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Full Length Article

The efficiency of urban public transport and its impact on environmental sustainability

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ABSTRACT

Promoting and popularly developing urban transport improves environmental sustainability by reducing traffic congestion and air pollution. In the last decade, bus and metro modes, in addition to being the most in-demand, have been the most utilized to offer a practical and sustainable public transport system.

In Spain, public transport services are bus, the mode of transport designed as a priority over metro. The significant investment in infrastructure required for its implementation and maintenance makes it necessary to assess these companies' efficiency and impact on the sustainability of the surrounding environment. For this reason, this study aims to analyze if the bus mode is more efficient and sustainable than public transport by metro. The sample comprises companies providing bus and metro transport services in four of the biggest cities in Spain during the period 2017 - 2021.

The methodology used will be (1) a description of the main variables of these companies and (2) a data envelopment analysis and the Malmquist index as statistical inference estimators to provide the productivity, efficiency change (EFCH) into Pure Technical Efficiency Change (PTECH), and Scale Efficiency Change of the analyzed companies. This analysis's main result shows that bus and metro efficiency is similar for the analyzed cities.

This study contributes to the academic literature because the comparative analysis by modes of transport has not been conducted and can be considered an influential variable when it comes to resource allocation, controlling the services provided, and improving the planning of these services by the competent authorities.

Introduction

The rapid growth of large cities means that the design and management of urban transport is a fundamental strategic tool to ensure efficient mobility and economic and social development (Oviedo & Attard, 2022; Zhu et al., 2024; Chang, 2014). Bus and metro systems, in addition to being the most in-demand modes of transportation, have the most significant influence on urban mobility due to the number of passengers they transport and their economic impact. Both modes are regarded as complementary (Huanjie et al., 2024).

The bus is the most widely used form of urban public transport worldwide. City mobility would not be sustainable without this mode of transport (Union Internationale des Transports Publics [UITP], 2022; Fitzová et al., 2018). In recent years, metro systems have been gaining relevance from the European Union as a sustainable and efficient method of public transport (González-Gil et al., 2014; Vuchic, 2007) and are currently present in >193 cities worldwide, being 46 European cities (UITP,2022; Morcillo, 2021).

Only nine Spanish municipalities share an urban bus service with a metro service (Madrid, Barcelona, Bilbao, Valencia, Málaga, Sevilla, Alicante, Palma de Mallorca, and Granada). These cities account for >40 % of trips made by urban transport, with buses being the mode with the

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highest number of users, except in the cases of Madrid and Barcelona (Instituto Nacional de Estadística, [INE], 2024)

The assessment of the efficiency of these companies and their impact on environmental sustainability can determine optimal long-term political planning financing plans, and tax reforms to meet investment needs (International Transport Forum, [ITF], 2023; Le et al., 2022; Catalano et al., 2019; Delgado et al., 2019; Yan et al., 2015; Sánchez de Lara, 2013).

In this context, this study aims to measure the efficiency of Spanish urban de las of bus and metro companies in the cities where both operate (Madrid, Barcelona, Sevilla, and Málaga) to evaluate economic management and its environmental impact (energy consumption and gas emissions). In this way, efficiency could indicate the best choice of investment in modes of transport by public administration. The election of these cities is based on the availability of the data provided by the operating companies.

We believe that this study contributes to the literature since we have not found studies that measure and compare both modes of transport and the management of public policies that allow for better organization in transport in Spain as well as in most European cities in our environment with a similar organization such as Germany, France, and Italy (Castagna et al., 2024; Pina y Torres, 2001).

Literature review

Challenges of urban public transport in Spain

The promotion and proper development of urban transport improve environmental sustainability by reducing traffic congestion and air pollution levels (Zhu et al., 2024; Epicoco & Falagario, 2022; Ceder, 2020; Zhao et al., 2020; Anguita et al., 2014; Lucas & Jones, 2012). It also favors the social and territorial integration of its inhabitants (Flores-Ureba et al., 2024), facilitating compliance with Sustainable Development Goals (SDGs) 3 and 11 related to reducing the number of deaths due to air pollution and achieving more inclusive, safe, resilient, and sustainable cities, respectively (United Nations, 2023; Shibayama, 2020).

Urban public transport in Spain is regulated by the Spain (1985), with municipalities with >50,000 inhabitants required to provide this service. Furthermore, the Spanish Sustainable Mobility Strategy (Spain, Ministerio de Fomento 2009) promotes the development of efficient urban transport. In 2022, these measures were complemented by the requirement for these municipalities to establish low-emission zones (ZBE) and adopt sustainable mobility plans (RD 1052/2022 of 27 December). The modes primarily designed by the competent authorities are urban bus transport and the metro.

In 2023, urban transport mobilized 3190.23 million passengers, of which 1869 million corresponded to the bus mode, an increase of 22.3 % compared to the previous year. Metro trips during 2023 reached 1321.14 million, an increase of almost 19 % compared with last year. These data show the recovery of passenger volumes after the COVID-19 pandemic, surpassing the 3102 million passengers transported by metro and bus in 2019 (INE, 2024).

The most widespread management models for the provision of public collective bus transport service are based on direct management through the creation of a 100 % public company, more common in large municipalities, and indirect management through administrative concession by private companies (Flores-Ureba et al., 2024; Delgado et al., 2009). For metro operators, administrative concessions and the establishment of mixed public-private limited companies are expected, except for Metro de Madrid and Metro de Barcelona, which remain publicly owned.

In recent years, operators have made significant investments in technologies that promote energy saving and efficient use, reduction of polluting gases, accessibility, and intermodality (Morcillo, 2021; González-Gil et al., 2014). This effort requires more significant investment for metro operators than bus operators and, therefore, more excellent optimization of the funding received from the competent authorities. For buses, new systems such as Bus Rapid Transit, dedicated lanes, and the transition to a zero-emission vehicle fleet are being sought (UITP, 2023; European Commission, 2021; Quintero & Quintero, 2015).

On the other hand, the metro is characterized by the short distance between stations, optimal travel times, and its high capacity per trip (Catalano et al., 2019), requiring significant investments in underground infrastructure, network electrification, and energy consumption and cost, implying a more excellent optimization of resource management while maintaining or improving service quality and capacity (González-Gil et al., 2014).

In this regard, autonomous communities and municipalities contribute to its financing, but without a stable commitment or planning, significant imbalances are generated between municipalities and transport modes. In large cities with relatively fixed or heavily subsidized costs and fares due to social policies, subsidies fluctuate more, straining a system that is in deficit (Duarte et al., 2022; Delgado et al., 2019; Ruiz Montañez, 2017).

In this context of scarce funding, the efficiency comparison between the metro and urban bus allows both operating companies and public administrations to evaluate whether the implemented transport measures achieve adequate resource management, are convenient for users, improve sustainability and capacity, provide sustainable energy use and emission control (The European Rail Research Advisory Council (ERRAC) 2020).

Sustainable mobility in large cities: efficiency of urban transport

The analysis of transport efficiency allows for better resource allocation, service control, and planning improvement (Hussain, 2022) through an appropriate combination of resources used for the service offered (Le et al., 2022; Alam et al., 2020). The literature on public transport efficiency is extensive (Flores-Ureba et al., 2024; Niu et al., 2023; Varabuntoonvit et al., 2023; Benga et al., 2022; Holmgren, 2018; Karlaftis & Tsamboulas, 2012; Sampaio et al., 2008; De Borger et al., 2002; Verano-Tacoronte et al., 2024).

Significant advancements have been made in studies related to efficiency in terms of sustainable transport (Hussain et al., 2023; Varabuntoonvit et al., 2023; Le et al., 2022), as well as studies linking efficiency and public bus transport, which is the most studied sector (Flores et al., 2024; Flores-Ureba et al.,2024; Machado et al., 2022; Holmgren, 2018; Karlaftis & Tsamboulas, 2012; Verano-Tacoronte et al., 2024), followed by rail transport (Niu et al., 2023; Benga et al., 2022; Holvad, 2020). Few studies focus on the efficiency analysis of metro rail transport (Le et al., 2022; Lobo & Couto, 2016). No papers have been found that conduct a comparative efficiency analysis of both modes of transport within a territorial scope.

In terms of sustainability, it is essential to include in the efficiency analysis variables that assess the environmental impact of the service both globally and at the micro level (Zaghdoud, 2025; Varabuntoonvit et al., 2023; Benga et al., 2022; Hussain et al., 2022; Lee et al., 2022; Heymann et al., 2021; Villalba et al. (2021); Lobo & Couto, 2016; Mäkelä & Vehmas, 2012). Most studies focus on evaluating energy or environmental efficiency, such as the work of Zaghdoud (2025), which indicates that improving energy efficiency is impossible in countries where growth is linked to increased energy consumption, using sustainable technological progress for this purpose. Lobo and Couto (2016) where energy efficiency is measured by the energy consumption required by the train service and the number of passengers transported per kilometer.

Works such as Heymann et al. (2021) and Mäkelä and Vehmas (2012) discuss eco-efficiency, considering it a concept similar to ordinary efficiency, as it aims to maximize service while minimizing negative externalities. Benga et al. (2022) analyze environmental efficiency, distinguishing it from energy efficiency and eco-efficiency.

Regarding the analysis of efficiency, the so-called economic or general efficiency has traditionally been based on indicators that measure the capital, labor, and energy of the firm (Flores-Ureba et al., 2024; Li et al., 2020; Sampaio et al., 2008; De Rus et al., 2003; De Borger et al., 2002). In this sense, capital can be represented by the number of vehicles or the depreciation and amortization expenses as an indicator of rolling stock expenses. Labor refers to the number of employees and the cost of employees, and the company's energy refers to the number of liters of diesel consumed per year or the cost of energy consumed.

Another input to consider in general efficiency is the revenue obtained (Le et al., 2022; Li et al., 2020; Holmgren, 2018, 2013). These revenues can be related to direct fare collection and the subsidies received, with the latter being the most analyzed (Holmgren, 2018). Lee et al. (2022) analyze revenue efficiency by considering the capacity of the lines to generate income from the services they offer. The competent public administrations heavily fund both modes of transport. According to the ITF analysis (2019), there is a relationship between the subsidies granted and operational efficiency. Subsidies can be used to assess whether funding is managed efficiently or reduced without affecting service efficiency, serving as a justification tool for subsidies for administrations and for comparison with other subsidized modes.

Along with these analyses, in urban bus transport efficiency, there is a significant debate regarding service management and company size (Prior et al., 2019; Pérez-López et al., 2015; De Borger et al., 2002). There is no consensus on whether public or private companies are more efficient (Flores-Ureba et al., 2024; Niu et al., 2023; Campos Alba et al., 2020; Holmgren, 2018). This discussion has not been found in the case of metro transport.

Regarding company size, the number of network lines, rail or road density, or kilometers per service are variables that determine company size and are considered fundamental to reflect the competitiveness of metro and bus transport (Niu et al., 2023; Holmgren, 2018), as well as the service provided by them (Holmgren, 2018; Sampaio, 2008).

In addition to these variables, several exogenous variables influence the efficiency of transport modes, with a direct correlation between demand variation and variables such as the employed population, gross domestic product (GDP), or disposable income, understood as the level of development where the service is provided (Niu et al., 2023; Hussain, 2022; Vigren, 2016; Piacenza, 2006). Niu et al. (2023) indicate that GDP notably impacts transport efficiency through the investment required, the movement volume, and the generated infrastructure. Regarding the employed population or population density, a study by Piacenza (2006) highlights that the higher the population density, the greater the cost efficiency of these companies. Meanwhile, the study by Vigren (2016) indicates that cost efficiency is lower in areas with high population density.

Along with these variables, governance, political, and structural decisions also affect the service provided (Niu et al., 2023).

The combination of the analyzed factors (inputs) with the services provided (outputs) and the method used for their calculation offers different ways to measure efficiency, both economic or operational and environmental, and energy efficiency (Karlaftis & Tsamboulas, 2012; Castelló & Giralt, 2008).

Regarding the methods used, Data Envelopment Analysis (DEA) is widely accepted for measuring transport efficiency in general terms (Niu et al., 2023; Machado et al., 2022; Jorda, 2012; Brons et al., 2005; De Borger et al., 2002; Pina & Torres, 2001) and in terms of bus and rail transport efficiency (Hussain, 2022; Niu et al., 2023; Le et al., 2022; Machado et al., 2022). Hussain et al. (2022) use DEA to evaluate the economic and environmental efficiency of the transport sector in general in 35 OECD countries, taking into account inputs such as the number of passengers transported and distinguishing outputs into desirable (value added and the number of employees in the sector) and undesirable (CO2 emissions).

DEA is also used to analyze transport sustainability (Benga et al., 2022; Djordjevic & Krmac, 2019). Benga et al. (2022) use DEA to evaluate railway companies' energy efficiency, environmental efficiency, and relative eco-efficiency through the relationship of inputs and outputs, which they consider desirable and undesirable (emissions). The analysis results indicate that incorporating undesirable outputs reduces the relative efficiency of some companies due to the environmental impact they generate. This approach allows for a comprehensive measurement and comparison of railway companies' energy and ecological sustainability, identifying areas for improvement in both policies and the company's operations.

Hypotheses

Considering the importance of transport and the need to ensure efficient management of resources (Martín Urbano *et al.*, 2012), the evaluation of efficiency becomes a fundamental indicator as a gauge of the transport system (Balboa *et al.*, 2014; Ruiz Montañez, 2014). For this reason, this paper aims to answer the following hypothesis:

H1: Bus mode is more efficient than metro mode in cities where both modes of transport operate.

The analysis of bus efficiency has been widely studied in the literature (Flores et al., 2024; Machado et al., 2022; Holmgren, 2018; Karlaftis & Tsamboulas, 2012), with numerous studies linking efficiency to the type of management of these companies (Flores et al., 2024; Campos Alba et al., 2020; Karlaftis & Tsamboulas, 2012; Roy & Yvrande-Billon, 2007) or to their size (Prior et al., 2019; Pérez-López et al., 2015; De Borger et al., 2002). Regarding the metro, studies have focused more on analyzing the rail system in general (Niu et al., 2023; Benga et al., 2022; Holvad, 2020) rather than the metro specifically (Le et al., 2022; Lobo & Couto, 2016).

No studies jointly analyze the efficiency related to resource management and the impact of the service of both modes in cities where the competent authorities provide services in a complementary manner.

Methodology, sample, and data

Methodology

Efficiency is measured in this work by considering Data Envelopment Analysis. This technique was first developed by Charnes, Coopers and Rhodes (1976) as a linear programming method based on the previous work of Farrell (1957). The units under analysis (Decision-making units, DMUs) considered in this work are the eight largest Spanish subway and bus transportation companies. The main objective of this work is to identify best management practices regarding the efficiency frontier and determine the best efficiency practices for inefficient ones.

As defined by Charnes, Coopers and Rhodes (1976), the purpose of the linear programming model is defined by eq. (1) is the identification of the best ponderations of the input and outputs representing the production model, such that the efficiency value is maximized for each DMU in the reference set. Let n be the number of DMUs in the sample, s the number of input variables, and m the number of output variables considered in the production model

$$maxE_j = \frac{\sum_r u_r y_{rj}}{\sum_i v_i x_{ij}}$$

$$s.t.\begin{cases} 0 \leq \dfrac{\sum_r u_r y_{rj}}{\sum_i v_i x_{ij}} \leq 1 \ \forall j = 1, \ldots, n \\ u_r, v_i \geq 0 \ \forall r = 1, \ldots, m; i = 1, \ldots, s \end{cases} \quad Model \qquad (1)$$

Where x_{ij} is the input variable i amount for DMU j, y_{rj} is the output variable r amount for DMU j, v_i is the weight value for input variable i, and u_r is the weight value for output r. The model defined by Eq.(1) is known as the Constant Return Scale (CRS), where an increase in the input volume produces a proportional increase in the output volume. To consider scale performance, we used the extended model known as

Variable Return to Scale (VRS) proposed by Banker et al. (1984). ~~[7]~~

The resulting model can measure the relative efficiencies of the given DMUs, classifying them as efficient and inefficient. The classification criterion is based on the organization's position relative to the efficient production frontier. This frontier consists of units that exemplify best management practices regarding outputs and the resources utilized in their production. Inefficient units are assessed by comparing them to one or more benchmark units on the frontier, which serve as reference points to guide improvement efforts (Bergendahl, 1998)

For each input or output variable that we incorporate into the model, the number of efficient DMUs increases by one unit, reducing the discrimination capacity of this technique. Boussofiane et al. (2021) propose the following rule to determine the maximum number of input and output variables in the model:

$$number_{inpunts} * number_{outputs} = s * m \leq n \tag{2}$$

To evaluate the performance of the DMUs in the reference set across the years explored in this work, we considered the Malmquist Productivity Index (MPI) developed by Färe and Grosskopf (1992). The index given in Eq.(3) represents the geometric mean of the two Malmquist indices developed by Caves et al. (1982), referring to the technologies at periods t and $t + 1$:

$$MI^{(t,t+1)} = \sqrt{\frac{D_i^t(y^{t+1}, x^{t+1})D_i^{t+1}(y^{t+1}, x^{t+1})}{D_i^t(y^t, x^t)D_i^{t+1}(y^t, x^t)}} \tag{3}$$

where $\mathrm{MI}^{(\mathrm{t},t+1)}$ is the input-oriented Malmquist index, y represents the output vector that can be produced using the input vector x, and $D_i^{t_2}(y^{t_1}, x^{t_1})$ shows the efficiency measure using observation of the period t_1 relative to the frontier technology at the period t_2. For a more detailed explanation of the methodology, see Coelli *et al.* (2005). The index can be decomposed into mutually exclusive indexes to differentiate the origin of the changes in productivity as MI = (TECH) x (PTECH) x (SEFCH) where SECH represents the Scale Efficiency Change, PTECH the Pure Technical Efficiency Change and TECH the technical efficiency as suggested by Grifell-Tatjé and Lovell (1995).

This decomposition is valuable as it helps differentiate the factors controlled by the urban transport company, like Pure Efficiency Change, from those beyond its control, such as technology and scale efficiency change.

Other productivity decompositions are suggested by Kerstens et al. (2022), including the attainable output-oriented plant capacity utilization measure, and by De Borger and Kerstens (2000), which could be explored in future research work.

The Kruskall Wallis distribution equity is used to find possible differences between bus and subway urban transport types, as the efficiency scores distribution fails in the normality assumption. The H statistic obtained in the test is compared to a Chi-Squared distribution. A mixed linear model was considered to find possible differences between the years under study, the type of urban transport (bus or subway), and the city under consideration.

The statistical analysis was performed using SPSS (IBM SPSS Statistics, version 24.0, IBM Corporation) and R programming language. P values of <0.05 were considered statistically significant.

Sample

The sample includes eight passenger transport companies in Spain between 2017 and 2022 in four cities (Madrid, Barcelona, Sevilla, and Málaga).

The sample selection is justified by the existence of both modes of transport in these municipalities and the availability of their operational data. The data for this study have been obtained from the annual accounts of the companies and the operational information provided directly by the operators through a questionnaire.[1]

The number of network kilometers indicates the size of the companies, with Madrid and Barcelona having the largest companies in both metro and bus services.

The evolution of urban transport passengers by modes can be seen in Fig. 1.

Variables

Given the limited reference set for this study, Data Envelopment Analysis (DEA) models with a single input and two output production frameworks were utilized. Four models were developed to evaluate general efficiency, environmental impact, energy usage, and income performance. A comprehensive literature review and the anticipated availability of data for both modes informed the selection of inputs and outputs. These are the variables:

Table 1.

Based on the efficiency analysis of the authors highlighted in Table 2, the following models have been proposed:

Model 1: General efficiency:

Input: Sum of personnel expenses, depreciation, and energy cost.

Output: Number of travelers and network kilometers.

Model 2: Energy

Input: Energy expenses.

Output: Number of travelers and network kilometers.

Model 3: Environmental

Input: CO2 emissions.

Output: Number of travelers and network kilometers.

In the three proposed models, the output is measured by the number of passengers transported and network service kilometers, which reflects the company's size (Niu et al., 2023; Holmgren, 2018).

Model 1 uses indicators measuring capital, labor, and energy regarding the inputs. However, due to the sample size, these have been combined into a single input representing the cost of the service provided, calculated as the sum of personnel, energy, and depreciation expenses.

Models 2 and 3 refer to the sustainability of these companies in terms of both energy consumption and environmental impact. Therefore, the inputs used are based on energy expenses as a measure of consumption and emissions (Benga et al., 2022).

A new economic efficiency (income) model has been included in what we have termed general efficiency. Following Lee et al. (2022), this considers income efficiency, where vehicle kilometers and number of passengers are considered inputs, as well as fare revenues and other transport-related income output. In this case, the income used is referred to as direct collection from the user, excluding transport subsidies. The model is defined as follows:

Model 4: Incomes

Input: Number of travelers and network kilometers.

Output: Fare income.

Results

Concerning the general efficiency model, Fig. 2 presents the

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[1] The data obtained by the operators is due to the reports these companies provide for the preparation of the Annual Reports on Urban Collective Transport compiled by the Costs and Financing of Urban Collective Transport Watchdog (Observatorio de Costes y Financiación del Transporte Urbano Colectivo, OTUC), to which members of this paper belong.

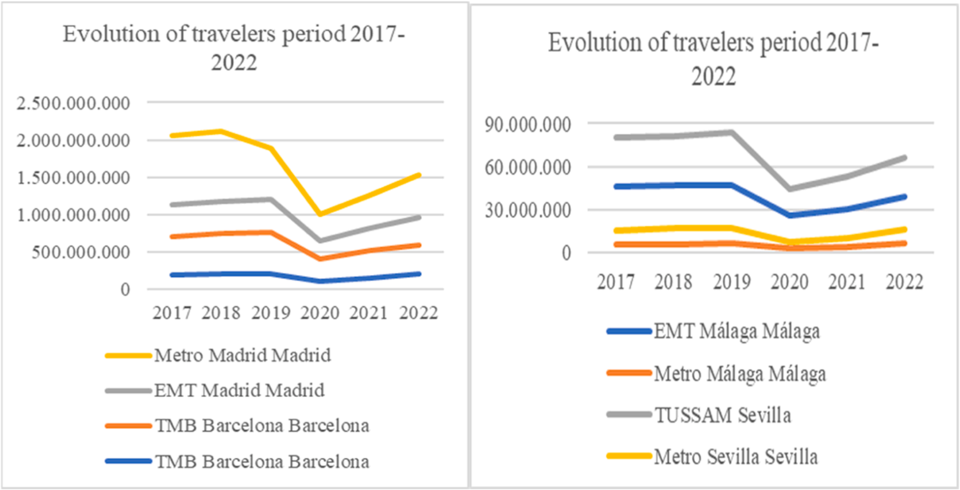

Fig. 1. Evolution of passengers in the analyzed companies and municipalities. Period 2017–2022. Source: Own elaboration.

Table 1
Sample description.

Municipality	Municipality density (inhab/km2) 2022	Company	Service Provided	Ownership	Network Kilometres
Barcelona	16.238,52	Transports de Barcelona S.A. (TB)	Bus	Public	839, 21
		Ferrocarril Metropolitano de Barcelona S.A.	Metro	Public	125,40
Madrid	5.415,89	EMT Madrid S.A.	Bus	Public	1988,84
		Metro de Madrid S.A.	Metro	Public	293,91
Málaga	1.463,42	EMT Málaga S.A.	Bus	Public	480,50
		Metro de Málaga S.A.	Metro	Public and private	10,80
Sevilla	4.802,80	Transportes Urbanos de Sevilla (TUSSAM) S.A.	Bus	Public	348,50
		Metro de Sevilla S.A.	Metro	Public and private	18

Source: Own elaboration.

Table 2
Inputs and outputs considered in the analysis.

Inputs and Outputs	References
Personnel expenses	Flores-Ureba et al., 2024; Li et al., 2020; Sampaio et al., 2008; De Rus et al., 2003; De Borger et al., 2002.
Depreciation	Flores-Ureba et al., 2024; Li et al., 2020; Sampaio et al., 2008; De Rus et al., 2003; De Borger et al., 2002
Energy cost.	Flores-Ureba et al., 2024; Benga et al., 2022; Li et al., 2020; Sampaio et al., 2008; De Rus et al., 2003; De Borger et al., 2002
CO2 emissions	Benga et al., 2022; Heymann et al., 2021; Lobo & Couto, 2016; Mäkelä & Vehmas, 2012
Fare income.	Lee et al., 2022; Li et al., 2020; Holmgren, 2018, 2013
Number of travelers	Niu et al., 2023; Holmgren, 2018
Network kilometres.	Niu et al., 2023; Holmgren, 2018

Source: Own elaboration.

efficiency for the DMUs in the reference set considering a VRS model input oriented in the period under consideration.

The DEA model in our study revealed that 5 of these were in the period under study. This represents 62 % of the companies in the sample. The average efficiency was maintained in the period under study in 2017 ($\overline{E}_{2018} = 0.88$); 2018 ($\overline{E}_{2018} = 0.868$); 2019 ($\overline{E}_{2019} = 0.877$); 2020 ($\overline{E}_{2020} = 0.871$); 2021 ($\overline{E}_{2021} = 0.868$); and 2022 ($\overline{E}_{2022} = 0.908$).

Table 3 shows productivity, technology, pure efficiency, and scale efficiency changes for the 2017–2022 sample period. The table indicates that the gradual productivity decrease from 2017 to 2020 was mainly attributed to the technical productivity recession. It can be the decrease in productivity from 3 companies in 2018, concerning 2017, and an increase in the subsequent periods. A slight increase in productivity is observed in 2021 concerning 2020, and improvement will be maintained in the next period. Pure and scale efficiency experience a moderate fluctuation compared to technical efficiency.

We understand it as a "technical productivity recession" when the score of the technical efficiency, as suggested by Grifell-Tatjé and Lovell (1995), in the period (t, $t + 1$), is less than one.

Regarding the energy model, Fig. 3 presents the efficiency for the DMUs in the reference set considering a VRS model input oriented in the period under consideration.

The DEA model in our study revealed that 5 of these were efficient in the sample period. This represents 62 % of the companies in the sample, with average efficiency. $\overline{E}_{2017} = 0.867$, maintained in the remaining periods in 2018 ($\overline{E}_{2018} = 0.857$); 2019 ($\overline{E}_{2019} = 0.829$); 2020 ($\overline{E}_{2020} = 0.841$); 2021 ($\overline{E}_{2021} = 0.867$); and 2022 ($\overline{E}_{2022} = 0.896$). Subway of Sevilla presents an anomalous inefficiency in its management process.

Table 4 shows productivity, technology, pure efficiency, and scale efficiency changes for the 2017–2022 sample period. The table indicates the gradual productivity decrease from 2017 to 2022, mainly attributed to the technical productivity recession. It can be the decrease in productivity from 3 companies in 2018 concerning 2017, which increased in the subsequent periods. Pure and scale efficiency experience a moderate fluctuation compared to technical efficiency.

Besides, the environmental model showed a dropout in the number of efficient DMUs in the period under study. Fig. 4 presents the efficiency of the DMUs in the reference set, considering a VRS model input oriented in the period under consideration.

The DEA model in our study revealed that 5 of these were efficient in 2017–2018. This represents 71 % of the companies in the sample, with average efficiency $\overline{E}_{2017} = 0.947$ and 2018 ($\overline{E}_{2018} = 0.929$). The number of efficient units during the period under study experienced a drop, up to 4 companies (57 % of the sample) from 2019 until 2022. The average

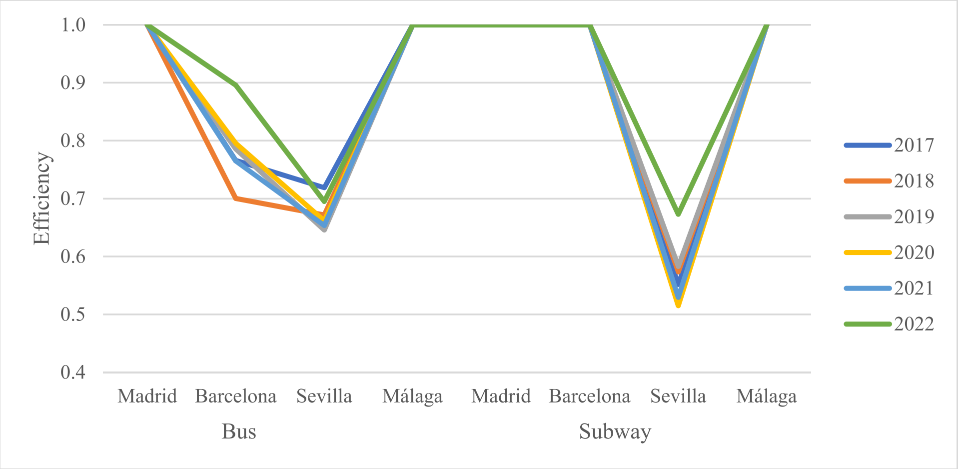

Fig. 2. Efficiency for each DMU in the reference set for the general efficiency model
Source: Own elaboration.

Table 3
Summary of changes in Malmquist index, technical change, and efficiency change.

Period	Summary	Malmquist index	Technical change	Efficiency change	Pure efficiency	Scale efficiency
	Progress	3	4	1	1	0
	No change	0	0	5	5	7
2017/18	Decline	3	2	1	1	1
	Mean	1003	1022	0,986	0,986	1
	Progress	2	1	2	2	0
	No change	0	1	4	4	7
2018/19	Decline	6	5	1	1	1
	Mean	0,849	0,835	1013	1013	1
	Progress	1	1	2	2	0
	No change	1	1	4	4	7
2019/20	Decline	5	5	1	1	1
	Mean	0,587	0,597	0,990	0,990	1
	Progress	4	4	1	1	0
	No change	0	0	5	5	7
2020/21	Decline	2	2	1	1	1
	Mean	1045	1051	0,997	0,997	1
	Progress	3	0	3	3	0
	No change	0	0	4	4	7
2021/22	Decline	4	7	0	0	1
	Mean	1016	0,935	1063	1063	1
	Progress	0	0	2	2	0
	No change	0	0	4	4	7
2017/22	Decline	8	8	1	1	1
	Mean	0,671	0,633	1	1	1

Source: Own elaboration.

efficiency is maintained in 2019–2022 being 2019 $\overline{E}_{2019} = 0.789$); 2020 ($\overline{E}_{2020} = 0.794$); 2021 ($\overline{E}_{2021} = 0.825$); and 2022 ($\overline{E}_{2022} = 0.841$). Malaga Subway was found to be a self-evaluator.

Table 5 shows productivity, technology, pure efficiency, and scale efficiency changes for the 2017–2022 sample period. The table indicates the moderated gradual productivity decrease from 2017 to 2020, mainly attributed to the technical productivity recession. A high increase in productivity was observed in 2019 and 2018, attributed to improvement in "best practices," reduced drastically in the next period. Pure and scale efficiency experience a moderate fluctuation compared to technical efficiency.

Finally, the income model presents a behavior similar to the environmental efficiency model. Fig. 5 presents the efficiency of the DMUs in the reference set, considering a VRS model input oriented in the period under consideration.

The DEA model in our study revealed that 5 of these were efficient in 2017–2019. This represents 71 % of the companies in the sample, with average efficiency $\overline{E}_{2017} = 0.847$; 2018 ($\overline{E}_{2018} = 0.848$); and 2019 ($\overline{E}_{2019} = 0.824$). The number of efficient units during the period under study experienced a drop, up to 4 companies (57 % of the sample) from 2020 until 2022. The average efficiency is maintained in 2020–2022 being 2020 ($\overline{E}_{2020} = 0.785$); 2021 ($\overline{E}_{2021} = 0.783$); and 2022 ($\overline{E}_{2022} = 0.760$).

Table 6 shows productivity, technology, pure efficiency, and scale efficiency changes for the 2017–2022 sample period. The table indicates moderate fluctuations in the period as a whole, as in the rest of the indices.

In the four models, Madrid Subway was found to be a self-evaluator, unable to emulate the management process of the rest of the inefficient DMUs.

The Kruskal-Wallis test was employed to identify potential differences between buses and subways during the period under study. No significant differences were found regarding the general efficiency model (p-value=0.343, H-Statistic=0.9), the energy model (p-value=0.515, H-Statistic=0.424), the environmental model (p-value=0.081, H-Statistic=3.048) and the income model (p-value=0.388,

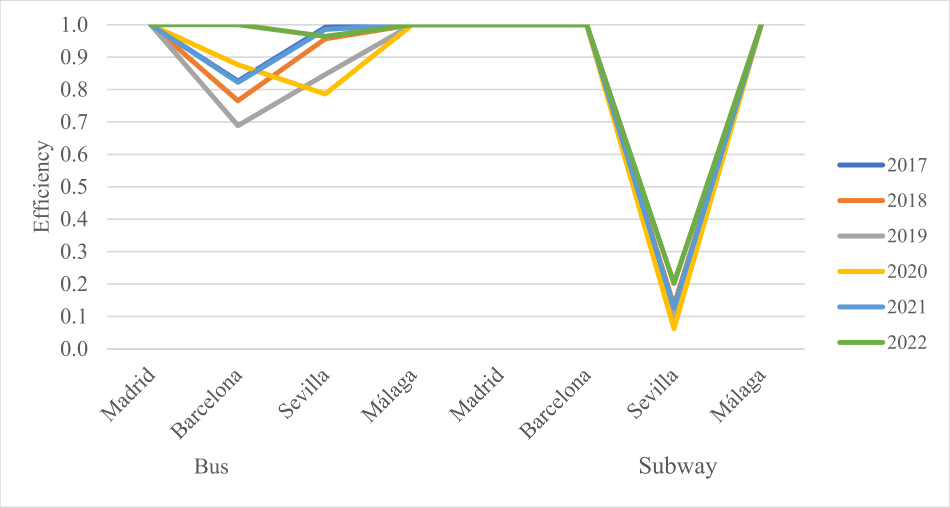

Fig. 3. Efficiency for each DMU in the reference set for the energy model. Source: Own elaboration.

Table 4
Summary of changes in the Malmquist index, technical change, and efficiency change.

Period	Summary	Malmquist index	Technical change	Efficiency change	Pure efficiency	Scale efficiency
	Progress	2	1	1	1	0
	No change	0	1	5	5	7
2017/18	Decline	4	4	1	1	1
	Mean	0,992	0,985	1005	1005	1
	Progress	2	5	0	0	0
	No change	0	0	4	4	7
2018/19	Decline	5	3	3	3	1
	Mean	0,957	1046	0,936	0,936	1
	Progress	4	5	1	1	0
	No change	0	0	5	5	7
2019/20	Decline	4	3	2	2	1
	Mean	0,827	0,846	0,983	0,983	1
	Progress	1	0	2	2	0
	No change	1	0	4	4	7
2020/21	Decline	3	6	0	0	1
	Mean	0,816	0,687	1151	1151	1
	Progress	1	0	2	2	0
	No change	1	0	4	4	7
2021/22	Decline	4	7	1	1	1
	Mean	0,805	0,716	1099	1099	1
	Progress	0	0	2	2	0
	No change	0	0	4	4	7
2017/22	Decline	8	8	1	1	1
	Mean	0,59	0,52	1,11	1,11	1

Source: Own elaboration.

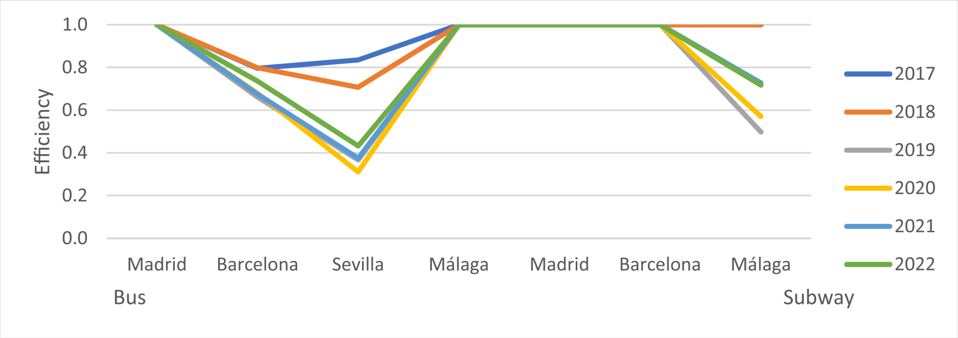

Fig. 4. Efficiency for each DMU in the reference set for the environmental model
Source: Own elaboration.

Table 5
Summary of changes in the Malmquist index, technical change, and efficiency change.

Period	Summary	Malmquist index	Technical change	Efficiency change	Pure efficiency	Scale efficiency
	Progress	3	4	1	1	0
	No change	0	0	5	5	6
2017/18	Decline	3	2	1	1	1
	Mean	1067	1100	0,979	0,979	1
	Progress	2	4	0	0	0
	No change	0	0	3	3	6
2018/19	Decline	4	3	3	3	1
	Mean	6593	6949	0,835	0,835	1
	Progress	4	3	2	2	0
	No change	0	0	3	3	6
2019/20	Decline	3	4	1	1	1
	Mean	0,732	0,734	1003	1003	1
	Progress	2	0	2	2	0
	No change	0	0	3	3	6
2020/21	Decline	2	5	0	0	1
	Mean	1033	0,927	1068	1068	1
	Progress	2	1	2	2	0
	No change	1	1	3	3	6
2021/22	Decline	2	3	1	1	1
	Mean	0,963	0,920	1033	1033	1
	Progress	5	5	0	0	0
	No change	0	0	3	3	6
2017/22	Decline	2	2	3	3	1
	Mean	1936	1675	0,880	0,880	1

Source: Own elaboration.

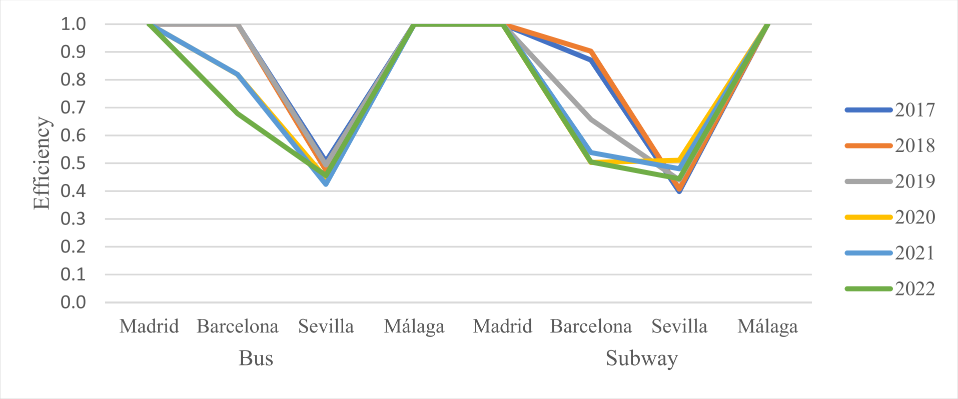

Fig. 5. Efficiency for each DMU in the reference set for the income model
Source: Own elaboration.

H-Statistic=0.747). Fig. 6 presents the boxplot for each model concerning the efficiency scores.

A fixed model was used to find possible differences between cities, the type of urban transport, and the period under study. No significant differences were found regarding the year and type of urban transport. However, significant differences were found by the city in the general efficiency model (p-value≈0, F-statistic =73.43), the energy model (p-value≈0, F-statistic =11.71), the environmental model (p-value≈0, F-statistic =15.17) and the income model (p-value≈0, F-statistic =83.97). Fig. 7 presents the boxplot for each model concerning the efficiency scores. Sevilla City resulted in significant inefficient respect for the remaining cities in the reference set in the four models under consideration,

Fig. 8 presents the boxplot for the Malmquist index for the four models in the sample period under study, omitting the case for TMB Barcelona in 2019/2018 because the environmental model attaches a weird value of 35.6. The energy model presents a higher variance concerning the remaining models, the model that experiences a higher decrease in productivity in the sample period. On the other hand, the environmental and income models present an average productivity maintenance in the sample period under study. These results are mainly attributed to technical productivity changes. Kruskall Wallys distribution equity was used to find possible differences between models in the sample productivity period. No significant differences were found regarding the four models (p-value=0.434, H-Statistic=2.734).

When considering solely the 2022/2017 productivity model, it is clear that there is an improvement in productivity in the environmental model and a decrease in the general and energy models (see Fig. 9 for details). Again, these results are mainly attributed to technical productivity changes. To find possible differences between models in the 2022/2017 productivity period, the Kruskall Wallys distribution equity was used. No significant differences were found regarding the four models (p-value=0.061, H-Statistic=7.37).

Discussion

Urban transport improves environmental sustainability, fosters social and territorial integration of its inhabitants, facilitates the achievement of sustainable development goals, and makes cities more inclusive, safe, and sustainable (United Nations, 2023; Shibayama, 2020).

Within urban transport, buses and the metro are the modes the

Table 6
Summary of changes in the Malmquist index, technical change, and efficiency change.

Period	Summary	Malmquist index	Technical change	Efficiency change	Pure efficiency	Scale efficiency
2017/18	Progress	4	5	2	2	0
	No change	0	0	4	4	7
	Decline	3	2	1	1	1
	Mean	1059	1058	1000	1000	1
2018/19	Progress	2	2	2	2	0
	No change	0	0	4	4	7
	Decline	4	4	1	1	1
	Mean	1036	0,994	0,981	0,981	1
2019/20	Progress	5	5	1	1	0
	No change	0	0	4	4	7
	Decline	3	3	2	2	1
	Mean	1105	1094	0,956	0,956	1
2020/21	Progress	2	2	2	2	0
	No change	0	0	3	3	7
	Decline	4	4	2	2	1
	Mean	1057	1053	0,995	0,995	1
2021/22	Progress	2	1	1	1	0
	No change	0	1	4	4	7
	Decline	4	4	2	2	1
	Mean	0,879	0,846	0,971	0,971	1
2017/22	Progress	4	3	1	1	0
	No change	0	0	4	4	7
	Decline	3	4	2	2	1
	Mean	1125	0,995	0,909	0,909	1

Source: Own elaboration.

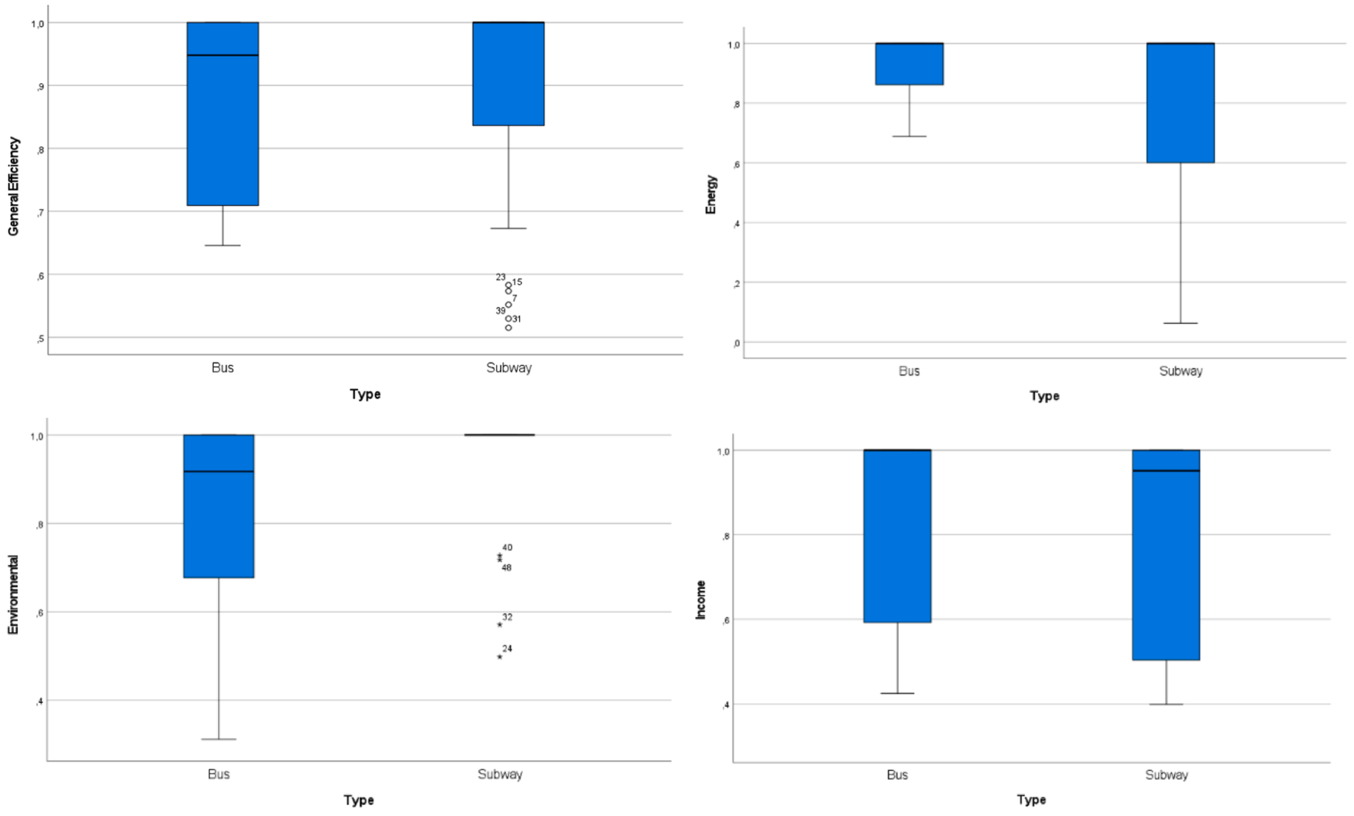

Fig. 6. Boxplot per model of the efficiency scores. Source: Own elaboration.

relevant authorities use for service provision. Although the management models for their provision differ when it comes to the metro and buses (Flores-Ureba et al., 2024; Delgado et al., 2009), both are highly subsidized services with significant investment needs to improve their sustainability and capacity (ERRAC, 2020).

Both modes of transport are provided complementarily in nine Spanish municipalities. Buses are predominantly used in cities with >50,000 inhabitants, although metro systems have evolved recently.

Analyzing metro and bus efficiency is necessary to improve resource allocation, control the services provided, and enhance planning (Hussain, 2022).

Efficiency has been extensively discussed concerning public transport in general, explicitly concerning buses. In contrast, it has been less analyzed for the metro and when comparing both modes (Flores et al.,

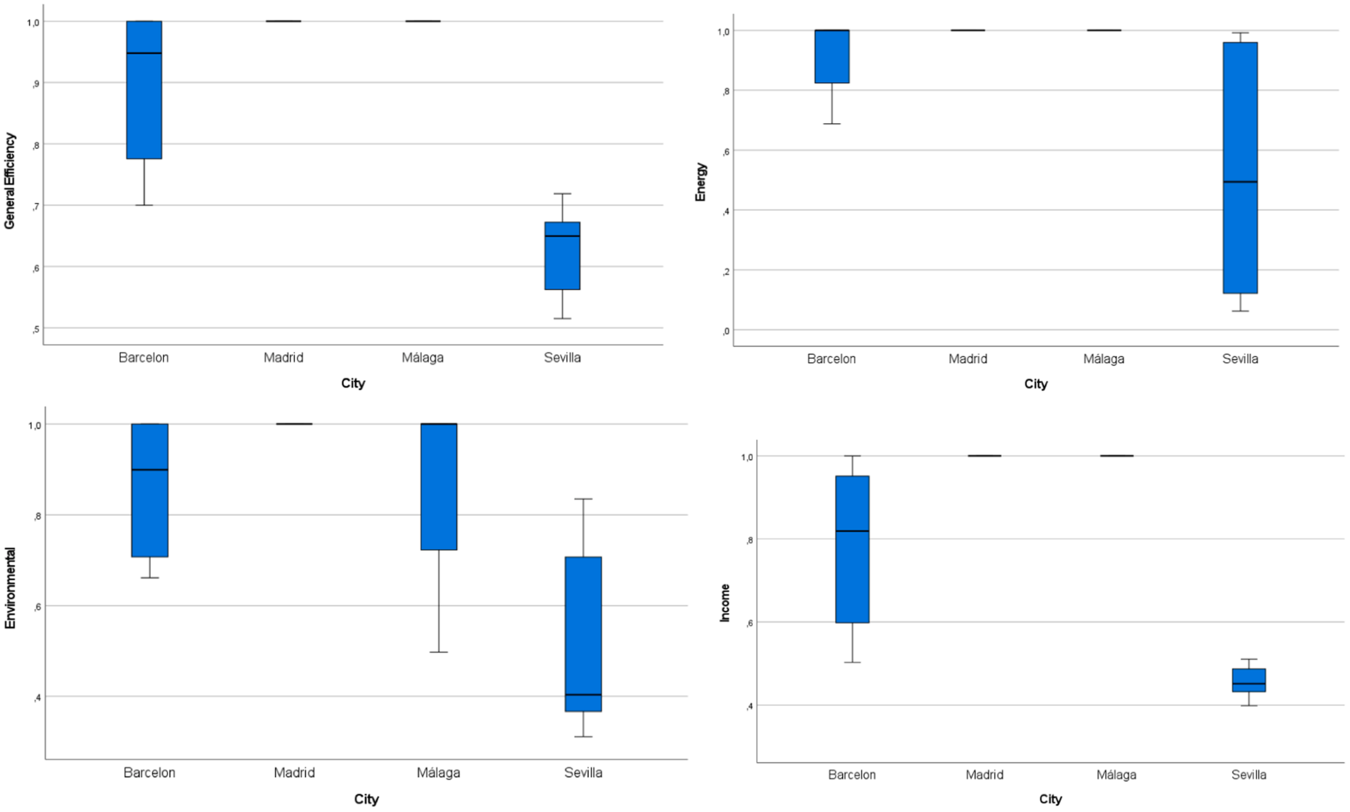

Fig. 7. Boxplot per city of the efficiency scores. Source: Own elaboration.

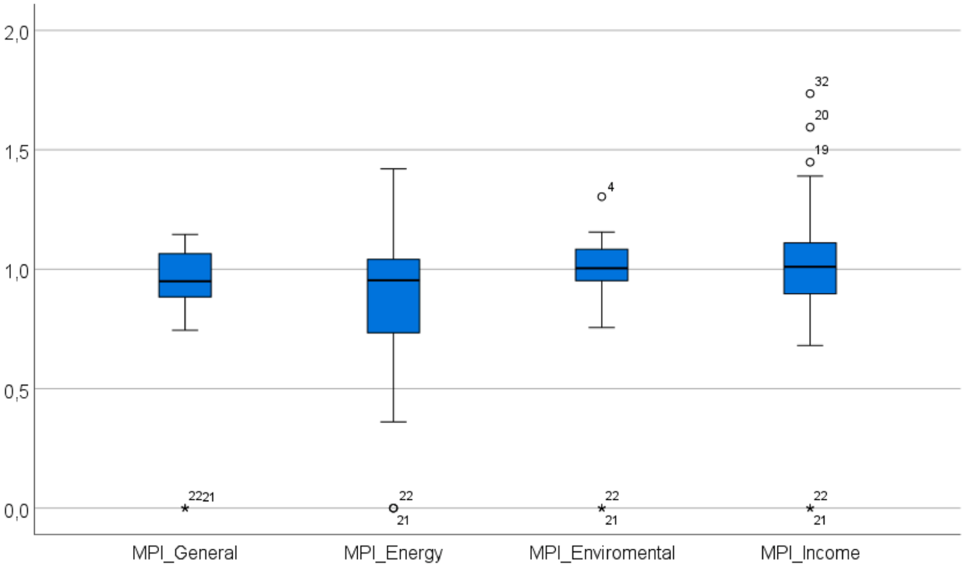

Fig. 8. Boxplot per model of the Malmquist index (MPI). Source: Own elaboration.

2024; Niu et al., 2023; Benga et al., 2022; Machado et al., 2022; Holvad, 2020; Holmgren, 2018; Karlaftis & Tsamboulas, 2012).

Therefore, this study addresses a significant gap in the literature regarding the comparative efficiency of urban public transport systems, specifically focusing on the bus and metro modes. Existing research predominantly examines the efficiency of these modes in isolation, neglecting the broader implications of their intermodal dynamics.

For this reason, the efficiency analysis presented in this work, through a DEA analysis from 2017 to 2022 of bus and metro modes in cities where both operate, provides data to inform investment and funding decisions. This is not only from an economic perspective but also considering the environmental impact these modes have in the cities where they operate. DEA allows for an analysis of the overall, economic, and energy efficiency and the environmental efficiency of the transport modes in the sample used.

Regarding possible practical implications, we believe that a series of recommendations can be made to policymakers.

Firstly, the age of the structures and the technology used affect the different efficiencies analyzed. It is necessary to study investments in renovation and adaptation of the elements used in production for

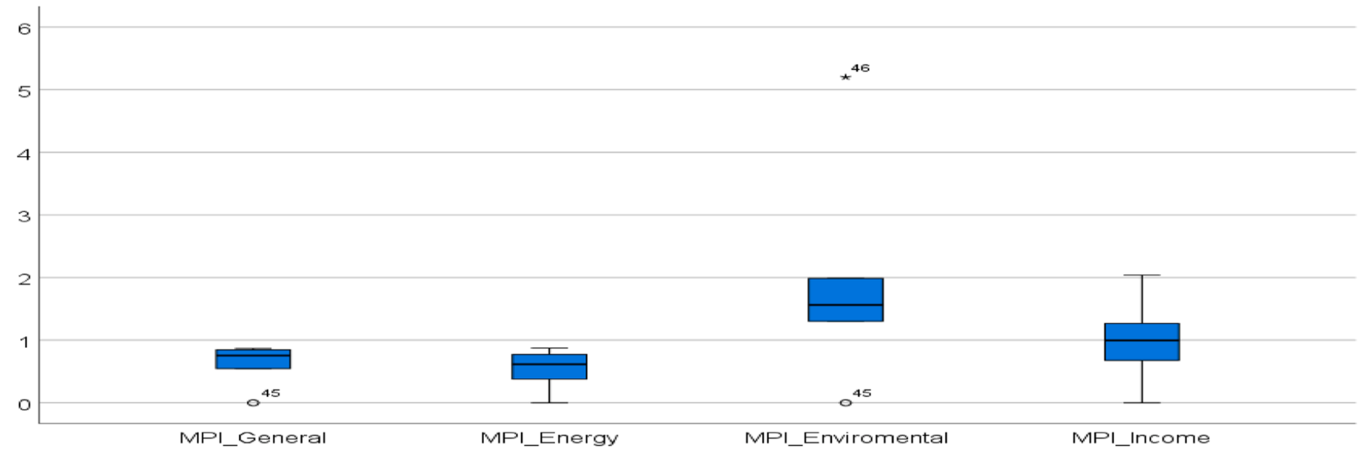

Fig. 9. Boxplot per model of the Malmquist index (MPI) for 2022/2017.
Source: Own elaboration.

technologies that use resources and energy more appropriately (Villalba et al., 2021).

A second recommendation is the use of benchmarking techniques on a national level. Madrid is the benchmark for both metro and bus modes, based on which comparisons can be made of what each operator is doing regarding supply, material, and technologies used.

As a third recommendation, it is necessary to review financing policies since possible relevant changes in structure will depend mainly on the public financing received, given that this is a highly subsidized sector. As has been established in the literature review, financing policies are disparate in the Spanish sector and affect the companies' operability. They can either incentivize or discourage the search for efficiency. Relevant modifications in the structure and offer of the operators would require specific financing, which is necessary not only to deal with internal aspects such as costs or the production process but also with the possibility of obtaining public resources through subsidies from competent institutions. Increases in specific funding for years in which restructuring and improvement of the elements are essential to obtain better efficiencies in the areas analyzed in this study will positively impact future years.

In addition, as a final recommendation, we believe that intermodality is fundamental and that the policies and decisions taken can benefit from a joint analysis of the operators of the two modes of transport within the same city. The results show that the efficiencies of the different modes in each city are similar, and we believe that the analyses and improvements to be implemented could be based on a joint study. We also understand that new investments are more cost-effective in the bus mode, as similar efficiency can be achieved with a lower investment in infrastructure.

While this study offers valuable insights, it is not without limitations. We understand that the following are some of the existing limitations that can be corrected in future research:

Firstly, the sample analyzed is small and localized in Spain, which may affect the results generality. Additional comparative analyses with other cities in different countries would strengthen the conclusions obtained.

Secondly, a significant limitation of this study is the notable difference observed between Madrid and the other analyzed cities. To address this, future comparisons should focus on cities with urban transport systems that are more comparable to Madrid, such as other European capitals or significant international cities with extensive and complex metro and bus networks. Additionally, the DEA methodology, while powerful, is sensitive to the selection of inputs and outputs. Future research could explore alternative metrics or hybrid approaches, combining DEA with other analytical tools to validate and extend the findings.

For future research, it would be interesting to compare the significant structures of European or international public urban transportation, as well as, at the national level, the inclusion of new analysis variables, such as population density, per capita income, and other operational data, such as the mobile material used, number of drivers, etc.

Conclusions

The general efficiency analysis shows similar results for bus and metro modes, which could suggest that the hypothesis under examination is rejected. However, considering the initial investment required, we can conclude that implementing new transport networks is more efficient in the bus mode, as similar results can be achieved with a lower initial investment.

Regarding general efficiency in bus mode, Madrid and Málaga were the most efficient in all periods analyzed, although passenger numbers dropped significantly in 2020 due to COVID-19. Passenger numbers had recovered by 2022 but had not reached 2019 levels. Sevilla Metro shows lower efficiency for the metro than the others in all periods analyzed, with a slight improvement in 2022.

Only minor resource management and service provision differences are found in Sevilla and Barcelona. In Sevilla, buses are more efficient, whereas, in Barcelona, the metro is slightly more efficient.

A similar pattern to general efficiency is observed for energy efficiency. Barcelona and Sevilla achieved near-complete efficiency in bus mode in 2022. Sevilla Metro is highly inefficient, nearing zero in 2020. However, it improved in 2022 due to energy costs being closer to companies like Metro Barcelona, which has a network size over six times larger.

Regarding environmental efficiency, considering the absence of CO2 data for Metro Sevilla, the results indicate similar CO2 emissions for both bus and metro, with improvements in all cases due to efforts to upgrade fleets and infrastructure.

Regarding income or economic efficiency, both bus and metro in Madrid and Málaga stand out for their efficiency. In contrast, Barcelona's efficiency decreases in 2022, and Sevilla shows the most inefficiency in both modes due to low fares and reduced passenger numbers.

Fare revenues are significantly lower than operating costs, making these companies highly subsidized. Further analysis is needed to determine if efficiency relates to subsidies, as ITF (2019) suggested, but this was impossible due to data limitations.

The analysis also shows that network size, as a measure of company size, is an efficiency indicator, as seen in the cases of Madrid, whose network size is almost double that of other companies analyzed, aligning more with large European capitals like London or Paris. Meanwhile, Málaga, with a network size similar to Sevilla, shows significantly higher efficiency.

In conclusion, bus and metro efficiency are similar in the cities analyzed, with Sevilla having the lowest efficiency in both modes. Future analyses should link subsidies to efficiency, consider external factors like population density, and include new variables such as mobile material and the number of drivers to compare major urban transport systems in Europe or internationally.

Analyzing metro and bus efficiency is essential because improving sustainable mobility is directly linked to investment in these modes of transportation. Investment affects the metro differently than the bus, with the former more related to infrastructure and the latter more associated with fleet investments. These investments require funding from the competent authorities of these modes, with the local authority bearing the most significant burden based on its financing structure.

In this context, analyzing the resource management of different modes of transportation can be considered relevant for making investment and financing decisions. This applies from an economic standpoint and when considering the environmental impact these modes have on the cities in which they operate.

DEA allows for an analysis of the general, economic, and energy-related efficiency, as well as environmental, of transportation modes in cities where both metro and bus operate together.

The number of network kilometers shows no significant variations during the analyzed periods.

Regarding the costs incurred by these companies, they have sustained growth for the analyzed period, except in 2020, where costs decreased, except for Madrid and Barcelona bus companies, where they increased.

As for the metro, Metro de Sevilla shows lower efficiency than the others in all analyzed periods, with a slight improvement in 2022. One of the causes was the antiquated network of trains and roads since it was a project that started in 1969. The fleet's lack of investment and renewal has led to a significant drop in efficiency compared to the rest of the DMUs in the reference set.

Taking general efficiency as a reference, in cities with a difference between the metro and bus, the bus mode is more efficient every year in Sevilla. In contrast, in the case of Barcelona, the metro is considered more efficient than the bus.

Regarding energy efficiency, a similar evolution to general efficiency is observed in the bus mode. Barcelona and Sevilla achieve almost complete efficiency in 2022. In the case of the metro, Metro Sevilla stands out for its significant inefficiency, close to zero in 2020, but gradually recovered in 2022 due to its energy cost during the analyzed years approached those of companies like Metro Barcelona, whose network length was more than six times greater than the one in Sevilla, being 125.40 and 18 respectively in 2022.

Regarding environmental efficiency, Madrid and Málaga are considered the most efficient in bus and metro transportation.

In calculating environmental efficiency and considering that we could not obtain the CO2 emissions of Metro Sevilla, the results again show that Madrid and Málaga managed to reach the efficiency frontier, along with Metro de Barcelona. However, the environmental efficiency for Barcelona's bus is around 0.75, and buses in Sevilla reach a lower level of around 0.4. As in previous cases, there are no significant differences between modes of transportation.

Regarding income efficiency, Madrid and Málaga have achieved total efficiency in bus and metro. In contrast, in bus mode, Barcelona decreased its efficiency in 2021 and 2022 (around 0.65 for the last year), and for metro Barcelona, it declined from a level close to 0.9 in 2017–18 to 0.5 in 2022. In the case of Sevilla, both the bus and metro companies are the most inefficient companies in the sample, with values between 0.4 and 0.5 in the years analyzed. This is due to the low fare revenues that coincide with the evolution of passengers and subsidized fares that have not fluctuated in the years analyzed.

As we have observed with the data, the companies' operating costs are much higher than their fare revenues, making them highly subsidized companies due to their social nature.

Generally, we can observe that network size is not a determining factor in achieving operational efficiency, as we can find cases of high efficiency with both minimal and extensive networks, such as the Málaga Metro or Madrid bus.

In summary, it is observed that the behavior of Madrid companies differs significantly from that of their Spanish counterparts, being more comparable in size to other significant European capitals such as London, Paris, or Berlin Castagna et al. (2024).

In summary, this article contributes to the analysis of urban transportation efficiency in a novel way by comparing the main modes of transportation, indicating no significant difference in general, energy-related, environmental, or income-related efficiency between the two systems.

Statements and declarations

The authors did not receive support from any organization for the submitted work.

CRediT authorship contribution statement

Joaquín Sánchez Toledano: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Conceptualization. **Beatriz Duarte Monedero:** Writing – review & editing, Writing – original draft, Formal analysis, Conceptualization. **Sandra Flores - Ureba:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Clara Simón de Blas:** Validation, Software, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.stae.2025.100097.

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