The ecological and economic impacts of the comprehensive implementation of electric buses in New York City

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Abstract. Electric buses usually use batteries or electric motors as power sources, which do not generate exhaust emissions and help reduce air pollution and greenhouse effect, making them more environmentally friendly than traditional fuel buses. In this study, we established a model for New York City to estimate the ecological consequences and financial implications of the transition from fuel powered buses to electronic buses. In addition, we have established an optimization model aimed at helping the New York government and bus companies better allocate funds. The research results indicate that compared to traditional fuel powered buses, electric buses have many positive impacts in both ecological and financial aspects. Therefore, it is necessary to gradually shift from fuel powered buses to electronic buses.

Keywords: VSP approach; emission factor; optimization metho.

1. Introduction

Traditional fuel buses rely on fossil fuels such as diesel or natural gas as their energy source, which may lead to greenhouse gas emissions and air pollution. Electric buses usually use batteries or electric motors as power sources, which do not generate exhaust emissions and help reduce air pollution and greenhouse gas emissions, improving urban air quality. The operating cost of electric buses is usually lower because electricity is relatively cheap and efficient, which can reduce energy consumption in the long run.

New York is the most populous city in the United States and currently does not have an all electric bus fleet.Therefore, we analyze the ecological consequences, financial costs, technological limitations, and other factors of New York City's transition to an all electric bus fleet by constructing a model.

2. Assumptions and Variables

Assumption 1: The number of passengers in the bus has no effect on the energy consumption

Justification 1: passenger load has almost no effect on fuel consumption during idling, or under very low speeds (610 km/h), and the number of passengers is relatively stable in normal times.

Assumption 2: The speed of the bus, the road grade, and the acceleration of the bus are constant values over time.

Justification 2: The bus normally runs at a slow, steady speed concerning the safety of the passengers, and the differences of the road grade within certain range could be neglected.

Assumption 3: All e-buses underwent slow nighttime charging, and the full battery capacity will support the whole day onboard operation.

Justification 3: It is feasible that e-buses underwent slow nighttime charging to ensure that they would be fully charged before departure the next day. And it also leads to the equal number of battery chargers and e-buses, which will simplify the calculation.

The definition of part signals and variables used in the model is shown in Table 1.

Table 1: Definition of Variables

Variables	Meaning
v	vehicle's instantaneous speed (m/s)
φ	instantaneous road grade
a	vehicle's instantaneous acceleration (m/s^2)
FR_j	fuel consumption rate (liter/s)
EF_{CO_2}	emission factor of CO_2
EF_{SO_2}	emission factor of SO_2
EF_{NO_X}	Emission factor of NO_X
C_{EB}	Total cost of e-bus

*Please refer to body context for unlisted variables

3. The Ecological Consequences of the Transition

In this section, the paper focus on the consequences of the e-bus transition in ecological way. Traditional diesel buses emit pollutants, including nitrogen oxides (NO_X), particulate matter, and CO_2, contributing to air pollution and climate change, while Electric buses produce zero tailpipe emissions, reducing air pollution and greenhouse gas emissions. Therefore, e-buses are more environmentally friendly.

3.1 Energy Consumption

In this paper, we use VSP model to analyze diesel-bus energy consumption. VSP is typically expressed as a function of vehicle speed, acceleration, and road grade.

where VSP is the Vehicle Specific Power (m^2/s^2); v is instantaneous speed at which the vehicle is traveling(m/s); a is instantaneous acceleration of the vehicle (m/s^2); φ is instantaneous road grade; 0.092 is rolling resistance term coefficient; 0.00021 is the drag term coefficient.

The value of VSP could be divided into VSP-based modes. Two considerations were taken into account when determining the number of discrete VSP modes: (a) each mode should produce an average fuel consumption rate that is statistically different from any other mode and (b) no single mode should dominate the estimate of total fuel consumption.[1] From the VSP mode, we could refer the corresponding fuel consumption rate given in reference [1]. The definition of VSP mode is shown as follows:

Table 2: Definition of VSP Mode

VSP mode	VSP range(m^2/s^3)	VSP mode	VSP range(m^2/s^3)
1	VSP≤0	5	6≤VSP<8
2	0<VSP<2	6	8≤VSP<10
3	2≤VSP<4	7	10≤VSP<13
4	4≤VSP<6	8	VSP≥13

Then we need to calculate the energy consumption.

$$E = FR \times TVSP$$

where E is the total trip fuel consumption (in liters), FR_j is the fuel consumption rate(liter/s), and $TVSP_j$ is the bus total running time(s), which is shown in the following formula:

$$TVSP = \sum_{i=1}^{m} Num_i * T_i$$

The above formula sums up the running time of each e-bus line.

3.2 Pollution Calculation

The construction of gas emission data tables for different energy types is calculated based on energy consumption table data displayed in Appendix. Gas emission data is obtained by multiplying energy consumption by gas emission factors[3], and now we try to analyze CO_2, SO_2, NO_X specifically.

3.2.1 CO_2

In this paper, all forms of carbon released are counted as carbon dioxide emissions, while non oxidized carbon such as particulate matter, soot, or ash is not included in the total carbon dioxide emissions.

Emission factor is a metric is used to assess the footprint of different energy sources, industrial processes, or modes of transportation, helping to quantify their contribution to climate change. Carbon emission factor is typically expressed as the amount of CO_2 emissions per unit of energy. By carbon emission factor, the CO_2 emissions can be calculated as follows:

$$EF_{co_2} = EF_C * B * \frac{CO_2}{C} * D$$

The carbon emission factor is EF_C. The carbon oxidation factor is B. Because the default carbon emission factor assumes complete oxidation of carbon, so here the carbon oxidation factor B=1. And CO_2/C is an coefficient equals 44/12, due to the chemical reaction equation $C + O_2 = CO_2$. The carbon oxidation ratio is D, which normally take as 1.

3.2.2 SO_2

The sulfur emission factor is mainly calculated by calculating the sulfur content in the fuel, the proportion of sulfur residue in soot, particulate matter, and ash, and the proportion of SO2 emissions reduced by desulfurization technology.

$$EF_{SO_2} = 2 * s * \frac{1}{Q} * (1 - r) * (1 - n)$$

EF_{SO_2} represents the sulfur emission factor, s is the sulfur content in the fuel, r is the proportion of sulfur residue in soot, particulate matter, and ash, and n is the proportion of SO_2 reduction by desulfurization technology. Q represents the net calorific value of energy. s is often taken between [0.3%, 3%], r is often taken as 0, different regions have different n values. In this paper, we take n as 0 for lack of information. And Q can be found in the table in Appendix, which is 42652 kWh for diesel.

3.2.3 NO_X

Like what was discussed above in terms of CO_2, we could draw similar formula:

$$EF_{So_2} = EF_S * B' * \frac{SO_2}{S} * D'$$

After figuring out the emission factors of CO_2, SO_2, and NO_X, we could calculate the total emission of the three types of pollution.

$$Emission_{total} = E * (EF_{SO_2} + EF_{CO_2} + EF_{NO_X})$$

E is the liters of diesel needed, as already discussed above.

3.3 Oil Extraction Consequences

Crude oil extraction, while crucial for meeting energy demands, often leaves behind a trail of ecological devastation and air quality concerns. Extracting oil typically requires extensive deforestation, which not only reduces carbon sequestration but also alters local climate patterns, leading to the loss of biodiversity. Burning diesel can produce many harmful gases and cause global warming. In addition, various pollutants, including harmful chemicals and heavy metals, are generated during the mining process. These pollutants can penetrate into soil and water, posing a threat to the health of wildlife and nearby communities. This may lead to a decrease in agricultural production capacity and contamination of drinking water sources.

3.4 Simulation

3.4.1 Parameters

From reference[2], we could get some valid experimental data describing bus routes in Porto. We assume the difference of the bus in different region and the road grade can be minimized. Therefore, it is reasonable that the data in Porto can be an estimation of the data in New York. The Spearman rank correlation between fuel consumption rates and selected three factors is shown in the following table:

Table 3: Spearman Rank correlation for fuel consumption rate & selected factors

Fuel Type	Speed	Acceleration	Road Grade
diesel	0.79	0.32	0.1

The table above shows Spearman correlation coefficients for fuel consumption rate and selected explanatory factors for all tested vehicles. All p values are less than 0.05, indicating that all correlation coefficients are statistically significant.

3.4.2 Experimental Results

First, we need to calculate the value of TSP, which is $\mathrm{VSP} = 0.79 * (0.32 + 1.2 * \sin(0.1) + 0.092) + 0.00021 * 0.79^3 = 0.42$, and by searching for information, it can be found that the fuel consumption rate for diesel is 0.9 g/s.

By reviewing relevant data, there are a total of 304 bus routes in New York, operating approximately 5700 buses. Assuming each route has a running time of 18 hours and a bus departs every 10 minutes, the total daily running time of all New York buses can be calculated to be 2490000 minutes.

Therefore, the total energy consumption is the multiplication of the total running period of all the e-bus and fuel consumption rate, which equals 134460 kg/day. Next, by calculating all the emission factors, multiplying them with the energy consumption, we finally draw the result.

Table 4: Emission Result

Item	Volume
CO_2(kg/day)	319821.86
SO_2(kg/day)	3553.58
NO_X(kg/day)	4738.10

4. Financial Implications

The conversion of the diesel bus to e-bus entail incremental costs in several aspects, such as capital costs, operational costs, labor costs, social cost, etc. Next, we try to analyze these factors in detail.

4.1 Capital Costs

The primary capital costs primarily include the funds spent on purchasing electric buses and the associated costs for batteries and charging infrastructure.

4.1.1 E-bus Cost

In our analysis, there are two types of e-bus, large-sized and medium-sized, the total cost of large and medium sized e-buses are estimated as follows:

$$C_{EB} = N_{LB} * C_{LB} + N_{MB} * C_{MB}$$

Where N_{LB} is the number of large e-buses, N_{MB} is the number of medium e-buses, C_{LB} is the price of large e-buses, and C_{MB} is the price of medium e-bus.

As for the bus depreciation, by public online resource, most bus will be used for over 15 years, so it is a long horizon. We suppose that depreciation cost is minimized compared to the maintenance cost every year. In the following subsection, we will later analyze maintenance cost in detail.

4.1.2 Battery Cost

4.1.2.1Original costs when buying the battery

The formula is shown in the following, which is similar for the formula in e-bus costs.

$$C_{BA} = \alpha * (N_{LB} * C_{BLB} + N_{MB} * C_{BMB})$$

α measures the proportion of backup batteries, if $\alpha = 1.2$, it means we prepare more of 20% batteries in advance.

4.1.2.2Annual Depreciation

Accelerated depreciation is a commonly used method for calculating asset depreciation, especially suitable for those who experience faster depreciation in the early stages of the asset lifecycle, such as electric bus batteries. There are different accelerated depreciation methods, such as the double declining balance method and the sum-of-the-years-digits method. These methods allow for a more significant depreciation expense in the asset's earlier years. The double declining balance method is shown as follows:

$$DE_T = \frac{2}{L} \times \mathrm{BV}_{\mathrm{T}-1}$$

Where DE_{T} is the abbreviation of depreciation expense in period T, L is the expected useful life of batteries, C_{BA} is the total cost of all the needed batteries. In the beginning, Book value of the batteries is $\mathrm{BV}_0 = \mathrm{C}_{\mathrm{BA}}$.

4.1.3 Battery Charger Cost

All e-buses underwent slow nighttime charging to ensure that they would be fully charged before departure the next day. Thus, the number of battery chargers and e-buses was equalized to satisfy this condition.

$$\mathrm{C}_{\mathrm{CH}} = \mathrm{N}_{\mathrm{LB}} * \mathrm{C}_{\mathrm{CLB}} + \mathrm{N}_{\mathrm{MB}} * \mathrm{C}_{\mathrm{CMB}}$$

where N_{LB} is the number of large e-buses, N_{MB} is the number of medium e-buses, $\mathrm{C}_{\mathrm{CLB}}$ is the charge price of large e-buses, and $\mathrm{C}_{\mathrm{CMB}}$ is charger price of medium e-buses.

4.1.4 Total Capital Cost

Total Capital Cost is calculated by the sum of the three costs listed above, specifically,

$$CC_{total} = C_{EB} + C_{BA} + C_{CH}$$

Where $\mathrm{CC}_{\mathrm{total}}$ is the total value of capital costs.

4.2 Maintenance Costs

The main maintenance costs include regular maintenance of buses and daily electricity expenses. We define the total maintenance cost as the combination of charging cost, regular maintenance cost, and additional reserve cost.

4.2.1 Regular Maintenance

Regular maintenance and inspection can help extend the service life of buses and reduce future maintenance costs. We estimate the annual regular maintenance cost per electric bus to be $1000. Additionally, $100 is reserved annually for each electric bus as an emergency reserve.

4.2.2 Charging Cost

The electricity costs were estimated as follows:

$$C_{EP} = \sum_{i=1}^{2} [kWh_i * EP_i] * CH$$

Where $i = 1$ means summer months, and $i = 2$ means non-summer months; kWh is the energy charged in an hour, EP_i is the electricity price, CH is the charging hours. We assume that the e-bus charges once in a day, and needs 6 charging hours one day.

4.3 External Funding

There are several ways that New York government can obtain external funding, such as from federal government,

4.3.1 Federal Government

Governments at all levels in the United States attach great importance to urban transportation construction. The federal government is mainly responsible for public welfare urban infrastructure projects that involve the overall national situation or require significant investment, and provides funding, loans, and tax subsidies to local governments accordingly. Therefore, local governments can apply for funding from the federal government.

4.3.2 Issue Municipal Bonds

The US government has established an effective investment and financing mechanism, which not only plays an important role in promoting the development of urban infrastructure construction in the United States, but also solves the problem of fair investment burden in urban infrastructure. Therefore, local governments can issue municipal bonds.

4.3.3 Absorb Private Capital

The Egyptian government has introduced a new law allowing private capital to participate in the construction of urban light rail systems. With the passage of this new legislation, Egypt has witnessed a new wave of investment in urban infrastructure development. The local government can learn from Egypt and introduce private capital.

4.4 Simulation

The relevant data found is shown in the table below

Table 5: The Price of relevant devices

price	e-bus type	
	large	medium
e-bus price(USD/e-bus)	186360	124240
price of full capacity battery(USD/e-bus)	80756	37272
price of battery charger(USD/site)	24848	18636

average electricity price(USD/kWh)	Summer: 0.091 Non-summer: 0.088

From table above, and put the figure into the formulas, we could finally figure out all types of costs. Total capital cost is 1412795160 USD, composed of 885210000 e-bus cost, 403655760 battery cost, and 123929400 battery charger cost. The maintenance cost is 6392436 USD/day, which means the total maintenance cost during the future 10 years is about 23012769600 USD. Therefore, the total funding that the government should provide is 60% of the sum of capital costs and maintenance cost, which is 14655338856 USD.

5. How to Invest over 10 years

We first need to clarify the range that the government is responsible in the conversion process. The conversion of e-bus event is usually not seen as the daily maintenance and operation of public transportation services. The government is usually responsible for funding or regulating public transportation systems. Therefore, we assume that the government will invest in 60% of the capital cost, maintenance cost we listed above, and other costs will be taken by the local bus company.

5.1 The Factors to be Considered

In this paper, we try to focus on the proportion of total e-bus to be invested over 10 years. N_{LB} is the number of large e-buses, N_{MB} is the number of medium e-buses, we assume that each year, the increase of the two types of e-bus is equal. And the problem turns to the solving of $\omega = (\omega_1, \omega_2, \ldots, \omega_{10})$, ω is the proportion of the total number of the e-bus.

Next, we discussed the factors that we need to consider.

5.1.1 Capital Costs

Now we have the total of the e-bus as C_{EB}, battery charger cost as C_{CH}, and battery cost of C_{BLB} for large-sized e-bus and C_{BMB} for medium-sized e-bus, considering the double declining depreciation method. And we suppose the price of the battery will decline with time. We assume that the price follows a parabolic curve, the price in the first year is the original price listed in the above section, and in the 10th year, the price will be half of the original price, and we further assume that the price of the battery will be lowest in the 20th year. So put (1,1), (10,0.5) into $\text{price}_t = b(t-20)^2 + c$, we can get $\text{price}_t = 0.0019(t - 20)^2 + 0.3141$

Because one e-bus need α battery and one battery charger, so for j-th year, the total capital costs should be

$$CC_j = \sum_{i=1}^{2} \frac{\omega_j}{2} * N_{iB} * (C_{iB} + \alpha * C_{BiB} + C_{CiB}) + dep_j$$

where i=1 stands for large-sized e-bus and i=2 stands for medium-sized e-bus. And dep_j stands for the depreciation cost of the battery in j-th year.

$$dep_j = \frac{2}{L} \times \mathrm{BV}_{j-1}$$

where BV_{j-1} is battery's book value in year j-1, and L is the useful life of the battery. We take L=10 in this paper.

5.1.2 Maintenance Costs

Total maintenance cost is composed of charging cost, regular maintenance cost, and additional reserve cost. And we see it as an annual cost.

$$MC_j = 2\omega_j * N_{LB}(1000 + 100 + C_{EP})$$

5.2 The Optimization Model

We hope to let this conversion benefit the environment as soon as possible, which means that we encourage more e-bus replacement in earlier years. What's more, we also want to minimize the volatility of every year's investment. Based on these two considerations, we set objective formula as

$$\min f \coloneqq -(\omega_1 + \omega_2 + \omega_3) + 20 * var\,(w)$$

The government input capital takes up 60% of the costs. Although the US government has established many investment and financing strategies, its financial resources are limited, and the annual expenditure it can support is denoted as AE. So, we could obtain the limiting conditions as follows:

$$CC_j + MC_j \leq AE, \text{ for j=1,2,…,10}$$

ω is the ratio of total e-bus, and it should subject to the condition

$$\sum_{i=1}^{10} \omega_i = 1\,, \qquad 0 \leq \omega_i \leq 1$$

5.3 Simulation

The result is shown in table below:

Table 6: Optimization Result

item	value	item	value
ω_1	0.140	ω_6	0.102
ω_2	0.122	ω_7	0.088
ω_3	0.121	ω_8	0.083
ω_4	0.111	ω_9	0.075
ω_5	0.109	ω_{10}	0.048

And we could also figure out that the variance of ω is 6.48×10^{-4}. This is a relatively balanced allocation method that takes volatility into account. Relatively speaking, this method guarantees volatility, and additionally considers time factor as well, which will be helpful in reducing fuel pollution to the environment as soon as possible.

6. Strengths and Weakness

6.1 Strengths

When calculating the emissions, our model considers modeling the relation between the energy consumption and emission volume in details, which is helpful for understanding the conversion process.

For question 3, many reference do not give quantified method to measure how to allocate fund in an investment horizon. In this paper, we established an optimization model to figure out how to invest in the conversion process.

6.2 Weaknesses

We use some idea status in the conversion process, which are: suppose that one bus match one battery charger; the e-bus will only need one battery charge a day at night times; the number of large-sized e-bus is equal to the number of medium-sized. In practical, the real case may be different. But for lack of concise data, we use these idea conditions for analyze.

We do not considering the source of electricity, it may also come from fuels such as coal and natural gas, resulting in the generation of exhaust gas

7. Conclusion

Traditional fuel buses have many negative consequences no matter in ecological aspects or financial aspects compared with electronic buses. Converting traditional fuel buses to electric buses is a trend, and more and more countries and cities are adopting policies and regulations to encourage or require the use of electric buses in public transportation systems to achieve environmental protection and sustainability goals. Converting traditional fuel buses to electric buses is of great importance for improving urban environment, reducing pollution, saving energy, improving transportation efficiency, and promoting sustainable development and technological innovation. This is an important measure that will help shape future urban transportation.

Appendix

Types of energy	Net calorific value(kWh)
crude oil	41816
gasoline	43124
kerosene	43124
diesel oil	42652
natural gas	38.93
raw coal	20908

Bus information can be found by MTA, for example:

Reference

[1] Zhai, H., Frey, H.C., Rouphail, N.M., 2006. Speed and facility-specific emissions estimates for transit buses based on measured speed profiles. In: Proceedings of the Annual Meeting of the Air & Waste Management Association, New Orleans, Paper No. 195.

[2] Frey H C , Rouphail N M , Zhai H ,et al.Comparing real-world fuel consumption for diesel- and hydrogen-fueled transit buses and implication for emissions[J].Transportation Research Part D Transport & Environment, 2007, 12(4):281-291.

[3] Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories: Reference Manual (Volume 3) , Intergovernmental Panel on Climate Change

[4] Fang S C , Ke B R , Chung C Y .Minimization of Construction Costs for an All Battery-Swapping Electric-Bus Transportation System: Comparison with an All Plug-In System[J].Energies, 2017, 10(7):890.

[5] Burke AF. Batteries and ultracapacitors for electric, hybrid, and fuel cell vehicles. IEEE Proc 2007;95:806–20.

[6] Ning W, Yun L, Yafei L. Economic evaluation of electric bus charging infrastructure. In: IEEE 17th International Conference on Intelligent Transportation Systems. p. 2799–804.