Assessing cost-effectiveness of alternative bus technologies: evidence from US transit agencies

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Abstract

This paper aims to analyze overall economic and environmental performances of alternative bus powertrains by focusing on U.S. active fleets in different urban contexts. We define a life cycle cost model related to bus technologies by referring to real-world data of 256 transport operators, which provide more than 80% of total vehicle revenue miles produced by urban transit mode across the U.S. in 2019. The proposed method includes some service parameters that significantly affect the supply cost (e.g., service speed, annual mileage), on which we perform scenario and sensitivity analysis. Results show that electric buses are cost-competitive in large cities and metropolises, where urban bus routes are characterized by a high level of congestion, high service frequency, and the highest marginal impact of harmful emissions. In towns and suburban areas, where bus routes are longer and faster, full electric technology still faces both economic and technical barriers.

Highlights

- Data-driven economic assessment of alternative power technologies for transit buses
- Life cycle social cost model as a tool for policy-making on alternative bus powertrains
- High purchase costs and limited battery range hinder electric bus deployment
- Congested urban routes are the most suitable for electric buses

Keywords

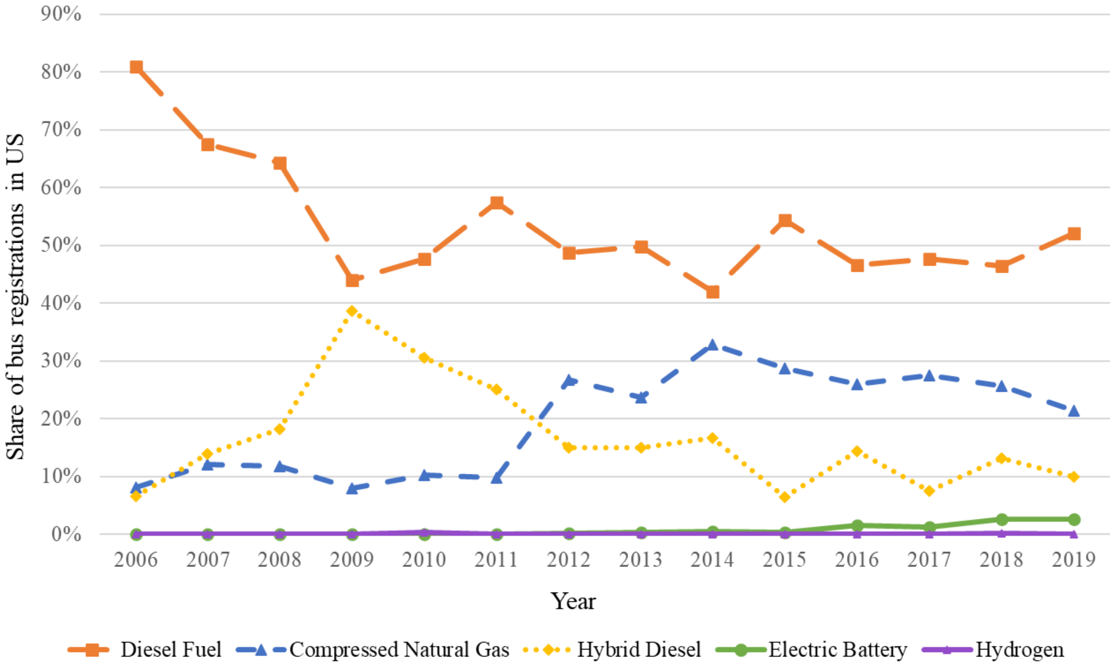
Transit buses, Electric buses, Life Cycle Cost, Total Cost of Ownership, Environmental benefit

1. Introduction

In recent years, the environmental emergency and the technological advancement of alternative power sources have posed deep challenges to the mobility system. Public buses represent an ideal test case to drive clean technology adoption in road transport vehicles (Gallo, 2016). Indeed, scientific literature and empirical evidence highlight that transit operators, compared to private vehicle owners, should be more willing to adopt alternative powertrains. This finding is firstly due to some peculiar characteristics of public transport provision, such as fixed routes and scheduling, distributed depots, and shared infrastructures (Eldeeb and Mohamed, 2022; Mohammed et al., 2020). In this context, for instance, the hindering impact of some electric vehicle issues, e.g., battery range limitation and charging time needs, is smoothed by centralized operational procedures. Moreover, high annual mileages run by transit buses increase the relevance of running and maintenance costs, which usually play in favour of electric powertrains (Tong at al., 2017). Transit providers have a heightened awareness to pursue environmental sustainability as a consequence of both obligations and incentives introduced by public authorities (Sierzchula, 2014; Golob et al., 1997). Finally, clean buses, in addition to directly cutting harmful emissions, indirectly improve air quality, traffic congestion, and noise levels within cities by increasing the attractiveness of public transport and hence reducing the modal share of single-occupant vehicles (Sunitiyoso et al., 2022; Tan and Lin, 2019). Moreover, the high visibility of city buses contributes to raising public awareness of the urgent need to reduce environmental pollution (Van der Straten et al., 2007).

For these reasons, alternative bus powertrains are receiving increasing attention from planners and decision-makers worldwide, especially electric buses in urban areas (ICCT, 2022). The main implemented dissemination policies result in subsidies for purchasing vehicles and infrastructures, tax incentives, and low-carbon vehicle mandates (Manzolli et al., 2022). According to some studies, electric buses will replace their ICE (Internal Combustion Engine) counterparts in the current decade (Pagliaro and Meneguzzo, 2019). However, the adoption rate of new green technologies is still low in bus transport. Figure 1 shows the trend of bus purchases in the U.S. in the last decades with respect to different power technologies.[1]

Figure 1. New registrations of urban buses in U.S. from 2006 to 2019 classified by power technology



Source: FTA, 2020

The percentages of zero-emission buses, i.e., electric battery and hydrogen fuel cells, introduced in 2019 for transit services are still negligible, 2.6% and 0.1%, respectively. After its initial success, the hybrid technology seems to decline. The amount of buses

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[1] This trend is confirmed by data related to 2020 and 2021, also considering that investments in new bus technologies significantly dropped during this period due to Covid-19 pandemic. This latter and the related mobility restrictions significantly affected public transport provision, then we prefer to use data up to 2019.

fuelled by Compressed Natural Gas (CNG) has grown in the last years to the detriment of conventional diesel. The latter has kept a stable adoption rate, and it is still accounting for around 50% of new bus registrations.

The study aims to analyze the overall economic and environmental performances of alternative bus powertrains by focusing on U.S. active fleets in different urban contexts. Recent studies still identify the increase in costs linked to low-carbon technologies as one of the main barriers to their large-scale adoption (e.g., Bae et al., 2022; Anderhofstadt and Spinler, 2019).

We define a life cycle cost (LCC) model in order to develop an economic assessment of the leading power technologies for city buses. The model structure is consistent with that already introduced in the literature; however, we carry out a data-driven estimation of different cost variables by considering a representative sample of U.S. transit agencies. Moreover, we link the cost performances to some exogenous key service variables that influence technology efficiency, enabled by integrating different databases related to the same transport operators. The analysis of real-world data related to different urban contexts (e.g., transit services in metropolitan areas or small towns) allows us to identify the operational features more suitable for clean buses adoption, also taking into account costs linked to the marginal damage of harmful emissions. In this way, we support policymakers in drawing up effective public funding strategies aimed at encouraging eco-friendly bus fleets by assessing the economic performances of different technologies in different scenarios.

The paper is organized as follows. Section 2 presents a literature review of studies focused on alternative bus technologies and sets the study’s contribution. Section 3 describes the methodology and the data used to design the model. Section 4 reports quantitative results and the related findings. Section 5 concludes.

2. Literature and contribution

The costs of transit bus services have been extensively addressed by empirical research with different approaches and purposes (for a critical review see Daraio et al., 2016). The scientific literature focused on transit companies' costs has often assessed the efficiency level of transport operators in order to study the role of public subsidies (e.g., Parry and Small, 2009; Basso and Silva, 2009) or to define a maximum economic compensation in the allotment of public services (e.g., Hensher et al., 2013; Avenali et al., 2016; Avenali et al., 2018). Many other papers take into account the transport operator costs as a critical component in the planning, design, and optimization stages (e.g., among others, Mohring, 1972; Börjesson et al., 2018; Harris et al., 2020).

In recent times, thanks to technological developments and stricter environmental standards across the world, we have moved from a market where conventional fossil fuels used to be the only viable option for buses and coaches (i.e., diesel) to a wide offer of alternative power sources (e.g., biofuels, hybrid solutions, electric batteries, and fuel cells). The characteristics of alternatively powered buses have been thoroughly addressed by academics (e.g., Deliali et al., 2021; Göhlich et al., 2018; Mahmoud et al., 2016) and policymakers.[2]

In this regard, alternative bus technologies are often compared and evaluated concerning two main elements: environmental impact and cost-effectiveness.

Life cycle assessment (LCA) tools are the most commonly used by scientists and practitioners to quantify vehicle and related power sources externalities, and a growing number of studies apply this methodology to alternative bus technologies (e.g., among

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[2] For instance, European Commission created the Clean Bus Europe Platform, where guidelines, publications, and legislative documentation are shared among stakeholders. Available at: https://cleanbusplatform.eu/ [Accessed 22/12/2022]

others, García et al., 2022; Jakub et al., 2022; Cooney et al., 2013; McKenzie and Durango-Cohen, 2012; Xu et al., 2015). Literature related to external costs estimation of transport services is characterized by high uncertainty and heterogeneous results, which depend on assumptions made in the calculation model and the characteristics of local areas under consideration (especially for air pollution emissions). For instance, the well-to-wheel external costs related to the 40-foot city bus estimated by Van Essen et al. (2019) are, on average, roughly double those of Tong et al. (2017). However, this strand of literature converges on some major findings. For one thing, there is no significant difference in environmental impact among new ICE bus generations (i.e., Diesel Euro VI and CNG). In both cases, the critical phase is the vehicle use, around 70% of well-to-wheel external costs are linked to the tank-to-wheel stage. Hybrid electric buses reduce harmful emissions costs by less than 20% compared to conventional diesel. In some areas, the actual share of energy produced from fossil sources generates the highest external costs related to the well-to-tank stage for electric buses (for a focus on regional electricity production in the U.S., see Sen et al., 2017; Holland et al., 2021). Therefore, considering the whole life cycle of the power source (i.e., energy or fuel), electric traction might not be significantly less polluting than ICE buses at present. However, managing the harmful emissions produced by an industrial plant should be easier than curbing smog in urban areas, especially concerning health effects connected to the inhalation of air pollutants (e.g., PM_{10}, $PM_{2.5}$, or NO_x). In addition, renewable energy sources can provide electricity by nullifying harmful emissions and hence the well-to-tank external costs of electric buses (Panwar et al., 2011; González et al., 2021).

The external cost is often an input for life cycle cost analysis in order to evaluate the social cost of different technologies (see, among others, Tong et al., 2017; Muñoz et al., 2022; Nurhadi et al., 2014; Lajunen and Lipman, 2016). In other cases, harmful emissions are excluded from the analysis (e.g., Kim et al., 2021; Blynn and Attanucci, 2019; Ally and Pryor, 2016), since the fleet owners are not charged for noise or pollutants produced by transit service. The concept of LCC is very similar to that of Total Cost of Ownership (TCO), both refer to the costs incurred during the entire life cycle of a good or service (i.e., acquisition, ownership, and subsequent disposal). The main difference is that LCC adopts a product perspective, independent from the subjects incurring the charges, while the TCO focuses on the purchaser's standpoint (Saccani et al., 2017). The latter is broader in scope and includes pre-purchase and transaction costs (Ellram, 1995), e.g., search and selection of suppliers. Thus, LCC and TCO are congruent with each other, and the total cost is often referred to as an output of the life cycle costing process.

A burgeoning literature deals with LCC and TCO estimation for transit buses by focusing on the economic performances of alternative power technologies for city buses. In this respect, the first evidence is still the variability of the findings among different studies linked to assumptions made in the LCC model and operation routes under consideration. Some papers find out the cost-effectiveness of electric buses compared to conventional diesel (Borén, 2020; Sheth and Sarkar, 2019; Bi et al., 2017), and some, on the contrary, assert that ICE ones are still cheaper (Muñoz et al., 2022; Blynn and Attanucci, 2019; Harris et al., 2018; Ally and Pryor, 2016; Lajunen, 2014). The critical assumptions of LCC bus analysis concern: the lifetime of vehicles, electric batteries, and charging infrastructures; the salvage value of the buses and supporting devices (in many cases set to zero in sight of technological development); the inclusion or not of external costs, some studies highlight their low impact on total cost (because of less public transport share and relatively higher other cost components); labor costs (mainly cost of drivers), which are often considered equal for all different powertrains and not included in the calculation; and fleet perspective (considering a single bus or whole fleet upgrade). In general, the literature shows that electric vehicles allow higher operational efficiency, which means lower energy and maintenance costs (Comello et al., 2021; Tong et al., 2017), and they significantly reduce the harmful emissions from the tailpipe, while life cycle GHG emissions are highly dependent on the renewable or fossil electricity generation source (Holland et al., 2021, Gustafsson et al., 2021). Moreover, the electrification of public transport raises the importance of route characteristics and driving conditions, which significantly affect the feasibility and cost-effectiveness of electric buses (Papa et al., 2022; Ma et al., 2021; Chen et al., 2018).

However, as recently stated by Eldeeb and Mohamed (2022), the feasibility of electric transit has been extensively tested by practitioners and scholars, while studies on the implementation of these new technologies can deepen their performances in real-world networks. Finally, it should be noted that LCC/TCO is only one of the key aspects that govern the implementation of low-carbon buses, indeed there are other decision-making factors to be taken into account concerning bus fleet electrification (see, for further details, Aldenius et al., 2022; Mohamed et al., 2018).

The economic performances of natural gas (CNG and LNG) rely heavily on local circumstances, such as the accessibility to gas distribution networks. In fact, there are countries where it can be cost-effective (e.g., across U.S., see Krelling and Badami, 2022) and others where it is uncompetitive (e.g., Australia, see Ally and Pryor, 2016) due to very high fuel costs. In terms of harmful emissions reduction, the literature shows that CNG is a successful solution if it comes from waste recycling (see, among others, Dyr et al., 2019; Rose et al., 2013), while they are not effective when the natural gas is produced from fossil sources.

Fuel cell buses have been extensively discussed as a possible alternative to conventional ICE buses. Several papers question the technical feasibility, key barriers, and potential impacts of hydrogen as an energy carrier of transit services (e.g., Ajanovic et al., 2021; Chen et al., 2007). Costs related to vehicle usage (both CAPEX and OPEX) and expenses connected with the different hydrogen supply pathways make this technology still too expensive for transport operators (Li and Kimura, 2021).

The existing research findings presented in this section are obtained from specific case studies based on data provided by interviews with transport authorities and manufacturers, simulation programs, literature reviews, and pilot projects that do not cover more than 10/15 transit operators. To the best of our knowledge, a cost comparison between alternative bus options based on a representative sample of transit companies and performed in different operational scenarios has not been developed yet.

In this paper, we build a life cycle cost model focused on bus powertrains and developed with reference to 256 transport operators that provided more than 80% of total vehicle revenue miles produced by transit mode across the U.S. in 2019. Moreover, some exogenous variables, which significantly affect the life cycle cost of the bus (i.e., service speed, bus size, and daily range), can be set in accordance with specific operational routes and procedures. In this way, we contribute to the literature in two aspects: first, we provide a cost model for alternative bus technologies that relies on empirical data from a representative sample of transport providers. Second, we answer the question of which types of bus services are more suitable for electric bus deployment in urban areas. In particular, we show how the cost structure of alternative bus technologies affects their economic performances in different operational scenarios, even taking into account the marginal impact of harmful emissions produced by transit services.

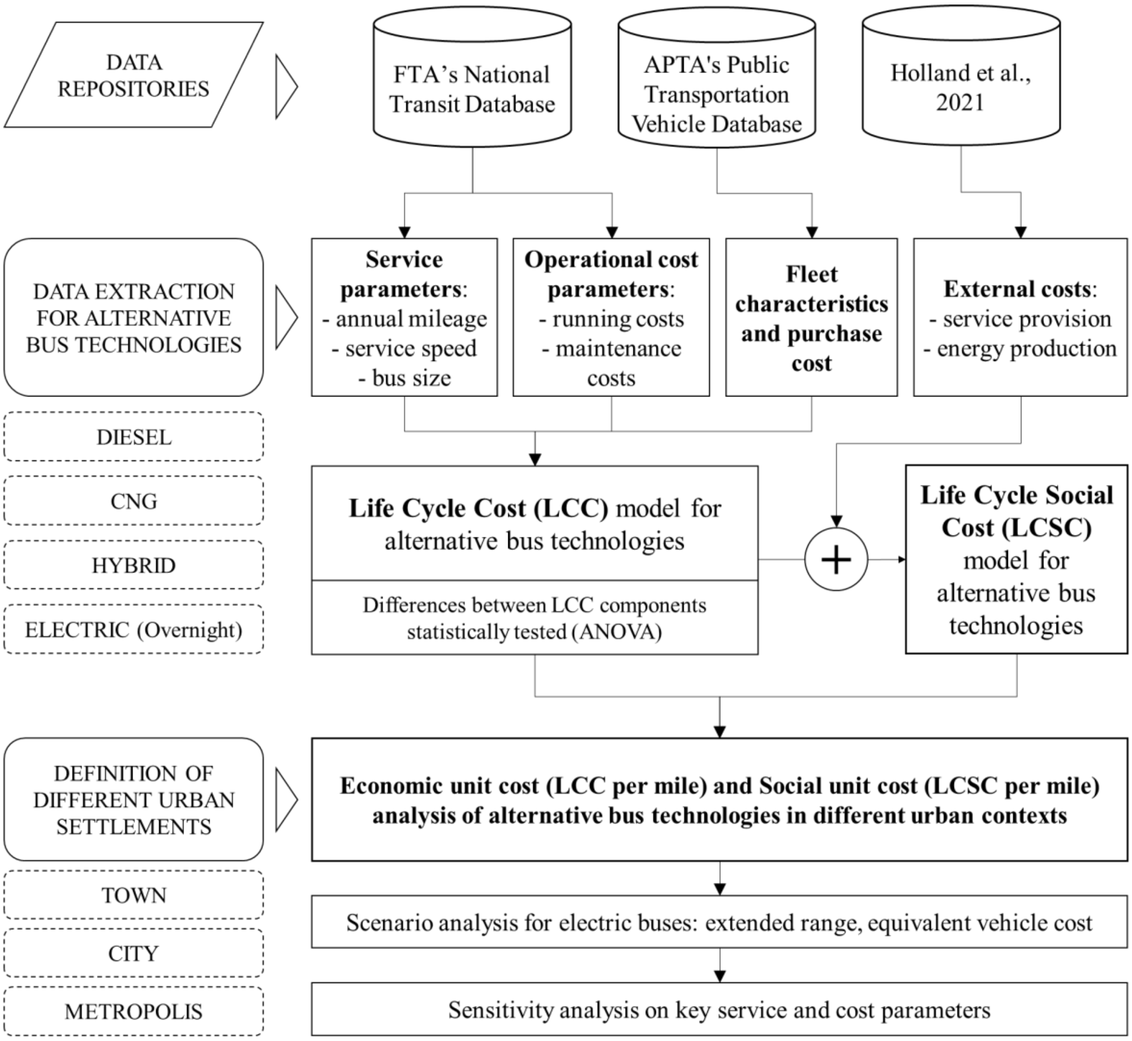
3. Data and methodology

3.1 Scope

This paper develops a data-driven economic assessment of the leading power technologies for city buses. Figure 2 displays a flowchart of the methodology proposed in order to evaluate costs-effectiveness of alternative bus technologies.

We focus on four alternative bus powertrains: conventional diesel (DF), compressed natural gas (CNG), hybrid diesel (HEB) and electric battery bus (BEB) with overnight charging.

Figure 2. Flowchart of the cost-effectiveness assessment proposed in the paper



The analysis is developed by following three steps. Firstly, we extract real-world data from different databases related to U.S. urban transit services, as described in Section 3.2. Secondly, based on data available for alternative bus technologies, we build a life cycle cost model by taking into account expenses related to running, maintenance, and purchase costs, which is consistent with previous studies on LCC and TCO for the transportation sector presented in the literature review section (Section 3.3). It is worth noting that an analysis of variance (ANOVA) is conducted to test if the differences among the cost components of the model related to different bus powertrains are statistically significant. We also integrate the external costs into the LCC model by taking input from recent literature focused on the environmental impact of power sources (Section 3.4). Finally, we assess cost-effectiveness of alternative bus technologies by focusing on the total cost per mile in different urban contexts (Section 4), namely, *town, city, and metropolis*. To this end, we also perform a scenario analysis with respect to different stages of development of electric buses and we carry out a sensitivity analysis on the input parameters of the model in order to identify the main variables that can significantly change the results of the analysis.

3.2 Data

The operational cost parameters of different bus technologies are estimated by using the FTA’s National Transit Database (FTA, 2020) with reference to the 2019 technical and financial data of U.S. city bus services. It is a public repository of data about the financial, operating and asset conditions of American transit systems. In particular, we have integrated 5 NTD Database File: “Agency Information”, “Service”, “Operating Expenses”, “Fuel and Energy”, and “Revenue Vehicle Inventory”. We have extracted the data from Full Reporter agencies (i.e., that operate more than 30 vehicles) by focusing on those that directly provide urban services. In this way, we define an integrated database that comprises 256 transit agencies, for each of which are reported data related to: general information (such as NTD ID, agency name, city, state, and population of the urbanized area primarily served); operating expenses (such as operator salaries and wages, fuel and lubricants, vehicle maintenance, facility maintenance, administrative activities); service characteristics (such as service speed, passengers, vehicle revenue miles and hours, deadhead miles); and fleet characteristics (such as active fleet per specific power technology, mileage of various power technologies, average fleet age, length, and seats). The transport operators have been divided into four groups according to the percentage use of the different power technologies:

(1) conventional diesel (“DF”) bus users that have a predominantly diesel fleet (at least 50%, 88% on average);
(2) compressed natural gas (“CNG”) bus users that have a predominantly CNG fleet (at least 50%, 82% on average);
(3) hybrid diesel (“HEB”) bus adopters that have a predominantly hybrid fleet (at least 30%, 48% on average);
(4) electric battery (“BEB”) bus pioneers that have a significant share of full electric in the fleet (at least 5%, 14% on average).

The identified clusters are used to derive the data of specific fuel options and estimate the related cost parameters. This allowed us to gather real-world data from a representative sample of U.S. transit agencies with respect to operational costs and characteristics of the urban services provided by different bus fleet types. Table 1 displays some descriptive statistics related to the fleet size of agencies included in the sample.

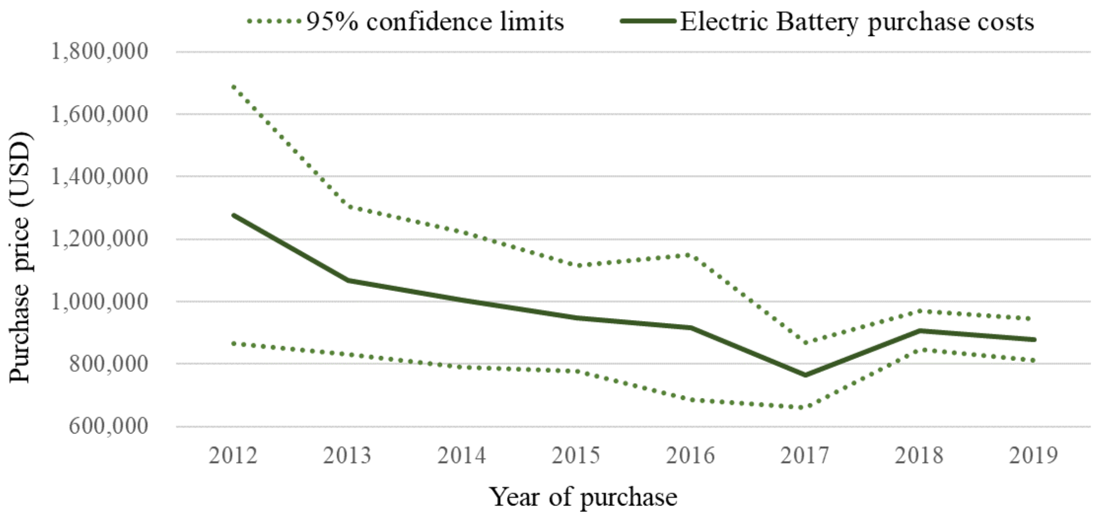
Table 1. Some descriptive statistics of agencies' fleets included in the sample

Power technology	*Number of agencies*	*Fleet size of specific power technology [number of buses]*						
		Mean	*Min*	*1° quartile*	*Median*	*3° quartile*	*Max*	*Coeff. of variation*
DF	153	142.02	4.00	23.00	39.00	108.50	2,395.00	2.28
CNG	40	170.35	7.00	37.50	87.00	175.50	2,110.00	2.02
HEB	41	129.95	3.00	18.00	36.00	83.00	1,145.00	1.99
BEB	22	10.68	2.00	5.00	7.50	16.25	36.00	0.75

Source: FTA, 2020

The NTD does not provide data on purchase prices of buses, for this cost variable we refer to the APTA's Public Transportation Vehicle Database (APTA, 2020). Particularly, we have considered all city bus purchase batches of transit agencies from 2010 to 2019 for diesel, CNG, and hybrid buses. However, in the case of electric buses, scale economies and technology developments have significantly affected the purchase cost and its variance in the last decade (data in Figure 3 brings to light the trend described). For this reason, we included in our sample only the electric bus purchase batches of the last three years (2017-2018-2019).

Figure 3. The trend of electric battery bus purchase price in U.S.



Source: APTA, 2020

Table 2 displays some descriptive statistics related to the sampled bus purchase batches. The bus's regular midlife costs (i.e., engine rebuild or battery replacement) for electric buses are based on the data collected from the California Air Resources Board (CARB, 2019).

Table 2. Some descriptive statistics of bus purchase batches included in the sample

Power technology	*Number of purchase batches*	*Batches size of specific power technology [number of buses]*						
		Mean	*Min*	*1° quartile*	*Median*	*3° quartile*	*Max*	*Coeff. of variation*
DF	661	18.10	1.00	3.00	7.00	18.00	317.00	1.90
CNG	321	23.97	1.00	4.00	8.00	20.50	550.00	2.19
HEB	283	17.51	1.00	3.00	6.00	16.00	169.00	1.54
BEB	40	7.00	1.00	2.25	5.00	9.50	25.00	0.88

Source: APTA, 2020

Finally, the main pollutants produced from the different bus powertrains are included in the analysis in a second step in order to switch from an economic to a social cost perspective. In this case, the marginal external cost parameters are based on the values presented by Holland et al. (2021) for 329 U.S. cities. Table 3 displays some descriptive statistics related to marginal external costs considered in the analysis. We assume that damages linked to the hybrid diesel bus are around 17% less than conventional diesel (Xu et al., 2015).

Table 3. Some descriptive statistics of marginal external costs related to US city buses

Power technology	*Marginal external costs [USD/mi]*						
	Mean	*Min*	*1° quartile*	*Median*	*3° quartile*	*Max*	*Coeff. of variation*
DF	0.135	0.083	0.121	0.130	0.140	0.697	0.283
CNG	0.116	0.077	0.111	0.115	0.120	0.330	0.137
BEB	0.109	0.048	0.091	0.121	0.126	0.154	0.235

Source: Holland et al. (2021)

3.3 Cost model and key assumptions

The life cycle cost model is developed in line with the literature and database assumptions mentioned above. Given the dataset related to economic performances of transit agencies, the identification and estimation of cost variables to include in the LCC model can be carried out with different methods: in bottom-up approaches, the cost items are identified and estimated through a detailed engineering analysis of the production process and in-use performances; on the opposite, top-down approaches rely on statistical parameters obtained from real-world data of transport operators; hybrid models combine the approaches mentioned above. We build a LCC model for bus powertrains using a hybrid approach. The bottom-up methods are adopted to identify crucial cost categories and the value of cost parameters are estimated by means of top-down techniques that may be very useful for understanding the real-world performances of various technologies. We also include some exogenous variables that significantly affect the cost of the service provision, such as service speed, annual mileage, and bus size, that can be adjusted with the operational context.

The assessment covers three main cost categories: the initial costs (i.e., vehicle and any related equipment acquisition), the maintenance costs (including regular midlife costs), and the running costs (reflected in fuel and lubricant costs for ICE buses and electricity costs for electric ones). It is worth pointing out that at the end of the time horizon used in the LCC model, there is a potential salvage value to be subtracted from the total cost of ownership. We define a flexible formula where some key service parameters (i.e., service speed, bus length, and vehicle mileage productivity) can be set with respect to the specific operational context.

The total life cycle cost of a city bus with power technology i and size j ($LCC_{i,j}$) can be determined as:

$$LCC_{i,j} = C_{pur_{i,j}} + \sum_{k=1}^{t} \frac{\left(C_{run_{i,j,k}}(s_k) + C_{mnt_{i,j,k}}\right) \cdot m_{i,k} + C_{mid_{i,j,k}}}{(1+r)^k} - \frac{SV_{i,j,t}}{(1+r)^t} \quad (1)$$

where:

- i represents the power technology, in this case we consider: diesel (DF), compressed natural gas (CNG), hybrid diesel (HEB), and electric battery bus (BEB) with overnight charging.
- j represents the bus size. For urban services standard sizes are: 30 feet (~ 9 metres), 35 feet (~ 10.5 metres), 40 feet (~ 12 metres), 45 feet (~ 14 metres) and 60 feet (~ 18 metres, articulated buses);
- $C_{pur_{i,j}}$ [USD] is the purchase cost of a bus with power technology i and size j, which includes also battery costs in the case of full electric buses;
- $C_{run_{i,j,k}}(s_k)$ [USD/mi] is the running cost per (produced) mile in year k related to carrying passengers on buses with power technology i and size j, mainly reflected in fuel and lubricant costs for ICE buses and energy costs for BEBs. By construction, the running cost per mile is the ratio between the running cost per (produced) hour and the average service speed s_k, which is calculated as the ratio of total vehicle miles to the vehicle hours (including idling time between routes). Moreover, both fuel and energy consumption are usually significantly affected by average service speed s_k.[3]

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[3] Actually, the literature has shown that different transit service features other than average speed may affect fuel and energy consumption (per mile), such as the average stop distance, the stop-level dwell time, driving style, route gradient, passengers load, degree of renewal of the bus fleet, and weather conditions (Papa et al., 2022; Ma et al., 2021; Chen et al., 2018, Avenali et al., 2018). However, the average speed often incorporates some effect of the mentioned factors and real transit services with close average speed are usually similar in terms of driving style, average stop distance, and the stop-level dwell time. Notwithstanding, a share of the variability of the fuel/energy consumption per mile is not captured by the average speed of the service, especially for electric buses.

Therefore, in (1) the running cost per mile is described as a function of the average service speed (s_k).

- $C_{mnt_{i,j,k}}$ [USD/mi] is the maintenance cost for a bus of size j powered by technology i per (produced) mile in year k, which relates to all activities aimed at keeping vehicles operational and in good repair. More specifically, it includes the cost of salaries and wages of maintainers, maintenance services purchased by outside organizations, insurance costs, tires and tubes, spare parts, and other materials;
- $C_{mid_{i,j,k}}$ [USD] concerns the regular maintenance midlife costs related to the single bus revamping to increase its lifespan. We assume that they occur in the seventh year of service and consist in the engine rebuild for internal combustion buses (i.e., diesel and CNG) and the battery replacement for electric buses;
- $m_{i,k}$ [mi] is the annual mileage produced by the bus powered by technology i;
- $SV_{i,t}$ [USD] is the salvage value of a bus with technology i at the end of the time horizon used in the model;
- t [year] is the time horizon of the model. In this study, it is assumed equal to 14 years, which is the mode of the bus useful life stated by the agencies sample (the second most frequent value is 12 years);
- r is the discount rate, it is set at 4.41%, consistent with Damodaran's estimation (2021) for the transportation sector.

Furthermore, we clarify some general assumptions that we made related to the LCC model of buses:

- the labor cost (i.e., driver cost) is considered equal for all different power technologies, this is attested by the statistical analysis carried out on our sample;

- $C_{run_{i,j,k}}(s_k)$ is a function that takes into account non-linearity between the running costs per mile in year k (strictly related to fuel/energy consumption) and the average service speed of the transit service. In particular, by construction it results:

  $$C_{run_{i,j,k}}(s_k) = \frac{CH_{run\ i,j,k}}{s_k} \tag{2}$$

  where $CH_{run_{i,j,k}}$ [USD/hour] is the running cost for a bus with technology i and size j per (produced) hour in year k and s_k [mi/hour] is the average service speed;
- the salvage value of ICE buses is assumed to be zero at the end of the model time horizon since the latter is the typical useful life of these technologies. However, some experts claim that it could be increased for electric buses. In particular, nine semi-structured in-depth interviews were conducted between March 2020 and October 2022 involving ten managers of transit operators in Italy and two managers of worldwide bus manufacturers. It emerged that BEBs have a longer useful life because electric engines are more durable than internal combustion ones and because of their lower mileage productivity (as verified by the statistical analysis described in the Appendix A). In light of that, we define the salvage value of BEBs by using the following formula:

  $$SV_{BEB,t} = (C_{pur_{BEB}} - C_{battery}) \cdot \left(1 - \frac{m_{BEB}}{m_{ICE}}\right) \tag{3}$$

  where $C_{battery}$ is the cost of installed batteries in BEB and m_i is the total mileage produced by the bus powered with technology i at the end of the time horizon t. In this way the useful life of electric buses relates to their annual mileage, which represents the key variable in determining the vehicle wear and tear;
- the costs related to supporting infrastructure updates, e.g., refueling/charging stations and bus depots, are not included in the model. We can also assume that they are purchased and built employing public funds. However, if capital

> expenditures related to infrastructures were considered, it would be essential to expand the perspective by taking into account other crucial aspects, e.g., fleet size, currently adopted technology, scope and scale economies. The proposed model limits to consider purchase and operating costs of different bus technologies, excluding investments in supporting infrastructures. Regarding electric buses, infrastructure costs depend on various factors, such as charging options (i.e., overnight, opportunity, or in-motion charging), electricity grid capacity and connection, and additional space availability in bus depots and bus lanes. Given the actual technology evolution, it is probably more effective to focus on specific case studies to assess infrastructure costs (De Briñas Gorosabel et al., 2022) until new empirical data will be available.

The economic unit cost per mile (LCC per mile) produced by a bus of size j and powered by technology i is calculated as the ratio between the Equivalent Annual Cost ($EAC_{i,j}$) and its annual mileage ($m_{i,k}$), where:

$$EAC_{i,j} = \frac{LCC_{i,j} \cdot r}{1-(1+r)^{-t}} \tag{4}$$

3.4 External costs

Policymakers usually support BEBs adoption driven by the need to reduce harmful emissions. In order to switch from the transport provider point of view to a social cost perspective, we include in our model the external costs related to different bus powertrains in the LCC model.

To this end, we leverage the estimates made by Holland et al. (2021) for city buses operating in the urban areas under study.

There are two main categories of negative externalities to consider over the life cycle of a city bus: Greenhouse Gas Emissions (GHGs), e.g. CO_2, N_2O and CH_4, which lead to global warming and climate change; and air pollutants, such as particles (PM_{10}, $PM_{2.5}$), nitrogen oxides (NOx), volatile organic compounds (VOCs), and sulfur dioxide (SO_2), which cause damages to human health, agricultural crops, biodiversity, and buildings. Holland et al. (2021) estimate marginal external costs generated by a variety of pollutants (i.e., CO_2, SO_2, NOx, $PM_{2.5}$, and VOCs) and then multiply their emissions rates by location-specific damage evaluations. For non-electric buses, the emissions rates come directly from the emissions tests (or from fuel economy, for CO_2 and SO_2). For electric buses, they calculate the hourly emissions related to electricity generation in U.S. power plants. This allows us to consider the marginal damage of emissions by taking into account harmful pollutants from both the tailpipe (i.e., tank-to-wheel stage) and the smokestack of the power plants providing energy to power the vehicle (i.e., well-to-tank stage). Holland et al. (2021) estimate the marginal damage linked to alternative bus powertrains in 329 U.S. cities as an external cost measured in terms of USD per mile, which can be easily integrated in our LCC model. Therefore, we define the life cycle social costs (LCSC) of a bus with power technology i and size j as follows:

$$LCSC_{i,j} = LCC_{i,j} + \sum_{k=1}^{t} \frac{C_{ext_{i,j,k}} \cdot m_{i,k}}{(1+r)^k} \tag{5}$$

where $C_{ext_{i,j,k}}$ [USD/mi] is the marginal external cost of a bus with power technology i and size j and other parameters are consistent with the previous LCC formula (1).

It is worth noting that, in addition to the emissions at the bus tailpipe and at the energy production stage, environmental impacts related to the cradle-to-grave life cycle of the vehicle components are increasingly important in LCA frameworks (Cooney et al., 2013). They include externalities produced from raw material extraction to recycling and disposal of the vehicle components (e.g., electric battery). In this context, BEBs also reduce noise pollution compared with ICE buses (Campello-Vicente et al., 2017).

No clear monetary evaluations are available for these LCA extensions at the moment, which represent interesting developments of the model for future studies.

4. Results

4.1 Cost parameters estimation in different scenarios

A key aim of the paper is to investigate the economic performances of different powertrain options in the real operational context of U.S. cities. To this end, an analysis of variance (ANOVA) is conducted to verify that the differences between the cost parameters considered in our LCC model are statistically significant according to different bus powertrains. This allows us to estimate reliable input parameters for the LCC analysis, Appendix A shows the numerical results of the ANOVA tests performed in this study.

Moreover, the proposed LCC model considers some key exogenous variables that depend on specific operational contexts, i.e., service speed, bus size, annual mileage, and external costs. These parameters are strictly connected with the human settlements of the urban areas, i.e., cities, towns, villages, or other agglomerations of buildings where people live and work. Features of the city (such as population density, urban sprawl, street design, etc.) significantly affect the transport system design and vice versa. For instance, the average bus speed is usually lower in big cities with a high level of congestion. It is important to note that the marginal cost of harmful emissions varies by location, basically higher is exposed population higher is the damaging impact (especially air pollutants such as particulate matter). In order to take into account these effects, we define three different scenarios: (i) towns with less than 300 thousand inhabitants, where the traffic moves smoothly, buses are smaller, and bus frequency is lower; (ii) cities with a population between 300 thousand and 5 million people, where congestion level is higher, buses are bigger, and transit services are more frequent; (iii) metropolises with more than 5 million inhabitants, characterized by very high traffic density and capillary bus supply. The service parameters used as input to the model are consistently defined by referencing the population of our sample's urbanized areas. Table 4 displays the average values of different scenarios.

As previously mentioned, the analysis is focused on the most used bus technologies in U.S., i.e., diesel, CNG, hybrid diesel, full electric with overnight charging.[4]

Full electric buses are still developing and significant improvements are expected regarding energy management (e.g., battery performances, power management, charging scheduling) and vehicle costs in the short-medium term. Consequently, we consider two other scenarios: one where the daily mileage of BEBs is extended and one that reduces the purchase cost of BEBs.

In the *BEB extended range scenario,* we suppose that the battery capacity and optimized bus shifts and charging timetables allow the BEB to reach the same productivity level as ICE buses in terms of annual mileage.

In the *BEB equivalent vehicle cost scenario,* along with an increase in mileage productivity of batteries, we assume that the acquisition cost of the electric bus is equal to that of conventional diesel plus the cost of the battery. Although it may seem too optimistic, while the electric motor requires more complex power electronics, it does not include automatic transmission and exhaust gas after-treatment systems (Kim et al.,

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[4] We focus on the most common electric bus technology in 2019, known as overnight charged BEB, where electric batteries are charged only during the operating pause in the bus depot. It needs a battery pack with high energy capacity (over 300 kWh) with an advertised range by the bus manufacturers of 150/200 miles on a single charge (Linscott and Posner, 2021).

2021). Consequently, supposing no cost differences in the vehicle body (i.e., without battery) is not unrealistic. Moreover, the electric bus price has shown a decreasing trend in the last decade due to economies of scale and supply chain development (see also Figure 1).

In this framework, we consider the possibility of accessing external public funding that the transport providers can use to renew their fleet and the related infrastructures. In the U.S., the Federal Transit Administration (FTA) provides grants to local public transit agencies that cover up to 80% of net capital project costs (namely, purchase costs and complementary equipment). However, in the Bipartisan Infrastructure Law (FTA, 2022), the federal share of eligible capital costs rises to 85% for low-carbon technologies (including CNG buses). Thus, we present LCC/LCSC simulations where the external funds reduce the investment costs by 85% from the perspective of transport providers for alternatively powered buses (i.e., CNG, hybrid, and full electric) and by 80% for diesel buses.[5]

Finally, it should be noted that the processed data refer to BEBs with overnight charging, so considering alternative options, i.e., opportunity and in-motion charging, implies some model changes. In particular, supporting infrastructures play a key role in the service production (Lajunen et al., 2018; Chen et al., 2018), in such cases the cost structure of full electric bus is more like that of a tramway than a conventional ICE vehicle (see Avenali et al., 2020). Table 4 summarizes key input parameters for the LCC/LCSC model in all proposed scenarios.

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[5] The Bipartisan Infrastructure Law includes two funding programs relating to transit bus investments (FTA, 2022): first the "*Modernizing Bus & Rail Fleets*", which aims to reduce average age of city buses regardless of the bus power technology (federal co-financing rate of 80%); and then the "*Low or No Vehicle Emissions Competitive Program*" in order to replacing transit vehicles with cleaner ones (federal co-financing rate of 85%). Note that CNG and hybrid vehicles are considered low emission vehicles.

Table 4. Summary of LCSC inputs parameters for a 2019 procurement

			Urban context	**DF**	**CNG**	**HEB**	**BEB base case scenario**	**BEB extended range**	**BEB equivalent vehicle cost**
Bus lifetime	t	[year]	*All*	14	14	14	14	14	14
Bus length	j	[foot]	*Town*	35	35	35	35	35	35
			City	40	40	40	40	40	40
			Metropolis	40	40	40	40	40	40
Service speed	s_k	[mi/ hour]	*Town*	14.22	14.22	14.22	14.22	14.22	14.22
			City	13.04	13.04	13.04	13.04	13.04	13.04
			Metropolis	11.61	11.61	11.61	11.61	11.61	11.61
Annual mileage	$m_{i,k}$	[mi]	*Town*	31,862	31,862	31,862	15,539	**31,862**	**31,862**
			City	37,401	37,401	37,401	18,241	**37,401**	**37,401**
			Metropolis	34,390	34,390	34,390	16,772	**34,390**	**34,390**
Purchase costs	$C_{pur_{i,j}}$	[USD]	*Town*	400,676	456,004	559,492	760,159	760,159	**465,676**
			City	457,916	521,148	639,420	868,753	868,753	**532,916**
			Metropolis	457,916	521,148	639,420	868,753	868,753	**532,916**
Running costs	$C_{run\ i,j,k}(s_k)$	[USD/ mi]	*Town*	0.48	0.32	0.43	0.16	0.16	0.16
			City	0.60	0.39	0.53	0.20	0.20	0.20
			Metropolis	0.67	0.44	0.60	0.23	0.23	0.23
Maintenance costs	$C_{mnt_{i,j,k}}$	[USD/ mi]	*Town*	1.09	1.30	1.10	1.06	1.06	1.06
			City	1.25	1.48	1.26	1.21	1.21	1.21
			Metropolis	1.25	1.48	1.26	1.21	1.21	1.21
Regular maintenance midlife costs	$C_{mid_{i,j,k}}$	[USD]	*Town*	30,000 k=7	30,000 k=7	30,000 k=7	65,000 k=7	65,000 k=7	65,000 k=7
			City	35,000 k=7	35,000 k=7	35,000 k=7	75,000 k=7	75,000 k=7	75,000 k=7
			Metropolis	35,000 k=7	35,000 k=7	35,000 k=7	75,000 k=7	75,000 k=7	75,000 k=7
Salvage value	$SV_{i,j,t}$	[USD]	*Town*	0 t=14	0 t=14	0 t=14	194,590 t=14	0 t=14	0 t=14
			City	0 t=14	0 t=14	0 t=14	222,189 t=14	0 t=14	0 t=14
			Metropolis	0 t=14	0 t=14	0 t=14	236,185 t=14	0 t=14	0 t=14
External costs	$C_{ext_{i,j,k}}$	[USD/ mi]	*Town*	0.126	0.112	0.105	0.110	0.110	0.110
			City	0.144	0.120	0.119	0.107	0.107	0.107
			Metropolis	0.201	0.141	0.167	0.113	0.113	0.113
Public funding scenario	*co-financing rate*	[%]	*All*	80%	85%	85%	85%	85%	85%

4.2 Outcomes of the unit cost analysis

In this section, we analyze cost-effectiveness of alternative bus technologies by focusing on economic unit cost (LCC per mile) and social unit cost (LCSC per mile) in different operational scenarios. For each of three urban contexts (town, city and metropolis) we study six different bus technology options (DF, CNG, HEB, BEB base case, BEB extended range, BEB equivalent vehicle cost) both with and without public funding opportunity.

Figure 4 displays the results of the cost analysis for urban buses in each defined scenario by focusing on economic and social unit cost per mile (USD/mi) of different power technologies. If public funding is not available, diesel buses reach the lowest unit cost per mile compared to CNG, hybrid and BEB in the base case scenario both including and excluding external costs. CNG buses reduce running expenses, but purchase and maintenance costs tip the scale in diesel favor. The same goes for hybrid vehicles, the improved efficiency in the service's provision does not balance the higher purchasing and maintenance costs. In the base case scenario, BEBs are currently facing heavy disadvantages from initial investments and limited range. However, the gap between conventional diesel and BEB in base case scenario significantly differs according to the various urban contexts. While BEBs (base case) result in an increase of the social unit costs up to 77% in town scenario (compared to 2.99 USD/mi of diesel option), this gap lowers up to 62/61% in big cities and metropolis scenarios, respectively. In town case, diesel buses take advantage from higher service speed and lower annual mileage that characterize transit services in small cities, as well as a smaller marginal impact of harmful emissions. When we assume that BEBs have the same mileage productivity as diesel buses, the unit cost per mile of BEBs significantly decease but still they do not reach the same level of efficiency as diesel. The economic and social unit cost gaps range between conventional diesel and BEBs (extended range) varies from 19% in metropolis to 29% in town scenarios. It is a different matter when we assume that, in addition to the same mileage productivity, BEBs have equivalent vehicle body costs as diesel buses. In fact, due to lower running and external costs, BEBs represent the most efficient technology in all urban contexts. The benefit in terms of social unit cost of BEBs (equivalent vehicle cost) compared to conventional diesel still change according to the different operational scenarios, respectively in town (-2.9%), cities (-6.0%), and metropolis (-7.8%) contexts. This is also applied when we do not consider external costs, showing how purchase expenses are currently the most influential cost component for BEBs. In this framework, it is worth noting that there are also significant differences in cost structure between ICE buses and BEBs (Figure 4). In the former case, much of LCC is linked to the operating expenses (running e maintenance costs exceed 10% and 40%, respectively), while in the latter case the most important component is the purchase cost (over 60% of the LCC are linked to acquisition expenses). In BEB base case scenario, the salvage value included in the model accounts for about 23% of the LCC, which depends on the mileage productivity of the electric bus.[6] This component does not affect other BEB scenarios since the electric bus has the same wear as conventional diesel, since it runs the same annual mileage. The impact of external costs appears limited due to the relatively higher other cost components (also stated by Sheth and Sarker, 2019), however there are meaningful differences between town, city and metropolis scenarios. External costs related to diesel buses in metropolitan areas are twice those in small cities.

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[6] The salvage value of BEB is realized only in the base case scenario, indeed the proposed model directly links the vehicle wear and tear to the annual mileage of the bus, which is assumed to be equal to that of conventional ICE buses in other BEB scenarios. This an evaluation based on standard vehicle productivity of transit buses over their useful life. However, the lack of reliable prediction about the second-hand market of new technologies is perceived as a financial risk by transport providers (Demeulenaere, 2019), also considering that purchasing BEBs means to invest in a technology that is still developing (Hensher, 2022).

Figure 4. Economic and social unit cost analysis (USD/mi) of alternative bus technologies in different scenarios (without public funding)

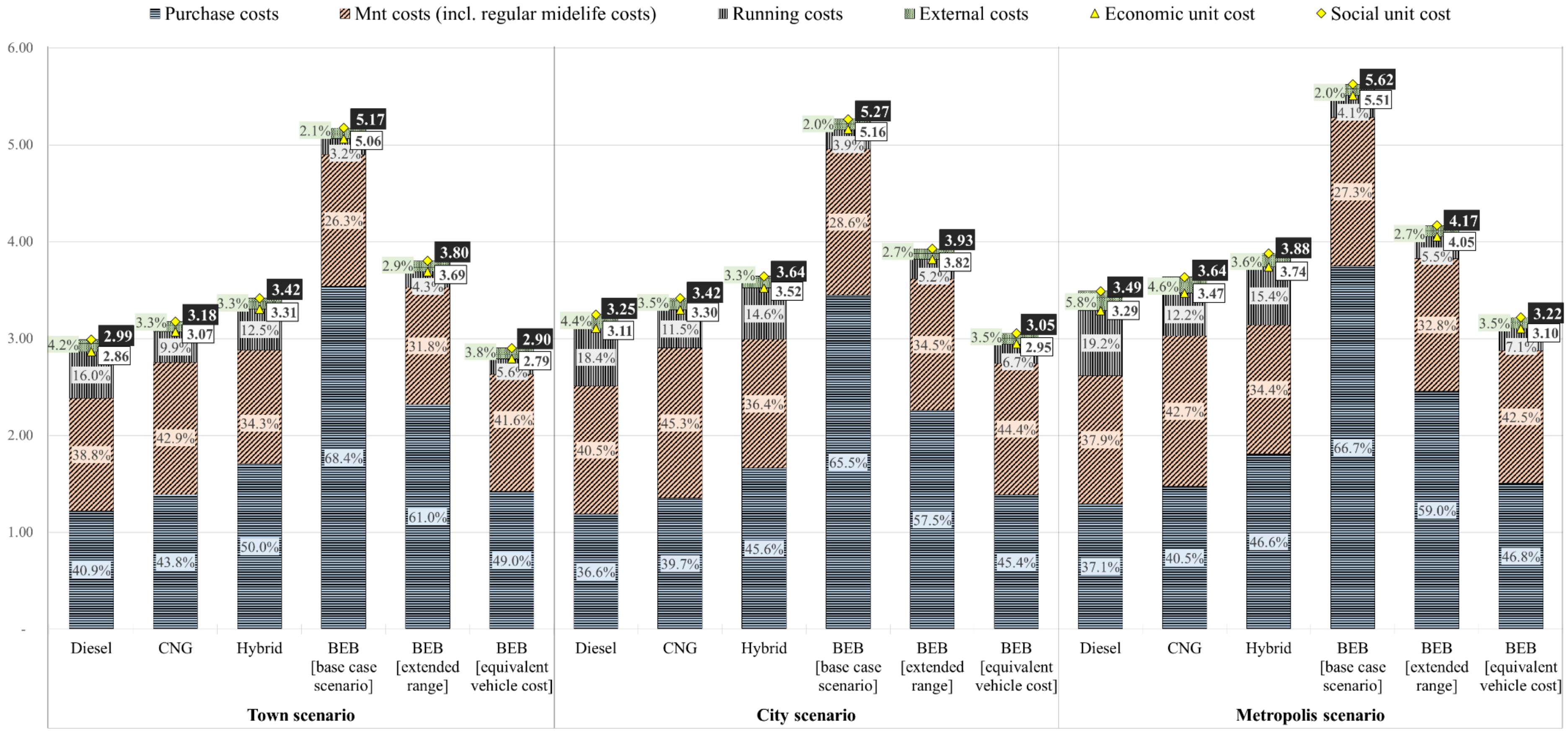


Figure 5. Economic and social unit cost analysis (USD/mi) of alternative bus technologies in different scenarios (with public funding)

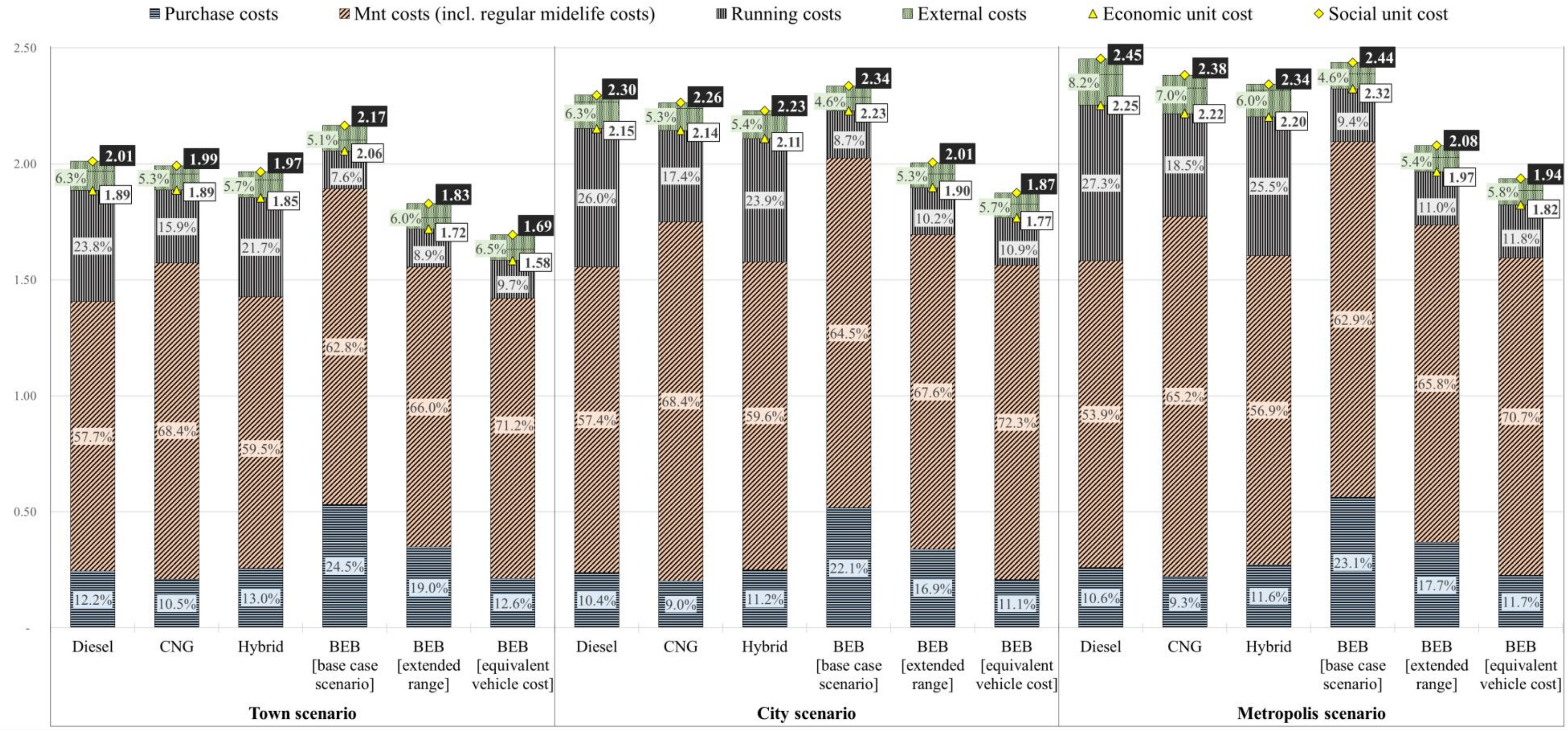


Figure 5 reports the results of the cost analysis when transport providers have access to public funds for bus fleet renewal projects. In this case, BEBs are cost-effective in all urban contexts when we assume the same mileage productivity or vehicle body costs as diesel buses. They leverage the lower operational costs (i.e., decrease in energy consumption and maintenance tasks), other than the reduced environmental impact.

In metropolitan context, BEBs are cost-effective even in the base case scenario, which explains why BEBs adoption in big cities has been increasing rapidly when public funds are available.

4.3 Sensitivity analysis on key input parameters

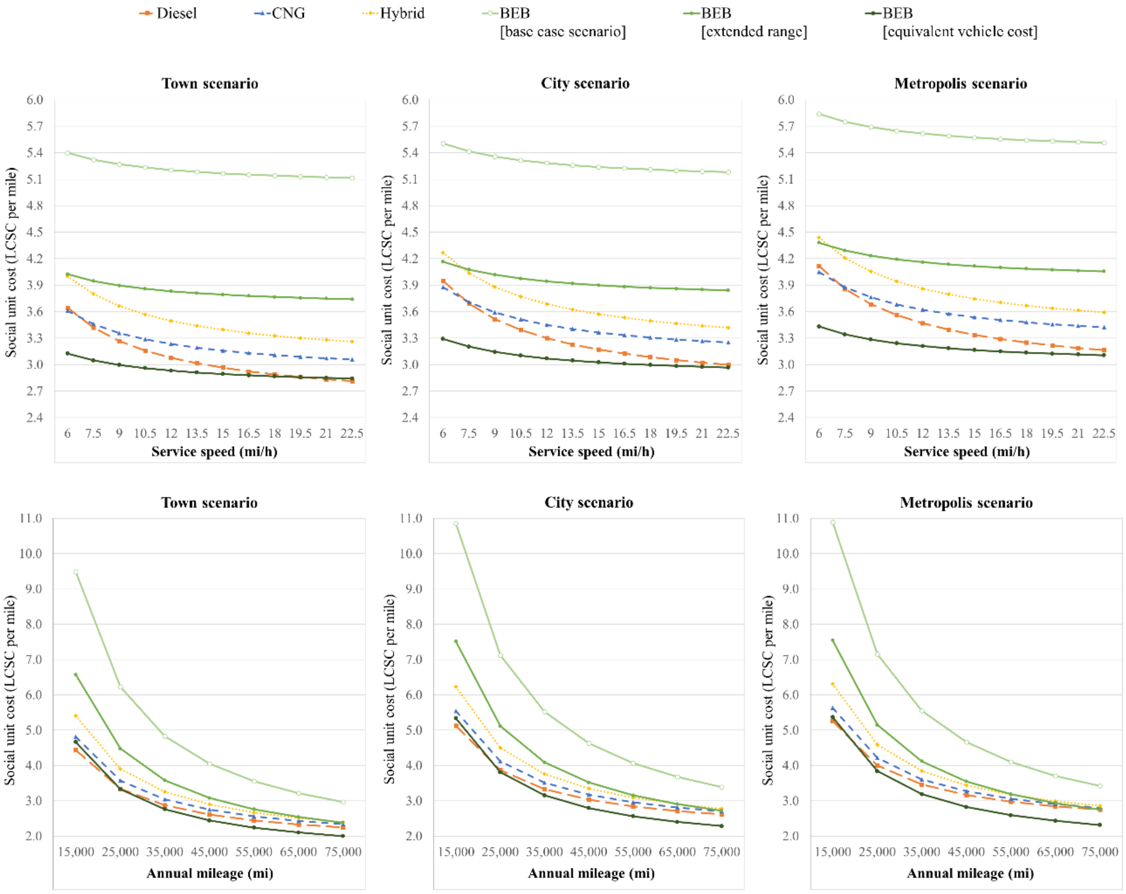
In this section, we perform a sensitivity analysis on key input parameters of the life cycle social cost model in order to identify the robustness of the results with respect to temporal and geographical changes. Indeed, the flexibility of the proposed model allows us to identify some operational contexts where BEBs would gain advantage from their higher efficiency in terms of running and maintenance costs.

Figure 6 displays a sensitivity analysis of the social cost per mile by focusing on key service parameters included in the model, i.e., service speed (Ss_k) and annual mileage ($m_{i,k}$). The results reveal that transit services with low service speed are the most suited to BEBs, and hence bus routes characterized by high levels of congestion linked to road crowding, a high number of bus stops, and dwell time at the bus stops (boarding and alighting of passengers).

In addition, the gap between the BEB base case and the BEB extended range shows that a higher share of short bus shifts (≤ 200 miles) is another enabling factor to large-scale deployment of full electric buses.[7] In this context, increasing the annual mileage productivity of the bus enhances the cost-effectiveness of BEBs compared to other power technologies (see also Comello et al., 2021; Topal and Nakir, 2018).

Low average speed, a high percentage of short bus shifts, and high mileage productivity are features that often characterize urban routes in large cities. So these latter represent the operational context more suitable for BEBs adoption from an economic point of view, and it becomes even more evident when we consider the marginal impact of harmful emissions.

Figure 6. Sensitivity analysis on service parameters



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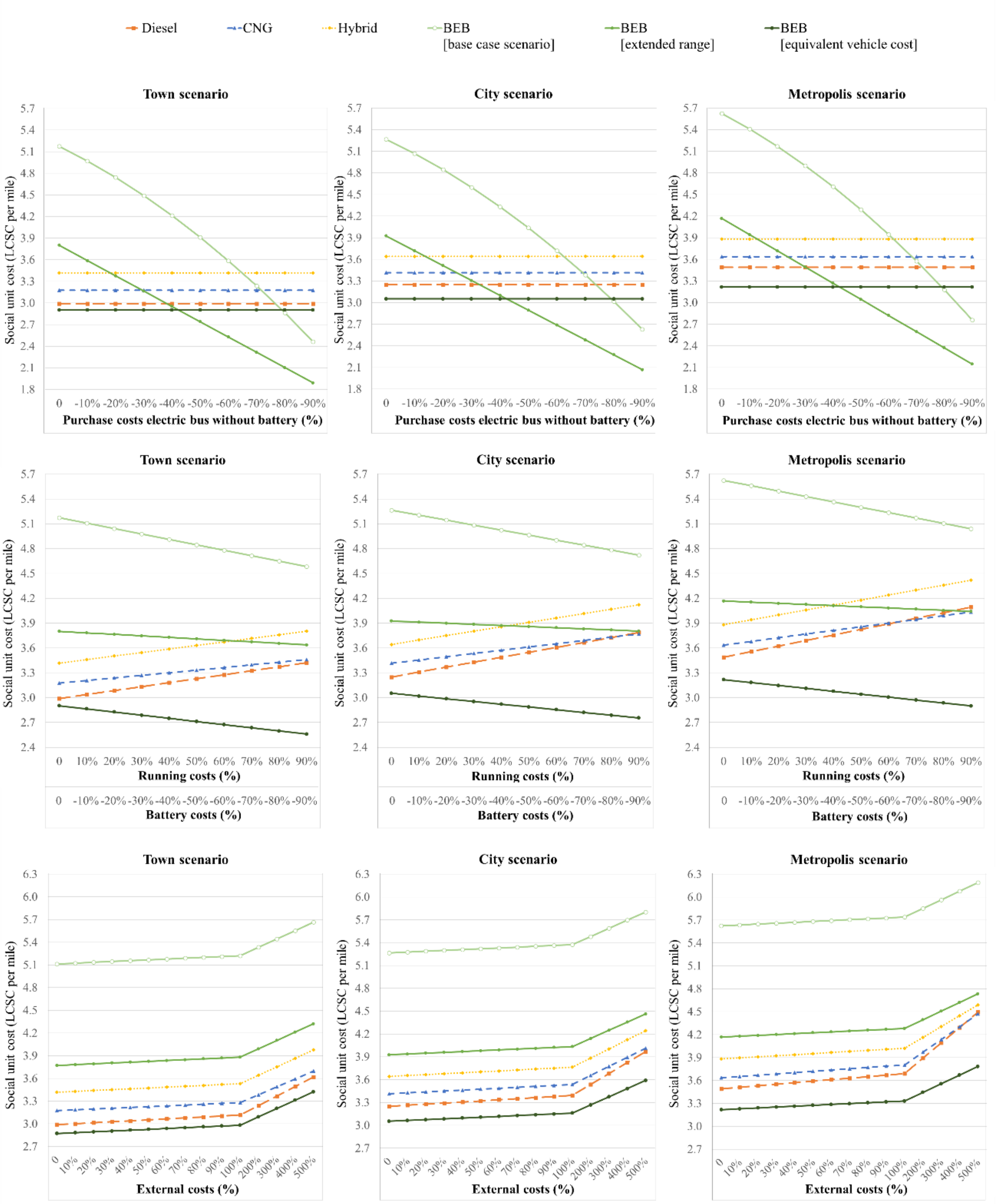
[7] Note that, theoretically, BEBs can produce around sixty thousand miles per year, i.e., 200 miles a day for 300 days per year (considering machine downtimes). To this end, it is crucial to implement service planning tools that optimize bus scheduling with respect to charging needs (Rodrigues and Seixas, 2022).

Figure 7 displays a sensitivity analysis of the social cost per mile by focusing on some key cost parameters that we would expect to change according to technological developments and other time trend effects.

Figure 7. Sensitivity analysis on key cost parameters



We investigate the impacts of four potential changes: decreasing purchase costs of BEBs body (without electric battery), decreasing battery costs, increasing fuel/energy prices (i.e., running costs), and increasing external costs (linked to a potential higher social cost of carbon in the future).

The plots confirm that the purchase cost is currently the most influencing variable that determines the higher cost of BEBs compared to conventional powertrains. It is affected by the vehicle body expenses (i.e., electric powertrain) and the electric battery costs.

In the first case, a decrease between -30% and -40% of BEB purchase costs (excluding the battery) allows to reach cost parity with diesel in all urban contexts (town, city, and metropolis). On the other hand, a decrease of electric battery costs does not significantly change the results, as well as an increase in fuel/energy prices. Indeed, even assuming a reduction of above 50% of the battery costs (which means less than 100 USD/kWh), the BEB is not cost-effective compared to the diesel counterpart.[8] The same applies if we consider higher fuel/energy costs, even doubling these latter, the rank of alternative power technology does not change. Finally, the sensitivity analysis remarks the limited impact of external costs compared to other components of the model, indeed even significant changes on the social cost of carbon (for instance, +300/400% compared to 43.5 USD per ton of CO_2 used by Holland et al., 2021) do not overturn the results. Therefore, we can conclude that the findings drawn in the main analysis are robust with respect to potential cost variations.

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[8] In the main analysis we consider a battery costs of 75,00 USD for an overnight BEB with a battery pack of around 300 kWh, which means about 250 USD/kWh (in line with 2019 prices, see Mauler et al., 2021).

5. Conclusions

In this paper, we define a life cycle social cost model for alternative bus powertrains in order to assess their economic and environmental performances in different urban contexts.

The cost variables are defined and estimated by referring to a sample of 256 transit agencies that directly provide bus services in U.S. cities. Furthermore, some exogenous characteristics of the service (e.g., service speed, annual mileage, and bus size), which significantly affect the efficiency of the transit service, are included in the analysis. The scenario analysis shows how the cost structure and marginal damage of alternative bus technologies impact their own economic competitiveness with respect to the urban context where the service is provided.

The findings obtained from the cost-effectiveness analysis determine the electric buses as the leading alternative to conventional diesel in congested urban areas, primarily due to higher energy efficiency and a reduction of the environmental impact. However, the results prove the need for public resources to enable the adoption of electric battery buses in these early years of technology deployment and development. Indeed, in real-world applications, cleaner bus alternatives are still more expensive than fuel-powered ones in terms of unit cost per mile. The main barriers to BEBs adoption are the high initial costs and the short operating range. However, if we take into account the expected technological and managerial developments for electric bus options, i.e., scale economies effects on purchase prices, longer range batteries, and improved optimization of timetable and charging scheduling, this latter is cost-effective even with no public incentives. Indeed, some studies have already developed optimization models that can support the choices transport providers make when deploying BEBs (e.g., Liu et al., 2022; Benoliel et al., 2021).

In this framework, large cities and metropolises, where urban bus routes are characterized by low average speed and high frequency (namely high mileage productivity), and the marginal damage of harmful emissions increases the external costs of transit services, represent the operational context most suitable for BEBs. In towns and suburban areas, conversely, where bus routes are longer and faster, full electric technology is still facing both economic and technical barriers. For these latter, alternative bus powertrains powered by biofuels and hydrogen fuel cells might be more competitive than electric traction.

Finally, the sensitivity analysis highlights how the purchase costs of BEBs are currently the most influential component in determining cost-effectiveness of transit services electrification. Indeed, the results are robust with respect to other cost parameters changes. In this context, it is important to remark that the scope of the present study does not include electric buses with opportunity or in-motion charging strategies. The infrastructure costs are not considered since we assume the availability of external funding. Moreover, it does not include the LCC analysis where fleets with different power technologies are compared. Therefore, including the expenses related to supporting infrastructures and evaluating cost-effectiveness of the whole fleet electrification represent an interesting development for future studies from an economic point of view. These upgrades related to electric technologies can be integrated within the proposed LCC model when sufficient empirical data are available, as well as for other alternative bus powertrains that are still in an early adoption stage, such as LNG (liquefied natural gas), renewable fuels, and fuel cell buses (i.e., hydrogen powertrains).

Appendix A

The statistical technique of one-way ANOVA is applied to detect the cost differences between alternative bus technologies by comparing the means of different samples. Table A.1 reports the results obtained for the cost parameters included in the LCC model.

Table A.1 Bus technology performances related to the main cost parameters of the LCC model

		DF	CNG	HEB	BEB
Purchase costs	*number purchase batches*	661	321	283	40
	C_{pur_i} [USD/foot]	11,448 $\pm$ 2,633	13,029 $\pm$ 2,520	15,985 $\pm$ 2,390	21,719 $\pm$ 3,233
	% change from diesel	-	+14%	+40%	+90%
Running costs	*number of agencies*	153	40	41	22
	$CH_{run_{i,k}}$ [USD/(hour·foot)]	0.1948 $\pm$ 0.0496	0.1283 $\pm$ 0.0533	0.1735 $\pm$ 0.0394	0.0665 $\pm$ 0.0476
	% change from diesel	-	-34%	-11%	-66%
Maintenance costs	*number of agencies*	153	40	41	22
	$C_{mnt_{i,k}}$ [USD/(mi·foot)]	0.0312 $\pm$ 0.0138	0.0370 $\pm$ 0.0142	0.0315 $\pm$ 0.0114	0.0303 $\pm$ 0.0085
	% change from diesel	-	18%	1%	-3%

Mean$\pm$ standard deviation

Table A.2 shows the outputs of the Test of Homogeneity of Variances and One-way ANOVA with respect to the differences in these cost variables between alternative bus options. Firstly, it is tested the null hypothesis of data homoscedasticity by Levene's test. The findings prove that the purchase costs of alternative powertrains (i.e., BEBs and HEBs) are significantly higher than those of ICE ones. On the other hand, the electric battery buses have the lowest running costs, followed by the CNG option, with a statistically significant difference on means. Variations in maintenance costs would appear to be not particularly evident when the cost of salaries and wages of maintainers is taken into account. However, the increase in maintenance costs linked to the CNG technology and the reduction connected with BEBs are confirmed.

Table A.2 ANOVA results when testing cost parameters differences between bus technologies

	Homogeneity of Variances		*One-way ANOVA*					
	Levene statistic	**Sig.**		**Sum of Squares**	**df**	**Mean Square**	**F**	**Sig.**
Purchase costs	1.813	**0.1428**	Between Groups	7,131,779,721	3	2,377,259,907	358.42	**0.0000**
			Within Groups	8,629,081,856	1,301	6,632,653		
			Total	15,760,861,578	1,304			
Running costs	0.985	**0.4004**	Between Groups	0.400	3	0.1330	56.43	**0.0000**
			Within Groups	0.595	252	0.0020	13.40	
			Total	0.995	255			
Maintenance costs	0.925	**0.4292**	Between Groups	0.001	3	0.0000	2.24	**0.0840**
			Within Groups	0.044	252	0.0000		
			Total	0.045	255			

The proposed LCC model aims to compare the alternative bus powertrains also on the basis of technical performances, mainly related to the operating range limits of electric battery buses. Even the latest BEBs have a significantly shorter range than other alternatives, which hardly exceeds 150/200 miles for overnight BEBs (currently the most used because of the lack of fast-charging infrastructures along the bus route). These constraints influence the scheduling of transport providers that use BEBs only on shorter bus shifts, reducing vehicle mileage productivity.

The NTD provides data on the annual mileage of different bus technologies for each transit agency. In Table A.3 the average annual mileage of BEBs is compared to that of ICE powertrains (i.e., diesel, CNG, and HEB). The results show relevant differences between alternative options in 2019.

Table A.3 Bus technology performances related to annual mileage and statistical results

			DF, CNG, HEB	**BEB**
Annual mileage	*number of active fleets*		2,926	46
	$mi_{i,k}$	[mi]	34,016 ± 12,147	16,590 ± 5,846
	% change		-	-51%

Mean± standard deviation

		Levene's Test for Equality of Variances		t-test for Equality of Means		
		F	**Sig.**	**t**	**df**	**Sig. (2-tailed)**
Annual mileage	Equal variances assumed	34.6048	0.0000	9.7110	2,970	0.0000
	Equal variances not assumed			**19.5646**	**51.3127**	**0.0000**

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