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Urban Electric Bus Fleet Transition Research Based on Eco-Impact Valuation Model and Discounted Cash Flow Analysis

Qijun He[1, *]

[1]Acabridge Academy, Shanghai, China
[*]Corresponding author: 1116828@qq.com

Abstract: This paper investigates the transition to an all-electric bus fleet as a strategy for sustainable urban development, focusing on its financial and environmental impacts. Utilizing the Eco-impact Valuation Model, Discounted Cash Flow Analysis (DCF), and the E-bus Replacement Model, the study assesses the feasibility and benefits of replacing conventional diesel buses with electric buses. Firstly, the Eco-impact Valuation Model analyzes and translates the environmental costs of diesel and electric buses into monetary social costs, evaluating the potential cost reduction to society offered by electric buses. Secondly, the DCF is used to demonstrate the potential cost-saving superiority of electric buses over diesel buses within a single investment period, providing a financial perspective on the transition. Lastly, the E-bus Replacement Model plans the phased introduction of electric buses and updates bus routes over the next ten years, based on air quality severity in different city zones. The severity of pollution is ranked using the TOPSIS evaluation model, with influencing factors weighted by the Analytic Hierarchy Process (AHP). The models are applied to three cities, including Houston, Buenos Aires, and Shenzhen, offering insights into the ecological, financial, and practical feasibility of electric buses for policymakers.

Keywords: Ecological impact valuation model; Discounted Cash Flow financial analysis (DCF); TOPSIS; Analytic Hierarchy Process (AHP).

1. Introduction

Diesel-fueled vehicles, significant contributors to greenhouse gas emissions and global warming, have led to increased extreme weather events, health issues, and severe pollution. The depletion of natural resources further challenges economic and ecological sustainability. In response, the 2022 Global Memorandum of Understanding on Zero-Emission Medium and Heavy-Duty Vehicles advocates for a transition to electrified vehicles, including buses, to capitalize on their long-term benefits such as lower maintenance costs and reduced energy consumption. Cities globally are adopting electric bus fleets as a key initiative towards a diesel-free society. This transition, however, necessitates a detailed ecological and financial analysis to justify the initial investments. Policymakers face the challenge of ensuring that the transition to electric bus fleets is not only environmentally beneficial but also economically viable. The Eco-impact Valuation Model and the financial analysis model DCF (Discounted Cash Flow) will be employed to assess the societal, environmental, and economic impacts of replacing diesel buses with electric alternatives. Additionally, our E-bus Replacement Model will provide a ten-year strategic plan for bus route development and electric bus replacement schedules, utilizing the TOPSIS and Analytic Hierarchy Process (AHP) evaluation models to measure air pollution and prioritize variables [1, 2].

2. Modeling

2.1. Eco-impact Valuation Model

This study aims to facilitate government decision-making and improve public understanding of the transition to an all-electric bus fleet by quantifying the positive ecological effects of this shift. The study innovatively translates the abstract ecological impacts of the electric bus fleet into tangible societal cost values, providing a more direct and concise representation of the environmental consequences. Consequently, the ecological benefits of the all-electric bus fleet are numerically expressed, highlighting the advantages of electric buses over diesel alternatives. The model envisions a ten-year timeline for the transition to electric buses, assuming an equal number of diesel vehicles are converted to electric each year. Given that each bus typically covers a similar distance daily, the model considers the distance traveled by newly replaced electric buses to be consistent annually. This assumption forms the foundation of the model's approach.

The eco-impact valuation model plays a crucial role in this study, focusing on assessing the environmental impact of transitioning to an all-electric bus fleet. It begins by calculating the annual environmental cost attributed to diesel buses, which is primarily due to the emission of pollutants such as nitrogen oxides, carbon monoxide, suspended solids, and carbon dioxide. These emissions are significant as they represent the social cost of environmental damage. The model quantifies this cost based on the marginal cost of reducing specific amounts of these pollutants, thus providing a tangible measure of the environmental impact of diesel buses. The flowchart is shown in Figure 1:

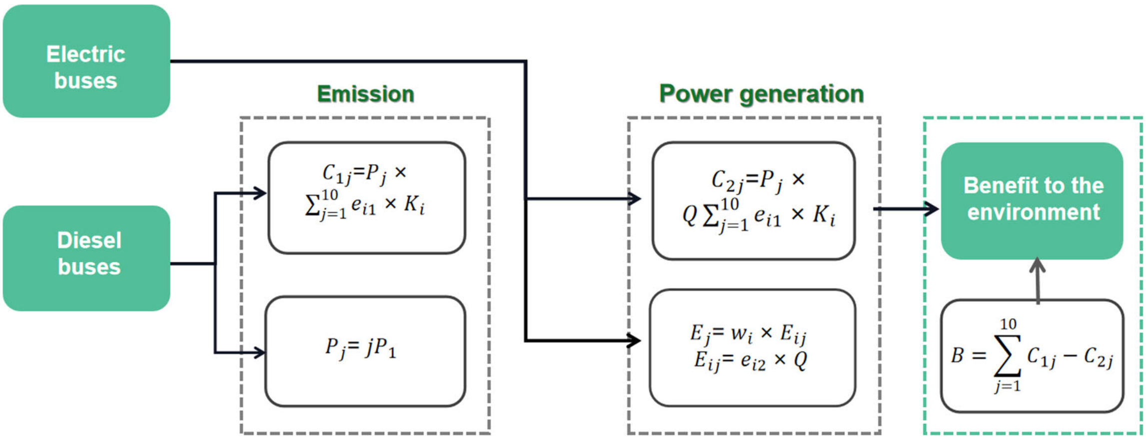


Figure 1. Flow chart

In contrast, the model also addresses the environmental cost associated with electric buses, particularly focusing on the impact of electricity generation. While electric buses are often touted for their zero-emission status, the model acknowledges and incorporates emissions from electricity generation. This approach includes considering the total electricity consumption needed to power electric buses and the varying emission levels from different electricity generation methods. The last step involves calculating the environmental benefits of the electric bus fleet transition. This is achieved by comparing the environmental costs between the replaced electric vehicles and the hypothetical impact if these vehicles had remained diesel-powered. This comparison offers a comprehensive view of the overall environmental impact of transitioning to an electric bus fleet, highlighting the tangible benefits of this shift.

2.2. Discounted Cash Flow Analysis

The discounted cash flow analysis, also known as DCF, is an economic valuation tool to determine the value of an investment today using expected future cash flow. The DCF models for both diesel buses and electric charging buses will be developed to further determine the worthiness of electrifying buses [3].

We calculate the free cash flow in the upfront year for α electric buses: based on current data regarding total revenue, operating costs, maintenance costs, and the value of capital investments in the first year, the free cash flow of α electric bus in the upfront year can be determined; while for the diesel buses, only total revenue and operation and maintenance costs are required to be taken into consideration. Then, for electric buses, we must compute the second year's free cash flow by subtracting operation and maintenance costs from the total revenue earned.

Subsequently, each year's free cash flow can be obtained to calculate its corresponding discounted cash flow value, according to an estimated constant growth rate of free cash flow (after the second year for electric buses; and after the first year for diesel buses). The salvage values for selling scrapped buses will be added to last year's free cash flow, after which the investment period we are interested in will end. Eventually, the difference between the DCF values for the two types of buses can be acquired for examining the cost-efficiency of the all-electric bus fleet program.

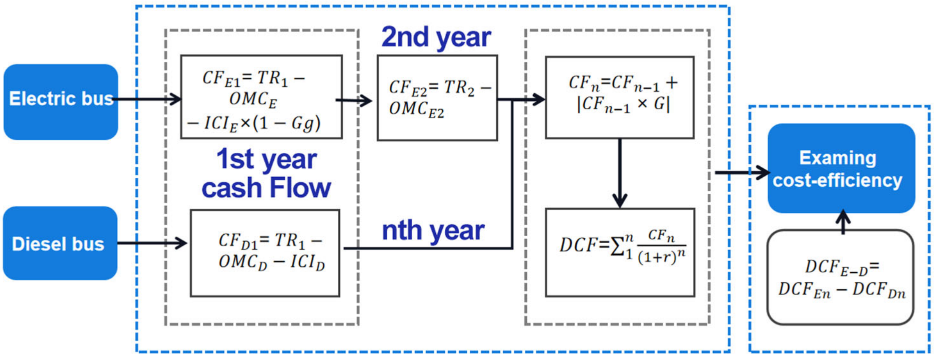


Figure 2. Discounted Cash Flow Analysis, Flow Chart

The Discounted Cash Flow Analysis (Figure 2) in this study meticulously evaluates the cost-efficiency of electric buses compared to diesel buses. For electric buses, the process begins with the calculation of free cash flow for the first two years. The initial year's calculation encompasses operation and maintenance costs, which include electricity expenses, labor costs, annual maintenance costs for buses, and maintenance costs for chargers. Additionally, the initial capital investment, comprising the purchase and installation costs of chargers and buses, is also considered. The free cash flow for the first year is then derived by subtracting these costs from total revenue, considering government grants. In the second year, the calculation excludes the initial capital investment, and from the third year onward, the free cash flow is assumed to grow at a constant rate. The discounted cash flow for each year is computed by adjusting the free cash flow for the required rate of return, and the salvage value of scrapped buses is added in the final year.

In contrast, the analysis for diesel buses focuses only on operation and maintenance costs, as these vehicles are pre-existing and do not entail initial capital investments. The operation and maintenance costs include diesel fuel consumption, labor costs, and total annual maintenance costs. The free cash flow for the first year is determined by deducting these costs from total revenue. The expected free cash flow for subsequent years is calculated in a manner akin to electric buses, including the addition of salvage value in the final year. The last step of the analysis is crucial as it examines the cost-efficiency of the all-electric bus fleet program. This is achieved by comparing the difference in discounted cash flow values between electric and diesel buses for each year of the investment period, providing an in-depth financial assessment of the feasibility of transitioning to an all-electric bus fleet.

2.3. E-bus Replacement Roadmap

Our economic profit model allows for the prediction of profits, enabling us to construct a comprehensive model to aid the transport authorities in planning their e-bus updates. For simplicity, we assume that everyone has the same opinion about the transformation of e-bus, and the opinions remain unchanged throughout the process (Figure 3).

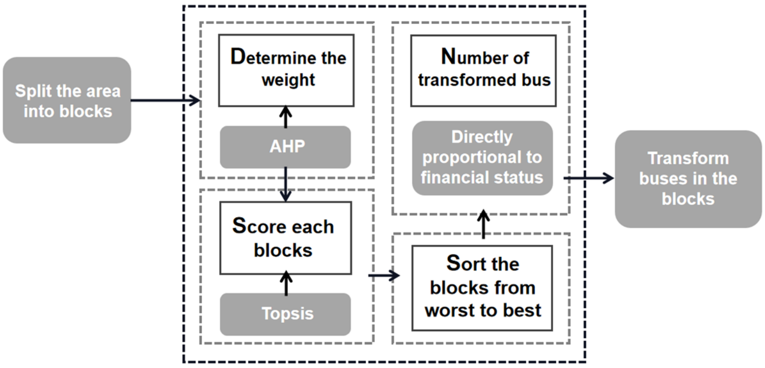


Figure 3. Flow chart

In Figure 4, to accurately evaluate regional environmental differences, the metropolitan area is subdivided based on the monitoring sites of the United States Environmental Protection Agency (EPA). The evaluation prioritizes key factors: concentration of Nitrogen Dioxide, PM2.5 concentration, Air Quality Index, and vegetation coverage, with particular emphasis on Nitrogen Dioxide due to its significant impact on human health. The Analytic Hierarchy Process (AHP) is employed to assign weights to these factors, using a judgment matrix that incorporates expert opinions. This matrix uses the 1-9 scale method, where Nitrogen Dioxide is rated as slightly more important than PM2.5 Concentration and Air Quality Index, and significantly more important than vegetation coverage. The resulting weight matrix, obtained by solving the eigenvector corresponding to the maximum eigenvalue, assigns the following weights: 0.5451 to Nitrogen Dioxide, 0.1931 to PM2.5 concentration, 0.1931 to Air Quality Index, and 0.0687 to Vegetation Coverage. The consistency ratio (CR) of this matrix is 0.00293, well below the threshold of 0.1, ensuring the validity and consistency of the hierarchical structure in the evaluation process. This approach ensures a precise and comprehensive assessment of environmental status across the subdivided sections, considering the varying impacts of different environmental factors.

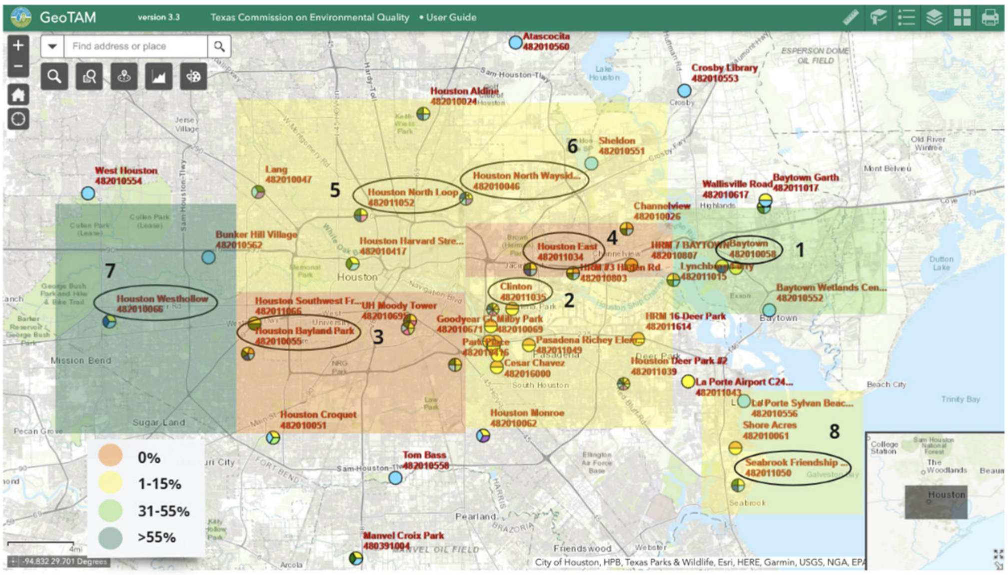


Figure 4. Subsection of Houston according to EPA monitoring sites

The air quality severity in different blocks of a metropolitan area is ranked using the TOPSIS method, integrated with a previously derived weight matrix. This process begins by unifying the indexes such as NO2 Concentration, PM2.5 Concentration, and Air Quality Index, which are considered optimal at their lowest values, and taking their reciprocals to make them minimum indexes. Vegetation Coverage, being a maximum index, keeps its original value. These indexes are then normalized or standardized, adjusting each index value based on the square root of the sum of the squares of all index values. This standardization identifies an optimal case where statistics are closest to the ideal values. The next step is to identify the best and worst subsections and calculate the relative distance of each block to these points, considering the weights of each index. Finally, an evaluating function is used to integrate these distances, ranking the regions from most urgent to least urgent in terms of air quality improvement needs. This approach ensures a prioritized and data-driven strategy for addressing air quality challenges across various urban areas.

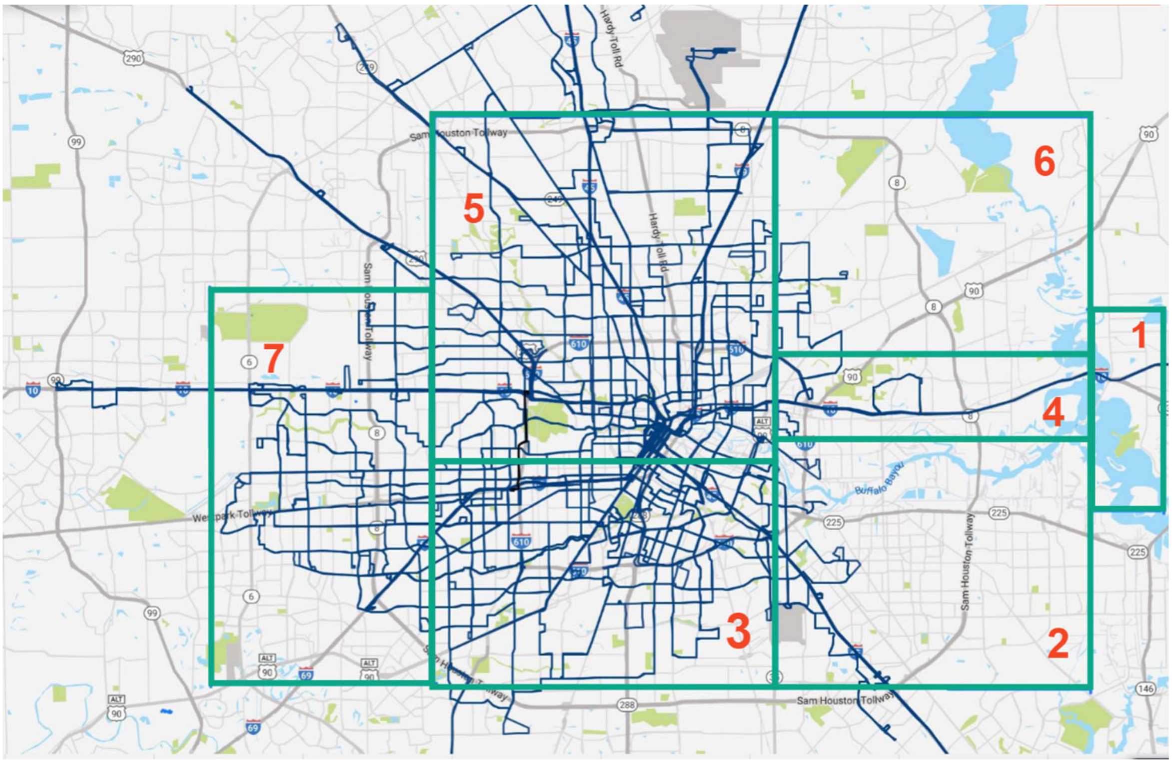


Figure 5. Subsections modified according to routes.

From the metro interactive system map (Figure 5), we obtain the routes of the buses. Implementing our subsections, we discover that the Seabrook subsection is no longer useful since no bus route goes through this area.

To construct the final model, we use the expressions in the economic model as the indicator of financial status. We define α_i As the number of diesel buses transformed into e-buses, we thus have:

$$f(t_{i+1}) = f(t_i) + TR - OMC_E - ICI_E \qquad (1)$$

Where TR is the total cost, expressed by

$$TR(\alpha) = AMT \times BF_M \times \alpha \qquad (2)$$

ICI_E Is capital investment, expressed by:

$$ICI_E(\alpha) = \alpha \times P_{BEB} + \alpha \times (P_{Cd} + IC_{Cd}) + \left\lceil \frac{\alpha}{8} \right\rceil \times (P_{Cf} + IC_{Cf}) \qquad (3)$$

OMC_E Is the maintenance cost.

Then, we establish a Linear Program Model to find the optimal choice of α that would provide the greatest finance at the end of the twelve-year program. The prerequisites of establishing the Linear Program Model are:

A deciding variable (independent variable).

A goal or aim function that shows the objective (max/min) Restrictions.

Deciding variable: α_i.

Goal: Max$f(t_{10})$ and Max$B$.

Restrictions:

$$\alpha_1 + \alpha_2 + \alpha_3 + \cdots + \alpha_9 + \alpha_{10} >= 1200 \qquad (4)$$

$$f(t_i) = \left[f(t_0) + \sum_{i=1}^{i} (TR - OMC_E - ICI_E)\right] >= 0 \qquad (5)$$

Where $f(t_{10})$ Is the finance at the end of the ten-year period and B is the environmental benefits throughout the ten years. They are assigned weights of 0.7 and 0.3 based on previous studies we use for reference.

Since the model is a general Linear Programming model, we use a solver to directly access the solution.

3. Results

3.1. Eco-impact Valuation Application: Houston, Texas, United States.

This part will show the results of the Eco-impact Valuation model works in Houston. Parameters' numerical values needed for calculation are listed in Table 1.

Table 1. Parameters' numerical values

Parameters	Description	Numerical Value
P_1	Mileage for all electric buses in the first year in km	14966840.00
e_{i1}	Unit emission (emission index) of the i th pollutants in g/km	2.07, 873.8, 0.17, 8.43
E_{1j}	Indirect emissions per 1km traveled by electric buses g/km	0.282, 1380.9, 0.045, 1.35
E_{2j}	Indirect emissions per 1km traveled by electric buses g/km	0.149, 391.5, 0.003, 0.15
K_i	Marainalabatement cost of i th pollutants in $	114918590009700.00
W_i	The weighting of i th modes of the generation of electricity	67.24, 32.76

To demonstrate the environmental benefits resulting from the transition to e-transit as it advances over time, we will utilize a dendrogram depicted in Figure 6 to illustrate the benefits.

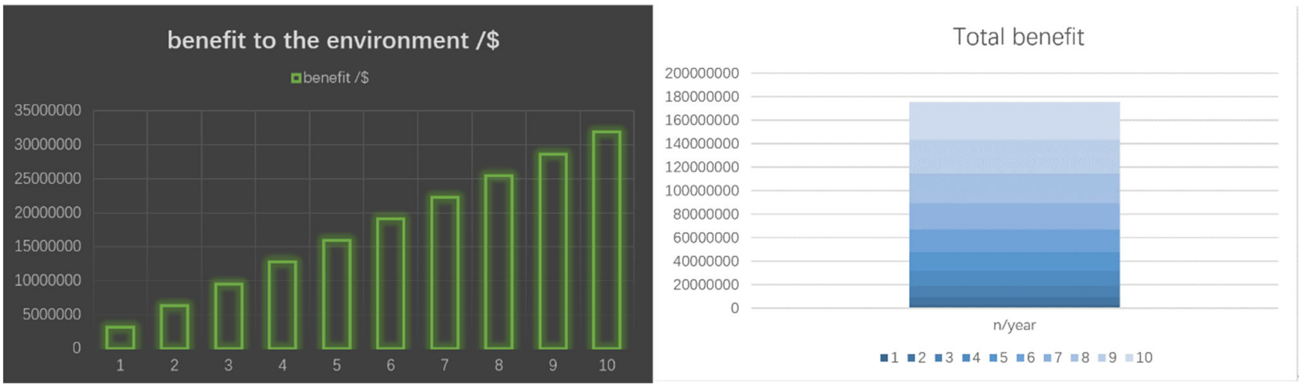
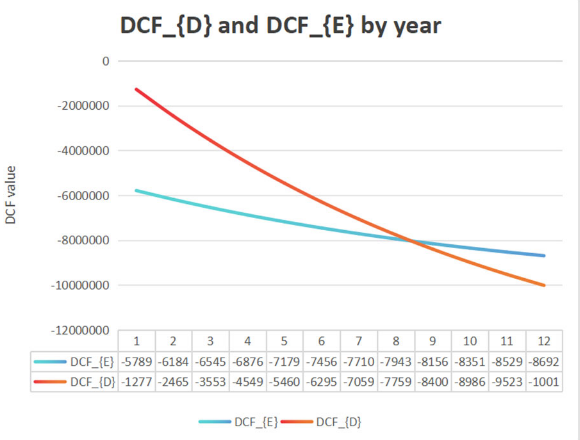


Figure 6. Evaluation of benefit to the environment by year (left) Total benefit to the environment (right)

3.2. Discounted Cash Flow Analysis Application

This paper collects data on three cities, Houston, Shenzhen, and Buenos Aires, and applies the financial model to these three cities to analyze the economic feasibility of transitioning to an all-electric bus fleet [4-6]. The model uses specific parameters to calculate discounted cash flows (DCF) for electric and diesel buses. The results show that when the DCF of electric buses exceeds that of diesel buses, an all-electric fleet program is economically beneficial and provides additional returns compared to conventional diesel buses. However, the analysis shows that under certain conditions, such as transitioning to 10 electric buses with government grants covering half of the initial capital investment, electric buses may suffer greater economic losses than gas buses. This is largely due to their higher purchase cost and the costs associated with installing charging infrastructure. The model therefore highlights the potential financial advantages and challenges of adopting an electric bus fleet in a metropolitan environment.



	1	2	3	4	5	6	7	8	9	10	11	12
DCF_{E}	-5789	-6184	-6545	-6876	-7179	-7456	-7710	-7943	-8156	-8351	-8529	-8692
DCF_{D}	-1277	-2465	-3553	-4549	-5460	-6295	-7059	-7759	-8400	-8986	-9523	-1001

Figure 7. Cumulative years of DCF_E and DCF_D.

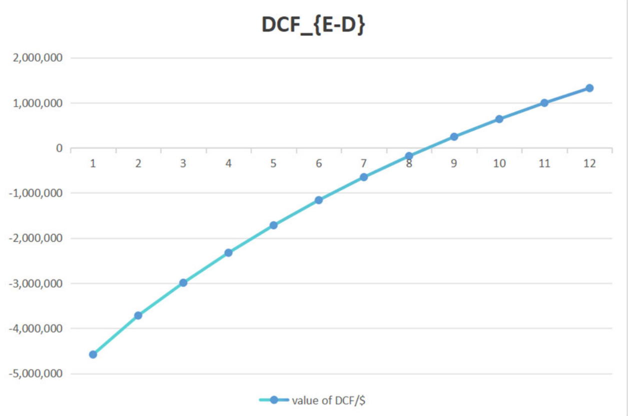


Figure 8. Cumulative years of DCF_{E-D}.

In Figure 7 and 8, the study reveals that in the timeline of the electric bus program, the economic advantage of electric buses over diesel buses becomes apparent between the 8th and 9th years. Despite this advantage, it is important to note that both electric and diesel buses still operate at a loss. Electric buses, seen as a public good, cannot rely on high fares to offset costs without deviating from their primary purpose of serving the community. An alternative to improve financial viability is through advertising revenue on buses. Significantly, the model highlights that the long-term benefits of electric buses extend to government savings. By reducing losses through electrification, funds can be redirected to other crucial sectors like healthcare and education. This perspective is particularly relevant for policymakers, as it showcases the broader economic and societal benefits of transitioning to an electric bus fleet, beyond immediate financial considerations.

By integrating the weight matrix and distance function, we receive a table of scores of the different regions in Figures 9 to 11.

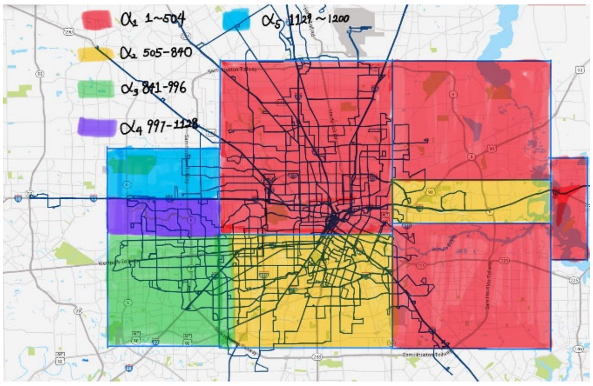


Figure 9. Roadmap of Houston

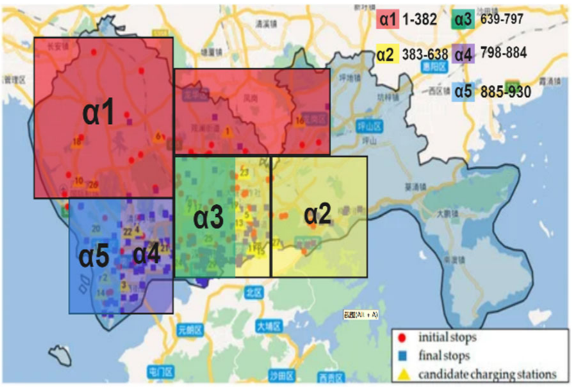


Figure 10. Roadmap of Shenzhen

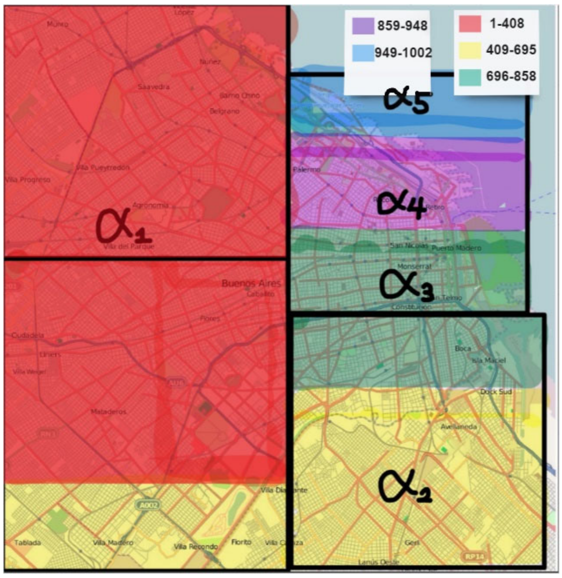


Figure 11. Roadmap of Buenos Aires

4. Conclusions

This study presents the environmental impact of the electric bus replacement program by uniquely converting ecological benefits into monetary values. This direct approach allows not only policymakers but also the public, who might previously have been unaware, to appreciate the environmental outcomes. Our models consider multiple factors across various dimensions, ensuring that the results are convincing and practical for future planning and design of an all-electric bus fleet. Additionally, the stability and feasibility of our financial model have been validated through sensitivity analysis, confirming the long-term cost-efficiency of transitioning to electric buses. However, there are limitations to this study. The accuracy and detail of the model's results could be enhanced with more regional data and extended research time. Future studies could also account for subjective factors difficult to standardize, such as cultural differences and consumer preferences, to improve the feasibility of policy implementation. Overall, this research offers a comprehensive assessment method for the transition to electric buses, contributing significantly to the advancement of sustainable transportation.

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