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Economic assessment of hybrid electric vehicles for sustainable transportation and decarbonization in Brazil

Laene Oliveira Soares [a,b], José Ricardo Sodré [c], Luis Hernández-Callejo [d], Paulo Sérgio Duque de Brito [e], Ronney Arismel Mancebo Boloy [a,b,e,*]

[a] Centro Federal de Educação Tecnológica Celso Suckow da Fonseca – CEFET/RJ, Maracanã 229, Rio de Janeiro, RJ, 20271-110, Brazil
[b] Group of Entrepreneurship, Energy, Environment and Technology – GEEMAT, Rio de Janeiro, RJ, 20271-204, Brazil
[c] College of Engineering and Physical Sciences, Aston University, Birmingham, B4 7ET, United Kingdom
[d] School of Engineering of the Forestry, Agronomy, and Bioenergy Industry, Universidad de Valladolid, Campus Duques de Soria, Soria, 42004, Spain
[e] Centro de Investigação para a Valorização Dos Recursos Endógenos – VALORIZA, Instituto Politécnico de Portalegre, Praça Do Município 11, Portalegre, 7300-111, Portugal

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ABSTRACT

The transportation sector is a significant contributor to global greenhouse gas emissions, demanding the adoption of low-carbon technologies. This study focuses on the economic assessment of two types of hybrid electric vehicles as taxis in Brazil, exploring their potential to ease electric vehicle adoption and contribute to decarbonizing the transportation sector. Environmental life cycle cost, net present value, and total cost of ownership were calculated for hybrid electric vehicles (HEVs) and plug-in hybrid electric vehicles (PHEVs), as taxis and private cars, fuelled by different fuels, in single-fuel and dual-fuel modes. It also compares the Brazilian scenario with Spain and the United Kingdom to examine their economic benefits, considering factors such as purchase costs, operating expenses, and government incentives. Results show that taxis outperform private cars in return on investment, with Spain performing best due to its lower discount rate. Brazil ranked between Spain and the United Kingdom in ELCC and TCO but was the least favourable in NPV. Overall, the research highlights that taxis are identified as a practical short-term alternative for introducing electric vehicles in Brazil, proving to be more economically favourable than private vehicles.

1. Introduction

Brazil, like many countries worldwide, faces the challenge of reducing its greenhouse gas emissions, particularly in the transportation sector, which accounts for a massive part of these emissions. Therefore, the adoption of electric vehicles has been identified as one of the main solutions to combat climate change and promote sustainable mobility. However, charging infrastructure and initial costs still present obstacles that hinder the widespread penetration of electric vehicles in the Brazilian market.

The central problem faced in transitioning towards electric mobility in Brazil lies in the need to overcome technological, economic, and structural barriers that impede the large-scale adoption of electric vehicles. Dependency on fossil fuels stays high and setting up a robust and accessible charging infrastructure is challenging, especially in a country as vast as Brazil. In this scenario, exploring the use of hybrid electric vehicles, combining readily available biofuels and the potential to produce other biofuels, appears as a promising strategy to accelerate the transition to sustainable mobility. The proposed solution in this study involves the adoption of hybrid electric vehicles (HEV) as taxis, making use of the existing infrastructure and experience with biofuels in Brazil, such as ethanol, which is widely used in the country.

Using HEV allows for combining an electric motor with an internal combustion engine and operating on biofuels it can helps reducing greenhouse gas emissions while using an already established refuelling network. Hybrid vehicles powered by biofuels were recently analysed, comparing their performance and life cycle with other electric vehicle technologies, such as battery electric vehicles and plug-in hybrid electric vehicles (PHEV), showing their key role in progressive and less aggressive decarbonization from a market point of view [1–3]. Soares et al. (2022b) compared the emissions of distinct types of electric vehicles powered by fossil fuel and biofuels and concluded that the hybrids in

* Corresponding author. Centro Federal de Educação Tecnológica Celso Suckow da Fonseca – CEFET/RJ, Maracanã 229, Rio de Janeiro, RJ, 20271-110, Brazil.
E-mail address: ronney.boloy@cefet-rj.br (R.A. Mancebo Boloy).

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dual-fuel mode are the most appropriated choice for the Brazilian scenario, when considering infrastructure and bioethanol availability. Furthermore, the use of biofuels, such as ethanol, contributes to reducing the shortage of fossil fuels by up to 65% by using gasoline mixed with 85% ethanol (E85), in flex-fuel engines, compared to pure gasoline [1].

Therefore, HEVs can be an alternative to accelerate the decarbonization of the country without increasing the demand for materials necessary to produce powerful batteries, as those ones used in purely electric vehicles, and causing a shortage in the supply chain. As Brazil can produce biofuels from biomass, it is fair to take advantage of this potential, initially, until electric vehicles reach affordable market prices and other types of batteries are developed with more abundant materials.

The use of the dual-fuel mode, combining two fuels, was also discussed as a strategy to accelerate the decarbonization of the transport sector. This is due to the possibility of replacing a percentage of the most polluting fuel with another less polluting fuel. In this alternative technology, the pilot fuel (liquid) is injected directly into the combustion chamber, while the primary fuel (gaseous) is injected together with atmospheric air. The studies published were focused on using the dual-fuel mode in the compression-ignition engines in conventional vehicles, combining diesel with biogas and/or natural gas, or diesel with hydrogen [4–6]. However, this mode was also applied to spark-ignition engines, i.e., combining gasoline with hydrogen [7]. On the other hand, the use of dual-fuel mode in electric vehicles was less analysed, with some studies found using bioethanol or fossil fuels with biogas in different proportions [3,8,9].

The economic assessment through the calculation of the total cost of ownership (TCO) was carried out to investigate the competitiveness of electric vehicles compared to conventional vehicles. Depending on the vehicle category, the high acquisition cost of battery electric vehicles is offset by low operating and maintenance costs, resulting in a lower TCO compared to conventional and hybrid vehicles. Furthermore, the presence of incentives for buying electric vehicles becomes a key factor in reducing TCO [10]. Furthermore, the TCO of battery electric vehicles tends to reduce significantly by 2040, while conventional vehicles show a continuous increase, meaning yet another disadvantage to conventional vehicles [11]. On the other hand, it was found that the price and temperature of the battery significantly affects the net present value (NPV), due to the need to replace this component more often [12].

Despite the growing interest in hybrids and biofuels, there is a gap in the literature about a detailed economic assessment of this approach in the Brazilian context, as well as a comparison with experiences in other countries, such as the United Kingdom and Spain, which could be applied in Brazil. This gap hinders a comprehensive understanding of the economic and environmental benefits of this strategy, including issues related to acquisition costs, maintenance, energy efficiency, biofuel availability, and government incentives. By filling this gap, this paper aims to analyse the economic feasibility of HEVs and PHEVs as taxis in Brazil, in single-fuel and dual-fuel modes, fuelled with different fuels, exploring their potential to ease electric vehicle adoption and contribute to decarbonizing the transportation sector. Also, British, and Spanish economic scenarios were considered to supply crucial insights to guide Brazilian public policies and business practices in the transportation sector, accelerating the transition to more sustainable mobility in Brazil and beyond.

Thus, this paper is divided into three other sections. Section 2 shows the vehicles chosen to be used as a taxi, considering two types of hybrid electric vehicles, and describes in detail the method used to calculate the economic viability of the Brazilian, British, and Spanish scenarios. In Section 3, the results found for each calculated economic indicator are shown and discussed. Finally, Section 4 brings the conclusions and final considerations.

2. Methodology

In this paper, a PHEV model, which is available in all countries analysed - Brazil, United Kingdom, and Spain - and similar models of HEV were chosen, because the same HEV was not available for all countries. The HEV and PHEV models chosen are shown in Tables 1 and 2, respectively. For PHEVs, a fuel consumption of 4.4 L/100 km (≈22.7 km/L or 53.4 mpg) was considered, consistent with real-world data for private plug-in hybrids reported by the ICCT/Fraunhofer ISI [13]. This value falls within the 22.72–25 km/L range commonly observed under real driving conditions. Although this value represents an averaged estimate under combined operation modes, it does not correspond directly to manufacturer test-cycle data. Instead, it reflects realistic consumption values observed in European fleet studies for plug-in hybrid vehicles. Therefore, the adopted figure may differ slightly from official specifications depending on user charging frequency and driving profile.

Electricity costs for PHEVs were explicitly included in the analysis. Country-specific residential electricity prices were converted into vehicle-level electricity costs expressed in USD per kilometre, based on the electric energy consumption of the PHEV. Average electricity prices of 34 pence/kWh in the United Kingdom, 0.307 €/kWh in Spain, and 1.105 R$/kWh in Brazil resulted in electricity costs of 0.0832 USD/km, 0.0631 USD/km, and 0.0382 USD/km, respectively. Annual electricity expenditure was then estimated by applying a proportional electric driving share – defined as the ratio between electric range and total driving range – to an assumed annual mileage of 15,000 km. Although a combined real-world fuel consumption value was adopted for PHEVs, electricity and fuel costs were allocated separately for economic calculations, ensuring consistency with the overall combined energy performance.

Different fuels were analysed, considering their availability in the selected countries, such as E5 gasoline (5% ethanol), E10 gasoline (10% ethanol), E27 gasoline (27% ethanol), sugarcane bioethanol, and biogas from vinasse. The first two are available in Europe, and E27 gasoline and sugarcane bioethanol are available in Brazil. As Brazilian gasoline is less polluting than the others analysed, it was not necessary to propose the use of E5 and E10 gasoline in Brazil. In addition, biogas from vinasse, composed of 70% CH_4 and 30% CO_2, was used as a suggestion for the transport sector, since Brazil is a major producer of sugarcane, generating molasses waste from its use in bioethanol production. However, biogas from another biomass can be used.

The analysis was made considering single-fuel and dual-fuel modes. In the single-fuel mode, all fuels previously described were analysed. In the dual-fuel mode, the following blend were examined: 50% E5 gasoline plus 50% biogas, 50% E10 gasoline plus 50% biogas, 50% E27 gasoline plus 50% biogas, 50% bioethanol plus 50% biogas, and 20% bioethanol plus 80% biogas.

The economic feasibility was conducted through analysis of three indicators, such as environmental life cycle costing (ELCC), NPV, and TCO, which are detailed described in the next subsections.

2.1. Environmental life cycle costing

ELCC is in line with ISO 14040 and 14,044 standards used in life cycle analysis and considers all costs associated with the life cycle of a product or process. In addition, this indicator helps to find critical points in relation to costs and environmental impacts, supporting the life cycle analysis [14]. Therefore, ELCC aims to evaluate all life cycle costs directly associated with a given product or process, involving internal expenses, such as capital cost, operating costs, and technology replacement costs, plus external costs and benefits expected to be internalized, such as CO_2 emission taxes. With these parameters, it is possible to obtain the ELCC, in USD/km, according to Eqs. (1)–(3) adapted from Refs. [15,16].

In this formulation, the capital cost (C_{cap}) is considered an upfront investment that occurs at the beginning of the project (year 0); there-

Table 1
HEV specifications for British, Spanish, and Brazilian scenarios.

			
Country	United Kingdom	Spain	Brazil
Purchase Price (USD)[a, b]	38,476	26,925	37,662
Brand	Toyota	Toyota	Toyota
Model	Corolla Hybrid Hatchback	Corolla Hybrid Business Hatchback	Corolla Altis Hybrid
Category	1.8	1.8	1.8
Fuel	E10/E5	E10/E5	E27
ICE Power (kW)	72	72	73
Consumption (km/l)	22.69	20.41	15.40
Range (km)	976	878	662
Flex-fuel engine	No	No	Yes - Ethanol
ICE Power (kW)	-	-	75
Consumption (km/l)	-	-	11.15
Range (km)	-	-	479
Motor power (kW)	70	70	54
Combined power (kW)	103	104	91
Battery Capacity (Ah)	4.08	4.08	1.30
Battery	Li-ion	Li-ion	Li-ion
CO_2 Emission (gCO_2/km)	111	111	84
Tank (l)	43	43	43
Weight (kg)	1345	1345	1440

[a] Purchase prices calculated through conversion factor given by Central Brank of Brazil (in Portuguese, Banco Central do Brasil - BCB), in October 2023.
[b] Incentives for each country were considered.

Table 2
PHEV specifications for British, Spanish, and Brazilian scenarios.

Country	United Kingdom	Spain	Brazil
Purchase Price (USD)[a, b]	76,450	59,410	83,226
Brand	Volvo	Volvo	Volvo
Model	XC60 T8 Recharge	XC60 T8 Recharge	XC60 T8 Recharge
Category	2.0	2.0	2.0
Fuel	E10/E5	E10/E5	E27
ICE Power (kW)	228	228	236
Consumption (km/l)	22.72	22.72	22.72
Range (km)	1613	1613	1590
Flex-fuel engine	No	No	No
Motor power (kW)	107	107	107
Combined power (kW)	339	339	345
Battery Capacity (Ah)	14.70	14.70	14.70
Battery	Li-ion	Li-ion	Li-ion
CO_2 Emission (gCO_2/km)	23	22	22
Tank (l)	71	71	70
Weight (kg)	2170	2170	2170

[a] Purchase prices calculated through conversion factor given by Central Brank of Brazil (in Portuguese, Banco Central do Brasil - BCB), in October 2023.
[b] Incentives for each country were considered.

fore, it is recorded at its full value rather than being discounted. The discount rate is applied only to operating and replacement costs, which occur throughout the vehicle's lifetime and are affected by the time value of money. This approach allows a consistent comparison of future expenditures while recognising that the initial purchase is an immediate cash outflow rather than a deferred cost. Moreover, Eq. (4) was elaborated to calculate the electricity consumption by the PHEV and, through Eqs. (5) and (6), the CO_2 emissions from fuel consumption in the engine in single-fuel and dual-fuel modes can be measured, respectively.

$$ELCC = C_{cap} + \left(C_{op} + C_{rep}\right) \times \left(1 + d_{rate}\right)^{-j} \tag{1}$$

$$C_{op} = C_m + C_{fuel} + \left(C_{periodic} \times n_{rev}\right) + C_{CO2} + C_{el} \tag{2}$$

$$C_{CO2} = E_{CO2} \times P_{CO2} \tag{3}$$

$$C_{el.per\ km} = \frac{C_{el.per\ kWh} \times Battery_{cap}}{AE_{range}} \tag{4}$$

$$E_{CO2,single-fuel} = \left(\frac{\dot{m}_{fuel} \times f_{fuel}}{v}\right) \tag{5}$$

$$E_{CO2,dual-fuel} = \frac{y\left(\dot{m}_{fuel.pi} \times f_{fuel.pi}\right) + z\left(\dot{m}_{fuel.pri} \times f_{fuel.pri}\right)}{v} \tag{6}$$

where, C_{cap} is the capital cost, in USD/km, calculated through the division of the vehicle acquisition value by the annual travelled distance; C_{op} is the operating cost, in USD/km; C_{rep} is the battery replacement cost, in USD/km, assumed as 10% of the vehicle acquisition value [17]; d_{rate} is the discount rate; j is the vehicle lifetime, in years; C_m is the maintenance cost, in USD/km, including insurance and taxes; C_{fuel} is the fuel cost, in USD/km; $C_{periodic}$ is the costs regarding periodic revisions, in USD/km; n_{rev} is the number of periodic revisions needed annually; C_{CO2} is the carbon footprint cost, in USD/km; $C_{el.per\ km}$ is the electricity cost, in USD/km; $C_{el.per\ kWh}$ is the electricity cost, in USD/kWh; $Battery_{cap}$ is the battery capacity, in kWh; AE_{range} is the all-electric range, in km; $E_{CO2,single-fuel}$ is the CO2 emission while the engine is powered in single-fuel mode, in kgCO2/km; $E_{CO2,dual-fuel}$ is the CO2 emission while the engine is powered in dual-fuel mode, in kgCO2/km, with y and z being the proportion of liquid and gaseous fuel, respectively; P_{CO2} is the carbon market pricing, in USD/kgCO2, assumed as USD 6 per each ton of CO2 (International Monetary Fund – IMF); $\dot{m}_{fuel}$ is the fuel mass flow, in kg/h, which can be calculated through Eq. (7), for single-fuel mode, and Eqs. (8) and (9), for dual-fuel mode, adapted from Soares et al. (2021); f_{fuel} fuel emission factor, in kgCO2eq/kg fuel; v maximum speed accepted in urban roads, in km/h, assumed as 80 km/h (Brazilian Traffic Code, in Portuguese, Código de Trânsito Brasileiro – CTB). The energy required by the internal combustion engine was calculated using Eq. (10).

$$\dot{m}_{fuel} = \frac{P \times 3600}{BTE \times LHV} \tag{7}$$

$$\dot{m}_{fuel.pri} = \frac{z \times P \times 3600}{BTE_{dual-fuel}\left[(1-z) \times LHV_{fuel.pi} + z \times LHV_{fuel.pri}\right]} \tag{8}$$

$$\dot{m}_{fuel.pi} = \frac{\frac{P}{BTE_{dual-fuel}} - \left(\frac{\dot{m}_{fuel.pri}}{3600} \times LHV_{fuel.pri}\right)}{LHV_{fuel.pi}} \times 3600 \tag{9}$$

$$E_{consump} = \frac{LHV_{manuf} \times \rho_{manuf}}{1000 \times FC_{manuf}} \tag{10}$$

where, P is the engine power, in kW; BTE is the brake thermal efficiency when the engine is on single-fuel mode; LHV is the low heating value, in kJ/kg; $\dot{m}_{fuel.pri}$ is the primary fuel (gaseous) mass flow, in kg/h; $\dot{m}_{fuel.pi}$ is the pilot fuel (liquid) mass flow, in kg/h; $BTE_{dual-fuel}$ is the brake thermal efficiency when the engine is on dual-fuel mode; $LHV_{fuel.pi}$ is the low heating value of the pilot fuel, in kJ/kg; $LHV_{fuel.pri}$ is the low heating value of the primary fuel, in kJ/kg; $E_{consump}$ is the energy consumption in the internal combustion engine, in MJ/km; LHV_{manuf}, ρ_{manuf}, and FC_{manuf} are the low heating value, density and consumption of the fuel given by the manufacturer as the standard fuel, in MJ/kg, kg/m^3, and km/l, respectively.

2.2. Net present value

The calculation of the net present value (NPV) is applied when it is necessary to compare the cost in different periods and is composed by the initial cost, the sum of the cash flows, including inflows and outflows, and the return-on-investment rate, as shown in Eq. 10–12, adapted from Ref. [18]. If the NPV is positive, then the project is accepted as it has a value greater than the initial cost of the project.

$$NPV = -C_i + \sum_{t=1}^{n} \frac{Cash_{total,t}}{(1+d_{rate})^t} \tag{10}$$

$$Cash_{total} = Cash_{inflow} - Cash_{outflow} \tag{11}$$

$$Cash_{outflow} = C_{fuel} + C_m + C_{rep} + (C_{periodic} \times n_{rev}) + C_{el} \tag{12}$$

Where, C_i is the initial cost, in USD, assumed as the vehicle acquisition cost; t is the year of investment; n is the vehicle lifetime, in years; $Cash_{inflow}$ is the incomes through taxi activities, in USD; $Cash_{outflow}$ is the costs regarding to fuel and electricity consumptions, maintenance, battery replacement, and periodic revisions.

2.3. Total cost of ownership

The TCO is a method to calculate the costs over the vehicle useful life, considering its purchase value and costs associated with operation and maintenance, such as fuel consumption, periodic revisions, and replacement of components. Therefore, TCO can be measured by Eq. (13), adapted from [19], where D_{Year} is the total travelled distance, in km. The specific parameters adopted for maintenance and battery replacement costs are detailed in the following subsection, where these variables are defined and applied consistently across all scenarios.

$$TCO = \frac{Cash_{outflow} + C_{cap}}{D_{Year}} \tag{13}$$

2.4. Parameters and considerations adopted

Taxi activities in United Kingdom, Spain, and Brazil, specifically in the cities of Birmingham, Soria, and Rio de Janeiro, respectively, were considered to calculate the taxi incomes, assuming a daily travelled distance of 300 km [20], 252 days per year, totalizing 75,600 km per year, while private cars travel up to 15,000 km annually.

The adopted consumption data correspond to combined-cycle values that already integrate both electric and fuel use according to standardised test procedures. Since the focus of this study is on economic viability rather than detailed operational modelling, regional variations in utility factors – representing the share of electric driving – were not modelled separately. Nonetheless, these effects are implicitly captured in the combined data used consistently for all countries.

The value of periodic revisions was provided by Toyota Brazil and Volvo Brazil. For the United Kingdom and Spain, maintenance costs were estimated based on Brazilian manufacturer data due to limited public availability of such information. This approximation ensures consistency but is recognised as a limitation of the study. According to the manufacturers, taxi activities are considered as severe conditions, suggesting the drivers to make periodic revisions for each 5,000 km travelled; thus, in this study, it was adopted that taxis need to conduct approximately fifteen periodic inspections annually. Unlike taxis, private cars need to conduct one periodic revision annually, or once each 10,000 km, according to the manufactures.

Regarding battery lifetime, assumed as 100,000 km [17], corresponding to 1.3 years of taxi activity. This value was used to determine the timing of battery replacement cost, each representing 10% of the vehicle purchase price [17]. Moreover, the vehicle lifetime will be kept as a private vehicle, which normally can reach 10 years of useful life. This is because every time the battery is changed, the vehicle lifetime is considered maintained, considering only the depreciation of the mechanical parts, which can be minimized as the automotive revisions are conducted periodically.

The discount rates considered were those provided by the Bank of England (BoE), European Central Bank (ECB) and Central Bank of Brazil (BCB). Central bank discount rates were adopted as proxies for the minimum attractive rate of return. This approach ensures comparability across countries and avoids firm-specific distortions introduced by private financing conditions. Also, taxes and incentive policies for electric vehicles, petrol price, and electricity price of each country were considered, therefore, British, Spanish, and Brazilian scenarios, respectively, could be evaluated (Tables 3–5).

Table 6 shows the average prices for different fuels analysed. Bioethanol price in the Brazilian scenario was considered, as it is the only

Table 3
Taxes and incentives adopted for the British scenario.

Taxes	Values	References
Ministry of Transport (MOT) test	USD 70.42	DVSA[e]
Insurance[a]	USD 582.85	GoCompare[f]
First time registered tax – HEV[b]	USD 269.60	DVLA[g]
First time registered tax – HEV[c]	USD 256.76	DVLA
First time registered tax – PHEV[b]	USD 10.00	DVLA
Second tax payment[d]	USD 218.27	DVLA
Incentive Policy	Values	References
Discount on electric vehicles priced under USD 41,000.00.	USD 1926.00	Department for Transport

[a] Average value.
[b] For E5, E10, E27, in single-fuel and dual-fuel modes.
[c] For bioethanol and biogas, in single-fuel and dual-fuel modes.
[d] For HEV and PHEV.
[e] Driver and Vehicle Standards Agency.
[f] British company used to compare financial services, available at www.gocompare.com.
[g] Driver and Vehicle Licensing Agency.

Table 4
Taxes and incentives adopted for the Spanish scenario.

Taxes	Values	References
Special tax on certain means of transport (IEDMT[a])	5% of the purchase price	Junta de Catilla y León
Insurance[b]	USD 438.44	[d][21]
Incentive Policy	Values	References
Purchase incentives on PHEV acquisition	USD 2700 - 5,500[c]	[21]

[a] In Spanish: Impuesto Especial sobre Determinados Medios de Transporte.
[b] Average value.
[c] Adopted the minimum value.
[d] European Automobile Manufacturers' Association.

Table 5
Taxes and incentives adopted for the Brazilian scenario.

Taxes	Values	References
Motor-vehicle ownership tax (IPVA[a])	1.5% of the purchase price	DETRAN[c]
Annual vehicle inspection	USD 51.23	Calculated by the authors.
Annual licensing fee	USD 37.55	DETRAN
Insurance	4% of the purchase price	Average value adopted.
First license – New vehicles	USD 37.55	DETRAN
First time registered tax	USD 44.92	DETRAN
Vehicle characteristic change[b]	USD 37.55	DETRAN
Incentive Policy		
Not found.		

[a] In Portuguese: Imposto sobre Propriedade de Veículos Automotores.
[b] For the use of biogas, both single-fuel and dual-fuel modes.
[c] Department of Traffic of the State of Rio de Janeiro.

Table 6
Average fuel and electricity prices adopted for each scenario.

Fuel Prices	Values	References	Scenario
E27 gasoline	1.174 USD/litter	ANP (2023)[b]	Brazil
E10 gasoline	1.900 USD/litter	Tolls.Eu[c]	United Kingdom and Spain
E5 gasoline	1.798 USD/litter	Tolls.Eu	United Kingdom and Spain
Bioethanol	0.988 USD/litter	ANP (2023)	Brazil
Natural gas[a]	1.039 USD/m[c]	ANP (2023)	Brazil
Electricity price	0.247 USD/kWh	EuroStat[d]	Spain
Electricity price	0.421 USD/kWh	EnergyGuide[e]	United Kingdom
Electricity price	0,226 USD/kWh	ANEEL (2023)[f]	Brazil

[a] Adopted as base price for biogas.
[b] National Agency for Petroleum, Natural Gas and Biofuels (data provided by worksheets through MS Excel for October 2023).
[c] Overview of fuel prices in Europe, available at www.tolls.eu.
[d] Statistical office of the European Union, available at www.ec.europa.eu.
[e] British organisation, available at www.energyguide.org.uk.
[f] National Electricity Agency (data provided by worksheets through MS Excel for October 2023).

country which uses bioethanol to power engines, as well as natural gas prices, which were used as the base price for biogas. The pollution factors were calculated following the method applied by Soares et al. (2022a). The costs associated to natural gas tank in all scenarios considered legislation and taxes from Brazilian scenario as base case, as Brazil is the only country which uses this component between the countries analysed in this paper. Table 7 shows other parameters used in this work.

Table 7
Other parameters adopted in this work.

Parameters	Values	Units	References
Carbon market pricing	6	USD/tonne CO_2	IMF[b]
Periodic revision – HEV	174.06	USD	Toyota – Brazil[c]
Periodic revision – PHEV	450.08	USD	Volvo – Brazil[c]
Pollution factor – E5	3.006	$kgCO_{2eq}$/kg fuel	Calculated by the authors.
Pollution factor – E10	2.941	$kgCO_{2eq}$/kg fuel	Calculated by the authors.
Pollution factor – E27	2.722	$kgCO_{2eq}$/kg fuel	Calculated by the authors.
Pollution factor – Bioethanol	1.783	$kgCO_{2eq}$/kg fuel	Calculated by the authors.
Pollution factor – Biogas	1.754	$kgCO_{2eq}$/kg fuel	Calculated by the authors.
Average Speed	80	km/h	Brazilian Traffic Code
Brake thermal efficiency – Gasoline	23	%	[22]
Brake thermal efficiency – Bioethanol	25	%	[22]
Brake thermal efficiency – Biogas	23	%	[22]
Brake thermal efficiency – Dual-fuel	36	%	[23]
Low heating value – E5[a]	42,750	kJ/kg	Calculated by the authors.
Low heating value – E10[a]	41,986	kJ/kg	Calculated by the authors.
Low heating value – E27	39,330	kJ/kg	[24]
Low heating value – Bioethanol	26,359	kJ/kg	[24]
Low heating value – Biogas	36,819	kJ/kg	[24]
Discount rate – United Kingdom	4.25	%	Bank of England
Discount rate – Spain	3.24	%	Europe Central Bank
Discount rate – Brazil	13.75	%	Central Bank of Brazil
Taxi activity – United Kingdom	1.44	USD/km	Birmingham[d]
Taxi activity – Spain	1.53	USD/km	Rio de Janeiro[d]
Taxi activity – Brazil	1.34	USD/km	Sória[d]

[a] Calculation considered the percentage of pure gasoline plus the percentage of ethanol.
[b] International Monetary Fund.
[c] Information provided by the manufacturer's manual.
[d] Average value for taxi activities in the city, in October 2023, according to taxi companies and city hall.

3. Results and discussion

In this section, the results found for ELCC, NPV and TCO are presented, along with considerations on the implementation of the flex-fuel engine in the British and Spanish scenarios, dual-fuel mode, and battery replacement, highlighting the advantages and suggestions for the taxi activity.

3.1. Environmental life cycle costing

The ELCC analysis, as outlined in Section 2.1, was applied to assess all costs associated with the life cycle of hybrid vehicles, in accordance with ISO 14040 and 14,044 standards. This indicator, which considers both internal and external costs, such as CO_2 emission taxes, is designed to identify critical points in terms of costs and environmental impacts. It is emphasised that the methodology employed is robust and can be replicated across different scenarios and conditions described in Section 2.4, such as lifespan, mileage, and discount rates, thus ensuring its applicability in various contexts.

When analysing the ELCC per distance travelled, the HEVs and PHEVs as taxis presented lower values than the electric vehicles as private cars (Fig. 1). The lowest values were found for the Spanish scenario due to its discount rate, which is 76.4% and 23.8% lower than Brazilian

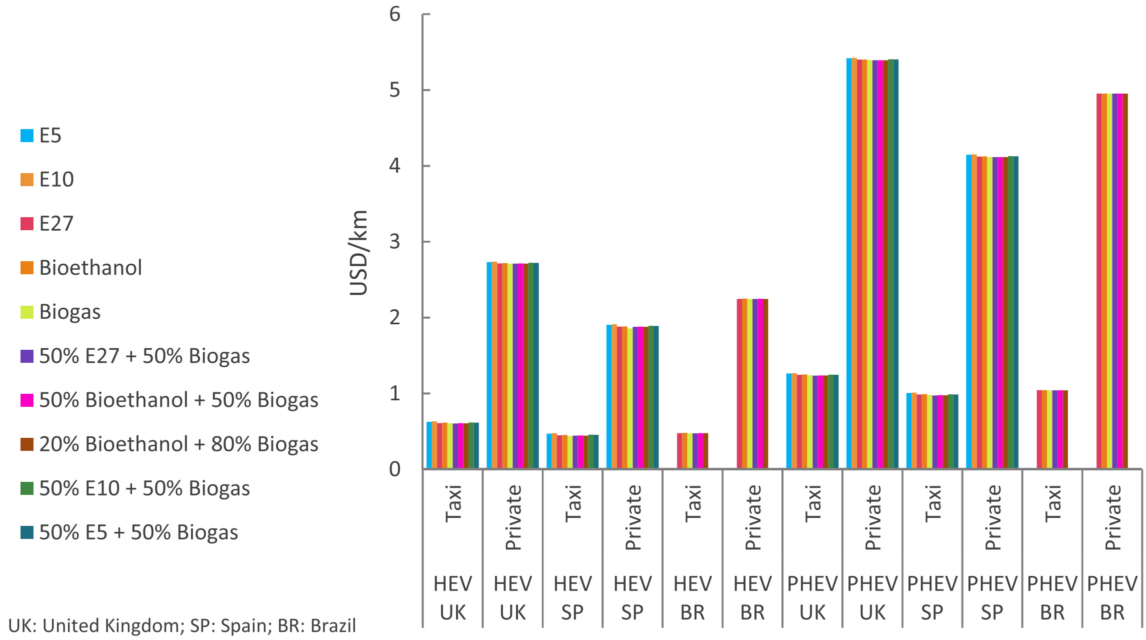

Fig. 1. Environmental life cycle costing of the HEVs and PHEVs, as taxi and private car, fuelled with different fuels.

and British discount rates, respectively. Taxis presented ELCC values, on average, 77.4% lower than those found for privates, with the highest difference between taxi and private car observed for the PHEV in the Brazilian scenario. This outcome reflects the high purchase price of the model in Brazil, combined with its relatively favourable official fuel economy. Although these values do not perfectly replicate real-world driving, they provide a standardised reference for comparison across the analysed countries. The use of different fuels, in the single-fuel or in the dual-fuel mode, did not significantly interfere with the results.

On the other hand, when considering the annual ELCC, taxis presented higher values than private vehicles, and differences between the fuels used slightly appear (Fig. 2). Taxis presented values, on average, 14.2% higher than privates ones, with the highest value being also found for the British scenario. In the British and Spanish scenarios, E10 and E5 gasolines showed the highest values, both in single-fuel and dual-fuel modes. For the Brazilian scenario, fuels in general did not influence the ELCC, with a slightly higher value for bioethanol. Biogas in single-fuel mode and bioethanol plus biogas in dual-fuel mode had the lowest values and presented similar values when compared to E27, emphasizing that they can be an alternative to fossil fuels. Overall, even though taxis are more expensive, the difference between the ELCC found for taxis and private cars was less than 25.7% annually, depending on the fuel chosen, and considering the higher income by travelling long distances, HEVs and PHEVs as taxis fuelled with biofuels become both economical and environmentally attractive.

In addition to the ELCC analysis, the energy consumption of each vehicle, expressed in MJ/km, was evaluated (Table 8). Results show comparable values between HEVs and PHEVs, with slightly lower

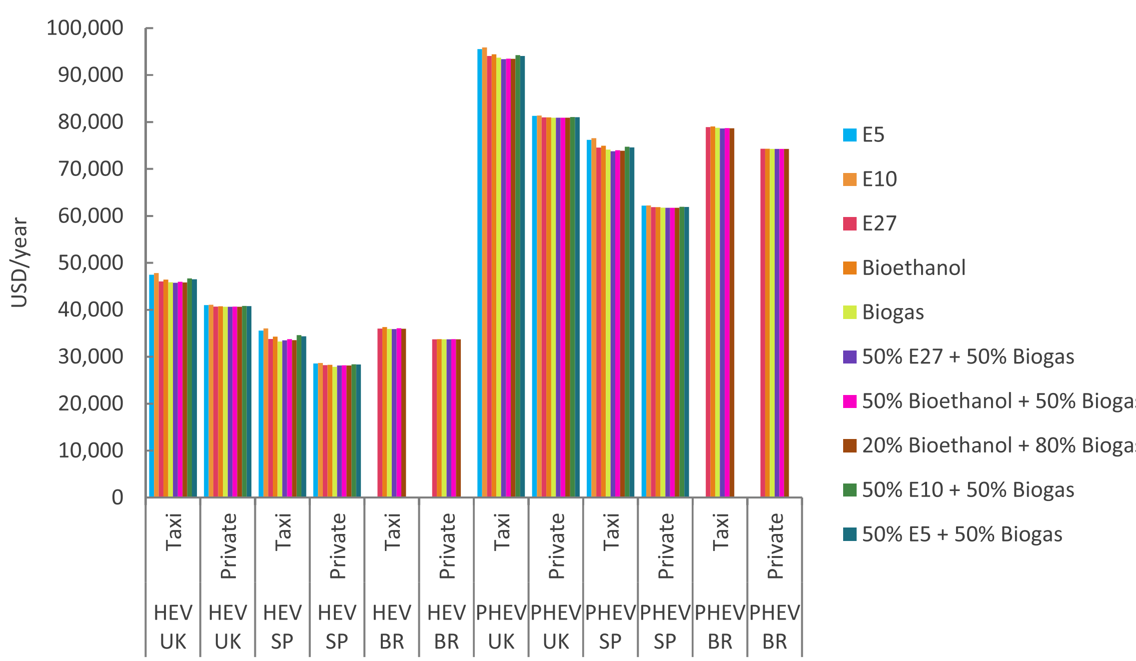

Fig. 2. Annual environmental life cycle costing of the HEVs and PHEVs, as taxi and private car, fuelled with different fuels.

Table 8
Energy consumption found for each vehicle's internal combustion engine.

Vehicle	Energy Consumption (MJ/km)
HEV – UK	1.38
HEV – SP	1.56
HEV – BR	1.66
PHEV – UK	1.38
PHEV – SP	1.40
PHEV – BR	1.31

energy use in the Brazilian case (1.31 MJ/km). The analysis also illustrates how different fuels impact vehicle efficiency: lower values were observed for bioethanol and biogas, confirming the potential of biofuels to reduce energy consumption. Although these variations are relevant, they do not alter the main conclusions of this study. Future research will address the influence of different ethanol proportions in gasoline on overall fuel efficiency.

3.2. Net present value

The NPV assesses the financial viability of HEVs and PHEVs by calculating the value of future cash flows in present terms. This metric evaluates the potential profitability and cost-effectiveness of the investment over time. Through the presented equations, it was possible to calculate the NPV of HEVs and PHEVs fuelled with different fuels in

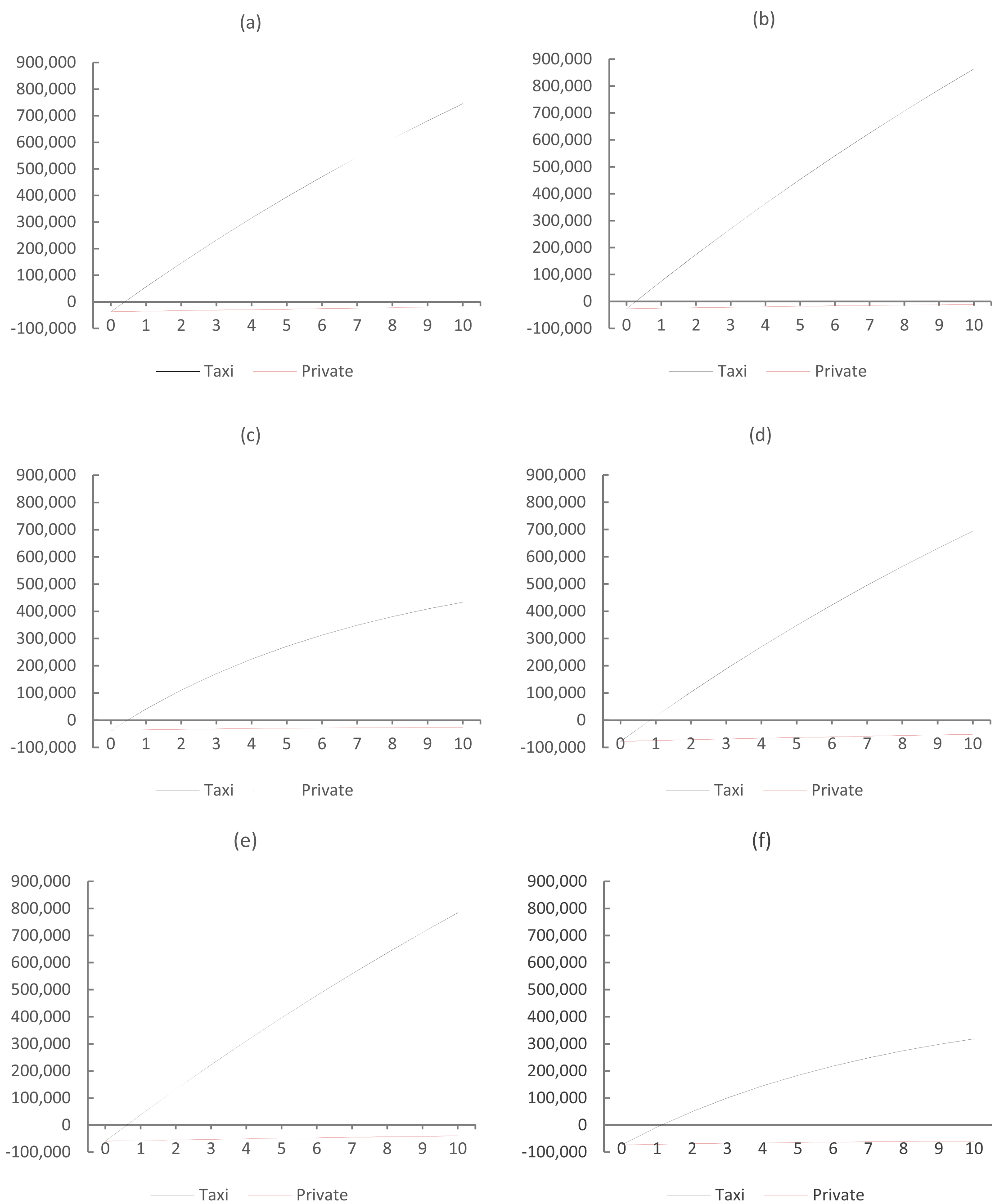

Fig. 3. Average net present value found for taxi or private cars (axis Y), in USD, and year of investment (axis Y) for: (a) British HEV, (b) Spanish HEV, (c) Brazilian HEV, (d) British PHEV, (e) Spanish PHEV, and (f) Brazilian PHEV.

different scenarios, during a vehicle lifetime of 10 years. However, as the difference between the NPV for each fuel was exceedingly small, an average value was used to better visualise the graphs (Fig. 3). HEV and PHEV owners had their investments returned in the first year when operating as taxis, except in Brazil, where PHEV owners required just over a year. The best results were observed in the Spanish scenario, explained by lower vehicle prices and discount rates.

On the other hand, private cars did not achieve a return on investment during the assumed useful life, with more favourable values for HEVs, although Spain reached values close to the investment threshold. This outcome represents a strictly financial evaluation and does not include non-monetary benefits that individuals may derive from private vehicle ownership, such as convenience, flexibility, comfort, and personal mobility preferences. Considering these behavioural aspects could modify the perceived attractiveness of electric vehicles for private users.

The Brazilian scenario achieved the lowest return on investment, with HEV returns 50.5% and 54.8% lower, and PHEV returns 54.1% and 59.4% lower than the United Kingdom and Spain, respectively. This is explained by higher taxes, insurance, and fewer incentives in Brazil. Unlike Spain, which offers purchase incentives and reduced taxes, Brazil only provides a partial reduction in the Tax on the Property of Motor Vehicles (IPVA), which the owner must pay annually 1.5% of the tabulated vehicle value provided by Economic Research Institute Foundation (in Portuguese, Fundação Instituto de Pesquisas Econômicas – FIPE). Public policies directly influence the adoption of electric vehicles, and in Brazil additional measures such as tax exemptions, inspection fee reductions, and financing programmes with lower interest rates could improve competitiveness.

Regarding fuels, results showed that the use of different fuels influenced the NPV of HEVs, particularly after the sixth year, when the impact of higher-cost fuels such as bioethanol, biogas, and dual-fuel blends became more evident. PHEV results were less sensitive to fuel costs, given their relatively efficient combined consumption.

Thus, generous incentives should be applied to eco-friendly fuels, so that owners can choose to use a less polluting fuel instead of a fossil fuel that provides more performance and lower consumption and, so, lower annual cost.

3.3. Total cost of ownership

The TCO provides a comprehensive overview of the financial impact of owning HEVs and PHEVs. By incorporating all costs throughout the vehicle's lifecycle, including acquisition, operation, and maintenance, TCO delivers a complete picture of the long-term economic effects. As shown in Fig. 4, taxis had advantages over private vehicles in all scenarios. Spain presented the lowest values in both cases, while the United Kingdom showed the highest. For HEVs, Spain's costs were up to 4% lower than those in Brazil and 18% lower than in the United Kingdom. For PHEVs, Spain's values were up to 14% lower than Brazil's and 23% lower than those of the United Kingdom. Brazil therefore occupied an intermediate position, consistently between Spain and the United Kingdom. Based on this indicator, fuel cost is the main factor in reducing the TCO, and Brazil can stand out due to its high potential for biofuel production. By leveraging resources such as bioethanol and biogas, the country can also benefit from carbon credits, transferring these advantages to consumers in the form of fuel discounts.

Fuel-related differences were more evident for HEVs, both for taxis (Fig. 5) and private cars (Fig. 6). HEVs powered by E5 and E10 gasoline and their dual-fuel blends, as well as by bioethanol, showed higher TCO values. PHEVs, with an official combined consumption of 22.72 km/L, also exhibited variations depending on fuel type, although these were less pronounced than for HEVs. In both cases, vehicles fuelled with Brazilian gasoline (E27) achieved the lowest TCO impact among the gasoline types analysed, suggesting a potential alternative for European markets if flex-fuel engines were adopted. Biofuels remained competitive overall, with biogas particularly advantageous compared with bioethanol in some scenarios, underscoring the importance of tax incentives to improve their economic attractiveness.

This finding highlights the distinction between the perspectives captured by NPV and TCO. While NPV measures long-term investment profitability and is sensitive to capital costs and discount rates, TCO focuses on cumulative operational expenses borne by users. Consequently, a technology such as flex-fuel engines may not appear financially optimal from an investment standpoint – particularly in high-cost contexts such as Europe – yet still deliver tangible short-term savings for consumers through lower fuel expenses. This divergence suggests that policies aimed at promoting flex-fuel technologies should differentiate between macroeconomic investment incentives and microeconomic

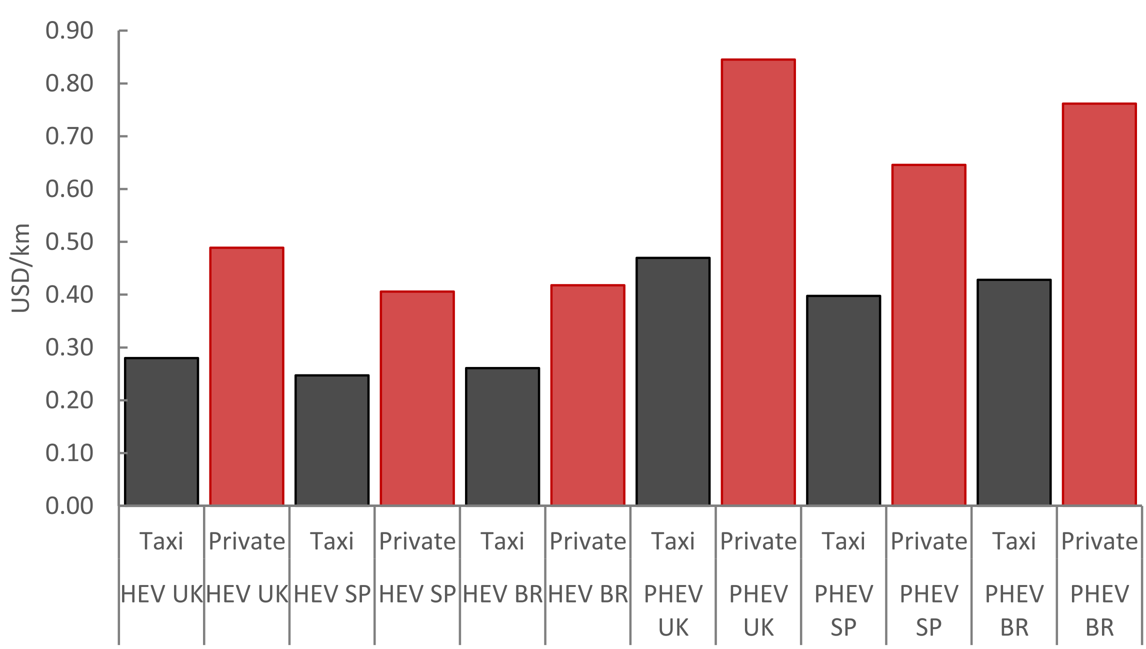

Fig. 4. Average total cost of ownership found for HEV and PHEV as taxis and private cars.

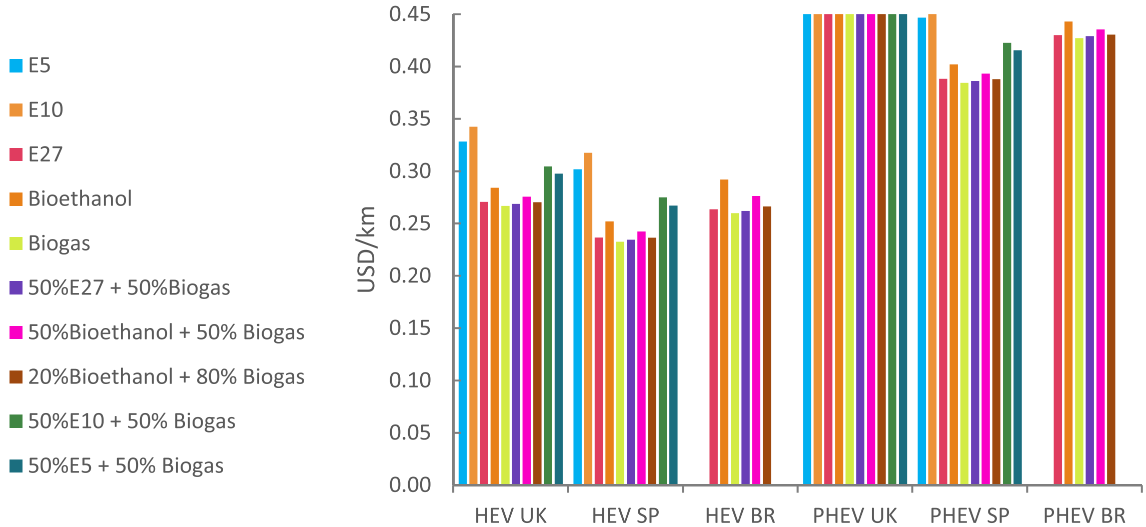

Fig. 5. Total cost of ownership found for HEVs and PHEVs, as taxis, fuelled with different fuels in each scenario.

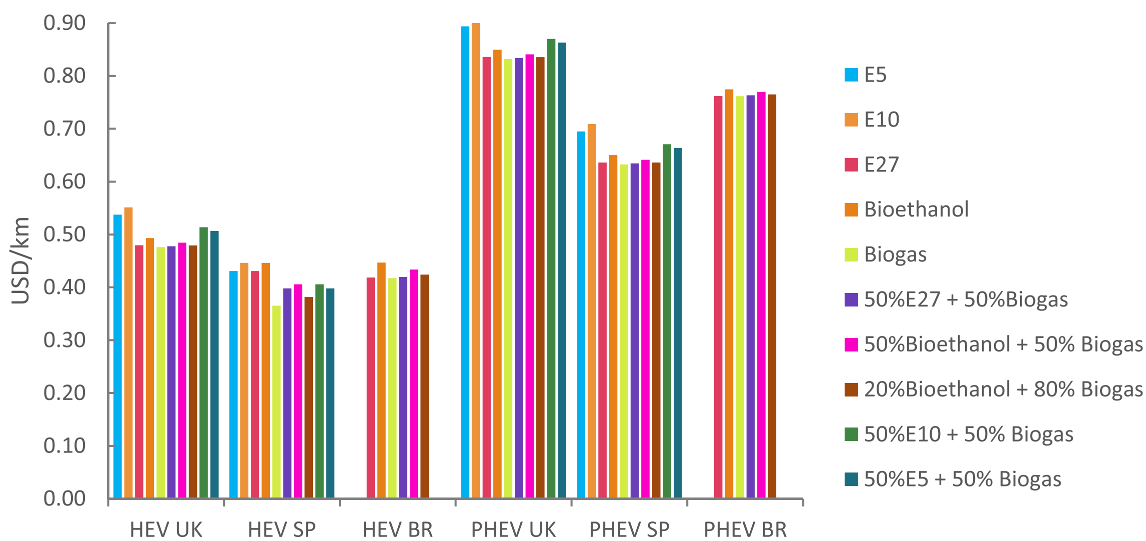

Fig. 6. Total cost of ownership found for HEVs and PHEVs, as private cars, fuelled with different fuels in each scenario.

benefits experienced by end-users.

3.4. Considerations upon flex-fuel engines, dual-fuel mode, and battery replacement

The differences between the NPV results found for each fuel were insufficient to propose the change from the current engine used in Europe to a flex-fuel engine, like the one used in Brazil. On the other hand, the TCO results show that this technology can help drivers achieve savings in fuel costs, where consumers can choose the cheapest fuel when needed. If this measure is implemented, the United Kingdom and Spain will be able to achieve lower pollution values using less harmful fuels for the environment, such as bioethanol, in the transport sector. However, this analysis would require considering other variables, such as import taxes, demand for biofuels and production potential, in addition to the costs associated with changing the current engine characteristic to a flex-fuel engine.

The dual-fuel mode helped to achieve the lowest cost values, as it allows replacing a percentage of the more expensive fuel with a cheaper one. Combining this technology with the flex-fuel technology, the advantages are even greater, allowing the driver to choose the cheapest choice between bioethanol and gasoline, the latter with any percentage of bioethanol. Thus, this mode is a promising alternative to reduce fuel costs, in addition to reducing the environmental impact by replacing part of the most polluting fuel with another with less negative environmental impact.

A sensitivity analysis was conducted to evaluate the influence of battery lifetime on the economic indicators. Extending the battery lifetime from 100,000 to 150,000 km led to considerable reductions in TCO, ranging from 12 to 18 % for private vehicles to 18–34% for taxis, while ELCC decreased more modestly, by up to 4%. NPV also improved for taxis by 2–9 %, reflecting the avoided replacement outflows under higher mileage. No further variation was observed at 200,000 km, since the vehicle lifetime (150,000 km) does not exceed the extended battery lifetime. These results confirm the robustness of the model and show that the comparative ranking among vehicle types and countries remains unchanged.

Another crucial point to consider when it comes to continuous route electric vehicles, such as taxis, is the reduced battery lifetime, leading to the constant replacement of this component throughout the vehicle's useful life. In this case, specific circular economy actions applied specifically for taxis should be considered, such as a closed-loop supply chain, to collect these batteries at the end of their lives and recycle them to remanufacture new ones. This should be widely applied as the fleet of taxis and private vehicles increases, avoiding shortages of critical battery component materials such as lithium, cobalt, and nickel. In addition, one should look for new battery technologies, using more abundant components, such as the promising Sodium-ion battery.

4. Conclusion

In this study, we conducted an economic assessment to support the introduction of electric vehicles in the Brazilian transport sector by prioritising their use in taxi fleets as a pathway to decarbonization. Hybrid models were selected given Brazil's strong potential for biofuel production, making this type of vehicle particularly suitable for the national context. Environmental life cycle costing, net present value, and total cost of ownership were calculated for HEVs and PHEVs, as taxis and private cars, fuelled with fossil fuels and biofuels, in single- and dual-fuel modes, across three economic scenarios: the United Kingdom, Spain, and Brazil.

The most favourable results were obtained for the Spanish scenario, explained by the lower discount rate provided by the European Central Bank. The United Kingdom presented intermediate outcomes, while Brazil recorded the least favourable results for all indicators. This highlights the need for strategies that go beyond purchase incentives, with priority given to reducing vehicle acquisition costs and discount rates, which are the most influential variables in economic viability.

Regarding fuels, E5 and E10 gasoline blends, whether in single- or dual-fuel modes, had the greatest impact on costs for HEVs, while PHEVs showed only moderate sensitivity to fuel type. Biofuels such as ethanol and biogas were associated with lower costs and can be made even more attractive through tax incentives. Differences in NPV and ELCC across fuels were insufficient to justify the introduction of flex-fuel engines in the United Kingdom and Spain. However, TCO results indicate that flex-fuel engines can be a viable option in Brazil, providing drivers with greater flexibility and potential savings.

Policy actions should also prioritise circular economy strategies for batteries, aiming to reduce shortages of critical raw materials through recycling and closed-loop supply chains. With respect to methodological limitations, this study did not account for the influence of vehicle depreciation on purchase values, which could provide additional precision in absolute cost estimates. Depreciation was intentionally excluded to isolate the effects of operational and replacement costs; although its inclusion would increase TCO and reduce NPV values, it would not alter the relative ranking among vehicle types or countries, as depreciation scales proportionally with vehicle price.

Another limitation concerns the PHEV fuel consumption adopted ($\approx$22.7 km/L, equivalent to 53.4 mpg). This value was derived from real-world usage data rather than official manufacturer test results and should therefore be interpreted as a realistic but approximate estimate, as it implicitly reflects average charging behaviour rather than explicitly modelling utility-factor-based operation. Future assessments could refine these results by integrating local driving data and official test-cycle consumption figures.

Future research will explore the impact of driving behaviour on vehicle efficiency, particularly how the frequency of recharges and refuelling influences electricity and fuel consumption, as well as emissions. Such analysis will contribute to a more comprehensive understanding of the real-world performance of hybrid vehicles.

CRediT authorship contribution statement

Laene Oliveira Soares: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **José Ricardo Sodré:** Writing – review & editing, Validation, Supervision, Formal analysis. **Luis Hernández-Callejo:** Writing – review & editing, Validation, Supervision. **Paulo Sérgio Duque de Brito:** Writing – review & editing, Validation, Supervision. **Ronney Arismel Mancebo Boloy:** Writing – review & editing, Validation, Supervision.

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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.

Data availability

No data was used for the research described in the article.

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