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Original Paper

Planning for Introducing Electric Buses Based on Ecological and Financial Impacts

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Abstract

The transition from fossil fuel-powered buses to electric buses has emerged as a central concern in recent years. Governments worldwide are urging this shift in major urban centers as a strategic response to ecological challenges, particularly issues related to pollution and carbon emissions. The primary impediment to the electrification transition lies in real-world financial constraints. Consequently, comprehending both the ecological benefits and financial intricacies of transitioning bus fleets is paramount.

In the initial section of this paper, we formulate a mathematical model to assess the reduction in carbon emissions and pollution resulting from a complete transition of the bus fleet. This model is then applied to the city of Sendai, Japan. By comparing the carbon dioxide and emission gases released by conventional buses with those emitted by electric buses, we can discern the impact of employing electric buses on the urban ecological environment.

Moving on to the second section, we present a mathematical model delineating the financial aspects of the transition. We use Sendai as a real-world exemplar for our model. The economic model is categorized into expenditures and revenues. Expenditures encompass the acquisition of electric buses, maintenance costs, and carbon taxes. On the income side, we consider bus fares, revenue from bus advertising, the budget of the bus company, and government subsidies. By subtracting expenditures from revenues, we can ascertain the financial ramifications of transitioning to electric buses.

Following the evaluation from both ecological and financial perspectives of the bus fleet's electric transition, a third model is constructed mathematically to address the optimal planning solution for a city aiming to fully electrify its bus fleet within a decade. The objective is to achieve cost-efficiency: to be the most economical while meeting ecological goals. Finally, the cities of Sendai, Kunshan, and Nashville serve as subjects for our model, each providing a tailored solution to the transition planning.

Keywords

Electric buses, Carbon emissions, Financial ramifications, Cost-efficiency

1. Introduction

Nowadays, air pollution and climate change have inflicted serious harm on the world. For instance, according to the World Health Organization, air pollution contributes to up to 7 million premature deaths annually. Simultaneously, climate change poses similar health risks. Furthermore, climate change is anticipated to bring about food security challenges, leading to reduced crop yields of staples like rice, wheat, and maize. There are additional adverse effects that won't be elaborated on here. The emergence of these issues has finally sparked intense public concern about air pollution and climate change.

One viable solution to address these problems is the gradual replacement of diesel buses with electric buses. This strategy could mitigate the impacts of climate change and air pollution by reducing emissions of carbon dioxide, $PM_{2.5}$, nitrogen dioxide, and sulfur dioxide. For instance, examining China as a system for evaluation and analysis, traditional oil vehicles emit 1146kg of air pollutants per year, whereas pure electric vehicles emit only 279kg, marking a 75% reduction in gas pollutant emissions. Additionally, pure electric buses solely produce CO_2 emissions during the power generation stage, in contrast to diesel vehicles and plug-in buses, whose CO_2 emissions are predominantly concentrated during the driving stage.

Analyzing the results further, the CO_2 emission per kilometer of a 12-meter bus, with a fuel consumption of 38L/100km under China IV standards, is 1103g. In comparison, the CO_2 emission per kilometer of a pure electric bus, with a power consumption of 120kWh, is 943g. Electrification leads to a 15%-20% reduction in CO_2 emissions compared to diesel vehicles.

However, electric vehicles encounter financial challenges. Firstly, the cost of electric buses is high—approximately 2-3 times that of traditional fuel vehicles—raising the operational threshold for enterprises. Secondly, the development of charging infrastructure lags behind. Insufficient dedicated charging stations and slow charging speeds significantly diminish operational efficiency. Urban areas often lack an adequate number of charging points, placing additional pressure on enterprises when driving distances are substantial and necessitate recharging.

Considering these factors, comprehensive planning is not only essential but also urgent.

1.1 Question Restatement

The problem we are addressing involves a series of steps, which can be outlined as follows:

1. City Selection and Ecological Impact Assessment:

- Identify a city with a population of at least 500,000 that currently lacks an all-electric bus fleet.

- Develop a model and input the city's data and current situation to comprehend the ecological consequences of transitioning to an all-electric bus fleet, including aspects such as pollution gases and carbon dioxide emissions.

2. Financial Implications Model:

- Recognizing the financial challenges associated with electric buses, establish a second model.
- This model should specifically concentrate on the financial implications linked to the transition to electric buses.
- Apply this financial model to the same cities as in the first step to gain a comprehensive understanding of both challenges and benefits.

3. 10-Year Road Map Development:

- Utilize our model to assist transportation officials in formulating a 10-year road map for the phased renewal of the electric bus fleet.
- Implement this road map model not only in the cities selected in the initial steps but also in two additional metropolitan areas, ensuring a thorough and inclusive approach.

4. Recommendation Letter to Transportation Official:

- Based on the results of the first three questions, we wrote the letter in terms of the broker's reliability and effectiveness in addressing environmental issues.

1.2 Analysis of the Question

For question 1, we are asked to build a model to show the impact of change to e-bus system will have on environment. We mainly focus on the emission of buses that have impact upon the environment. We divide emissions in to two parts: carbon emission and pollutant emission and build model 1 to evaluate the emission level of each substance, and give a comprehensive index to evaluate the influence of bus emission. And use real data in Sendai to see the effectiveness of e-bus transitional plan.

For question 2, we need to focus on the financial impact of the plan. We build model 2 to calculate the cost and the revenue of the transitional plan. Then we plug in Sendai’s data to the model 2 to see whether it can afford the 50% transitional cost. Furthermore, we use the result of the model 2 to give practical advises to Sendai government to eliminate costs in transitional period.

The electric transition planning is considered in this section. We seek to find the optimal planning solution that can satisfy the emission reduction goal that we set while being the most economical, the most cost-efficient solution. The finance of the transition is related to the last problem. Containing the price of electric buses, the salvage revenue of diesel buses, the price of chargers and their installation, the price difference between the maintenance of electric buses and diesel buses, and the operational cost. Since we are considering a time span as long as a decade, the inflation of currency must as well be considered. A mathematical function can be established to describe the total finance of the transition; additional equations and in-equation must be set to serve as constraints, some describing the emission goal. At last, we can find the computational result of the planning in each year.

2. Assumptions and Justifications

2.1 General Assumptions

Assumption 1: We assume that electric buses do not produce polluting gases when they are traveling, but only when they are generating electricity.

Assumption 2: In order to simplify our calculation, we assume that all electric buses that are switched are all of the same type, and there is no difference between large and small. The speed and price of such a replacement electric bus are certain.

Assumption 3: I assume that the relationship between the number of conventional buses to electric buses and the carbon emissions found in the first question is true for electric buses in any city.

Assumption 4: In solving the second question, we assume that the conversion rate from conventional buses to electric buses is constant and the time period is ten years

2.2 Variables and Definitions

variable	*description*
t	*Time*
vs	*The velocity of the small bus*
vm	*The velocity of the medium bus*
vb	*The velocity of the big bus*
EQ_{jw}	*the annual emissions of bus type j for emission substance w*
P_j	*the inventory of bus type j in the statistical year*
M_j	*the average annual mileage of bus type j*
Ef_{jw}	*the emission factor of bus type j for emission substance w*
E	*the energy in once electricity*
η	*the efficiency of thermal power generation*
ΔH	*the enthalpy change that 1 mol carbon interacts with 1 mol oxygen to produce 1 mol carbon dioxide*
M_s	*the average annual mileage of the small buses*
M_m	*the average annual mileage of the medium buses*
M_b	*the average annual mileage of the big buses*
P_s	*the inventor of the small buses*
P_m	*the inventor of the medium buses*
P_b	*the inventor of the big buses*
k_i	*the electricity cost of bus type i per kilometer*
B_j	*the emission factor of atmospheric pollutants from thermal power generation*
K	*the ratio that the area use thermal power generation to generation electricity*
$D_{i,j}$	*the annual mileage of Class j vehicles using fuel i*
$S_{i,j}$	*the energy consumption per unit mile of Class j vehicles using fuel i*
P_i	*the fuel density of fuel i*
G_i	*the net calorific value of fuel i*
$EF_{i,j}$	*the carbon emission factor of fuel i*

c	*the concentration of the emission*
Em	*the total annual emission*
S	*the area of the city*
Z_t	*the total expenditure*
Z_c	*the cost of transitioning to electric buses*
Z_r	*the revenue that will be generated after the replacement*
P_{eb}	*the cost of purchasing electric buses and the batteries*
P_{cs}	*the cost of building charging stations*
P_c	*the fee of maintaining electric buses and diesel buses*
P_e	*the carbon tax*
P_w	*the total wage given to the drivers*
x_t	*the amount of e-buses that are used in year t*
$P_{e\text{-}bus}$	*the expense of purchasing one e-bus*
p_c	*the price of per unit charging pile*
n_p	*the number of new parking lot build to charge electricity bus*
p_p	*the price to build a new parking low*
c_e	*the cost of generating electricity sufficient for an electric bus to travel 1 kilometer*
c_d	*the cost of purchasing diesel fuel sufficient for a diesel bus to travel 1 kilometer*
x_e	*the total distance covered by all electric buses during the transitional period*
x_d	*the total distance covered by all diesel buses during the transitional period*
T	*the regular inspection cycle of the diesel/electricity bus*
c_{in}	*the cost of each inspection of one diesel/electricity bus*
p_b	*the cost to change one battery, with the unit dollar*
tax	*the carbon tax imposed on per unit of carbon emission*
w	*annual wage of drivers*
R_f	*the revenue from car fares*
R_{ad}	*the revenue from advertisement*
R_s	*the subsidy from Japanese government*
R_b	*the budget from the government*
N_p	*the number of passenger*
P_t	*the prices of the tickets*
N_e	*the number of e-buses with ads*
P_{ad}^{1}	*the ad-rates on e-buses*
N_d	*the number of traditional diesel buses with ads*
P_{ad}^{2}	*the ad-rates on diesel buses*
p_e	*the average price per advertisement on electric*

p_d	*the average price per advertisement on diesel buses*
$F_{(k)}$	*Total cost of transition of the K year*
k	*The k'th year*
xi	*Number of buses switched from diesel bus to electric bus*
β	*Coefficient of inflation*
N	*Total number of buses*
p_i	*Cost per charging pile*
fe	*Price per electric bus*
We	*Expenditure on maintenance per EB per year (without battery replacement)*
Wb	*Expenditure on maintenance per diesel bus per year*

3. Ecological Consequence

In problem 1, we will analyze Sendai, a city in Japan situated on the main island of Honshu. It spans approximately 800 square kilometers, with a population of 1.09 million. Thanks to governmental efforts, Sendai boasts a relatively favorable ecological environment. To the northwest lie Okoyama and Nishiyama, where forests are diligently protected and managed to preserve biodiversity, absorb carbon dioxide, and purify water.

The southeastern edge of Sendai features pastoral and coastal areas, benefiting from Pacific cold summer sea breezes that extend inland, alleviating rising temperatures in the downtown area. The urban zone, nestled between western mountains and the eastern coast, sees the government strategically arranging green spaces and promoting green building development to enhance carbon dioxide absorption, improve the landscape, and provide leisure opportunities.

Despite the government's commendable planning, Sendai faces atmospheric challenges. According to the summary of Sendai's greenhouse gas emissions, carbon dioxide emissions have shown a downward trend in the past decade, amounting to 7.45 million tons in 2021. While Sendai's urban carbon dioxide emissions are comparatively low compared to major cities like Tokyo, Osaka, and Nagoya, the global context reveals that 7.45 million tons of carbon emissions remain relatively high.

Many cities worldwide are taking steps to reduce carbon emissions and promote sustainable development. For instance, Helsinki, Finland, estimates annual emissions of 3.2 million tons, and Stockholm, Sweden, estimates 4.5 million tons. One significant factor contributing to Sendai's situation is its reliance on traditional forms of buses, with approximately 50 routes, all serviced by diesel buses and diesel-electric hybrid buses.

Therefore, it is imperative for Sendai to implement additional measures to reduce carbon emissions, making the establishment of an all-electric bus fleet an urgent necessity. Through our research, we aim to assist Sendai in addressing ecological and environmental challenges to some extent. The overall plan of our study is shown in the figure below.

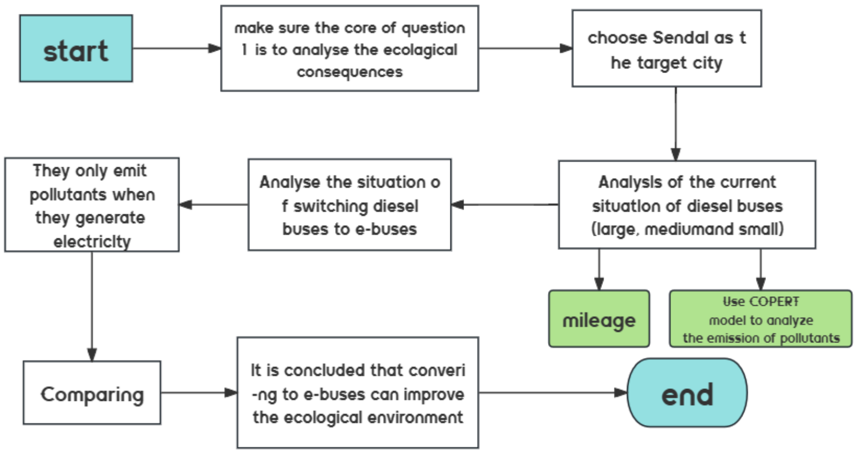

Figure 1. Modeling Process

3.1 Reduction of Polluting Gases

To thoroughly assess the impact of electric buses on Sendai's ecological environment, our first step is to gather information on the current environmental conditions in Sendai and the existing bus data. By consulting the Sendai Transportation Bureau's website, we can glean insights into the current bus fleet in Sendai, which includes:

Table 1. Different Bus Classes in Sendai

Type		Number of bus
Large size	General type	7
	Low floor	419
Medium size	Low floor	28
Small size		12
All		466

To streamline our calculations, we assume that the "general type" and "low floor" large-sized buses are equivalent, resulting in three distinct bus categories: "Large size buses," "Medium size buses," and "Small size buses."

Next, we delve into the analysis of emitted pollutants from different bus types. For this study, we employ the COPERT IV model to calculate bus emission factors in Sendai City. The COPERT model, originating from research conducted by the European Commission (EC) on vehicle emission factors, draws upon a wealth of reliable experimental data. It is designed to be compatible with the statistical criteria and parameter variables of various countries. Given that Sendai's bus types, vehicle emission regulations, and classification standards closely align with European standards, utilizing the COPERT IV model stands as our optimal choice.

Regarding the parameters of the COPERT model, key factors include cumulative mileage, the number of buses, travel time, and speed. According to data from the Sendai City Transportation Bureau, the average speed for large, medium, and small buses is 35 km/h, 30 km/h, and 25 km/h, respectively. By inputting these essential parameters into the model through the "emisa" website, we can derive the fundamental emission factors for the three types of buses.

Table 2. Emission of Different Bus Classes

Types of bus	The Emission Factor of Different Substances ($g \cdot km^{-1} \cdot veh^{-1}$)			
	CO	VOC	NO_x	$PM_{2.5}$
Small bus	2.653	0.075	7.377	0.105
Medium bus	3.105	0.623	11.587	0.261
Big bus	3.306	0.989	12.773	0.492

We discovered that the operational hours of buses in Sendai extend from 8:30 a.m. to 6:30 p.m., totaling 10 hours each day. Throughout the entire year, the bus system operates daily, with the exception of the period from December 29th to January 3rd. Therefore, it operates for 360 days

$$t = 360 \cdot 10 = 3600 hours \tag{1}$$

annually, and the annual operation time is as follows:

Additionally, we have assumed that the average speed of a small bus (v_s) is 35 km/h, the average speed of a medium bus (v_m) is 30 km/h, and the average speed of a large bus (v_b) is 25 km/h.

With the data presented above, we can calculate the average annual mileage (M) for different types of buses using the formula. The resulting average annual mileage (M) is presented in the table below:

Table 3. Average Annual Mileage of Different Bus Classes

Type of bus	The average annual mileage
Small bus	1.26×10^5
Medium bus	1.08×10^5
Big bus	9.00×10^4

We use following equation to calculate the emissions of bus.

$$EQ_w = \sum_j EQ_{jw} = \sum_j 10^{-6} \cdot P_j \cdot M_j \cdot Ef_{jw} \tag{2}$$

Let EQ_{jw} be the annual emissions of bus type j for emission substance w, measured in t · a-1; P_j represents the inventory of bus type j in the statistical year, measured in veh; M_j represents the average annual mileage of bus type j, measured in km ·a-1; Ef_{jw} represents the emission factor of bus type j for emission substance *w*, measured in g ·km-1 ·veh-1.

This approach allows us to calculate the total emissions for each substance:

Table 4. Total Emission Level of Different Substances

Type of emission	Total Emission level(t.a-1)
CO	140.152
VOC	39.9155
NOx	535.9098
PM2.5	19.8111

3.2 Reduction of Carbon Dioxide

After computing the emissions of these pollutants, the next step is to calculate the carbon dioxide emitted by conventional diesel vehicles. Utilizing the bottom-up method endorsed by the Intergovernmental Panel on Climate Change (IPCC), this paper computes carbon emissions by considering vehicle ownership, unit mileage, fuel consumption, and the fuel carbon emission coefficient. The calculation formula is as follows:

$$\text{Emission} = \sum_{i,\ j} [D_{i,j} \cdot S_{i,j} \cdot P_i \cdot G_i \cdot EF_{i,j}] \quad (3)$$

"Emission" represents the total carbon emission of urban traffic over a specific period, measured in kilograms. The variable "*i*" signifies the type of fuel consumed by urban transportation, predominantly diesel in the case of all buses in Sendai City. "*j*" represents the vehicle type in urban traffic. "$D_{i,j}$" denotes the annual mileage of Class *j* vehicles using fuel i, measured in kilometers. "$S_{i,j}$" represents the energy consumption per unit mile of Class *j* vehicles using fuel i, expressed in L/km or kwh/km. "P_i" indicates the fuel density of fuel *i*, measured in L/kg. "G_i" is the net calorific value of fuel *i*, measured in TJ/kg. "$EF_{i,j}$" is the carbon emission factor of fuel *i*, kg/TJ or kg/Kwh.

To calculate the number of carbon dioxide molecules produced to generate one unit of electricity, we use the following formula:

$$n_{CO_2} = \frac{E}{\eta \Delta H} \quad (4)$$

E is the energy in once electricity, with the unit KJ; η is the the efficiency of thermal power generation; ΔH is the enthalpy change that 1 mol carbon interacts with 1 mol oxygen to produce 1 mol carbon dioxide, with the unit KJ/mol.

The energy in once electricity is 33600KJ, and the efficiency of thermal power generation is about 30% to 40%, so we assume it to be 35%. So we can calculate the thermal energy to generate once electricity:

$$3600 \div 35\% = 10287\text{KJ}$$

We know the principle of thermal power generation is the complete combustion of carbon to generate carbon dioxide:

$$C(s)+O_2(g)=CO_2(g) \quad (5)$$

$$\Delta H=-393.51KJ\cdot mol^{-1} \quad (6)$$

Therefore, we can calculate that to generate once electricity, it will produce following amount of CO2.

$$10287\div 393.51=26.14\text{mol} \quad (7)$$

We observed that electric buses consume an average of 0.736 kWh per kilometer. Consequently, we make the assumption that small buses will consume 0.55 kWh per kilometer, medium buses will require 0.70 kWh per kilometer, and large buses will use 0.80 kWh per kilometer.

With this information, we can proceed to calculate the total carbon emissions (mCO2):

$$m_{CO_2}=(M_s\cdot P_s\cdot 0.55+M_m\cdot P_m\cdot 0.70+M_b\cdot P_b\cdot 0.80)\cdot 26.14\cdot 4.4\times 10^{-5}t \quad (8)$$

Ms represents the average annual mileage of the small buses; Mm represents the average annual mileage of the medium buses, and Mb represents the average annual mileage of the big buses. P_s represents the inventor of the small buses, P_m represents the inventor of the medium buses, and P_b represents the inventor of the big buses.

So we get that the carbon emission of the electricity bus system is:

$$m_{CO_2}=3.8668\times 10^4\text{ t} \quad (9)$$

Now, let's consider the pollutant emission if we use electricity bus. We use following formula to calculate the emission of each type of pollutant:

$$EQ_j=\sum_i EQ_{i,j}=\sum_i P_i\cdot M_i\cdot k_i.B_j\cdot 10^{-6}\cdot K \quad (10)$$

$EQ_{i,j}$ represents the annual emission of pollutant j from bus type i, with the unit t a-1; P_i represents inventory of bus type *i*, with the unit veh. Mi represents average annual milage of bus type *i*, with the unit km a-1. k_i represents the electricity cost of bus type *i* per kilometer, with the unit kWh km, we have mentioned before this is 0.55, 0.70, 0.80 for small bus, medium bus and big bus respectively. And B_j represents the emission factor of atmospheric pollutants from thermal power generation, with the unit g kWh. Lastly, *K* represents the ratio that the area use thermal power generation to generation electricity.

By inviting the government websites in Sendai, we get the power structure of Sendai:

Table 5. Energy Structure

Power Generation Method	Percentage of Power Generation
Thermal power generation	71.5%
Atomic power generation	26.8%
Hydroelectric power generation	1.4%

Wind power generation	0.3%
Other	0%

So we get the equation that is showed below.

$$K = 0.715$$

We found that the main emission pollutants of thermal power generation is NOx, SO_2 and dust. Using formula above, we calculate the emission level of each pollutant:

Table 6. Total Emission Level of Thermal Power Plants

Type of emission	Total Emission level($t.a^{-1}$)
NO_x	165.86
SO_2	193.028
Dust	80.528

Compared with the emission of diesel bus system, they have one common pollutant: NOx. We can calculate the percentage reduction of the emission level of NOx:

$$\frac{535.909\text{-}165.865}{535.909} \times 100\% = 69.0\% \tag{11}$$

Switching from a diesel bus system to an electric bus system could result in a nearly 70% reduction in NOx emissions, a significant advantage for atmospheric environmental protection. Although the thermal power generation process for electricity production introduces pollutants such as dust and SO_2, these emissions occur at the factory and can be more effectively processed, resulting in substantially lower actual emission levels.

In contrast, diesel buses immediately release pollutants like CO, VOC, and $PM_{2.5}$ into the air at high levels, causing irreversible damage to the environment. The carbon emission factor for diesel is 74,100 kg/TJ, the net calorific value of diesel is 4.3x10 -5 TJ/kg, and the density of diesel is 0.85 g/ml. The energy consumption per unit mile for small, medium, and large buses is 0.33 L/km, 0.35 L/km, and 0.40 L/km, respectively.

Moreover, since the bus system exclusively uses diesel as fuel, we can simplify the formula to:

$$\text{Emission} = \sum_{\text{j}} [D_j \cdot S_j \cdot P_{diesel} \cdot G_{diesel} \cdot EF_{deisel}] \tag{12}$$

Substitute the data, we can calculate the total emission of CO_2 of the diesel bus system:

$$\text{Emission} = 4.5753 \times 10^4 t$$

If we change the diesel bus system to electricity bus system, we can calculate the percentage reduction in CO_2:

$$\frac{4.5753\times10^{4}-3.8668\times10^{4}}{4.5753\times10^{4}}\times100\%=15.5\% \tag{13}$$

A reduction of approximately 15% in greenhouse gases can significantly contribute to slowing down global warming and advancing efforts towards carbon peaking and carbon neutrality. By comparing the annual carbon dioxide emission levels between the diesel bus system and the electric bus system, we can create a histogram to visually depict the disparity in carbon dioxide emissions.

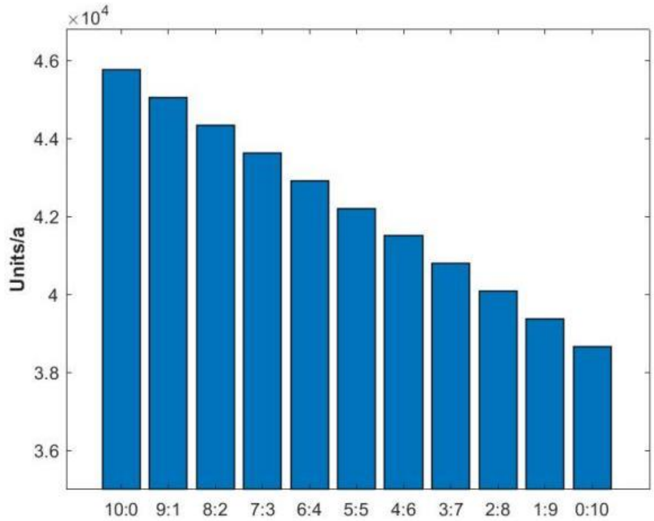

Figure 2. Carbon Dioxide Emission Level to Ratio of Traditional Buses and e-buses Graph

Furthermore, we can holistically assess the environmental pollution levels of both bus systems by considering all their emissions.

Initially, we must convert emissions into concentrations. Assuming an even distribution of emissions from diesel and electric vehicles in the air of Sendai City, we can utilize the following formula to convert emissions into concentrations:

$$c=\frac{E_m}{S} \tag{14}$$

c is the concentration of the emission, with unit t/km^2; E_m is the total annual emission, with unit t; and S is the area of the city, with unit km^2.

3.3 The Results of Reducing Pollution

We know that the area of Sendai is 2305 km^2, then we can get the concentration of each emissions in the two bus systems:

Table 7. Emission for Diesel Bus

The Diesel Bus System	
Emission	Concentration of The Emission (t/km^2)
CO	0.0608
VOC	0.0173
$PM_{2.5}$	0.0086
NO_x	0.2323
CO_2	19.87

Table 8. Emission for EBs

The electricity bus system	
Emission	Concentration of the Emission (t/km^2)
SO2	0.0838
Dust	0.0349
NO_x	0.0720
CO_2	16.78

Subsequently, we can employ a formula akin to the Air Quality Index (API) to compute a comprehensive indicator. Given that the specific calculation methods of API vary by country and region, we will utilize a simplified approach to determine these indicators:

$$index = \frac{c_{CO} + c_{VOC} + c_{NO_x} + c_{PM_{2.5}} + c_{SO_2} + c_{Dust}}{c_{CO_2}}$$

By calculation, we can get the index of the two bus system:

$$index_{diesel} = 0.0177 \qquad index_{electricity} = 0.0144$$

Since $index_{electricity}$ is smaller than $index_{diesel}$, we are able to make the overall conclusion that electricity bus system is more beneficial to the environment than the diesel bus system.

4. Economic Consequences

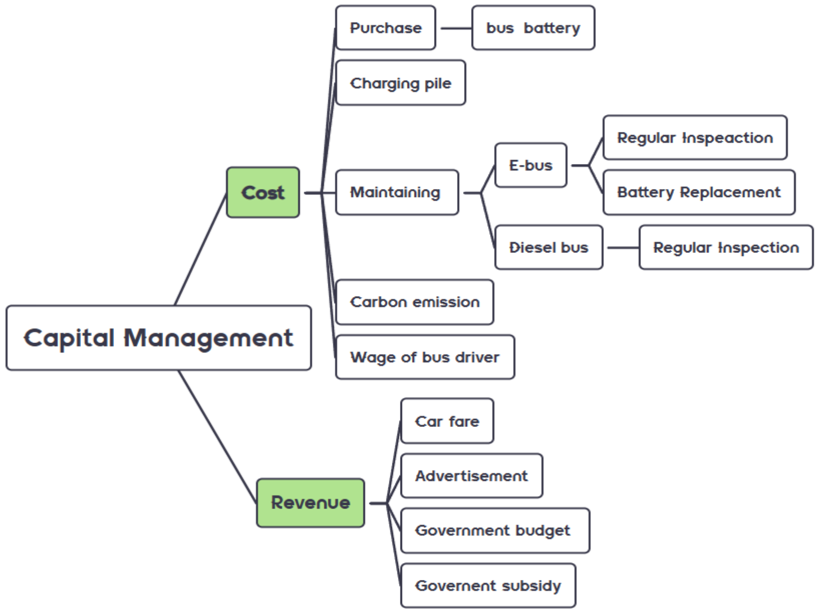

Figure 3. Capital Management Structure

When addressing the financial implications associated with the transition to electric buses, we categorize it into two components: costs and profits. The equation is displayed as follows:

$$Z_t = Z_c - Z_r \tag{16}$$

In this equation, Z_t represents the total expenditure, Z_c represents the cost of transitioning to electric buses, and Z_r represents the revenue that will be generated after the replacement.

In the following section, we will provide the general formula for each cost component while providing a rough estimate of the transition cost for Sendai. However, as the cost is contingent on decision-making regarding the shift from the diesel bus system to the electric bus system, for the purposes of this discussion, we will assume a continuous and constant rate of the transition process.

4.1 Cost of Switching to e-buses

For the Z_c component, the expenditure is bifurcated into two segments: one entails the funds required to operate the traditional bus, and the other involves the funds necessary to operate the electric bus. Regarding the cost of electric buses, it encompasses the expenses associated with procuring buses and batteries, the charging infrastructure costs, the construction of charging stations, and the maintenance costs of electric buses, and the emission of carbon dioxide. In this manner, we can derive the formula for Z_c.

In this formula, P_{eb} represents the cost of purchasing electric buses and the batteries, P_{cs} represents the cost of building charging stations, P_c represents the fee of maintaining electric buses and diesel buses, P_e shows the carbon tax, and P_w is the total wage given to the drivers.

$$Z_c = P_{eb} + P_{cs} + P_c + P_e + P_w \tag{17}$$

4.1.1 Purchasing Electric Buses

Based on the data from the Sendai Transportation Bureau, it is evident that Sendai employs the BYD K9 series e-buses exclusively. We assume that all the electric buses in use are BYD K9 e-buses. Upon consulting BYD's official website, we determined that the cost of an electric bus (inclusive of the battery) is 270 thousand dollars. Therefore, P_{eb} can be expressed using the equation outlined below:

In this equation, x_t is the amount of e-buses that are used in year t, $P_{e\text{-}bus}$ is the expense of purchasing one e-bus. From the passage above, we are capable to know that $\mathrm{P}_{\text{e-bus}}$ is 270 thousand dollar.

$$\mathrm{P}_{\mathrm{eb}} = \sum_t x_t \cdot P_{e-bus} \tag{18}$$

Bring the data of Sendai in the formula, we can get the cost of purchasing electric buses and the batteries:

$$\mathrm{P}_{\mathrm{eb}} = 270 \times 10^3 \cdot 466 = 1.2582 \times 10^8\, dollar \tag{19}$$

Furthermore, to determine Pcs, we need information about the mileage of electric buses. As per the data from the Sendai Transportation Bureau, we find that the average speed of an electric bus is 30 km/h, which is the same as that of a medium diesel bus. Additionally, in the course of addressing the initial question, we established that each bus operates for 3600 hours per year. Consequently, the annual mileage achievable for each electric bus is equivalent to that of a medium diesel bus: 1.08×10^5 km annually.

4.1.2 Cost of Charging Piles

A big difference between diesel bus system and electricity bus system is that electricity bus system need charging piles to charge the electricity bus. Every electricity bus will be charged at night at a bus parking lot when it’s not operating. So we think the coast of charging piles consists of two part: the cost of building charging piles and the cost of build new parking lot.

We use following formula to calculate the fee: I is the inventor of the electricity bus, with unit veh; p_c is the price of per unit charging pile, with unit yuan; n_p is the number of new parking lot build to charge electricity bus; p_p is the price to build a new parking low, with the unit yuan.

$$P_{cs} = I \cdot p_c + n_p \cdot p_p \tag{20}$$

For Sendai, since it’s bus system scale is not so big, we think that there is no need to build extra bus parking lot, so we can simplify the P_{cs} of Sendai to be:

$$P_{csSentai} = I \cdot p_c \tag{21}$$

We searched that the cost of per charger is 15000 dollar, so we can calculate that the cost of charging piles:

$$P_{csSentai} = 466 \cdot 15000 = 6.99 \times 10^6 \, dollar \tag{22}$$

4.1.3 The Cost of Maintaining

During the transition period from the diesel bus system to the electric bus system, there are costs associated with maintaining the existing mixed bus system. This type of cost comprises two parts: the cost of power generation and the cost of maintaining and renewing equipment.

To begin with, let's consider the cost of power generation. For diesel buses, power is supplied by burning diesel fuel, while for electric buses, power is generated through thermal power generation.

We can formulate the following equation to calculate this component of the cost: Here, c_e represents the cost of generating electricity sufficient for an electric bus to travel 1 kilometer, and c_d represents the cost of purchasing diesel fuel sufficient for a diesel bus to travel 1 kilometer, both measured in yuan per kilometer. The variables x_e represent the total distance covered by all electric buses during the transitional period, and x_d represents the total distance covered by all diesel buses during the transitional period (regardless of whether these diesel buses are replaced by electric buses after the transitional period), both measured in kilometers.

$$P_{c_1} = c_e \cdot x_e + c_d \cdot x_d \tag{23}$$

Upon research, we found that ce is 0.02725 dollars, and cd is 0.03950 dollars. As per our earlier assumption, the bus system undergoes a continuous and constant rate transformation from a diesel system to an electric system. It's evident that the total mileage of diesel buses and electric buses is the same and equals half of the total mileage. Additionally, assuming our transitional period is 10 years (consistent with the condition in problem 3), we can calculate x_e and x_d:

$$x_e = x_d = \frac{x_{total}}{2} = \frac{1.08 \times 10^5 \times 466 \times 10}{2} = 2.5164 \times 10^8 \tag{24}$$

So then we can calculate the P_{c1}:

$$P_{c_1} = 0.02725 \times 2.5164 \times 10^8 + 0.03950 \times 2.5164 \times 10^8 = 1.685 \times 10^7 \, dollar \tag{25}$$

Then let's consider the cost to maintain and renew equipment. For the two buses, they all need to be regularly inspected and maintained; but for electricity bus, there is one another important component of this cost: the cost of battery replacement. As a result, we get the formula to calculate this part of cost:

$$P_{c_2} = \sum_i \left\lfloor \frac{t_i^d}{T_d} \right\rfloor \cdot c_d^{in} + \sum_i \left\lfloor \frac{t_i^e}{T_e} \right\rfloor \cdot c_e^{in} + \sum_i \left\lfloor \frac{t_i^e}{T_b} \right\rfloor \cdot p_b \tag{26}$$

d always represents the diesel bus and e always represents the electricity bus. t represents the time the diesel/electricity bus have been operating during the transitional period of each bus, with the unit day; and T represent the regular inspection cycle of the diesel/electricity bus, with the unit day; c_{in} represents the cost of each inspection of one diesel/electricity bus, with the unit dollar; p_b represents the the cost to change one battery, with the unit dollar.

Based on data we have researched, we assumed that T_d to be 30 days, Te to be 50 days, the c_{in} of diesel bus and the c_{in} of electricity is 1000 dollars. T_b is 2500 days, p_b is 150000 dollars per battery.

So now we can get the P_{c2}, by calculating with the help of program, we can get that:

$$P_{c_2} = 6.6943 \times 10^7 \, dollar \tag{27}$$

Now we get the final formula to calculate the cost of maintaining:

$$P_c = P_{c_1} + P_{c_2} = c_e \cdot x_e + c_d \cdot x_d + \sum_i \left\lfloor \frac{t_i^d}{T_d} \right\rfloor \cdot c_d^{in} + \sum_i \left\lfloor \frac{t_i^e}{T_e} \right\rfloor \cdot c_e^{in} + \sum_i \left\lfloor \frac{t_i^e}{T_b} \right\rfloor \cdot p_b \tag{28}$$

So we can get the total pc:

$$P_c = P_{c_1} + P_{c_2} = 1.685 \times 10^7 + 6.6943 \times 10^7 = 8.3793 \times 10^7 \, dollar \tag{29}$$

4.1.4 The Cost of Carbon Emission

To achieve the goals of carbon peaking and carbon neutrality, governments worldwide are implementing carbon taxes on emissions per unit. These taxes are directed towards higher levels of government or environmental protection organizations, further contributing to environmental conservation in various sectors.

Hence, we can derive the formula to calculate the cost of carbon emissions:

$$P_e = E \cdot tax_u \tag{30}$$

E is the annual total carbon emission of the area, with the unit t. tax unit is the carbon tax imposed on per unit of carbon emission, with the unit dollar/t.

The carbon tax in Japan is 10 dollars per ton, and we have calculate the annual carbon emission level of diesel bus system and electricity system before. We can generally think the average carbon emission level in transitional period is the average of the level of the two system. So we can calculate the cost of carbon emission of Sendai:

$$P_e = \frac{3.8668 \times 10^4 + 4.5753 \times 10^4}{2} \times 10 \times 10 = 4.2211 \times 10^6 \, dollars \tag{31}$$

4.1.5 The Cost of Wage

We can easily get the formula to calculate the wage expenditure:

$$P_w = 10 \times w \times I \tag{32}$$

w is the annual wage of drivers, and I is the inventor of all buses.

We assumed the annual wage of bus driver in Sendai 60000 per year, so we can get the wage cost:

$$P_w = 10 \times 60000 \times 466 = 2.796 \times 10^8 \, dollar \tag{33}$$

4.1.6 The Total Cost

Now, we can finally calculate the total money send out during the transitional period of Sendai:

$$Z_c = P_{eb} + P_{cs} + P_c + P_e + P_w$$
$$= 1.2582\times10^8 + 6.99\times10^6 + 8.3793\times10^7 + 4.2211\times10^6 + 2.796\times10^8 = 5.004\times10^8 \, dollar \quad (34)$$

We can draw a pie cart to see the proportion of each branch's expenditure to total expenditure:

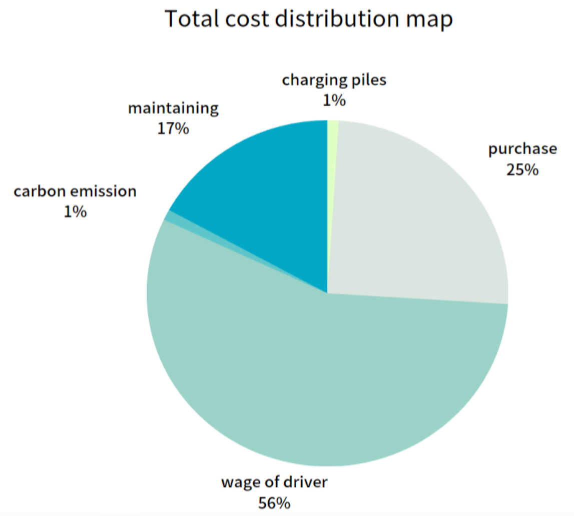

Figure 4. Cost Components Pi-chart

We found that the bus driver's wages contribute to more than half of the total cost. Therefore, if Sendai wants to eliminate transitional costs, it should consider options such as cheaper labor or technologies like driverless operation.

Additionally, purchasing and maintenance also have a relatively large proportion. Plans that aim to eliminate these costs should be considered. Meanwhile, the expenses related to carbon emissions and charging piles are negligible.

4.2 Revenue of Switching to e-buses

For the Z_r part, it includes first, the fares that passengers pay for the rides. Second, advertising, to be more specific, using electric bus vehicles as an advertising platform will bring additional advertising revenue to the Sendai government. Third, external funding, such as subsidies from the Japanese government. And, Sendai's government's budget. In this way, we can get the formula of Z_r.

$$Z_r = R_f + R_{ad} + R_s + R_b \quad (35)$$

In this formula, R_f represents the revenue from car fares, R_{ad} represents the revenue from advertisement, R_s indicates the subsidy from Japanese government. R_b represents the budget from the government.

4.2.1 Revenue of Car Fares

R_f is the total car fares that can earn, it depends on the number of passengers taking the buses and the ticket prices, thus we can get the formula of R_f.

$$R_f = N_p \cdot P_t \tag{36}$$

In this formula, N_p is the number of passenger, and P_t represents the prices of the tickets. According to Sendai's bus station, the average price ticket for each station is 200 yen, which is about 1.3 dollar.

We also research that the average daily discharge of Sendai bus system is 50000 people. So we can calculate it's revenue of car fares during the transitional period:

$$R_f = 5\times10^4 \times 365\times10\times1.3 = 2.3725\times10^8 \, dollar \tag{37}$$

4.2.2 Revenue of Advertisement

R_{ad} is the total money that buses can earn by being the platform of advertising. It depends on the ad-rates, the number of buses, and different types of buses. As a result, we can get the formula of R_{ad}.

$$R_{ad} = \frac{(N_e \cdot p_1^{ad} \cdot p_e + N_d \cdot P_2^{ad} \cdot p_d) \cdot T}{28} \tag{38}$$

In this formula, N_e represents the number of e-buses with ads, and Pad1 represents the ad-rates on e-buses. Moreover, N_d represents the number of traditional diesel buses with ads, and P_{ad2} represents the ad-rates on diesel buses. T represents the total time for advertising, measured in days. p_e and pd represent the average price per advertisement on electric and diesel buses, respectively.

The division of T by 28 is based on our findings that the advertisement change cycle on buses is typically 28 days. The discrepancy in advertising fees between diesel buses and electric buses in our formula is due to several reasons. Electric buses feature more advanced equipment and electronic screens compared to traditional diesel buses, which tend to be older. As a result, electric buses are more effective in helping other companies achieve advertising objectives, such as attracting more customers, leading to higher advertising costs for electric buses.

In our research, the cost of advertising on buses ranges from \$150 to \$600, influenced by factors such as brand awareness, vehicle type, advertising format, and geographical location. We assumed costs within this range, with the advertising cost for any diesel bus set at \$250 and the cost for an e-bus at \$500. These amounts are costs for advertising companies but represent revenue for bus companies, specifically the government of Sendai.

Based on the data we gathered, we assumed an ad-rate of 2 for e-buses and an ad-rate of 1.5 for diesel buses. Thus, we can calculate the revenue from advertising in Sendai:

$$R_{ad} = \frac{(233\times1.5\times250 + 233\times2\times500)\times365\times10}{28} = 4.1648\times10^7 \, dollar \tag{39}$$

4.2.3 Government Budget

We search that Sendai government has 14 billion yan for the transitional plan, that's equal to 0.092 billion dollar. So R_b *is* 9.2×10^7*dollar*.

4.2.4 Revenue of Subsidy

R_s is the subsidies from the Japan government. According to the question we know that 50% of the conversion cost can be covered by external funds. In this case, we believe that this 50% external funding comes from the highest government subsidies in Japan.

As we get the total money send out and all other types of revenue, we can now calculate the subsidy and determine whether it's feasible.

The subsidy from government is:

$$R_s = Z_t - R_f - R_{ad} - R_b$$
$$= 5.004\times10^8 - 2.3725\times10^8 - 4.1678\times10^7 - 9.2\times10^7 = 1.2947\times10^8\,dollar \quad (40)$$

And we can calculate the ratio of subsidy in total expenditure to see whether the subsidy is feasible:

$$\frac{R_s}{Z_t} = \frac{1.2947\times10^8}{5.004\times10^8}\times100\% = 25.8\% < 50\% \quad (41)$$

Because the subsidy we need is smaller than the maximum level, so we think the subsidy is feasible.

4.2.5 The Total Revenue

Similarly, we can draw a pie cart to see the proportion of each branch's revenue to total revenue:

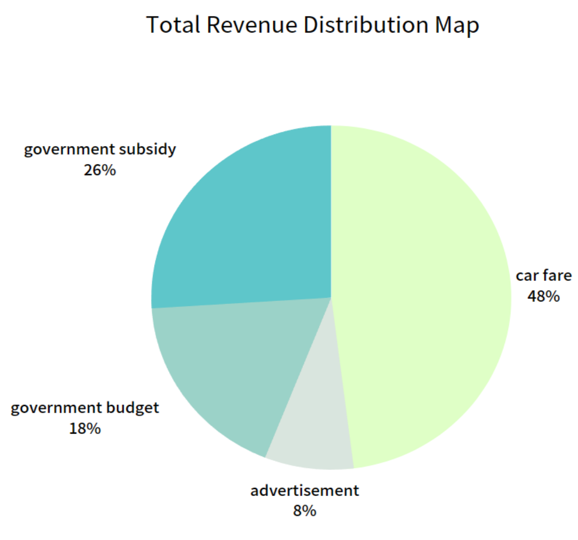

Figure 5. Revenue Component Pi-chart

We observe that the car fare (48%) and government support (subsidies and budget, 44%) collectively constitute almost half of the total revenue. For the Sendai government, there is room to reasonably increase bus ticket fees as a means to boost revenue.

In conclusion, we assert that the transitional plan will absorb a portion of the losses, but the government subsidy can compensate for these losses, rendering the transitional plan acceptable in Sendai. However, our assumption here is that the transitional process continues at a constant rate. In question 3, we will delve into further discussions on how to strategize the process to enhance the financial situation and social perception.

5. 10 Years Plan

In order to discuss the plan for transitioning the city's traditional bus fleet to an electric bus fleet within a decade, we aim to identify an optimal solution for the shift from fuel vehicles to electric vehicles, essentially electrifying the bus fleet. Such transitions must take into consideration the primary goal of emission reduction and the associated costs. In this section, we have devised a mathematical model to represent the financial costs incurred during the transition and the emission reduction goals that must be achieved. This model helps identify the most cost-efficient solution for the electrification of the bus fleet. According to our goal, we can make a formula.

$$\mathrm{F(k)} = [\sum_{i=1}^{k} x_i \cdot o_e + (N - \sum_{i=1}^{k} x_i) o_d + x_k \cdot f_e + p_k \cdot f_p - x_k \cdot r_d] + x_{k-s_1} \cdot W_e + x_{k-s_2} \cdot W_b \quad (42)$$

In this formula, we have adopted an analytical approach similar to that of Samuel et al., 2019, by dividing the transition time-span into multiple periods. We consider the planning horizon as a total of periods, converting the problem into an examination of operations within each period, which are elements of the set T.

Additionally, F(k) represents the expense of year k, β denotes the coefficient of inflation, k represents the number of years, x_k indicates the number of electric buses switched in that year, o_e signifies the cost of operating one electric bus for a whole year, N is the total number of buses, o_d stands for the cost of operating one traditional bus for a whole year. f_e denotes the expenditure of purchasing one electric bus, p_k signifies the expenditure of purchasing one electric charging station. rd represents the revenue gained when selling one traditional bus; s_1 represents the time needed to maintain electric buses, W_e is the cost to maintain one electric bus; s_2 represents the time needed to replace batteries of electric buses; W_b denotes the expense of one battery.

Furthermore, we should focus on the carbon emission condition. To simplify our calculation, we will standardize the models of traditional buses and calculate the emissions per kilometer of traditional buses based on the average carbon emissions of large, medium, and small buses. The formula we utilize is formula (3)

$$C_{emi} = \sum_{i=1}^{10} x_i \cdot E_{ce} \cdot M_e + \sum_{i=1}^{10} (N - x_i) \cdot E_{tb} \cdot M_{tb} \quad (43)$$

In order to encourage the government to commit to continuing its support for the electric bus project, our plan must achieve a significant reduction in the city's carbon emissions in the initial years. According to data from the World Environment Information website and the information obtained in the first question, it is evident that replacing all conventional buses with electric buses can result in a 15% reduction in carbon emissions. Therefore, to showcase the effectiveness of our plan in reducing carbon emissions, our target is to decrease the total carbon emissions from buses by approximately 6% within the first three years. With this objective in mind, we aim to identify the solution with the lowest cost.

In the initial question, we analyzed the impact of reducing CO_2 emissions under different ratios of the number of electric buses to the number of conventional buses. From this analysis, we determined the point at which CO_2 emissions were reduced by 6%. Consequently, we found that when carbon emissions reduce by 6%, the optimal ratio of electric buses to traditional buses is approximately 6:4.

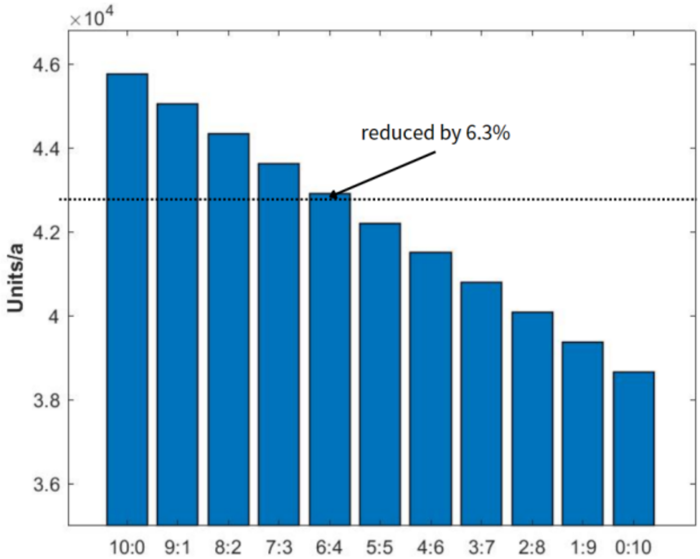

Figure 6. Emission Goal Chart

As a result, after three years, the number of electric buses must greater than 40% of total number of buses. In this way, we are able to get the equation:

$$\sum_{i=1}^{3} xi \geq 0.4 \cdot N \tag{44}$$

In addition, there are other restrictions. Adding up the number of electric buses that are switched each year must equal the total number of original buses. Therefore, we can get the formula as follows:

$$\sum_{i=1}^{10} x_i = N \tag{45}$$

To determine the limitation on the number of charging stations, I searched for information on the official website of the Transportation Bureau. We discovered that each electric bus requires a dedicated charging station. Therefore, ten years later, the total number of charging stations must be equal to the total number of electric buses. The equation is presented below.

$$\sum_{i=1}^{10} p_i = N \tag{46}$$

Besides, in our plan, all electric buses are charged at the same time, so the number of charging stations must be greater than or equal to the number of electric buses at any given moment.

$$\sum_{i=1}^{k} x_i \le \sum_{i=1}^{k} p_i, \forall k \in [1,10], k \in Z \tag{47}$$

All in all, according to our goals and limitation, the comprehensive formula stated as the following integer linear program.

$$\min \sum_{k=1}^{10} F(k) \cdot \beta_k \tag{48}$$

$$\mathrm{F(k)} = [\sum_{i=1}^{k} x_i \cdot o_e + (N - \sum_{i=1}^{k} x_i) o_d + x_k \cdot f_e + p_k \cdot f_p - x_k \cdot r_d] + x_{k-s_1} \cdot W_e + x_{k-s_2} \cdot W_b \tag{49}$$

Subject to

$$\sum_{i=1}^{10} x_i = N \tag{50}$$

$$\sum_{i=1}^{10} p_i = N \tag{51}$$

$$\sum_{i=1}^{3} xi \ge 0.4 \cdot N \tag{52}$$

$$\sum_{i=1}^{k} x_i \le \sum_{i=1}^{k} p_i, \forall k \in [1,10] | k \in Z \tag{53}$$

In the formula above, β is the coefficient of inflation. We're going to analyze Sendai, Nashville and Kunshan. First of all, these three cities have a population of more than 500,000, so they are considered big cities. In addition, these three cities have plans to replace traditional gasoline buses with electric buses, so our group thinks these three cities are good choices to discuss this question. By querying the data, we incorporated the data of Sendai, Nashville and Kunshan into this formula. The data we have queried is shown below:

Table 9. Information for Different Cities

	Sendai	Nashville	Kunshan
Cost of running a e-bus a year	2943	3239	2845
Fuel money for a diesel bus per year	4266	4529	4100
Price of an e-buses	270000	320000	280000
Charging pile price	15000	18000	15000
Money for recycling diesel buses	4000	6000	4200
Time between repairs e-buses	7.3 years	5 years	6.8 years
Maintenance fee	1000	2000	1200
Time between repair a battery	12.16 years	9.2 years	10.4 years

Taking this data into the model we built earlier, we can conclude that the number of electric buses

Sendai should replace each year over this decade is as follows:

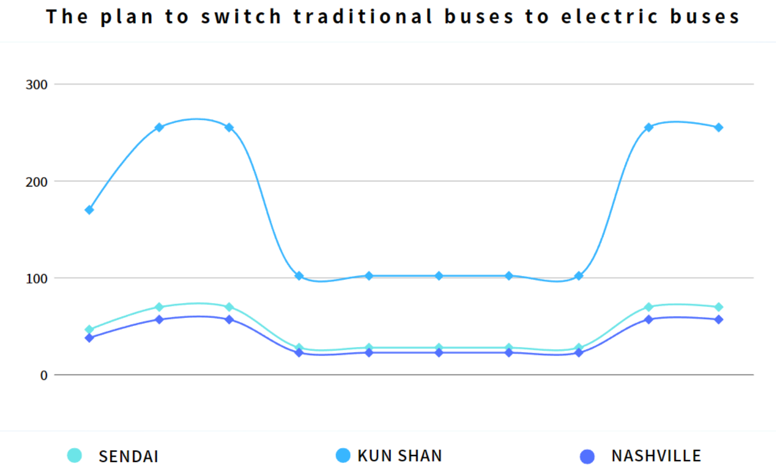

Figure 7. Number of e-buses to Switch in Each Year

From this chart, we can find that the overall trend of the 10-year plans of the three cities is that a large number of traditional buses will be converted into electric buses in the first three years, a small number of Great Wall buses will be converted into electric buses in the middle stage of 4-8 years, and a large number of traditional buses will continue to be converted into electric buses in the later period, that is, 9-10 years. Such a plan can better accomplish our goals and reduce government spending as much as possible.

6. Strengths and Weaknesses

6.1 Strengths

- Deep and detailed data analysis: Our model has conducted detailed research and analysis on multiple parameters such as operating time, speed, mileage, and searched for a large amount of data, providing sufficient data support for the establishment of the model.
- Comprehensive consideration from multiple perspectives: Not only have the carbon emissions of public transportation vehicles and the financial issues of the plan been studied separately, but a comprehensive solution with comprehensive benefits has also been proposed by combining the two in Model 3.

6.2 Weaknesses

- Limitations of assumptions: Our model has some assumptions, such as assuming the transformation of e-buses in batches, which may be more complex in reality due to factors such as policies and external environment.
- Parameter certainty: Our model has a certain degree of subjectivity in setting parameters that are difficult to find accurate values, such as the advertising parameters of buses and the true average speed of buses in the city. This may affect the accuracy and reliability of the model.

7. Conclusion

For the first question, we developed Model 1 to precisely calculate and compare the emission levels of the electric bus (e-bus) system against the diesel system. Our findings indicate that transitioning from a diesel system to an e-bus system could result in a 15% reduction in carbon emissions, a remarkable 70% decrease in NOx levels, and a more effective approach to managing various other emissions in Sendai. These results strongly support the assertion that the proposed transition plan will unquestionably yield significant environmental benefits.

Moving on to the second question, Model 2 was constructed to assess the total cost and revenue of the transition plan. Our preliminary calculations suggest that the government subsidy required in Sendai is approximately 25% of the total transitional cost, falling within an acceptable range. This implies that the transition plan is financially feasible.

Addressing the third question, Model 3, based on the Electric Bus Fleet Transition Planning (EBFTP), was devised to offer a more nuanced and optimized plan for the replacement of diesel buses with electric buses. This model takes into account both environmental considerations, specifically carbon emissions, and financial aspects. We applied Model 3 to three diverse cities—Sendai, Nashville, and Kunshan—to generate tailored and specific electric bus transition plans.

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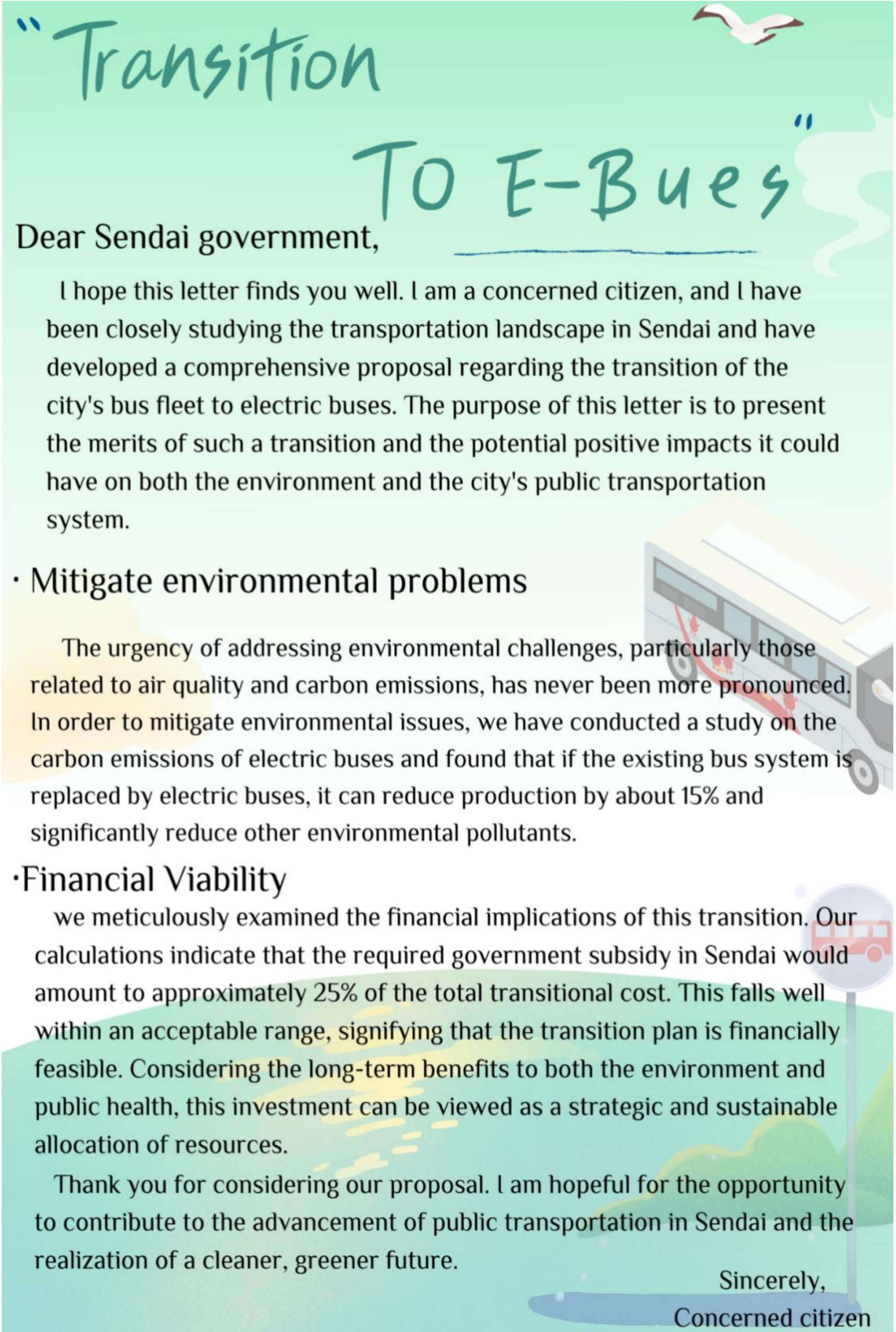

"Transition TO E-Bues"

Dear Sendai government,

I hope this letter finds you well. I am a concerned citizen, and I have been closely studying the transportation landscape in Sendai and have developed a comprehensive proposal regarding the transition of the city's bus fleet to electric buses. The purpose of this letter is to present the merits of such a transition and the potential positive impacts it could have on both the environment and the city's public transportation system.

· Mitigate environmental problems

The urgency of addressing environmental challenges, particularly those related to air quality and carbon emissions, has never been more pronounced. In order to mitigate environmental issues, we have conducted a study on the carbon emissions of electric buses and found that if the existing bus system is replaced by electric buses, it can reduce production by about 15% and significantly reduce other environmental pollutants.

·Financial Viability

we meticulously examined the financial implications of this transition. Our calculations indicate that the required government subsidy in Sendai would amount to approximately 25% of the total transitional cost. This falls well within an acceptable range, signifying that the transition plan is financially feasible. Considering the long-term benefits to both the environment and public health, this investment can be viewed as a strategic and sustainable allocation of resources.

Thank you for considering our proposal. I am hopeful for the opportunity to contribute to the advancement of public transportation in Sendai and the realization of a cleaner, greener future.

Sincerely,

Concerned citizen

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