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Persistence and dynamics in the efficiency of toll motorways: The Spanish case

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A B S T R A C T

This study performs an empirical analysis of the productive efficiency of toll motorway concessionaire companies in Spain. We estimate a dynamic stochastic frontier model using an input-oriented distance function for 30 concessionaires during the 2003–2015 period. Considering a multi-output production technology with light and heavy vehicles, we estimate an autoregressive dynamic specification under a Bayesian framework that acknowledges persistence in firm efficiency due to adjustment costs. Our results reveal: (i) large persistence in productive inefficiency in the toll motorway sector, (ii) technical change from 2006 onwards, and (iii) increasing returns to scale. We derive both short- and long-run inefficiency estimates and document that long-run inefficiency increases with the number of stretches a firm manages; however, inefficiency is unrelated to the political authority that grants the concession. We also find that the marginal cost of light vehicle-kilometres is about half that for heavy vehicles.

1. Introduction

Road transport infrastructures are projects of economic and strategic relevance for those areas where they are developed. User benefits include travel-time savings, travel costs reductions and safety enhancements, among others. In this regard, the positive relationship between road infrastructures development and economic growth is well-documented in the economic literature (Melo et al., 2013; Elburz et al., 2017). This type of infrastructure typically requires high levels of investment for their construction and putting into service, which has traditionally relied on public funds. However, because the public sector usually faces budget constraints, alternative financing mechanisms have been developed.

One well-known infrastructure funding tool is the Public-Private-Partnership system (henceforth PPP), which has been extensively analysed in the literature (Hart, 2003; Engel et al., 2007; Maskin and Tirole, 2008; Oliveira-Cruz and Sarmento, 2018). It consists of a principal (the public sector) that grants an agent (a private company) either the management alone of an infrastructure project or more complex responsibilities for design, construction and management. This system gives the concessionaire the right to exploit the motorway and charge fees to users for its use.[1] It has a long tradition in Spain, the country with the longest motorway network among European countries (Holl, 2011) and one of the most experienced regarding private participation in toll motorway projects (Albalate and Bel-Piñana, 2016).

The recent bankruptcies of several concessionaire companies resulted in the Spanish government having to rescue some of them, thereby assuming the management of their motorway stretches. In this context and given the high regulation of the toll motorways sector, it seems necessary to examine concessionaires' performance from the regulator's perspective. Even if companies have little capacity to increase demand (Engel et al., 2001b), it would be helpful to know the firm efficiency in the use of factor inputs. This would enable governments to define regulatory incentives that enforce better management practises when auctioning future concessions or renegotiating current contracts.

The main objective of this paper is to estimate the productive efficiency of Spanish toll motorway concessionaire companies. To this end, we utilise an unbalanced panel dataset for 30 concessionaire companies during the 2003–2015 period. We employ stochastic frontier analysis (SFA) using an input-oriented distance function approach with a multi-output production technology. A novel aspect of our analysis is that it acknowledges the dynamic nature of technical inefficiency. That is, our

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[1] Throughout the paper we use the terms 'concessionaire', 'company' and 'firm' interchangeably to refer to toll motorway companies that are granted the exploitation of the infrastructure.

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model recognizes that there might be some persistence in the degree of inefficiency over time due to quasi-fixed input adjustment costs. This arises as a consequence of learning and training costs in the reallocation of inputs. Accordingly, our modelling approach explicitly captures changes in efficiency scores that occur as firms adjust to their individual long-run equilibriums. This allows us to compute concessionaire-specific short- and long-run technical efficiency scores.

The econometric model used is an extension of the one introduced by Tsionas (2006) and aligns closely with Skevas et al. (2018a; 2018b). It considers that productive inefficiency follows an autoregressive process in the adjustment process towards the long-run equilibrium. Our model specification allows for heterogeneity in inefficiency in two ways. First, the autoregressive term is assumed to be a normally distributed random parameter that lies within the unit interval and varies across concessionaires. Second, we specify some firm characteristics as inefficiency shifters. Specifically, we consider: (i) the number of toll motorway stretches managed by each concessionaire, and (ii) whether the concession was awarded by the State (central government) or by regional governments. The latter is particularly relevant given the public debate about the appropriate regional authority that should finance transport infrastructure projects (Hammes and Mandell, 2019).

The model is estimated under a Bayesian framework using Monte Carlo Monte Chain (MCMC) techniques. Contrary to frequentist approaches that distinguish persistent from transient inefficiency by exploiting two time-varying and time-invariant skew normally distributed error terms (Tsionas and Kumbhakar, 2014; Filippini and Greene, 2016), our model defines a recursive structure that captures the inertia in inefficiency under a long-run adjustment process. Empirical applications of this type of dynamic SFA modelling using an input-oriented distance function for productive efficiency are Galán and Pollitt (2014), Galán et al. (2015) and Minviel and Sipiläinen (2018). To the best of our knowledge, this study is the first application of this modelling approach in the field of transport economics.[2]

The contribution of this paper is twofold. First, we add new empirical evidence about the technical efficiency of toll motorway companies. To date, this issue has been scarcely studied in the literature due to the unavailability of suitable data, with Odeck (2008), Massiani and Ragazzi (2008), Welde and Odeck (2011), Sarmento et al. (2017) and Albalate and Rosell (2019) representing the only exceptions. We employ a self-constructed dataset for Spain, the country with the largest number of toll motorway concessionaires based on profit maximization (Albalate and Rosell, 2019). Second, we provide an economic analysis of the sources of inefficiency related to heterogeneity in the speed of adjustment to the long-run equilibrium, which allows us to evaluate the transient and persistent inefficiency levels of each toll company. Therefore, the paper presents relevant information for policy makers in relation to future auctions and renegotiations in this sector.

It is important to highlight at this stage that the paper does not analyse whether the infrastructure should have been developed or not. Instead, our interest lies in the efficiency in infrastructure usage once it has been built. In this way, our analysis of productive efficiency in the toll motorway sector follows previous research concerned about productive efficiency in regulated service industries like port terminals (Cullinane and Song, 2006; Chang and Tovar, 2014), railways (Smith, 2012; Bougna and Crozet, 2016) or airports (Assaf et al., 2012; Pavlyuk, 2016).

The paper is structured as follows. After this introductory section, we review the related literature in Section 2. Section 3 outlines the evolution of toll motorways in Spain and their public rescue. In Section 4, we describe the database and the variables employed in the analysis. Section 5 explains the methodology and the econometric specification. Section 6 reports and discusses the estimation results. The last section concludes with the main findings and some implications for policy and practice.

2. Literature review

Toll motorways are a type of infrastructure that has exhibited great expansion in the last two decades, both in Spain and internationally. We first provide a general overview of the literature on toll motorways, reviewing some empirical evidence about the competitive structure of the industry, optimal toll pricing, and its productive technology. We then review the few existing studies that have formally examined efficiency in this sector.

2.1. Toll motorways: a general overview

Several studies have analysed the economic and social effects of toll motorways. De Palma and Lindsey (2000) compare private toll roads and public free-access infrastructures in terms of social surplus, concluding that private toll roads enhance the system's operation when tolls rates vary over time to reduce possible queueing, and when private roads do not receive a dominant fraction of the total capacity. Odeck and Bråthen (2002) discuss the successes and failures of the toll motorway system in Norway, highlighting the importance of the price mechanism as a tool to reduce pollution in the areas around large cities. Xiao et al. (2007) examine the competitiveness of the toll motorway industry in terms of social welfare. They conclude that, although a competitive industry is more desirable than a monopolist market, the two market structures do not exhibit major differences in terms of congestion. Odeck and Bråthen (2008) estimate the elasticity of demand in the Norwegian toll motorway sector, both in the short and in the long run. Their estimates suggest that demand for toll motorways is inelastic in the short-run but approaches the unit in the long-run.

An issue of concern in the literature is the appropriate design of concession contracts. Chen and Subprasom (2007) analyse alternative models for toll road pricing under demand uncertainty considering the different interests of the parties involved. Their results indicate that subsidies to cover construction costs and granting concession period extensions are two suitable policies. Ubbels and Verhoef (2008) address the optimal administrative design for governments when auctioning concessions for private roads. They specifically focus on the effects of defining various indicators in the auction process and the inclusion of potential subsidies. Albalate and Bel (2009) compare fixed versus flexible contracts that depend on results in the administrative auctions for toll motorways under demand uncertainty. Their analysis shows that the latter would have been a better option given the erroneous predictions of traffic demand. Quiggin and Wang (2019) discuss the successes and failures of the toll motorways industry in Australia. They conclude that inefficient tolls funded by PPPs should be gradually removed; they propose a road pricing system based on congestion that would optimize the existing road network, reduce traffic congestion, and internalise negative externalities.

To improve incentive regulation, another body of research has examined the production technology and cost functions of concessionaire companies. By estimating a translog cost function for 26 Norwegian toll concessionaires from 1998 to 2004, Amdal et al. (2007) report important unexploited economies of scale. For a given a level of traffic, increases in the number of lanes, levels of debt and passenger charging will increase average operating costs. Similarly, Benfratello et al. (2009) study technological change at 20 Italian concessionaire companies, finding significant technical change over time and important benefits in the sector from the privatization process. Odeck (2019) relates Norwegian concessionaires' annual average operating costs to a set of operators' characteristics and demand indicators. He finds that a 1% increase in the number of vehicles reduces average cost by about 13%, which implies the existence of economies of scale. Additionally, the use of

[2] Assaf et al. (2012) apply a Bayesian dynamic frontier model to study UK airports' performance but focused on cost efficiency rather than productive efficiency.

On-Board-Unit (OBU) system decreases operation costs, whereas the age of the toll operator is not significant. More recently, Yarmukhamedov et al. (2020) find that, in Sweden, the state-run provider faces significantly higher maintenance costs than private firms, which suggests that competitive tendering has delivered substantial savings.

For the Spanish case, some scholars have evaluated and discussed the economic consequences of its auction and exploitation system for toll motorways projects. Albalate and Bel (2012) study the relationship between motorway quality and fatality rates. They show that the extension of the motorway network decreases fatality rates, but this only holds for the case of free-access motorways and not for tolled ones. Bel et al. (2017) discuss the reasons behind the bankruptcies of some concessionaires and the costs these bankruptcies have caused to taxpayers. Turró and Penyalver (2019) examine toll-free motorways in Andalusia and conclude that several toll projects have become white elephants. More recently, Carrillo de Albornoz et al. (2021) evaluate the bankruptcy of the R-3 and R-5 PPP motorway projects in Madrid. The authors conclude that although it went badly for private investors, it should not be labelled as a complete failure: apart from the important benefits to users, the Granting Authority is estimated to have saved up to 512 million euros if compared to the project being completely delivered through traditional procurement.

2.2. Efficiency analysis in the toll motorway sector

Despite the existence of a large body of literature that investigates the externalities and social consequences of toll motorways, few empirical studies examine the productive efficiency of the companies in charge of toll motorways' construction, management and maintenance. We are aware only of the works by Odeck (2008), Massiani and Ragazzi (2008), Welde and Odeck (2011), Sarmento et al. (2017) and Albalate and Rosell (2019). Table 1 summarises these studies.

3. Toll motorways in Spain

3.1. The evolution of the toll motorway network and Public-Private-Partnerships (PPPs)

Toll motorways have operated in Spain since 1967, when the Spanish National Motorways Program was approved. This project saw the construction of 3160 km (km) of toll motorways. This toll system, which requires users rather than taxpayers to finance the infrastructure, offers important incentives for their construction in areas with high traffic and growth prospects. For this reason, the Mediterranean and the Ebro's Valley areas were prioritized. The first 167 km of toll motorways commenced construction in 1967.

Fig. 1 depicts the growth in the total length of toll motorways in Spain belonging to private companies during the 1967–2015 period. Three main waves can be identified (Albalate et al., 2015a). The first lasted from 1967 to 1975, when the total length increased from 500 km of operating motorways in 1970 to around 2000 km in 1975. The second one corresponds to the 1976–1995 period, during which the total length of the network remained virtually constant. Finally, the most recent wave between 1996 and 2007 saw the total length reach 3250 km. By the end of 2015, Spain became the European country with the most extensive (3307 km) motorway network (Albalate et al., 2015b). With an annual average daily traffic (AADT) of 19,090 vehicles, the network is composed of 54 stretches that belong to 32 different concessionaires.

Spain is one of the leading countries in the use of PPPs for road infrastructures. Theoretically, the concessional system is characterized by companies taking all the risk (Baeza and Vassallo, 2010). If the contract is adequately designed so that the private company has the incentives to prevent and minimize risks, the transference of the competences for the motorways' exploitation from the public sector (taxpayers) to the private sector is an optimal arrangement (Albalate et al., 2015a). However, concession contracts are incomplete because it is difficult to consider ex-ante all the possible contingencies that might arise throughout the infrastructure's lifetime. This uncertainty forces the public sector to conduct continual renegotiations with concessionaires, which are only suitable if the company's search for revenues is compatible with the pursuit of efficiency.

The economic literature argues that construction, land expropriation and maintenance risks should be transferred to the private sector because of its greater capacity to control extra costs, without prejudice they could be partially shared with the public sector. However, the so-called 'demand risk' is the most prominent problem, not only because it is beyond the concessionaires' control but also because traffic predictions are usually erroneous (Hensher, 2018). In general, there is a great overestimation of demand and optimism bias in the sector (Bain, 2009) as bidders tend to present overly optimistic offers regarding traffic previsions because their main objective is 'to get' the concession (Bel et al., 2017; Baeza and Vassallo, 2012).[3] In addition, infrastructure concessions are usually granted for long periods. Because renegotiations are allowed when the original circumstances change, these lengthy periods encourage opportunistic behavior in renegotiations (Engel et al., 2007).

3.2. Bankruptcy and public rescue of concessionaire companies

The toll motorway sector in Spain is currently undergoing important restructuring following the bankruptcy of some concessionaires. In fact, eight of the thirty-two existing toll companies have declared a state of insolvency since 2012, and the rest are heavily indebted.[4] Albalate et al. (2015a) document that extra costs in expropriation and construction due to the real estate boom along with faulty traffic projections are the two main reasons for the companies' current bankruptcy.

The Public Sector has assisted these companies via various strategies, including: (i) rate increases, (ii) concession extensions, (iii) loans to finance extra costs, and (iv) the establishment of a compensation account by which the State covers the differences between expected and current revenues. The reader is referred to Albalate and Bel-Piñana (2016) for a review of toll motorway renegotiations in Spain. However, these measures have proven insufficient, and banks have requested the implementation of the State's financial liability (*Responsabilidad Patrimonial de la Administración*), a type of contractual safeguard that covers the risk companies have undertaken. In practice, this measure represents a kind of bail-out that uses public money to rescue private companies.[5] Given this safeguard, private investors behind concessionaires have incentives to undertake investments of uncertain profitability or to incur

[3] Nevertheless, Odeck and Welde (2017) show that, in Norwegian case, the mean percentage error in forecasts is only 4%.

[4] *Autopista Madrid Toledo Concesionaria Española de Autopistas SA* (2012), *Autopista Madrid-Sur, Concesionaria Española, S.A.* (2012), *Accesos de Madrid Concesionaria Española SA* (2012), *Autopista Madrid Levante Concesionaria Española SA* (2013), *Autopista del Henares, S.A, Concesionaria del Estado [Henarsa]* (2013), *Ciralsa Sociedad Anónima Concesionaria del Estado* (2013), *Autopista de la Costa Cálida Concesionaria Española de Autopistas SA [Aucosta]* (2013) and *Autopista Eje-Aeropuerto Concesionaria Española SA* (2016). From January 2018 onwards, they have been under the control of a public company called SEITT. The accumulated debt of the sector exceeds four billion euros (Albalate et al., 2015a).

[5] This refers to economic compensation for the early cancellation of the concession, by which the State must pay the concessionaire the (depreciation discounted) amount of: (i) the investments made for the land's expropriation, and (ii) the construction costs and those associated with the acquisition of other assets for the exploitation of the infrstructure (article 247 of the Public Sector Contracts Law). See Bel et al. (2017) for more details.

Table 1
Summary of studies on toll motorways' efficiency.

Author	Model	Data	Productive vs Cost efficiency	Inputs	Outputs	Main conclusions
Odeck (2008)	DEA	18 Norwegian toll concessionaires Period: 2001–2004	Productive efficiency	• Operation costs	• Number of vehicles • Lanes offered	• Unexploited economies of scale • Larger concessionaires are more efficient • There is a productivity increase in the sector (around 1%)
Massiani and Ragazzi (2008)	SFA (translog)	18 Italian highway operators Period: 2006	Cost efficiency	• Intermediate goods • Service • Rental • Personnel	• Network length (in km) • Traffic (vehicles per km)	• Operating costs depend on traffic and capacity • Economies of scale are relevant • Large heterogeneity in cost efficiency
Welde and Odeck (2011)	DEA and SFA (translog)	20 Norwegian toll companies Period: 2003–2008	Productive efficiency	• Operation costs •Administrative costs	• Annual traffic divided by the number of lanes	• Large potential for efficiency improvements • No evidence of economies of scale
Sarmento et al. (2017)	DEA with Malmquist Index	7 Portuguese highway companies Period: 2003–2012	Productive efficiency	• Operating costs • Maintenance costs • Total assets (investment) • Number of employees	• Daily average traffic • Revenues	• Technical efficiency decreases over time • The efficiency performance of each highway is driven by its local context, particularly location and district
Albalate and Rosell (2019)	SFA (translog)	32 Spanish toll motorways Period: 1988–2014	Cost efficiency	• Labor force (full-time equivalent workers) • Capital	• Number of vehicle-kilometres	• Technical progress in the sector • No differences in efficiency based on the public/private ownership • Unexploited economies of scale and density • Regional governments grant more efficient projects

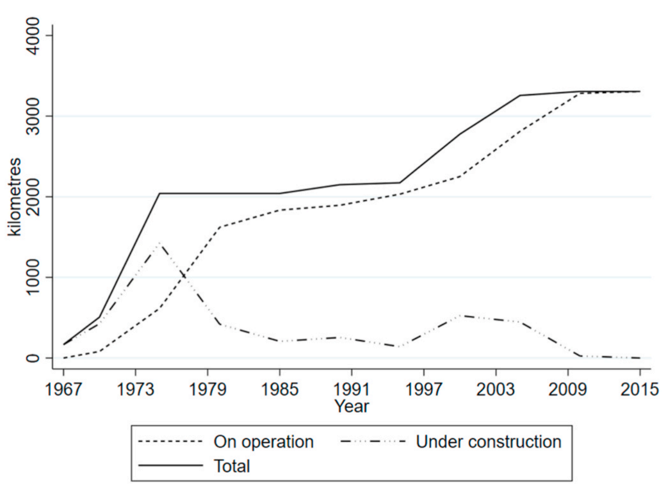

Fig. 1. Evolution of the length (in km) of Spanish toll motorways (1967–2015) Source: Own elaboration from the Annual Reports of the Toll Motorway Sector in Spain.

in extra costs at the expense of taxpayers (Albalate and Bel, 2009; Bel et al., 2017).[6]

4. Data

We employ a novel self-constructed dataset for Spain obtained from two sources. The first source is the *Annual Reports of the Toll Motorways Sector*. Provided annually by the Spanish Ministry of Infrastructure, these reports contain information about annual traffic volume, the number of stretches and toll rates, among others. They also provide data on the balance sheets and financial accounts of the concessionaire companies. The second source is the *Iberian Balance Sheets Analysis System (SABI)*, which complements the information provided by the annual reports.

Our study covers the 2003–2015 period, which is of great interest because it comprises both expansions and recessions. Although the annual reports contain information for 32 companies, the resulting dataset in our analysis involves 30 firms.[7] Because some mergers have occurred and some companies have collapsed due to bankruptcy since 2013, we have an unbalanced panel dataset with 343 observations. Fig. 2 maps the toll motorway stretches in Spain.

The main output a toll motorway produces is the traffic volume circulating through it. We measure this by the total number of vehicle-kilometres (i.e., the product of the number of vehicles on a given motorway and the average length of their trip in kilometres). This is a common way to measure the distance travelled by every vehicle (Albalate and Rossell, 2019). We distinguish between light (Y_1) and heavy vehicles (Y_2).[8] This distinction is relevant because heavy and light vehicles exert different effects on pavement deterioration (Newbery, 1988) and therefore on motorways' maintenance costs (Small and Winston, 1988; Lu and Meng, 2018).

Concerning the variable inputs, we first consider the number of workers, who are classified into two categories: (i) employees engaged in maintenance tasks (L_1), and (ii) employees charged with rate collection and 'general services' (L_2). This information is obtained by combining the data from the annual reports and SABI. Second, the value of intermediate inputs (*INT,* expressed in thousands of euros) is considered. This variable reflects annual expenditures for the motorway maintenance and operation costs. Some examples include patching, inspections and road sealing, adaptation to the weather conditions (e.g., snowploughs), road cleaning, lighting costs, accident repairs or tunnel maintenance costs. Finally, the value of the infrastructure's capital stock

[6] The shareholding composition by the end of 2015 was as follows: construction companies (70%), other concessionaire companies (16.1%), public administrations (2.5%), banks and saving banks (6.1%) and private investors (5.3%).

[7] We lack relevant data on one firm *(Interbiak)*. We merged the data for *Castellana de Autopistas* and *Iberpistas* because the former is owned by the latter and the information for their workers is provided jointly.

[8] We multiply the total vehicle-kilometres by the shares light and heavy vehicles represent over total traffic for each concessionaire.

Fig. 2. Toll motorway stretches in Spain
*Note: stretches in blue are granted by the Central Government while those in red depend on regional authorities.

(K, expressed in thousands of euros) is included as a measure of capital input (and treated as quasi-fixed).[9] To alleviate the potential effects of price inflation, all monetary variables are deflated by the Consumer Price Index (CPI; 2011 = 100).

Since the analysis is done at the concessionaire level, we also consider the following firm characteristics: (i) the number of stretches managed by the concessionaire (*stretches*), and (ii) a dummy variable indicating whether the concession was granted by the State (*State*-granted) or by regional authorities (*regional*-granted). By ‘granted’, we mean that the right to manage the infrastructure and the potential renegotiations are held between the company and the central government or between the company and the corresponding autonomous community.

Table 2 presents the definitions and descriptive statistics of the variables introduced above. The mean number of light (heavy) vehicle-kilometres in our study period is 758 (114) million. On average, each concessionaire has 43 employees engaged in maintenance tasks and 140 workers charged with rate collection and other activities. The value of the capital stock is approximately 540 million euros; however, it exhibits substantial variability across concessionaires. Firms have 1.68 stretches on average, with 67% under the control of the central government.

5. Methodology

5.1. The input distance function

The first step in analysing the technical efficiency of the Spanish toll motorways is to define the production technology. Since a toll motorway provides transport services to two types of outputs (light and heavy vehicles) using multiple inputs, we propose an input-oriented distance function approach (henceforth IDF). The IDF can be seen as a production frontier that accommodates a multi-output production technology and has a long tradition in empirical studies about efficiency (Trujillo and Tovar, 2007; Tovar and Martín-Cejas, 2010; Galán et al., 2015). The input orientation derives from the fact that in some service industries

[9] Capital input measures the stock value of the investment without appreciation or balance sheet asset revaluations. Some studies use the length of the infrastructure instead. Note that the value of the capital stock (in real terms) captures the length of the motorway together with other orography-related aspects that could determine the use of the labour and intermediate inputs.

Table 2
Variable definition and descriptive statistics (NxT = 343).

Label	Definition	Mean	SD	Min	Max
Outputs					
Y_1	Number of light vehicle-kilometres (millions)	758.59	1238.62	6.97	7173.34
Y_2	Number of heavy vehicle-kilometres (millions)	114.31	248.86	0.02	1538.51
Inputs					
L_1	Total workers in maintenance tasks	43.50	46.16	2.00	274.00
L_2	Total workers in charge of rates collection and who belong to the 'general services' category	140.95	220.98	10.00	1457.00
INT	Intermediate inputs expenditure (thousands of euros)	11,884.37	14,516.73	84.72	86773.47
K	Infrastructure capital stock (thousands of euros)	540,378.00	481,625.30	10,351.95	2,341,576.00
Firm characteristics					
stretches	Number of toll motorway stretches managed by the concessionaire	1.68	1.11	1	5
State-granted	= 1 if the concession is granted by the Central Government	0.67	0.46	0	1

such as banking, post offices or transport, outputs are exogenously given and firms have only control over inputs usage (Kumbhakar, 2013). Therefore, we treat the output (traffic volume) as exogenous, in line with Engel et al. (2001a, 2001b, 2007).

The IDF satisfies the duality theorem with the cost function and has the advantage of not requiring information about input prices. Importantly, the IDF is robust to systematic deviations from cost-minimising behaviour (Kumbhakar, 2012). This is relevant in this context because the shareholding of some concessionaires belongs to public entities, who might prioritise the purpose of providing an appropriate public service over profit maximization. Furthermore, the IDF also satisfies the following properties: (i) it is non-decreasing in variable inputs, (ii) it is decreasing in outputs, and (iii) it is homogeneous of degree one and concave in inputs.

Similarly to Kumbhakar (2013) and Das and Kumbhakar (2016), we use a transformation function $AF(\theta x,\ y,\ k, t) = 1$ to represent the *IDF* as the production technology, where x is a vector of J variable inputs, y is a vector of M outputs, k refers to a quasi-fixed input (capital stock), A is a neutral shift parameter, t denotes a time trend that captures technical change, and θ is a parameter that gathers input-oriented measures of technical efficiency in the production process ($0 < \theta \leq 1$). Because the transformation function $F(.)$ is also homogeneous of degree one in inputs, the transformation function can be written as follows:

$$A\theta F(x, y, k, t) = 1 \tag{1}$$

If we normalise the input variables arbitrarily by one of them (x_1), then the *IDF* becomes:

$$IDF = A\theta F(\tilde{x}, y, k, t) = 1 / x_1 \tag{2}$$

where $\tilde{x} = (x_2/x_1, \ldots, x_J/x_1)$, x_1 is the normalising input and the subscripts for firm and period are omitted for notational convenience.

Taking natural logarithms and rearranging, the *IDF* can be expressed as follows:

$$\ln(IDF) = -\ln x_1 = \ln A + \ln F(\tilde{x}, y, k, t) + \ln \theta \tag{3}$$

Equation (3) assumes that the production process is deterministic. If we add a disturbance term (v) to account for random noise, the *IDF* becomes a stochastic frontier model in the following manner:

$$\ln(IDF) = -\ln x_1 = \ln A + \ln F(\tilde{x}, y, k, t) - u + v \tag{4}$$

where $u = -\ln \theta$ is the inefficiency term and $u \geq 0$.

5.2. Empirical model

The empirical application of the *IDF* requires the choice of an appropriate functional form for the production function. We propose a translog form due to its flexibility (Christensen et al., 1971). Assuming a multioutput technology with two outputs (Y_1, Y_2), three variable inputs (L_1, L_2, INT), a quasi-fixed input (K), and a time trend, both in level and in squared form (t and t^2), the transformation function for N ($i = 1, \ldots, N$) firms and T time periods ($t = 1, \ldots, T$) is specified as:

$$\begin{aligned} -\ln L_{1_{it}} = & \sum_{m=1}^{2} \alpha_m \ln Y_{m_{it}} + \frac{1}{2}\sum_{m=1}^{2}\sum_{n=1}^{2} \alpha_{mn} \ln Y_{m_{it}} \ln Y_{n_{it}} + \sum_{j=1}^{2} \beta_j \ln \tilde{X}_{j_{it}} + \frac{1}{2}\sum_{j=1}^{2}\sum_{k=1}^{2} \beta_{jk} \ln \tilde{X}_{j_{it}} \ln \tilde{X}_{k_{it}} + \frac{1}{2}\sum_{j=1}^{2}\sum_{m=1}^{2} \gamma_{jm} \ln \tilde{X}_{j_{it}} \ln Y_{m_{it}} + \pi_1 \ln K_{it} + \frac{1}{2}\pi_2 (\ln K_{it})^2 \\ & + \frac{1}{2}\sum_{m=1}^{2} \theta_m \ln K_{it} \ln Y_{m_{it}} + \frac{1}{2}\sum_{j=1}^{2} \varphi_j \ln K_{it} \ln \tilde{X}_{j_{it}} + \varsigma_1 t + \varsigma_2 \frac{1}{2}(t)^2 + \sum_{m=1}^{2} \kappa_m \ln Y_{m_{it}} t + \sum_{j=1}^{2} \varphi_j \ln \tilde{X}_{j_{it}} t + \eta \ln K_{it}\, t + \delta_i + v_{it} - u_{it} \end{aligned} \tag{5}$$

where $\tilde{X}$ is a vector of $J = 2$ normalised variable inputs ($\widetilde{L_2} = L_2/L_1$, $\widetilde{INT} = INT/L_1$); L_1 is the numeraire input; $\alpha_m, \alpha_{mn}, \beta_j, \beta_{jk}, \gamma_{jm}, \pi_1, \pi_2, \theta_m, \varphi_j, \varsigma_1, \varsigma_2, \kappa_m, \varphi_j$ and η are parameters to be estimated; $\delta_i = lnA_i$ are concessionaire-specific random effects capturing any time-invariant heterogeneity affecting the technological frontier, $\delta_i \sim N(0, \sigma_\delta^2)$; v_{it} is an idiosyncratic error term, $v_{it} \sim N(0, \sigma_v^2)$; and u_{it} is the non-negative time-variant inefficiency term (to be developed below). Importantly, v_{it} is assumed to be independent of u_{it} and δ_i. Furthermore, we impose the following symmetry properties on Equation (5): $\alpha_{mn} = \alpha_{nm}$, $\beta_{jk} = \beta_{kj}$ and. $\gamma_{jm} = \gamma_{mj}$.[10]

Traditionally, the inefficiency term in SFA models was assumed to be time invariant. This imposes the restriction that any time-invariant unobserved factor can be wrongly considered as inefficiency. For this reason, scholars have favoured the use of time-variant inefficiency models together with individual effects. Earlier proposals by Cornwel et al. (1990), Kumbhakar (1990) and Battese and Coelli (1992) specify the inefficiency term to be a function of time. However, these models have the drawback of assuming that efficiency can either increase or

[10] As mentioned before, the assumption that outputs are exogenously given seems to be plausible given that concessionaires have little capacity to increase demand (Engel et al., 2001b, 2007). Rates are regulated by the public authority that grants the concession so that traffic cannot be stimulated through the price mechanism as in other service industries. Concerning the potential endogeneity of the inputs, some authors argue that because they are input ratios, they are unlikely to suffer from an endogeneity problem (Kumbhakar, 2012; Mundlak, 1996; Feng and Serletis, 2010).

decrease monotonically for all units and time-periods, which might not be the case in turbulent sectors and time periods like ours.

The True Random Effects and the True Fixed Effects SFA models proposed by Greene (2005a; 2005b) relax this limitation by estimating an unstructured time varying inefficiency term that allows for time-specific shocks together with individual effects by exploiting the skewness of the composite error term. More recently, the Generalized True Random Effects (GTRE) model developed by Tsionas and Kumbhakar (2014) and Filippini and Greene (2016) goes further, distinguishing transient from persistent inefficiency in a four-disturbance model, with two composite time-varying and time-invariant error terms. The latter approach has received growing acceptance and has been applied to the study of efficiency in different contexts, such as electricity distribution (Filippini et al., 2018), health care (Colombi et al., 2017), the airlines (Heshmati et al., 2018), and the toll motorways sector (Albalate and Rosell, 2019), among others.

The GTRE captures time-varying efficiency shocks but does not impose any structure on them. Indeed, this lack of structure can produce erratic results and ignores the potential existence of inertia in firm efficiency (Skevas et al., 2018a). Concessionaires are granted the right to manage the infrastructure for long but limited periods. Consequently, their management decisions have an intertemporal nature. Firms face adjustment costs by which they might be inefficient in the short-run to be more efficient in the long-run (Emvalomatis et al., 2011; Emvalomatis, 2012). These adjustment costs, which might arise from quasi-fixed inputs in the short run, are likely to prevent concessionaires from instant adaptation towards efficiency (Minviel and Sipiläinen, 2018). In our study, the quasi-fixed input is capital stock, which cannot be instantaneously and costlessly reallocated to improve efficiency (Choi et al., 2006).[11] Likewise, variable inputs might not be instantaneously adjusted (Tsionas and Mamatzakis, 2017). As such, inefficiency might be autocorrelated following an adjustment process towards the long-run equilibrium. Moreover, this adjustment process might be heterogeneous across firms.

Therefore, we propose a dynamic specification for the inefficiency term that allows for persistent shocks in efficiency. Following Tsionas (2006), the inefficiency term (u_{it}) is assumed to have an autoregressive structure AR(1) as follows:

$$\log u_{it} = \rho_i \log u_{it-1} + Z_i^{'}\psi + \xi_{it} \; ; \quad \xi_{it} \sim N\left(0, \sigma_\xi^2\right); \; t = 2, \ldots, T \tag{6}$$

$$\log u_{i1} = \frac{Z_i^{'}\psi}{1-\rho_i} + \xi_{i1} \; ; \quad \xi_{i1} \sim N\left(0, \frac{\sigma_\xi^2}{1-\rho_\xi^2}\right); \; t = 1 \tag{7}$$

where ρ_i is an elasticity parameter that measures the persistence in inefficiency from one period to another and is firm-specific; Z_i is a set of concessionaire-specific time-invariant variables that introduces observable sources of heterogeneity in the dynamics of inefficiency (inefficiency shifters); ψ represents parameters to be estimated (including a constant term); and ξ_{it} is a two-sided error term with constant variance σ_ξ^2 that accounts for statistical noise. To guarantee stationarity so that the expected value of $\log u_{it}$ does not approach either positive or negative infinity (i.e., productive efficiency does not approach zero or one[12]), the distribution of the inefficiency term in the first period is specified as shown in Equation (7). The higher the ρ_i, the higher the persistence of inefficiency and the slower the adjustment towards the long-run equilibrium. Note that if $\rho_i = 0 \; \forall i$, the model would be reduced to a static SFA model.

An appealing feature of this model specification is that it allows for heterogeneity in the persistence parameter, as done by Galán et al. (2015) and Skevas et al. (2018b). Since companies have been in operation for different lengths of time, have different shareholding compositions and face different circumstances depending on the region in which they operate, they might exhibit different adjustment costs. Indeed, the literature agrees that their behaviour is heterogeneous (Odeck, 2019). Econometric identification is achieved by imposing the same structure of adjustment to the long-run equilibrium, although with different speeds.

In our main analysis, Equations (6) and (7) take into consideration the following concessionaire-specific time-invariant characteristics (Z_i): (i) the number of stretches managed by the concessionaire (*stretches*); and (ii) whether the concession is awarded by the central government (*State*-granted). As argued by Galán et al. (2015), the inclusion of firm characteristics in the inefficiency equation is important to distinguish time-invariant sources of systematic inefficiency from heterogeneity in the adjustment process.

Another appealing feature of our econometric modelling is the possibility of computing each concessionaire's long-run technical efficiency (henceforth LRTE). The steady-state value of $\log u_{it}$ in Equation (6) (i.e., $\ln u_{it} = \ln u_{it-1}$) is given by:

$$\ln \; u_i = \frac{Z_i^{'}\psi}{1-\rho_i} \tag{8}$$

Since technical efficiency is $TE_i = exp^{-u_i}$, based on Equation (8), LRTE is expressed as follows:

$$LRTE_i = exp\left(-exp\left(\frac{Z_i^{'}\psi}{1-\rho_i}\right)\right) \tag{9}$$

The computation of Equation (9) is straightforward based on the estimated values of ρ_i and ψ. Note that the LRTE for each company would not be defined if Z_i were time-varying because its value in the long-run would be undetermined (Skevas et al., 2018b). The marginal effects of changes in Z_i on LRTE are:

$$\frac{\partial LRTE_i}{\partial z_i} = LRTE_i \cdot \left(-exp\left(\frac{Z_i^{'}\psi}{1-\rho_i}\right)\right) \cdot \left(\frac{\psi}{1-\rho_i}\right) \tag{10}$$

The model is estimated using Bayesian inference, which produces lower mean square errors and better estimates than the traditional maximum likelihood method (Ortega and Gavilan, 2014). MCMC methods and the Gibbs sampling algorithm with data augmentation are employed for model estimation, with 50,000 iterations in which the first 10,000 are discarded as a burn-in phase. To remove potential autocorrelation, we applied a thinning equal to 8, leaving a total of 5000 draws for posterior inference. The estimation is conducted in WinBUGS software. Following Skevas et al. (2018b), we impose persistence parameters to lie on the unit interval so that $0 \leq \rho_i \leq 1 \; \forall i$ because we share their view that observing negative autocorrelations of inefficiency is highly unlikely. Therefore, we specify $\rho_i = \exp(h_i)/(1+\exp(h_i))$ where $h_i = \mu + \omega_i$ and $\omega_i \sim N(0, \sigma_\omega^2)$. This offers the advantage that the estimation process is less computationally demanding than the one proposed by Galán et al. (2015), where ρ_i is not restricted.

We assume the following priors for the parameters. A normal distribution is used for parameters α, β, γ, π, θ, φ, ς, κ, φ and η in the distance function frontier, with zero mean and precision diagonal matrix priors equal to 0.001 for all coefficients. In line with Galán and Pollitt (2014), the distribution for the concessionaire-specific random effects in the frontier is specified to have a hierarchical structure, where $\delta_i \sim N(\delta, \sigma_{\delta_i}^2)$ and the hyper-parameter $\delta \sim N(0, \sigma_\delta^2)$, with $\sigma_{\delta_i}^{-2} = 0.1$ and $\sigma_\delta^{-2} = 0.001$. As shown in Equations (6) and (7), the inefficiency term follows a log-normal distribution (i.e. $u_{it} \sim LN(\rho_i \; \log u_{it-1} + Z_i^{'}\psi, \sigma_\xi^2)$ for $t = 2, \ldots,$

[11] Contrary to other settings, here the capital stock can increase through new investments (e.g., an extra lane) but concessionaires cannot adjust it as a response to a negative demand shock. Therefore, capital is described as not putty-putty; the motorway cannot be reallocated, nor the capital stock be disinvested.

[12] Note that non-stationarity would imply either that fully inefficient concessionaires would continue operating or that fully efficient firms exist, which would contradict the theory of adjustment costs.

T; and $u_{i1} \sim LN\left(\frac{Z_i'\psi}{1-\rho_i}, \frac{\sigma_\xi^2}{1-\rho_\xi^2}\right)$ for $t = 1$). The parameter vector ψ is assumed to be normally distributed, with prior means equal to zero and priors for the diagonal precision matrix equal to 0.01. Additionally, given the above-described specification for ρ_i, we impose a normal distribution for the parameter μ, with a prior mean set equal to 2.3 and a precision prior set to 0.1. This follows Skevas et al. (2018b). Finally, the variances of the idiosyncratic error term (v_{it}), the inefficiency component (u_{it}) and the variable that defines the autoregresive parameter (h_i) are assumed to follow inverse gamma distributions. Specifically, for σ_v^{-2} the shape and scale hyper-parameters are both set equal to 0.01; for σ_u^{-2} the shape hyper-parameter is set to 10 and the scale hyper-parameter is set to 0.01; finally, for σ_ω^{-2} the priors for the shape and scale hyper-parameters are set to 0.1 and 0.01, respectively.

6. Results

6.1. Main findings

Table 3 presents the posterior means, standard errors and 95% confidence intervals for the parameter estimates of the IDF. The input and output variables have been normalised by their geometric means so that the first-order coefficients can be interpreted as distance elasticities at the sample means. In Model 1, we do not consider firm heterogeneity in the production frontier (i.e., $\delta_i = \delta\ \forall i$), whereas in Model 2 we specify concessionaire random effects ($\delta_i \neq \delta\ \forall i$). In this respect, related studies entail some controversy regarding the need to specify these effects. Skevas et al. (2018b) argue that they are not needed if the model allows for a firm-specific autoregressive parameter. By contrast, Emvalomatis (2012) notes that the estimates of ρ_i could be inflated if unobserved heterogeneity is not accounted for because in that case the model would interpret part of the neglected heterogeneity in the frontier as inefficiency. The two models produce similar points estimates for the first-order elasticities. To discriminate between the two, we rely on the Deviance Information Criterion (DIC). This is a within-sample measure of fit introduced by Spiegelhalter et al. (2002) that is commonly employed in Bayesian analysis. Since Model 2 has a lower DIC value, the inclusion of individual firm effects seems to better fit the data. We explore this in more detail below.

All the first-order coefficients are significant and have the expected signs. The negative distance elasticities with regard to the outputs imply that a 1% increase in the number of light (heavy) vehicle-kilometres leads to a 0.19% (0.06%) decrease in the distance to the frontier, as predicted by economic theory. The positive distance elasticities with respect to the variable inputs indicate that a 1% increase in the inputs, *ceteris paribus*, increases the distance to the frontier. Several of the second-order coefficients are also statistically significant, which supports our decision to specify a translog production function as opposed to a Cobb-Douglas.

In the inefficiency equation, the average posterior value of the autoregressive parameter is 0.75. This suggests there is substantial persistence in the technical inefficiency of toll companies over time. That is, most of the productive inefficiency is transmitted from one period to the following one. This finding is consistent with related

Table 3
IDF posterior means, standard deviations and 95 percent credible intervals of parameter distributions (NxT = 343).

Variable	Parameter	Model (1): without firm individual effects ($\boldsymbol{\delta_i} = \boldsymbol{\delta}$)			Model (2): with firm individual effects $\boldsymbol{\delta_i} \neq \boldsymbol{\delta}$)		
		Post. Mean	Post. SD	95% credible interval	Post. Mean	Post. SD	95% credible interval
Constant	δ	0.7106*	0.0751	[0.5837, 0.8633]	0.2546*	0.0619	[0.1319, 0.3693]
Ln Y_1	α_1	−0.2818*	0.0480	[-0.3660, −0.1806]	−0.1908*	0.0507	[-0.2956, −0.0967]
Ln Y_2	α_2	−0.0683*	0.0163	[-0.1096, −0.0505]	−0.0616*	0.0110	[-0.0916, −0.0503]
Ln L_2	β_1	0.7347*	0.0531	[0.6290, 0.8356]	0.7582*	0.0477	[0.6593, 0.8476]
Ln *INT*	β_2	0.1216*	0.0399	[0.0447, 0.2006]	0.1103*	0.0368	[0.0417, 0.1862]
Ln *K*	π_1	−0.3245*	0.0603	[-0.4394, −0.1991]	−0.1428*	0.0585	[-0.2475, −0.0218]
Trend	ς_1	−0.0027	0.0101	[-0.0227, 0.0167]	−0.0165*	0.0078	[-0.0313, −0.0006]
Trendˆ2	ς_2	0.0013*	0.0006	[0.0002, 0.0025]	0.0022*	0.0005	[0.0011, 0.0032]
0.5· Ln Y_1 · Ln Y_1	α_{11}	−0.1636	0.1035	[-0.3735, 0.0359]	−0.0781	0.1181	[-0.3137, 0.1442]
Ln Y_1 · Ln Y_2	α_{12}	0.0414	0.0547	[-0.0690, 0.1483]	0.0524	0.0568	[-0.0579, 0.1633]
0.5· Ln Y_2 · Ln Y_2	α_{22}	−0.0232	0.0336	[-0.0851, 0.0459]	−0.0166	0.0281	[-0.0757, 0.0386]
0.5· Ln L_2 · Ln L_2	β_{11}	0.2667*	0.0465	[0.1766, 0.3586]	0.2872*	0.0427	[0.2050, 0.3715]
Ln L_2 · Ln *INT*	β_{12}	0.0114	0.0433	[-0.0737, 0.0963]	−0.0233	0.0459	[-0.1143, 0.0672]
0.5· Ln *INT* · Ln *INT*	β_{22}	−0.0275	0.0436	[-0.1109, 0.0599]	−0.0249	0.0497	[-0.1162, 0.0797]
0.5·Ln *K*· Ln *K*	π_2	−0.2904*	0.1177	[-0.5377, −0.0737]	−0.2525*	0.0941	[-0.4476, −0.0734]
Ln *K*· Ln L_2	φ_1	0.0348	0.0444	[-0.0487, 0.1260]	0.0519	0.0482	[-0.0516, 0.1387]
Ln *K*· Ln *INT*	φ_2	0.0017	0.0366	[-0.0704, 0.0747]	0.0237	0.0402	[-0.0517, 0.1029]
Ln Y_1 · Ln L_2	γ_{11}	−0.0583	0.0377	[-0.1330, 0.0161]	−0.0958*	0.0453	[-0.1817, −0.0043]
Ln Y_2 · Ln L_2	γ_{21}	0.0306	0.0287	[-0.0269, 0.0856]	0.0559*	0.0270	[0.0015, 0.1097]
Ln Y_1 · Ln *INT*	γ_{12}	0.0629	0.0435	[-0.0216, 0.1502]	0.0439	0.0478	[-0.0504, 0.1375]
Ln Y_2 · Ln *INT*	γ_{22}	−0.0443	0.0302	[-0.1049, 0.0134]	−0.0326	0.0289	[-0.0912, 0.0234]
Ln Y_1 · Ln *K*	θ_1	0.1151	0.1090	[-0.0720, 0.3728]	0.0585	0.0952	[-0.1261, 0.2591]
Ln Y_2 · Ln *K*	θ_2	−0.0125	0.0561	[-0.1361, 0.0905]	−0.0310	0.0581	[-0.1523, 0.0787]
Ln Y_1 · Trend	κ_1	−0.0160*	0.0057	[-0.0277, −0.0050]	−0.0004	0.0057	[-0.0113, 0.0113]
Ln Y_2 · Trend	κ_2	0.0044	0.0037	[-0.0025, 0.0123]	0.0005	0.0029	[-0.0050, 0.0063]
Ln L_2 · Trend	φ_1	−0.0061	0.0060	[-0.0179, 0.0056]	−0.0093*	0.0047	[-0.0185, −0.0004]
Ln *INT* · Trend	φ_2	−0.0057	0.0045	[-0.0146, 0.0030]	0.0003	0.0042	[-0.0082, 0.0079]
Ln K · Trend	η	0.0282*	0.0073	[0.0141, 0.0430]	0.0104	0.0061	[-0.0018, 0.0218]
Inefficiency							
Constant	ψ_0	−0.0789*	0.1081	[-0.4422, −0.0095]	−0.5595*	0.1589	[-1.0090, −0.4291]
Stretches	ψ_1	0.0067	0.0077	[-0.0122, 0.0169]	0.1030*	0.0493	[0.0627, 0.2917]
State-granted	ψ_2	0.0394	0.1021	[-0.0179, 0.3830]	−0.0056	0.0876	[-0.3379, 0.0780]
Lag (mean value)	ρ	0.8693*	0.0804	[0.6441, 0.9712]	0.7528*	0.0548	[0.5983, 0.8197]
Constant	μ	2.5690*	0.5655	[1.3250, 3.6781]	1.1510*	0.2768	[0.4576, 1.5590]
	σ_v	0.0381*	0.0071	[0.0272, 0.0553]	0.0249*	0.0051	[0.0162, 0.0355]
	σ_ξ	0.1334*	0.0243	[0.1015, 0.1986]	0.3521*	0.0737	[0.2378, 0.5159]
	σ_ω	1.2440*	0.4708	[0.1015, 0.1986]	0.2035*	0.0927	[0.0677, 0.4867]
DIC		−1250.88			−1282.02		

Note: *denote that the corresponding credible interval does not contain zero.

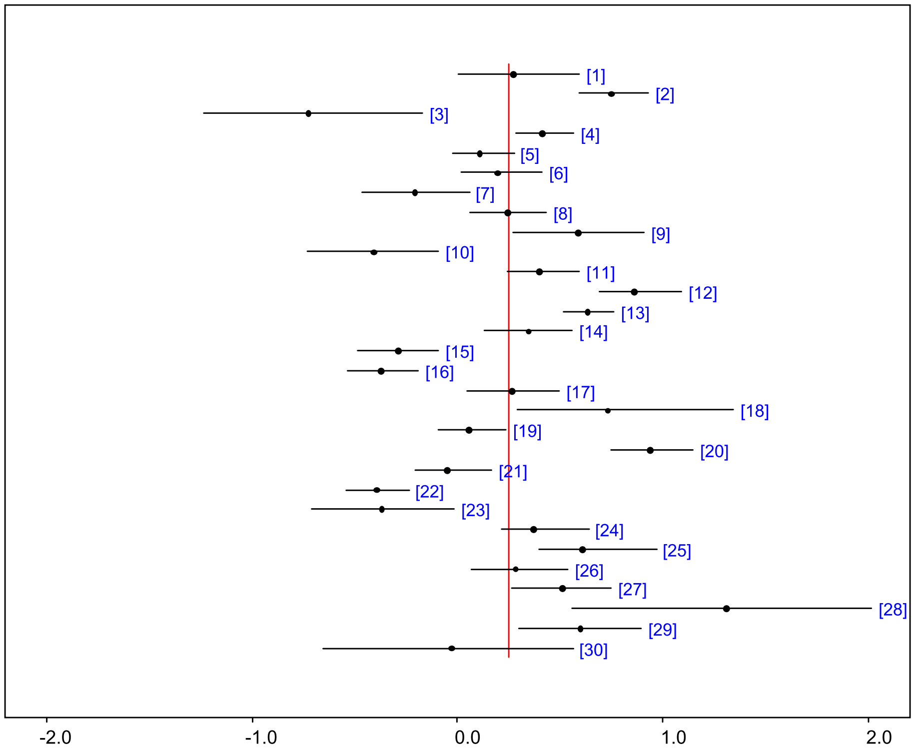

Fig. 3. Posterior distribution of individual random effects in the production frontier (δ_i).

studies on dynamic inefficiency (Tsionas, 2006; Galán and Pollitt, 2014; Galán et al., 2015; Skevas et al., 2018a, 2018b). Given the expected longevity of the infrastructure and the existence of large adjustment costs (mainly due to the quasi-fixed capital input), companies might accept some levels of inefficiency in the short run to become more efficient in the long run. Put another way, the reallocation of variable inputs, the adoption of new technologies such as electronic tolls or the uncertainty over future production conditions involve learning and training costs and a restructuring of production activities that might generate inefficiencies in the short run (Winston and Mannering, 2014). We also document that the log of inefficiency increases with the number of stretches the concessionaire manages but is not related to those stretches being under the control of the central government. We will return to this result later.

Fig. 3 plots the posterior distribution and 95% probability intervals for the concessionaire-specific random effects in the production frontier (δ_i, Model 2 in Table 3).[13] Important latent time-invariant heterogeneity appears across firms, which confirms the superiority of a model that considers concessionaire-specific random effects in the production frontier. Recall that these terms capture technology shifters ($\delta_i = ln A_i$) together with any other concessionaire-specific factor like adjacency to other concessions or the availability of free access to high-capacity roads. Because concessionaires operate in areas with different climate conditions and potential demand, controlling for this unobserved heterogeneity seems necessary to avoid a misspecification bias not only in the frontier parameters but also in the inefficiency estimates (Greene, 2005a, 2005b). As such, the discussion that follows is based on the results from Model 2 in Table 3. Worthy of note, the mean's estimate of ρ is closer to one in the model that ignores unobserved heterogeneity (model 1), possibly because that model wrongly interprets part of the concessionaires' heterogeneity as inefficiency persistence (Emvalomatis, 2012).

Fig. 4 presents boxplots for the posterior distribution of the concessionaire-specific autoregressive parameters (ρ_i). Here, little dispersion appears in their mean values, which range from 0.70 for firm 21 to 0.78 for firm 11 (sample average = 0.75). The confidence intervals lie between 0.45 (firm 21) and 0.88 (firm 11). Nonetheless, a model that allows for heterogeneous persistence parameters seems to be preferred as it recognizes the heterogeneity in adjustment to the long-run equilibrium.

6.2. *Short-run and long-run technical efficiency*

As mentioned earlier, in the recent years there has been great interest in separating persistent from time-varying (transient) inefficiency because of its important policy implications (Filippini and Greene, 2016; Colombi et al., 2017; Filippini et al., 2018). Whereas transient (short-run) inefficiency fades away considering long time spans, persistent inefficiency is more problematic as it reflects systematic management shortfalls and structural problems that hinder adequate functioning (Kumbhakar and Lien, 2017). Table 4 reports the mean estimates, standard deviations and 95% credible intervals for the short-run and long-run technical efficiency scores (TE and LRTE, respectively). The former is computed as $TE_i = exp^{-u_i}$ based on Equation (6), whereas the latter is given by Equation (9):

We find that the average TE in the short run is 0.77, while the average LRTE is almost 0.8. This means that although there is room for efficiency improvements, there is a non-negligible persistent inefficiency in the long run (around 0.2). In other words, keeping the outputs levels constant, the use of each variable input could be reduced by 20% to eliminate persistent inefficiency. Fig. 5 presents a histogram and the associated kernel density of the posterior short-run TE distribution on the 0–1 interval. Similar to other applications, the distribution is right-skewed, with firms exhibiting moderate to high levels of efficiency in the short-run. To inspect its dynamics, Fig. 6 plots the evolution over time of the TE and LRTE for the entire sector. We note that TE decreased following the 2008 economic crisis but began to improve from 2011 onwards. Nevertheless, TE scores by the end of 2015 remained far

[13] The corresponding IDs associated with each company are provided in Appendix A.

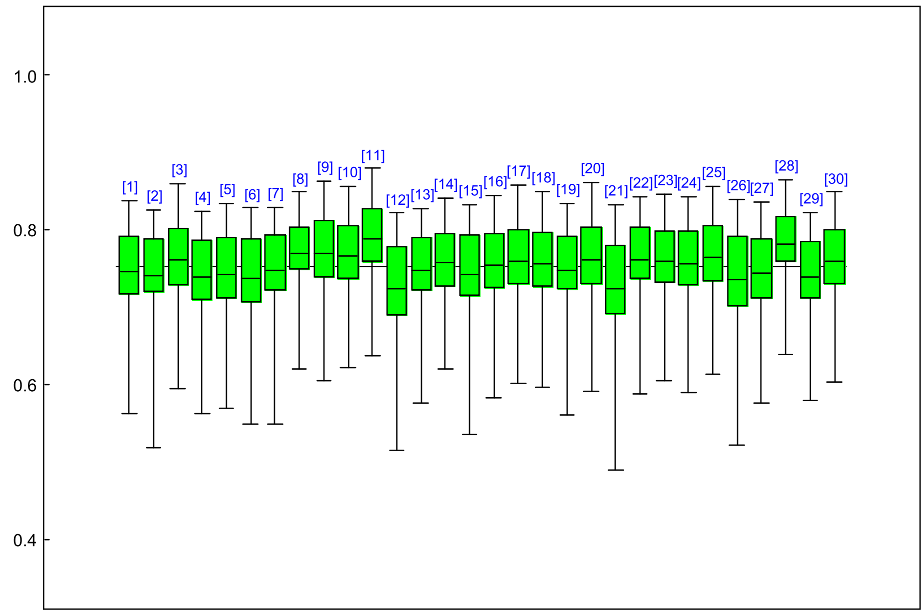

Fig. 4. Posterior distribution of individual persistence parameters (ρ_i).

Table 4
Posterior means, standard deviations and 95 percent credible intervals for the short-run and long-run technical efficiency.

	Mean	SD	95% credible interval
TE: short-run technical efficiency	0.7749*	0.0381	[0.6977, 0.8384]
LRTE: long-run technical efficiency	0.7946*	0.0414	[0.7114, 0.8655]

Note: *denote that the corresponding credible interval does not contain zero.

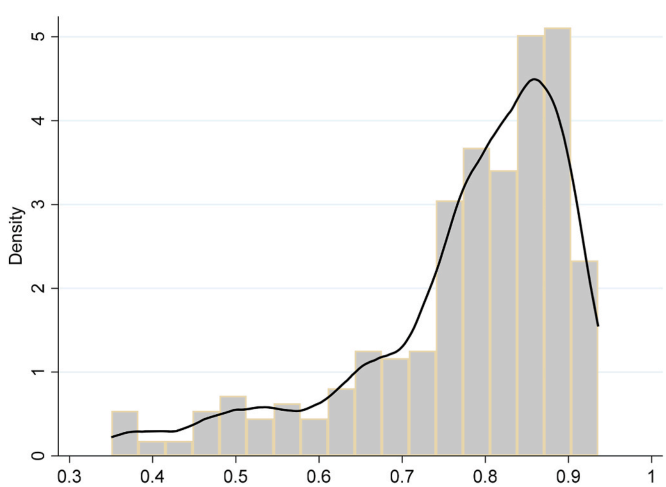

Fig. 5. Histogram and kernel density of the posterior short-run technical efficiency distribution.

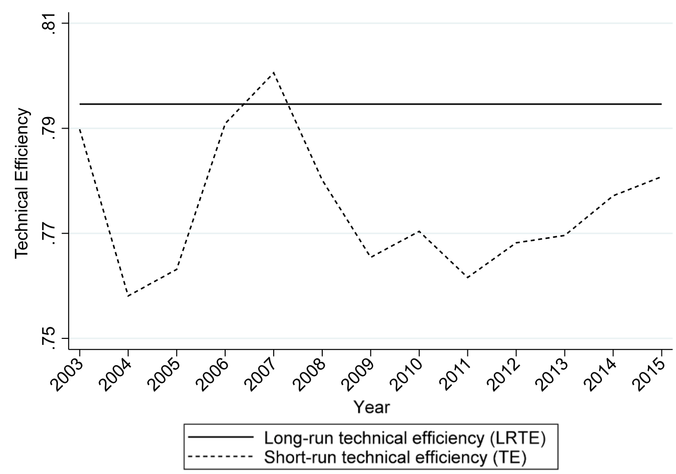

Fig. 6. Time evolution of TE and LRTE.

below their pre-crisis levels. In any case, the magnitude of the change in TE scores over time is not very large. The corresponding graphs for each company are presented in Appendix B. As these graphs show, firms exhibit different LRTE values and distinct dynamics towards it. Whereas some appear to have improved their input management over time (for instance firms 2, 4 or 9), others seem to have moved off from their equilibrium levels, especially in the recent years (firms 6 and 12, and in particular firms 26, 27 and 29).

Table 5 presents the marginal effects on the LRTE of both the number of stretches and the concession having been granted by the central government following Equation (10). Consistent with the results in Table 3, there are no significant differences in the LRTE based on the type of government that grants the infrastructure. This contrasts with evidence presented by Albalate and Rosell (2019) suggesting that regional governments grant more efficient projects. Nevertheless, these authors do not directly model the type of granting authority; rather, they compare mean efficiency scores by subgroups. Because our estimates are conditional on the firm-specific inefficiency persistence parameter, it could happen that neglected heterogeneity could be driving their findings. As a result, there is no empirical evidence to support the argument that a greater decentralisation in toll motorways concession achieves

Table 5
Posterior means, standard deviations and 95 percent credible intervals for the marginal effects of the inefficiency shifters (Z_i) on the LRTE.

Variable	Mean	SD	95% credible interval
stretches	−0.0702*	0.0170	[-0.1053, −0.0382]
State-granted	0.0052	0.0388	[-0.0610, 0.1306]

Note: *denote that the corresponding credible interval does not contain zero.

greater efficiency, at least in our data. On the other hand, we document that concessionaires with a larger number of toll stretches are less efficient in the long-run. Specifically, a one-unit increase in the number of stretches is associated with a decline of 0.07 points in the LRTE. This could reflect greater management complexity through coordination problems as the number of stretches increases. In any case, the magnitude of the effect given the range of stretches is reduced.

6.3. Returns to scale, technical change and marginal costs

The properties of the IDF can also be exploited to compute other interesting characteristics of the underlying technology. For example, returns to scale (RTS) are calculated from the estimated IDF as the sum of output elasticities in the following manner (Atkinson and Primont, 2002):

$$\text{RTS} = -\frac{1}{\sum_{m=1}^{2}\frac{\partial Ln(IDF)}{\partial Ln(Y_m)}} \tag{11}$$

Since at the sample means RTS>1, toll concessionaires operate under increasing returns to scale. Therefore, there is evidence of unexploited economies of scale, in line with the related literature (Amdal et al., 2007; Odeck, 2008; Benfratello et al., 2009; Albalate and Rosell, 2019). In terms of cost elasticity with respect to the output vector, this means that a simultaneous increase in all outputs (heavy and light vehicles) of 1% produces a decline in average total costs of 0.75% (see Appendix C). Accordingly, a higher volume of traffic reduces average operation costs. This figure aligns with Odeck (2019), although ours is smaller in magnitude.

Concerning technical change (TC), although it seems there is technical regress based on the negative sign of the first-order time trend parameter in Table 3, if we calculate the partial derivative of the IDF (in logs) with respect to time evaluated at the sample means (making use of the duality property between the IDF and the cost function, C), we have the following result:

$$\text{TC} = -\frac{\partial Ln(\text{C})}{\partial t} = \frac{\partial Ln(\text{IDF})}{\partial t} = -0.0166 + 0.0044^{*}t \tag{12}$$

There is technical progress (TC > 0) at an average annual rate of 2.1% from 2006 to 2015. This differs from Albalate and Rosell (2019), who report an average technical regress of around 0.4% per year. The reason for this discrepancy could be that, unlike the earlier study, this work allows for non-linearities in the evolution of production possibilities and non-neutral technological change.

Utilising the estimated parameters of the IDF frontier and exploiting again the fact that the IDF is dual to the cost function, the marginal cost for each output Y_m can be computed as follows (see Das and Kumbhakar, 2016 for further details):

$$MC_m = -\frac{\frac{\partial Ln(IDF)}{\partial Ln\ Y_m}}{\sum_{j=1}^{3}\frac{\partial Ln(IDF)}{\partial X_j}}\frac{C}{Y_m}\ for\ m = 1,2 \tag{13}$$

At the sample means and considering the homogeneity of degree one in inputs ($\sum_{j=1}^{3}\frac{\partial Ln(IDF)}{\partial X_j} = 1$), the marginal costs (MC) of an increase in the number of light and heavy vehicle-kilometres (Y_1 and Y_2, respectively) are given by:

$$\begin{aligned} MC_{Y_1} &= -\frac{\partial Ln(IDF)}{\partial Ln\ Y_1}\frac{C}{Y_1} = 0.1908\frac{C}{Y_1} \\ MC_{Y_2} &= -\frac{\partial Ln(IDF)}{\partial Ln\ Y_2}\frac{C}{Y_2} = 0.0616\frac{C}{Y_2} \end{aligned} \tag{14}$$

Consequently, the ratio between both marginal costs is:

$$\frac{MC_{Y_1}}{MC_{Y_2}} = \frac{0.1908}{0.0616}\frac{Y_2}{Y_1} = 3.10\frac{Y_2}{Y_1} \tag{15}$$

Table 6
Toll rates charged on light and heavy vehicle-kilometres.

	2004	2008	2012	2015	Average period 2003–2015 (SD)
Light (Y_1) rates	0.188	0.166	0.173	0.169	0.172 (0.242)
Heavy (Y_2) rates	0.313	0.255	0.263	0.253	0.269 (0.393)

Source: Annual Reports of the Toll Motorways Sector.

Since the sample mean of the output ratio $\frac{Y_2}{Y_1}$ is 0.15, then:

$$\frac{MC_{Y_1}}{MC_{Y_2}} = 3.10\cdot 0.15 = 0.46,\ \text{or alternatively},\ MC_{Y_1} = 0.46\cdot MC_{Y_2} \tag{16}$$

Toll rates applied to light and heavy vehicles should reflect a certain mark-up over their corresponding marginal costs. Therefore, the optimal toll rates should satisfy the following condition:

$$Rate\ Y_1 = 0.46\cdot\ Rate\ Y_2 \tag{17}$$

Equation (17) implies that the optimal rates charged on light vehicles should be around half the rates charged on heavy vehicles. In contrast, Table 6 presents the average rates charged on both types of vehicles per kilometre during the period 2003–2015.

On average, the toll rates charged on light vehicles were 0.63 times the rates charged on heavy vehicles (0.172 = 0.63 × 0.269), and this proportion has remained stable over the study period. These figures are fairly consistent with the optimal price relationship derived from our model estimates. However, it seems that heavy vehicles are paying *relatively less* than light vehicles per kilometre. Put another way, light vehicles are partially subsidising heavy vehicles' use of toll motorways. There is fair evidence in the literature that heavy vehicles damage the pavement more than light vehicles (Newbery, 1988). Since this translates into greater maintenance costs, heavy vehicles should be highly priced to compensate for the greater infrastructure deterioration they produce. Nevertheless, it could be the case that the mark-up over marginal costs applied to light vehicles is greater than that applied to heavy vehicles.

Finally, we examine the role of the quasi-fixed capital input on the cost function (including the cost of capital services). Again exploiting the duality property of the IDF and evaluated at the sample means, we have:

$$\frac{\partial Ln\ C}{\partial Ln\ K} = -\frac{\partial Ln(IDF)}{\partial Ln\ K}\frac{C}{K} = -(-0.1428)\frac{C}{K} > 0 \tag{18}$$

Since the derivative is always positive, there is evidence that greater capital stock *increases* operation total costs. Indeed, the detected persistence in inefficiency could arise from the difficulties involved in adjusting the quasi-fixed input. Contrary to other industries which usually entail a substitution between capital and variable inputs, in our context an increase in capital investment is associated with an increase in both labour and intermediate costs due to the complementarity among these production factors.[14]

7. Conclusions

Public-Private-Partnerships have a long tradition as a form to replace the public provision of transport infrastructures with private firms, which are granted the construction and management of a project under long-term contracts (typically spanning several decades). To compensate for the investment and other costs incurred, during the concession period the concessionaire company charges users fees and, in some

[14] For instance, the construction of bridges and tunnels in a stretch increases the capital stock and likely demands more operation and maintenance costs.

instances, receives further government transfers. Once the concession expires, the transport infrastructure reverts to government ownership. The economic rationale for the participation of private capital in public services is that such financing tool releases public funds and is said to be more efficient. However, given the usual erroneous forecasts of traffic demand and other contingencies, contracts need to be renegotiated in favour of concessionaire companies, which, in practice, generates opportunistic behaviour at the taxpayers' expense. In this context, it is of great importance from a policy viewpoint to examine concessionaires' performance for future renegotiations.

This paper studies the productive efficiency of toll motorway concessionaire companies in Spain, the country with the largest motorway network and the largest number of toll operators in Europe. We use panel data for 30 companies from 2003 to 2015. Because light and heavy vehicles exert different effects on asphalt degradation and therefore on operational costs, we consider a multi-output production technology. Since traffic demand can be considered exogenous, we define an input-oriented distance function under a *trans*-logarithmic specification with three variable inputs, a quasi-fixed input (capital stock) and non-neutral technical change.

Unlike previous studies in this sector, we specify a dynamic Bayesian stochastic frontier model that allows inefficiency to follow a first-order autoregressive process. Based on the theory of adjustment costs, the long-term nature of concessions might lead some firms to accept a certain level of inefficiency in the short run to become more efficient in the long run through management learning. Contrary to frequentist approaches, imposing an autoregressive structure on the evolution of inefficiency allows us to derive firm-specific long-run (steady-state) technical efficiency scores. Because companies operate in different areas and have different characteristics, we allow the speed of adjustment (the persistence of inefficiency) to differ across firms. We also include the number of stretches and the level of government authority that grants the concession as mean inefficiency shifters. Furthermore, to avoid biased estimates due to unobserved heterogeneity, we consider concessionaire-specific random effects in the production frontier.

The output and input elasticities are statistically significant, and their signs are consistent with microeconomic theory. Based on the output elasticities, we document important unexploited economies of scale. Indeed, a 1% increase in output levels would reduce average operating costs by 0.75%. The estimates show there has been technical change in the sector from 2006 onwards and different levels of persistence in firms' inefficiency scores. Specifically, long-run inefficiency is approximately 0.2 on average. Interestingly, we find evidence that inefficiency increases as the company manages more toll stretches. By contrast, no significant differences in inefficiency are detected between concessions granted by the State or by regional governments. More importantly, based on the duality property between the IDF and the cost function and assuming that the mark-up over marginal costs is the same for heavy and light vehicles, we have shown that the optimal toll rates for light vehicles should be around half the rates for heavy vehicles.

Our findings thus contribute to the literature on the appropriate design and management of toll motorway projects and have important implications. First, companies are operating under an excess of capacity. This finding, which is consistent with previous studies, suggests that the toll motorway sector has been overcapitalised and traffic demand is substantially lower than expected. The economic crisis might have played a role here, since the short-run efficiency scores sharply decreased between 2007 and 2011. Nevertheless, our findings are in line with fair evidence in the literature showing optimistic biases in the auction process that result in subsequent failures and the necessity of public rescues. Second, apart from the potential misallocation of the concessions, our firm-level analysis of the evolution of productive efficiency over time can be useful for public authorities when defining the conditions of future renegotiations. As we have shown, companies exhibit heterogeneous dynamics. Given their output levels, some have smoothly improved their efficiency over time while others have followed a decreasing trend. In line with the related literature, firm management should be considered when defining the conditions for concession renegotiations. Finally, our analysis has revealed that, in equilibrium, light vehicles should be charged around half the rates applied to heavy vehicles. During the period of study, however, the relationship between official rates has been around 0.63. This suggests that light vehicles are partially subsiding heavy vehicles' use of toll motorways, and we therefore advocate for a revision of official rates.

Avenues for future research could include the role played by public subsidies conceded to private companies and negative externalities in the form of accidents and pollution. In particular, the social costs imposed on neighbouring areas and adjacent free-access roads should be examined in more depth. Similarly, the great economic importance of toll motorway projects and the scarce empirical literature on their productive efficiency require additional studies considering different countries and periods to draw more general conclusions.

Author contributions

José F. Baños-Pino: Conceptualization; Data curation; Formal analysis; Methodology; Project administration; Software; Supervision; Validation; Writing - original draft; Writing - review & editing.

David Boto-García: Formal analysis; Methodology; Resources; Writing - original draft; Writing - review & editing.

Emma Zapico: Data curation; Investigation; Methodology; Formal analysis; Writing - review & editing.

Declaration of competing interest

None.

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APPENDIX A

Table A1
List of concessionaire companies by ID

ID	Company name
1	ACCESOS DE MADRID
2	ACEGA
3	ACESA
4	AUCALSA

(*continued on next page*)

Table A1 (*continued*)

ID	Company name
5	AUCAT
6	AUCOSTA
7	AUDASA
8	AUDENASA
9	AULESA
10	AUMAR
11	AUSOL
12	AUSUR
13	AUTEMA
14	AUTOESTRADAS
15	AVASA
16	BIDEGI
17	CIRALSA
18	EJE AEROPUERTO
19	EUROPISTAS
20	GUADALCESA
21	HENARSA
22	IBERPISTAS
23	INVICAT
24	MADRID LEVANTE
25	MADRID SUR
26	MADRID TOLEDO
27	TABASA
28	TÚNEL DE SÓLLER
29	TÚNEL DEL CADÍ
30	TÚNELES DE ARTXANDA

APPENDIX B

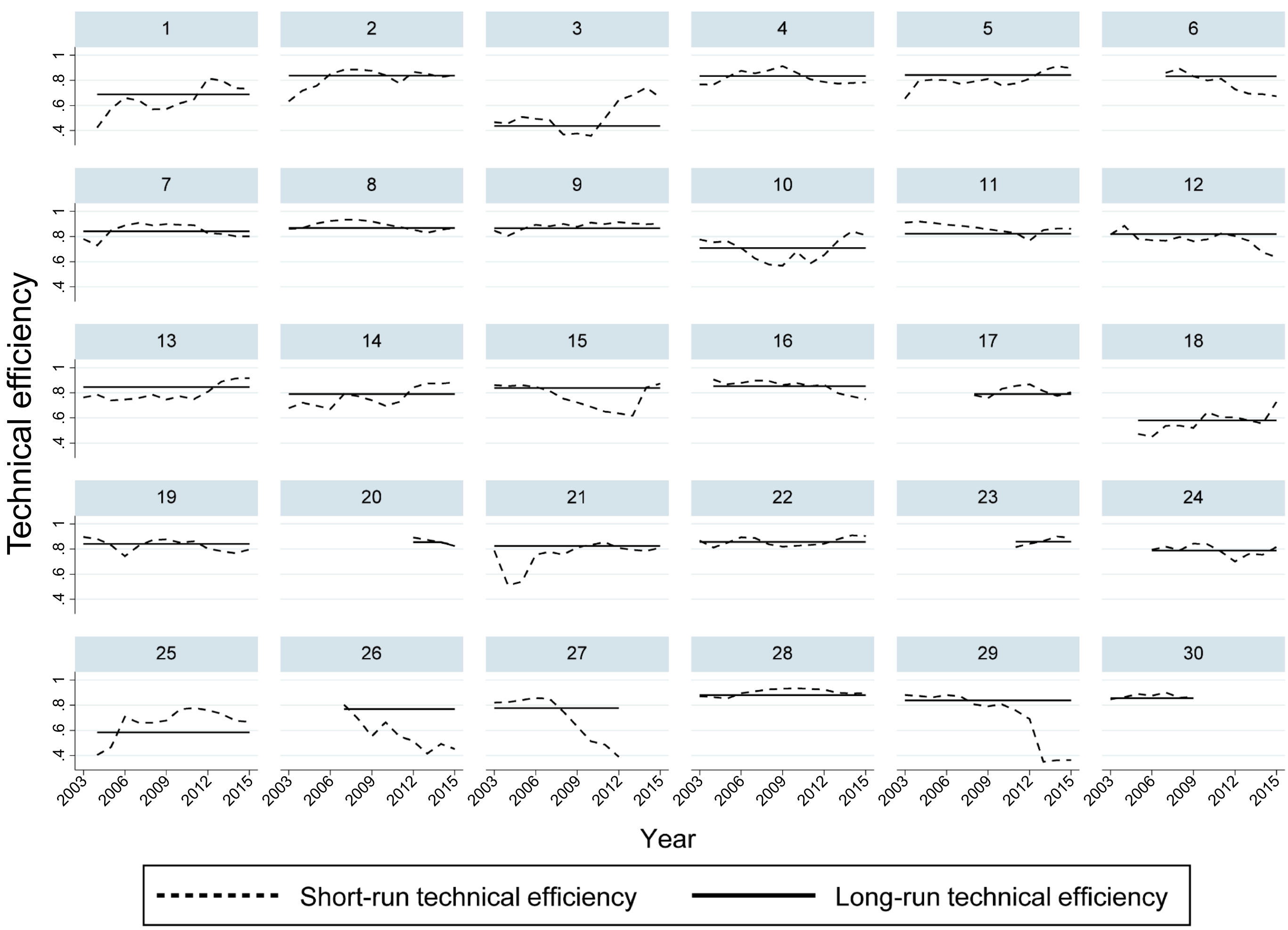

Fig. A1. Time evolution of (short-run) TE and LRTE by company.

APPENDIX C

The average cost elasticity with respect to the output vector Y ($\varepsilon_{AC,Y}$) c an be derived from expression (11) as follows:

$$\varepsilon_{AC,Y} = \frac{\partial Ln(AC)}{\partial Ln\ (Y)} = \frac{\partial Ln(C)}{\partial Ln\ Y} - 1 = \frac{1}{RTS} - 1$$

Considering the relationship between RTS and the IDF, the $\varepsilon_{AC,Y}$ can be calculated at the sample means in the following manner:

$$\varepsilon_{AC,Y} = \left(-\sum_{m=1}^{2} \frac{\partial Ln(IDF)}{\partial Ln\ Y_m} \right) - 1 = 0.253 - 1 \approx\ -0.75$$

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