ISSN 2959-6130

Navigating the Path to Electric Bus Integration: Ecological, Financial, and Strategic Analyses

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Abstract:

Electric buses (E-buses) are gaining global attention for their positive impact on the environment and urban living. Governments worldwide recognize their potential to reduce air and noise pollution, ultimately enhancing urban environments. Despite their high energy conversion rates and economic advantages, widespread adoption faces challenges such as the need for extensive charging infrastructure, financial constraints, and concerns over long charging times and battery replacement costs. Due to these complexities, developed regions like Europe and North America have been cautious in fully embracing electric buses. To assess the pros and cons of transitioning to E-buses, this article examines factors including charging infrastructure, financial implications, and the challenges associated with long charging times and battery replacement costs.

(1) Analysis of the ecological consequences of the E-bus transition is crucial for promoting its adoption, focusing on a five-dimensional comparison with diesel buses. Qualitative and quantitative methods were used to analyze air pollution using selected city data.

(2) A financial implications model examined investment and returns, encompassing operational, capital, and overall costs for E-bus replacement. Expected returns were calculated considering three factors, providing a comprehensive financial overview.

(3) Leveraging the financial analysis results, we devised a 10-year roadmap for full electric bus integration using linear programming. This approach maximizes expected returns by solving the investment portfolio proportions.

Finally, we detailedly calculated the ecological sequence cost of conversion to fully electric flies for the selected city.

Keywords: E-bus; diesel bus; ecological consequence; financial implication.

1 Background

E-Bus offers eco-friendly public transportation, reducing environmental and noise pollution compared to traditional diesel buses. This paper explores the transition from diesel to e-buses, addressing the health impacts of air pollution caused by vehicle emissions. While diesel buses have power and fuel efficiency advantages, they contribute to noise discomfort and environmental pollution through petroleum extraction. The move to e-buses is crucial for mitigating these issues and promoting sustainable urban transport.

E-buses, powered by batteries, offer environmental benefits by eliminating harmful emissions, reducing air pollution, and lowering operating costs. The transition to e-buses is gaining global attention as cities recognize their potential for green travel. Despite improved charging facilities, safety concerns, especially related to battery exposure in some models, need consideration. Planning and investment in supporting facilities are essential for a successful transition. Mathematical models can aid in creating effective 10-year plans for cities shifting from diesel to e-buses.

2 Restatement of the Transition from Diesel Buses to E-Bus

E-bus tech is mature, offering environmental advantages over fuel buses, making the shift from diesel inevitable in urban transportation. Challenges include infrastructure needs and long charging times. The mass replacement of diesel buses poses financial strain, demanding a scientific analysis. Establishing a mathematical model is crucial to assessing environmental and economic benefits and replacement costs. A reasoned roadmap for e-bus fleet updates, derived from costing methodology, is essential. Ongoing work focuses on addressing these challenges.

·Establish a mathematical model for ecological impact analysis: Consider reduction in fuel consumption and environmental pollution by replacing diesel with e-buses, including remediation, fuel, pollution reduction, energy production, and noise costs. Test model in a metropolitan area of at least 500,000 people.

· Develop funding model: Assess the financial implications of transitioning to e-buses, considering external funding covering up to 50% of costs.

· Create a 10-year roadmap: Aid transit authorities in planning e-bus fleet renewal based on an established model.

· Draft letter to transportation officials: Present analysis results and recommendations for transitioning to e-buses.

3 Assumptions

Assumption 1: in this essay, we only consider a bus's energy consumption when operating in normal conditions.

Justification 1: Seasonal changes impact e-bus energy consumption. In summer, air conditioning increases energy use, while snowy conditions demand extra energy to overcome obstacles.

Assumption 2: we assume that in a city, the same type of bus is used throughout the city.

Justification 2: Competing transportation companies may use various bus types, causing prediction inaccuracies. To ensure efficiency and uniformity, managing different bus types is essential. The impact of using diverse buses on the overall bus system efficiency is minimal.

Table 1 Definition of Variables

Variables	Meaning
R	conversion rate
E_1	energy content fuel 1
E_2	energy content fuel 2
n	Sum of noise
B	reduction of decibel per bus
N	number of e-buses
W_t	work done in total
W_i	work done per hundred kilometer
N	Number
D	Total distance
W_c	energy consumption
W_t	work done in total
E	efficiency
E_r	element recovery
P_w	Waste power battery according to a certain production process to recover the target element weight
W_e	Weight of the corresponding element in the prime power battery
R_m	material recovery rate
P_m	Waste power battery according to a certain production process to recover the material weight
W_m	Weight of the corresponding material in the power battery
R_a	Overall recovery rate
S_e	The sum of the weight of multiple target elements recovered
P_b	Prime power battery in the pair sum of prime weight
C_{em}	maintenance cost for all e-buses in a year
P_{em}	maintenance cost per e-buses in a year
C_{te}	total electricity consumed by all e-buses in a year
P_e	the price of a kilowatt-hour of electricity
C_{ea}	maintenance cost for all e-buses in a year
P_{tf}	the total facilities cost
C_t	the total cost of using e-buses for one year
C_t	total costs of addressing this problem
C_e	cost of addressing carbon emission per ton
V_s	mass of carbon emissions saved by using e-bus
Cp	CO_2 emissions from public transportation(kg)
Fc	fuel consumption(L)

4 Ecological Consequences Analysis of Using E-Bus

4.1 Problem Analysis

By transitioning to an all-electric bus fleet, the benefit to the environment can be divided into four aspects: air pollution, energy resources, exploitation of natural resources, and noise pollution. The further analysis is listed below:

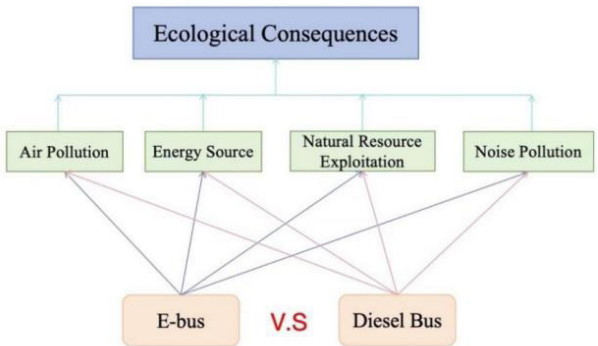

Figure 1 Ecological consequences of using electric bus VS diesel bus

4.2 Air Pollution

(1) Air Pollution by Diesel Bus

E-buses are more environmentally protected than diesel counterparts, emitting less heat and producing no fuel-related pollution. Diesel buses, on the other hand, release harmful pollutants like PM, NOx, CO2, and HC, impacting both the environment and human health. Transitioning to e-buses is necessary for cleaner air and better public health.

To precisely assess the environmental impact of shifting to an all-electric fleet, use equation (1) to calculate the ecological consequences of air pollution. This method enables the estimation of emissions for each exhaust gas.

$$Emission(k) = u_e(k) \times C_f \times \sum_{i=1}^{N} 365 \times d_i \times round_i \quad (1)$$

where, $Emission(k)$ represents the total mass of the k-th pollution gas in one year. $u_e(k)$ represents the mass of the k-th pollution gas per kilometer. C_f represents the amount of diesel fuel consumed per kilometer. Represents the total number of kilometers traveled by all buses in a year. d_i represents the number of kilometers traveled by the i-th bus per trip. $round_i$ represents the number of trips made by i-th bus in a day.

We used the data in Table 1 to calculate the amount of each type of pollution gas emitted by diesel buses. The current number of buses in Ottawa is 855. (*Public transit in Ottawa: Kilometres and litres* 2021). d_i=18, round=6

Table 2 Unit emissions of pollutants of a diesel bus (Marczak, 2017)

Diesel bus with Euro VI emissions (length 12m)		
Pollution Gas	g/km	Fuel Consumption/[g/km]
CO	1.09	277
NO_x	0.45	
HC	0.03	
PM	0.00	
CO_2	826.1	

Emission (CO)= 1.09*277*33704100 = $1.02*10^{10}$

Emission (NO_x)= 0.45*227*33704100 = $3.44*10^{9}$

Emission (HC)= 0.03*227*33704100 = $2.3*10^{8}$

Emission (PM)= 0

Emission (NO_x)= 826.1*277*33704100 =$7.71*10^{12}$

(2) Air Pollution by E-bus

Diesel Buses: Besides fuel consumption, diesel buses emit pollutants (PM, NOx, CO2) during operation, contributing to air pollution and greenhouse gases.

Electric Buses: Electric buses have zero tailpipe emissions when charged with clean and renewable energy. Their overall impact depends on electricity generation sources.

Additionally, e-buses, while emission-free during operation, produce pollutants (SOx, NOx, CO, CO2) during electricity generation. Equation (2) estimates these pollutants during power generation.

$$Emission(k) = u_e(k) \times C_f \times \sum_{i=1}^{N} 365 \times d_i \times round_i \quad (2)$$

Emissions(j) represents the total mass of the j-th pollution gas in one year. $u_e(j)$ represents the mass of the j-th pollution gas per kilowatt-hour(kw*h). C_e represents electricity consumption per kilometer.

The pollution gas emitted per kilowatt hour of electricity is shown in Table 2. Based on the data in Table 2, we can make specific calculations.

Table 3 Unit emissions of pollutants of the electricity generation process (Marczak, 2017)

Pollution gas	g/[km*h]	Electricity consumption/[kwh/km]
SO_2	26.3	1.5
NOx	0.9	
CO	0.188	
CO_2	920.6	

Emission (SO_2) = 26.3*1.5*33704100

Emission (NO_x) = 0.9*1.5*33704100

Emission (CO) = 0.188*1.5*33704100

Emission (CO_2) = 920.6*1.5*33704100

4.3 Energy Source

Diesel Buses: Operate on internal combustion engines that burn diesel with varying energy efficiency. Typically, a fraction of diesel energy is converted to work, with sub-

stantial heat loss.
Electric Buses: Powered by electric motors using battery packs. Electric motors generally have higher efficiency than internal combustion engines, leading to better conversion of electrical energy to mechanical work.
Fuel Type and Conversion Efficiency:
Diesel Buses: Diesel fuel conversion efficiency is influenced by combustion, heat loss, and mechanical factors in the engine.
Electric Buses: Energy consumption in electric buses is tied to battery system, charging, and drivetrain efficiency. Despite losses in battery processes, electric propulsion can achieve higher efficiency than internal combustion engines.
Regenerative Braking:
Electric Buses: Often equipped with regenerative braking, capturing and storing kinetic energy during braking to recharge batteries. Enhances energy efficiency and lowers consumption compared to traditional diesel buses.

4.4 Exploitation of Natural Resources

Diesel Car: Consumes 600-800 gallons of diesel annually, requiring approximately 14-19 barrels of crude oil for production.
Electric Bus: Consumes 28,000-34,000 kWh of electricity yearly, equivalent to approximately 85,000-102,000 kWh of coal energy based on a coal-fired power plant efficiency of 33%.

4.5 Noise Pollution

Diesel Buses: Noise results from engine, exhaust, and tire noise, varying during start, acceleration, and deceleration. Engine noise includes combustion, mechanical, and cooling fan noise and exhaust noise from discharge.
E-Buses: Quieter than diesel counterparts due to no exhaust pipes and electric propulsion. Main noise sources are motor operation, electromagnetic field during energy conversion, and low-speed operation of associated equipment like motors and electronic controls.
Noise Dangers: Prolonged noise exposure can result in hearing loss, discomfort, irritability, lack of concentration, and impact overall health. Choosing low-noise vehicles is essential to minimize harm. Next, we'll compare the noise levels of the two buses.

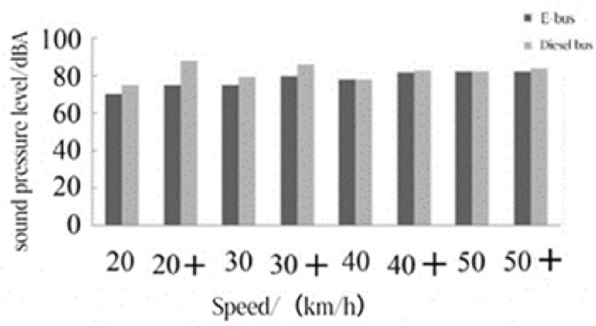

Figure 2 Maximum A sound level for buses (Qin,2014)

Diesel Bus vs. E-Bus Noise Levels: At 30 km/h, diesel bus engine noise peaks at 93 dB, while e-bus noise is 66 dB; at 20 km/h, diesel bus acceleration hits 104 dB, and e-bus noise is 70 dB. E-buses exhibit 4 to 12 dB lower noise pollution than diesel counterparts. Overall, converting all diesel buses to electric ones could significantly reduce noise pollution and improve the sound environment quality along roads.

5 Financial Implications

Financial Impact: Divided into costs (operating and capital) and benefits (environmental, operational, and capital), as illustrated in Figure 3.

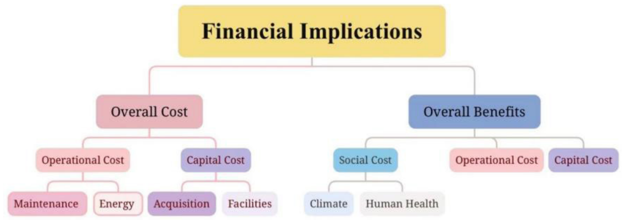

Figure 3 Financial Implications

5.1 Cost for E-bus Transition

5.1.1 Operational Cost

Electric Bus Operating Costs: Primarily maintenance (battery, motor, etc.) and energy costs. Energy costs depend on electricity prices, directly influencing operational expenses. The following section will detail a more precise calculation of electric bus operational costs.
(1) Maintenance Cost:
E-Bus Maintenance: Maintenance is less burdensome with no fuel engines and fewer mechanical components. The key focus is battery maintenance, requiring regular checks and activities like a monthly charge-discharge cycle for optimal conditions. Battery replacement costs are relatively high in case of failure.
Therefore, the maintenance cost calculation method, as shown in equation (3)

$$C_{em} = P_{em} * N \quad (3)$$

We set the annual maintenance cost of an e-bus at $4,000 and then calculated the annual bus maintenance cost in Ottawa.

C_{em} = 4000*855 = $3,420,000

where C_{em} represents the maintenance cost for all e-buses in a year. P_{em} represents the maintenance cost per e-buses in a year.

(2) Energy Cost

E-Bus Power Generation Costs: Electricity production involves raw materials, labor, and equipment costs. Assuming coal-based generation, we denote the cost per kilowatt-hour as Pe. Energy cost is then calculated using equation (4) for simplicity.

$$C_{em} = P_{em} * C_e * \sum_{i=1}^{N} 365 \times d_i \times round_i \quad (4)$$

where C_{te} represents the total electricity consumed by all e-buses in a year. P_{em} represents the price of a kilowatt-hour of electricity. C_e represents electricity consumption per kilometer.

We set the cost of charging an electric bus in Ottawa at $0.08 per kilowatt hour and then calculated the total electricity consumption of all buses in Ottawa for a year.

C_{em} = 0.08*1.5*33704100

5.1.2 Capital Cost

Capital cost includes not only the acquisition of e-buses but, in most cases, also requires changes in the electronic energy, maintenance, and storage facilities at the site.

(1) Additional Bus Acquisition Costs

Bus Cost Comparison: Diesel bus ≈ USD 500,000, Electric bus ≈ USD 750,000. Additional electric bus costs (charging infrastructure, Battery Management System, training, maintenance equipment, infrastructure upgrade, software, and telematics) are combined as Pa. For simplicity, the total additional bus acquisition cost is calculated using equation (4).

$$C_{ea} = P_a * N \quad (4)$$

Where C_{ea} represents the maintenance cost for all e-buses in a year.

(2) Facilities Cost

E-Bus Facility Costs: Centralized storage and charging in transit agency-owned facilities. Crucial to factor in capital and operating costs for facility adjustments to accommodate E-buses. Denoting facilities cost as Pf, the formula below calculates the facilities cost.

$$p_{tf} = p_f * N \quad (5)$$

Where P_{tf} represents the total facility cost.

5.1.3 Overall Cost

$$C_t = C_{em} + C_{te} + C_{ea} + p_{tf} \quad (6)$$

where C_t represents the total cost of using e-buses for one year.

5.2 Expected Return from Conversion to E-bus

5.2.1 Social Cost of Carbon Abandonment

(1) Climate

Social Cost of Carbon Emission: Carbon emissions result in negative impacts such as the greenhouse effect, health issues, and climate change. This discussion focuses on health and climate effects, assessing costs to address carbon emission problems.

Climate Changes: Carbon emissions contribute to climate change, manifesting in droughts, increased natural disasters, and unpredictable weather patterns. These changes pose risks to agriculture, causing substantial losses for farmers relying on predictable climates. Towns in high-risk areas face significant influences from climate disasters like flooding, resulting in loss of life. The government allocates monetary funds to address these issues, estimating a cost of $50 per ton to tackle carbon emission problems.

$$Ct = Ce * Vs \quad (7)$$

C_t=total costs of addressing this problem

*C*ost of addressing carbon emission per ton

V_s=mass of carbon emissions saved by using e-bus

(2) Human Health

$$Cp=Fc*0.785 \quad (8)$$

Where Cp represents CO_2 emissions from public transportation(kg). Fc represents fuel consumption(L)

Climate Impact & Canada's Plan: Carbon emissions cause 7 million global deaths yearly, resulting in a $5.11 trillion welfare loss. Air pollution's health impact in the top 15 emitting countries exceeds 4% of GDP. To control global warming, efforts aim for a two °C limit, pushing for 1.5°C.

Canadian Fiscal Budget: The April 2021 budget underscores emission reduction for economic recovery, allocating $17.6 billion to green recovery and clean economy initiatives. Measures include Launching a federal green bond framework for climate initiatives, Offering interest-free loans totaling CAD 4.4 billion over five years for eco-friendly housing renovations, Implementing a mechanism to halve income tax rate for enterprises and small businesses producing zero-emission tech by 2022, Investing $1 billion over five years to attract private sector investment in clean technology projects.

5.2.2 Reduction of Operational Cost

The calculation of the reduction in maintenance cost only needs to reduce the maintenance cost of the original diesel bus and the maintenance cost of the current e-bus. So, we can use equation (9) to calculate the reduced maintenance cost.

$$C_{dm} = P_{dm} * N \quad (9)$$

where C_{dm} represents the maintenance cost for all diesel buses in a year. P_{dm} represents the maintenance cost per diesel bus in a year.

$$C_{td} = P_d * C_d \quad (10)$$

where C_{td} represents the total electricity consumed by all e-buses in a year. P_d represents the price per liter of diesel. C_d represents diesel consumption per kilometer.

$$C_{?oc} = C_{dm} - C_{em} + C_{td} - C_{te} \quad (11)$$

where $C_{?oc}$ represents original and current reduced operational costs.

5.2.3 Reduction of Capital Cost

The reduction in capital cost only needs to be calculated by reducing the facilities cost of the original diesel bus and the cost of the current e-bus. So, we can use equation (12) to calculate the reduced facilities cost.

$$C_{df} = P_{df} * N \quad (12)$$

where C_{df} represents the facility cost for all diesel buses in a year. P_{df} represents the facilities cost per diesel bus in a year.

$$C_{tf} = P_d * C_d * \sum_{i=1}^{N} 365 \times d_i \times round_i \quad (13)$$

C_{tfc} represents the total facility costs used by all e-buses in a year. P_f represents the price of a facility. C_f represents the number of facilities they used.

$$C_{?fc} = C_{df} - C_{ea} + C_{tfc} - C_{tf} \quad (14)$$

where $C_{?fc}$ represents original and current reduced capital costs.

Financial Implications of Electric Bus Replacement: Explored the accounting method for transitioning to fully electric buses, considering investment costs and expected returns. Detailed the financial aspects involved in the replacement process. Financial implications involve analyzing investments and returns. Order signifies the proportion of bus replacement achievable with corresponding investment funds. The return is represented proportionally to the replacement.

Investment: αC_{tb}

Return: $\alpha\left(C_{dm} - C_{td}\right) \times L$

C_{tb} represents the economic benefits of converting diesel buses to e-buses for one year.

6 10-year Roadmap for Maximum Return

Cost Optimization for Electric Bus Transformation: Sections 4.1 to 4.6 outline equations for purchasing and maintaining electric buses and diesel costs. Ottawa's goal over ten years is a cost-efficient shift from diesel to electric buses. Given the trend towards electric buses, our premise assumes universal replacement. The focus is maximizing returns and minimizing investment, considering time-varying factors like electric bus battery prices and fuel cost fluctuations.

Financial Constraints and 10-Year Electric Bus Plan: Considering the bus company's financial constraints, the annual investment must stay within acceptable limits to ensure normal operations. The goal is to develop a 10-year plan, calculating the annual replacement ratio for electric buses. This roadmap represents a portfolio of investment ratios adhering to specified conditions.

a) $\sum_{t=1}^{10} \alpha(t) = 1$;

b) $0 \leqslant \alpha(t) \leqslant c$;

Where c represents the upper limit of the investment ratio, it cannot exceed the maximum financial tolerance of the bus company.

According to the analysis of financial implications in section 5, we establish the optimization objective function as follows:

$$\max \quad Z = \sum_{t=1}^{10} \alpha(t) \times \left(R(t) - C(t)\right)$$
$$s.t. \begin{cases} \sum_{t=1}^{10} \alpha(t) = 1 \\ 0 \leqslant \alpha(t) \leqslant c; t = 1, 2, \cdots, 10 \end{cases} \quad (15)$$

Based on the relevant data from Ottawa calculated above, substitute it into the formula (15) model for calculation. The 10-year conversion roadmap to all E-buses is obtained using linear programming as in Table 4.

Table 4 10-year roadmap for conversion to all E-bus in Ottawa

Year	1	2	3	4	5
Ratio	0.15	0.13	0.12	0.11	0.11
Year	6	7	8	9	10
Ratio	0.10	0.08	0.08	0.07	0.05

7 Conclusion

7.1 Strengths

l The environmental benefits of bus electrification on air pollution depend on the damage of abandoned non-electric buses relative to electric buses. Air pollution damage from non-electric buses comes from pollutants emitted directly from the tailpipes.

l Self-driving buses can dramatically reduce or eliminate driver costs and improve safety, and smoother, fully autonomous driving may improve fuel efficiency, emissions, and rider comfort. Autonomous driving technologies currently being tested have a good safety record and have the potential to be much safer than human drivers.

7.2 Weakness

While our mathematical model offers numerous benefits, it also has several potential weaknesses. The first weakness is that we might simplify the assumptions. Our mathematical models often rely on simplifications and abstractions to make complex systems manageable. These assumptions may oversimplify real-world phenomena and lead to inaccuracies in the model's predictions. The second drawback I can come up with is that our real-world systems are often characterized by inherent uncertainty, measurement errors, or unpredictable external factors that may cause the uncertainty. Our models may struggle to fully account for these uncertainties, affecting their predictive capabilities.

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