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A Roadmap for Detroit to Bolster E-bus Adoption by 2033

Pengyu Tang*, Ziyang Zhang, Xinhang Li, Yixi Wu

Hefei No.1 Middle School, Hefei, China

Email address:
tpy_peter@163.com (Pengyu Tang)
*Corresponding author

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Abstract: Compared with internal combustion engine vehicles, electronic vehicles are quiet and comfortable, with no noise from the engine, no consumption of fossil fuels, and no emission of smelly air pollutants. The only drawback of electronic vehicles is they take a long time for the batteries to be charged. This could be solved by optimizing bus routes, building more charge stations, and adopting fast charge technology. In this paper, the ecological and financial consequences of replacing diesel buses with electronic buses is analyzed. As the result shows it not only saves energy and reduces the emission of air pollutants, but also minimizes the operational costs and therefore greatly increases the profits. A model based on revenue and expenditure is built, which is capable of plotting a detailed roadmap, with the specific number of electronic buses to upgrade, and the forecast of corresponded financial implication on expenses and income year by year. Based on the model, two different kinds of path of transition are analyzed. The first kind is to do it slowly and upgrade only a limited number of electronic buses every year, especially in the beginning years. This kind of plan would minimize the external funding needed during the transition, but cannot repay the external funding by the end of 10 years. The other kind is to upgrade as many electronic buses as the external funding could provide at the beginning. Although it would cause a heavy burden on fiscal revenue, the transition can be achieved faster and make more profits by the end of 10 years, eventually able to repay the external funding.

Keywords: Electronic Bus Fleet, Revenue and Expenditure Model, Environmental Protection

1. Introduction

In general, the public transportation system in the US is underdeveloped compared to other developed countries [1, 2]. Considering the large number of daily commuters, citizens need a sufficient and efficient public transportation system. Primarily, people often use private cars rather than buses. However, in recent years, the US government has promoted the use of public transportation to tackle the problem of traffic congestion and air pollution [3]. Initially, the traditional diesel was used. However, there are some serious problems associated with it that cannot be ignored. The main reason is the emission of harmful gasses such as nitrogen oxides and carbon dioxide, which severely affect air quality. The small particles of these gasses can penetrate directly into the human lungs and cause serious damage to the human body. In fact, A typical diesel bus emits 103,948,402.66g of greenhouse gases annually [4]. In addition, the engines and exhaust systems of conventional diesel buses require regular maintenance and replacement, which drives up maintenance costs. Due to its complex operating principle, it is much more difficult to maintain.

The situation seems to be changing as electric buses gradually enter our lives. They are more environmentally friendly as the electric energy they use does not emit exhaust fumes, reducing air pollution and greenhouse gas emissions. This helps to improve air quality in cities and reduce pollution. In addition, the price of electricity is relatively low. In contrast, diesel buses require expensive diesel fuel, and diesel prices are susceptible to fluctuations in international markets.

However, the electronic bus also faces some challenges. Firstly, the initial cost of an electronic bus is relatively high, including the cost of electric drive systems, batteries, and so on. This can be a major financial burden for some public transport operators with limited budgets. Secondly, electronic buses need to be equipped with charging facilities, and the construction of charging facilities is very costly and time-consuming. Some studies show that the charging time of electronic buses is usually between 2 to 8 hours, while the charging time of diesel buses is usually only a few minutes [5, 6]. Thirdly, setting up the charging infrastructure is also expensive. Finally, the range of electronic buses is generally shorter than that of conventional diesel buses. Some studies show that the range of electronic buses is usually about 340 kilometers, while diesel buses have an average range of 1100.45 kilometers [7, 8]. It is therefore crucial for us to develop a sound understanding of the feasibility of universal electric buses, their ecological consequences, and the associated financial implications.

This paper constructs a mathematical model to understand the environmental consequences of the Detroit's conversion to an all-electric bus fleet. Another mathematical model that focuses on the financial impact of switching to e-buses is also built. Based on these two models, the ecological and financial consequences of replacing diesel buses with electronic buses in Detroit are analyzed. Two roadmaps of this transition are analyzed and compared. We chose Detroit as our target. Populated with 630,000 people [9], Detroit was known as the "City of Cars" in the 20th century and is famous for its booming automotive industry. Although Detroit has flourished in the development of fuel vehicles, the development of electronic vehicles is fallen behind. Specifically, there are 292 buses but there are only 4 electronic buses [10]. At the same time, Detroit's air quality and ecological environment were severely damaged by large-scale automobile production in the 20th century.

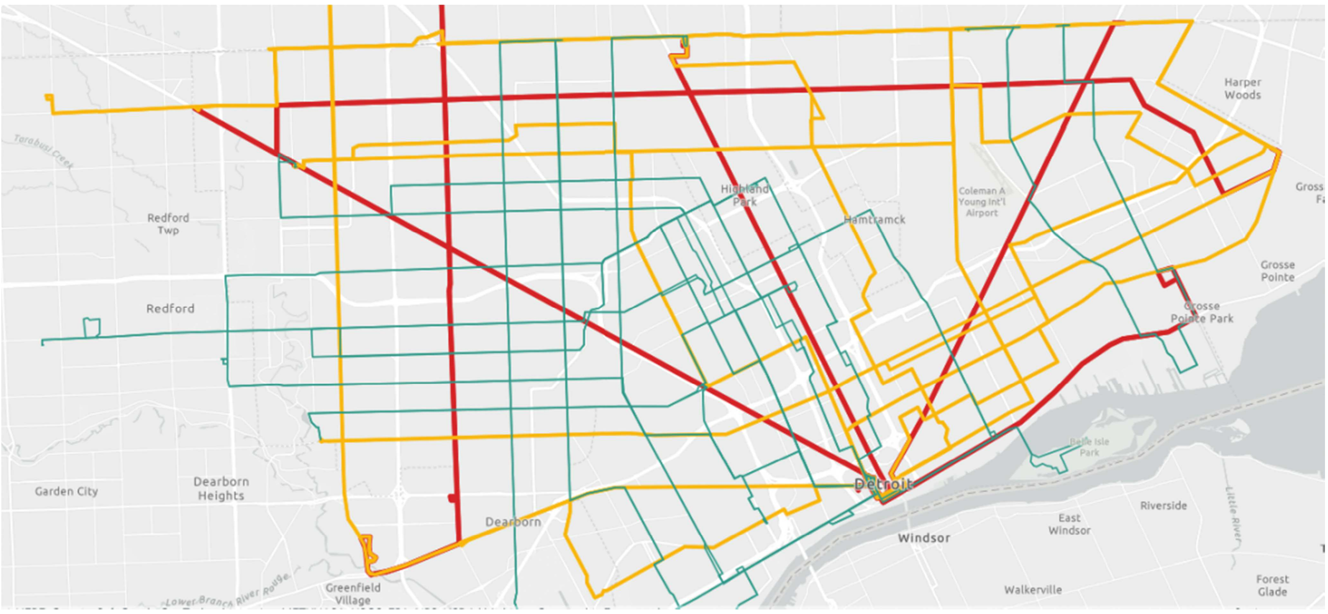

Figure 1. *The bus map of Detroit city [11].*

2. Ecological Consequences Comparison

2.1. Comparison of Air Pollutant Emissions

The quantification of carbon emissions

According to the data from the United States Department of Transportation, the emission of carbon dioxide from one diesel bus in 2021 is approximately 1547.187 grams per mile. According to data from Evobsession, the overall average efficiency of the Proterra electronic bus is 2.15 kilowatt-hours (kWh) per mile [12]. At the same time, according to the United States Environmental Protection Agency, The United States emits an average of 433 grams of carbon dioxide to produce 1kWh of electricity. By multiplying these two data together, the carbon dioxide emitted from electricity generation for one electronic bus to travel one mile can be calculated accordingly, and the result is about 930.95 grams of carbon dioxide. The reduction of CO_2 emission of every diesel bus replaced by an electronic bus would be 616 grams per mile, as shown in Table 1.

Table 1. *Reduction of CO_2.*

	Emission of CO_2 (g/mile)
Per diesel bus	1547.487
Per electronic bus	930.95
reduction	616.537

The quantification of PM2.5 emissions

According to the data from the United States Department of Transportation, the emission of PM2.5 from one diesel bus in 2021 is approximately 0.169 grams per mile. According to the data from Evobsession, the overall average efficiency of the Proterra electronic bus is 2.15 kilowatt-hours (kWh) per mile. In addition, according to the data from Statista, Electronic utilities in the United States emitted approximately 85,000 tons (which is 8.5×10^{10} grams) PM2.5 in 2022 from fuel combustion, while the overall electricity consumption in the United States is 4,050 terawatt-hours (which is 4.05×10^{12} kWh) in 2022, the highest value in the period under consideration. Thus, the average PM2.5 emission per 1kWh of electricity production can be calculated, which is 0.02g. Combined with the energy consumption of electronic bus, the

PM2.5 emitted from electricity generation for one electronic bus to travel one mile can be calculated, which is 0.043 grams. The reduction of PM2.5 emission of every diesel bus replaced by electronic bus would be 0.126 gram per mile, as presented in Table 2.

Table 2. *Reduction of PM2.5.*

	Emission of PM2.5 (g/mile)
A diesel bus	0.169
An electronic bus	0.043
reduction	0.126

The quantification of CO emissions

According to the data from Ref [13], Conventional diesel buses emit 12.7 grams of CO per kilometer traveled. Harmonizing the units to grams per mile gives 13.382 grams per mile. According to the data from Ref [13], electronic buses emit 3.382 grams per mile. The reduction of CO emission of every diesel bus replaced by an electronic bus would be 10 grams per mile, as Table 3 below describes:

Table 3. *Reduction of CO.*

	Emission of CO (g/mile)
A diesel bus	13.382
An electronic bus	3.382
reduction	10.000

The quantification of NO_x emissions

According to the data from Ref [13], Conventional diesel buses emit 30.435 grams per kilometer traveled. According to the data from Ref [13], electronic buses emit 16.908 grams per mile. The reduction of NO_X emission of every diesel bus replaced by an electronic bus would be 13.5 grams per mile, as shown in Table 4.

Table 4. *Reduction of NO_x.*

	Emission of NO_x (g/mile)
A diesel bus	30.435
An electronic bus	16.908
reduction	13.527

2.2. Modelling Process

Normalization of the environmental factors

The data need to be normalized in order to unify the order of magnitude, which is presented in Table 5.

Table 5. *Normalization of data.*

	Diesel bus (g/mile)	Electronic bus (g/mile)	Diesel bus (normalization)	Electronic bus (normalization)
CO_2	1547.487	930.95	1	0.601
PM2.5	0.169	0.043	1	0.254
CO	13.382	3.382	1	0.253
NO_x	30.435	16.908	1	0.556

Constructing the model of pollution indicator

Considering the above four factors, the following model is made:

$$y = (\sum_{i=1}^{n} k_i x_i) \cdot C$$

y is the indicator of collective pollution made.

k_i represents the coefficient of item i environmental factor. (The more relevant the factor is to the pollution caused by emissions from conventional energy vehicles, the larger the value. The range of values of k is from 0 to 1, and $\sum_{i=1}^{n} k_i = 1$).

x_i represents the specific value of pollution generated by a conventional energy vehicle for the environmental factor of item i.

C represents the number of buses in the corresponding city.

Diesel bus:

$$y = C\,(k_{CO_2}X_{CO_2} + k_{air\ pollutant}X_{air\ pollutant})$$

Because three air pollutants are chosen PM2.5, CO, and NOx, these three variables will bisect k. Thus, the model changes to:

$$y = C\,(k_{CO_2}X_{CO_2}\ k_{PM2.5}X_{PM2.5} + k_{CO}X_{CO} + k_{NO_x}X_{NO_x})$$

Next, consider the problem from both short-term and long-term perspectives and bring the previous data directly into the model. The difference between long-term and short-term is mainly due to the different focus of the model. In the short term, air pollutant emissions have a direct impact on air quality, which can jeopardize human health [14]. Therefore, it's necessary to adjust the k-value of air pollutants to be higher than that of carbon emissions. In the long term, greenhouse gas emissions have the effect of destroying the overall ecosystem of the planet [15]. Therefore, it's necessary to adjust the k-value of air pollutants to be higher than that of carbon emissions. The values of k for short-term and long-term consideration are shown in Table 6.

Table 6. *The value of k for short-term and long-term consideration.*

	Short-term	Long-term
k_{CO_2}	0.05	0.5
$k_{PM2.5}$	0.25	0.2
k_{CO}	0.6	0.2
k_{NO_x}	0.1	0.1

2.3. Results and Comparison

Table 7. *Comparison of ecological impact of diesel bus and electronic bus.*

	Short term y	Long term y
Diesel bus	292	292
Electronic bus	87.87	133.59
Percent decrease by introducing e-bus	70%	54%

As shown in Table 7, the net air pollutant emission is decreased by 70% in short-term and 54% in long term by replacing diesel buses with electronic buses. The ecological model establishes the total ecological impact formula and analyzes the model sensitivity by changing the weights to make the model more reliable. The ecological model considers short-term and long-term impacts. It analyzes the ecological consequences from many angles, making the model widely applicable and more convincing.

3. Financial Implications Analysis

3.1. Cost Modelling

According to the Greet-Based Full Life Cycle Analysis of All-Electric Buses and Conventional Buses, the acquisition cost, annual energy cost, and infrastructure cost for a diesel bus are $82.3 thousand, $20.3 thousand, and 0, respectively. Since there are no new diesel buses, only the annual cost needs to be considered, which is $20.3k per diesel bus according to the table. According to the Greet-Based Full Life Cycle Analysis of All-Electric Buses and Conventional Buses, the acquisition cost, annual energy cost, and infrastructure cost (such as the establishment of charging stations and related maintenance) for each electronic bus are $164.6 thousand, $4.9 thousand, and $13.7 thousand, respectively. The acquisition cost and infrastructure cost are "one-time", while the energy cost is annual. Thus, the cost per bus for replacing all diesel buses with electronic buses can be calculated at $178.3k, while the annual cost of one electronic bus is $4.9k. The cost comparison between diesel and electronic buses is shown in Table 8.

Table 8. *Cost comparison between diesel and electronic buses.*

	Cost (diesel bus)	Cost (electronic bus)
acquisition	$82.3k	$164.6k
annual operational cost	$20.3k	$4.9k
Infrastructure	0	$13.7k

Multiplying the transition cost of one electronic bus ($178.3k) by the total number of buses that need to be replaced (which is 288, because the government has already bought four electronic buses) yields a full replacement cost of $51.35 million. Therefore, the maximum potential external funding is assumed as:

$$\$51.3504 \times 50\% = \$25.68 \text{ million}$$

3.2. Revenue and Expenditure Modelling

The annual revenue of a diesel bus and an electronic bus are assumed as the same. According to the Greet-Based Full Life Cycle Analysis of All-Electric Buses and Conventional Buses, the annual ticket revenue and annual advertising revenue of one bus amount to 20.0 thousand dollars and 6.9 thousand dollars respectively, presented in Table 9.

Table 9. *Cost comparison between diesel and electronic buses.*

	Revenue (per bus)
annual tickets sale	$20.0k
annual advertising	$6.9k

Thus, the total annual revenue of one bus is determined as $26.9k. The annual profit P can be calculated as:

$$P = I - E$$

I and E respectively represents the annual Income and annual expenditure, which can be calculated as:

$$I = (AR_t + AR_a) \times N_{total-bus}$$

$$E = AC_{d-bus} \times N_{d-bus} + AC_{e-bus} \times N_{e-bus}$$

AR_t: the average ticket revenue per bus per year.
AR_a: the average advertising revenue per bus per year.
AC_{d-bus}: the total cost of energy consumption per diesel bus per year.
AC_{e-bus} : the total cost of energy consumption per electronic bus per year.
$N_{total-bus}$: the total number of buses in designated urban area.
N_{d-bus}: the total number of diesel buses in year t.
N_{e-bus}: the total number of electronic buses in year t.

3.3. Results and Comparison

Before transitioning to electric buses:
$I_1 = (20k + 6.9k) \times 292$ = 7.8548 million dollars
$E_1 = 20.3k \times 288 + 4.9k \times 4$ = 5.866 million dollars
P_1 = 7.8548m – 5.866m = 2.1888m dollars
After transitioning to an all-electric buses fleet:
$I_2 = (20k + 6.9k) \times 292$ = 7.8548 million dollars
$E_2 = 20.3k \times 0 + 4.9k \times 292$ = 1.4308 million dollars
P_2 = 7.8548m – 5.866m = 6.424m dollars

Table 10. *Revenue and Expenditure results comparison.*

	Before transitioning	After transitioning
I	$7.8548 million	$7.8548 million
E	$5.866 million	$1.4308 million
P	$2.1888 million	$6.424 million

As shown in Table 10, transitioning to an all-electric bus fleet, the eventual payoff would be much greater than during the diesel buses era, bringing a significant amount of revenue to the city.

4. Roadmaps for Detroit

As we assumed the bus company must maintain the state of income no less than expenses. Therefore, the detailed roadmap of transitioning to full electronic bus fleet in ten years can be constructed by building the following model.

$$D(t) = I(t) - E(t)$$

$$I(t) = (AR_t + AR_a) \times N_{total-bus}$$

$$E(t) = AC_{d-bus} \times N_{d-bus} + AC_{\ e-bus} \times N_{e-bus} + P_{e-bus} \times N_{e-bus\ bought} + P_{chrage\ station} \times N_{charge\ station\ build}$$

Above which the definitions of the variables are presented below:
$D(t)$: the total profit earned / external funding needed in year t. If D(t) is positive, then income is greater than expenses and no external funding is needed. If D(t) is negative then income is less than expenses and corresponding external funding will provided to maintain the operation of the bus company.
$E(t)$: total operational cost of all the buses in year t.
$I(t)$: total revenue earned in year t.

AR_t: the average ticket revenue per bus per year.

AR_a: the average advertising revenue per bus per year.

AC_{d-bus}: the total cost of energy consumption per diesel bus per year.

AC_{e-bus}: the total cost of energy consumption per electronic bus per year.

P_{e-bus}: the price of purchasing an electronic bus.

$P_{chrage\ station}$: the cost of building a charging station, and other cost infrastructure construction cost combined together.

$N_{total-bus}$: the total number of buses in designated urban area.

N_{d-bus}: the total number of diesel buses in year t.

N_{e-bus}: the total number of electronic buses in year t.

$N_{charge\ station\ build}$: the number of new charging stations constructed in year t.

In the process of transitioning, the number of diesel buses and electronic buses changes every year. With this model, the annual income and expenses during the transition can be estimated year by year. Which paves the way for constructing a reasonable 10-year roadmap of transitioning.

4.1. Roadmap 1

The detailed result generated by the model, including the number of electronic buses bought per year, yearly income and expenses, is presented in Table 11.

Table 1. *Roadmap 1 for Detroit.*

Year	income (per bus)	Expense (k$)	Total bus (k$)	D-bus total	Ebus bought	Charge station build	Profit (k$)
0	7854.8	5866	292	4	288	0	
1	7854.8	10590.1	292	33	259	1	-2735.3
2	7854.8	10143.5	292	62	230	1	-2288.7
3	7854.8	9696.9	292	91	201	1	-1842.1
4	7854.8	9250.3	292	120	172	1	-1395.5
5	7854.8	8803.7	292	149	143	1	-948.9
6	7854.8	8357.1	292	178	114	1	-502.3
7	7854.8	7910.5	292	207	85	1	-55.7
8	7854.8	7463.9	292	236	56	1	390.9
9	7854.8	7017.3	292	265	27	1	837.5
10	7854.8	6272.3	292	292	0	1	1582.5
11	7854.8	1430.8	292	292	0	0	6424
12	7854.8	1430.8	292	292	0	0	6424

The table above shows that the government only needs to provide external funding for six years, and as the proportion of electronic buses increases year by year, the external funding decreases from $2735.3k in the first year to only $55.7k in year 7. The trend of yearly decreasing external funding with the increasing proportion of electronic buses is graphed in Figure 2, as the blue histogram shows:

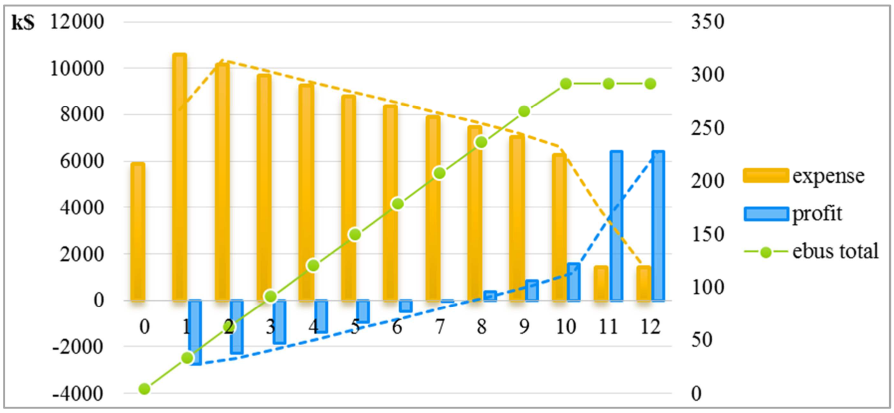

Figure 1. *Trend of expense decreases and profit increases as more and more electronic buses updated during transition in roadmap 1.*

The total external funding provided from year 1 to year 7 in this plan is:

$$TEF = \sum_1^7 D(i) = \$9768.5k$$

Which is only 19% of the total transitioning cost ($51.35 million).

4.2. Roadmap 2

In the case of more sufficient external funding (up to 50 percent of the total transitioning cost), it is a better option to replace the diesel buses with bigger steps. For example, replace 60 diesel buses with electronic buses in the first year, then the number is down to 53 in the second year and drops by 7 every year. The target of a fully electronic bus fleet is achieved earlier in year 8. The detailed result generated by the model, including the number of electronic buses bought per year, yearly income, and expenses, is presented in Table 12.

***Table 12.** Roadmap 2 for Detroit.*

Year	income (per bus)	Expense (k$)	Total bus (k$)	D-bus total	Ebus bought	Charge station build	Profit (k$)
1	7854.8	15612.6	292	64	60	2	-7757.8
2	7854.8	13644.2	292	117	53	2	-5789.4
3	7854.8	15612.6	292	163	46	2	-3928,8
4	7854.8	9633.5	292	202	39	1	-1778.7
5	7854.8	7988.5	292	234	32	1	-133.7
6	7854.8	6451.3	292	259	25	1	1403.5
7	7854.8	5021.9	292	277	18	1	2832.9
8	7854.8	3700.3	292	288	11	1	4154.5
9	7854.8	2486.5	292	292	4	0	5368.3
10	7854.8	1828.1	292	292	0	0	6026.7
11	7854.8	1430.8	292	292	0	0	6424
12	7854.8	1430.8	292	292	0	0	6424

As the table shows, although the external funding needed in the first year ($7757k) is much more compared with the first plan ($2735k), the rate of yearly external funding required drop is also faster than the first plan. It also makes a profit without external funding early in year 6, compared with year 8 of the first plan. The trend of yearly decreasing external funding with the increasing proportion of electronic buses is graphed in Figure 3, as the blue histogram shows:

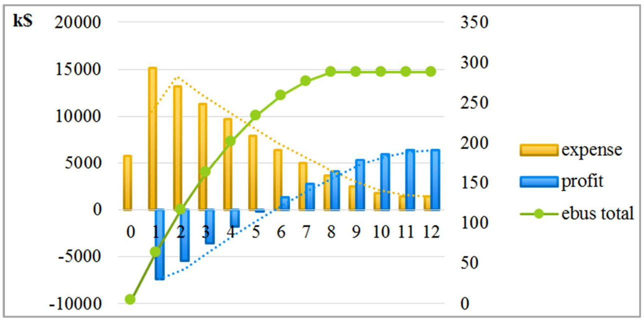

***Figure 2.** The trend of expense decreases and profit increases as more and more electronic buses are updated during the transition in roadmap 2.*

The total external funding provided from year 1 to year 5 in this plan is:

$$TEF = \sum_1^5 D(i) = \$19388.4k$$

Which is 38% of the total transitioning cost ($51.35 million).

4.3. Comparison of Roadmap 1 and Roadmap 2

Comparing the data of roadmap 1 and 2, we can see that although the second plan requires relatively high external funding at the beginning years, by the end of 10 years, the net profit of the electronic fleet exceeds the total external funding. The second plan requires less external funding, but by the end of 10 years, the net profit does not cover the total external funding. For economically well-developed urban areas, more external funding is expected to be provided in the short term, the second kind of roadmap is recommended. Replacing as many diesel buses with electronic buses as soon as possible. For economically less-developed urban areas, and the bus company is short of external funds and cannot acquire a large amount of funds in a short period, the first kind of roadmap, which is to replace diesel buses by 10% yearly, is recommended.

5. Conclusion

The ecological consequences of the transition to the electronic bus, we build an ecological model and calculate the total impact by establishing the completed formula. In the short term, air quality has a direct impact on the health of people in the region. After the transition, the emission of air pollutants decreased by 69.9%. In the long term, it decreases by 54.25%. The conversion to electronic buses, increase the annual profit by 193.49%. This brings significant revenue to the city. The government can use the money to invest in other construction projects for the benefit of the residents. The 10-year plan: we have designed two schemes. Plan 1 requires less subsidies and is suitable when the government budget is limited. Plan 2 is suitable when the government budget is sufficient. When the percentage of electronic cars replaced in the beginning years is larger, the time required will be shorter to start making profits, and the annual profits will also increase year to year. The total net profits would be greater than Plan 1.

Conflicts of Interest

The authors declare no conflicts of interest.

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