (2007). Kepaptsoglou and Karlaftis (2009) focus on the state of the art of strategic transit network design, while Guihaire and Hao (2008a, 2008b) cover both strategic and tactical planning levels. The most recent reviews include the works of Farahani, Miandoabchi, Szeto, and Rashidi (2013), that show the common points between transit and road network design, and Yan, Liu, Meng, and Jiang (2013), that focus on researchers jointly addressing the design of the routes and of the service frequencies. Even if our perspective is different, since we are particularly interested in making a connection with economic efficiency studies, in the following we are mainly focusing on more recent works, or works that have not been included in the above reviews, letting the interested reader to extend the analysis to the wealth of previous works that were already considered there. In most cases, those reviews are in fact already presenting some summary tables with an indication of the objective functions, the constraints or the model parameters of the considered papers.

Table 10
Distribution of papers by country and coverage of the study.

			Coverage						Data source					
	International		National		Regional		City		Official data		Ad hoc survey			
Country	No.	Percent	No.	Percent	No.	Percent	No.	Percent	No.	Percent	No.	Percent	No.	Percent
Australia	3	2.4			1	33	1	33	1	33			3	100
Belgium	1	0.8			1	100							1	100
Canada	1	0.8			1	100					1	100		
France	6	4.8			5	83			1	17	6	100		
Germany	2	1.6			2	100					2	100		
India	4	3.2			3	75	1	25			1	25	3	75
Israel	2	1.6			2	100					2	100		
Italy	7	5.6			5	71	2	29					7	100
Japan	2	1.6			2	100					2	100		
Korea	3	2.4			1	33			2	67	3	100		
The Netherlands	1	0.8			1	100							1	100
Norway	11	8.9			10	91	1	9			11	100		
Portugal	2	1.6			2	100							2	100
Spain	5	4.0			4	80	1	20			1	20	4	80
Sweden	4	3.2			4	100					4	100		
Switzerland	5	4.0			5	100					5	100		
Taiwan	11	8.9			8	73			3	27	11	100		
UK	4	3.2			4	100					4	100		
United Arab Emirates (UAE)	1	0.8			1	100							1	100
USA	36	29.0			30	83	2	6	4	11	35	97	1	3
EU	7	5.6	7	100							3	43	4	57
International	6	4.8	6	100							6	100		
Total	124	100	13	10	92	74	8	6	11	9	97	78	27	22

Table 11
Classification of recent papers dealing with the tactical design of urban public transport.

Reference	Addressed problem	Objective function*	Decision variables**	Relevant constraints***
Castelli, Pesenti and Ukovich (2004)	Transfer synchronisation	Operator cost + wait time		
Ting and Schonfeld (2005)	Headway setting and transfer synchronisation	Operator cost + wait time + number of transfers	Headway	
Cevallos and Zhao (2006)	Transfer synchronisation	Wait time for transfers		
Fleurent, Lessard and Séguin (2007)	Transfer synchronisation	Difference between actual and ideal wait time, headway evenness, fleet size, deadheads		
Guihaire and Hao (2008a, 2008b)	Headway/frequency setting	Difference between actual and ideal wait time, headway evenness, fleet size	Timetables	
Sun, Zhou and Wang (2008)	Headway/frequency setting	Operator cost + total travel time (transfer, in-vehicle and wait)		Headway
Zhao and Zheng (2008)	Network design and headway setting	Total travel time (transfer, in-vehicle and wait)		Headway, capacity
Bruno, Improta and Sgalambro (2009)	Transfer synchronisation	Operator cost + wait time		
Michaelis and Schöbel (2009)	Network design and headway setting	Difference between bus and car travel time		Fleet size
Mauttone and Urquhart (2009)	Network design, headway setting	Transfers, travel time, wait time and min fleet size (multi-objective)		load factor, frequency
Guihaire and Hao (2010)	Timetabling optimisation, vehicle scheduling	Difference between actual and ideal wait time, headway evenness, fleet size, dead-ending trips	Timetables	
Shafahi and Khani (2010)	Transfer synchronisation	Wait time		Headway
Yu, Yang, and Yao (2010)	Bi-level: headway setting and assignment	Total travel time (in-vehicle and wait)	Headway	Fleet size
Szeto and Wu (2011)	Network design and headway setting	Total travel time (transfer, in-vehicle and wait)		Fleet size, frequency
Gallo et al. (2011)	Headway setting	Operator cost + travel cost + environmental cost	Frequency	Frequency, fleet size, fleet run, capacity
Yu et al. (2011)	Headway/frequency setting	Operator cost + total travel time (in-vehicle and wait)	Headway	Fleet size
Chowdhury and Chien (2011)	Headway setting and transfer synchronisation	Operator cost + total travel time (transfer, in-vehicle and wait)	Headway, bus size	
Hadas and Shnaiderman (2012)	Headway/frequency setting	Cost of capacity shortage + cost of capacity overage	Headway, bus size	
dell'Olio, Ibeas and Ruisánchez (2012)	Bi-level: headway setting and assignment	Operator cost + total travel time (transfer, in-vehicle and wait)	Headway, bus size	Fleet size, capacity
Ruisanchez, dell'Olio and Ibeas (2012)	Bi-level: headway setting and assignment	Operator cost + total travel time (transfer, in-vehicle and wait)	Headway, bus size	Fleet size, capacity
Ferguson et al. (2012)	Headway/frequency setting	Accessibility evenness		Capital and operating budget
Ibarra-Rojas and Rios-Solis (2012)	Transfer synchronisation	Number of synchronised transfers		Headway
Verbas and Mahmassani (2013)	Headway/frequency setting	Ridership + wait time		Subsidy or profit, fleet size, headway, capacity
Li and Xu (2013)	Headway/frequency setting	Profits (revenues − costs), wait time (multi-objective)		Headway, capacity
Petersen et al. (2013)	Timetabling optimisation, vehicle scheduling	Operator cost + transfer cost (wait time)		Fleet size
Szeto and Jiang (2014)	Bi-level: network design and assignment	Transfers		Fleet size, frequency, line capacity
Saharidis, Dimitropoulos and Skordilis (2014)	Transfer synchronisation	Wait time		Headway
Hu and Liu (2014)	Headway/frequency setting	Operator cost + wait time		Headway, fleet size
Ibeas, Alonso, dell'Olio and Moura (2014)	Bi-level: headway setting and assignment	Operator cost + total travel time (transfer, in-vehicle and wait)	Headway, bus size	Fleet size
Martínez, Mauttone and Urquhart (2014)	Headway/frequency setting	Travel time + wait time		Frequency

*in case of bi-level studies, only objective functions and constraints related to the tactical problem are indicated.
**if not indicated, then objective functions are usually defined in terms of the quantities indicated in the third column of the table.
***not including the "obvious" ones from mathematical programming (e.g. subtour elimination, flow continuity …).

Keeping into consideration such framework, we analyse a representative set of 30 papers that have been published in the last 10 years. Table 11 lists such works, indicating the kind of tactical problem being studied in the second column. It can be seen that the two most studied problems are the setting of headways (or their reciprocal, i.e. service frequencies) and the synchronisation of timetables at transfer points. Actually the two problems are related, and some works are explicitly addressing both in their modelling efforts. In other works, such tactical problems are embedded in the network design or in a bi-level optimisation approach, involving either the interaction between transport offer and demand (definition of passenger paths to find the flows in all lines through an assignment model) or operational problems such as vehicle scheduling.

The definition of the objective function that is of central interest in our analysis is reported in the third column of the table. Almost all the considered works include the minimisation of wait times at bus stops, or the minimisation of its difference from an ideal wait time in case of transfers, when transfer times from one line to another are taken into account. Other measures related to service quality include the minimisation of in-vehicle travel times and transfer times. Two thirds of the works are also considering efficiency aspects, minimising operator costs (sometimes defined also considering capital costs), fleet sizes, or the difference between subsidies and costs. These two clearly conflicting objectives are jointly considered in most objective functions through a weighted sum (we put a "+" sign in the table whenever this is the case), even if other approaches, including Pareto frontiers and multi-objective programming techniques, are sometimes employed. Headways are explicitly considered in virtually all works, either directly entering the objective function or as decision variables that are used to express the quantities in the objective function itself (for example, expressing wait times or operator costs as a function of headways). In many works headway values are bounded to some upper and lower limits, while additional operational constraints, such as fleet sizes, are sometimes considered.

By considering in particular the objective function definitions, we are in the position of mapping such works against the six evaluation dimensions represented by the rows of Table 1. The following considerations are stemming out:

- Profit and cost aspects related to the operation of the service are considered in all the reviewed works. In most cases, operator cost minimisation is directly considered, while in others the available resources are a modelling constraint. The operator viewpoint is therefore well taken into account in the state of the art.
- Service performances are considered mainly in terms of travel and wait times, and as such they enter in all models as well. This portion of OR literature is therefore equally addressing the operator and the customer viewpoint, a first difference from economic efficiency studies reviewed so far. From a transport planning viewpoint, it is particularly interesting that some works are addressing relative performances rather than absolute ones within a multimodal network setting (Michaelis & Schöbel, 2009; Verbas & Mahmassani, 2013).
- The other four evaluation perspectives, i.e. the last four rows of Table 1, are much less consistently studied, as in the economic efficiency literature, but some notable exceptions could be spotted. In particular, congestion issues are at least indirectly considered whenever competing travel means are analysed (Michaelis & Schöbel, 2009; Verbas & Mahmassani, 2013). Gallo, Montella, and D'Acierno (2011) show how sustainability issues, in particular related to environmental external costs, can be embedded into an objective function formulation within the tactical design process of a public transport service, whereas Ferguson, Duthie, Unnikrishnan, and Waller (2012) exclusively focus on equity, social inclusion and accessibility issues, considering service production costs issues ancillary.

In summary, the reviewed literature shows that both the service operator and the customer viewpoints are fully embedded in the tactical design of transit services. The community viewpoint is more sporadically considered, even if a handful of works has already shown how this could be achieved. We hope that the short overview we offered in this section can contribute in accelerating the evolution of the state of the art towards a more systematic consideration of transit service effectiveness issues also in the service design phase. This would undoubtedly imply an increased computational complexity of the OR model: more research would probably be needed to design targeted heuristics to solve this new class of problems albeit not to optimality, and to determine if such methods can handle problem instances of realistic size.

8. Conclusions and directions for further research

In their quest for relevance, economics, both as a positive and as a normative discipline, and engineering, the science of design, have increasingly recurred to mathematical and statistical modelling to advance their understanding of technologies and behaviours and to improve the effectiveness of the design of goods, policies, and institutions. Production research is the subject in which, at least conceptually, the scope and reward from cooperation would be highest. Transportation is probably the application ambit in which the two disciplinary fields have more concretely verified the importance of analytical approaches that are at the same time theoretically and empirically sound.

This review has systematically analysed objectives, methods, kind of data used, main results and policy implications of the existing literature related to the evaluation of urban public transport services. Thus, by combining the effectiveness indicators from the transport engineering and planning literature with the variables and the methods from the literature on efficiency, and by matching them with the most relevant typology of research questions and results of the previous studies, we offered a comprehensive reference framework to provide insightful indications to both researchers and policy makers in this area. We hope to have shown both the benefits of a closer match between such different evaluation perspectives, and the actual gap that needs to be bridged between the two research fields. The systematic investigation carried out in this paper therefore highlights some areas of potential improvements for future studies that we briefly outline below.

(a) *Widening the policy questions addressed.* The analytical needs of transportation research, in each of its declinations, are propelled by the more and more challenging objectives that modern societies are pursuing. This still exerts a pressure to increase the accuracy in the representation of technical details that affect cost, quality, impacts, and their distribution in space and time, and among users. A representative case in the economics literature is the treatment of dimensional economies and capacity constraints. The landmark introduction of the concept of *density economies* in Caves, Christensen, and Tretheway (1984) is only a first step towards a full representation of the multiproduct and network nature of the transportation services. This is even more important in an urban setting, where time and space patterns of use of transport infrastructures have a direct impact on property values, urban attractivity, congestion costs, and so on. We think this is an interesting area to be developed in future studies.

(b) *Using more general and flexible quantitative methods.* As the analysis of the evolution of the econometric methods used in the surveyed studies showed (from ordinary least squares to parametric frontiers towards nonparametric frontiers to estimate inputs–outputs relations, average or total cost functions), the operations research and technological proxy models that are available today to decision makers and analysts are incomparable for sophistication and details with those models that inspired, more than 60 years ago, the concept of engineering production function (Chenery, 1949) or activity analysis (Koopmans, 1951). In fact, recent developments in mathematical programming techniques used in design and management context are part of a toolbox that different stakeholders can use flexibly, for different goals. We see a great potential of applications of recently introduced techniques for future studies in this area.

(c) *Deepening the coverage and comparability of available data for the empirical analysis*, by promoting and developing international comparable data at the national and regional level. This is another important area in which to invest in the future to provide sound empirical evidence at the European level that, as the analysis of existing literature showed, is still scant.

In this context, public agencies could take into account the complexities of external effects of urban transport without resorting only to aggregated, monetary measures of the welfare effect of policy measures, but also using the disaggregated physical indicators, that better represent the impact of policies on the community. Transport planning methods routinely deal with such indicators, and their use also for evaluation purposes is a potentially promising avenue of research.

Acknowledgement

We thank Giuseppe Catalano for useful comments on the paper.

Appendix A. List of keywords used in the automatic literature search

Urban bus service	Urban transit	Performance measures
Urban public transportation	Public transit performance	Assessing measurement
Measuring accessibility	Transit systems	Performance assessment
Network connectivity	Transit evaluation	Performance evaluation
Index of transit service	Index of transit	Efficiency
Productivity frequency index	Transit performance	Measurement
Transit network	Transit productivity	DEA
Public services	Public transit	Frontier estimation
Transit performance	Public transportation	Production frontiers
Transit systems	Performance	Cost efficiency
Transportation	Evaluation	Cobb–Douglas
Public transport	Productivity	Cost function approach
Public transit	Indicators	Returns to scale
Transit service	Methodology	Cost

Appendix B. Outline of the grid used for the analysis of the selected papers

Paper reference		
Objectives of the study		
Method		
Kind of data and indicators	Data_source	O = official statistics A = ad-hoc survey
	Data_kind	C = cross section T = time series P = panel PC = pooled cross section
	Reference years T (number of years analysed) No. of observations (sample size)	
	Coverage	I = international comparison N = national level R = regional level C = metropolitan level
	Sample unit	L = large-scale (national, regional or provinces) C = city-wide system, transit agency O = operator (whole firm) T = transit line V = vehicle
	Country Comments on data	
Variables		I = input O = output P = parameter
Main results Policy implications Comments		

Appendix C. Distribution of papers by journal and area of research

Area	Journal	Papers published	Percent
Economics and industrial organisation	*Annals of Public and Cooperative Economics*	4	3.2
	Applied Economics	8	6.5
	Applied Economics Letters	1	0.8
	Contemporary Economic Policy	1	0.8
	Empirical Economics	1	0.8
	Journal of Economic Behavior and Organization	1	0.8
	Journal of Industrial Economics	4	3.2
	Journal of Productivity Analysis	3	2.4
	Journal of Regulatory Economics	2	1.6
	Journal of the Economics of Business	1	0.8
	Review of Industrial Organization	1	0.8
	The RAND Journal of Economics	1	0.8
Engineering, operations research and statistics	*Advances in Operations Research*	1	0.8
	Annales d'Economie et de Statistique	1	0.8
	Decision Support Systems	1	0.8
	European Journal of Operational Research	2	1.6
	Journal of Applied Statistics	1	0.8
	OPSEARCH	1	0.8
	PesquisaOperacional	1	0.8
	ISRN Civil Engineering	1	0.8
	KSCE Journal of Civil Engineering	3	2.4
	WSEAS Transactions on Mathematics	1	0.8
Regional and social science	*Annals of Regional Science*	2	1.6
	Journal of Regional Science	2	1.6
	Journal of Urban Planning and Development	1	0.8
	Local Government Studies	1	0.8
	Public Administration Review	1	0.8
	Socio-Economic Planning Sciences	1	0.8
Transport economics and policy	*International Journal of Transport Economics*	3	2.4
	Journal of Transport Economics and Policy	16	12.9
	Journal of Transportation and Statistics	1	0.8
	Research in Transportation Economics	6	4.8
	Transport Policy	2	1.6
Transport engineering and planning	*Journal of Transportation Engineering*	1	0.8
	Journal of Transportation Systems Engineering and Information Technology	1	0.8
	Logistics & Transportation Review	3	2.4
	European Transport/TrasportiEuropei	1	0.8
	International Journal of Sustainable Transportation	1	0.8
	Journal of Public Transportation	1	0.8
	Transport	1	0.8
	Transport Reviews	3	2.4
	Transportation	11	8.9
	Transportation Planning and Technology	1	0.8
	Transportation Research Part A	11	8.9
	Transportation Research Part B	1	0.8
	Transportation Research Part D	1	0.8
	Transportation Research Part E	7	5.6
	Transportation Research Record	1	0.8
	Transportmetrica	2	1.6

References

*(PR/C/III-IV) Alexandersson, G., Hulten, S., & Folster, S. (1998). The effects of competition in Swedish local bus services. *Journal of Transport Economics and Policy, 32*(2), 203–219.

Badin, L., Daraio, C., & Simar, L. (2012). How to measure the impact of environmental factors in a nonparametric production model. *European Journal of Operational Research, 223*, 818–833.

Badin, L., Daraio, C., & Simar, L. (2014). Explaining inefficiency in nonparametric production models: The state of the art. *Annals of Operations Research, 214*, 5–30.

Battese, G. E., & Coelli, T. J. (1995). A model for technical inefficiency effects in a stochastic frontier production function for panel data. *Empirical Economics, 20*(2), 325–332.

∗(PR/C/II) Berechman, J. (1983). Costs, economies of scale and factor demand in bus transport—An analysis. *Journal of Transport Economics and Policy, 17*(1), 7–24.

∗(NFA/IO/I) Boame, A. K. (2004). The technical efficiency of Canadian urban transit systems. *Transportation Research Part E: Logistics and Transportation Review, 40*(5), 401–416.

Brons, M., Nijkamp, P., Pels, E., & Rietveld, P. (2005). Efficiency of urban public transit: a meta analysis. *Transportation, 32*(1), 1–21.

(∗∗) Bruno, G., Improta, G., & Sgalambro, A. (2009). Models for the schedule optimization problem at a public transit terminal. *OR Spectrum, 31*(3), 465–481.

∗(PR/C/V) Cambini, C., Piacenza, M., & Vannoni, D. (2007). Restructuring public transit systems: Evidence on cost properties from medium and large-sized companies. *Review of Industrial Organization, 31*(3), 183–203.

(∗∗) Castelli, L., Pesenti, R., & Ukovich, W. (2004). Scheduling multimodal transportation systems. *European Journal of Operational Research, 155*(3), 603–615.

Caves, D. W., Christensen, L. R., & Tretheway, M. W. (1984). Economies of density versus economies of scale: Why trunk and local service airline costs differ. *The RAND Journal of Economics, 15*(4), 471–489.

(∗∗) Ceder, A. (2002). Urban transit scheduling: Framework, review and examples. *Journal of Urban Planning and Development, 128*(4), 225–244.

(∗∗) Ceder, A. (2007). *Public transit planning and operation: Theory, modeling and practice* Elsevier / Butterworth-Heinemann.

(∗∗) Cevallos, F., & Zhao, F. (2006). Minimizing transfer times in public transit network with genetic algorithm. *Transportation Research Record: Journal of the Transportation Research Board, 1971*(1), 74–79.

Chang, Y. T., Zhang, N., Danao, D., & Zhang, N. (2013). Environmental efficiency analysis of transportation system in China: A non-radial DEA approach. *Energy Policy, 58*, 277–283.

Charnes, A., Cooper, W. W., & Rhodes, E. (1978). Measuring the inefficiency of decision making units. *European Journal of Operational Research, 2*(6), 429–444.

Chenery, H. B. (1949). Engineering production functions. *The Quarterly Journal of Economics, 63*(4), 507–531.

(∗∗) Chowdhury, M. S., & Chien, S. I. J. (2011). Joint optimization of bus size, headway, and slack time for efficient timed transfer. *Transportation Research Record: Journal of the Transportation Research Board, 2218*(1), 48–58.

∗(NFA/IO/V) Cowie, J. (2002). Acquisition, efficiency and scale economies: An analysis of the British bus industry. *Transport Reviews, 22*(2), 147–157.

Daraio, C., & Simar, L. (2007). *Advanced robust and nonparametric methods in efficiency analysis. Methodology and applications*. New-York: Springer.

Daraio, C., & Simar, L. (2014). Directional distances and their robust versions. Computational and testing issues. *European Journal of Operational Research, 237*, 358–369.

De Borger, B., Kerstens, K., & Costa, Á. (2002). Public transit performance: What does one learn from frontier studies? *Transport Reviews, 22*(1), 1–38.

∗(NFA/IO/I-II) De Borger, B., Kerstens, K., & Staat, M. (2008). Transit costs and cost efficiency: Bootstrapping non-parametric frontiers. *Research in Transportation Economics, 23*(1), 53–64.

(∗∗) dell'Olio, L., Ibeas, A., & Ruisánchez, F. (2012). Optimizing bus-size and headway in transit networks. *Transportation, 39*(2), 449–464.

(∗∗) Desaulniers, G., & Hickman, M. (2007). Public transit. In C. Barnhart, & G. Laporte (Eds.), *Transportation. handbooks in operations research and management science: vol. 14* (pp. 69–127) AmsterdamNorth-Holland.

Diana, M. (2012). Measuring the satisfaction of multimodal travelers for local transit services in different urban contexts. *Transportation Research Part A: Policy and Practice, 46*(1), 1–11.

Diana, M., & Daraio, C. (2014). Evaluating the effectiveness of public transport operations: A critical review and some policy indicators. *International Journal of Transport Economics, XLI*(1), 75–107.

(∗∗) Farahani, R. Z., Miandoabchi, E., Szeto, W. Y., & Rashidi, H. (2013). A review of urban transportation network design problems. *European Journal of Operational Research, 229*(2), 281–302.

(∗∗) Ferguson, E. M., Duthie, J., Unnikrishnan, A., & Waller, S. T. (2012). Incorporating equity into the transit frequency-setting problem. *Transportation Research Part A: Policy and Practice, 46*(1), 190–199.

(∗∗) Fleurent, C., Lessard, R., Séguin, L. (2007). Transit timetable synchronization: Evaluation and optimization. GIRO working paper. Available on http://www.researchgate.net/profile/Charles_Fleurent/publication/248584397_Transit_Timetable_Synchronization_Evaluation_and_Optimization/links/0046353875f4f7e5ea000000.pdf Accessed 08.06.15.

∗(PR/C/V) Fraquelli, G., Piacenza, M., & Abrate, G. (2004). Regulating public transit networks: How do urban-intercity diversification and speed-up measures affect firms' cost performance? *Annals of Public and Cooperative Economics, 75*(2), 193–225.

(∗∗) Gallo, M., Montella, B., & D'Acierno, L. (2011). The transit network design problem with elastic demand and internalisation of external costs: An application to rail frequency optimisation. *Transportation Research Part C: Emerging Technologies, 19*(6), 1276–1305.

(∗∗) Guihaire, V., & Hao, J. K. (2008a). Transit network design and scheduling: A global review. *Transportation Research Part A: Policy and Practice, 42*(10), 1251–1273 .

(∗∗) Guihaire, V., & Hao, J. K. (2008b). Transit network re-timetabling and vehicle scheduling. In H. A. Le Thi, P. Bouvry, & T. Pham Dinh (Eds.), *Modelling, computation and optimization in information systems and management sciences* (pp. 135–144). Berlin, Heidelberg: Springer .

(∗∗) Guihaire, V., & Hao, J. K. (2010). Transit network timetabling and vehicle assignment for regulating authorities. *Computers & Industrial Engineering, 59*(1), 16–23.

(∗∗) Hadas, Y., & Shnaiderman, M. (2012). Public-transit frequency setting using minimum-cost approach with stochastic demand and travel time. *Transportation Research Part B: Methodological, 46*(8), 1068–1084.

∗(PR/C/II) Hensher, D. A. (2014). The relationship between bus contract costs, user perceived service quality and performance assessment. *International Journal of Sustainable Transportation, 8*(1), 5–27.

(∗∗) Hu, S. R., & Liu, C. T. (2014). Optimizing headways for mass rapid transit services. *Journal of Transportation Engineering, 140*(11), 04014053 1–14.

(∗∗) Ibarra-Rojas, O. J., & Rios-Solis, Y. A. (2012). Synchronization of bus timetabling. *Transportation Research Part B: Methodological, 46*(5), 599–614.

(∗∗) Ibeas, A., Alonso, B., dell'Olio, L., & Moura, J. L. (2014). Bus size and headways optimization model considering elastic demand. *Journal of Transportation Engineering, 140*(4), 04013021 1–9.

∗(NFA/IO/I) Karlaftis, M. G. (2003). Investigating transit production and performance: A programming approach. *Transportation Research Part A: Policy and Practice, 37*(3), 225–240 .

(∗∗) Kepaptsoglou, K., & Karlaftis, M. (2009). Transit route network design problem: Review. *Journal of Transportation Engineering, 135*(8), 491–505.

∗(NFA/IO/I) Kerstens, K. (1996). Technical efficiency measurement and explanation of French urban transit companies. *Transportation Research Part A: Policy and Practice, 30*(6), 431–452.

∗(NFA/IO/II) Kerstens, K. (1999). Decomposing technical efficiency and effectiveness of French urban transport. *Annales d'Economie et de Statistique, 54*, 129–155.

Koopmans, T. C. (1951). Analysis of production as an efficient combination of activities. *Activity Analysis of Production and Allocation, 13*, 33–37.

∗(PR/C/V) Koshal, R. (1970). Economies of scale in bus transport II: India. *Journal of Transport Economics and Policy, 4*(1), 29–36.

Kumbhakar, S. C., & Lovell, C. A. K. (2000). *Stochastic frontier analysis*. Cambridge: Cambridge University Press.

(∗∗) Li, Y., Xu, W., & He, S. (2013). Expected value model for optimizing the multiple bus headways. *Applied Mathematics and Computation, 219*(11), 5849–5861.

(∗∗) Liebchen, C. (2007). Periodic timetable optimization in public transport. In K.-H. Waldmann, & U. M. Stocker (Eds.), *Operations research proceedings 2006—Selected papers of the annual international conference of the German Operations Research Society (GOR)* (pp. 29–36). Berlin, Heidelberg: Springer.

(∗∗) Martínez, H., Mauttone, A., & Urquhart, M. E. (2014). Frequency optimization in public transportation systems: Formulation and metaheuristic approach. *European Journal of Operational Research, 236*(1), 27–36.

(∗∗) Mauttone, A., & Urquhart, M. E. (2009). A multi-objective metaheuristic approach for the transit network design problem. *Public Transport, 1*(4), 253–273.

∗(NFA/IO/II) McMullen, B. S., & Noh, D. W. (2007). Accounting for emissions in the measurement of transit agency efficiency: A directional distance function approach. *Transportation Research Part D: Transport and Environment, 12*(1), 1–9.

∗(PR/C/IV) Merewitz, L. (1977). On measuring the efficiency of public enterprises: Bus operating companies in the San Francisco bay area. *Transportation, 6*(1), 45–55 .

(∗∗) Michaelis, M., & Schöbel, A. (2009). Integrating line planning, timetabling, and vehicle scheduling: A customer-oriented heuristic. *Public Transport, 1*(3), 211–232.

∗(PR/IO/II) Miller, D. R. (1970). Differences among cities, differences among firms, and costs of urban bus transport. *Journal of Industrial Economics, 19*(1), 22–32.

∗(PR/IO/III) Mouwen, A., & Rietveld, P. (2013). Does competitive tendering improve customer satisfaction with public transport? A case study for the Netherlands. *Transportation Research Part A: Policy and Practice, 51*, 29–45.

∗(NFA/IO/II) Nolan, J. F. (1996). Determinants of productive efficiency in urban transit. *Logistics & Transportation Review, 32*(3), 319–342.

∗(NFA/IO/II-III) Nolan, J. F., Ritchie, P. C., & Rowcroft, J. R. (2001). Measuring efficiency in the public sector using nonparametric frontier estimators: A study of transit agencies in the USA. *Applied Economics, 33*(7), 913–922.

∗(NFA/IO/I) Nolan, J. F., Ritchie, P. C., & Rowcroft, J. E. (2002). Identifying and measuring public policy goals: ISTEA and the US bus transit industry. *Journal of Economic Behavior and Organization, 48*(3), 291–304.

∗(PR/C/II) Obeng, K., & Sakano, R. (2002). Total factor productivity decomposition, input price inefficiencies, and public transit systems. *Transportation Research Part E: Logistics and Transportation Review, 38*(1), 19–36.

(∗∗) Odoni, A. R., Rousseau, J. M., & Wilson, N. H. M. (1994). Models in urban and air transportation. In S. M. Pollock, M. H. Rothkopf, & A. Barnett (Eds.), *Operations research and the public sector. Handbooks in operations research and management science: vol. 6* (pp. 107–150) AmsterdamNorth-Holland.

∗(NFA/IO/I) Oh, M., Shon, E., Kim, S., & Park, D. (2011). Efficiency analysis of Seoul's urban bus agencies considering emissions. *KSCE Journal of Civil Engineering, 15*(5), 899–905.

Ortúzar, J. d. D., & Willumsen, L. G. (2011). *Modelling transport* (4th ed.). New York: Wiley.

∗(PR/C/V) Ottoz, E., & Di Giacomo, M. (2012). Diversification strategies and scope economies: Evidence from a sample of Italian regional bus transport providers. *Applied Economics, 44*(22), 2867–2880.

∗(NFA/IO/I) Pestana Barros, C., & Peypoch, N. (2010). Productivity changes in Portuguese bus companies. *Transport Policy, 17*(5), 295–302.

(**) Petersen, H. L., Larsen, A., Madsen, O. B., Petersen, B., & Ropke, S. (2013). The simultaneous vehicle scheduling and passenger service problem. *Transportation Science, 47*(4), 603–616.
*(PFA/C/III) Piacenza, M. (2006). Regulatory contracts and cost efficiency: Stochastic frontier evidence from the Italian local public transport. *Journal of Productivity Analysis, 25*(3), 257–277.
*(NFA/IO/IV) Pina, V., & Torres, L. (2001). Analysis of the efficiency of local government services delivery: An application to urban public transport. *Transportation Research, Part A: Policy and Practice, 35A*(10), 929–944.
*(PR/C IO/III) Pucher, J., Markstedt, A., & Hirschman, I. (1983). Impact of subsidies on the costs of urban public transport. *Journal of Transport Economics and Policy, 17*(2), 155–176.
(**) Ruisanchez, F., dell'Olio, L., & Ibeas, A. (2012). Design of a tabu search algorithm for assigning optimal bus sizes and frequencies in urban transport services. *Journal of Advanced Transportation, 46*(4), 366–377.
(**) Saharidis, G. K. D., Dimitropoulos, C., & Skordilis, E. (2014). Minimizing waiting times at transitional nodes for public bus transportation in Greece. *Operational Research, 14*(3), 341–359.
(**) Shafahi, Y., & Khani, A. (2010). A practical model for transfer optimization in a transit network: Model formulations and solutions. *Transportation Research Part A: Policy and Practice, 44*(6), 377–389.
Sheth, C., Triantis, K., & Teodorovic, D. (2007). Performance evaluation of bus routes: a provider and passenger perspective. *Transportation Research Part E: Logistics and Transportation Review, 43*(4), 453–478.
Simar, L., & Wilson, P. W. (2007). Estimation and inference in two-stage, semi-parametric models of production processes. *Journal of Econometrics, 136*(1), 31–64.
*(NFA/IO/II) Söderberg, M. (2009). A broad performance benchmark based on citizens' preferences: The case of Swedish public transportation. *Annals of Public and Cooperative Economics, 80*(4), 579–603.
(**) Sun, C., Zhou, W., & Wang, Y. (2008). Scheduling combination and headway optimization of bus rapid transit. *Journal of Transportation Systems Engineering and Information Technology, 8*(5), 61–67.
(**) Szeto, W. Y., & Jiang, Y. (2014). Transit route and frequency design: Bi-level modeling and hybrid artificial bee colony algorithm approach. *Transportation Research Part B: Methodological, 67*, 235–263.
(**) Szeto, W. Y., & Wu, Y. (2011). A simultaneous bus route design and frequency setting problem for Tin ShuiWai, Hong Kong. *European Journal of Operational Research, 209*(2), 141–155.
(**) Ting, C. J., & Schonfeld, P. (2005). Schedule coordination in a multiple hub transit network. *Journal of Urban Planning and Development, 131*(2), 112–124.
*(NFA/IO/I-IV) Tsamboulas, D. A. (2006). Assessing performance under regulatory evolution: A European transit system perspective. *Journal of Urban Planning and Development, 132*(4), 226–234.
UITP. (2009). *Assessing the benefits of public transport*. Brussels: Union Internationale des Transports Publics.
(**) Verbas, I. Ö., & Mahmassani, H. S. (2013). Optimal allocation of service frequencies over transit network routes and time periods. *Transportation Research Record: Journal of the Transportation Research Board, 2334*(1), 50–59.
*(NFA/IO/I) von Hirschhausen, C., & Cullmann, A. (2010). A nonparametric efficiency analysis of German public transport companies. *Transportation Research Part E: Logistics and Transportation Review, 46*(3), 436–445.
Waltman, L., & Van Eck, N. J. (2013). A smart local moving algorithm for large-scale modularity-based community detection. *European Physical Journal B, 86*(11), 471.
(**) Yan, Y., Liu, Z., Meng, Q., & Jiang, Y. (2013). Robust optimization model of bus transit network design with stochastic travel time. *Journal of Transportation Engineering, 139*(6), 625–634.
*(NFA/IO/I) Yu, M. M. (2008a). Measuring the efficiency and return to scale status of multi-mode bus transit—Evidence from Taiwan's bus system. *Applied Economics Letters, 15*(8), 647–653.
*(NFA/IO/I) Yu, M. M. (2008b). Productivity change and the effects of the enhancement of the mass transportation programme on the bus transit system in Taiwan. *Transport Reviews, 28*(5), 573–592.
*(NFA/IO/I) Yu, M. M., & Fan, C. K. (2006). Measuring the cost effectiveness of multimode bus transit in the presence of accident risks. *Transportation Planning and Technology, 29*(5), 383–407.
(**) Yu, B., Yang, Z., Sun, X., Yao, B., Zeng, Q., & Jeppesen, E. (2011). Parallel genetic algorithm in bus route headway optimization. *Applied Soft Computing, 11*(8), 5081–5091.
(**) Yu, B., Yang, Z., & Yao, J. (2010). Genetic algorithm for bus frequency optimization. *Journal of Transportation Engineering, 136*(6), 576–583.
Zellner, A. (1962). An efficient method of estimating seemingly unrelated regressions (SUR) and tests for aggregation bias. *Journal of the American Statistical Association, 57*(298), 348–368.
(**) Zhao, F., & Zeng, X. (2008). Optimization of transit route network, vehicle headways and timetables for large-scale transit networks. *European Journal of Operational Research, 186*(2), 841–855.

Further Readings

For the sake of briefness, not all 124 papers that we analysed in the first part of the present research are cited in the main text of this article. The uncited ones are listed hereafter, while the reference list reports the complete set. In the latter list, we identify those 124 reviewed papers with (*), while with (**) we identify the papers reviewed in Section 7. For each paper with (*) we also report a code that connects the paper to the classification of Table 4 (PR, PFA, and NFA) and to the taxonomy of Table 1 (right hand side).

*(PR/IO/II) Albalate, D., & Bel, G. (2010). What shapes local public transportation in Europe? Economics, mobility, institutions, and geography. *Transportation Research Part E: Logistics and Transportation Review, 46*(5), 775–790.
*(PR/IO/V) Lee, N., & Steedman, I. (1970). Economies of scale in bus transport: I. *Journal of Transport Economics and Policy, 4*(1), 15–28.
*(PFA/IO/II) Lin, E. T. J., Lan, L. W., & Chiu, A. K. Y. (2010). Measuring transport efficiency with adjustment of accidents: Case of Taipei bus transit. *Transportmetrica, 6*(2), 79–96.
*(PFA/C/V) Matas, A., & Raymond, J. L. (1998). Technical characteristics and efficiency of urban bus companies: The case of Spain. *Transportation, 25*(3), 243–263.
*(NFA/IO/I) Boame, K. A., & Obeng, K. (2005). Sources of productivity change: A Malmquist total factor productivity approach. *Transport Reviews, 25*(1), 103–116.
*(PR/C/II) Nguyen-Hoang, P., & Yeung, R. (2010). What is paratransit worth. *Transportation Research Part A: Policy and Practice, 44*(10), 841–853.
*(NFA/IO/I-V) Novaes, A. G. N. (2001). Rapid-transit efficiency analysis with the assurance-region DEA method. *PesquisaOperacional, 21*(2), 179–197.
*(PR/C/III) Obeng, K., & Azam, G. A. (1997). Type of management and subsidy-induced allocative distortions in urban transit firms: A time series approach. *Journal of Transport Economics and Policy, 31*(2), 193–209.
*(NFA/IO/I-V) Boilé, M. P. (2001). Estimating technical and scale inefficiencies of public transit systems. *Journal of Transportation Engineering, 127*(3), 187–194.
*(PR/C/III) Obeng, K. (2011). Indirect production function and the output effect of public transit subsidies. *Transportation, 38*(2), 191–214.
*(PFA/C/I) Obeng, K. (2013). Bus transit technical efficiency using latent class stochastic indirect production frontier. *Applied Economics, 45*(28), 3933–3942.
*(NFA/IO/II-IV-V) Odeck, J., & Alkadi, A. (2001). Evaluating efficiency in the Norwegian bus industry using data envelopment analysis. *Transportation, 28*(3), 211–232.
*(NFA/IO/I-V) Odeck, J. (2003). Ownership, scale effects and efficiency of Norwegian bus operators: Empirical evidence. *International Journal of Transport Economics, 30*(3), 305–325.
*(NFA/IO/II-IV-V) Odeck, J., & Alkadi, A. (2004). The performance of subsidized urban and rural public bus operators: Empirical evidence from Norway. *Annals of Regional Science, 38*(3), 413–431.
*(NFA/IO/II) Odeck, J. (2006). Congestion, ownership, region of operation, and scale: Their impact on bus operator performance in Norway. *Socio-Economic Planning Sciences, 40*(1), 52–69.
*(NFA/IO/II) Odeck, J. (2008). The effect of mergers on efficiency and productivity of public transport services. *Transportation Research Part A: Policy and Practice, 42*(4), 696–708.
*(PR/C/III-IV) Boitani, A., Nicolini, M., & Scarpa, C. (2013). Do competition and ownership matter? Evidence from local public transport in Europe. *Applied Economics, 45*(11), 1419–1434.
*(PFA/C/IV) Ottoz, E., Fornengo, G., & Di Giacomo, M. (2009). The impact of ownership on the cost of bus service provision: An example from Italy. *Applied Economics, 41*(3), 337–349.
*(PR/IO/IV) Perry, J. L., & Babitsky, T. T. (1986). Comparative performance in urban bus transit: Assessing privatisation strategies. *Public Administration Review, 46*(1), 57–66.
*(PFA/C/I) Pestana Barros, C. (2005). Estimating the efficiency of the Portuguese bus industry with a stochastic cost frontier model. *International Journal of Transport Economics, 32*(3), 323–338.
*(NFA/IO/IV) Pina, V., & Torres, L. (2006). Public–private efficiency in the delivery of services of general economic interest: The case of urban transport. *Local Government Studies, 32*(2), 177–198.
*(PFA/IO/III-IV) Roy, W., & Yvrande-Billon, A. (2007). Ownership, contractual practices and technical efficiency: The case of urban public transport in France. *Journal of Transport Economics and Policy, 41*(2), 257–282.
*(PR/C/III) Sakai, H., & Shoji, K. (2010). The effect of governmental subsidies and the contractual model on the publicly-owned bus sector in Japan. *Research in Transportation Economics, 29*(1), 60–71.
*(PFA/C/III) Sakai, H., & Takahashi, Y. (2013). Ten years after bus deregulation in Japan: An analysis of institutional changes and cost efficiency. *Research in Transportation Economics, 39*(1), 215–225.
*(PFA/C/I) Sakano, R., & Obeng, K. (1995). Re-examination of inefficiencies in urban transit systems: A stochastic frontier approach. *Logistics and Transportation Review, 31*(4), 377–392.
*(PFA/C/I-III) Sakano, R., Obeng, K., & Azam, G. (1997). Subsidies and inefficiency: Stochastic frontier approach. *Contemporary Economic Policy, 15*(3), 113–127.
*(NFA/IO/I) Sampaio, B. R., Neto, O. L., & Sampaio, Y. (2008). Efficiency analysis of public transport systems: Lessons for institutional planning. *Transportation Research Part A: Policy and Practice, 42*(3), 445–454.
*(NFA/IO/I) Saxena, P., & Saxena, R. R. (2010). Measuring efficiencies in Indian public road transit: A data envelopment analysis approach. *OPSEARCH, 47*(3), 195–204.
*(NFA/IO/I-III) Button, K., & Costa, A. (1999). Economic efficiency gains from urban public transport regulatory reform: Two case studies of changes in Europe. *Annals of Regional Science, 33*(4), 425–438.
*(PR/C/II) Shaw-Er, J., Chiang, W., & Chen, Y. W. (2005). Cost structure and technological change of local public transport: the Kaohsiung City Bus case. *Applied Economics, 37*(12), 1399–1410.
*(NFA/IO/I) Sloboda, B. W. (2008). Performance measurement of U.S. transit systems, 1982–2001. *International Journal of Transport Economics, 35*(1), 15–30.
*(PFA/NFA/IO/IV) Buzzo Margari, B., Erbetta, F., Petraglia, C., & Piacenza, M. (2007). Regulatory and environmental effects on public transit efficiency: A mixed DEA-SFA approach. *Journal of Regulatory Economics, 32*(2), 131–151.
*(PR/C/II) Viton, P. A. (1981). A translog cost function for urban bus transport. *Journal of Industrial Economics, 29*(3), 287–304.

∗(PFA/C/I) Viton, P. A. (1986). The question of efficiency in urban bus transportation. *Journal of Regional Science, 26*(3), 499–513.
∗(NFA/IO/I-IV) Viton, P. A. (1997). Technical efficiency in multi-mode bus transit: A production frontier analysis. *Transportation Research Part B: Methodological, 31*(1), 23–39.
∗(NFA/IO/I-IV) Viton, P. A. (1998). Changes in multi-mode bus transit efficiency, 1988–1992. *Transportation, 25*(1), 1–21.
∗(PR/C/V) Wabe, S. J., & Coles, O. B. (1975). The short and long run cost of bus transport in urban areas. *Journal of Transport Economics and Policy, 9*(2), 127–140.
∗(PFA/C/II) Walter, M. (2011). Some determinants of cost efficiency in German public transport. *Journal of Transport Economics and Policy, 45*(1), 1–20.
∗(PR/C/V) Williams, M. (1979). Firm size and operating cost in urban bus transportation. *Journal of Industrial Economics, 28*(2), 209–218.
∗(PR/C/II) Williams, M., & Dalal, A. (1981). Estimation of the elasticity of factor substitution in urban bus transportation: A cost function approach. *Journal of Regional Science, 21*(2), 263–275.
∗(PR/C/II) Wunsch, P. (1996). Cost and productivity of major urban transit systems in Europe. *Journal of Transport Economics and Policy, 33*(2), 171–186.
∗(NFA/IO/I) Yu, M. M., & Fan, C. K. (2004). The joint determination of efficiency in multi-mode bus transit. *WSEAS Transactions on Mathematics, 3*(4), 1808–1813.
∗(NFA/IO/I) Yu, M. M., & Fan, C. K. (2009). Measuring the performance of multimode bus transit: A mixed structure network DEA model. *Transportation Research Part E: Logistics and Transportation Review, 45*(3), 501–515.
∗(NFA/IO/IV) Chang, K. P., & Kao, P. H. (1992). The relative efficiency of public-versus private municipal bus firms: An application of data envelopment analysis. *Journal of Productivity Analysis, 3*(1/2), 67–84.
∗(NFA/IO/I) Chen, C. M., Du, J., Huo, J., & Zhu, J. (2012). Undesirable factors in integer-valued DEA: Evaluating the operational efficiencies of city bus systems considering safety records. *Decision Support Systems, 54*(1), 330–335.
∗(NFA/IO/I) Chiou, Y. C., Lan, L. W., & Yen, B. T. (2010). A joint measurement of efficiency and effectiveness for non-storable commodities: Integrated data envelopment analysis approaches. *European Journal of Operational Research, 201*(2), 477–489.
∗(NFA/IO/I) Chiou, Y. C., Lan, L. W., & Yen, B. T. (2012). Route-based data envelopment analysis models. *Transportation Research Part E: Logistics and Transportation Review, 48*(2), 415–425.
∗(NFA/IO/II) Chu, X. H., Fielding, G. J., & Lamar, B. W. (1992). Measuring transit performance using data envelopment analysis. *Transportation Research Part A—Policy and Practice, 26*(3), 223–230.
∗(NFA/IO/II-IV) Cowie, J., & Asenova, D. (1999). Organisation form, scale effects and efficiency in the British bus industry. *Transportation, 26*(3), 231–248.
∗(PR/C/II) Croissant, Y., Roy, W., & Canton, J. (2013). Reducing urban public transport costs by tendering lots: A panel data estimation. *Applied Economics, 45*(26), 3711–3722.
∗(PFA/IO/II) Cullmann, A., Farsi, M., & Filippini, M. (2012). Unobserved heterogeneity and efficiency measurement in public transport. *Journal of Transport Economics and Policy, 46*(1), 51–66.
(∗∗) Daduna, J. R., & Paixão, J. M. P. (1995). Vehicle scheduling for public mass transit—An overview. *Computer-aided transit scheduling* (pp. 76–90). Berlin, Heidelberg: Springer.
∗(PFA/C/I-III) Dalen, D. M., & Gomez-Lobo, A. (2003). Yardsticks on the road: Regulatory contracts in the Norwegian bus industry. *Transportation, 30*(4), 371–386.
∗(PR/C/I) De Borger, B. (1984). Cost and productivity in regional bus transportation: The Belgium case study. *Journal of Industrial Economics, 33*(1), 37–54.
∗(PR/C/I-IV) De Rus, G., & Nombela, G. (1997). Privatisation of urban bus services in Spain. *Journal of Transport Economics and Policy, 31*(1), 115–129.
∗(PFA/C/I-V) Farsi, M., Filippini, M., & Küenzle, M. (2006). Cost efficiency in regional bus companies: An application of alternative stochastic frontier models. *Journal of Transport Economics and Policy, 40*(1), 95–118.
∗(PR/C/V) Farsi, M., Fetz, A., & Filippini, M. (2007). Economies of scale and scope in local public transportation. *Journal of Transport Economics and Policy, 41*(3), 345–361.
∗(NFA/IO/I) Barnum, D. T., Karlaftis, M. G., & Tandon, S. (2011). Improving the efficiency of metropolitan area transit by joint analysis of its multiple providers. *Transportation Research Part E: Logistics and Transportation Review, 47*(6), 1160–1176.
∗(PR/C/III-V) Filippini, M., Maggi, R., & Prioni, P. (1992). Inefficiency in a regulated industry: The case of the Swiss regional bus companies. *Annals of Public and Cooperative Economics, 63*(3), 437–455.
∗(PFA/C/I) Filippini, M., & Prioni, P. (1994). Is scale and cost inefficiency in the Swiss bus industry a regulatory problem? Evidence from a frontier cost approach. *Journal of the Economics of Business, 1*(2), 219–231.
∗(PR/C/IV-V) Filippini, M., & Prioni, P. (2003). The influence of ownership on the cost of bus service provision in Switzerland—An empirical illustration. *Applied Economics, 35*(6), 683–690.
∗(PFA/C/I-II) Gagnepain, P., & Ivaldi, M. (2002a). Stochastic frontiers and asymmetric information models. *Journal of Productivity Analysis, 18*(2), 145–159.
∗(PR/C/II-III) Gagnepain, P., & Ivaldi, M. (2002b). Incentive regulatory policies: The case of public transit systems in France. *The RAND Journal of Economics, 33*(4), 605–629.
∗(NFA/IO/I-IV) García Sánchez, I. M. (2009). Technical and scale efficiency in Spanish urban transport: Estimating with data envelopment analysis. *Advances in Operations Research, 2009*, 15 .
∗(NFA/IO/II) Gathon, H. J. (1989). Indicators of partial productivity and technical efficiency in the European urban transit sector. *Annals of Public and Cooperative Economics, 60*(1), 43–60.
∗(NFA/IO/I) Barnum, D. T., Gleason, J. M., Karlaftis, M. G., Schumock, G. T., Shields, K. L., Tandon, S., & Walton, S. M. (2012). Estimating DEA confidence intervals with statistical panel data analysis. *Journal of Applied Statistics, 39*(4), 815–828.
∗(PR/C/III) Gupta, S., & Mukherjee, A. (2013). Utilization of passenger transport subsidy in Kolkata: A case study of Calcutta State Transport Corporation. *Research in Transportation Economics, 38*(1), 3–10.
∗(NFA/IO/II) Hahn, J. S., Kim, H. R., & Kho, S. Y. (2011). Analysis of the efficiency of Seoul Arterial Bus routes and its determinant factors. *KSCE Journal of Civil Engineering, 15*(6), 1115–1123.
∗(NFA/IO/I) Hahn, J. S., Kim, D. K., Kim, H. C., & Lee, C. (2013). Efficiency analysis on bus companies in Seoul city using a network DEA model. *KSCE Journal of Civil Engineering, 17*(6), 1480–1488.
∗(PFA/C/II) Harmatuck, D. J. (2005). Cost functions and efficiency estimates of midwest bus transit systems. *Transportation Research Record, 1932*(1), 43–53.
∗(NFA/IO/I) Hawas, Y. E., Khan, M. B., & Basu, N. (2012). Evaluating and enhancing the operational performance of public bus systems using GIS-based data envelopment analysis. *Journal of Public Transportation, 15*(2), 19–44.
∗(PR/C/II) Hensher, D. A. (1987). Productive efficiency and ownership of urban bus services. *Transportation, 14*(3), 209–225.
∗(PR/C/II-IV) Hensher, D. A., & Daniels, R. (1995). Productivity measurement in the urban bus sector. *Transport Policy, 2*(3), 179–194.
∗(PR??/IO?/III) Holmgren, J. (2010). Putting our money to good use: Can we attract more passengers without increasing subsidies? *Research in Transportation Economics, 29*(1), 256–260.
∗(PFA/C/I) Holmgren, J. (2013). The efficiency of public transport operations—An evaluation using stochastic frontier analysis. *Research in Transportation Economics, 39*(1), 50–57.
∗(NFA/C/I) Holvad, T., Hougaard, J. L., Kronborg, D., & Kvist, H. K. (2004). Measuring inefficiency in the Norwegian bus industry using multi-directional efficiency analysis. *Transportation, 31*(3), 349–369.
∗(PR/C/IV) Iseki, H. (2010). Effects of contracting on cost efficiency in US fixed-route bus transit service. *Transportation Research Part A: Policy and Practice, 44*(7), 457–472.
∗(PFA/IO/I) Jarboui, S., Forget, P., & Boujelbene, Y. (2015). Efficiency evaluation in public road transport: A stochastic frontier analysis. *Transport, 30*(1), 1–14.
∗(PR/C/III) Bekken, J. T., Longva, F., Fearnley, N., & Osland, O. (2006). Norwegian experiences with tendered bus services. *European Transport/TrasportiEuropei, 33*, 29–40.
∗(PFA/IO/I) Jarboui, S., Forget, P., & Boujelbene, Y. (2013). Public road transport efficiency: A stochastic frontier analysis. *Journal of Transportation Systems Engineering and Information Technology, 13*(5), 64–71.
∗(NFA/IO/I) Jordá, P., Cascajo, R., & Monzón, A. (2012). Analysis of the technical efficiency of urban bus services in Spain based on SBM models. *ISRN Civil Engineering, 2012*, 13.
∗(PR/C/II) Jørgensen, F., Pedersen, P. A., & Solvoll, G. (1995). The costs of bus operations in Norway. *Journal of Transport Economics and Policy, 29*(3), 253–262.
∗(PFA/C/I) Jørgensen, F., Pedersen, P. A., & Volden, R. (1997). Estimating the inefficiency in the Norwegian bus industry from stochastic cost frontier models. *Transportation, 24*(4), 421–433.
∗(PR/IO/I-III) Karlaftis, M. G., & McCarthy, P. S. (1997). Subsidy and public transit performance: A factor analytic approach. *Transportation, 24*(3), 253–270.
∗(PR/IO/III) Karlaftis, M. G., & McCarthy, P. S. (1998). Operating subsidies and performance in public transit: An empirical study. *Transportation Research Part A: Policy and Practice, 32*(5), 359–375.
∗(PR/C/IV) Karlaftis, M. G., & McCarthy, P. S. (1999). The effect of privatization on public transit costs. *Journal of Regulatory Economics, 16*(1), 27–43.
∗(PR/C/II) Karlaftis, M. G., McCarthy, P. S., & Sinha, K. C. (1999). The structure of public transit costs in the presence of multiple serial correlations. *Journal of Transportation and Statistics, 2*(2), 113–121.
∗(PR/C/II) Karlaftis, M. G., & McCarthy, P. S. (2002). Cost structures of public transit systems: A panel data analysis. *Transportation Research Part E: Logistics and Transportation Review, 38*(1), 1–18.
∗(NFA/IO/II-V) Karlaftis, M. G. (2004). A DEA approach for evaluating the efficiency and effectiveness of urban transit systems. *European Journal of Operational Research, 152*(2), 354–364.
∗(PFA/C/IV) Karlaftis, M. G. (2010). Ownership and competition in European transit: Assessing efficiency. *Transportmetrica, 6*(2), 143–160.
∗(PFA/IO/I) Karlaftis, M. G., & Tsamboulas, D. (2012). Efficiency measurement in public transport: Are findings specification sensitive PR. *Transportation Research Part A: Policy and Practice, 46*(2), 392–402.
∗(PR/C/II) Kim, M. (1985). Total factor productivity in bus transport. *Journal of Transport Economics and Policy, 19*(2), 173–182.
∗(PFA/C/IV) Kumbhakar, S., & Bhattacharyya, A. (1996). Productivity growth in passenger–bus transportation: A heteroskedastic error component model with unbalanced panel data. *Empirical Economics, 21*(4), 557–573.