Public transit performance: what does one learn from frontier studies?

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This paper provides a comprehensive survey of the literature on production and cost frontiers for public transit operators, and it evaluates the contributions of frontier analysis to the understanding of the performance of the public transport sector. The authors first succinctly contrast best practice (or frontier) and average practice specifications of technology. They also review relevant performance indicators and the methods to measure them. Next, the existing frontier studies measuring urban transit performance are systematically summarized and critically assessed. It is shown that the organization of the market, contract design, the degree and nature of the regulatory regime, and the characteristics of the network being served are all important determinants of inefficiency. However, although the frontier literature has substantially contributed to the knowledge of urban transit technologies and the determinants of performance, it is found that many important issues remain unresolved.

1. Introduction

Despite a declining trend in transit demand in most industrial economies, urban transit remains an important transport mode. Companies under different ownership regimes provide urban passenger services in a highly regulated environment, making use of a diversity of vehicles (bus, tramway, metro, light rail, etc.). Government intervention in the sector is widespread and has traditionally been justified by reference to a series of market failures. In the past two decades, however, concerns about possible regulatory failures led to a reassessment of the role of the state in the organization of the sector (for reviews, see Glaister 1990, Berechman 1993). The relative merits of public and private provision and the implications of different pricing policies and regulatory regimes for the performance of urban transit firms became important issues. In this respect, a crucial question is which type of operating and regulatory environment is best suited to stimulate productivity growth and

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efficiency in the industry. Not surprisingly, efficiency has played a prominent role in political and academic arguments guiding recent privatization and deregulation policies (e.g. Mackie et al. 1995).

It is only quite recently that appropriate methodologies have been developed that allow a careful study of the efficiency of urban transit firms. Indeed, the early analyses of the supply of urban transit services relied on estimating average practice technologies by simply estimating functions through the middle of the data. This traditional analysis is of little help when looking for excellence in production and ignores the inherent frontier nature of cost and production functions. Conceptually based on the seminal contribution by Farrell (1957), from the early 1980s on various frontier estimation techniques have been developed to determine ‘best practice’ behaviour in an industry (e.g. Lovell 1993). The frontier methodologies allow one to distinguish between efficient and inefficient production, and to estimate the degree of inefficiency by considering observed best practice standards in the industry as a benchmark. Moreover, the estimated frontiers allow separation of productivity changes over time from changes in efficiency. Finally, it has been recognized that frontier estimates of technologies may well imply different production characteristics (e.g. scale and scope economies) than average practice functions.

Not surprisingly, frontier methods have found their way to the transport sector, and studies on the productivity and efficiency of almost all transport modes are now available in the literature. For instance, Viton (1997) considered technical efficiency of US multimode bus transit, Good et al. (1993) compared the performance of European and US airlines, Norwegian ferries were analysed in Førsund (1992), while De Borger (1993) studied the behaviour of the Belgian railroads, etc. The primary purpose of this paper is to provide a comprehensive survey of the literature on production and cost frontiers for the public transit sector, and critically to assess the contributions of this literature to one’s understanding of performance of this sector. What are the main determinants of efficiency differences between transit firms? What determines productivity growth in the sector? What is the role of ownership in determining efficiency? To what extent do environmental factors and network characteristics affect performance? What are the effects of different regulatory regimes on performance? This survey provides information on these questions and on a number of related issues.

The survey presented below hopes to fill a small gap in the available literature. Indeed, whereas an overview of frontier studies on railroads has recently appeared (Oum et al. 1999), a comprehensive survey of frontier methodologies and empirical results for public transit is not yet available. Although some results are reviewed in Berechman (1993) and De Borger and Kerstens (2000), neither study serves this purpose. The former obviously does not contain information on recent frontier estimates; the latter is more selective and condensed. In addition, neither study specifically focuses on frontier analyses.

The material is organized as follows. Section 2 introduces efficiency and productivity measurement using cost and production frontiers. Section 3 discusses the appropriate specification of inputs and outputs in the available studies, and some general characteristics of the typical urban transit technology specifications are summarized. Section 4 systematically and critically assesses the contributions of the frontier studies in evaluating urban transit performance. Finally, Section 5 concludes.
2. Efficiency and productivity measurement: concepts and methodologies

The purpose of performance measurement is to compare behaviour of organizations over time, across space, or both. Furthermore, benchmarking comparisons can be made within a sector or across sectors, comparisons can be limited to the national level or may have an international character, etc. Of course, a crucial preliminary question is to specify the goals of the organizations being evaluated. In principle, public sector activities (such as public transit) may serve a series of objectives, making the evaluation of their performance a difficult exercise. Indeed, from a welfare economic viewpoint, the public sector serves four main goals: efficiency, equity, financial balance and macroeconomic stabilization (Marchand et al. 1984, Rees 1984). However, despite the existence of multiple objectives, the focus in many empirical studies in the transport industry is on issues of productivity and (mainly technical) efficiency. There are at least two reasons for this phenomenon. First, a transparent framework for productivity and efficiency measurement has been developed, unlike for the other objectives. Second, it has been forcefully argued that, independent of the other objectives, a first and indispensable demand for all public sector activities is to operate technically efficient (Marchand et al. 1984, Pestieau and Tulkens 1993). In the remainder of this section, we, therefore, review the most relevant efficiency and productivity notions and explain how to make them operational.

2.1. Efficiency and productivity

Farrell (1957) introduced the idea of best-practice frontiers and provided the first measurement scheme for efficiency. Recent contributions have defined more elaborate taxonomies of efficiency concepts (Färe et al. 1994). In a static context, one distinguishes between technical, scale, structural and allocative efficiency.

First, technical efficiency (TE) is defined as production on the boundary of the production possibility set. This set summarizes all technological possibilities of transforming inputs into outputs open to the organization. A producer is technically inefficient if production occurs in the interior of this production possibility set. Second, scale efficiency (SCE) relates to a possible divergence between actual and ideal production size. The ideal configuration coincides with the long run competitive equilibrium, where production is characterized by constant returns to scale. A producer is scale efficient if its choice of inputs and outputs is situated on a constant returns to scale frontier; it is scale inefficient otherwise. Third, structural efficiency (STE) is closely related to the definition of technical efficiency. A technically efficient producer is structurally efficient if production occurs in the uncongested or ‘economic’ region of production. Structural inefficiency occurs when production experiences congestion. In that case, some of the inputs have negative marginal products. Otherwise stated, the producer could benefit from actually reducing the congesting input factors. Common examples of congestion include agriculture (too much rain spoils crops) or today’s city traffic. Finally, allocative (or price) efficiency (AE) requires the specification of a behavioural goal and is defined by a point on the boundary of the production possibility set that satisfies this objective, given certain constraints on prices and quantities. Most often organizations are thought to be minimizing costs. In that case, a technically efficient producer is allocatively inefficient if there is a divergence between observed and optimal costs.

These static efficiency concepts, except structural efficiency, are illustrated in figure 1. (Graphically, structural inefficiency would imply that the input sets bend
backward at the extremes.) Figure 1 presents two input sets, describing all combinations of inputs able to produce a given output level, and their boundaries. The input set $L(y)_{\text{CRS}}$ is characterized by constant returns to scale, embodying the ideal of a long run competitive equilibrium, while the input set $L(y)_{\text{VRS}}$ allows instead for variable returns to scale.

Efficiency is traditionally measured equiproportionally (Farrell 1957). The radial efficiency measure in the inputs varies between 0 and 1, with efficient production on the boundary represented by unity. It has a cost interpretation and indicates the proportional reductions in inputs that leave the output level unaffected. For instance, an efficiency measure of 0.80 means the organization could produce the same outputs with only 80% of its current inputs, making a 20% cost reduction feasible. (Similarly, output-oriented efficiency measures have a revenue interpretation.)

This radial measurement of static efficiency concepts is illustrated on figure 1 for observation a in the interior of input set $L(y)_{\text{VRS}}$. First, this observation implies technical inefficiency, since it uses more of both inputs to produce exactly the same output vector as, for example, observation a' on the boundary of the input set $L(y)_{\text{VRS}}$. The degree of technical efficiency (TE) is represented by the ratio of distances $Oa'/Oa$ and is measured relative to the variable returns to scale technology $L(y)_{\text{VRS}}$. If both inputs are reduced according to the scalar $Oa'/Oa$, then the resulting input vector a' on the boundary of input set $L(y)_{\text{VRS}}$ is technically efficient. Second, observation a' is scale inefficient (SCE) because it needs more inputs to deliver the same output level as e.g. observation a'' on the boundary of the constant returns to scale technology $L(y)_{\text{CRS}}$. SCE is defined by the ratio $Oa''/Oa'$, i.e. by comparing short ($L(y)_{\text{VRS}}$) and long ($L(y)_{\text{CRS}}$) run technologies. This ratio indicates the lowest

![Figure 1. Static efficiency concepts.](image-url)
possible input vector \( a'' \), situated on the boundary of the long run constant returns to scale technology \( (L(y)_{\text{CRS}}) \), able to produce the same output as the technically efficient combination \( a' \). Finally, observation \( a'' \) is still not allocatively efficient. If the producer aims to minimize costs, then the given input prices define an isocost line \( CC' \). For these prices, total costs are minimized at the intersection of the input set \( L(y)_{\text{CRS}} \) and this line \( CC' \) (point \( b' \)). Observation \( a'' \) is, therefore, not allocatively efficient, since it requires a higher budget to produce the same outputs. Allocative efficiency (AE), captured by the ratio \( Oa''/Oa'' \), indicates the cost reduction resulting from reallocating inputs from \( a'' \) to \( a''' \). Of course, the inputs of \( a''' \) cannot yield output \( y \) on the boundary of \( L(y)_{\text{CRS}} \) but, at the same cost, input vector \( b'' \) is available that does produce this output level.

In a dynamic perspective it is important to allow for the possibility of technological innovation. Technical or productivity change is traditionally conceived as a move of the production possibilities set over time due to product and process innovations. When the frontier has shifted over time due to productivity change, then it is essential to know whether production units have been able to catch up with these developments. Dynamically, measuring productivity changes and technical efficiency are, therefore, related: the former measures the shift in the production possibilities, whereas the latter indicates the extent to which organizations maintain their position relative to an eventual shifting frontier.

This basic idea is illustrated on figure 2: two production functions are shown at two different points in time. The shift of the production function is caused by technological innovation that allows producing the same outputs with less inputs (or more outputs with the same inputs). Organizations may or may not adjust to these new production possibilities. For instance, firm \( b \) is positioned on the frontier both

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**Figure 2. Technical change and technical efficiency.**
in periods \( t \) (\( b' \)) and \( t + 1 \) (\( b'^{t+1} \)), implying that it has immediately managed to incorporate technical progress. Firm a on the contrary took no advantage of the new production methods. Being technically inefficient, its performance even deteriorates relative to the production function at \( t + 1 \). Firms c and d illustrate the cases of respectively technically inefficient and efficient firms that have been able to (c) or that have failed (d) to keep up with the new frontier.

For completeness sake, note that the notion of economies of scope, a traditional characteristic of multiple output technologies, can also be evaluated directly using an estimated frontier. Economies of scope or diversification require that the costs of simultaneously producing several outputs are lower than producing each of these outputs separately using a specialized technology.

2.2. Frontier methodologies and efficiency measurement

To estimate production or cost frontiers, methods have been developed for analysing time series, cross-section or panel data. Our discussion focuses on cross-section data and on production frontiers. Minor adjustments are needed for cost frontiers and for other types of data. Once frontiers have been estimated, productivity changes can directly be derived from shifts in the frontier over time. Technical inefficiency estimates are readily available as well, as is illustrated below.

Existing approaches to reconstruct production frontiers can be usefully distinguished along the lines below. (A general survey is found in Lovell (1993). Färe et al. (1994) overviewed non-parametric methods, while Greene (1997) surveyed parametric frontiers.)

- **Parametric versus non-parametric frontier specifications:**
  - The parametric approach assumes that the boundary of the production possibility set can be represented by a particular functional form with constant parameters.
  - The non-parametric approach imposes minimal regularity axioms on the production possibility set and directly constructs a piecewise technology on the sample.

- **Deterministic versus stochastic frontier specifications:**
  - Stochastic methods make explicit assumptions with respect to the stochastic nature of the data by allowing for measurement error.
  - Deterministic methods take all observations as given and implicitly assume that these observations are exactly measured.

Combining these distinctions yields a four-way classification, as illustrated in table 1. Since the literature on stochastic non-parametric frontiers is still burgeoning (recent proposals include resampling (bootstrap), chance constrained programming, etc.) and no consensus has yet emerged, this issue was not pursued here (Grosskopf 1996). The present authors, therefore, focus on a representative selection of methods in the three other cells of table 1.

First, the early literature often used deterministic parametric frontier methods. However, given that they combine the most restrictive assumptions (deterministic and parametric) they are no longer very popular (Lovell 1993). The present authors, therefore, only briefly mention the ‘corrected’ OLS procedure commonly used. This method assumes a particular functional form for the boundary of the production
possibility set, i.e. $y = f(x_i; \beta)$, and estimates an average practice frontier using OLS. The estimates resulting from OLS are then transformed into frontier estimates by shifting the intercept of the average function so that one of the transformed residuals is zero, while all others become negative. The results are illustrated in figure 3 for the case of a linear frontier. The average OLS and corrected OLS (COLS) frontiers are respectively given by the lowest and highest curve. Note that relative to the latter, one observation has zero residual (point A), while all other residuals are negative. In the single output case, the radial measure of technical efficiency in the outputs is equal to the ratio of observed to maximal output ($TE = y/y^*$), where $y^*$ is the fitted frontier output. For example, in figure 3, TE for observation $a = 0b/0d$.

Second, stochastic parametric frontiers allow for composed errors that include both measurement error and technical inefficiency. Observed output can fall short of maximal output by a positive amount $u$ due to technical inefficiency, but in addition

| Functional form | Deterministic | Stochastic |
|-----------------|---------------|------------|
| Parametric      | corrected OLS, etc. | frontiers with explicit assumptions (exponential, half-normal, etc.) for the TE distributions |
| Non-parametric  | FDH, DEA-type models, etc. | resampling; chance constrained programming, etc. |

Table 1. Taxonomy of frontier methodologies.

![Figure 3. Stochastic and deterministic parametric frontiers.](image-url)
there is a random error term $v$ with mean zero. In other words, $y \leq f(x; \beta) + v$ or $y = f(x; \beta) + v - u$, where $u \geq 0$. Both OLS or maximum likelihood (ML) estimators are available by making assumptions on the asymmetric distribution of $u$. Traditionally the assumption has been that the highest probability is associated with small amounts of inefficiency. Specific distributions for $u$ explored in the literature are, among others, exponential, half-normal, truncated normal and gamma.

In figure 3 the middle curve represents a typical stochastic parametric frontier. It is situated below the corrected OLS frontier, because apart from inefficiency, it also accounts for random measurement errors, so that the degree of technical inefficiency is lower on average. Moreover, technical inefficiency can no longer be directly measured as distance to the frontier, because the latter is partly due to measurement errors. However, given specific assumptions on the distribution of the one-sided technical efficiency component, methods are available to determine technical efficiency for each observation (Lovell 1993). Finally, typically there is no observation being part of the frontier itself.

Third, deterministic non-parametric methods assume no particular functional form for the boundary and ignore measurement error. Instead, the best practice technology is the boundary of a reconstructed production possibility set based upon directly enveloping the observations. These extremal methods use mathematical programming techniques to envelop the data as tightly as possible, in a piecewise linear way, subject to certain maintained production assumptions. These assumptions are generally less restrictive than those used in parametric approaches. The most important technologies of this kind are briefly presented.

A production technology only assuming strong input and output disposability is known as the free disposal hull (FDH). Strong input disposability means that any given level of outputs remains feasible if any of the inputs is increased. Strong output disposability means that with given inputs it is always possible to reduce outputs. Figure 4 shows a section of a FDH production possibility set in a single input and output dimension. The FDH frontier derives its typical staircase form from these maintained assumptions. Observation C, for instance, should produce less output while keeping the same input, simply by wasting part of current production (hence the line from C down south). For this same observation, it is feasible to produce the same level of outputs with more inputs by simply wasting any additional input available (hence the line originating in C and going eastwards). Note that observations c – g are all technically inefficient, since they are situated below the frontier.

An alternative production technology adds convexity to the assumptions maintained by FDH. Convex non-parametric frontiers, known as Data Envelopment Analysis (DEA) models, allow for linear combinations of observed production units. In terms of figure 4, for instance, convexity implies that all linear combinations of observations C and E are feasible. The immediate ramification is that observation D is no longer part of the boundary, since there are linear combinations of C and E that need less inputs to produce the same output level. Figure 4 illustrates two types of DEA-technologies. The first allows for variable returns to scale and is graphically represented by the piecewise linear convex frontier. The second assumes constant returns to scale so that all observed production combinations can be scaled up or down proportionally. The constant returns to scale DEA frontier is simply given by the ray through the origin passing through point E (figure 4).
The three frontiers discussed are based upon slightly different hypotheses concerning the nature of production possibilities. It is trivial to illustrate that the amount of technical inefficiency depends on the choice of hypotheses. Take observation c as an example, and let us measure efficiency in the inputs. Relative to the FDH frontier this inefficiency is measured by the ratio $O_c'/O_c$. For the convex, variable returns to scale technology inefficiency is given by the distance $O_c''/O_c$, while for the constant returns to scale case this ratio equals $O_c'''/O_c$.

Finally, note that there also exist combinations of methods. For example, a semi-parametric procedure first filters inefficient observations using non-parametric frontiers and then fits a parametric frontier (e.g. Thiry and Tulkens 1992).

### 3. Urban transit technology specifications

A wide variety of different specifications of the urban transit technology has been used in the frontier literature. An overview of parametric and non-parametric frontier studies is given in tables 2 and 3. The tables contain information about the authors, the type of data used (i.e. cross-section, time-series or panel data), sample size (number of operators and years analysed), transport modes being analysed, and the countries concerned. If nothing to the contrary is mentioned, then the data have a yearly periodicity. Moreover, summary information is provided on the precise parametric or non-parametric methodology being used, and on the definition of inputs (input prices in case of a cost approach), outputs and (mainly for the parametric studies) technology characteristics included in the analysis.

The tables clearly show that frontier studies are a relatively recent business: the majority of studies have been published during the 1990s. They also illustrate that
Table 2. Performance of urban bus companies: parametric frontier methodologies.

| Reference                        | Database                                      | Sample size | Country, city          | Function                              | Inputs, input prices¹ Outputs³                  | Characteristics                                                                                           |
|----------------------------------|-----------------------------------------------|-------------|------------------------|---------------------------------------|------------------------------------------------|----------------------------------------------------------------------------------------------------------|
| Bhattacharyya et al. (1995)      | panel data (yearly) 1983–87                   | 32 bus      | India                  | stochastic translog cost frontier     | fuel, prod. labour², admin. labour, no. of vehicles on road per day | Pk % fleet utilization, load factor, vehicle utilization, no. of breakdowns, three types of public ownership analysed |
| Costa and Markellos (1997)       | time series                                   | 1970–94     | London metro, UK       | deterministic CD production frontier  | vehicles, staff                                  | Vk                                                                                                       |
| De Jong and Cheung (1999)        | unbalanced panel 1994–95                      | 19 urban and regional | The Netherlands        | stochastic CD production frontier     | staff, total seats, energy costs                | Pk                                                                                                       |
| Delhause et al. (1992)           | panel data (yearly) 1978–87                   | 13 all, five urban SNCV (eight geographical units) | Belgium                | stochastic cost frontier              | staff², seats, energy                          | Sk passengers                                                                                           |
| Fazioli, et al. (1993)           | panel data (yearly) 1986–90                   | 40 bus regional | Emilia-Romagna, Italy  | deterministic translog cost frontier  | labour, capital                                 | Sk network length Ownership dummy                                                                   |
| Filipini et al. (1992)           | panel data (yearly) 1986–89                   | 62 bus regional | Switzerland            | deterministic translog cost frontier  | labour, energy, capital                         | Sk no. of stops, time trend                                                                           |
| Gathon (1989)                    | cross-section (yearly) 1984                   | 60 all urban | Europe                 | deterministic translog production frontier | staff, seats                                    | Sk                                                                                                       |
| Hanusch and Cantner (1991)       | panel data (yearly) 1970–83                   | 13 all urban | Germany                | stochastic translog cost frontier     | labour, capital                                 | Sk                                                                                                       |
| Kumbhakar and Bhattacharyya (1996)| unbalanced panel (yearly) 1983–87            | 28/28/24/31  | India                  | stochastic translog cost frontier     | fuel, prod. labour, admin. labour, no. of vehicles on road/day | Pk % fleet utilization, load factor, four types of public ownership analysed                           |
| Reference          | Database                        | Sample size | Country, city  | Function                                      | Inputs, input prices | Outputs                        | Characteristics                                                                 |
|--------------------|---------------------------------|-------------|----------------|-----------------------------------------------|----------------------|--------------------------------|--------------------------------------------------------------------------------|
| Lijesen (1998)     | unbalanced panel (yearly) 1992–94 | 14/16/9     | The Netherlands | deterministic translog cost frontier          | labour               | Pk, revenues, other activities | % urban public transport                                                        |
| Levaggi (1994)     | cross-section (yearly) 1989      | 55 bus urban| Italy          | stochastic translog cost frontier             | labour, fuel, other materials | Pk                             | network length, average speed, no. of vehicles, load coefficient, population density |
| Loizides and Giahalis (1995) | Time series (yearly) 1971–89 | one bus regional | Greece | stochastic Cobb Douglas production and cost frontier | staff, capital and other services | Pk                             |                                                                                  |
| Matas and Raymond (1998) | panel data (yearly) 1983–95 | nine bus    | Spain          | stochastic translog frontier                  | labour               | Vk, passenger trips            | network length                                                               |
| Sakano and Obeng (1995) | cross-section (yearly) 1988     | 84 bus      | USA            | stochastic translog production frontier       | labour, fuel, vehicles | Vk                             | average bus age, network size                                                   |
| Sokano et al. (1997) | unbalanced panel (yearly) 1983–92 | 439 bus in total | USA          | stochastic translog production frontier       | labour, fuel, vehicles | Vk                             | population density, network size                                               |
| Thiry and Tulkens (1992) | time series (monthly) 1977–85/79–85 | three all   | Belgium        | translog production frontier                  | labour, energy, seats | Sk                             |                                                                                  |
| Viton (1986)       | cross-section (yearly) 1979/80  | 67 bus      | USA            | stochastic translog production frontier       | drivers labour, other labour, fuel vehicles | Vk                             | average bus age, peak–base ratio                                               |
| Reference       | Database                          | Sample size | Country, city | Function                       | Inputs, input prices          | Outputs                           | Characteristics                      |
|-----------------|-----------------------------------|-------------|---------------|--------------------------------|-------------------------------|-----------------------------------|-------------------------------------|
| Viton (1992, 1993) Cross-section (yearly) 1984 – 86 | USA                  | flexible, quadratic cost frontier | labour                         | vehicle miles/mode            | average speed/mode, peak and base ratio, modal dummy |

¹Contains inputs in case of a production approach and input prices when a cost function is estimated. ²Staff is number of workers; labour is hours of work. ³Pk, passenger-km; Sk, seat-km; Vk, vehicle-km.
| Reference                        | Data type | Sample size      | Country | Function | Inputs                                      | Outputs²          |
|---------------------------------|-----------|------------------|---------|----------|---------------------------------------------|-------------------|
| Button and Costa (1999)         | Panel     | nine bus 1985–93 | Italy   | DEA      | vehicles staff                              | Vk (Sk)           |
| Chang and Kao (1992)            | time series | one bus 1956–88 | Taiwan  | DEA      | vehicles staff, fuel                         | Vk, Vk revenue    |
|                                 | panel     | five bus 1970–88 | Taiwan  | DEA      | vehicles staff, fuel                         | Vk, Vk revenue    |
| Chu et al. (1992)               | cross-section | 86 bus 1986     | USA     | DEA      | vehicle operating expenses, maintenance    | revenue vehicle   |
|                                 |           |                  |         |          | expenses, general/administration expenses   | hours             |
|                                 |           |                  |         |          | other expenses                              |                   |
|                                 |           |                  |         |          | revenue vehicle hours                       |                   |
|                                 |           |                  |         |          | population density                          |                   |
|                                 |           |                  |         |          | % of households without car subsidy passenger |                   |
| Costa and Markellos (1997)      | time series | 1970–94 London | UK      | DEA      | vehicles staff                              | Vk                |
|                                 |           | metro           |         |          |                                              |                   |
| Costa (1998)                    | time series | one underground | Spain   | DEA      | staff, vehicles, energy                      | Vk                |
|                                 |           | Madrid          |         |          | network route length                         | passengers        |

(continued)
| Reference                | Data type       | Sample size       | Country | Function | Inputs                  | Outputs              |
|--------------------------|-----------------|-------------------|---------|----------|-------------------------|----------------------|
| Cowie and Asenova (1999) | cross-section   | 141 all urban     | UK      | DEA      | staff vehicles • 35 seats | operating revenue    |
|                          |                 | 1995 – 96         |         |          | vehicles < 35 seats      |                      |
| Gathon (1989)            | cross section   | 60 all urban      | Europe  | FDH      | staff seats              | Sk                   |
|                          |                 | 1984              |         |          |                         |                      |
| Kerstens (1996, 1999)    | cross-section   | 114 bus           | France  | DEA a,b  | vehicles staff energy   | VK (Sk)              |
|                          |                 | 1990              |         | FDH a    |                         | passengers            |
| Levaggi (1994)           | cross-section   | 55 bus            | Italy   | DEA      | load staff costs fuel costs other variable costs kms of route population density vehicles same without load | load |
|                          |                 | 1989              |         |          |                         | Pk                   |
| Loizides and Giahalis    | time series     | one bus           | Greece  | DEA      | staff capital and other services |                      |
| (1995)                   | (yearly) regional | 1971 – 89         |         |          |                         |                      |
| Nolan (1996)             | panel           | 25 bus            | USA     | DEA      | staff fuel vehicles     | Vk                   |
|                          |                 | 1989 – 93         |         |          |                         |                      |
| Reference                  | Data type | Sample size       | Country | Function | Inputs                                                                 | Outputs                                      |
|----------------------------|-----------|-------------------|---------|----------|------------------------------------------------------------------------|----------------------------------------------|
| Nolan et al. (2000)        | panel     | 20 bus 1990–95    | USA     | DEA      | staff, fuel, vehicles, input efficiency score (previous model)         | vehicle revenue miles, vehicle miles         |
| Nollet et al. (1988)       | time series (monthly) | one all 1977–98  | Belgium | FDH      | labour, energy, seats                                                  | Sk                                           |
| Obeng (1994)               | cross-section | 73 bus 1988       | USA     | DEA      | labour, fuel, vehicles, operational subsidies, capital subsidies, price of capital | vehicle miles                               |
| Tone and Sawada (1990)     | cross-section | 207 bus 1985     | Japan   | DEA      | vehicles, staff, operating expenses                                   | Vk                                           |

(continued)
| Reference                        | Data type          | Sample size                                      | Country | Function | Inputs                                                                 | Outputs |
|---------------------------------|--------------------|--------------------------------------------------|---------|----------|------------------------------------------------------------------------|---------|
| Tulkens et al. (1988)           | time series (monthly) | three bus 1979–1985                             | Belgium | FDH      | labour, energy, seats                                                  | Sk      |
| Tulkens (1993)                  | time series (monthly) | one all 1977–89                                 | Belgium | FDH      | seats, labour, energy                                                  | Sk      |
| Tulkens and Vanden Eeckaut (1995) | time series (monthly) | one all 1977–91                                 | Belgium | FDH (benchmark) | seats, labour, energy                                                | Sk      |
| Tulkens and Wunsch (1994)       | time series (monthly) | one all 1977–92                                 | Belgium | FDH      | seats, labour, energy                                                  | Sk      |
| Viton (1997)                    | cross section      | 217 bus motor bus (MB) or demand-responsive (DR) 1990 | USA     | DEA      | labour (four types per MB/DR: vehicle miles, transportation, maintenance, administrative, other) fuel (MB/DR) vehicles (MB/DR) tires + materials cost (MB/DR) services cost utilities cost insurance cost average speed (MB/DR) average fleet age directional miles |         |

(continued)
Table 3. Continued.

| Reference    | Data type | Sample size | Country | Function | Inputs                                                                 | Outputs                      |
|--------------|-----------|-------------|---------|----------|------------------------------------------------------------------------|------------------------------|
| Viton (1998) | panel     | 183 bus in 1988, 169 bus in 1992, motor-bus (MB) or demand-responsive (DR) | USA      | DEA (Malmquist)          | labour (four types per MB/DR: transportation, maintenance, administrative, other) | vehicle miles (MB/DR) passenger trips (MB/DR) vehicle hours (MB/DR) |
| Wunsch (1994) | cross-section | 53 all 1988–93 | Europe | DEA FDH | costs                                                                 | Vk, Sk                       |

1The published version (Wunsch 1996) does not contain the frontier efficiency results. 2Pk, passenger-km; Sk, seat-km; Vk, vehicle-km.
the majority of frontier analyses deal with European or US data, but that there are many exceptions. For example, Bhattacharyya et al. (1995) provided an Indian application, Chang and Kao (1992) used data from Taipei (Taiwan) and Tone and Sawada (1990) studied Japanese data. Unfortunately, very few studies have taken a comparative international perspective (Gatho 1989) and Wunsch (1994) are relevant exceptions.) In terms of methodology, tables 2 and 3 suggest that most parametric studies employ some kind of flexible functional form, often the translog. In the non-parametric cases both DEA and FDH are widely used.

Probably the most striking feature of tables 2 and 3 is the wild variability in the use of inputs and outputs in urban transit technology specifications. Most studies use labour and capital as inputs (Viton 1992 has an application using labour as the only input), but not all of them include energy (e.g. Hanusch and Cantner 1991, Fazioli et al. 1993). Some applications include environmental variables to provide more detail on input quality. For instance, Levaggi (1994) included a load factor, population density and network length as inputs, Chu et al. (1992) considered revenue, population density and percentage of households without a car, Tone and Sawada (1990) included operating expenses, and Costa (1998) included the network route length of the metro operator. A similar wide variety of indicators is observed at the output side. Parametric studies mainly use supply-oriented indicators such as seat-km or vehicle-km, with the exceptions of Bhattacharyya et al. (1995) and Levaggi (1994) who both selected passenger-km as appropriate measure of output. In non-parametric work, there is a broader choice of outputs, although the vehicle-km or seat-km specifications are still the most common. Levaggi (1994) also considered passenger-km, Tone and Sawada (1990) had four applications with outputs of different nature. While most studies include a single output, Chang and Kao (1992), Costa (1998), Tone and Sawada (1990) and Wunsch (1994) included applications with multiple outputs.

This variability in the input and output measures simply suggests that there is no generally accepted set of relevant variables in the bus industry. Traditionally, the input set in the transport sector consists of capital, labour and energy. Of course, differences between operators may exist in terms of quality and composition of inputs, since the latter may be highly heterogeneous. For example, not only should one in principle differentiate between driving and non-driving labour, but in addition the definition of ‘effective’ labour time may be quite difficult for drivers due to interrupted shifts, etc. Rolling stock, a major part of capital, typically consists of various vintages used at different intensities, implying different patterns of depreciation. Moreover, some variability exists in terms of fuels used. Conceptually, however, if the data incorporate the required information, it is quite feasible to correct for input quality differences.

The definition of outputs is much more problematic. The early literature focused on the distinction between pure supply indicators (vehicle-km or seat-km) and output measures that at least to some extent reflect the demand for transit services (e.g. passenger-km and number of passengers). Arguments for and against either specification are found in the literature.

Many authors have argued that demand-related output specifications are very relevant when evaluating the firm’s effectiveness (Chu et al. 1992, Costa 1998, Tone and Sawada 1990), but that one should be careful when the focus is on costs and productivity. The main arguments have been nicely summarized by, for example, Berechman (1993). First, inputs do not vary systematically with demand-related
output measures so that they do not allow an adequate description of transit technology. Second, supply-related output indicators are to a larger extent under the control of operators than demand-related outputs. In unregulated environments they actually would be direct decision variables for the transit companies. Even if this is not the case due to government regulation of service levels, operators do have some control via the negotiation process with the authorities. Third, independent of the achievement of broader goals defined in terms of passenger transit services actually consumed, supplying bus services in the least costly way may be considered a reasonable requirement for operators. Therefore, the argument continues, when measuring productivity and efficiency the focus should be on pure supply indices. This is especially the case since it is unlikely that all parties involved can agree upon possible broader objectives. For instance, regulators may be interested in the efficient use of their funds, while operators may be inclined to stress effectiveness in terms of the number of passengers, service availability, etc.

A simple but powerful counter-argument, suggesting that demand factors should play a relevant role in output definitions, is that any realistic output measure should take into account the objectives of the firms under consideration. Since passengers or passenger-km at least partially capture the economic motive for providing the services, such demand-oriented output measures must indeed be relevant. After all, if one ignores demand altogether, then the most cost efficient and productive bus operators may be the ones not servicing any passengers. Furthermore, it is now better understood that there is a strong interdependency between the characteristics of demand, the spatial and quality attributes of supply and the appropriate specification of technology for the purpose of performance evaluation. When these issues are accounted for, the early debate between demand or supply oriented output measures loses much of its significance.

To substantiate this claim, first note that there is no overall consensus on the goals of transit firms. Normative models (e.g. Rees 1984) have put forward traditional public enterprise objectives resulting from welfare maximization (efficiency, equity, deficit finance, and macro-economic objectives). In positive models, by contrast, actual objectives result from the interaction between operator preferences, the political and regulatory environment, and pressure groups (Berechman 1993: 95–8). In any case, the proper objective function of transit firms is intimately related to its surrounding social, political and regulatory environment. For instance, when the regulator implicitly stimulates over-hiring labour, then cost minimization at observed input prices is an inappropriate benchmarking model yielding highly misleading results. Second, there is now a general recognition of the heterogeneity of transport output in terms of temporal, spatial and quality characteristics. To illustrate, networks may be dense or sparse; companies may always offer a complete range of services or have distinct services during peak and off-peak periods; their services may differ in quality as reflected in speed, punctuality, frequency, travel links, etc. These characteristics should be an integral part of the technology description.

The above discussion implies some practical problems for both parametric and non-parametric approaches. For parametric specifications, in particular flexible functional forms, the number of parameters to be estimated quickly becomes very large. To circumvent this problem, Spady and Friedlaender (1978) suggested the specification of hedonic output composites correcting the generic output vehicle-km for variations in the above characteristics. These are estimated jointly with the
structure of the technology. A completely different solution is to define outputs in a very disaggregated way, namely at the level of individual origin-destination flows per period (Jara Díaz 1982). However, this method raises questions about the relation between technology characteristics (e.g. returns to scale) and the underlying origin-destination flows.

In the case of non-parametric technology specifications, the problem is more severe. Defining hedonic outputs does not seem feasible because, if a large number of dimensions representing the characteristics are added to inputs and outputs, then this almost automatically increases efficiency and leads to a larger number of efficient observations (Kerstens and Vanden Eeckaut 1995). With only few test procedures to guide the selection of additional dimensions, this could ultimately undermine the discriminatory power of the analysis. (This topic undoubtedly deserves more systematic attention. Developments in including non-discretionary environmental (e.g. categorical) variables can provide a solution. Another possibility is to construct parametric hedonic outputs in a first stage, and to measure efficiency based on inputs and hedonic outputs in a second step (Obeng 1995). This semi-parametric approach reverses the combination of non-parametric and parametric methods relative to Thiry and Tulkens (1992).) Another fruitful approach, however, is to ignore the characteristics in the frontier specification itself, but to include them into a second explanatory stage. The assumption underlying this second phase is that the characteristics only affect the distance to the frontier, but do not influence its shape (Lovell 1993).

Despite these difficulties, over the past decade many empirical models have incorporated various output quality characteristics, several of which are demand-related (e.g. Filippini et al. 1992, Hensher 1992, Prioni and Hensher 1999). If both demand and supply attributes are appropriately accounted for, the discussion with respect to the choice of demand versus supply related indicators is no longer crucial. Of course, to the extent that service quality indicators map into both supply and demand characteristics it seems desirable to analyse their impact on performance within the framework of a joint demand–supply equation system (Prioni and Henscher 1999).

4. Urban transit efficiency and productivity: results from frontier studies

The main findings of the literature on urban transit performance are outlined in tables 4 and 5 for parametric and non-parametric approaches respectively. The present authors consecutively discuss efficiency and productivity results, returns to scale and scope, the relation between efficiency and effectiveness, the impact of ownership, subsidies and contracts, and the role of environmental variables and network characteristics.

4.1. Efficiency and productivity

When interpreting results note that, to some extent, the distribution of efficiency is determined by the methods employed. For example, differences in underlying assumptions imply that deterministic non-parametric and stochastic parametric methods may generate efficiency scores that substantially diverge. Similarly, among non-parametric approaches it is well known that the FDH specification is more conservative than a DEA model, automatically resulting in higher efficiency scores. Finally, it should be borne in mind that frontier methods only yield relative efficiencies. Efficiency scores are relative to the sample considered and are not based
Table 4. Performance of urban bus companies: parametric frontier findings.

| Author                      | Efficiency findings                                                                                                                                                                                                 | Returns of scale and scope                      | Observations                                                                                                                                                                                                 |
|-----------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Bhattacharyya et al. (1995) | average TE per operator: between 51 and 98% form of public ownership and management structure influence efficiency (to some extent related to no. of breakdowns) performance deteriorates over time (need to replace old fleet) nationalized companies are the least efficient (had problems at origin) units directly run by government transport department are most efficient | decreasing returns to scale                    | three types of public ownership analysed: government owned corporations; nationalized units and ownership and operation in state depart. average technical regress: 3.7%, due to the rapid deterioration of vehicles (poor state of the roads) |
| Costa and Markellos (1997)  | average TE: 99% small range of values inhibits detecting any temporal pattern                                                                                                                                                                                                       |                                                 |                                                                                                                                                                                                             |
| De Jong and Cheung (1999)   | average TE: 80% regional firms more efficient than urban firms                                                                                                                                                                                                                  | economies of scale                              | compute subsidy allocation models: subtracting the inefficiency components would lead to drastic changes reduced substitution possibilities between labour and energy substitution possibilities between the variable factors (work and energy) and no. of vehicles |
| Delhausse et al. (1992)     | average TE per operator: between 92 and 94% important efficiency differences among companies average TE improves over time                                                                                                                                                  |                                                 | reduced substitution possibilities between labour and energy substitution possibilities between the variable factors (work and energy) and no. of vehicles                                                                                                                                 |
| Fazioli et al. (1993)       | average cost efficiency per operator between 78 and 100% ownership irrelevant to efficiency (absence of effective competition and strong regulation)                                                                                                                                 | important economies of scale and density (merger policy justified) importance of scale economies decreases with operator size | no evidence of technical change positive influence of network length on costs                                                                                                                                 |

(continued)
| Author                        | Efficiency findings                                                                                                                                                                                                 | Returns of scale and scope                                                                 | Observations                                                                                                                                                           |
|------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Filippini et al. (1992)      | efficiency positively correlated to degree to which Cantons subsidize deficits and to compensating payments for public services, and negatively correlated with size and alpine region                                    | important economies of scale and density (selective mergers welcomed)                                                                                     | no neutral technical change regress efficiency measures on explanatory variables:                                                                                                                                                   |
| Gathon (1989)                | TE per operator: between 58 and 100% TE postively correlated with operational speed                                                                                                                                  | increasing returns to scale                                                                                                                                  |                                                                                                                                                                                                                                     |
| Hanusch and Cantner (1991)   | efficiency levels on average between 80 and 84% depending on the specification                                                                                                                                       |                                                                                                                                                                 | average technical progress of 1% per year                                                                                                                                                                                            |
| Kumbhakar and Bhattacharyya (1996) |                                                                                                                                                                                                                     |                                                                                                                                                                 | technical regress for 55% of operators (need to replace old fleet) form of public ownership influences productivity: nationalized companies grow best; and units directly run by government transportation departments perform worst over time |
| Lijesen (1998)              | average TE per operator: 74%                                                                                                                                                                                                                                                | almost constant returns to scale no economies of scope                                                                                                         | speed and load reduce costs network length and population density increase costs                                                                                                                                                     |
| Levaggi (1994)              | average cost inefficiency per operator: between 14 and 40% all firms are inefficient in their use of capital (excess capacity)                                                                                         | short and long run economies of passenger (load) density (low level of capacity utilization)                                                              | speed and load reduce costs network length and population density increase costs                                                                                                                                                     |
|                             |                                                                                                                                                                                                                     | short run scale economies and network, density economies, but not in the long run                                                                         |                                                                                                                                                                                                                                     |
| Author                      | Efficiency findings                                                                 | Returns of scale and scope                                                                 | Observations                               |
|-----------------------------|--------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------|--------------------------------------------|
| Loizides and Giahalis (1995) | no TE or AE found                                                                     |                                                                                          | average total factor productivity decline  |
|                             |                                                                                      | increasing returns to density                                                            | of 2%, but no systematic tendencies        |
|                             |                                                                                      | almost constant returns to scale, with slight diseconomies for the largest companies      |                                            |
| Matas and Raymond (1998)    | average efficiency increases with size                                               | efficiency negatively related to share of subsidies and average speed                      |                                            |
|                             | efficiency decreases with average bus age, the range of night routes, network-km per vehicle |                                                                                          |                                            |
| Sakano and Obeng (1995)     | average TE per operator: 94% AE: capital is 68% overallocated relative to labour and 123% relative to fuel | on average increasing returns to scale                                                    | efficiency decreases with average fleet age |
|                             | negative impact of subsidies on TE, no effect on AE                                   |                                                                                          |                                            |
|                             | no relation between size and TE, but AE decrease with size                            |                                                                                          |                                            |
| Sakano et al. (1999)        | average TE per operator: 83%                                                         | mild increasing returns to scale                                                          | positive impact of network size and       |
|                             | average AE: 23% excess labour relative to capital, 88% excess fuel relative to capital, and 65% excess fuel relative to labour |                                                                                          | population on performance                 |
|                             | impact of subsidies on AE is small relative to other internal factors                 |                                                                                          |                                            |
| Author            | Efficiency findings                                                                 | Returns of scale and scope                                                                 | Observations                                                                                   |
|-------------------|---------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------|
| Thiry and Tulkens (1992) | TE of the three firms are quite different: STIB: minimum of 79%; STIL: minimum of 98%; and STIC: minimum of 90% | increasing returns to scale (only slightly for STIB-Brussels)                                | progress up to 10% in a single year semi-parametric methods: frontier estimated after elimination of inefficient observations with FDH filtering improves the quality of the estimation (more consistent with economic theory) |
| Viton (1986)      | TE per operator ranges between 30 and 100% no systematic pattern of AE TE and AE are correlated substantial TE prevails inefficiency unrelated to size | decreasing returns to short and long run scale economies (fleet sizes smaller than optimal) | little substitution possibilities large transit monopolies have no cost advantages over an industry with many firms |
| Viton (1992, 1993)| consolidations of scale depend on output levels provided by the merging parties consolidations of scope depend most heavily on resulting systemwide wage, and also on outputs and modes | operators analysed have 100 or more vehicles anaomalous results in the sign of peaking Viton (1993) provides details on all possible consolidations of seven operators in the San Francisco Bay Area (1988 data) |
Table 5. Performance of urban bus companies: non parametric frontier findings.

| Author | Database | Inputs | Outputs | Efficiency findings | Observations |
|--------|----------|--------|---------|---------------------|--------------|
| Button and Costa (1999) | time series 1956–88 | vehicles, staff, fuel to reduce subsidies | average TE increases over time, except for smallest operators evolution probably explained by pressure | also discuss the Madrid metro results earlier reported in Costa (1998) |
| Chang and Kao (1992) | time series 1956–88 | vehicles, staff, fuel | Vk revenue bus trips | public operator increased efficiency after liberalization in 1969 public operator decreased efficiency after liberalization public operator did not increase efficiency after liberalization | one public operator and four private operators private firms more flexible in adopting different technologies (when considering three outputs) |
| | panel data 1970–88 | vehicles, staff, fuel | Vk revenue bus trips | lower efficiency scores of public operator | |
| | | | revenue | | |
| Chu et al. (1992) | | | | average input TE: 85% average input effectiveness: 65% | identification of peer groups performance evaluation must distinguish TE and effectiveness measures |
| Costa and Markellos (1997) | | | | average TE: 90% average SCE: 87%<sup>1</sup> efficiency improves over time | also use multi-layer perception neural networks model: detect congestion |

(continued)
| Author                | Database | Inputs                                                   | Outputs                                                                 | Efficiency findings                                                                 | Observations                                                                 |
|----------------------|----------|----------------------------------------------------------|--------------------------------------------------------------------------|--------------------------------------------------------------------------------------|--------------------------------------------------------------------------------|
| Costa (1998)         |          |                                                          |                                                                          | average input TE: 91%\(^1\) (range: 83–100%)                                         | measures of efficiency and effectiveness must be distinguished                   |
|                      |          |                                                          |                                                                          | average input effectiveness: 89%\(^1\) (range: 78–100%)                           |                                                                                |
|                      |          |                                                          |                                                                          | reorganization of public transport affected efficiency and effectiveness, but in different forms |                                                                                |
| Cowie and Asenova    |          |                                                          |                                                                          | low average TE: 68%                                                               |                                                                                |
| (1999)               |          |                                                          |                                                                          | public companies less efficient than private ones                                   |                                                                                |
|                      |          |                                                          |                                                                          | TE far more important than SCE                                                     |                                                                                |
|                      |          |                                                          |                                                                          | most companies operate under IRS (up to about £12 million operating revenue, or about 250 buses) |                                                                                |
| Gathon (1989)         |          |                                                          |                                                                          | average TE: 96% (range: 65–100%)                                                   | inefficient firms with FDH are classified likewise with COLS                     |
| Kerstens (1996, 1999)|          |                                                          |                                                                          | average TE varies between 82 and 89% for DEA depending on specification           | importance of outliers (in particular for SCE)                                   |
|                      |          |                                                          |                                                                          | private ownership, risk-sharing and duration of contracts have a positive effect on TE | explanation of TE scores on limited subsample (33 observations)                  |
|                      |          |                                                          |                                                                          | subsidies diminish TE; French transportation tax promotes performance              | small operators experience IRS; large operators DRS                             |
|                      |          |                                                          |                                                                          | heterogeneity of network justifies some differences in TE (length of line with    | efficiency and effectiveness are uncorrelated                                     |
|                      |          |                                                          |                                                                          | positive effect and distance between stops with a negative effect)                | impact of measurement orientation                                                |
|                      |          |                                                          |                                                                          | TE is most important, followed by SCE and congestion                              |                                                                                |
| Author                  | Database | Inputs                      | Outputs                          | Efficiency findings                                                                 | Observations                                                                 |
|-------------------------|----------|-----------------------------|----------------------------------|--------------------------------------------------------------------------------------|------------------------------------------------------------------------------|
| Levaggi (1994)          |          |                             | Average TE between 41 and 59%,   | slacks are usually related to labour and load                                          |                                                                              |
|                         |          |                             | depending on model               | high rank correlation between DEA and parametric results                               |                                                                              |
|                         |          |                             | plausible causes of inefficiency: |                                                                              |
|                         |          |                             | use of excess capital; large spare capacity; and high share of labour input         |                                                                              |
| Loizides and Giahalis   |          |                             | TE between 94 and 100%           |                                                                              |
| (1995)                  |          |                             | AE between 94 and 100%           |                                                                              |
| Nolan (1996)            |          |                             | Average TE scores per year:      |                                                                              |
|                         |          |                             | around 1.10                      |                                                                              |
|                         |          |                             | TE more important than SCE       |                                                                              |
|                         |          |                             | peak – base ratio, share of maintenance personnel to total employees, average      |                                                                              |
|                         |          |                             | fleet age have negative effect on TE |                                                                              |
|                         |          |                             | state subsidies diminish TE, while federal subsidies improve it                    |                                                                              |
|                         |          |                             | network heterogeneity justifies some differences in performance (average speed with positive effect) |                                                                              |
| Nolan et al. (2000)     |          | staff vehicles              | Veh. revenue miles               |                                                                              |
|                         |          |                             | Veh. miles                       |                                                                              |
|                         |          |                             | TE ranges between 76 and 100%    |                                                                              |
|                         |          |                             | Input effic. score (prev. model) |                                                                              |
|                         |          |                             | Non-diesel staff                 | ISTEA legislation did not make a change (lack of proper monitoring mechanisms)     |
|                         |          |                             | safety incidents                 |                                                                              |
|                         |          |                             | route miles                      |                                                                              |
|                         |          |                             | ‘social efficiency’ ranges between 20 and 100%                                   |                                                                              |
|                         |          |                             | ‘social efficiency’ targets among large firms                                     |                                                                              |
|                         |          |                             | no trend in ‘social efficiency’ after 1991 (= introduction of ISTEA legislation)  |                                                                              |
| Nollet et al. (1988)    |          |                             | more efficient in the beginning (1977) and                                      | minor technical progress                                                         |
|                         |          |                             | in the end (1985), after a significant decline                                   |                                                                              |

(continued)
| Author | Database   | Inputs                      | Outputs | Efficiency findings                                                                 | Observations                                                                 |
|--------|------------|-----------------------------|---------|--------------------------------------------------------------------------------------|------------------------------------------------------------------------------|
| Obeng (1994) |            |                              |         | TE between 54 and 100% operating and capital subsidies enhance TE                     | conclusions may be affected by a methodological error                          |
| Tone and Sawada (1990) | cross-section 1985 | vehicles staff               | Vk      | service efficiency concept public companies use excess inputs                         | initial data set had 207 bus operators (163 provate and 44 public) conclusion are taken with 22 (16 private and six public) companies operating in North Kyushu |
|        |            | operating expenses          | vehicles staff | cost efficiency concept results reflect differences in labour costs between urban and rural regions |                                                                              |
|        |            | vehicles staff              | operating income | income efficiency concept urban companies more efficient than rural companies |                                                                              |
|        |            |                              |         | in urban areas public companies are more efficient than private (reverse in rural areas) |                                                                              |
|        |            | vehicles staff              | density of service | public service efficiency concept rural companies more efficient | public transport in rural (urban) areas should be publicly (privately) managed the more a company is income efficient, the less it serves the area |
| Tulkens et al. (1988) |            |                              |         | Liège (STIL) most efficient; Charlerloï (STIC) in between; Verviers (STIV) least efficient | Liège: low value of technical progress Charlerloï: more frequent technical progress Charlerloï: more frequent technical progress Verviers: no technical progress |
|        |            |                              |         | STIL and STIC: input and output orientated efficiency measures give similar results; STIV: results diverge |                                                                              |
| Author               | Database | Inputs                                                                 | Outputs                                                                 | Efficiency findings                                                                 | Observations                                                                                       |
|----------------------|----------|------------------------------------------------------------------------|------------------------------------------------------------------------|---------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------|
| Tulkens (1993)       |          |                                                                        |                                                                        | TE ranges between 82 and 100% 73 months are inefficient 61 months are sequentially inefficient | FDH calculated sequentially to detect technical progress 19 observations exhibit technical progress: occasionally in 1984–85–86; and systematically in 1988–89 maximum technical progress in November 1988 (11.7%) |
| Tulkens and Vanden    |          |                                                                        |                                                                        | occasional progress between 1985 and 1988 substantial and consistent progress after 1989 | results less favourable concerning effectiveness (Pk/Sk)                                                                                             |
| Eeckaut (1995)       |          |                                                                        |                                                                        |                                                                                       |                                                                                                  |
| Tulkens and Wunsch    |          |                                                                        |                                                                        | TE increases in recent period, especially after a formal contract between operator and regulator has been agreed | conclusions w.r.t congestion are affected by a methodological error                                                                                   |
| (1994)               |          |                                                                        |                                                                        |                                                                                       |                                                                                                  |
| Viton (1997)          |          |                                                                        |                                                                        | mean input and output TE of 0.96 resp. 1.06 (Russell index) majority of units operates under CRS; less under IRS; few under DRS | uses Russell index to compute Malmquist productivity index                                                                                             |
| Viton (1998)          |          |                                                                        |                                                                        | mean input and output productivity change of 2.1% resp. 2.6% productivity change mainly due to changes in relative TE (catching up) | identification of role models per mode                                                                                                             |
| Wunsch (1994)         |          |                                                                        |                                                                        | TE ranges from 43–100% (FDH) and from 26–100% (DEA) UK operators perform very well         |                                                                                                |

<sup>1</sup>Own computations. Pk, passenger-km; Sk, Seat-km; Vk, vehicle-km.
on some absolute (e.g. engineering) standards, making, for instance, comparisons of efficiency levels between studies impossible.

With these caveats in mind, we turn to the main findings. First, in terms of technical efficiency most studies report substantial remaining inefficiency among urban transit operators in the different countries (e.g. Viton 1986, Hanusch and Cantner 1991, Fazzioli et al. 1993, Levaggi 1994, Bhattacharyya et al. 1995, Kerstens 1996, Lijesen 1998). Of course, though the evidence of substantial technical inefficiencies among urban transit operators in the different countries is undeniable, it is less clear how these performance results compare to other sectors of the economy. Second, comparative work of transit operators in different countries (e.g. Gathon 1989, Wunsch 1994) reveals a huge variability in technical inefficiency, both across and within countries. This observed variation captures differences in the regulatory framework, in managerial quality and in operating environment, among others. For example, operators in the UK appear to do very well compared to other countries, a phenomenon that has been attributed to recent regulatory changes. As observed by Glaister (1997), deregulation in the UK brought about drastic cost reductions for at least two reasons. One was that it introduced productivity enhancing working practices and led to reduced wage rates. The other cost-reducing factor was the requirement that the remaining subsidized (social) bus services should be subjected to competitive tendering, i.e. a bidding process for the monopoly right to supply a predefined service at a particular spatial level during a particular period. This is believed to have lowered subsidies by \( \sim 20\% \).

Third, the available efficiency studies clearly illustrate the relative nature of best-practice comparisons and the importance of underlying assumptions. The Brussels public bus operator, for example, seems to perform reasonably well when studied in isolation using time series techniques (e.g. Tulkens and Wunsch 1994), but in a comparative perspective it turns out to perform far below average.

Frontier methods have also been used to study scale, structural (congestion) and allocative efficiency. From the scarce available literature it appears that scale inefficiencies are no major source of poor performance (Nolan 1996, Cowie and Asenova 1999, Kerstens 1999). Results on congestion are mixed. In Kerstens (1999) structural inefficiencies do not appear to be important for a sample of French public transport operators, but Costa and Markellos (1997) found evidence of congestion for the London Underground. Finally, the few studies (Viton 1986, Loizides and Giahalis 1995, Sakano and Obeng 1995) considering allocative inefficiencies suggest that the nature of these inefficiencies strongly depend on the regulatory environment. On the one hand, the existence of capital subsidies encourages capital-intensive production methods. On the other hand, union influence and managerial preferences may induce excessive labour utilization in producing transport services (e.g. De Borger 1993). Empirically, only Sakano and Obeng (1995) reported important allocative inefficiencies. They suggest that the subsidy effect dominates in their sample and that production is relatively too capital intensive. Some of these findings are less pronounced in their sequel work (Sakano et al. 1997), where allocative inefficiency is mainly caused by factors internal to the firm instead of subsidies.

Regarding productivity change, a mixed picture arises. Most of the time, very small or negligible rates of productivity growth are obtained. In a sense, this is expected given the mature nature of bus technology and its operating environment. Technology is well established, since major improvements in fuel efficiencies were achieved in the past, and further labour efficiency improvements are unlikely given
that one man-one bus operation are nowadays the rule. Moreover, increasing traffic congestion decreases commercial speeds and lowers performance despite counteracting measures (e.g. exclusive lanes, etc.).

There are, however, both negative and positive exceptions to the general picture of small or zero productivity changes. For example, Bhattacharyya et al. (1995) and Kumbhakar and Bhattacharyya (1996) reported very large productivity declines over time in Indian urban transit. On the positive side, Delhausse et al. (1992), Button and Costa (1999), Costa and Markellos (1997), Tulkens and Wunsch (1994) and Viton (1998) all reported positive productivity changes. In the case of the Belgian and UK studies these are partially attributed to regulatory changes that increased financial responsibility. According to Viton (1998), productivity growth was apparently largely due to a catching-up effect (i.e. an improvement in technical efficiency over time) and not so much due to technological frontier shifts.

4.2. Returns to scale and scope

Although the frontier studies reviewed are not specifically designed to study returns to scale and scope, they often produce interesting results as an automatic by-product. While numerous frontiers point at economies of scale and density (e.g. Filippini et al. 1992, Thiry and Tulkens 1992, Fazioli et al. 1993, Sakano et al. 1997), most recent studies provide evidence in favour of the classical U-shaped cost functions. These imply increasing returns to scale for the smaller operators, then constant and finally decreasing returns to scale for big companies. Examples of non-parametric studies reporting these firm-specific scale economies are Viton (1997) and Kerstens (1999). These findings are largely consistent with earlier non-frontier work surveyed in Berechman (1993). He points out that, in the very short-run, i.e. holding both network structure and fleet size constant, there appear to be large economies of capital stock utilization. In addition, most studies find that bus technology is characterized by economies of traffic density so that more intensive use of a given network reduces the cost per vehicle-km. This appears to be true in the short run because of the aforementioned capital stock utilization economies, but it is also valid in the medium run when fleet size can be adjusted. Finally, the overall picture in terms of scale economies is one of a U-shaped relation between average cost per vehicle-km and output expressed in vehicle-km, with a very broad range of constant returns to scale. Berechman (1993) also argued that small firms typically experience increasing returns to scale; while medium-sized companies face limited increasing or constant scale returns; and that the large systems are subject to decreasing returns to scale. The transition point from increasing to decreasing returns to scale seems to be situated somewhere between 250 and 400 buses (cf. Berechman 1993, Cowie and Asenova 1999).

Viton (1992, 1993) is the only work reporting in detail on economies of scope. In particular, an attempt is made to answer the question whether a consolidation operation could lead to cost savings for the seven companies in the San Francisco Bay Area. It turns out that the answer to some extent depends on the modes being offered by the potentially merging companies and by the number of companies being merged. In general, benefits fall as the number of companies involved increases.

4.3. Relation between efficiency and effectiveness

An interesting question is the extent to which efficiency and effectiveness are related. This issue directly bears on the specification of the appropriate objectives for
public transit firms. If empirical studies do not sufficiently incorporate output characteristics reflecting these objectives (e.g. demand-related output attributes), then efficiency and effectiveness may be not at all, or even negatively, related. Empirical evidence corroborates this view. Kerstens (1999) noticed that there is almost no correlation between technical efficiency and effectiveness, and finds that conclusions regarding performance are strongly conditional on output specification. Casual evidence reported by others even points at negative relations between efficiency and effectiveness (e.g. Tone and Sawada 1990, Chu et al. 1992, Schinnar 1993). (In fact, Schinnar (1993) cites a study of 145 public bus companies reporting such a negative association.)

There is also mixed evidence with respect to the time pattern of efficiency and effectiveness, again suggesting that both concepts may be unrelated unless all relevant characteristics are accounted for. For example, Costa (1998) considered a single operator (Metro de Madrid) over a small time span and finds a simultaneous improvement in efficiency and effectiveness after the introduction of organizational reforms. Equally focusing on a single operator, Tulkens and Wunsch (1994), by contrast, find a temporal pattern of improving efficiency and deteriorating effectiveness.

4.4. Ownership

A popular informal argument states that productivity and efficiency are higher in the private than in the public sector. Earlier surveys for the transit sector by Perry et al. (1988) and Berechman (1993) do not provide much support for this view. Variations in ownership and management systems are little correlated with performance, although it turns out that public operators generally offer higher service levels in general as well as during peak hours.

Frontier studies provide some more detailed and recent information on this highly controversial issue. Although Fazioli et al. (1993) found no relation between technical efficiency and ownership among Italian urban transit firms, most studies do suggest positive associations between efficiency and private ownership. For example, Tone and Sawada (1990) and Chang and Kao (1992) reported a better performance of private operators in Japan and Taiwan, respectively. Cowie and Asenova (1999) found public companies to be less efficient than private ones in the deregulated UK markets, while Kerstens (1996) also finds a positive effect of private ownership on efficiency in France.

However, ownership comes in different kinds and this may well prove important. This is illustrated by Bhattacharyya et al. (1995) analysing several types of ownership in India. They conclude that the form of public ownership and management structure affect efficiency levels. Nationalized firms experience the highest degree of inefficiency, but one reason could be that that the nationalization only affected units with problems right from the outset. Furthermore, the autonomous public transport corporations are less efficient than the operations organized directly by the transport department itself. Kumbhakar and Bhattacharyya (1996), in a complementary study, reported that the nationalized firms grow fastest while the units run directly by the government transport department perform worst over time. Hence, static and dynamic efficiency patterns need not coincide.

Unfortunately, the evidence provided by frontier studies in favour of private sector provision should be weighted against the fact that almost none of these studies controls for the degree of competition and the nature of government regulation in the
sector. Indeed, it is often argued that for strongly regulated markets (in terms of entry and exit, pricing, etc.) like urban transit, ownership is of little relevance on its own, though the market structure and the nature of competition is. The deregulation of UK and US bus markets led to an extensive discussion regarding the impact of potential competition in urban transit (Mackie et al. 1995, De Borger and Kerstens 2000).

4.5. Subsidies and contract design

Filippini et al. (1992) reported that government subsidies can have positive or negative impacts on performance, depending on the political proximity of the regulator and on whether the regulator can or cannot control company information. More specifically, they argue that local or regional government bodies are better able to monitor the performance of urban transit operators than the central government. Nolan (1996), however, did not find support for this view for the USA: state subsidies diminish efficiency, while federal subsidies improve it. Kerstens (1996) and Matas and Raymond (1998) found a clear negative relation between subsidies and urban transit performance, but do not control for the sources of subsidies. (Obeng 1994) concluded that operating and capital subsidies enhance technical efficiency. However, the latter inference is based on comparing a DEA model with and without subsidies. Since efficiency measurement is sensitive to the number of dimensions, the result may be an artefact of the methodology (Kerstens and Vanden Eeckaut 1995, Obeng 1995). Sakano and Obeng (1995) also reported a negative impact of subsidies on technical efficiency, but no effect on allocative efficiency. Sakano et al. (1997) found that allocative inefficiencies are mainly caused internally, instead of being induced by subsidies. Finally, Tulkens et al. (1988) related the bad performance of one Belgian operator to excess capacity resulting from seemingly redundant investments in additional buses. Probably this is linked with investment subsidies.

Kerstens (1996) also reported on other contractual arrangements. The negative effect of subsidies is independent of the risk sharing agreed upon in contracts between operators and public authorities. Sharing risks was found to enhance performance, as did the contract duration. Another important determinant of performance was a locally levied, earmarked tax on the wage bill (‘versement transport’) that turns out to have a positive impact. It is conjectured that tax rates affect monitoring efforts of citizens and, indirectly, regulators.

The findings on subsidies are certainly in line with the extensive literature documenting that subsidies in fact contribute to cost escalation in the sector, and not the reverse (Pucher 1988), though the size of this effect partly depends on the political proximity of the regulator. Subsidies tend to worsen the performance of urban public transport in a variety of ways: higher costs, fewer revenue-passengers, excessive wage growth, and technical inefficiency. Furthermore, specific capital subsidies tend to create excess capacities. Too few studies have so far empirically looked at the impact of contractual arrangements to derive useful conclusions for regulatory policies.

4.6. Environmental variables, network characteristics and size

As to the spatial characteristics affecting performance, Filippini et al. (1992) reported a negative effect of the number of stops served in the network, the latter being an element of environmental heterogeneity. Similarly, Fazioli et al. (1993) and Levaggi (1994) observed that network length affects performance negatively. Sakano et al. (1997), however, came to an opposite conclusion. Gathon (1989) detected that
technical efficiency is positively related to average operational speed. This result is confirmed in Levaggi (1994), Nolan (1996) and Viton (1992, 1993). Kerstens (1996) noticed that the distance between stops has a negative effect on efficiency levels, while the length of lines is positively related to performance. Matas and Raymond (1998), Nolan (1996) and Sakano and Obeng (1995) reported that efficiency decreases with average fleet age. By contrast, Kerstens (1996) and Viton (1986) found no significant capital-vintage effects. Tone and Sawada (1990) discovered that urban companies perform better than rural operators.

Temporal service characteristics also affect the performance of transit operators. Not surprisingly, Nolan (1996) observed a negative relation between peak-to-base ratios and technical efficiency. Matas and Raymond (1998) detected a similar negative relation between efficiency and the range of night routes, i.e. another determinant of network heterogeneity. A bit surprisingly, Viton (1986) found no effects at all of the peak-to-base ratio on urban transit performance, while Viton (1992, 1993) even reported the anomalous result that higher peak-to-base ratios lower costs.

For a sample of US urban transit operators Obeng (1994) reported efficiency levels declining with size. Analysing Swiss companies Filippini et al. (1992) discovered that technical efficiency is negatively related to the size of companies, which is interpreted as evidence of bureaucratic influences. This finding can also qualify their above-mentioned conclusion that the prevalence of economies of scale and density may legitimate a selective merger policy. Viton (1986) is less conclusive since inefficiency is unrelated to the size of operations. Sakano and Obeng (1995) found no relation between size and technical efficiency, but report allocative inefficiencies decreasing with size.

5. Conclusions and policy implications

The survey on urban transit performance suggests that frontier methodologies have substantially increased our knowledge of the determinants of productivity growth and efficiency changes in the sector. In particular, technical inefficiencies are widespread and technical progress is low and not unequivocal. Frontier studies even suggest that technical inefficiency is the dominant source of poor performance, rather than congestion, inefficiencies in scale or allocative inefficiency. Furthermore, the finding of a negative relation between efficiency and effectiveness certainly requires further investigation. One implication for regulatory policies is that the choice between input and output monitoring as well as the precise specification of outputs may demand more reflection.

The frontier evidence clearly shows that the regulatory environment and the characteristics of the network substantially influence efficiency and productivity. With respect to the former, it was found that ownership, the risk sharing properties of contracts between operator and public authority, and the level and nature of subsidies to operators all directly affect public transit performance. (The destructive impact of subsidies may call for making them conditional on performance. De Jong and Cheung (1999) developed a subsidy allocation mechanism net of technical inefficiency.) With respect to the latter, although network characteristics are always found to be highly relevant, their role in explaining efficiency is not entirely obvious. Indeed, while some characteristics influencing efficiency levels are under the control of the companies or the public authorities (e.g. number of stops; network length; length of lines, etc.), others are largely exogenous (e.g. the average operational speed is mainly determined by transport infrastructure and congestion levels). The results
do suggest that it may be wise to allow operators some freedom to organize their production to achieve maximum efficiency. Moreover, public authorities can influence the efficiency of transport operations by improvements in the transport network so as to reduce, for instance, congestion levels.

Unfortunately, the overall picture is not entirely positive. Although frontier methodologies have, as highlighted above, enlarged our knowledge on the determinants of efficiency, a large number of basic problems persist. First, many studies suffer from the lack of appropriate data. For this reason, correcting for differences in quality of inputs and outputs remains difficult for these new methods. Second, appropriately accounting for the network structure of transit operators remains a challenge. Again, data on attributes are often unavailable. In addition, as argued above, many relevant characteristics are largely outside the control of operators but imposed by the regulatory environment, or partly determined by demand. This makes it unclear whether such characteristics are part of technology or determinants of performance. Third, in many cases insufficient evidence is available on economically crucial issues. For example, the efficiency effect of improving competitive conditions in the industry has not convincingly been shown. In this respect it is especially unfortunate that few frontier studies have focused on the effects of privatization and regulatory changes (e.g. in countries like the UK). (Interestingly, Nolan et al. (2000) showed that regulatory policies should be carefully designed to have efficiency effects. The ambitious Intermodal Surface Transportation Efficiency Act (ISTEA) seems to have very little effect on transit firms’ efficiency.) Fourth, it is evident that there is a huge need for comparative international research to provide more details on the relative performance of operators working under different regulatory regimes.

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