HIGH SCHOOL EDITION
Journal of Student Research
Volume 13 Issue 3 (2024)

Prediction of Ecological and Economic Impact of a Fuel-to-Electric Bus Engine Transition– With a Case Study of Shanghai

Kyle Long[1], Zimo Tu[1] and Haochen Wang[1#]

[1]Wuhan British China School
[#]Advisor

ABSTRACT

Replacing fuel buses with electric buses is a key step for sustainable development. From the perspectives of both firms and the government, the process requires quantitative analysis to understand its ecological and economic impacts. However, current studies lack certain analysis, which hinders their ability to understand the benefits and make valuable decisions. In this paper, we study the ecological and economic impacts. First, we establish an ecological model to evaluate the reduction in harmful emissions resulting from bus conversion. Next, we build the economic model to calculate the cost of electric bus purchases and the construction of charging stations. Last, we integrate ecological and economic models to quantitatively analyze the long-term benefits of the fuel-to-electric bus engine transition. We also include a case study with empirical data from Shanghai to illustrate the real-world application of our model. This comprehensive approach enables a deeper comprehension of the transition's benefits, supporting more cases for sustainable urban transportation solutions.

Introduction

In the long history of mankind, we have never stopped exploring new sources of energy for sustainable development [1,2]. We started by harnessing the natural force of fire, followed by coal, steam, petrol, gasoline, and finally electricity [3]. In 2015, the International Energy Agency reported that 13.7% of the world's energy was generated by renewable sources [4]. This percentage mix is predicted to double by 2040 due to a sharp decline in the cost of renewable energy [5].

In the realm of public transportation, conventional engines for buses are mainly fueled by diesel and petrol, which will generate substantial harmful emissions [6,7]. Transportation contributes to around one-fifth of global carbon dioxide emissions, and road transport accounts for three-quarters of transport emissions [8,9]. This conclusion is confirmed by the Congressional Budget Office [10], showing that the transportation sector is responsible for 38% of energy-related carbon emissions in the US in 2021 and ranked number one in comparison to other sectors [11]. Given that major road transport emissions come from passenger vehicles, it is reasonable and practical to ameliorate the environmental impact of the typical public transportation system—bus travel.

Thus, with growing concerns about air pollution and climate change, many cities are beginning to shed light on the potential adjustments in bus travel and rethink the use of traditional diesel buses [12， 13]. Cities around the world are also working to gradually integrate electric buses into their public transportation systems [14]. Aside from its ecological advantages, such an electric bus system would be economically efficient in operation, user-friendly, and highly likely to be incorporated into the existing city infrastructure [15,16]. However, challenges faced by an electric bus fleet transition include high initial costs, charging infrastructure development, lengthy charging times, and potential range limitations. Therefore, it would be essentially valuable to evaluate the economic cost and environmental impact from the perspectives of both firms and the government [17].

In this paper, we construct a model to show the ecological enhancements of transitioning to an all-electric bus fleet (such as air pollution and greenhouse effects) and help cities predict the economic consequences. Our model quantifies not only ecological impacts but also the economic costs of the transition to offer an all-encompassing view of this potential solution to the global emission issue. We comprehensively consider the emission intensity and operation length of buses and establish an ecological impact estimation model. In addition, we set up an economic impact estimation model combining short-term and long-term effects. Our goal is to guide the government in making realistic arrangements and future plans to maximize the benefits of this fuel-to-electric bus engine transition.

Materials and Methods

Models for Ecological Impact Evaluation

We would quantify the harmful emissions that can be reduced from the original fuel bus before the replacement and then the additional emissions from changing electric generation for comparison. The daily air polluting gases and carbon emissions for fuel buses($E_{f,k}$)could be calculated directly by multiplying the emission per kilometer and total distance traveled($e_{f,k}$) by all the buses(d).

$$E_{f,k} = e_{f,k}\, d \tag{1}$$

Unlike fuel buses, electric buses do not emit harmful gases during operation. Their ecological cost could be identified as the indirect consequences of generating electricity from thermal power plants. The gas emission from a electric car per kilometer traveled($E_{ele,k}$) is calculated as the consumption of electricity per kilometer(η) times the emission produced from generating per kilowatt-hour of electricity ($E_{TPP,k}$) weighted by the percentage of electricity generated from coal-burning (A_{TPP}),which is:

$$E_{ele,k} = \eta\, A_{TPP}\, E_{TPP,k}\, d \tag{2}$$

We divide the overall distance covered by all buses, d into shorter segments corresponding to the distances traveled within various regions. The total distance traveled by buses in an area(d_i) is calculated by estimating the region's shape with the ratio of its longest to shortest line segments(h_i), dividing the area into segments, applying formulas to determine the covered area(s_i), and incorporating an urban transit-specific constant(c). The distance traveled by all buses in the area i is:

$$d_i = c\,\frac{{h_i}^2}{sqrt(s_i)} \tag{3}$$

Table 1 gives the estimation values of the corresponding parameters.

Table 1. Value of Parameters [18]

Symbol	Meaning	Value
P_{fbus}	Price of fuel bus	90000
P_{ebus}	Price of electric bus	300000

C_c	Price of a charger	40000
r	Interest rate of loan	3.45
P_{oil}	Price of oil per km	0.167
P_{ele}	Price of electricity per km	0.0291
C_{dmain}	The annual maintenance cost fuel bus	11400
C_{emain}	The annual maintenance cost electric bus	18495
R_{de}	The impairing rate of fuel buses	20%
C_f	The remaining value of fuel buses	19300
A_a	The average lifecycle of fuel buses	6.9
C_{fix}	The cost of replacing one fuel bus	360000

Models for Economy

We quantify the cost and profits of replacing fuel buses with electric buses. The electric bus purchase expenditure is calculated by the price of E-bus(P_{ebus}) times the quantity of purchase(n) until all the fuel buses are replaced with electric buses. The transition process is associated with necessary construction of recharge stations and other infrastructures, we collectively refer to it as the construction cost C_c. Therefore, the initial fixed transition cost would be:

$$C_{fix} = n\,P_{ebus} + C_c \tag{4}$$

We assume a maximum of fifty percent transition cost would be covered by the government. After the subsidy from the government, the portion that has to be paid by the firm would hence be the fifty percent of the fixed cost, which would be paid by making loans. Dynamically, this part of the cost grows exponentially as the debt is compounded according to the interest rate(r). The long-term additional cost of the firm in the tth year is:

$$C_t = \left(\frac{C_{fix}}{2}\right)(1+r)^t \tag{5}$$

E-bus operation cost($Prf_{ope,i}$) includes the price of energy (for fuel((P_{oil}) and electricity(P_{ele})) per kilometer and the maintenance cost(C_{dmain}, C_{emain}). Therefore, the gained profit from operation in area i would be:

$$Prf_{ope,i} = \Delta C_{ope,i} = (P_{oil} - P_{ele})\,d_i + C_{dmain} - C_{emain} \tag{6}$$

We establish the long-term model to evaluate the total change in profit(Prf_i) in area i after t years of the transition, which would be the accumulated gains minus total cost in the years:

$$Prf_i = t\,Prf_{ope,i} - \left(\frac{C_{fix}}{2}\right)(1+r)^t \tag{7}$$

When fuel buses are replaced and put out of use, the remaining value of these capitals(C_s) is counted as the value loss for society. The impaired value of fuel-powered buses depreciates, starting from their initial price(P_{fbus}) and declining over time throughout their average lifecycle. R_{de} is a parameter for decreasing value and A_a is the average age of fuel buses.

$$C_s = P_{fbus} * (1 - R_{de})^{t-A_a} \tag{8}$$

The benefits of environmental governance($\mathrm{Environ}_{\mathrm{Bonus}_i}$) are now measured by carbon emissions in the mainstream perspective. Often, carbon emissions, a more measurable metric, are linked to other pollutants as well. Carbon pricing, or carbon taxation(tax), is the most used approach to gauge carbon emissions. Thus, we have:

$$Environ_{Bonus_i} = tax\, n_t\, E \tag{9}$$

Balance of Economy and Ecology

Given the economic constraints, we are endeavoring to replace fuel-powered buses with electric ones on the largest possible scale, taking the environment into consideration. The model constructed must consider that the total amount of electric buses purchased should not exceed the annual fiscal loan limit; that is:

$$\sum_{i \in \Gamma} (C_{i,total}/2)\, n_i < loan_t \tag{10}$$

As well as being proportional to the number of electric buses planned to be replaced.

$$loan_t = kn_t \tag{11}$$

Our goal is to buy as many electric buses as we can for each district while staying within the allocated budget. We also make sure that every year's revenue and expenses are balanced. Therefore, our combinatorial optimization model is:

$$\max_{\Gamma} \sum_{i \in \Gamma} Balance_{i,t} = \max_{\Gamma} \sum_{i \in \Gamma} n_i\, prf_{i,t} + n_i\, (T - t) Environ_{Bonus_i} \tag{12}$$

All the buses be replaced for T years, and we assume $T = 10$in our case. We assume bus transition mainly operate within the scope of each district We use computer simulation to iterate through all possible combinations to find solutions that best satisfy these principles. In each iteration, we generate a set of regional combinations and randomly select a solution that meets the above conditions. The algorithm flows as shown in Table 2:

Table 2. Algorithm for randomly generating combinations of regions and solving for optimization

Input: year t, The $loan_t$
Output: The best set combination $BestSet_t$

Pseudocode:
$BestSet_t = None$
$BestBalance_t = 0$
Build the combination of all of the district combinations Set_c

For $Subset$ belongs to the Set_c:
If $Subset$ satisfy:

$$\sum_{i \in Subset} (Cost_{i,total}/\,2) * n_i < loan_t$$

$RecordBalance\_t = 0$
For $i \in\ Subset$
$Balance_{i,t} = n_i *\ profit_{i,t} * (1+r)^{10-t} + n_i * (10-t) Environ\_Bonus_i$
$RecordBalance_t = RecordBalance_t + Balance_{i,t}$
If $RecordBalance_t > BestBalance_t$:
$BestBalance_t = RecordBalance_t$
$BestSet_t = Subset.$
Return $BestSet_t$

Results and Discussion

Annual Change in Harmful Emissions for All Substances

We calculate the annual emissions using the methods in 2.1. From the table 3, it is obvious that making the complete switch to electric buses has the most significant impact on CO2 emissions [18]. Therefore, reducing its impactful consequences on the climate, such as rapidly rising temperatures and extreme weather. Besides ameliorating green house gas emissions, the results reflect reductions in pollutant emissions of gases such as carbon monoxide, nitrogen oxides, sulfur dioxide, and hydrocarbons as well. Although switching to electric buses incurs a minor increase in certain pollutants, such as PM2.5, it is generally more environmentally and ecologically friendly than fuel buses.

Table 3. Annual Emission

	Fuel Bus (kt/year)	Electric Bus (kt/year)	Annual Emission Change (kt/year)
CO2	1.573385282	1.13035311	443.032171
CO	3.719538013	0.152507959	3.567030054
HC	0.325718357	/	0.325718357
NOX	6.355648441	0.441652009	5.913996432
PM2.5	0.117313815	0.057138729	0.060175086
PM10	0.130425359	0.142846822	-0.012421463
SO2	0.656957363	0.48581721	0.171140153

Additional Operation Profit and the Accumulative Firm Debt Over Time

The graphs for additional operation profit and the accumulative firm debt over time are drawn for the three areas in Shanghai [19,20]: Chongming representing remote areas (Fig. 1a), Pudong representing suburban areas (Fig. 1b), and Minhang (Fig. 1c) in the debt graph is a curve, hence there are two intersects representing the point that the firm starts to make profit and the period that it is making positive profit. According to the Fig. 1a for Chongming region, the total profit in the first ten years after the transition in the district is positive. Factually, its additional profit would balance the compounded debt and allows the firm to earn positive profit from operation within 6.99 years. The Fig. 1b for Pudong shows the analysis for the district. In the first ten years, the accumulative profit continues to be negative; However, the first intercept shows that the profit would be able to cover the additional cost. For Minhang, the gained profit is always below debt cost due to limited operation distance. Even after 10 years, Minhang district in the city would always make negative profit.

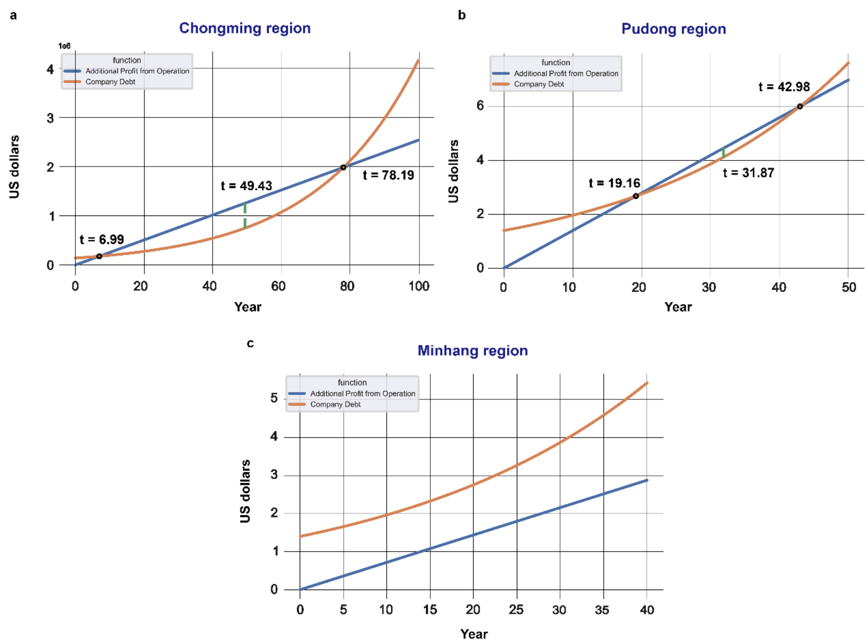

Figure 1. Profit-debt Analysis of three region in Shanghai.

Through the results, we could summarize the typical situations for firms to consider to balance payment. For areas with longer operation distances, the transition would be more profitable in the long-term and is likely to cover the transition cost. The replacement in the city should therefore start in regions with greater bus operation density. After years of positive profit, the firms should fully pay for the loans with interest costs before the second intercept to avoid negative loss.

Prediction of The Order for Converting Fuel Buses to Electric Buses

The replacement of fuel buses with electric buses may generally be carried out in phases; if there are n phases altogether, each phase will be assigned a different execution rate. According to the method in 2.3, we break down the implementation approach into four stages: in the first, third, fifth, and eighth years, district-level fuel buses will be replaced by electric buses. The following are the execution rates for each phase: 10% during the first phase, 20% during the second, 30% during the third, and 40% throughout the fourth, and apply the plan to three cities. The results are shown in the Figure 2:

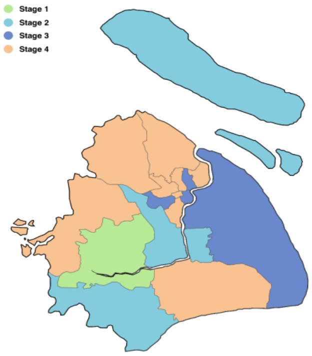

Figure 2. Districts for 4 stages Replacement – Shanghai

Table 4. Environmental and Economic Balance – Shanghai

Stage	Selected Districts	Replaced Ratio	Environmental Benefit	Economic Benefit	Balance
1	Songjiang	0.077	48932131	42341122	-1.75*108
2	Minhang, Jinshan, Chongming	0.242	83883654	235625319	-2.13*108
3	Huangpu, Changning, Hongkou, Pudong	0.555	119343563	291969965	-5.34*108
4	Xuhui, Jingan, Putuo, Yangpu, Baoshan, Jiading, Qingpu, Fengxian	1.000	84646233	-15094783	-1.14*109

We noted that Shanghai needs to complete the transition from oil to electric buses over a ten-year period, with the bus company incurring a debt close to 1.8 billion USD. We compared Table 4 with the actual subsidies provided by China for the operational costs of electric buses. According to the notice jointly issued by China's Ministry of Finance, Ministry of Industry and Information Technology, and Ministry of Transport, titled "On Improving the Subsidy Policy for Urban Public Bus Fuel Prices and Accelerating the Promotion and Application of New Energy buses", the annual operation subsidy for an electric bus ranges from 40,000 to 80,000 RMB. Taking the median value of 60,000 RMB for our calculations, the subsidy for Shanghai's 17,600 buses over ten years amounts to 10.56 billion RMB, approximately 1.468 billion USD. This is fairly close to our calculated debt figure, which demonstrates the reasonableness of our model. It also indicates that, in practical scenarios, this deficit needs to be subsidized by the government to reduce the debt burden on the bus company.

Conclusions

As the public transportation systems gradually transition towards electric buses in response to growing environmental concerns, we recognized the inevitable challenges that this shift entails, including unfinished infrastructure and high acquisition costs. To address these, we have developed a comprehensive mathematical model that takes into account both economic and ecological impacts. After the comprehensive modeling, we review our work and analyze the strengths and weaknesses of the model. Based on the rationale that greenhouse gases and air pollutants have different environmental damage indices, we have divided gas emissions into these two categories. This makes our model accurate when used in real-world scenarios.

Besides, it might be challenging to meet the project's funding requirements by depending only on government grants as the city switches to all-electric buses. We have thought about luring investment from other businesses to broaden the project's funding sources. By doing this, we can both quicken the fundraising process and lessen the burden on public funds. We included a realistic interest mechanism in the model to ensure that businesses could anticipate a specific return on their investment in order to entice them to invest. This effort not only facilitates the project's quick execution but also improves the model's comprehensiveness and completeness by accounting for a variety of funding sources and offering a more sustainable and strong backing for the city's switch to an entirely electric bus fleet.

However, in order to simplify the model, we constructed the ecological model without considering the possible pollution of the environment from the recycling and disposal of electric bus batteries at the end of their lives. The model mainly focuses on the pollution caused by the power generation process, as this is the main source of pollution compared to the lesser pollution caused by battery recycling. In our model, we focus mainly on the benefits of electric buses relative to traditional fuel buses in the transition process, specifically in terms of fuel cost savings and reduced environmental pollution. However, we have not adequately considered the revenue that may be generated by the electric buses themselves, such as advertising revenue. This source of revenue could not only add additional funding to the project but also help accelerate the transition process. The calculation of benefits does not take into account the potential for discounted time periods due to the charging of electric buses. This includes the processes of charging, connecting to charging equipment, and potentially waiting for the charging equipment to become idle, which can affect the actual operating time of the vehicle. Considering these discounted time periods when improving the model in the future will make the model more comprehensive and closer to actual operational scenarios.

Acknowledgments

I would like to thank my advisor for the valuable insight provided to me on this topic.

References

DOE, 2012. Philippine Energy Plan 2012-2030. Philippines' Department of Energy. https://www.doe.gov.ph/sites/default/files/pdf/pep/2012-2030_pep.pdf, Accessed 18th Janu 2024

Kim, K., Park, H. and Kim, H., 2017. Real options analysis for renewable energy investment decisions in developing countries[J]. *Renewable and Sustainable Energy Reviews*, 75, pp.918-926. https://doi.org/10.1016/j.rser.2016.11.073

Wu, R., Liu, F., Tong, D., Zheng, Y., Lei, Y., Hong, C., Li, M., Liu, J., Zheng, B., Bo, Y. and Chen, X., 2019. Air quality and health benefits of China's emission control policies on coal-fired power plants during 2005–2020[J]. *Environmental Research Letters*, 14(9), p.094016. https://doi.org/10.1088/1748-9326/ab3bae

IEA, S., 2017. International Energy Agency, 2016. Key World Energy Statistics, ed.

BNEF, 2017. New energy outlook 2017. Bloomberg New Energy Finance. https://data.bloomberglp.com/bnef/sites/14/2017/06/BNEF_NEO2017_ExecutiveSummary.pdf?elqTrackId=4

31b316cc3734996abdb55ddbbca0249&elq=0714ab8b3c51467a8b29e864d6fff67a&elqaid=7785&elqat=1&elqCampaignId=, Accessed 18th Janu 2024

Tzeng, G.H., Lin, C.W. and Opricovic, S., 2005. Multi-criteria analysis of alternative-fuel buses for public transportation[J]. *Energy policy*, 33(11), pp.1373-1383. https://doi.org/10.1016/j.enpol.2003.12.014

Miles, J. and Potter, S., 2014. Developing a viable electric bus service: The Milton Keynes demonstration project[J]. *Research in Transportation Economics*, 48, pp.357-363. https://doi.org/10.1016/j.retrec.2014.09.063

Hannah Ritchie, 2020. Cars, planes, trains: where do CO2 emissions from transport come from? https://ourworldindata.org/co2-emissions-from-transport, Accessed 18th Dec 2023

Ritchie, H. and Roser, M., 2023. Cars, planes, trains: where do CO2 emissions from transport come from? Our world in data. Global Change Data Lab.

Shirley, C. and Gecan, R., 2022. Emissions of Carbon Dioxide in the Transportation Sector.
EPA, 2023. Carbon Pollution from Transportation. https://www.epa.gov/transportation-air-pollution-and-climate-change/carbon-pollution-transportation, Accessed 15th Janu 2024

Brunekreef, B. and Holgate, S.T., 2002. Air pollution and health[J]. *The lancet*, 360(9341), pp.1233-1242. https://doi.org/10.1016/S2468-2667(16)30023-8

Laib, F., Braun, A. and Rid, W., 2019. Modelling noise reductions using electric buses in urban traffic. A case study from Stuttgart, Germany[J]. *Transportation Research Procedia*, 37, pp.377-384. https://doi.org/10.1016/j.trpro.2018.12.206
Shan, X., Chen, X., Jia, W. and Ye, J., 2019. Evaluating urban bus emission characteristics based on localized MOVES using sparse GPS data in Shanghai, China[J]. *Sustainability*, 11(10), p.2936. https://doi.org/10.3390/su11102936

Kühne, R., 2010. Electric buses–An energy efficient urban transportation means[J]. *Energy*, 35(12), pp.4510-4513. https://doi.org/10.1016/j.energy.2010.09.055

Quarles, N., Kockelman, K.M. and Mohamed, M., 2020. Costs and benefits of electrifying and automating bus transit fleets[J]. *Sustainability*, 12(10), p.3977. https://doi.org/10.3390/su12103977

Vepsäläinen, J., Otto, K., Lajunen, A. and Tammi, K., 2019. Computationally efficient model for energy demand prediction of electric city bus in varying operating conditions[J]. *Energy*, 169, pp.433-443. https://doi.org/10.1016/j.energy.2018.12.064

Merkisz, J., Fuć, P., Lijewski, P. and Pielecha, J., 2016. Actual emissions from urban buses powered with diesel and gas engines[J]. *Transportation Research Procedia*, 14, pp.3070-3078. https://doi.org/10.1016/j.trpro.2016.05.452

Stats.gov.cn., 2019. National Bureau of Statistics. http://www.stats.gov.cn. Accessed 20th Dec 2023
GlobalPetrolPrices., 2021. Diesel prices in Shanghai. https://www.globalpetrolprices.com/China/Shanghai/diesel_prices, Accessed 30th Oct 2023