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Article

Assessment of Sustainable Mobility Initiatives Developed in Montevideo, Uruguay †

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Abstract: This article presents an assessment of sustainable mobility initiatives developed in Montevideo, Uruguay, in the period from 2020 to 2023. The significance of sustainable mobility is underscored due to its far-reaching implications for the environment, energy efficiency, and the overall quality of life of citizens. This study focuses on crucial aspects of four initiatives deployed in Montevideo in 2020–2023: electric mobility solutions using scooters, the development of infrastructure and services for urban cycling, the development of electric public transportation, and private electric transportation. Important results are obtained and commented on for each of the studied initiatives, regarding efficiency, environmental impact, accessibility, the quality of the service, and other relevant indicators. Based on the analysis, valuable knowledge is acquired to guide the future development of efficient and sustainable transportation modes in Montevideo, Uruguay.

Keywords: sustainable mobility; smart cities; case study

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1. Introduction

In the last thirty years, there has been growing global recognition among cities regarding the significance of sustainable transportation to confront important urban mobility challenges and enhancing the well-being of citizens [1]. As a result, numerous noteworthy initiatives have been developed, including the encouragement of public transportation usage, the establishment of cycling and pedestrian infrastructures, the implementation of electric mobility solutions, and the integration of intelligent transportation technologies.

The study of sustainable mobility plays a vital role in the development of cleaner transportation methods and the assessment of their environmental impact [2]. The results from these studies help city planners and administrators optimize energy efficiency, improve connectivity and accessibility, ensure social equity, and promote healthier mobility alternatives and the integration of different modes of transportation. These endeavors align with urban planning strategies aimed at creating livable, resilient, and sustainable communities, ultimately enhancing the quality of life for citizens. Sustainable mobility is one of the sustainable development goals (SDGs). SDGs provide a framework for cities to prioritize sustainability in their development strategies, with specific targets. By embracing sustainable mobility initiatives, cities contribute to the advancement of these goals, fostering a more inclusive, resilient, and environmentally responsible urban environment. This integration of sustainable mobility practices not only improves the daily lives of residents but also contributes to broader global efforts toward a more sustainable future [3].

This article builds upon our initial study of sustainable mobility in Montevideo [4], exploring pertinent issues of sustainable mobility initiatives: the analysis of the unsuccessful implementation of an on-demand electric scooter (e-scooter) service, an in-depth analysis of the expansion of cycling infrastructure and services, an evaluation of newly deployed electric bus lines in the city, and the study of the development of private electric transportation. The main goal is to offer relevant insights and suggestions to inform the development of sustainable mobility options in Montevideo. This research is very relevant, considering that no global Sustainable Urban Mobility Plan has been proposed for Montevideo. The development of sustainable mobility has been performed through different initiatives, which are not always coordinated, under the Mobility Plan proposed for the city [5].

The key findings of the analysis reveal that sustainable mobility initiatives in Montevideo have progressed slowly, partly due to external factors and policy shortcomings. Efforts made in the development of electric bus lines and the expansion of urban cycling infrastructure have not reached a consolidated stage. The applied business model for the e-scooter service faced significant problems, particularly concerning safety, coverage, and affordability, that resulted in the discontinuation of the service. Furthermore, inadequacies in policy implementation and some externalities have hindered progress. Taxation, regulation, and subsides play critical roles in shaping the success of new business models [6]. Some externalities, like subsides, have a positive impact on the success of sustainable mobility initiatives, but regulations and taxation can affect or slow down their development.

The cycling infrastructure deployed between 2020 and 2023 extended the network, but several concerns still exist regarding connectivity, maintenance conditions, and intermodal connection. Montevideo is still way behind other Latin American cities in terms of the extent and quality of its bicycle network. The technical evaluation of electric buses in Montevideo indicates adequate operational efficiency and energy efficiency. However, the implemented electric lines do not provide service to the entire city, leaving important neighborhoods without access to electric public transportation benefits. Electric private transportation has developed quickly, and the forecasts are promising for the next decades.

This article has the following structure: The next section gives an overview of the key concepts of sustainable mobility and reviews the relevant literature on the subject. Section 4 outlines the applied methodology and details about the main features of the initiatives analyzed in this study. The analysis itself is presented in Section 5, along with relevant results and discussions. Finally, Section 6 summarizes the research findings, presents the conclusions drawn from this study, and outlines potential areas for future research.

2. Sustainable Mobility

Sustainability has emerged as a significant concern for contemporary society. It has evolved into a vital aspect for communities due to its direct impact on the quality of human life [7]. There is growing recognition of the central issues and threats posed by environmental problems, which further underscores the importance of sustainability.

Sustainability encompasses three main concepts: the environment, equity, and economics [8]. Recognizing the significance of these three dimensions allows for a holistic approach to sustainability. By considering the interconnections and interdependencies between these concepts, societies can strive towards a sustainable future that harmonizes environmental stewardship, social equity, and economic prosperity and perform specific actions in the present to preserve the environment for future generations [9]. Sustainability is within the broader concept of sustainable development, defined as the process of improving the quality of life of current and future generations by integrating economic growth, social inclusion, and environmental protection [10,11].

Among many other key aspects of sustainability, sustainable mobility plays a pivotal role in achieving the overall objectives of sustainability and sustainable development. The concept of sustainable mobility encompasses a range of strategies and guidelines aimed at fostering a transition in transportation systems towards more environmentally and socially conscious mobility options [1]. Sustainable mobility addresses the detrimental effects of conventional fossil fuel transportation on the environment, public health, and the general well-being of individuals, in line with SDG Target 11.2, to provide access to safe, affordable, accessible and sustainable transportation systems, specially focusing on the needs of vulnerable persons. This paradigm centers around the promotion of transportation methods that minimize energy usage, decrease greenhouse gas emissions, and prioritize the welfare of both individuals and communities.

Sustainable mobility plays a vital role in modern smart cities, as highlighted in recent research articles [12,13]. The paradigm is based on several key principles. These include the promotion and development of public transportation systems, the emphasis on active modes of transportation like walking and cycling, the incorporation of clean and energy-efficient technologies (e.g., electric vehicles), and the development of multimodal systems. Collectively, these principles represent a comprehensive approach to transportation that aims to reduce its impact on the environment, improve the quality of air, improve public health, and foster inclusive and livable communities. Achieving these goals requires a synergistic combination of technological advancements, policy measures and regulations, changes in behavior, and investments in infrastructure. From the perspective of citizens, the main purpose is to recognize and prioritize mobility as a valuable activity [1]. Simultaneously, the shift towards environmentally friendly cities and the adoption of decarbonized solutions and technologies for mobility contribute to the development of more livable communities. This development involves leveraging sustainable transportation solutions, particularly focused on bicycles and walking [14], and new urbanization models. Through this, cities can enhance their long-term economic and environmental resilience [15].

In particular, the socioeconomic aspect plays a crucial role in formulating effective mobility strategies that ensure equitable access to opportunities such as employment, education, culture, and recreation through public transportation. Sustainable mobility is closely connected to mitigating climate and environmental impacts, promoting energy efficiency, fostering innovative urban planning, and addressing several social–economic concerns like equity, safety, inclusion, health, and economic implications. By addressing these factors, sustainable mobility endeavors to enhance the overall quality of life of citizens.

3. Related Work

Many studies have studied sustainable mobility and its impacts in developed countries. Researchers have focused on assessing the environmental, economic, and equity-related consequences of sustainable mobility practices. Key factors, such as greenhouse gas emissions, air pollution levels, socioeconomic implications, and fairness, have been specifically analyzed in these studies, as evidenced by previous research conducted by Johnston et al. [16] and Ravagnan et al. [17]. By examining these aspects, researchers strive to gain a better understanding of the positive effects of sustainable mobility. These positive effects include reducing environmental harm, promoting economic well-being, and ensuring equitable access to transportation options for all members of society. Moreover, extensive analysis has been dedicated to evaluating the alignment of public transportation initiatives with sustainable development goals and exploring the contribution of smart city concepts to enhance the sustainability and appeal of public transportation systems, as highlighted by Bieliska et al. [18]. These studies have delved into the significant challenges, crucial problems, and associated benefits of sustainable mobility. The findings derived from these studies offer valuable insights that can be applied in the development of Mobility Plans and the design of sustainable public transportation systems, ultimately contributing to the realization of more sustainable and efficient transportation options. Previous research conducted by Miller et al. [19] has played a significant role in expanding the knowledge in this field.

In Latin America, several studies have focused on promoting sustainable mobility and reducing car dependence. Rodrigues et al. [20] developed an index to assess sustainable mobility in Brazilian cities in order to evaluate the adoption of sustainable transportation practices. In Colombia, Lyons [21] examined the effective implementation of sustainable mobility initiatives in Bogotá in order to reduce reliance on automobiles. Huertas et al. [22] developed a methodology for assessing sustainable mobility from relevant factors in Latin American countries. The methodology incorporated technological tools and considered economic, environmental, and social aspects. The approach was evaluated in a medium-sized city in Mexico, and the authors emphasized its replicability at a minimal additional cost in other cities. These studies in Latin America provide valuable insights into the efforts being made to promote sustainable transportation and reduce car dependency in specific urban areas.

Our article [23] developed a comprehensive study of sustainable public transportation initiatives implemented in Montevideo, Uruguay, until 2020. Quantitative (coverage, accessibility, and affordability) and qualitative indicators (public finance, integration, comfort, and pleasure) were computed for three sustainable mobility initiatives developed in Montevideo, providing an initial characterization of sustainable mobility and offering specific recommendations for developing sustainable Mobility Plans. A mobility analysis was conducted for a residential zone in the Parque Rodó neighborhood of Montevideo, Uruguay [24], employing the paradigm of Transit-Oriented Development (TOD) [25,26]. The research studied the inter-relationships between the urban environment, urban activities, and mobility indicators, with a particular focus on sustainable mobility. Various methods, including the analysis of urban data, conducting mobility surveys, and performing inspections of the infrastructure on-site, were utilized to assess the mobility demands, the use of different transportation modes, the land use patterns, and the condition of existing infrastructure for mobility within the study area [27,28]. The Parque Rodó neighborhood showed positive values for essential TOD indicators, indicating a solid base for the implementation of cleaner and environmentally friendly transportation systems. The study highlighted specific weaknesses and shortcomings, providing targeted recommendations to address these issues and enhance the overall sustainability of the transportation system in the area.

4. Description of the Studied Modes and the Applied Methodology

This section describes the studied sustainable transportation modes and outlines the methodology used for the analysis in the considered case study (Montevideo, Uruguay).

4.1. Overall Considerations

The description of the studied sustainable transportation modes was based on relevant articles from the related literature. In turn, the methodology employed for analyzing and assessing the technical viability of the studied sustainable transportation modes was based on studying the main aspects and issues identified as relevant in the related literature.

The main goal was to understand the reasons and factors that promote the use of the studied sustainable transportation modes, and also identify obstacles and opportunities for the development of each mode. For these reasons, each mode was analyzed considering some relevant factors that are common for them (e.g., environmental impact, economic cost, and travel time), and others that mainly apply to one or two of the studied transportation modes (e.g., operational and energy efficiency for electric public transportation).

The following subsections describe the factors considered in the analysis of each mode.

4.2. Electric Scooters

In the last ten years, electric scooters gained prominence in urban transportation. They provide a convenient and environmentally friendly option for short-distance commutes, particularly for the last-mile segment [29]. According to the National Association of City Transportation Officials (NACTO), shared e-scooters doubled the number of shared micromobility trips in the USA in 2018 [30]. E-scooters provide users with a self-sufficient transportation mode to replace walking and reduce travel time for their journeys [31]. E-scooters are also an alternative for short trips, reducing congestion and enabling public transportation to focus on longer trips [32]. The shared e-scooter service is highly appealing for users of other mobility services, such as car-sharing, that must perform trips of up to 3 km [33]. Furthermore, e-scooters act as a complement to existing public transportation systems, effectively providing feeder services, and as a connecting link between the (larger) public transportation network. Scientific publications and technical assessments from cities that have adopted shared e-scooters have identified relevant factors for this analysis. In this regard, the main methodological aspects to study are described next.

Characteristics of e-scooter users. Articles that have examined e-scooter services around the world have found that e-scooter users are predominantly male, young, from higher-income households, and possess higher levels of education [34,35]. Women tend to exhibit less interest in riding e-scooters [36], and have more safety-related concerns compared to men [37]. Regarding age, a younger age is a significant factor in e-scooter adoption [38]. Generally, e-scooter usage tends to decline as age increases [39]. However, older adults who initially try riding an e-scooter often become frequent users [36]. Although e-scooter usage patterns vary among different user groups, some users may rely on e-scooters as their primary mode of transportation, while others may use them occasionally for specific purposes, such as delivery operations [40] or as a recreational activity.

Characteristics of e-scooter trips. E-scooter trips vary across different cities and regions, depending on local factors such as infrastructure, regulations, and user preferences. However, some common characteristics have been found in related studies. E-scooter trips are typically short-distance journeys, i.e., last-mile trips. They are commonly used for distances within a few (3) km or less. E-scooter trips tend to be relatively short in duration, usually lasting between a few minutes to a maximum of half an hour, since they are primarily used for quick and convenient transportation over short distances. Studies also have shown that the length of e-scooter trips is influenced by the cost of the service [41].

Spatial distribution and service operation. The analysis of case studies showed that the majority of e-scooter trips predominantly take place in the city center and other central areas with high mobility demands [42]. E-scooters are predominantly found in areas characterized by high population density, abundant job opportunities, and a diverse range of activities. This operational strategy is rational as these areas experience higher usage rates, making them more profitable for businesses. However, the imbalanced distribution of shared e-scooters restricts access for a significant portion of the population [43], exacerbating transportation inequities rather than addressing existing shortcomings [44,45]. Certain barriers are associated with e-scooter services, including restricted deployment areas, limited availability of scooters at pickup points, technical problems, and high pricing.

Purpose of trips and peak usage. E-scooters are frequently used for a variety of purposes, including commuting to work or school, running errands, or leisure rides within urban areas. They are particularly popular for short and convenient trips within busy city centers. E-scooters are often also used for intermodal mobility, in combination with other modes of transportation, such as buses, trains, or bicycles, to complete a longer journey. E-scooters provide a convenient option for the last-mile connection between transit stops and final destinations [46]. The analysis of peak usage times indicated that e-scooters are commonly used during peak travel times (morning and evening commuting hour) as well as during lunch breaks and on weekends when people engage in leisure activities and social outings.

Safety. Safety is one of the main factors that deters potential riders from fully adopting shared e-scooters [36,37]. The feeling of insecurity primarily arise from interactions with motorized vehicles, urging a demand for better-separated infrastructure for micromobility and improved road conditions. Commuters who have not experienced e-scooters often feel negative perceptions regarding safety, due to a lack of familiarity with the operation of vehicles. Limitations imposed by certain characteristics of e-scooters, such as inconvenience in adverse weather conditions and being uncomfortable for long trips or when carrying goods, further discourage potential riders. Two controversial measures are the prohibition of riding on sidewalks when no specific infrastructure is available for e-scooters (forcing e-scooters to share the road with cars and other motorized vehicles), and the establishment of fixed parking locations that restrict the flexibility of door-to-door trips [47].

Cost-effectiveness and business model. In general, e-scooters tend to be more economical than public transportation and bicycle-sharing systems, particularly for short distances (e.g., 2 km). For example, a study developed in Chicago, USA, showed that e-scooters become expensive when the trip exceeds 1.5 km [48]. NACTO confirmed this result by indicating that shared scooter cost is significantly higher than that for shared bicycles, nearly doubling the price for an equivalent trip distance [30]. Additional limitations include the limited diversity of payment methods, the requirement of owning a smartphone for using the service, the lack of integration with smart cards used for public transportation, and inadequate information regarding the regulations for the service [49].

Environmental impact. E-scooters entered the mobility market as a sustainable transportation solution, which serves as a motivating factor for some users. However, studies that have applied Life Cycle Assessments have revealed various environmental concerns associated with e-scooters [50,51]. Based on current usage patterns and operational practices, there is a debate about if the e-scooter service leads to a reduction in environmental impact compared to the motorized transportation modes they replace [52]. Gebhardt et al. [53] found that the potential savings on greenhouse gas emissions when switching to e-scooters is low, 1.2% less than using gasoline cars, and that the reductions heavily depend on the usage patterns. Moreover, e-scooters can be more polluting than battery electric-powered cars, potentially steering the transportation system towards less sustainable mobility means.

Despite the reservations about the riding experience, economic cost, and safety, studies have shown that certain demographic groups, i.e., young people and those with medium–high incomes, are likely to overcome these concerns and become regular users of e-scooter systems [37,54].

4.3. Urban Cycling

Cycling has witnessed a substantial global increase over the past decade, and it is perceived as a viable and sustainable mode of transportation [55,56]. Several factors have contributed to the increase in cycling worldwide, including the development of dedicated bicycle lanes and paths, the implementation of bicycle-sharing systems, the adoption of new technologies and increased safety measures, and the promotion of active transportation by governments and organizations as a way to improve health and environmental awareness.

The surge and increased use of bicycles is a worldwide phenomenon. It has been observed in cities with a cycling tradition and in those where cycling was not previously a common mode of daily transportation. Notable samples include European cities, such as Amsterdam, London, Paris, and Vienna; North American cities, such as Chicago and Portland; and also Latin American cities, such as Bogotá, Rio de Janeiro, Santiago de Chile, Mexico City, and Buenos Aires [57]. Several relevant factors are considered in the related literature for the evaluation of cycling in smart cities, focusing on the development of cycling infrastructure, safety, accessibility, integration, environmental impact, and policy and regulations [58]. The main topics related to these factors are commented on next

Cycling infrastructure. The existence of cycling infrastructure is the primary factor often assessed to determine the effectiveness of strategies to promote cycling. Several infrastructure deployments are considered, including bicycle lanes, bicycle paths, parking facilities, workshops for self-maintenance, etc. The directness evaluates how efficient the cycling infrastructure is, in terms of providing convenient and time-saving routes for cyclists and minimizing detours and unnecessary diversions. It is also important to evaluate the proper integration of infrastructure with the urban environment, taking into account aesthetics and landscaping considerations. Another aspect to consider is the land uses of the surrounding areas, following the main concepts of TOD, to determine the bikeability of the zone [59] and the sustainability of the infrastructure [60]. It is crucial to evaluate the maintenance condition of cycling infrastructure, assessing the quality of the pavement, the implementation of regular maintenance practices, and the promptness of repairs.

Comfort and convenience. Relevant factors to evaluate comfort and convenience include the smoothness of bicycle lanes or paths, the provision of amenities (resting areas, bicycle parking), and the presence of facilities like bicycle-sharing or repair stations. The historical evolution of cycling infrastructure installation must be considered to determine if cycling is properly promoted and actively under development in the city. Evaluating the adaptability and the future growth is crucial for dynamic and well-planned cycling infrastructure, taking into account population growth in advance, ever-evolving mobility demands, and the existing options for expanding and modifying the existent infrastructure, in case it is needed. From the evaluation of the aforementioned factors, important outcomes are made available to policymakers, urban planners, and researchers to assess the effectiveness and quality of the cycling infrastructure. The resulting outcomes are very relevant to making informed decisions regarding the development and improvement of cycling infrastructure.

Safety. Safety is a major concern for cycling. The perceived risk of traveling alongside motor vehicle traffic is a significant obstacle to increased cycling participation [61]. Therefore, a crucial strategy for promoting cycling, particularly among vulnerable and risk-averse population segments, has been the establishment of dedicated off-road lanes for bicycles, mixed-use paths shared with pedestrians, and protected on-road cycling facilities that are physically separated from motor vehicles by barriers or buffer zones. This approach requires substantial investments in expanding and enhancing cycling infrastructure. The installation of clear signage and ensuring proper lighting and adequate visibility for both cyclists and motorists are relevant issues too [62]. In turn, ensuring appropriate width for cycling lanes and paths is important for accommodating cyclists comfortably and safely, allowing for overtaking and maneuvering, and reducing the risk of conflicts with other road users. Proper line width contributes to the overall effectiveness and usability of cycling infrastructure [63]. These factors play a crucial role in enhancing safety and communication between road users, contributing to a more efficient and secure cycling experience.

Cost-effectiveness. The cost-effectiveness evaluation must consider the financial investments required for planning, construction, and maintenance, in relation to the benefits and usage levels of the infrastructure [60,64]. Sophisticated and complete cost–benefit analyses for cycling infrastructure are relatively limited, and are less common than those for automobile and public transportation systems [65]. Key considerations for cost–benefit analyses involve assessing how a modification in cycling infrastructure affects factors such as cycling route preferences, transportation mode selection, potential destination choices, and the generation of new mobility demands. Additionally, it is important to evaluate the impact of the number of bicycles that will potentially use each link on a given or projected bicycle network [66]. To capture the influence of cycling infrastructure and the required investments, generalized cost models must be applied that take into account mode and route choice, and the main features of the studied area.

Connectivity and multimodality. Finally, it is crucial to evaluate the connectivity between vital destinations such as residential areas, business districts, education centers, parks, and public transportation hubs. The connectivity between key destinations is crucial for creating a comprehensive cycling network [64]. The evaluation involves assessing how well cycling infrastructure integrates with other transportation modes, particularly public transportation systems. Seamless transitions between cycling and walking, i.e., providing easy access to bicycle racks or sharing stations near bus stops or train stations, encourage combined bicycle and transit trips. This integration promotes the use of bicycles as a first-mile/last-mile solution, allowing commuters to conveniently switch between cycling and public transit for their daily journeys [67]. Additionally, providing adequate bicycle parking facilities at public transit stations is essential for encouraging and promoting multimodal transportation and enhancing the overall effectiveness of the cycling network. Moreover, evaluating and improving the integration of cycling infrastructure with key destinations extends beyond transportation hubs. It encompasses facilitating access to important locations such as schools, business districts, recreational areas, and residential neighborhoods. By providing safe and direct cycling routes to these destinations, cycling becomes a practical and attractive option for various purposes, including commuting, leisure, and social activities. The development of bicycle-sharing systems is another relevant factor to consider in modern cities to reduce the dependence people have on non-sustainable means of transportation [68], and also to increase livability and sustainability.

4.4. Electric Public Transportation

For the analysis of electric public transportation, the literature has identified several relevant factors related to sustainability, technology assessment, and operational strategies for a proper business model [69,70]. Manzolli et al. [71] concluded that the main lines of research on electric public transportation are related to the dimensions of environmental factors, economic factors, and the quality of the service; the efficiency and effectiveness of energy use; and fleet management and operation (scheduling, routing, and maintenance).

Environmental impact. It is important to evaluate the reduction in greenhouse gas emissions and air pollutants in comparison to traditional fossil fuel-powered buses [72]. This assessment should consider factors such as the source of electricity used for charging the buses and the overall lifecycle emissions associated with the manufacturing, operation, and disposal of the buses. Considering these factors provides a comprehensive understanding of the environmental benefits and sustainability of electric bus systems [73].

Cost-effectiveness. Another relevant factor is the economic feasibility of an electric public transportation system. The viability analysis of electric bus lines includes assessing the upfront costs of acquiring electric buses, installing charging infrastructure, and ongoing operational expenses. Additionally, considering factors such as potential savings on fuel costs and maintenance expenses over the lifespan of the buses is crucial [74].

Operational efficiency. To evaluate the operational efficiency of electric public transportation, it is necessary to analyze various factors, such as the energy consumption of vehicles; the efficiency of regenerative braking technologies; the distribution and accessibility of charging stations; the availability, charging speed, and energy efficiency of charging infrastructure; the operational range of vehicles regarding the considered line lengths; and the technology, energy storage capacity, and life of the battery installed on buses [75]. This evaluation helps ascertain the overall effectiveness and feasibility of electric buses in meeting transportation demands. By assessing these aspects, it becomes possible to gain insights into the operational performance and capabilities of electric bus systems [76].

Equity and accessibility. When assessing social equity and accessibility factors, it is important to analyze if the electric bus lines are effectively providing a proper mobility service to different communities, including suburban areas and neighborhoods with a lower socioeconomic reality [77]. This evaluation involves considering various aspects of accessibility, such as the location of bus stops, the frequency of the service, and the affordability of electric bus transportation across various demographic groups. By evaluating these factors, it becomes possible to determine if electric bus lines are providing equitable and accessible transportation options for all members of the community. The public perception of electric buses and their social acceptance play an important role in their adoption and success [78].

Passenger experience and comfort. Another important issue to consider is passenger experience and comfort when using electric bus lines. Several factors that contribute to overall satisfaction need to be assessed [79]. These factors include the existing noise and vibration levels, the capacity of vehicles (both for seated and standing passengers), the provision of air conditioning, and other comfort-related amenities. By understanding and analyzing these aspects, the evaluation allows one to determine if a positive and satisfactory travel experience is provided to commuters using electric bus services [80].

Integration. Finally, it is also important to assess the integration of electric bus lines with existing infrastructure by analyzing factors such as the compatibility of charging stations with the electrical grid, the availability of suitable depots, and the feasibility of integrating electric buses into existing maintenance and operational systems.

The mentioned factors are vital for assisting stakeholders in making well-informed decisions for implementing, operating, and optimizing electric public transportation systems. By considering these factors, stakeholders can maximize the benefits of electric buses and certainly contribute to the development of sustainable and efficient mobility. This analysis aids in identifying opportunities for improvement, addressing challenges, and guiding the development of strategies that align with sustainability goals and transportation objectives.

4.5. Electric Private Transportation

Several considerations described for electric public transportation are also important for electric private transportation. Additional factors include the economic analysis and the incentives and policies applied by the government. The main factors are described next.

Environmental impact. Those factors related to sustainability and environmental impact are crucial, especially considering that the number of private electric vehicles is several orders of magnitude higher than that of electric buses. Evaluating the overall reduction in emissions helps determine the environmental benefits of electric private transportation. Usually, Life Cycle Assessment methodologies are applied for a comprehensive evaluation of the environmental impact of electric vehicles [81]. These involve analyzing the environmental burdens associated with the production, use, and disposal of electric vehicles, including the extraction of raw materials, manufacturing processes, energy sources used in production, vehicle operation, and end-of-life management. The analysis considers emissions, energy consumption, and resource depletion, enabling a holistic understanding of the environmental footprint of electric private transportation [82].

Range and battery life. Considerations about range and battery life include the distance the vehicle can travel on a single charge and how long the battery retains its capacity over time [83]. These factors must be analyzed considering the particularities of the city, such as common-origin-destinations for trips, orography, and the quality of roads [84]. Both of them determine the practicality and usability of electric private transportation.

Charging infrastructure and support services. The availability and accessibility of charging infrastructure is essential for evaluating the development of electric private transportation. Factors to consider include the availability of charging stations, the charging speed, and the geographical location of charging points. The availability of different charging options (e.g., fast charging, level 2 charging) and the time required to fully recharge a vehicle influence the convenience and usability of electric private transportation. These factors help in determining whether the necessary infrastructure is in place to support electric private transportation, and it is a very relevant issue since the availability of private charging infrastructure influences the readiness to buy and use electric vehicles [85]. Regarding support services, the availability of maintenance and repair services and the support provided by manufacturers and dealerships are also very relevant.

Economic analysis. A proper cost–benefit analysis is crucial for understanding the financial implications of electric private transportation [86]. The main factors to evaluate include the purchase cost of electric vehicles, comparing them to conventional vehicles, and the potential savings in fuel and maintenance costs over the lifetime of vehicles [87].

Government incentives and policies. Assessing government incentives and related policies is also very relevant for a correct evaluation and development of electric private transportation [88]. Relevant factors to analyze, including financial incentives, tax credits, and the construction of dedicated infrastructure for electric vehicles, significantly influence the adoption and viability of electric private transportation [89].

By considering the described main factors, stakeholders can evaluate the feasibility, benefits, and challenges of electric private transportation and make informed decisions regarding its adoption, implementation, and development.

4.6. Methodology

The described factors were studied applying a methodology based on urban data analysis [90], considering several sources of data, both public and proprietary. A thorough review and analysis of existing information from the city administration, stakeholders, and transportation companies was performed. In turn, interviews with relevant actors were conducted. The data from our previous sustainable mobility survey [23] were also analyzed in the study of relevant factors. Comparative analyses were also are used as a main component of the applied methodology, and statistical analyses were applied, when corresponding. Finally, specific models were developed or adopted for the analysis of specific factors, such as business, energy efficiency, and environmental impact considerations.

5. Sustainable Mobility in Montevideo: Results and Analysis

This section discusses the results of the analysis conducted on the studied initiatives regarding sustainable mobility in Montevideo. The analysis was developed applying the methodology described in Section 4. Data processing was carried out using the high-performance computing platform of the National Supercomputing Center (Cluster-UY) [91].

5.1. Shared Electric Scooters in Montevideo

Uruguay introduced e-scooters as a mode of transportation six years ago (in 2018). Three companies introduced their services in Montevideo to offer and evaluate the reception of e-scooters. Whereas e-scooters offered a more environmentally friendly and user-friendly mode of transportation, the disadvantages outbalanced the perceived benefits for users. The e-scooter companies operated until 2019, and then made the decision to gradually discontinue their mobility services. The main features of the service were studied in our previous article [4], applying a quantitative approach considering various indicators. The analysis was complemented by several qualitative indicators to evaluate government regulations, subsidies and financial issues, the energy efficiency, and intermodal connectivity. The experience of shared e-scooters in Montevideo encountered significant challenges that hindered its operational success, as discussed in the following paragraphs.

Spatial distribution and socioeconomic characterization. The distribution of e-scooters in Montevideo reflected a common trend observed in many cities worldwide, where companies strategically deploy e-scooters in regions characterized by high economic indicators and income, densely populated areas, and areas with many job opportunities. In the case of Montevideo, the operational area of service for e-scooters was along the coast of Río de la Plata (the southern part of the city). This strategy aligns with profit objectives for companies, since these areas naturally have more potential users and experience higher utilization rates. However, in Montevideo, this concentration in specific areas caused an uneven e-scooter distribution, thereby restricting the accessibility for a significant number of citizens.

The Socioeconomic Level Index (INSE) [92] was used for the socioeconomic evaluation of neighborhoods in Montevideo. The INSE is a concise analytical instrument for assessing the economic situation of households, obtained through a short questionnaire [93,94]. The INSE classifies households based on their consumption capacity, ranging from 0 (representing the lowest socioeconomic level) to 9 (representing the highest socioeconomic level), to characterize neighborhoods according to their income levels. The mean value of the INSE in Montevideo is 4.5. The mean value of the INSE for neighborhoods served by the e-scooter service was 7.1 and all neighborhoods in the operation zone had larger INSE values than the mean value for Montevideo. Figure 1 clearly illustrates the trend, depicting the coverage area of the e-scooter service along the southern coast, which is predominantly inhabited by high-income residents. Darker shades of blue represent neighborhoods with a higher INSE value and lighter shades represent neighborhoods with lower INSE values.

Affordability. In line with the previous factor, the affordability of the system was also a problem for the consolidation of the e-scooter service. According to the average (time-based) fares for the e-scooter service, and considering a trip length of 12 min (the average travel time for using scooters), the cost of each trip is about UYU 60 (about USD 1.54, considering an average exchange rate of UYU 39 per USD in the period of 2019–2022). The cost of performing 45 trips (round trip for 22 or 23 business/education days in a typical working month) was UYU 2 700, which represents 12.4% of an average low-income salary (UYU 21,744, USD 558) and 7.6% of an average medium-income salary (UYU 35,444, USD 908). In turn, the cost of performing 60 trips was 16.5% of an average low-income salary and 10.1% of an average medium income. These values are significantly higher than owning a standard or electric bicycle, or using public transportation (two trips per day), as shown in Figure 2. A standard bus ticket price using a smart card of the Metropolitan Public System was considered (USD 1.10). Costs for e-bicycles correspond to a national electric bicycle, assuming one battery charge (36 V, 7.8 A/280 W) per day and a battery life expectancy of two years. Bicycle costs correspond to a standard national/international bicycle. Both bicycle costs are pro-rated to the expected life of vehicles (five years).

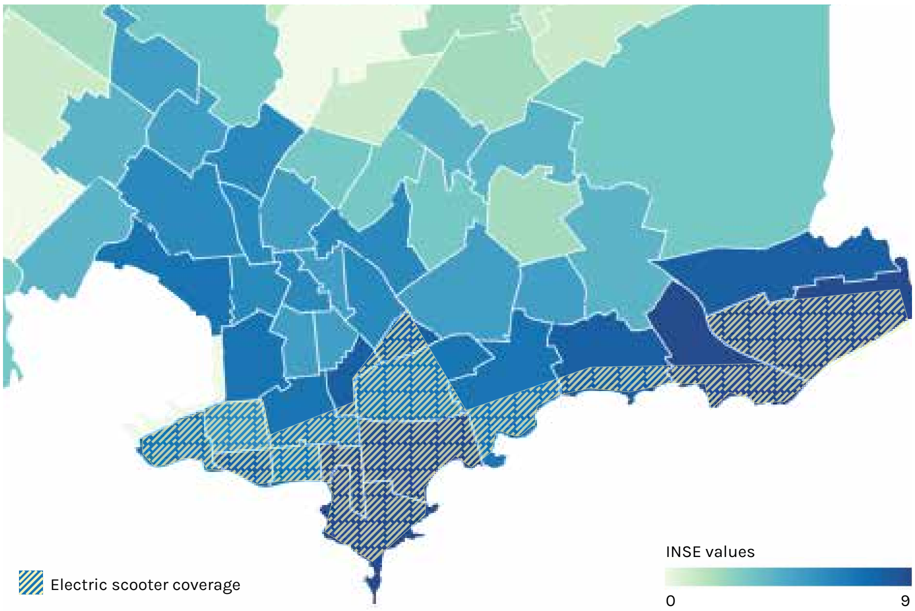

Figure 1. Coverage area of e-scooter service and INSE values for neighborhoods in Montevideo.

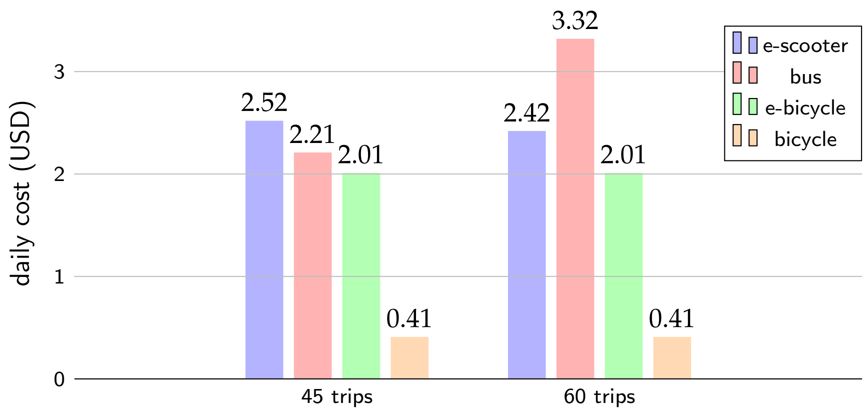

Figure 2. Cost comparison of the e-scooter service, bus, electric bicycle (e-bicycle), and standard bicycle in Montevideo. Comparisons are shown for common packages of 45 and 60 trips.

The cost of the e-scooter service was high, even prohibitive, for low-income citizens, especially considering that they are often used sporadically for rides and/or for first–last mile trips in multimodal mobility, which involves an additional cost (e.g., the cost of a bus ticket). Whereas e-scooters may be affordable for short trips for medium- and high-income citizens, the cost-effectiveness of the service diminishes for longer distances. As the fare charged users based on the distance traveled, the overall cost for longer trips became less favorable compared to other transportation modes, like buses, which offered flat-rate fares regardless of the distance traveled. The limited accessibility and affordability of the e-scooter initiative went against the principles of shared mobility, as it failed to provide a convenient and sustainable transportation option for a broad segment of the population.

Environmental impact. Important doubts were raised regarding the sustainability of e-scooters as an environmentally friendly mode of transportation in Montevideo. The practices employed by the e-scooter companies involved collecting scooters for charging and redistributing them using non-sustainable transportation (i.e., fuel-based) means.

Intermodal integration. In the case study of Montevideo, the limited coverage area for e-scooters created significant challenges in achieving meaningful intermodal integration. Users faced difficulties in efficiently combining e-scooters with other transportation modes, such as buses, to complete their journeys. This lack of integration hindered the overall effectiveness of e-scooters as an integral part of the transportation network. This limitation was an important drawback of the e-scooter service, since seamless intermodal transportation is a key component of a well-functioning urban transportation system.

Comfort. For trips outside the coastal promenade, users faced diverse topography, including hills and uneven terrain, which made longer rides less comfortable and physically challenging. Furthermore, users considered e-scooters to be inconvenient for long rides, or when they need to carry personal items. Inclement weather conditions, such as rain, strong winds, and extreme temperatures, have a notable impact on the usability of e-scooters, prompting users to choose more weather-resistant modes of transportation, such as buses.

User behavior and regulations. Other factors, such as the conduct of users of the e-scooter system while riding and parking vehicles, as well as their interaction with pedestrians and the environment, indicated the need for regulations to foster improved coexistence. The city government introduced specific measures to mitigate these concerns, including the definition of limited operational areas for e-scooters, the prohibition of riding e-scooters on sidewalks, the limitation of speed for e-scooters, and the enforcement of strict parking regulations. Other measures, such as mandating helmet usage and driver's licenses, were not effectively enforced during the brief period that the service was operating. These measures led to a significant decrease in user preference for e-scooters as a mean of transportation.

Commuting Travel Time. E-scooters were limited for long trips. When the distance grows, e-scooters became less suitable for commuting purposes [33,54]. In line with previous research that emphasized the ability of e-scooters to enhance travel time for trips, users in Montevideo perceived e-scooters as a viable option for trips up to 3 km. Beyond this, the comparatively low speeds of e-scooters in comparison to public buses impacted the overall travel time for commuters. Users found that e-scooters were not as time-efficient for longer journeys, diminishing their appeal as a primary means of daily transportation.

Safety. Consistent with findings in other zones of the city, the responses of commuters interviewed in the Parque Rodó neighborhood revealed that a prevailing sense of insecurity among riders is a notable impediment to the widespread adoption of e-scooters [4]. This insecurity primarily arises from interactions with motorized transportation means, underscoring the need for improved and segregated infrastructure and better road conditions to facilitate the growth of e-scooters for micromobility.

In conclusion, the unsuccessful implementation of a shared e-scooter service in Montevideo is attributed to a range of factors. Key issues included the limited spatial coverage of the service, the limitations for long trips, cost and comfort considerations, operational constraints, and regulatory challenges. Additionally, a lack of diverse payment methods, smartphone ownership requirements, poor integration with public transportation passes, and insufficient information regarding regulations hindered the adoption and usability of e-scooters. Collectively, these challenges hampered the viability and attractiveness of shared e-scooters as a sustainable mode of urban transportation in the city.

5.2. Urban Cycling

Urban cycling has been promoted as a healthy and sustainable transportation mode in Montevideo. The percentage of daily trips made by bicycle in Montevideo has shown a steady increase in the last decade, rising from approximately 1.5% in 2015 to less than 2% in 2017, out of a total of over three million trips daily. In 2022, a report from the city administration identified seven specific locations where bicycles accounted for as much as 4% of the total number of circulating vehicles [95]. The city boasts a bicycle population of over 300,000, owned by more than 100,000 individuals, with more than 80% of them relying on bicycles as their primary means of transportation. However, despite these promising statistics, the analysis reveals significant inconveniences that hinder urban cycling in Montevideo. These challenges include inadequate infrastructure, safety issues, poor connectivity, and a lack of modal integration, as described in the following subsections.

5.2.1. Infrastructure for Cycling

In the last decade, Montevideo took a commendable step towards improving its urban infrastructure by developing and expanding its bicycle network. This initiative exemplified the dedication of the city administration to promote sustainable mobility and offer its residents environmentally friendly and efficient transportation options. However, the cycling network deployed in the city has been inadequate to meet the escalating demands of a growing number of users. The survey of commuters in the Parque Rodó neighborhood [23] unveiled that a considerable portion of travelers are willing to transition from their current mode of transportation to cycling as a sustainable alternative.

Montevideo has implemented three types of cycling infrastructure that aim to enhance the safety and convenience of cyclists, namely the following:

- Bicycle lanes (*ciclovía*): these are designated sections of the road, typically a lane, exclusively dedicated to the circulation of bicycles.
- Bicycle paths (*bicisenda*): these are located on sidewalks, central flower beds, or landscaped areas; are separate from the road; and are exclusively designated for bicycle use.
- Streets with 30 km/h limits: This is when a speed limit of 30 km/h is enforced to promote coexistence with bicycles. Signage is installed to establish the priority of bicycles in the circulation.

From 2020 to 2023, significant progress was made in expanding the cycling network in Montevideo, in line with the goal of developing sustainable mobility and promoting cycling. However, certain aspects of the expansion of the cycling network require further attention. While progress has been made, the design of cycling lanes and paths has not yet met the established standards outlined in related studies, which play a crucial role in ensuring the safety and comfort of cyclists. Furthermore, the connectivity remains inadequate, with significant room for improvement.

In 2020–2022, new bicycle lanes were built on several important streets in the city:

1. In Luis Morquio (city center, Parque Batlle neighborhood), with a length of 0.5 km.
2. In Hocquart, from Arenal Grande to Bulevar Artigas (city center, La Comercial and Villa Muñoz neighborhoods), with a length of 1.4 km.
3. In Nueva Palmira, from Bulevar Artigas to Arenal Grande (city center, La Comercial and Villa Muñoz neighborhoods), with a length of 1.4 km.
4. In Isidoro de María, from Arenal Grande to General Flores (city center, Aguada neighborhood), with a length of 0.4 km.
5. In Luis Alberto de Herrera, from 8 de Octubre to Mazzini (city center, Parque Batlle neighborhood), with a length of 1.2 km.
6. In Belloni, from Perimetral to Instrucciones (north-east of the city, Villa Española neighborhood), with a length of 1.6 km.
7. In Cibils, from Route #1 to Tomkinson (west of the city, Las Torres and Paso de la Arena neighborhoods), with a length of 1.6 km.

In turn, new bicycle paths were built in other locations:

8. In Avenida Italia, from Gallinal to Albo (city center, Malvin, Buceo, and Parque Batlle neighborhoods), with a length of 5.9 km.
9. In Avenida Larrañaga, from the Hippodrome to Varela (north-east of the city, Ituzaingó and Villa Española neighborhoods), with a length of 2.5 km.
10. In Avenida Ricaldoni, from Vidiella to Morquio (city center, Parque Batlle neighborhood), with a length of 1.8 km.
11. In Bulevar Artigas, from Batlle Berres monument to Garibaldi (center to north of the city, Jacinto Vera neighborhood), with a length of 1.5 km.

12. In Avenida Larrañaga, from Varela to Joanicó (city denter, Larrañaga neighborhood), with a length of 1.9 km.
13. In Luis Alberto de Herrera, from Anador to Mazzini (city center, Parque Batlle neighborhood), with a length of 0.5 km.
14. In Cibils, from Ramírez to Route #1 (west of the city, Cerroa neighborhood), with a length of 2.6 km.

Finally, a new 30 km/h street was built in one location:

15. In Avenida Italia, from Gallinal to Bolivia (south-east of the city, Malvin and Portones neighborhoods), with a length of 1.5 km.

In 2023, a new bicycle lane was built on 18 de Julio, the main avenue of Montevideo, and San José street, connecting Plaza Independencia, the main square of the city where the House of Government is located, and the Obelisk, an emblematic monument located in Parque Batle, the main central park of the city. This bicycle lane has a length of 3.5 km.

Figure 3 shows the current cycling infrastructure in Montevideo and the new infrastructure constructed between 2020 and 2023. Table 1 provides details on the length of the newly built bicycle infrastructure in Montevideo during the period 2020–2023, based on information provided by the Mobility Observatory from Intendencia de Montevideo [96].

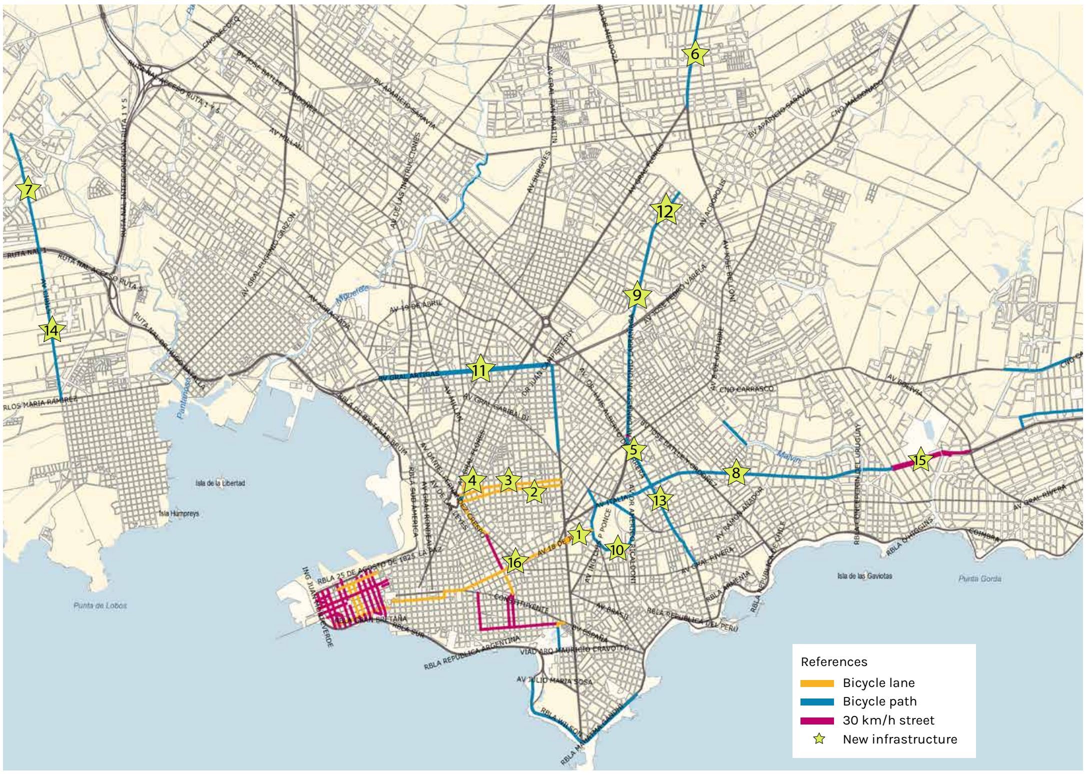

Figure 3. Infrastructure for cycling in Montevideo. Own design, base map from SIG Montevideo.

Table 1. Details of the cycling infrastructure in Montevideo (existing and built in 2020–2023).

Infrastructure Type	Existing (km)	New 2020–2023 (km)	Percentage	Over Total
bicycle lane	12.5	8.7	69.6%	0.32%
bicycle path	42.2	16.9	40.0%	0.98%
30 km/h street	16.6	1.5	9.0%	0.44%
total	71.3	25.8	32.6%	1.79%

The results in Table 1 show an important increase in bicycle lanes and paths in Montevideo in 2020–2023. The expansion of the bicycle network accounted for one-third of the

71.3 km within the city. However, this figure remains relatively small compared to the road network of Montevideo (3783 km) as shown in the last column in Table 1.

The cycling network in Montevideo accounts for a mere 1.79% of the road network. Furthermore, taking into account that 30 km/h streets are not considered fully safe for cycling because bicycles share the way with motorized vehicles without any physical separation, the percentage of dedicated cycling infrastructure is lower than 1.4%, which is a significantly low value in terms of built infrastructure specifically designed for cycling.

In comparison to other cities in the world, cycling infrastructure is significantly less deployed in Montevideo. For instance, Barcelona (Spain) has deployed an extensive network of dedicated paths for bicycles of more than 250 km, and the city has plans for 95% of its citizens to be within 300 m of a nearby bicycle path. Amsterdam (the Netherlands) provides over 500 km of infrastructure for bicycles, which has made cycling the first mode of transportation, accounting for a share of 36% and more than 700,000 daily bicycle trips. In Latin America, Bogotá (Colombia) has become a frontrunner in cycling infrastructure, offering an impressive length of 500 km of dedicated cycling infrastructure and a plan to expand the infrastructure to 800 km in two years. Buenos Aires (Argentina) has also made important advances, deploying over 250 km of cycling infrastructure that has contributed to the fast growth of cycling as a preferred transportation mode. Curitiba and Rio de Janeiro (Brazil), Mexico City, and Santiago de Chile have also made substantial investments in building and deploying cycling infrastructure. All of these cities are positioned ahead of Montevideo by a significant margin in terms of cycling infrastructure.

5.2.2. Safety and Maintenance

One of the most critical issues is ensuring adequate separation between cyclists and motorized vehicular traffic. Regrettably, this crucial safety measure is only implemented in a portion of the currently developed bicycle infrastructure. Protected cycling lanes separated from the roadway by physical barriers significantly reduce the risk of accidents and injuries for cyclists. The findings regarding lower risks on quiet streets and with cycling-specific dedicated infrastructure along busy streets provide support for the route-design approach commonly employed in countries in Northern Europe, where cycling is used as a primary mode of transportation [97]. Furthermore, it has been demonstrated that the risk of cyclist crashes and falls varies among different types of protected bicycle lanes. Specifically, bicycle lanes that feature a heavy separation from the road have been associated with a decreased risk, whereas other types of protected bicycle lanes are not effective at reducing the risk [98]. The safest options for cycling infrastructure are dedicated bicycle-only paths, which are separated from motorized traffic and exclusively designated for cycling, as well as cycle tracks, which are separate routes specifically designed for bicycles and not shared with motor vehicles. These types of infrastructure provide the highest level of safety for cyclists and they must be considered as the primary goal in extending the cycling network in Montevideo.

Ensuring appropriate lane widths for cycling infrastructure is another crucial factor to be addressed. Proper lane widths provide enough space for cyclists to maneuver and maintain a safe distance from other vehicles. Narrow lanes increase the risk of collisions, especially when vehicles invade the cycling lane. The recommended minimum width is typically 1.5 to 1.8 m for bicycle lanes. Wider bicycle lanes (e.g., 2 m or more) enhance safety and comfort, especially on high-volume or high-speed roads. On these heavy traffic roads, the construction of buffer zones between cyclists and motorized vehicles, which are not present in Montevideo, are are much needed on the main avenues (18 de Julio, Avenida Italia) and high-speed streets (Nueva Palmira, Hocquart, Fernández Crespo). The recommendation is wider (2.5 to 3 m) for physically separated cycling lanes.

Another relevant issue for safety is installing clear signaling, specifically designed for cyclists, to improve the guidance shown at intersections and areas where cyclists need to interact with motorized vehicles and pedestrians. Dedicated cyclist-specific signals are useful to indicate when it is safe for cyclists to proceed, helping to prevent conflicts and collisions with motorized traffic. By having separate signals that are positioned at appropriate heights and locations for cyclists, they are more likely to be noticed and acknowledged by all road users, reducing the risk of accidents. Cyclist-specific signals also increase the visibility of cyclists to other road users and improve the understanding of the intended actions to better comply with traffic regulations. Appropriate signals reduce ambiguity and confusion, ensuring that cyclists know when to stop, yield, or proceed, aligning their actions with the signals, and promoting a more orderly flow of traffic.

In general, there has been a satisfactory installation of signals in the cycling infrastructure deployed in Montevideo. However, newer infrastructures tend to have a higher number of clear, high-quality signals, whereas older bicycle lanes and paths often lack an adequate quantity of signals and they are not promptly replaced when damaged. Furthermore, the city lacks dedicated traffic lights installed for cyclists. Figure 4 presents two contrasting examples of adequate and inadequate signaling within the cycling infrastructure of Montevideo. In Figure 4b, although the bicycle path has the give-way signal for pedestrians, the adjacent street lacks any signal indicating the presence of the bicycle path.

(**a**) (**b**)

Figure 4. Examples of adequate and inadequate signaling within the cycling infrastructure of Montevideo (own photographs). (**a**) Bicycle path with proper signaling (location: 18 de Julio, aerial view). (**b**) Bicycle path without proper signaling (location: Avenida Italia).

Other specific issues have affected the normal safety of cycling infrastructure in Montevideo. For example, the bicycle lane on Avenida Italia has been used for driving cars and beacons have been installed along the lane. Cars and trucks are often parked in bicycle lanes, and large, city waste bins are even installed over bicycle lanes and paths.

The quality of the pavement in the cycling infrastructure is also very relevant. It is crucial to consider not only the pavement of bicycle lanes and paths, but also the overall condition of streets and roads where cycling infrastructure is absent. Unfortunately, many of these non-designated areas suffer from severe deterioration, creating hazardous conditions for cyclists during their commute. In this regard, three different situations happen in Montevideo. The new cycling infrastructure (constructed between 2020 and 2023) exhibits excellent or good quality pavement, well-maintained painting, and appropriate accessories. However, there have been reports highlighting specific cases of damaged pavement and poor signage. In turn, older bicycle lanes and paths experience infrastructure deterioration, faded painting, and inadequate signaling. Furthermore, numerous streets and avenues lacking dedicated cycling infrastructure, where cyclists must share lanes with other vehicles, suffer from poor pavement quality. This unfavorable condition presents challenges for cyclists traveling through such traffic routes, as exemplified in Figure 5.

(**a**) (**b**) (**c**)

Figure 5. Examples of different pavement maintenance conditions within the cycling infrastructure of Montevideo (own photographs). (**a**) Bicycle path with good quality pavement (location: 18 de Julio). (**b**) Bicycle path with deteriorated pavement (location: Avenida Italia). (**c**) Street with poor conditions for cycling (location: Bulevar Artigas).

5.2.3. Connectivity, Multimodality, and Socioeconomic Characterization

The cycling infrastructure in Montevideo is fragmented into multiple disconnected sub-networks, with several routes being significantly distant from the main core area. The construction of the bicycle lane on 18 de Julio in the last months of 2023 played a crucial role in connecting existing bicycle lanes and 30 km/h streets in the Downtown (Ciudad Vieja) area with the bicycle path in Parque Batlle, extending towards the east along Avenida Italia. This development served as a much-needed connection, facilitating smoother travel for cyclists. Currently, the most crucial connection that is needed is the construction of cycling infrastructure on Bulevar Artigas, spanning from Rambla to Nueva Palmira, to connect cycling infrastructures in the city center with those in the center–north. This infrastructure was approved in the participatory budget of the city government in 2013; however, it has yet to be built and deployed. Other bicycle lanes and paths in the west and in the north are very far away from the infrastructure deployed in the center. For example, the bicycle lane and bicycle path in Cibils (west of the city) would need 7.3 km of cycling infrastructure to be built to be connected with the nearest bicycle path in Bulevar Artigas. The bicycle path in Belloni (north of the city) would require building 2.3 km of cycling infrastructure to be connected with the nearest bicycle path in Larrañaga. Bicycle paths in Tajes and Camino Carrasco (east of the city) would need 1.9 km of cycling infrastructure to be built to be connected with the nearest 30 km/h street in Avenida Italia and Bolivia and would need 3.4 km to be built to be connected with the nearest bicycle path in Avenida Italia and Gallinal.

The absence of multimodal transportation in Montevideo is another significant issue of concern. Regarding cycling, buses are not designed for carrying and are not equipped to accommodate bicycles, and there is a lack of nearby parking infrastructure at major bus stations and terminals. These two main issues make it impossible for commuters to engage in multimodal trips, using a bicycle as either feeder or last-mile transportation options. This problem is particularly notable nearby main terminals where buses from medium or long distances end or pass through. Users must switch from medium- or long-distance buses to city buses, as there are no provisions for combinations with cycling. Moreover, the lack of safe and designated areas for bicycle parking creates a non-seamless transition between cycling and walking. Consequently, cyclists are compelled to use improvised parking locations on the street or in public places, which may lack essential safety measures. Overall, citizens rely on a single mode of transportation, mainly private cars or buses, which often leads to congestion, overcrowding, and the inefficient use of resources.

Regarding socioeconomic characterization and accessibility, cycling is significantly better than other sustainable transportation modes studied in this article.

5.2.4. Public Bicycles

A pilot plan for implementing a public bicycle-sharing service was developed by the city administration from 2015 to 2019. The system consisted of just 8 public bicycle stations located in Downtown (Ciudad Vieja) and 80 vehicles. Users of the service had to unlock bicycles and pay with a smart card of the Metropolitan Transportation System, and previous registration was required. The fist half-an-hour had no cost, and then the cost was proportional to the time until the vehicle was returned to a station. The system was not well received by citizens, although it was fairly used by tourists. The main issues were related to security; the registration process was reported to be unfriendly, and cases of vandalism were frequent. Despite an ambitious plan for extending the system to up to 60 stations in several neighborhoods and 600 vehicles, the system was discontinued in 2019.

The city administration has advertised the intention of reviving the public bicycle-sharing system in Montevideo to promote transportation equity, sustainability, and accessibility, learning from the past experience to create an improved and successful system [99]. However, up to March 2024, no public bicycle-sharing service is operating in Montevideo.

The factors discussed show that urban cycling in Montevideo is still in a developing stage. Overall, Montevideo has been classified as a city that is not very friendly to cyclists [100]. Despite its cost-effectiveness, and the increase in cycling trips due to the reduction in public transportation usage during the COVID-19 pandemic [101], there is progress to be made in establishing cycling as a prominent transportation mode in the city.

5.3. Electric Public Transportation

The environmental advantages and potential for reducing greenhouse gas emissions have propelled the global adoption of electric public transportation [102]. Numerous cities are embracing the transition of their public transportation systems to electric alternatives as part of their efforts to enhance sustainability and mitigate air pollution. Electric buses, in particular, have become a popular choice for electrifying public transportation fleets. With the demonstrated commitment of Uruguay to renewable energy and its substantial integration into the energy mix [103], there exists a distinct potential for the advancement of electric public transportation. The main advances and shortcomings of electric public transportation in Montevideo are described in the following subsections.

5.3.1. Development of Electric Bus Lines

Despite its acknowledged potential, the progress of electric public transportation in Montevideo has been limited. After the initial pilot plan using a single electric vehicle for various bus lines [4], there have been few significant advancements. By 2021, only one electric bus line had been fully deployed [23]. As of the year 2023, the bus company CUTCSA, which holds a large share of the public transportation in Montevideo, operates merely three electric lines: central line CE1 (formerly line CA1), differential line DE1 (formerly line D1), and line E14 (formerly line 14, but with a new route). CUTCSA has 20 electric vehicles in its fleet, all of them BYD model K9W. Smaller public transportation companies, namely COETC, COMESA, and UCOT, have incorporated a few Yutong model ZK 6128BEVG electric vehicles. COETC owns four buses, COMESA owns three buses, and UCOT owns three buses [104].

UCOT allocated two of its electric buses to serve line 316. However, in its more recent acquisitions in March 2023, UCOT opted to not incorporate new full-electric buses into its fleet, but hybrid buses instead. Enrique Garabato, UCOT Chief Technician, affirmed that "at present, the electric bus cannot fully substitute conventional gasoline or diesel buses, as it would need to offer an additional 30% range to be equally operational" [105]. In turn, as part of the pilot plan operated between 2020 and 2021, COMESA deployed electric buses on routes with fewer turns and complex maneuvers. COMESA assigned electric buses to several lines in Montevideo, among them lines 505, 524, 526, 538, 546, 582, and L24. Finally, COETC deployed electric buses to operate on central line CA1 and line 407. However, the company has not explored additional options for electric buses. Fernando Fernández, the President of COETC, stated that "an intermediate step exists: the hybrid bus" [105].

To expand the initial progress of electric public transportation in Montevideo, various alternatives have been explored. These include the establishment of a dedicated fund to encourage the acquisition of electric buses [106] and the introduction of a new financial program by the Ministry of Industry, Energy, and Mining. This program aims to develop tools to promote a smooth transition towards clean energy [107].

Regarding the three electric bus lines in operation, some advances and shortcomings are identified. The three lines enter Downtown and travel along 25 de Mayo Street, in line with the objective of creating an exclusive corridor for electric vehicles. Electric line E14 modifies the route of previous line 14, providing a faster trip from Downtown to Pocitos, Punta Carretas, and Parque Rodó. However, ten new bus stops were created, which do not include basic infrastructure for commuters (shelter, a bench, and signs).

5.3.2. Coverage, Accessibility, and Socioeconomic Characterization

Considering the standard technique of defining a buffer area delimited by parallel roads up to 300 m of the bus route to determine the acceptable walking distance accessible to the nearest bus stop [108], the coverage of electric lines is 11.7% of the total area of Montevideo. The accessibility calculation for bus stops on electric lines in Montevideo is 0.098, showing that there is significant room for improvement.

Regarding the socioeconomic characterization of electric public transportation in Montevideo, an analysis of the INSE values reveals that the three electric bus lines primarily prioritize offering mobility services to neighborhoods with higher socioeconomic index values, whereas peripheral neighborhoods are not included in the routes of the electric bus lines. The neighborhoods served by electric bus lines possess significantly higher INSE values compared to the average for Montevideo (up to 8.00 for electric lines E14 and DE1).

Figure 6 shows the routes of electric bus lines in Montevideo and the socioeconomic characterization of neighborhoods, clearly showing the discussed trend: electric lines serve the neighborhoods on the southern and eastern coasts, where citizens with high incomes live.

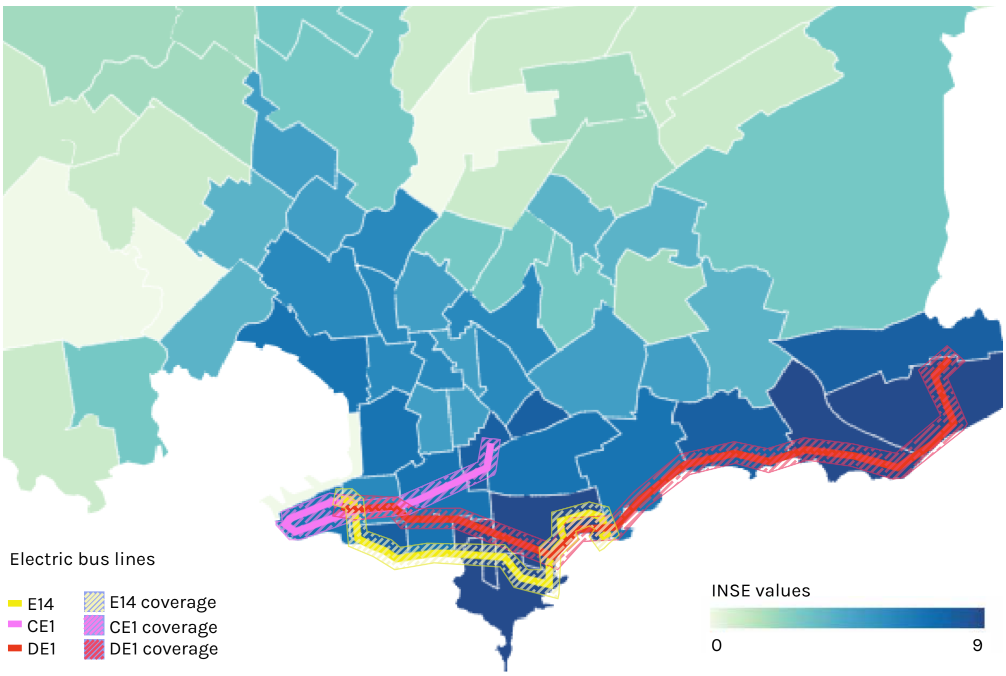

Figure 6. Electric bus lines and socioeconomic characterization of neighborhoods in Montevideo.

5.3.3. Operational and Energy efficiency

The average distance traveled by an electric bus in Montevideo is 161 km/day. A total of 73% of buses travel between 150 and 250 km per day, whereas 36% of travels are between 200 and 225 km [104]. However, except for DE1 (19.9 km), the route length of electric lines is significantly shorter than the average length for bus lines in Montevideo (16.7 km). The route for line CE1 is 7.0 km long, and the route for line E14 is 9.6 km long. At the end of the day, electric buses typically have a battery charge level between 50% and 60%. In 97% of cases, the electric buses arrive at their destination with at least 20% charge remaining in the battery, indicating the high level of adaptability of buses to the route and usage conditions.

Based on the study conducted by the Uruguayan government [104], the power consumption of electric buses varies between a minimum of 0.56 kWh/km and a maximum of 1.60 kWh/km. The average consumption is 1.11 kWh/km. Most of the operating units (75%) demonstrated an operational efficiency ranging from 0.9 kWh/km to 1.1 kWh/km. The number was 88% when extending the range between 0.7 kWh/km and 1.2 kWh/km. These are appropriate values for the operational efficiency of electric public transportation [109].

The energy efficiency of electric public transportation varies depending on several factors, including the bus model, the battery and engine technology, and the operational conditions. Common values for the energy efficiency of electric buses are between 0.8 and 1.5 kWh/km. This range is widely regarded as a favorable level of energy efficiency for electric buses: 0.8 kWh/km is considered appropriate for buses with a length of 12 m operating under typical daily conditions with an average temperature of 20 °C, encountering low traffic and operated by a skilled driver. Conversely, an energy efficiency of 1.5 kWh/km is considered reasonable for buses operating in winter with electric heating activated [110].

When compared to a diesel vehicle with a fuel efficiency of 2.51 km/L, the operation of electric buses results in a savings of over 615,000 L of fuel per year. The resulting energy difference, defined as the difference between the baseline diesel consumption and the current electricity consumption, is equivalent to 380 tons of oil. This value results in the avoidance of 1620 tons of CO_2 emissions in one and a half years. Additionally, the adoption of electric buses prevents the release of 344 kg of PM10, which represents about 5% of the total PM10 emissions generated by public transportation in Montevideo.

5.3.4. Passenger Comfort

To evaluate the passenger experience and comfort provided by electric bus lines, it is essential to analyze various factors, including noise, vibrations, seating capacity, air conditioning, and overall convenience and comfort for passengers. By understanding these factors, it becomes possible to ensure a satisfactory commuting experience for passengers.

Electric buses operating in Montevideo provide passengers with exceptional conditions that greatly enhance the commuting experience: a low level of noise, efficient air conditioning, and ample space for both seated and standing passengers. However, the experience of waiting for and boarding the electric buses is currently not satisfactory due to the inadequate infrastructure provided at several bus stops.

All the newly introduced bus stops (ten) for bus line E14 lack any form of infrastructure, such as shelters, seating benches, and information regarding the bus route and timetable. The bus stops lacking infrastructure are located in the Barrio Sur, Palermo, and Parque Rodó neighborhoods: Sarmiento between Patria and Maggiolo (in both directions), Rambla and Eduardo Acevedo (in both directions), Rambla and Barrios Amorín (in both directions), Rambla and La Cumparsita (in both directions), Ferreira Aldunate and Durazno, and Río Negro and Durazno. Six of these ten bus stops are situated along the promenade, directly facing the sea shore. This location poses significant challenges for passengers as it becomes exceedingly difficult to wait for the bus during rainy and windy weather conditions. Unlike the previously mentioned bus stops, lines CE1 and DE1 do not face a complete absence of infrastructure. This is because they utilize the existing bus stops from previous lines, namely D1 and CA1, which already have some form of infrastructure in place. Nevertheless, it is important to note that for many bus stops, the existing infrastructure is incomplete or damaged, and the availability of route and timetable information is limited to only a few stops. This situation represents a significant drawback of the electric bus lines, particularly taking into account that they have been in operation for over three years.

In summary, Montevideo has made gradual progress in promoting sustainable transportation through the implementation of electric bus lines. However, the city still has significant potential to proactively confront important issues in its goal of reducing greenhouse gas emissions, particularly related to public transportation. In this direction, the implementation of more electric bus lines will certainly allow for the expansion of the current transition from standard fossil fuel buses to more sustainable options. There is ample opportunity for strategic planning to extend the coverage of electric public transportation, ensuring that various parts of the city can benefit from the environmental advantages they provide. It is crucial to prioritize the inclusion of neighborhoods with medium and lower socioeconomic indexes to ensure a broader reach and enable a larger number of passengers to experience the benefits of sustainable and cleaner transportation.

5.4. Electric Private Transportation

The main factors described for the evaluation of electric private transportation are presented in the following subsections.

5.4.1. Electric Vehicle Market and Projections

By December 2023, the market of electric vehicles in Uruguay reached over 4000 vehicles. The introduction of electric cars in Uruguay began in 2015 with the sale of the Mitsubishi i-Miev model [111]. The progress was slow, but the market gradually expanded each year. In 2019, there were approximately 140 electric vehicles in circulation, which increased to 250 in 2020, then further grew to 800 in 2021, and reached 2000 in 2022 [112].

Based on data from the Uruguayan Association of Automotive Business (ACAU), the sales of new electric vehicles in Uruguay showed significant growth. In 2019, 160 new electric vehicles were sold. The number of new units increased to 300 in 2020, 697 in 2021, and reached 1044 in 2022. In 2023, 1887 new electric vehicles were sold [113], which was an an 80.92% increase in sales compared to the previous year. Out of the 1887 electric vehicles sold, 78.2% (1475 units) were in the car (648) and SUV (827) segments, representing a 72.9% increase over 2022 when both segments combined accounted for 853 vehicle sales. The number of SUVs quadrupled from 224 in 2022 to 827 in 2023 (43.8% of the electric vehicles sold). Figure 7 presents the number of new electric vehicles sold each year from 2020 to 2023.

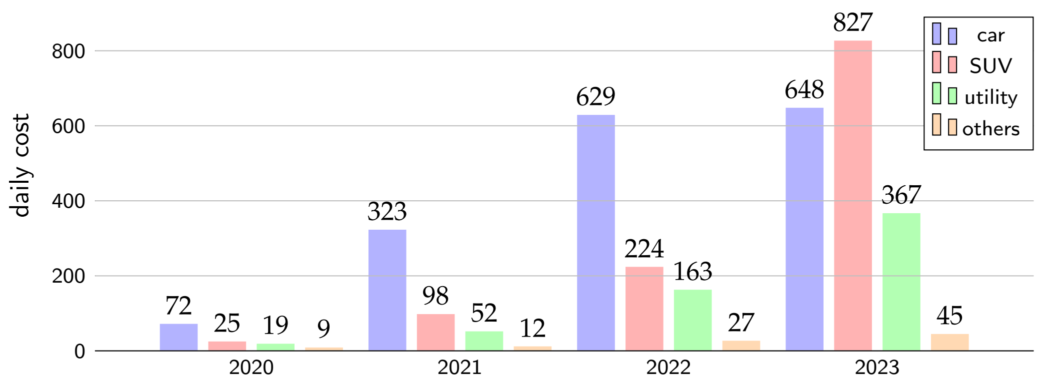

Figure 7. New electric vehicles sold in Uruguay by category, 2020 to 2023.

The growth of electric vehicles in Uruguay was higher than the increase in electric car sales worldwide, which averaged around 25% per year [114]. This trend is projected to continue from 2023 to 2030, indicating a sustained rise in the adoption of electric vehicles in Uruguay. Overall, in 2023 the number of electric cars was 3.2% of the total new car sales, which amounted to 58,367 new vehicles. Even though this number may seem relatively small, it represents a significant increase from previous years, where electric cars represented only 0.5% in 2020, 1.0% in 2021, and less than 2.0% in 2022. Table 2 reports the number of electric vehicles in Uruguay, the number of new vehicles sold each year, and the percentage increase compared to the previous year, covering the period from 2019 to 2023.

Table 2. Electric vehicles in Uruguay and new vehicles sold per year between 2019 and 2023.

Year	Electric Vehicles			
	Total	**Increase**	**New**	**Increase**
2019	140	-	160	-
2020	250	78.6%	300	87.5%
2021	∼600	240.0%	697	132.3%
2022	∼2000	333.0%	1044	49.8%
2023	+4000	>100.0%	1887	80.7%

Forecasts project that Uruguay will have around 82,000 electric vehicles in 2030. More optimistic projections suggest that the number of electric vehicles in circulation could reach 100,000 by 2030 [115]. This value would represent a significant share of the overall vehicle count in Uruguay, which is estimated to be between 450,000 and 500,000 units. The projected growth in the electric vehicle market of Uruguay aligns with global forecasts, which anticipate a 10–12% increase over the next four years [116].

Montevideo accounts for the highest demand for electric vehicles in Uruguay, representing 62% of the total market share. The ACAU concluded that "electric vehicles are establishing themselves in the market with great momentum, accompanying the global trend" [117]. According to studies by the United Nations Development Programme on the updated Nationally Determined Contributions, Chile, Colombia, Mexico, and Uruguay are the countries with the highest level of commitment to electric transportation in Latin America. These nations are leading the way in embracing and promoting electric mobility as part of their sustainable transport strategies. Uruguay has emerged as a frontrunner in electric car sales within the Latin American region. The country has been recognized for its notable achievements and advancements in promoting and selling electric vehicles, positioning Uruguay as a leader in the adoption of electric cars across Latin America [118].

In 2023, BYD sold the largest number of cars and SUVs. In cars, 72.7% of the vehicles sold (469 units) were produced by BYD. The best-selling model was BYD new e2 GS A/T (70 kW engine and 44.9 kWh battery) with 368 units sold, by far the most popular electric vehicle in the country. For SUVs, BYD sold 31.4% of the vehicles sold (260 units) in 2023, and the distance with competitors was not as large as in cars: 17.1% of the SUV sales (141 units) were from JAC and 16.8% (139 units) were from BMW. The best-selling model was BYD Yuan Plus EV480 GS A/T (150 kW engine and 60.5 kWh battery) with 226 units. Overall, BYD sold 951 units in 2023 (50.4%), far ahead of JAC with 219 (11.6%) and BMW with 148 (7.8%).

5.4.2. Environmental Impact

The environmental impact of electric vehicles in Uruguay has been analyzed in three scenarios, defined by Di Chiara et al. [119]:

- Reference scenario: assuming the trend of electric vehicles in 2021–2022.
- Energy efficiency scenario: assuming a positive result of existing energy efficiency policies in Uruguay for the promotion of electric vehicles, based on the government incentives described in Section 5.4.6.
- Sustainable development scenario: assuming a strong commitment towards reducing pollutant emissions to meet global climate goals in line with the Paris Agreement [116].

The environmental impact of electric vehicles is computed by applying the modeling for electromobility described by Di Chiara et al. [119] and the model for CO_2 avoided thanks to the use of electric vehicles developed by the MOVES project for Uruguay [120].

Electric vehicles do not emit CO_2 directly, but the emissions attributed to the electricity production used to charge the battery must be considered. In the case of Uruguay, the emissions associated with electricity generation are relatively low due to the highly clean electricity generation mix (more than 95% from renewable sources). A reference value for the emission factor for the electrical network is 13 tons of CO_2 per GWh [121]. It is also important to account for the CO_2 emissions associated with the extraction, transportation, manufacturing, and distribution of fossil fuels used in conventional vehicles. The reference values for CO_2 emissions are 0.21 kg/km for standard fuel-powered vehicles using either gasoline and gas oil, with an average performance of 12 to 14 km/L [122,123]. The estimation of the average distance traveled by private cars in Montevideo is 6370 km per year, based on data from the 2016 origin-destination survey for Montevideo [124]. Thus, an average medium-size electric vehicle for the Uruguayan market saves approximately 1.4 tons of CO_2 per year. The estimated overall reductions in CO_2 emissions with the use of electric cars (excluding motorcycles and buses) for the considered scenarios are as follows:

- Reference scenario: 8.479 tons of CO_2 in 2024 and 28.000 tons of CO_2 in 2030.
- Energy efficiency scenario: 8.479 tons of CO_2 in 2024 and 93.639 tons of CO_2 in 2030.
- Sustainable development scenario: 9.364 tons of CO_2 in 2024 and 219.383 tons of CO_2 in 2030.

According to the analysis by Tanco et al. [125], to fulfill the fundamental goal of achieving CO_2 neutrality by the year 2050, several milestones must be accomplished in Uruguay, including the following: all new passenger vehicles must be zero-emission by 2035, all new light-duty vehicles must be zero-emission by 2040, and new vehicles must also be zero-emission by 2045. This progression would result in more than half of the vehicles in Uruguay, including automobiles, SUVs, and utility and heavy-duty vehicles, being powered by non-fuel technologies by 2050. The reduction in emissions compared to 2021 is expected to begin from 2040, as older vehicles with low regulations will be gradually replaced by electric vehicles. The most favorable scenario (sustainable development scenario) predicts a CO_2-equivalent of 2065 kilotons in 2050, which is 42.9% lower than the reference scenario. In the current energy efficiency scenario, a CO_2-equivalent of 2540 kilotons is projected for the same year, representing a 29.8% reduction compared to the reference scenario. As part of the national strategy, Uruguay aims to achieve carbon neutrality by ensuring that the entire transportation sector emits only 1100 kilotons of CO_2-equivalent in 2050, taking into account the presence of CO_2-absorbing sources.

5.4.3. Range and Battery Life

The majority of the batteries used in electric vehicles in Uruguay use lithium-ion chemical combinations, which are widely available in the market. These combinations are the focus of extensive research and development, leading to significant improvements in battery performance. Lithium-ion batteries are known for their ability to provide high energy densities, making them a preferred choice for current electric vehicles.

According to the data provided by the Uruguayan Electricity Company UTE [126], the practicality and usability of electric private transportation in Montevideo is very high. The best-selling electric vehicle in the country, BYD model new e2 GS A/T, has a lithium battery of 44.9 kWh and an autonomy of 400 km. The second best, Changan E-STAR, has a lithium battery of 32.2 kWh and an autonomy of 300 km (New European Driving Cycle). The most sold SUV in the Uruguayan market, BYD Yuan Plus EV480 GS A/T, has a battery of 60.48 kWh and an autonomy of 300 to 400 km. The JAC e-S1 A/T has a battery of 30.2 kWh and an autonomy of 251 km. All other models currently sold in Uruguay use lithium or lithium-iron phosphate batteries and have an autonomy between 211 and 400 km. Considering that the estimated average distance traveled by private cars in Montevideo is 6370 km per year [124], i.e., less than 20 km per day, all electric vehicles in the market reach the required operating range for about a week, without the need to recharge in between.

Another important aspect related to sustainability is the reutilization and disposal of batteries. In this regard, there have been research initiatives for the reutilization of batteries used in electric vehicles in the country [127]. The Ministry of Industry, Energy, and Mining has allocated a portion of the Renewable Energy Innovation Fund to enhance its internal capabilities for better management of batteries and to encourage the adoption of technologies that promote reuse. This initiative aims to strengthen local capabilities to handle used batteries and foster the development of innovative technologies in this regard [128].

5.4.4. Charging Infrastructure and Support Services

The available charging infrastructure is crucial for the correct development of electric private transportation. It has been acknowledged that the primary barrier considered by users when it comes to adopting electric mobility is the availability of charging infrastructure [129]. Nearly half of the users surveyed take this concern into account [130]. This issue is closely related to the psychological barrier of the worry about running out of energy during a trip [131]. In this regard, UTE has deployed a network of charging stations in Montevideo, in other important cities in the country, and on the road network. As of December 2023, the charging infrastructure in Montevideo includes 25 locations with up to six charging connectors. Three standards are deployed: Mennekes type 2 (48 connectors), CCS2 (28 connectors), and CHAdeMO (2 connectors), for a total number of 78 charging connectors in the city, out of 288 in the country (also including 2 GB/T connectors). Regarding power, connectors with 7.7 KW, 22 kW, 43 kW, 50 kW, and 60 kW are available. The number of charging stations is deemed sufficient according to international standards, which suggest that there should be one charger available for every 10 vehicles.

At the end of 2018, the first public on-street charging station was inaugurated in collaboration between UTE and the Municipality of Montevideo (five chargers for electric taxis). In 2020, Uruguay had 66 electric charging points spread across the country, with a distance of 60 km between each point. The number of charging points increased to 115 in 2021 and to over 200 points in 2022. UTE has outlined its intentions to invest over USD 5 million for the expansion of the charging network in the country, in line with a national development plan for electric mobility [132]. An expansion plan will install 124 new charging points in the country, 100 of them for fast charging. The main goal of this initiative is to enhance the density of the electric charging infrastructure, aiming to establish a charging point every 50 km. This strategic approach aims to provide electric vehicle owners with greater autonomy and convenience while traveling within Uruguay.

Charging points in Montevideo operate in five charging modes:

- Slow: Conceived for emergency charging, using the standard electricity grid, alternate current, and a Schuko connector, with an associated power of 2.2 kW.
- Standard: Conceived for slow charging, using an Electric Vehicle Charging System, and alternate current, with an associated power of up to 7.4 kW. The estimated time for a full charge is between 5 and 8 h.
- Semi-fast: Conceived for moderate slow charging, using an Electric Vehicle Charging System, and alternate current, with an associated power of up to 22 kW. The estimated time for a full charge is between 1 and 3 h.
- Fast: Conceived for fast charging, using an Electric Vehicle Charging System, and alternate current, with an associated power of up to 43 kW. The estimated time for a full charge is one hour.
- Ultra fast: Conceived for moderate slow charging, using an Electric Vehicle Charging System, and direct current, with an associated power of up to 120 kW. The estimated time for a full charge is between 15 and 30 min.

Figure 8 presents the charging infrastructure for electric vehicles in Montevideo.

In 2020, Risso et al. [133] concluded that the charging infrastructure was adequate for the number of electric vehicles. However, it may not be sufficient to meet the anticipated demand in the near future based on the studied scenarios. Increasing the number of charging points was crucial to provide electric vehicle owners with convenient access to effectively meet their driving range needs. As a result of the expansion plan implemented between 2021 and 2023, the situation has improved. However, for certain growth scenarios, it will be necessary to further upgrade the infrastructure to accommodate mid- to long-term recharging requirements. Despite the substantial growth, the number of charging points in the country is still low (10% of the number of gas stations). This comparison highlights the need for further development and investment in charging infrastructure to bridge the gap and ensure sufficient coverage for electric vehicles across the country.

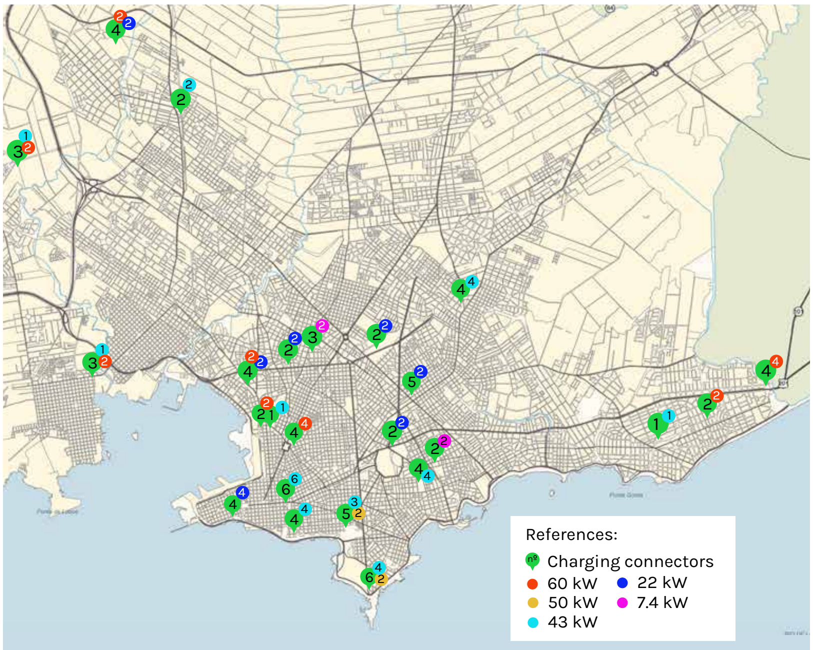

Figure 8. Charging infrastructure for electric vehicles in Montevideo (own design).

5.4.5. Economic Analysis

The average price of electric vehicles is USD 35,000 [113]. The BYD Seagull is the most affordable electric vehicle, with a price of USD 22,000. On the other end, BMW, Mercedes, and Tesla offer luxury electric vehicles for over USD 200,000. The best-seller BYD new e2 GS A/T costs USD 29,000. Prices decreased by 11.4% in 2023 compared to the previous year (USD 39,000), and the trend suggests that the value will continue to decline in the future.

Although the purchase cost of electric vehicles is higher than conventional vehicles in Uruguay (estimated average price of USD 29,000 [134]), the operating cost of electric vehicles is notably economical. Maintenance expenses are over three times cheaper than those for conventional vehicles. The maintenance of shock absorbers, tires, and brakes is similar, but other maintenance cost are significantly lower. Electric vehicles have fewer moving parts compared to conventional vehicles, primarily consisting of a motor with minimal components that operate continuously and smoothly. Thus, wear and tear are significantly reduced, and the stationary nature of batteries further contributes to their longevity.

The Director of Smart Projects in UTE, Eduardo Bergerie, commented that electric vehicles are more profitable in professional uses such as taxis [135]. For vehicles not used for business purposes, the estimated travel distance in Montevideo is between 6000 and 8000 km/year. For this short distance, an electric car is not the most cost-effective transportation mode, but it is preferred for a comfortable lifestyle, freedom of movement, and the inclination towards environmental consciousness, rather than as an economic decision.

The average expense for a charge to travel between 150 and 200 km is UYU 128 (USD 3.2), resulting in a cost of USD 0.18 per kilometer. The cost is even lower for users that install a charger at home and take advantage of multi-hour electricity tariffs provided by UTE, charging during the cheapest (valley) hours. The cost of domestic chargers in Uruguay ranges from USD 600 and the installation cost is approximately USD 1200 [136].

In terms of energy consumption, there is a notable disparity between electric vehicles and combustion vehicles, with a ratio of one to eight. This means that the distance traveled by a combustion car can be covered with only one-eighth of the energy consumed by an electric vehicle. The savings obtained from reduced operational costs quickly offset the higher initial investment required for purchasing an electric vehicle.

The reported numbers demonstrate the superiority of electric vehicles in terms of energy efficiency and overall cost-effectiveness, as they consume less energy per kilometer traveled compared to standard vehicles. Furthermore, the efficiency of electric vehicles can be further enhanced through advancements in battery technology and vehicle design.

5.4.6. Government Incentives and Policies

The government of Uruguay has been actively involved in promoting the electric mobility market through various measures and incentives:

- Uruguay has practically eliminated all taxes imposed on electric vehicles, with only the Value Added Tax remaining.
- Since 2011, electric vehicles have had a reduced Internal Specific Tax (IMESI) rate of 5.75% until 2021, and from then onward, it has been excempted (reduced to 0%). This substantial tax advantage contrasts with the tax rates imposed on combustion vehicles, which range from 23% to 46% for gasoline-powered vehicles.
- An additional tax benefit is the exclusion of the 23% import tariff (TGA).
- There is a reduction in the vehicle circulation fee. The value used for calculating the fee for electric vehicles excludes the Value Added Tax, and the applied percentage is reduced to half (2.5%) of the rate applied to combustion vehicles (5%).
- The government has introduced assistance programs aimed at promoting the use of electric vehicles in taxi, ride-hailing, and on-demand mobility services. These initiatives offer vehicle-specific discounts of up to USD 11,500.
- Decree 268/23 from the Executive Power has extended provisions that allow vehicles registered under the Investment Promotion Law to benefit from substantial tax reductions, encouraging the adoption of clean energy usage.

There is consistent adherence to the policy guidelines that various governments have been implementing for several years. In fact, since the inception of the initial incentive all the mechanisms aimed at promoting the adoption of electric vehicles have been preserved or enhanced, aligning with the environmental and energy objectives of Uruguay.

Other indirect initiatives and programs have been developed by the Uruguayan government to promote and foster electric private transportation:

- Support measures in the form of Energy Efficiency Certificates have been implemented since 2016. In 2022, the Vehicle Energy Efficiency Labeling Regulations were established, including significant advantages to the labeling system. Once the Ministry of Industry, Energy, and Mining establishes the regulations and the voluntary adoption period for vehicle importers concludes, prospective buyers of new vehicles will have access to an adhesive label displaying information such as fuel consumption per kilometer and CO_2 emissions, which are associated with the respective fuel types. For combustion vehicles, fuel consumption information will be indicated in km/L, while for electric and plug-in hybrid vehicles, consumption will be represented as km/kWh [137].
- From 2023 to 2025, private investors incorporating charging services are eligible for a 100% discount on the connection fee.
- The State Insurance Bank (Banco de Seguros del Estado, BSE) provides better insurance conditions and prices for electric vehicles in comparison to combustion vehicles.
- The government advanced on an ecosystem of capabilities for battery management.
- During the period between 2019 and 2022, the Subite Prueba initiative was developed. A one-month free trial of electric vehicles was offered to companies and institutions, who were encouraged to incorporate electric vehicles for urban cargo transportation and last-mile logistics. The vehicles were provided at no cost for a month-long trial period, allowing the beneficiaries to evaluate the benefits in their regular operations [138].

All the commented measures have contributed to promoting the integration of electric vehicles into the national vehicle fleet. The main efforts have been focused on two aspects. The first aspect is breaking down the cultural barriers and the distrust towards a new technology. The second is enabling the initial critical mass of vehicles, which creates the minimum viability conditions necessary for the development of an ecosystem encompassing workshops, technical services, insurance, spare parts, infrastructure, and other essential components. Without this ecosystem, the widespread adoption of electric mobility is not feasible [118].

6. Conclusions and Future Work

This article examined the recent progress made in implementing sustainable mobility initiatives in the public transportation of Montevideo, Uruguay. This study focused on the analysis of e-scooters, urban cycling, and electric public transportation. Important factors that contribute to the correct and sustainable development of the initiatives and the quality of service provided to commuters were assessed.

The main conclusion drawn from the analysis is that, despite the recent endeavors oriented to promote sustainable mobility in Montevideo, the developed initiatives have not consolidated yet. Specifically, the e-scooter business model encountered substantial challenges in Montevideo, mostly related to coverage, affordability, and safety, ultimately leading to the discontinuation of this service within the city. While there has been significant advancement in the establishment of urban cycling infrastructure between 2020 and 2023, it is important to acknowledge that the network in Montevideo still lags behind other capital cities in Latin America. Various challenges persist, including issues related to connectivity, the lack of intermodal connections, and maintenance conditions for bicycle lanes and paths. Although the operational efficiency of electric buses in Montevideo is commendable, only three electric bus lines have been implemented in the city. Furthermore, these electric bus lines predominantly serve the wealthier coastal neighborhoods, leaving a significant portion of the population without access to the benefits of electric public transportation.

Private electric transportation has developed steadily in the country, with an increasing number of vehicles and reasonable development of the ecosystem, including the charging infrastructure, services, and regulations. The anticipated environmental impacts are projected to be significant under different scenarios by 2030 and 2040. The Uruguayan government has developed a series of incentives and programs to promote electric public transportation, which have been positively received by the public. Nevertheless, there is a need to improve the infrastructure and guarantee the best conditions for the proper development of electric mobility in the near future. A comparison of the common factors analyzed for each sustainable mobility initiative is shown in Table 3.

Table 3. Comparison of common factors for each studied sustainable mobility initiative in Montevideo (references: ✓: good; ↗: rather good; ↘: rather bad; ✗: bad).

Factor	Initiative			
	E-Scooter	**Bicycle**	**Electric Bus**	**Electric Vehicle**
spatial distribution	✗	✓	✗	✓
safety	✗	✗	✗	↗
cost-effectiveness	✗	✓	✓	↘
environmental impact	↘	✓	✓	✓
infrastructure	✗	✗	↘	✓
comfort	✗	↘	✓	✓
accessibility	✗	✓	✗	✗
integration	✗	✗	✗	✗

The advancements made by Montevideo towards sustainable mobility are promising. However, it is crucial for both the city administration and the national government to demonstrate stronger commitment and collaboration to ensure the well-rounded and consistent development of integrated sustainable transportation solutions. The lack of an integrated Sustainable Urban Mobility Plan negatively affects the success of developing isolated, non-integrated initiatives.

The main focus for future work is on expanding this study to include other non-conventional sustainable transportation initiatives implemented in Montevideo. In this regard, that research effort should entail examining various initiatives involving private electric transportation, such as ride sharing and electric bicycles, shared electric cars, and electric cargo fleets, as well as exploring app-based electric mobility options. In order to gain a comprehensive understanding of the sustainable transportation panorama in Montevideo, it is important to analyze these additional aspects.

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