

## Article

# Managing Sustainable Urban Public Transport Systems: An AHP Multicriteria Decision Model

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**Abstract:** The current combination of sustainable social awareness and the improved decision support systems, including multiple criteria decision models for sustainable development, creates the need for more efficient and accurate public policy decisions based on available technology. The continuous growth of urban public road transport in large cities, and therefore the worsening of air quality, along with recent economic crisis derived from the COVID-19 pandemic, is forcing public administrations to analyze the viability of current models, taking into consideration sustainable alternative energies. This study proposes a novel and consistent analytic hierarchy process (AHP) multicriteria decision-making (MCDM) model that combines both economic and environmental criteria, to evaluate public road transportation vehicles according to their alternative engine technologies and combustion characteristics. The proposed model has been applied to evaluate Madrid's urban public road transport, based on 2020 data published by the Madrid City Council, compiled by authors, and assessed by a panel of 20 experts to identify criteria and factors included in the AHP-MCDM model. The findings illustrate the economic and environmental impact of alternative vehicles, show that the most sustainable alternative is the plug-in electric vehicle in economic and environmental terms, and assist policymakers and firms in future strategic decisions regarding sustainable urban transport policies.

**Keywords:** sustainability; sustainable public transport; urban transport policies; environment; sustainable social awareness; green vehicles; AHP multicriteria decision-making



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## 1. Introduction

Sustainability is a concept of essential importance in modern societies, and therefore today's policymakers must take into consideration not only economic, but also environmental criteria. In this sense, decisions related to urban public road transport in large cities are one of the best examples of how traditional models undergo metamorphosis due to green technologies.

The current tendency in modern large cities is to incorporate vehicles with sustainable alternative energies into their urban public road transport networks, with old and new technologies coexisting with different sustainability levels, i.e., dissimilar economic performance and environmental impact.

The aim of this research is to assess public buses depending on their fuel technologies in terms of sustainability. In this paper, the attention is focused on the case of Madrid; nevertheless, the results can be extrapolated to other densely populated cities, because both vehicle alternatives and city transport necessities are similar in large cities.

Although two centuries ago Malthus [1] urged the need to study and determine the impact of human activity on the environment together with a concern for finding a form of economic development that meets people's current needs without compromising the

ability of future generations to meet their own, the concept of sustainability is actually relatively new.

The concept of sustainability appeared for the first time in the Brundtland Report [2], which was drawn up on 4 August, 1987, by several countries in the United Nations (UN) [3]. The aim of the report was to complement the concept of economic development with environmental sustainability. Sustainability, particularly in reference to ecology and economics, refers to “the ability to be maintained at a certain rate or level and the avoidance of the depletion of natural resources in order to maintain an ecological balance” [4].

Sustainable development expands development concerns with monetary capital to consider natural, social, and human capital. Broadly speaking, sustainable development is referred to as combining three fundamental elements that must complement one another in harmony. These three elements are environmental sustainability, economic sustainability, and social sustainability [5,6]. In practical terms, environmental sustainability requires a planning process that allows human society to live within the limitations of the biophysical environment. Economic sustainability involves a system of production that satisfies present consumption levels without compromising future needs. Social sustainability implies preserving the environment through economic growth and the alleviation of poverty [6].

Consistent with these definitions, the 2030 Agenda for Sustainable Development was approved by the UN in 2015 [7]. The 2030 Agenda consists of 17 Sustainable Development Goals that cover protecting the environment and reflect the goals that private and public organizations must endeavor to meet before 2030 to build a cleaner world with less social inequality. As an antidote to economic, social, and environmental issues, city and regional planning regimes embodying “urban sustainability” must be constituted. The 2030 Agenda calls for appropriate technology, transport reform, and urban renewal. Similarly, governments and public administrations have launched international and local recommendations to develop strategies aligned with the Sustainable Development Goals [8].

Despite technological advances that have promoted energy efficiency gains, energy use in OECD countries grew by another 35% by 2020. In fact, transport is the first most rapidly growing area of global energy use [9]. Companies in the transport sector play a particularly important role in sustainable development because of environmental pressure, the associated social and economic effects, and linkages with other sectors. The continued growth of this sector in recent years and its expected increase make the challenge of achieving sustainable transport a strategic priority at local, national, European, and global levels [10]. Road transport in particular is one of the primary sources of pollution in urban areas. The massive rise in journeys and the use of fossil fuels entail an increase in local air pollutants such as nitrogen oxides (NO<sub>x</sub>) and particulate matter (PM<sub>10</sub> and PM<sub>2.5</sub>), which city inhabitants breathe and which are extremely harmful to health. In addition, they contribute to ozone layer destruction and emissions of greenhouse gases such as carbon dioxide (CO<sub>2</sub>), which accelerates climate change [11].

Given the high share of total energy consumption by the transport sector, sustainable mobility should also play a prominent role in decisions on energy system transition, especially after the crisis caused by the COVID-19 pandemic, where both companies and public administrations are checking the viability of their current economic and productive models in the private and public transport sectors. The abundance of scientific articles on this topic reflects its relevance, largely driven by the strong pressure constantly placed on companies to comply with the strict regulations of many countries that face major pollution problems, such as the United States, the United Kingdom, China, Austria, and Spain [12–16], and related to public transport systems [17].

Some publications and research projects have studied the advantages, trends, and challenges associated with electric vehicles as a sustainable mobility alternative [18], which primarily relate to difficulties in introducing electric vehicles to the market because of their limited range [19–21] and the lack of a charging network infrastructure [22,23]. Even the European Commission [24,25] supports the assertion that electric vehicles could redress

the growing trend of greenhouse gas emissions caused by the transport sector in the European Union [26].

However, other researchers have broadened the scope of their analyses by also considering other fuels such as compressed natural gas (CNG) and hybrid engines as short- and long-term sustainable alternatives [13,27–30]. Numerous studies have also compared vehicles that use different alternative fuels [31–33], assessing their impact [34,35]. However, the rapid evolution of energy technology means that these research streams must be continually reviewed to account for the decline of some technologies and the emergence of new fuel alternatives.

The European Commission takes a vigilant stance with regard to pollution levels in major European cities. Accordingly, numerous formal requests have been directed at Spain in relation to the poor air quality in Madrid, which is one of the European capitals with the highest levels of local air pollution. Its concentration of pollutants consistently reaches values considered dangerous by the World Health Organization (WHO) [36]. Therefore, Spain has committed to meeting the objectives established in international agreements such as the Paris Agreement and the Kyoto Protocol. To do so, Spain must focus on significantly reducing its current emissions of air pollutants [37] in areas that are under its administration and control, such as public road transport.

Public road transport companies in Spain have made a firm commitment to alternative fuels. For example, in Madrid, more than 80% of the current fleet of vehicles used for urban public transport is green, meaning that the vehicles in the fleet comply with the Euro V European regulations on emission levels of air pollutants [38].

Nevertheless, the poor air quality in Madrid today and the continual complaints to the city filed by the European Commission to the European Court show that these efforts are not enough. Public administrations are therefore being forced to continue innovating and investing in sustainable alternative energies for urban public road transport [39]. This investment entails progressively replacing vehicles with others that use more environmentally friendly technologies, including CNG, hybrid, or electric engines, even though these technologies are not mature enough to provide these intensive road transport services.

Furthermore, the diversity and varying degree of development of technologies and fuels are factors that hamper decisions given the uncertainty surrounding which technology will become a viable alternative to existing diesel or petrol engines. Therefore, the objective of this study is to evaluate the different technological alternatives of engines in terms of their combustion characteristics to identify the most sustainable alternative in environmental and economic terms to provide urban public transport services.

To confirm and ensure the relevance of this study, different engine technology alternatives are assessed according to the fuel used by public buses in the urban area of Madrid, whose fleet is representative of the following technologies: diesel engines, compressed natural gas (CNG) engines, diesel hybrid engines, plug-in electric motors, and electric induction motors. The results enable testing of the effectiveness of the method and can assist decision-making with respect to investing in the most sustainable technology.

This paper assesses the sustainability of a city's public bus system in environmental and economic terms to identify the most sustainable fuel from the alternatives included in the model (diesel, CNG, diesel hybrid, plug-in electric, and induction electric). These alternative fuels are considered because of their potential to replace traditional fossil fuel as the primary source of fuel for buses in urban public transport. The results illustrate the optimal path for future strategic decisions by public administrations regarding sustainable urban transport policies.

Therefore, this study raises three research questions:

Research Question I: Which type of public bus is the best economic alternative?

Research Question II: Which type of public bus is the best environmental alternative?

Research Question III: Which type of public bus is the most sustainable alternative?

The rest of this paper is organized as follows. Section 2 presents the data source and methodological description. This section explains the model alternatives, the model evalua-

tion criteria, and the building of the applied multicriteria decision model. Section 3 includes model results and discussion. Section 4 offers the main conclusions and recommendations of the study, including result implications for management, research limitations, and future lines of research.

## 2. Materials and Methods

This study proposes a novel and consistent analytic hierarchy process (AHP) multicriteria decision-making (MCDM) model that combines both economic and environmental criteria, to evaluate public road transportation vehicles according to their alternative engine technologies and combustion characteristics. It is based on 2020 data published by the Madrid City Council [40], which were compiled by authors and assessed by a panel of 20 experts to identify criteria and factors included in the AHP-MCDM model.

MCDM is a branch of operations research (OR) that deals with how to help people making decisions when several criteria exist that are, most of the time, in conflict.

One of the most powerful and most-used MCDM methods is AHP, developed by Saaty [41]. AHP can be used in problems where the decision-maker has a set of alternatives to choose from and a set of attributes on which the decision is based. The problem is structured into a hierarchy and the objective is to obtain values for each alternative. AHP derives ratio scales, both from discrete and continuous paired comparisons, to obtain a ranking of the alternatives considered in the decision problem. It is an Eigenvalue approach to pair-wise comparisons.

Some key and basic steps involved in this methodology are explained in [42]: 1. State the problem; 2. broaden the objectives of the problem or consider all actors, objectives, and its outcome; 3. identify the criteria that influence the behavior; 4. structure the problem in a hierarchy of different levels constituting goal, criteria, sub-criteria, and alternatives; 5. compare each element in the corresponding level and calibrate them on the numerical scale. This requires  $n(n - 1)/2$  comparisons, where  $n$  is the number of elements with the considerations that diagonal elements are equal or "1" and the other elements are simply the reciprocals of the earlier comparisons. Qualitative comparisons are done with the Miller [43] scale; 6. perform calculations to find the maximum Eigenvalue, consistency index (CI), consistency ratio (CR), and normalized values for each criteria/alternative; and 7. if the maximum Eigenvalue, CI, and CR are satisfactory then a decision is made based on the normalized values, otherwise the procedure is repeated until these values lie in the desired range.

In this paper we used the AHP version implemented in Web-HIPRE software [44], which is a web version of the Hipre 3+ multicriteria decision support software [45].

AHP is a pairwise comparison method that offers a tested method for evaluation and decision-making assistance in complex scenarios of transport, energy, technology, and environmental planning [14,15,33,46–54]. The AHP method is used to establish a series of criteria that are assigned weights of importance according to the advantages and disadvantages of the different alternatives. The output is a hierarchy in order of preference of the alternatives [55]. Studies have also applied similar AHP models to evaluate alternative fuels and assess future transport policies [14,15,39,56,57].

The weights of the criteria and sub-criteria were determined using the Delphi method [58] according to the average value attributed by consensus across a panel of experts. The Delphi method is a technique to structure a group communication process so that the interactions between group members effectively allow a group of individuals to deal with a complex problem [59], and it is widely used for forecasting in economics and social sciences [60–63], energy, and transportation [58,64,65] and combined with AHP models [66], gathering information for decision-making processes as in this study.

The selection of experts was crucial in this multicriteria decision-making process [67]. In this study, a panel of 20 experts was formed. All experts were professionals or scholars of the transport industry (45%) or energy in transport (35%) or both (20%), with at least three years' experience (see Tables 1 and 2).

**Table 1.** Distribution of experts by domain of expertise.

Domain of Expertise	Initial Panel	After 1st Round	After 2nd Round	Percentage
Transport	9	9	9	45
Energy	7	7	7	35
Transport and Energy	4	4	4	20
Total	20	20	20	100

**Table 2.** Distribution of experts by experience.

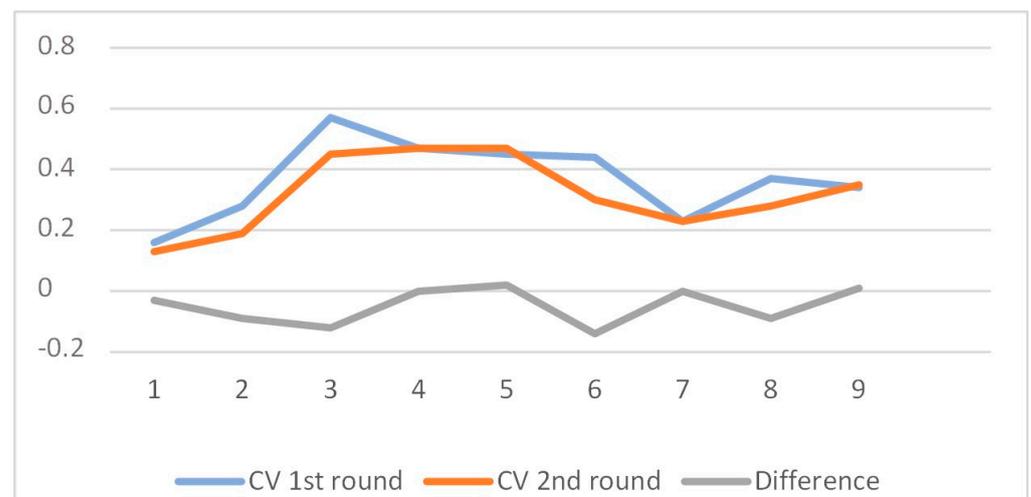
Number of Years	Initial Panel	After 1st Round	After 2nd Round	Percentage
Less than three years	0	0	0	0
From three to five years	6	6	6	30
More than five years	14	14	14	70
Total	20	20	20	100

Two rounds were needed for a convergence of opinion on the importance of the criteria and sub-criteria in the model. The consultation instrument in the first and second round was a questionnaire that included the criteria and sub-criteria for being assessed by the panel of experts according to their importance for achieving the goal of sustainability. In the first round, the panel members received a dossier containing notable studies, European regulations on environmental impact, and strategic guidelines of private and public bodies, as well as the following key information on the fuel alternatives assessed in this study: service life of vehicles, bus purchase prices, fuel and battery prices, range and charging times, emissions factors of local pollutants and particles, maintenance costs, resources in terms of staffing and fleet size, engine performance, and type-approval emissions factors for local pollutants and particles. To assess the environmental sub-criteria, additional information was provided to enable proper assessment on the basis of danger to human health according to the parameters set by the WHO [36]. The data provided to the experts are summarized in Appendices A–H.

For the second round, the results of the first round were provided to the experts for re-evaluation or to confirm their opinions, including (a) mean values for the whole responses, (b) standard deviations for the total dataset, (c) individual response for the former round, and d) the interquartile range (IQR).

There is a debate about when and which assumption has to be used to stop the Delphi methodology. The literature does not provide absolute recommendations while referring to the hierarchical stopping criteria [60,68] devised by [69]. Several consensus measurement strategies are available in the literature [68]. The standard deviation is used as an indicator of the dispersion of the dataset, hence the higher it is, the more scattered the experts' responses are [60,70]. According to [71], standard deviation values greater than 1.5 correspond to a lower consensus.

As stated by [69], the IQR indicator is not sufficient to be considered a stopping criterion, as significant fluctuations might occur between the rounds, and therefore stability is a more reliable concept. This stability can be assessed as described by [60,72] by means of the adoption of the coefficient of variation, which entails the calculation of the ration between the standard deviation and mean across all the criteria and sub-criteria and it is applied in this study. Based on the values of mean and standard deviation, the coefficient of variation was calculated and its trend is presented in Figure 1. The dotted line represents the absolute difference between the coefficients of variation between the two rounds. According to [64] a coefficient of variation between 0 and 0.5 is acceptable to consider consensus achieved and hence terminate the process.



**Figure 1.** The coefficients of variation for the criteria and sub-criteria over the first and second rounds of consultation.

Based on this, the consensus was reached after the second round, when the difference between the coefficients of variation (CV) of both rounds was not significant [60,64] (see Figure 1).

Table 3, based on the 20 experts' consensus, summarizes the elements used to build the AHP multicriteria decision model and the weighting and statistical data.

**Table 3.** The AHP multicriteria decision model: consensus on elements, weights, and statistical data.

Elements	Nomenclature	Unit	Weighting	SD	Q1	Q3	IQR	CV1	CV2	CV1-CV2
Goal	Sustain									
Criteria										
Economic criterion	Economic	EUR	0.6	0.129	6	6	0	0.16	0.13	0.03
Environmental criterion	Environm	Kg	0.4	0.194	4	4	0	0.28	0.19	0.09
Sub-criteria										
Depreciation	Deprec	EUR	0.2	0.474	1	2	1	0.57	0.45	0.12
Traction cost	Tract	EUR	0.2	0.474	1	3	2	0.47	0.47	0.00
Maintenance cost	Mainten	EUR	0.2	0.474	1	3	2	0.45	0.47	0.02
Operating cost	Operat	EUR	0.4	0.296	3	5	2	0.44	0.30	0.14
NOx emissions	NOx	Kg	0.5	0.228	4	6	2	0.23	0.23	0.00
Particular matter emissions	PM	Kg	0.3	0.279	3	4	1	0.37	0.28	0.09
CO <sub>2</sub> emissions	CO <sub>2</sub>	Kg	0.2	0.354	2	2	1	0.34	0.35	0.01

SD = standard deviation; Q1 = first quartile; Q3 = third quartile; IQR = interquartile range; CV1 = coefficient of variation 1st round; CV2 = coefficient of variation 2nd round.

In multicriteria analysis, not all criteria and sub-criteria contribute equally to achieving the goal. In the AHP model, each criterion and sub-criterion is assigned a value between 0 and 1 depending on the degree to which it contributes to achieving the goal. A value of 0 implies that the criterion or sub-criterion has no contribution, and a value of 1 indicates the maximum contribution. Table 3 shows the weights that the panel of experts assigned by consensus to the criteria and sub-criteria of the decision model according to their importance for achieving the goal of sustainability.

A decade ago, most companies defined sustainability solely in terms of economic criteria. Today, genuine social concern for the environment has forced companies to consider environmental criteria in their strategic decisions. This global social concern over pollution has led to the development of new technologies that are more environmentally friendly. However, their implementation in companies is limited because their cost is considerably higher than the cost of traditional technologies. Therefore, the economic

criterion continues to outweigh the environmental criterion in business strategies, although it is only a matter of time before this preference is reversed.

The final assessments by the panel of experts reflect the trend of the current European guidelines on environmental sustainability issued by the WHO [36] and the European Commission [24,25] to encourage public and private organizations to define strategic plans that seek organizational sustainability through a sustainable economic and financial model. Specifically, this model enables urban transport companies to make strategic decisions to steer their infrastructure and fleet towards sustainability, progressively replacing their vehicles with non-polluting alternative technologies certified with the “ECO” label (or higher), as established by the air quality plans of the public administrations of European cities [72–74].

### 2.1. Solution Alternatives

The alternatives consist of different vehicles classified according to the type of fuel they use:

- Diesel: These are diesel-powered combustion engine vehicles. This engine is the conventional engine that is traditionally used in urban public transport services because it is the most efficient internal combustion engine [21].
- CNG: These vehicles use Otto-cycle combustion engines that run on CNG. CNG vehicles emit small amounts of carbon dioxide, which makes them feasible for urban public transport [75].
- Diesel hybrid: These vehicles use a diesel-cycle combustion engine that feeds an electric generator that is responsible for moving the vehicle. They use diesel fuel.
- Plug-in electric: These vehicles have an electric motor, run on electricity, and are recharged using a socket.
- Induction electric: These vehicles have an electric motor, run on electricity, and are recharged by induction.

Each alternative has different characteristics in terms of range, type of engine, and time spent to refuel. Therefore, to cover the same journey, the number of vehicles, distance traveled, and time taken also differ. For this analysis, a bus line with an average distance of 9.21 km per journey was chosen [76]. The time horizon was 12 months of service and 18 h of service per day, guaranteeing that demand was fully met with regular, stable frequency.

To provide the same level of service under the same conditions, more plug-in electric and induction electric vehicles are needed because their limited range (maximum 155 km without refueling) prevents them from performing a full day’s service. Furthermore, electric induction vehicles must recharge their batteries at bus terminals, which forces them to remain stationary for 10 min per journey. They therefore take 20 min longer than the other alternatives to complete a full journey. Diesel, CNG, and hybrid vehicles have identical requirements in terms of range. Appendix D shows the resource requirements for each alternative.

### 2.2. Evaluation Criteria and Sub-Criteria

The vehicle alternatives by fuel type were analyzed using different criteria and sub-criteria. Two types of criteria were considered in this study. The first consisted of economic criteria relating to the cost of providing the service, with the sub-criteria of depreciation costs, traction costs, maintenance costs, and operating costs. The second type was environmental criteria, which encompassed emissions of global and local pollutants and had the sub-criteria of emissions of NO<sub>x</sub>, CO<sub>2</sub>, and PM.

#### 2.2.1. Depreciation Costs

The depreciation of a vehicle depends on its purchase price and service life. Electric induction buses also require the installation of a specific infrastructure to charge the battery at terminals. The formula for calculating the depreciation cost is defined below.

$$\text{Depreciation costs} = [\text{Vehicle purchase price (€)/Vehicle service life (years)}] \times \text{Number of vehicles} + \text{Infrastructure} \quad (1)$$

The depreciation costs for each alternative for a year of service were calculated (see Table 4). Appendix E summarizes the data used for the analysis in terms of the depreciation costs for each alternative.

**Table 4.** Costs in the AHP model by alternative.

Alternative	Depreciation Costs (EUR)	Traction Costs (EUR)	Maintenance Costs (EUR/km)	Operating Costs (EUR)
Diesel	479,167	475,797	0.4193	4,225,560
GNC	555,833	333,557	0.4845	4,225,560
Diesel hybrid	651,667	380,661	0.5425	4,225,560
Plug-in electric	1,420,834	168,918	0.2280	4,320,045
Induction electric	960,500	214,517	0.2280	5,079,285

Source: compiled by the authors based on data from the Madrid public road transport company [40].

### 2.2.2. Traction Costs

The traction costs depend on the energy consumption of each type of vehicle and the price of the fuel it uses. Each type of vehicle consumes a certain amount of fuel per kilometer traveled, and each fuel has a different price, which tends to vary monthly. The formula for calculating the traction costs is defined below.

$$\text{Traction costs} = \text{Consumption (liters per km)} \times \text{Fuel price (€ per km)} \times \text{Kilometers traveled} \quad (2)$$

For electric vehicles, a certain electric power must be supplied. Induction vehicles are fast charging, so they require greater electric power than slow-charging vehicles. This is also the case with plug-in electric vehicles. The study assessed the traction costs for each alternative for a year of service (see Table 4). Appendix F summarizes the data used to calculate the traction costs for each alternative.

### 2.2.3. Maintenance Costs

Maintenance costs relate to ensuring that the vehicle functions in a safe, reliable, comfortable, and environmentally sustainable way. These costs gradually increase over time as the vehicle ages and the warranty period expires. The formula for calculating the maintenance costs is defined below.

$$\text{Maintenance costs Alternative X} = \text{Average maintenance costs (€ per km)} \times \text{Kilometers traveled} \quad (3)$$

The maintenance costs of a diesel hybrid vehicle increase slightly more than the costs of a conventional diesel technology engine because of the mechanical complexity of the electric part of the engine. In contrast, the maintenance costs of plug-in and induction electric vehicles are half those of conventional diesel vehicles because both mechanical complexity and preventive maintenance are lower. However, the additional cost of maintaining the batteries must be added for hybrid and electric vehicles [77,78]. For this study, the maintenance costs for one year of service were calculated for each alternative (see Table 4).

### 2.2.4. Operating Costs

The operating costs consist of the total cost of the salaries of the staff required for each type of vehicle. These costs depend on the total hours of service and differ depending on the technology of each alternative. Diesel, CNG, and hybrid vehicles have the same requirements in terms of the time taken to provide the service. However, the operating costs of an electric induction bus are higher because its battery must be charged on each journey, which equates to an increase in time [38]. The formula for calculating the operating costs is defined below.

$$\text{Operating cost Alternative X} = \text{Average operating costs (€ per hour)} \times \text{Hours in service} \quad (4)$$

For this study, the operating costs were calculated for one year of service for each alternative (see Table 4).

### 2.2.5. Pollutant Emissions

For this criterion, emissions of NO<sub>x</sub>, CO<sub>2</sub>, and PM pollutants by each type of vehicle were analyzed individually. Each engine was assigned an emission value in its type-approval, which enabled calculation of emissions according to the fuel used and the carbon footprint [79]. The carbon footprint consisted of quantifying the CO<sub>2</sub> emissions by companies when performing any activity, which allows consumers to see how much pollution the manufacture of a product causes before purchasing that product or how much pollution a service causes before using that service, in this case, public road transport.

Electric vehicles emit no direct emissions when in operation, but they do emit pollutants indirectly by consuming electricity. To quantify this indirectly emitted CO<sub>2</sub>, an emissions factor of the electricity mix is established [79]. This emissions factor depends on the energy source used to produce the electricity. Renewable sources or those with low CO<sub>2</sub> emissions have a low or zero mix factor. In this study, NO<sub>x</sub>, CO<sub>2</sub>, and PM emissions by each alternative for one year of service were assessed separately as three independent criteria (Table 5). Appendices G and H summarize the data used to calculate the emissions for each alternative.

**Table 5.** Pollutant emissions in the AHP model by alternative.

Alternative	NO <sub>x</sub> Emissions (kg)	PM Emissions (kg)	CO <sub>2</sub> Emissions (kg)
Diesel	1138	3.9	1,589,471
GNC	1044	3.4	1,833,113
Diesel hybrid	910	3.1	1,264,616
Plug-in electric	-	-	724,612
Induction electric	-	-	926,059

Source: compiled by the authors based on data from the Madrid public road transport company [40].

### 2.3. Solution Alternatives

The criteria and sub-criteria used to build the AHP multicriteria decision model are described below.

- Economic criterion: The most sustainable alternative in economic terms is the one with the lowest cost.
- Environmental criterion: The most sustainable alternative in environmental terms is the one that minimizes pollutant emissions.
- Depreciation: Depends on the purchase price of the vehicle and its service life.
- Traction costs: Depend on the fuel consumption of each vehicle and the price of fuel.
- Maintenance costs: Cost of maintaining each type of vehicle in optimum operating conditions.
- NO<sub>x</sub> emissions: Emissions of nitrogen oxide gases by each type of vehicle: responsible for local pollution.
- Particulate matter emissions: Emissions of particulate matter by each type of vehicle: responsible for local pollution.
- CO<sub>2</sub> emissions: Direct or indirect emissions of CO<sub>2</sub> by each type of vehicle: responsible for global pollution.

Figure 2 shows the tree diagram of the AHP multicriteria decision model defined in this paper. This tree shows how the goal, criteria, sub-criteria, and different alternatives under study link together.

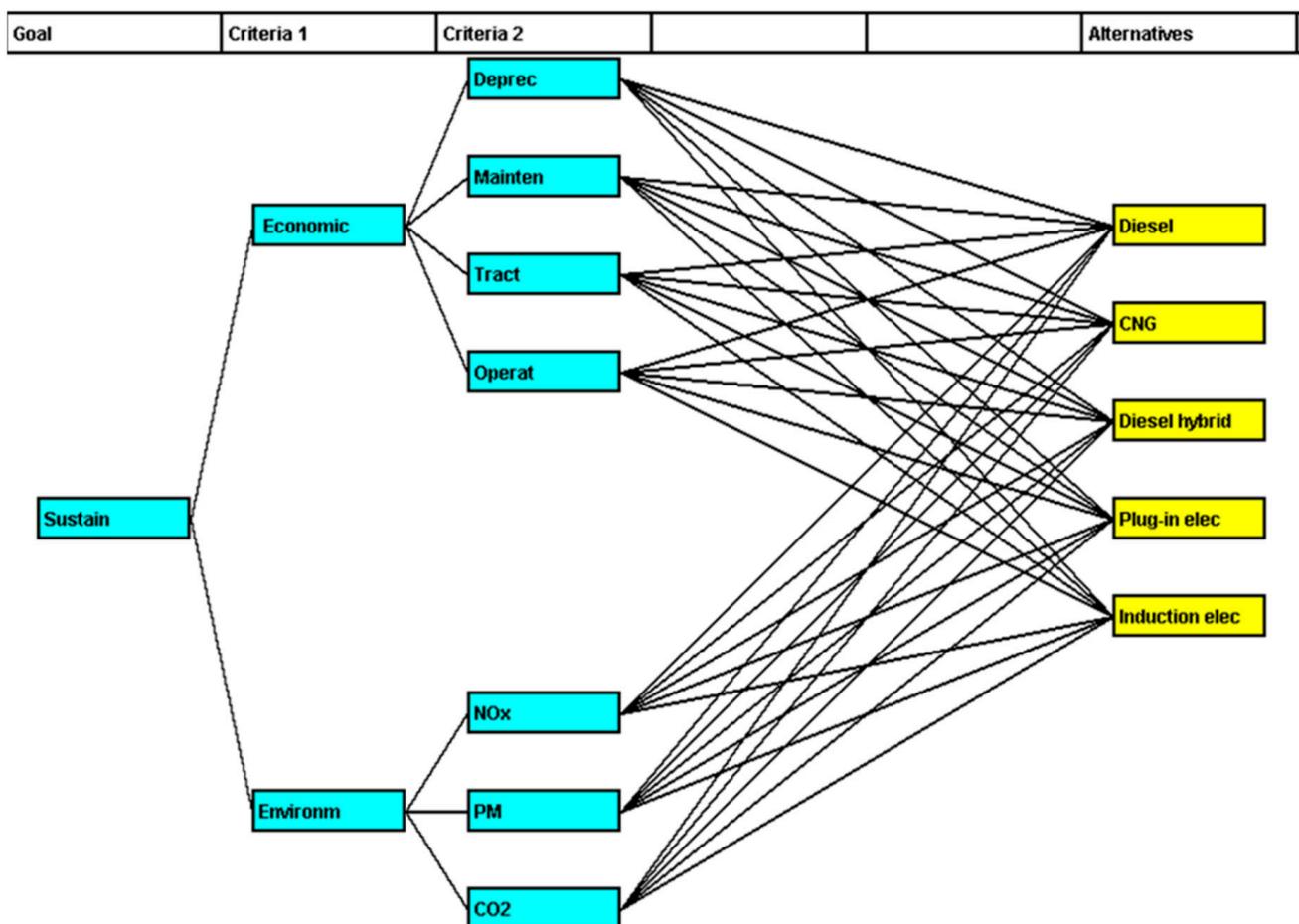


Figure 2. Tree diagram of the AHP multicriteria decision model.

### 3. Results and Discussion

After data had been entered into the Hipre 3+ software in accordance with the multicriteria decision model tree, the data matrix was observed to be valid, with an inconsistency ratio of 0.06 [41]. A ranking of the alternatives with respect to the goal and by each criterion was obtained.

The most sustainable alternative was the one that minimized the costs in the economic criterion and the pollutant emissions in the environmental criterion. Therefore, the alternatives that minimized both costs and emissions had values of importance that were close to 1, whereas alternatives with high costs and higher pollutant emissions were assigned values close to 0.

#### 3.1. Ranking of Alternatives by the Economic Criterion

Figure 3 shows the ranking of alternatives by the economic criterion. The use of CNG vehicles in public transport was the best alternative in economic terms, in accordance with [13,27]. The second-best alternative was diesel vehicles, which is the most conventional technology. The level of economic benefit of CNG compared to diesel was not significant. CNG vehicles were the alternative with the lowest economic cost for companies, primarily because of their low operating costs and depreciation costs. CNG vehicles' range minimizes the number of vehicles needed to provide the same service on a public transport line and optimizes the time spent because they can remain in service for a full day without refueling. Diesel vehicles also minimize the fleet size, outperforming plug-in electric vehicles in economic terms because of the latter's high maintenance costs. Hybrid vehicles were at a disadvantage because of the mechanical complexity of hybrid diesel and electric engines.

Electric induction vehicles were the least cost-effective alternative because of the high operating costs associated with charging the batteries on each journey.

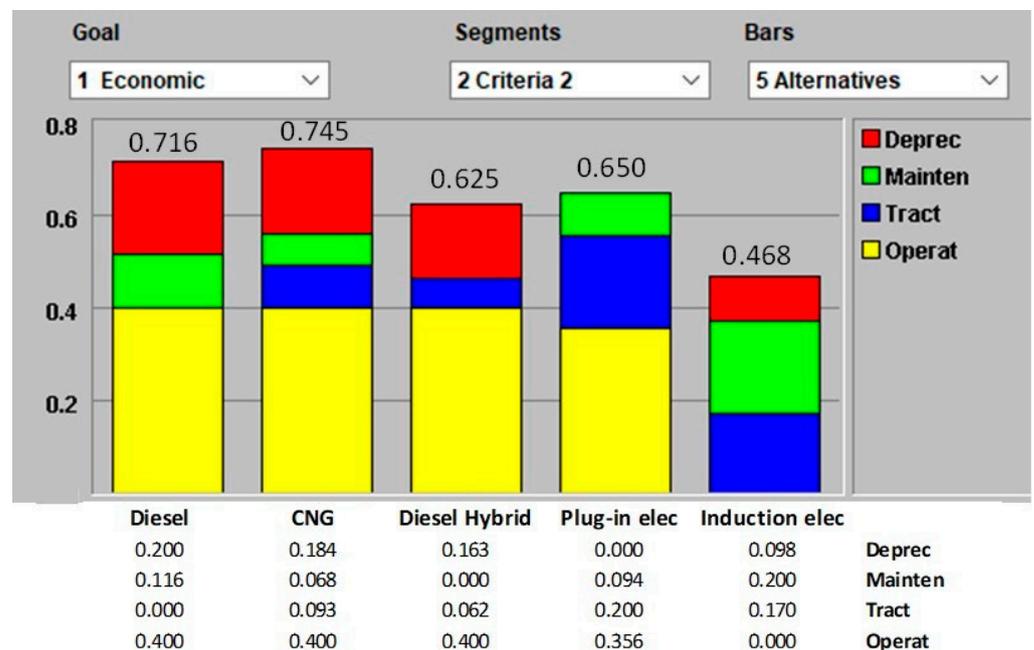


Figure 3. Results of the analysis for the economic criterion.

### 3.2. Ranking of Alternatives by the Environmental Criterion

Figure 4 shows the ranking of alternatives with respect to the environmental criterion. The most sustainable alternative in environmental terms was the plug-in electric vehicle, which was practically the same as the electric induction vehicle in the sense that it did not emit nitrogen oxides or particulate matter, in accordance with [18–23]. The level of environmental benefit between the plug-in electric vehicle and the electric induction vehicle was very close. However, there was a very significant difference compared to other technologies (diesel hybrid, CNG, and diesel). Diesel vehicles polluted the most of any alternative. However, CNG vehicles, despite having been awarded the “ECO” environmental label, were also amongst the biggest polluters. Although the local pollution that they produced was lower than that of diesel vehicles, because their nitrogen oxide emissions and particulate matter emissions were lower than those of diesel vehicles, their contribution to global pollution was greater because their carbon dioxide emissions were higher.

### 3.3. Ranking of Alternatives with Respect to the Goal of Sustainability

The aim of this study was to identify the best alternative, taking into consideration economic and environmental terms. The ranking of alternatives with respect to the goal of sustainability was obtained in Hipre 3+ software. The ranking by criteria is shown in Figure 5; meanwhile, Figure 6 shows the ranking of sustainability by sub-criteria.

The final results of the AHP multicriteria decision model indicate that, in economic and environmental terms, the plug-in electric vehicle is the most sustainable alternative for urban public road transport services, which is in accordance with [18–26]. The zero emissions of local pollutants and the low indirect emissions of carbon dioxide make the plug-in electric vehicle the cleanest alternative. Combining the emission results with the economic results, which are supported by low operating costs, shows that the plug-in electric vehicle is the most sustainable alternative for urban public transport. The electric induction vehicle is the second-most sustainable alternative because of its higher operating costs than plug-in electric technology.

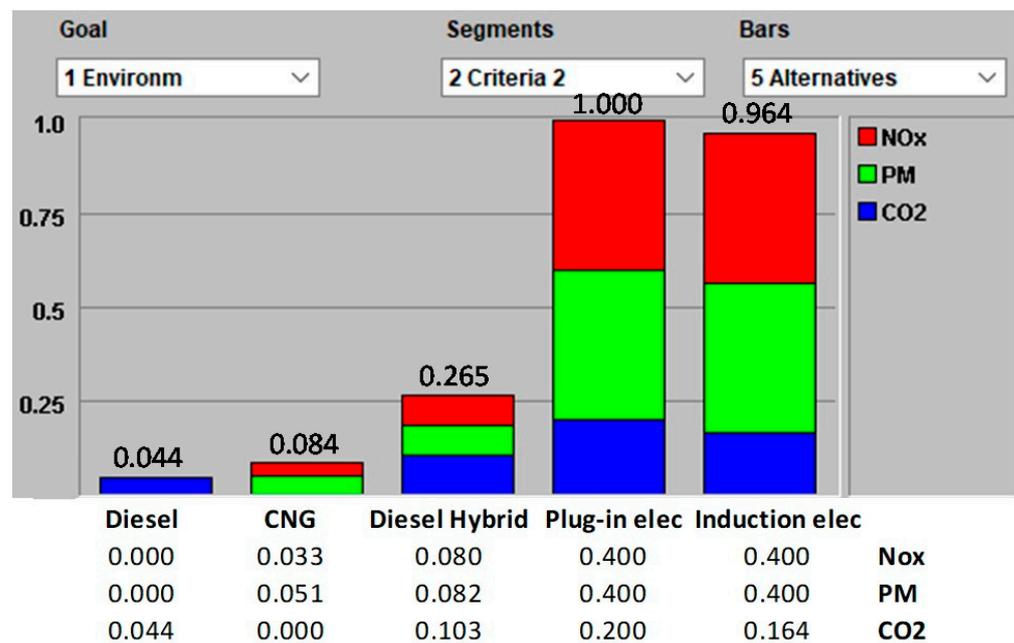


Figure 4. Results of the analysis for the environmental criterion.

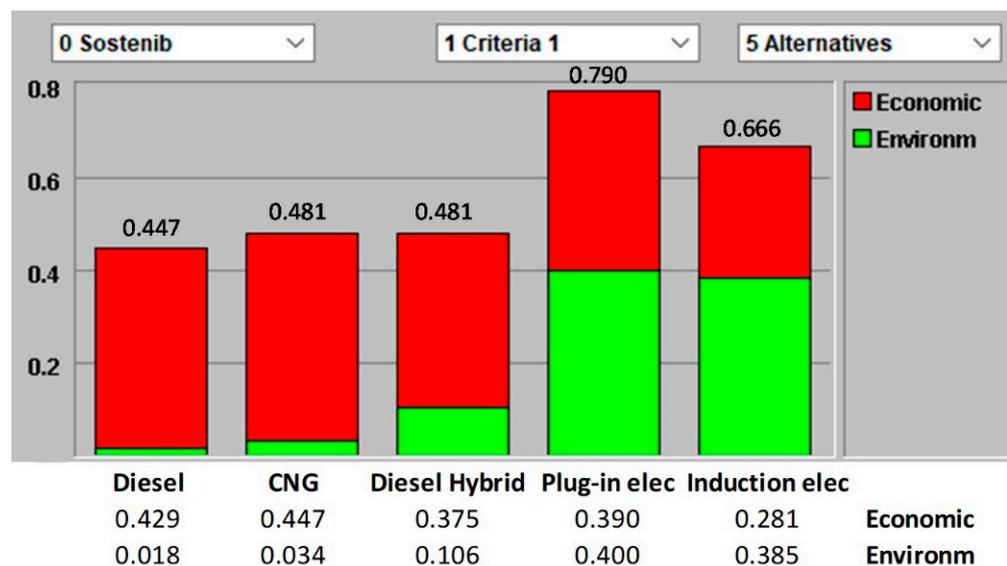


Figure 5. Final results of the analysis by criteria.

There is a significant distance between the first two vehicle technologies and the rest of the alternatives, which were heavily penalized for their reduced environmental benefits. Diesel, CNG, and hybrid vehicles were considered the least sustainable overall because of the importance attached to the environmental criterion, even though the environmental criterion had a lower weighting than the economic criterion. In the future, these technologies will be at even more of a disadvantage given the tendency to increasingly prioritize environmental criteria over economic criteria.

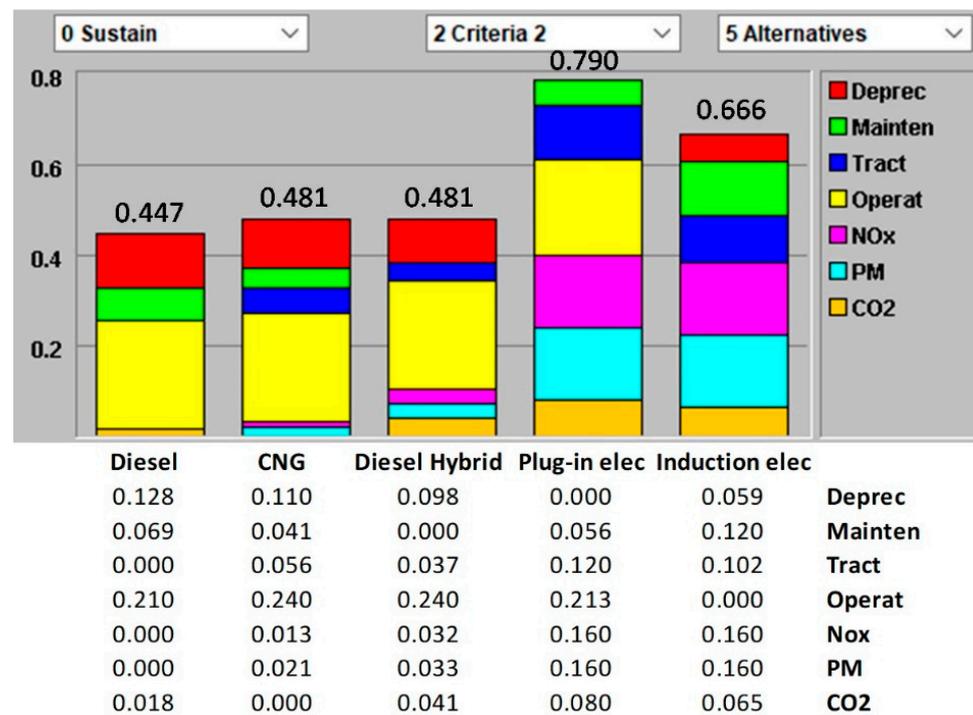


Figure 6. Final results of the analysis by sub-criteria.

#### 4. Conclusions and Recommendations

Nowadays, policymakers and companies also consider the environment as a criterion when making strategic decisions. Social concern for the environment is growing, which is forcing public and private firms to seek sustainability in both economic and environmental terms.

Criteria and factors involved with transport system sustainability were identified in this research to propose a model that illustrates the economic and environmental impact of alternative vehicles by transport technology.

The research shows that the most economically viable alternative is the CNG vehicle, whereas the most environmentally friendly alternative is the plug-in electric vehicle.

When both criteria are combined, the findings of the proposed model shed light on the plug-in electric vehicle as the most sustainable viable alternative for urban public transport.

Based on research results, the answers to the three previously posed research questions are:

Answer to Research Question I: The use of CNG vehicles in public transport is the best alternative in economic terms.

Answer to Research Question II: The use of plug-in electric vehicles in public transport is the best alternative in environmental terms.

Answer to Research Question III: The plug-in electric vehicle is the most sustainable alternative for urban public road transport services.

##### 4.1. Implications for Management

Although greater importance was attached to the economic criterion than to the environmental criterion in this analysis, the results indicate that the electric vehicle is the most sustainable.

Social concern for the environment is expected to continue to grow, which makes the electric vehicle the future of transport. However, converting the current vehicle fleet to a fully electric fleet is not feasible in the short and medium term.

Therefore, the commitment and collaboration of society on an individual and business level is also necessary to achieve real overall sustainability. Hence, raising awareness of the importance of sustainability is fundamental.

Connecting Nobel Laureate Amartya Sen dimensions for social sustainability [80] with previous research results, it can be concluded that public administrations should implement policies promoting public transport in cities in order to contribute to the social sustainability dimension of equity. If this transport is sustainable, it will also contribute to the social sustainability dimension of quality of life by being respectful of the environment and consequently of the quality of the air that we breathe. In addition, to the extent that public transport systems triumph and citizens use them in a majority way, it will also contribute to achieving the social sustainability dimension of maturity, which is related to the individual acceptance of the responsibility of consistent growth and improvement through broader social attributes.

In the transport sector in cities such as Madrid, public transport is a key tool to genuinely raise social awareness of the importance of sustainability. The fleet of public vehicles is where the shift from conventional to clean fuels should begin so that this shift can act as an example and the local government representatives in large cities such as Madrid may use the obtained results in their future strategic plans for developing public bus transport systems.

Public policies should favor the mobility of citizens based on sustainable public transport and not on private transport. Additionally, to invest in plug-in electric vehicles for urban public road transport services, which has been hereby identified as the most sustainable alternative, it is required to invest in research and development policies to develop renewable energies that can run electric buses, subways, commuter trains, and even electric taxis.

Governments should encourage citizens to have a social conscience and, from the point of view of transport in cities, to opt for forms of mobility that improve the quality of life of the general population. Commitment, effort, and collaboration by the public and its local administrations to achieve sustainability are the only way to ensure that the ability of future generations to meet their own needs is not compromised.

#### *4.2. Research Limitations and Future Lines of Research*

Finally, not all urban public road transport companies attach the same importance to environmental considerations as the importance these considerations are given in this analysis. The main research limitation, which could be an inspiration for future lines of research, is that other factors that were not considered in this research also influence the strategic decisions of managers and policymakers. Many of them opt for CNG and hybrid vehicles, which were awarded the “ECO” environmental label [81]. Although these vehicles contribute to local and global pollution, this label means that companies that use this type of vehicle have a social image that is almost as good as the image of companies that use electric vehicles, yet also achieve much better economic profitability. Nevertheless, replacing diesel vehicles with vehicles that use alternative fuels is beneficial for the quality of city air.

Besides previous lines of future research, new avenues for research in this field should, on the one hand, evaluate the introduction of green energy alternatives in urban public road transport services, such as solar energy, and on the other hand, update the multi-criteria decision model proposed in this analysis, taking into account the aforementioned limitations, the continuous innovations in the automotive sector, and upcoming fuel alternatives.

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## Appendix A

**Table A1.** Dossier of relevant information for panel members: studies of the sector.

Reference	Title of the Publication
[82]	Do you know when sustainability is born?
[83]	Greenhouse effect, global warming and climate change.
[84]	Carbon Footprint Measurement Methodology.
[85]	Mauna Loa Observatory.
[86]	What is global warming?
[87]	Empirical study of the willingness of consumers to purchase low-carbon products by considering carbon labels.
[88]	A review of carbon labeling: standards, implementation and impact.
[89]	Green House Gas Predictions.
[90]	Effects of ozone on health.
[91]	Prospects of carbon labelling—a life cycle point of view.

## Appendix B

**Table A2.** Dossier of relevant information for panel members: European regulations on environmental impact.

Reference	Title of the Publication
[92]	Sulfur dioxide environmental evaluation.
[93]	Tropospheric ozone precursor gases environmental evaluation.
[94]	Suspended particles environmental evaluation.
[81]	ECO environmental label.
[79]	Carbon footprint registry, compensation and CO <sub>2</sub> absorption projects.

## Appendix C

**Table A3.** Dossier of relevant information for panel members: reports on strategic guidelines for private and public organizations.

Reference	Title of the Publication
[95]	Sustainable development objectives for companies.
[96]	Sustainable urban mobility plan of the city of Madrid.
[97]	Madrid City Council transport company acquires 200 new buses.
[98]	Decision process of the Madrid City Council on the air quality plan.
[99]	Air quality and climate change plan of the Madrid City Council.
[74]	Nitrogen dioxide and health.
[78]	Electric car battery types.
[77]	Zebra batteries, another alternative for electric vehicles.
[100]	Spain ratifies its signature to the Kyoto protocol until 2020.

## Appendix D

**Table A4.** Data on requirements by type of fuel.

Alternative	Kms Traveled	Hours in Service	Number of Vehicles
Diesel	1,160,198	94,568	23
GNC	1,160,198	94,568	23
Diesel hybrid	1,160,198	94,568	23
Plug-in electric	1,187,888	96,001	31
Induction electric	1,172,226	112,873	27

Source: compiled by the authors based on data from the Madrid public road transport company [40].

## Appendix E

**Table A5.** Data for the analysis of depreciation costs by type of fuel.

Alternative	Purchase Price (EUR/Bus)	Service Life (Years)	Depreciation (EUR/Year)	Infrastructure (EUR/Year)
Diesel	250,000	12	20,833	-
GNC	290,000	12	24,167	-
Diesel hybrid	340,000	12	28,333	-
Plug-in electric	550,000	12	45,833	-
Induction electric	425,000	12	35,417	EUR 4250/year

Source: compiled by the authors based on data from Madrid public road transport company [40].

## Appendix F

**Table A6.** Data for the analysis of traction costs, before taxes, by type of fuel.

Alternative	Consumption	Price of Fuel	Traction (EUR/km)
Diesel	0.5425 L/km	EUR 0.76/L	0.4101
GNC	0.5958 kg/km	EUR 0.48/Kg	0.2875
Diesel hybrid	0.4340 L/km	EUR 0.76/L	0.3281
Plug-in electric	1.4217 kWh/km	EUR 0.10/kWh	0.1422
Induction electric	1.8303 kWh/km	EUR 0.10/kWh	0.1830

Source: compiled by the authors based on data from the Madrid public road transport company [40].

## Appendix G

**Table A7.** Average emissions of pollutants by type of fuel.

Alternative	NOx Emissions (mg/km)	PM Emissions (mg/km)	CO <sub>2</sub> Emissions (kg/km)
Diesel	980.86	3.37	1.37
GNC	899.54	2.93	1.58
Diesel hybrid	784.68	2.69	1.09
Plug-in electric	-	-	0.61
Induction electric	-	-	0.79

Source: compiled by the authors based on data from Madrid public road transport company [40].

## Appendix H

**Table A8.** Performance and emissions factors by type of fuel.

Alternative	Diesel	GNC	Diesel Hybrid	Plug-In Electric	Induction Electric
Approved emissions factor (kg CO <sub>2</sub> /L)	2.52	0.203	2.52	-	-
Lower heating value (KWh/kg)	10.1	13.1	10.1	-	-
Engine efficiency	40%	30%	40%	-	-
Emissions factor of type approval for NOx	0.4475	0.38417	0.4475	-	-
Emissions factor of type approval for PM	0.00154	0.00125	0.00154	-	-
Emissions factor (electricity mix: kg CO <sub>2</sub> /KWh)	-	-	-	0.43	0.43

Source: compiled by the authors based on data from the Madrid public road transport company [40].

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