Team Control Number

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Problem Chosen

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Summary Sheet

As cities strive to shift towards more sustainable environmental development, one of the most pivotal initiatives is to transition to a fully electric bus fleet. While many people cite lower greenhouse gas emissions and operational costs as reasons for a rapid change towards e-buses, some are still skeptical of potentially economically damaging upfront costs and uncertainties surrounding electric bus technology. As such, to effectively determine the consequences of a city transitioning to electric buses, our group constructed a rigorous mathematical model to fully consider the nuanced balance between environmental impacts and economical effects, in order to develop a final plan that can be applied universally to any metropolitan area of choice.

Our team constructed our model from the bottom-up, first considering the basic ecological and financial impacts of individual buses. After identifying the most commonly employed bus types in the world—**compressed natural gas, diesel, hybrid, battery electric, and trolley electric**—we determined the four major stages in any given bus' lifespan: **production, operation, maintenance, and disposal**. These observations serve as the backbone of all of our later models.

We selected **Vancouver, Canada** as the metropolitan area to apply and evaluate our mathematical models. We considered many factors specific to our selected cities that impact bus operation, including their electricity production, energy prices, and bus fleet composition.

To evaluate the environmental ramifications of each model of bus, our team employed aspects of **life-cycle analysis** to identify the lifetime carbon emissions of each of our bus models according to the previously outlined framework, noting that BEVs and trolley buses produced nearly ten times less emissions over their lifespans compared to their fossil-fuel based counterparts.

Our team then separately considered the financial costs of our bus models over their full lifespan, focusing only on the costs directly incurred by the city. We found that although electric buses are more expensive to purchase initially on their own, they become cheaper both to obtain and to operate when factoring in external funding.

Applying our models of individual buses to Vancouver's fleet electrification, we consider both the instantaneous costs of purchasing a new, fully electric bus fleet and the usage costs of the new fleet for every subsequent year. Overall, transitioning to a fully electric fleet offsets the carbon emissions from manufacturing the new BEVs almost immediately, and their lower operational costs, combined with external funding, make switching to an electrified fleet more economical than renewing the original fleet for Vancouver.

In order to provide our selected metropolitan area with a comprehensive plan of action, we developed a **depth-first-search algorithm** that allowed us to compare all possible electrification strategies for each of the next ten years, considering the yearly budget of the transportation department. We created an index considering both total emissions and total costs in our selected timeframe, allowing us to identify the optimal transition plan with the lowest costs and emissions. We recommend this plan to city officials in a letter.

We then proceeded to extend our models to two other cities: **São Paulo, Brazil**, and **Boston, USA**. Each has very different fleet compositions and economic situations compared to Vancouver, demonstrating our model's versatility. A sensitivity analysis conducted on our allotted yearly budget for electrification then determined that the best strategy for most cities is to **electrify their bus fleets as quickly as finances allow for, minimizing both greenhouse gas emissions and overall implementation costs**.

Table of Contents

1 Introduction 3
1.1 Background 3
1.2 Problem Restatement 3
2 Assumptions and Justifications 3
3 Setting Up 4
3.1 Model Overview 4
3.2 Representative Buses 4
4 Ecological Modelling (Requirement 1) 4
4.1 City Selection 4
4.2 Variables 5
4.3 Evaluation Factors 5
4.4 Model Construction 5
a. Production Emissions 6
b. Operation Emissions 6
c. Maintenance Emissions 8
d. Disposal Emissions 8
e. Overall Emissions 9
4.5 Sensitivity Analysis 10
4.6 Application and Results 10
5 Financial Modelling (Requirement 2) 13
5.1 Variables 13
5.2 Evaluation Factors 13
5.3 Model Construction 13
a. Production Costs 13
b. Operational Costs 14
c. Maintenance Costs 14
d. Disposal Costs 15
e. Overall Costs 16
5.4 Application and Results 16
5.5 Sensitivity Analysis 17
6 Roadmap Modelling (Requirement 3) 18
6.1 Variables 18
6.2 Evaluation Factors 18
6.3 Model Construction 19
6.4 Application and Results 20
a. Vancouver 20
b. Extending the Model 21
6.5 Sensitivity Analysis 22
7 Strengths and Weaknesses 23
7.1 Strengths 23
7.2 Weaknesses 23
8 Conclusion 23
9 Letter to the Officials (Requirement 4) 24
10 References 25

1 Introduction

1.1 Background

Accounting for 55.7% of all public transport journeys made in the EU [1], buses play a critical role in cities adopting more sustainable forms of public transportation. However, even as concerns about the impacts of global warming continue to mount, traditional, diesel-reliant buses remain the most popular option for many cities despite their detrimental environmental impacts. Often, financial and technological difficulties slow down the transition to eco-friendly electric buses, for upfront, operational, and maintenance costs prove daunting to cities while the specific ecological benefits of e-buses remain uncertain. As such, in this paper, our group presents our general mathematical models, demonstrating the environmental and economical consequences of adopting an all-electric bus fleet. We separately model diesel-based and electric buses to compare their impacts when employed at varying rates in fleets, ultimately aiming to provide cities with a quantitative, simulated framework to develop an implementation plan.

1.2 Problem Restatement

Our team's overall goal is to evaluate the financial and environmental impacts of e-buses, and construct comprehensive plans for cities to electrify bus fleets, as follows:

1. Develop models to evaluate the ecological and financial effects of adopting a fully electric bus fleet for individual cities

2. Apply the above models to one representative metropolitan area of our choice

3. Develop a method to construct a 10-year roadmap based on our models for an efficient transition to e-buses for the above city, as well as two others of our choice

4. Write a brief letter to city officials outlining our suggested plan of action

2 Assumptions and Justifications

Assumption 1: All relevant data regarding bus models and energy production is accurate and historical trends will continue into the next 10 years. We must assume that the data available to us is reliable, even if some may be estimates from other research. While we will account for changes in energy and technology prices as cities transition towards electric buses, we assume no revolutionary shifts in these markets will occur.

Assumption 2: Only 5 bus types in a city will be considered: diesel, natural gas, hybrid, battery electric, and trolley electric. Statistically, these five types of buses make up the vast majority of all bus fleets around the world [2], and are distinct enough in technology to be considered separately.

Assumption 3: All brands or makes of buses in the same category are effectively identical in terms of cost, materials, size, and capacity. This is a necessary assumption to simplify our model, as we lack the specifications for the different makes of buses employed by different cities. Since buses of one category are based on similar technology, they should not differ significantly among themselves.

Assumption 4: Ridership will not be impacted by a change in bus technology. When transitioning towards e-buses, the priority of cities is to avoid altering bus schedules and routes, something that e-bus technology is mature enough to handle. This minimally alters ridership, as demonstrated by previous cases like Shenzhen [3].

Assumption 5: The emissions produced when producing the same types of energy and manufacturing or disposing of bus components are the same around the world. It is unrealistic to consider regional differences in manufacturing materials when constructing a generalized model, especially when we are using the same model and manufacturer of buses to represent each category.

Assumption 6: Cities will not expand the size of their fleet during the transition, only replace current non-electric buses with e-buses. We cannot model the decisions of cities to add buses to their fleet, and any reasons for them to do so are generally irrelevant to our topic.

Assumption 7: The percentage of materials recycled in disposal is the same as the percentage of recycled materials used in production. Since all recycled material eventually becomes reused, it is reasonable to assume that a higher rate of recycling corresponds to a higher rate of recycled materials used.

3 Setting Up

3.1 Model Overview

All the requirements in the competition tasked us with comparing the impact of non-electric buses to electric buses, and representing the differences between the two. So, we decided to model each type of bus separately, calculating the ecological impact and financial cost of **a single bus** over its lifespan. This allows our model to be flexible enough to represent the different fleet compositions and sizes. From there, we were able to multiply our results for a single bus by the size of our current and projected fleets for each type of bus in order to effectively represent the overall impacts for any given city.

3.2 Representative Buses

Our team selected five categories of buses to represent in our model: diesel, natural gas, hybrid, battery electric, and trolley electric, which covers the majority of all bus fleets worldwide.

Type of Bus:	Diesel	Natural Gas	HEV	BEV	Trolley
Model of Bus:	Volvo B8RLE (chassis) [4][5]	Orion VII [11]	Volvo B5LH (chassis) [10][5]	BYD K9 [3][5][21]	Xcelsior Trolley XT40 [12]

We selected the 40’ model for all our bus models to control for size in our calculations. Additionally, our team treated hybrid buses similarly to diesel buses as their batteries are not separately charged like their electric counterparts. Though both trolley and battery buses are electricity-based, trolley buses are continuously charged while battery buses store their energy.

4 Ecological Modelling (Requirement 1)

4.1 City Selection

We selected Vancouver, Canada as our representative metropolitan area to analyze. Vancouver has detailed data on the composition of its bus fleet and grid mix for e-buses, and it currently employs all of our established types of buses. Their current bus fleet composition is as follows:

Bus Type	Natural Gas	Diesel	HEV	BEV	Trolley	Total
Initial # of buses	299 (20.9%)	401 (28.0%)	466 (32.5%)	4 (0.3%)	262 (18.3%)	1432

4.2 Variables

Variable	Definition	Variable	Definition
W_m	weight of material *m*	t	trolley electric bus
L_{bus}	lifetime of type of *bus*	d	diesel bus
M_{bus}	total maintenance emissions of type of *bus*	h	hybrid bus
Fe_{bus}	amount of fuel used per km of type of *bus*	n	compressed natural gas bus
$R\%$	percentage of material recycled	d_{bus}	lifetime distance travelled by *bus*
N_x	number of different kinds of *x*	r_m	global warming potential of using recycled material *m*
GWP_m	well-to-wheel global warming potential of producing material *m*	C_x	carbon equivalent emissions of process *x*
b	battery electric bus	T	time passed since replacement

4.3 Evaluation Factors

In order to determine the ecological impacts of transitioning to a fully electric bus fleet, we conducted life-cycle analyses on each category of bus. To represent the general ecological impact, we evaluated the total **global warming potential (GWP)** over a period of 100 years of the overall emissions throughout the lifespan of each type of bus in kilograms of **Carbon Dioxide Equivalent (kgCO_2eq).** As a measure of the energy-absorbing capabilities of a gas compared to CO_2, GWP provides a quantitative, long-term, and general measure of environmental harm. Since emissions impacting air quality are generally correlated to carbon emissions and more difficult to quantify under a single standard, we opted to not explicitly consider it in our model.

4.4 Model Construction

To construct our ecological model, we essentially conduct a full life cycle analysis on the various types of buses based both on our calculations and estimations from previous literature. This is divided into two parts: Cradle-to-Grave analysis on the lifespan of the actual bus equipment itself—including production, maintenance and disposal, and Well-to-Wheel analysis on the emissions due to energy usage in vehicle operation—specifically the emissions for diesel, natural gas, and electricity in our case. We first identified the 4 main stages of a bus' lifespan in which emissions are released, and individually modeled each of them depending on the type of bus. Therefore, the equation for the total lifetime carbon cost of a single bus in kgCO_2eq is the sum of all 4 stages, or as follows:

$$C_{total} = C_{production} + C_{maintenance} + C_{operation} + C_{disposal}$$

We are also able to find their yearly average emissions to adjust for their operational lifespan:

$$C_{average} = C_{total}/L_{bus}$$

a. Production Emissions

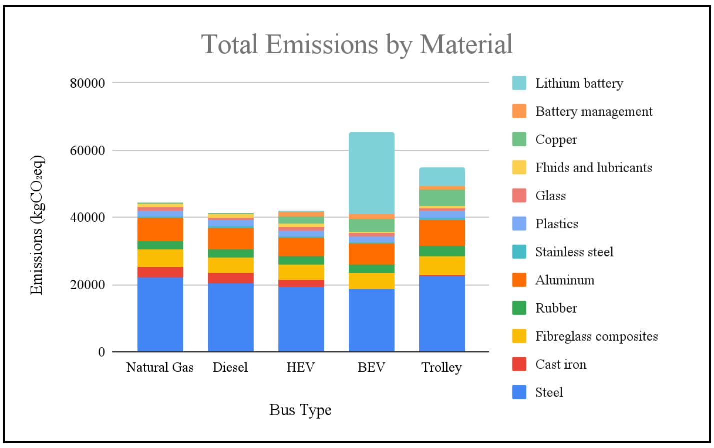
The production of all buses requires the extraction of raw materials and manufacturing processes, all of which produce emissions. To derive the total production emissions, we first need to find the material composition of our various bus models by weight. Our team referenced the estimations produced by Zhao et. al. (2021) [5] to find the most important materials used in producing our diesel, hybrid, and battery electric bus models; we subsequently calculated the build materials for our remaining two types of buses by scaling them by curb weight to existing data. We used our diesel bus model and our battery electric bus model as the reference for our CNG buses and trolley buses, respectively. However, we directly found the battery specifications for our hybrid, battery electric, and trolley electric models as battery capacity and weight are not scalable across models.

Then, we are able to estimate the GWP of producing one kilogram of each material based on data provided by the GREET® 2022 as well as other research conducted for LCA of other materials [5][13][24][25][26]. Therefore, the total cost of production is the sum of the weight of material produced multiplied by the CO_2 equivalent of producing said material for each material in our bus models:

$$C_{production} = \sum_{m=1}^{N_m} (W_m * GWP_m)$$

Here, we note that our team calculated the emissions for producing a lithium-ion battery based on kWh capacity instead of weight to be more appropriate.

Our final results for **production emissions per bus** are below:

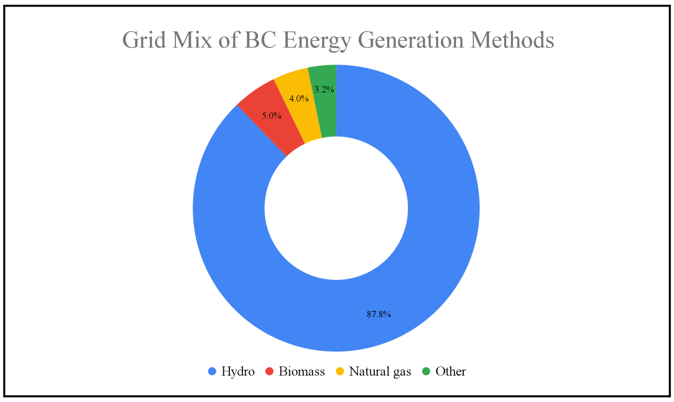


Surprisingly, we found that battery e-buses created the greatest amount of emissions in production by far, primarily because of the high emissions from producing high-capacity lithium-ion batteries, while our trolley bus model was also high in emissions because of its overall greater curb weight.

b. Operation Emissions

Diesel, natural gas, and hybrid buses all emit various greenhouse gases when operated from burning their respective fuels, so we were able to obtain the total Well-to-Wheel emissions per megajoule of compressed natural gas or diesel, respectively [15]. We converted these numbers to 3.49 $kgCO_2eq/L$ for diesel and 3.17 $kgCO_2eq/kg$ for compressed natural gas [16]. On the other hand, battery and trolley e-buses produce no tailpipe emissions, though the process of generating electricity may still generate emissions depending on the source of electricity.

As such, we found the grid mix, or composition of provincial electricity by method of production, for British Columbia, as follows [14]:



Then, we determined the global warming potential of all applicable forms of energy production used [13] and found the kgCO_2eq produced per kWh of electricity specific to Vancouver after weighing them based on BC grid mix. Therefore,

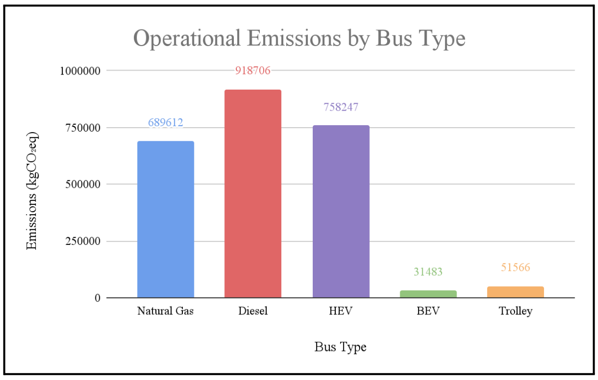
$$GWP_{electricity} = \sum_{s=1}^{N_{source}} (P_s\% * GWP_s)$$

where $P_s\%$ is the percentage of BC electricity produced from a particular source, and GWP_s is the kgCO_2eq produced by generating 1 kWh of electricity via the source. Thus, we found Vancouver's $GWP_{electricity}$ to be **0.044848 kgCO_2eq/kWh**.

The operational emissions per kilometer of a bus is the amount of energy consumed per kilometer by said bus (i.e. fuel efficiency) multiplied by the emissions of the fuel source the bus uses. Our team was able to obtain the fuel efficiency numbers from official manufacturer sources for the Xcelsior XT40 and the BYD K9 [12][21], while third-party testing and estimates provided data for the remaining models [22]. Having obtained this, we simply multiply the emissions per kilometer by the lifespan kilometers traveled by each bus, as previously surveyed [19], to obtain their lifetime emissions from operation. Thus,

$$C_{operation} = d_{bus} * Fe_{bus} * GWP_{fuel}$$

Our final results for **operational emissions per bus** in Vancouver are below:



Due to Vancouver's clean, hydro-based grid mix, we see that BEVs create nearly thirty times less emissions compared to diesel buses, while trolley buses are slightly more emissions-intensive over their lifespan because of their longer service life and slightly inferior fuel efficiency.

c. Maintenance Emissions

Buses experience various kinds of degradation throughout their lifetime, with tires and batteries being considered as exposed to the most wear. In these cases, the city must obtain replacement parts for the bus to keep them in working condition, inevitably producing emissions. We obtained the lifetime distance traveled and lifespan for each type of bus, being 15 years on average for every type of bus [19], with trolley being the sole exception at 20 years [20], and divided it by the expected lifespans of tires (4 per 50,000 km) [5] and batteries (12 years) [23], respectively, to find the mean number of parts required per lifetime. The number of part replacements will be the number of required parts minus the initial set that comes with production. Via GREET® 2022, we were able to obtain the emissions of producing one vehicle part using a similar formula as the one we used to calculate **production emissions** by scaling emissions to kWh capacity for batteries and weight for tires [28][29], as our bus models had differing tire sizes [13].

$$C_{maintenance} = \sum_{p=1}^{N_{parts}} (((L_{bus}/L_p) - 1) * GWP_p)$$

Our results for **maintenance emissions per bus** are as follows:

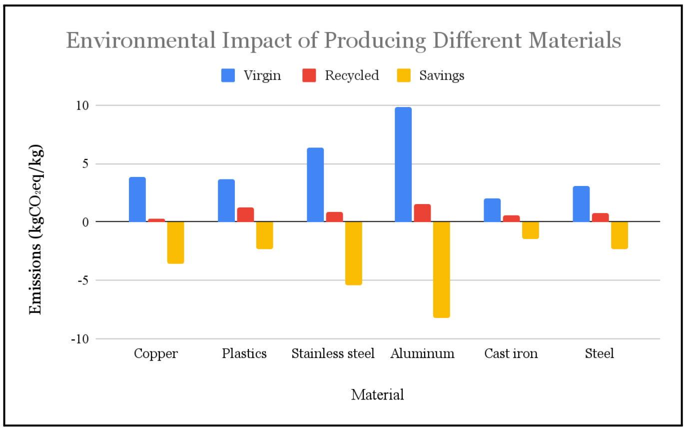
Bus Type	Natural Gas	Diesel	HEV	BEV	Trolley
Maintenance per bus (kgCO2eq)	5651.400502	7717.498006	7863.990506	13881.59801	11329.49184

Once again, due to the high life-cycle emissions of large lithium-ion batteries, maintenance of BEVs and trolleys generate greater kgCO_2eq emissions compared to other buses, similar to the production phase.

d. Disposal Emissions

When buses reach the end of their lifespans or are replaced, they need to be processed and disposed of, likely by a third party separate from the city. The main materials we identified as recyclable based on our research were copper [24], plastics [25], stainless steel [13], aluminum [13], cast iron [13][26], steel [13], and the lithium battery [27].

If the disposer does not process materials, no emissions are produced, which means that only recycled materials have an impact on carbon emissions. In our model, we treat recycling as a net negative in emissions, as materials that are recycled are processed (causing emissions), but they can immediately be reused, saving the kgCO_2eq emissions of producing the virgin resources from scratch. Since we did not consider recycled materials in our production section, we can deduct these saved emissions due to disposal retroactively. Therefore, the kgCO_2eq saved per kilogram of material is the emissions of producing one kilogram of virgin material (GWP_m) subtracted from producing one kilogram of recycled material, as below.



We then multiply this by the total weight of the material as obtained in our production model to find the total recycling deductions from one material, and sum it across all the materials we have identified. Depending on recycling rates, emissions released during this stage can vary significantly, so we additionally introduced a variable ($R\%$) representing the percentage of all materials to be recycled. Hence, we find that

$$C_{disposal} = \sum_{m=1}^{N_m} (W_m * R\% * (r_m - GWP_m))$$

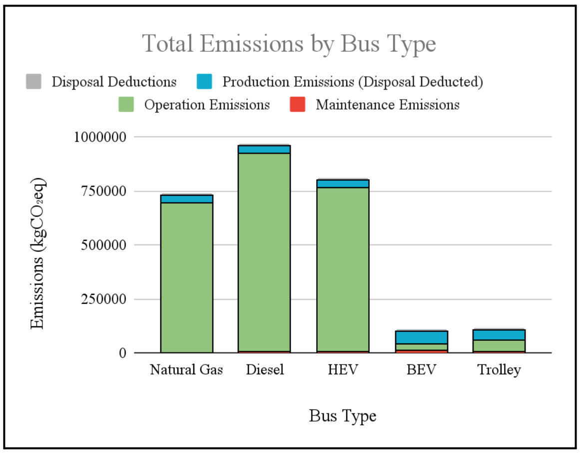
When we set $R\%$ as 50%, our **disposal emission** savings can be seen below.

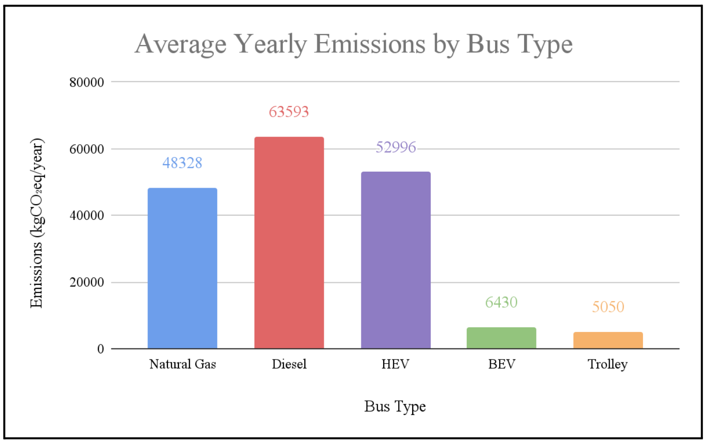
Bus Type	Natural Gas	Diesel	HEV	BEV	Trolley
Disposal Emissions (kgCO_2eq)	-14740.57106	-13657.07966	-13310.94091	-14409.45886	-16633.66143

The amount of emissions saved by recycling are generally proportional to the amount of materials used for our bus models. BEVs are not a significant outlier in this stage of LCA because recycling for lithium-ion batteries is relatively limited with current technology, with few components being reusable [27].

e. Overall Emissions

Combining the results of the previous four sections, we can calculate the yearly average ($C_{average}$) and lifespan total (C_{total}) emissions for each bus model.

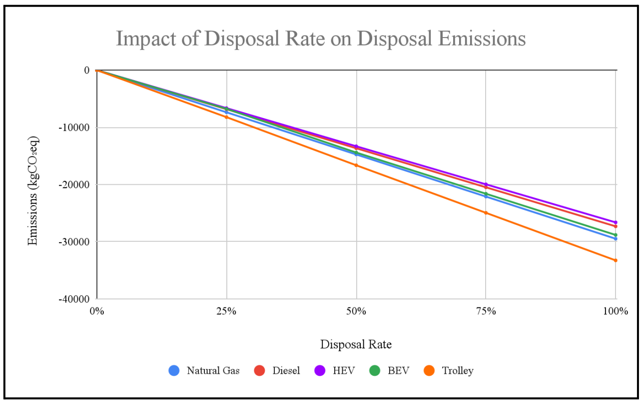


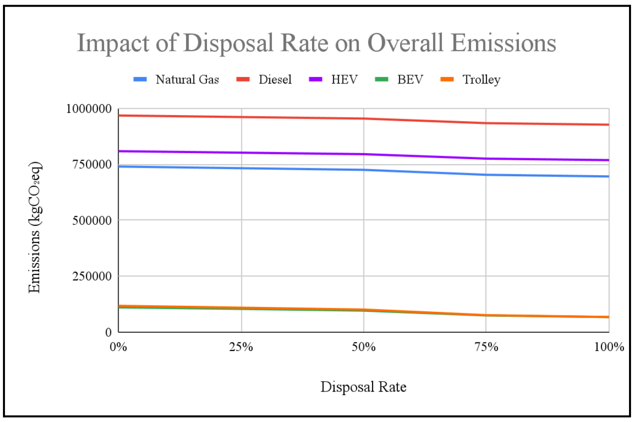


Our team found that trolley buses produced the least amount of yearly emissions due to their lower maintenance and production emissions compared to BEVs, as well as far lower operational emissions compared to non-electric buses. Here, we note that we did not consider emissions from constructing trolley infrastructure as it would require complex city-specific data regarding trolley routes that are unsuited for our generalized models of individual buses; by extension, expanding the trolley fleet is not suitable for consideration in a generalized model despite its potential benefits. Furthermore, operational emissions were by far the greatest contributor to emissions across most models. Overall, we find that e-buses using green electricity sources like those in Vancouver are far cleaner than non-electric buses both across their entire lifespan and on yearly average.

4.5 Sensitivity Analysis

Although the majority of our variables are based on researched, real-world data, there are few assumed variables for us to test. One such variable we conducted a sensitivity analysis on was our recycling rate, $R\%$, which could impact disposal emissions and overall emissions of individual buses.





When altering $R\%$ from our default value of 50%, we can notice a substantial, linear change for all models in disposal emission deductions, particularly for the heavier trolley bus, but its impact on overall emissions is relatively unnoticeable. The overall emission rankings of our different bus models do not change with $R\%$ either. Therefore, our model is **highly robust** against changes in our assumed input variables.

4.6 Application and Results

In order to construct the new e-bus fleet for Vancouver, we simply converted all non-electric buses to battery buses and kept the number of trolley buses the same. For battery buses, the equations for transition are as follows:

$$\mathbf{o} = (n, d, h)$$

$$N_{(final,b)} = \sum_{i \in \mathbf{o}} N_{(start,i)} + N_{(start,b)}$$

Therefore, Vancouver's new e-bus fleet has 1170 BEVs (81.7%) and 262 trolley buses (18.3%).

After we model the overall emissions for individual buses, we can apply our models to the entire Vancouver bus fleet by simply calculating the amount of emissions each type of bus in the fleet contributes and summing their impacts. Therefore, we iterate through the set $\mathbf{B}$ that includes all types of buses, as below:

$$\mathbf{B} = (n, d, h, b, t)$$

We are asked to model the ecological impact of the city's **transition** towards an all e-bus fleet, so our team calculated the difference between the emissions per year of the original fleet and the new e-bus fleet, giving us the year-by-year decrease in emissions from switching to e-buses. For this, we only consider the "**usage emissions**" of our buses (i.e. operational and maintenance emissions, excluding production and disposal).

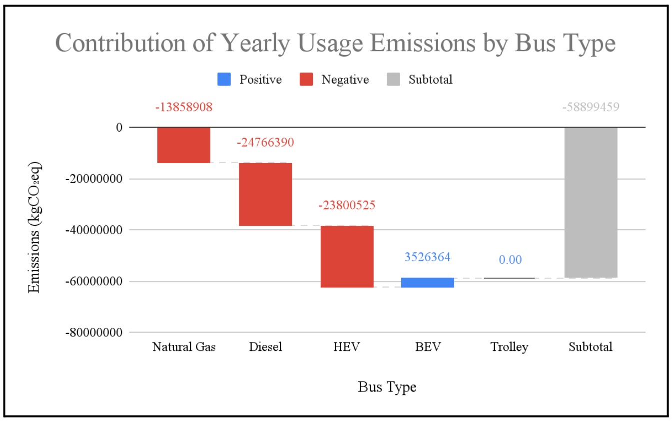
The equation for the yearly "usage emissions" of one bus is the sum of the lifetime operational and maintenance emissions for each bus divided by its lifespan. Therefore, the usage emissions across an entire fleet is the sum of the usage emissions for all buses present:

$$C_{usage} = \sum_{i \in \mathbf{B}} \left(\frac{C_{operation,i} + C_{maintenance,i}}{L_i} * N_i \right)$$

The change in usage emissions from switching fleets is the usage emissions of a bus model multiplied by the change in the number of buses of that model:

$$\Delta C_{usage} = C_{(usage,final)} - C_{(usage,start)} = \sum_{i \in \mathbf{B}} \left(\frac{C_{o,i} + C_{m,i}}{L_i} * \Delta N_i \right)$$

The results we obtained for Vancouver's fleet yearly **usage emissions** are below:



Non-electric buses contribute negative emissions as their decommission means fewer emissions are produced. BEVs produce positive emissions because emissions increase when more BEVs are introduced. Finally, trolley buses cause no change in emissions as they are not impacted by replacement. We see that there is a very great reduction in usage emissions from transitioning to e-buses for Vancouver.

Next, we consider the "**instantaneous emissions"** of transitioning to an e-bus fleet, being the one-time costs of **production of new buses** and **disposal of the old fleet**. This replacement process does not have to happen all at once, but these emissions will be produced eventually regardless of the transition process. The deduction from recycling the old fleet is the number of disposed buses multiplied by the savings for disposing of each bus:

$$C_{retire} = \sum_{i \in \mathbf{o}} (C_{disposal,i} * N_{(start,i)})$$

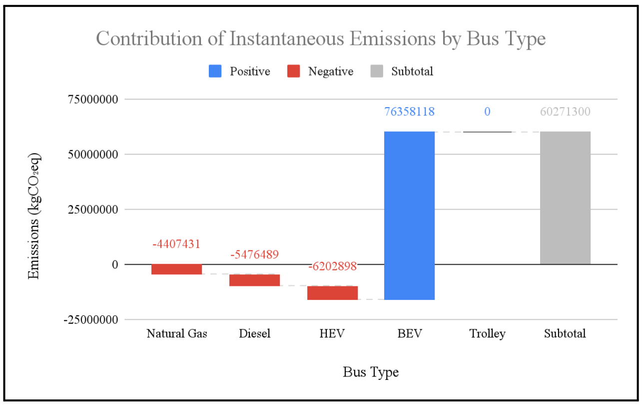
The emissions from expanding the fleet are equal to the amount of new battery buses produced multiplied by the production emissions of one battery bus:

$$C_{expand} = C_{production,b} * (N_{(final,b)} - N_{start,b})$$

Thus, the instantaneous emissions of transition for the whole fleet is the sum of the above equations.

$$C_{inst} = C_{retire} + C_{expand} = \sum_{i \in \mathbf{o}} (C_{(disposal,i)} * N_{(start,i)}) + C_{production,b} * N_{(final,b)}$$

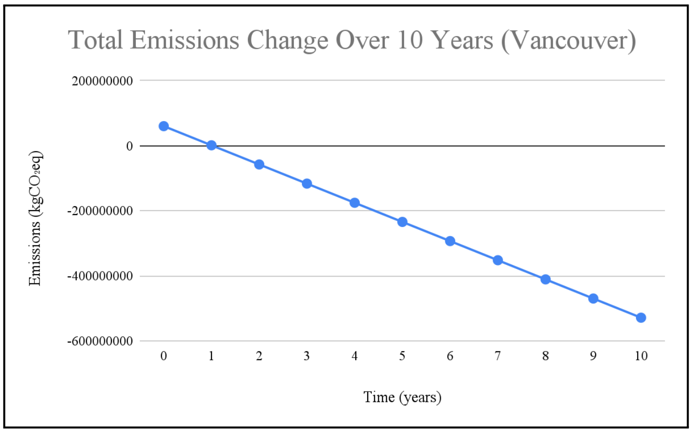
Our results for calculating the **instantaneous emissions** are below:



We see that the production of battery buses causes a sharp increase in emission production for the city.

Combining the instantaneous reduction in emissions and Vancouver's yearly usage emission reductions, we can project the net emission change after we transition to an e-bus fleet T years after transition:

$$C_{(saved,fleet)} = C_{inst} + \Delta C_{usage} * T$$



The usage emissions savings are far more substantial compared to the instantaneous emissions of adopting an e-bus fleet, particularly over a medium-to-long-term timeframe. The city of Vancouver would "break-even" with emissions after the first year of full e-bus usage, and it would save approximately **57 million kgCO$_2$eq every year** afterward. Clearly, the impact of an e-bus fleet on reducing emissions is very substantial.

5 Financial Modelling (Requirement 2)

5.1 Variables

We **reuse relevant variables** from our **ecological model** (requirement 1), and define additional ones below.

Variable	Definition	Variable	Definition
$S\%$	% of costs subsidized by the government	Td	distance of trolley infrastructure present
F_x	financial cost of process *x*	M	maintenance cost per km of trolley infrastructure
Fc_f	fuel cost per unit of fuel *f*	P_{bus}	buy price of *bus*
Yc_f	yearly delivery charge of fuel *f* (if applicable)	V_{bus}	scrap value of *bus*
E_p	cost of purchasing part *p*	$B_{battery}$	battery capacity of *battery*

5.2 Evaluation Factors

We model the **monetary costs (in USD)** directly incurred by the city when purchasing, operating and disposing of the various bus models to evaluate the financial impact.

5.3 Model Construction

To model the financial impacts of transitioning to a fully electric fleet, we employed a similar method to our ecological model. Once again, we opt to model the lifetime costs of individual buses by dividing our considerations into stages of a bus's life cycle before applying these models to the city of Vancouver's fleet. However, we do not have to conduct an Economic Life Cycle Analysis on our bus models, as we only need to consider the city's expenses, meaning we employ some different processes when modeling finances compared to emissions. The key sections of the lifespan of a bus remain production, operation, maintenance, and disposal. Thus,

$$F_{total} = F_{production} + F_{operation} + F_{maintenance} + F_{disposal}$$

$$F_{average} = F_{total}/L_{bus}$$

a. Production Costs

As we are only considering the immediate cost to the city when purchasing buses and the city will not be manufacturing the buses itself, we do not have to conduct a material breakdown analysis on our bus models. Instead, we simply apply the market prices for our bus models or other buses of the same type to estimate the city's charge per bus [17][18][33][34]. To account for government subsidies in transitioning to electric buses, we can multiply the total production costs of battery and trolley buses by (1-$S\%$). Thus,

$$F_{production} = P_{bus} * (1 - S\%_{bus})$$

Unless otherwise mentioned in the paper, our team assumes a 50% funding rate ($S\%$). With that, the **financial cost** to the city is as below:

Bus Type	Natural Gas	Diesel	HEV	BEV	Trolley
Financial Cost per Bus (USD)	$470,000.00	$435,000.00	$500,000.00	$375,000.00	$400,000.00

We see that BEVs and trolley buses become cheaper for the city to purchase than non-electric buses thanks to external funding.

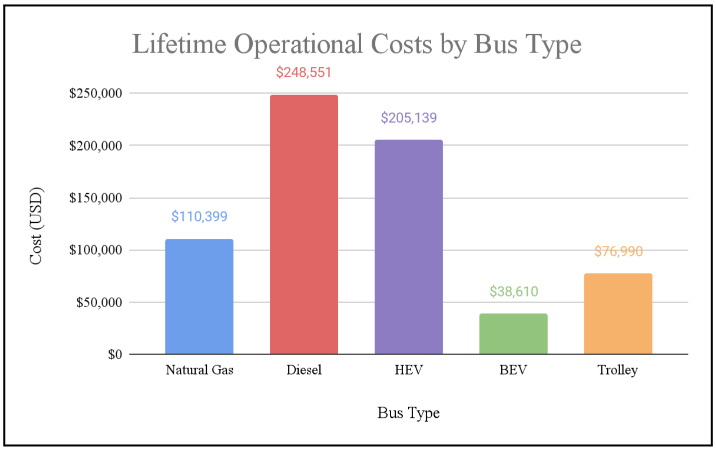
b. Operational Costs

To determine the operational costs of each bus, our team needed to determine the cost of our various sources of energy, specific to Vancouver. We were able to obtain the commercial price per liter of diesel [30], per kilogram of natural gas [31], and per kWh of electricity [32] from local fuel suppliers. Judging from prior implementation in Shenzhen, battery buses can last long enough to run for an entire day, so they often charge during the night, and thus, we use nighttime electricity prices for their operation [3]. Additionally, natural gas and electricity both have a yearly cost added on for delivery, which we calculated to be $530.483 [31] and $73.05 [32], respectively. In this section of our paper, we disregard changes in fuel prices in the future.

The amount of fuel a bus burns throughout its lifespan is its total distance traveled in kilometers multiplied by its fuel consumption per kilometer. Therefore, the cost of the energy due to fuel usage is simply fuel consumed multiplied by fuel cost. The yearly delivery cost of fuel is irrespective of individual buses and should be separately considered.

$$F_{operation} = Fc_f * Fe_{bus} * d_{bus}$$

The **lifetime operational costs** are illustrated here:



We see that diesel-based buses are far more expensive to operate compared to all other types of buses because of recent inflated diesel prices, with HEVs being slightly cheaper because of improved fuel efficiency from electric operation. Comparatively, trolley buses are more expensive over their lifespan compared to BEVs because of their longer service life as well as slightly worse fuel efficiency.

c. Maintenance Costs

Similar to our ecological model, we determined the rate of replacement for commonly degrading bus parts, being tires and batteries, using the same lifespans determined previously. Our team selected representative tires for each of our models based on tire size and determined their prices [28][29]. Then, referencing previous literature, we found the price of a battery to be scalable based on capacity at $111/kWh [35], and we separately estimated the battery prices for each of our bus models based on kWh capacity.

Therefore,

$$F_{maintenance} = \sum_{p=1}^{N_{parts}} ((L_{bus}/L_p - 1)/E_p)$$

where

$$E_{battery} = B_{battery} * \$111/kWh$$

Bus Type	Natural Gas	Diesel	HEV	BEV	Trolley
Total Maintenance Costs (USD)	$36,847.61	$28,419.61	$28,633.28	$37,410.61	$55,637.46

We see that battery buses are surprisingly cost-efficient as it is relatively unlikely for their battery to break down in their lifetime, meaning the average battery maintenance costs are decreased. Trolley buses are more expensive due to their long lifetimes.

Here, our team also separately considered maintenance costs for trolley infrastructure, particularly for overhead wires. The yearly maintenance costs of the whole trolley line are simply the line's distance maintained multiplied by the yearly maintenance cost per kilometer:

$$F_{(maintenance,trolley)} = M * Td$$

Vancouver currently has trolley lines spanning across the entire city, 315 km in total [9], and our team simply modeled the cost of keeping the current system operational. Based on our research, we estimated power line maintenance costs to be roughly $38399.3, accounting for inflation and currency conversion from our reference study [7][8]. We found the yearly costs of trolley infrastructure maintenance to be **$12,095,779.50.** Our team added this figure to our calculations of the total cost of Vancouver's entire trolley fleet, but did not factor it into the cost of individual buses.

d. Disposal Costs

At the end of a bus's service life, cities often attempt to sell the used bus either for scrapping or for another party to operate them [36]. Therefore, we only have to calculate the scrap value of an end-of-life bus to estimate the costs recouped by the city with disposal. With research, we determined the salvage values of diesel and battery buses [6]. Then, by scaling similar natural gas and hybrid buses by price with the diesel bus, and scaling trolley with battery, we estimated the scrap values of the 3 other types of buses.

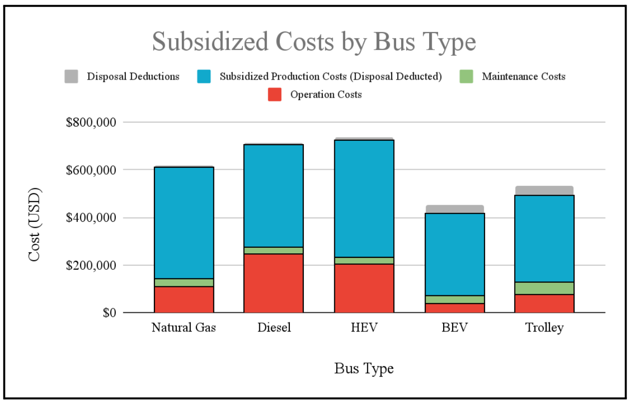
$$F_{disposal} = S_{bus}$$

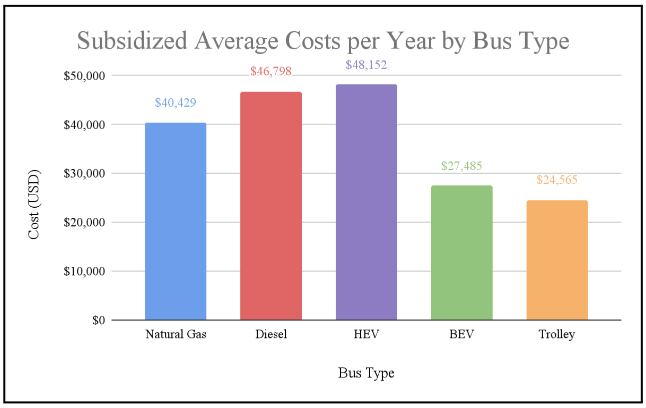
Bus Type	Natural Gas	Diesel	HEV	BEV	Trolley
Disposal Costs (Scrap Value)	-10804.5977	-10000	-11494.25287	-38750	-41333.33333

BEVs and trolleys are initially more expensive to purchase, and thus have higher scrap values after depreciation, allowing the city to recover more expenses when disposing of them.

e. Overall Costs

Applying all of the previous models, we can find F_{total} and $F_{average}$ for each model of bus, factoring in government subsidies for purchasing e-buses and setting $S\%$ as 50%:



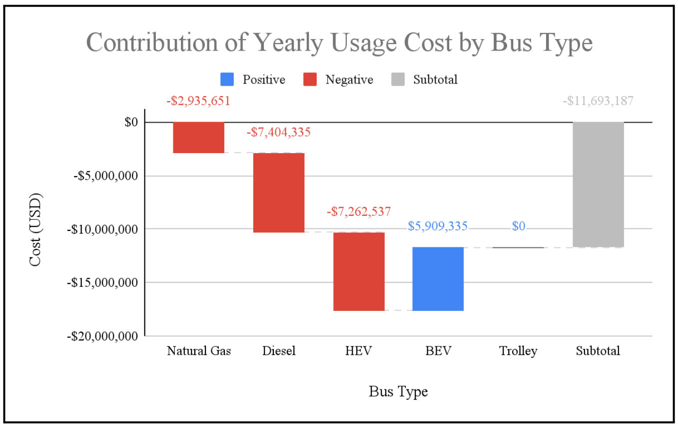


Overall, we see that the substantially lower operational costs of e-buses are able to compensate for their higher production and maintenance costs. With external funding to cover half of the initial costs, electric buses become the most cost-efficient option over their lifetime for cities.

5.4 Application and Results

Considering the same process of fleet replacement as outlined in our ecological model, our team is able to apply our financial estimates for individual buses toward Vancouver's transition to e-buses. Our change in average **usage cost per year**, as defined previously, is as follows:

$$\Delta F_{usage} = F_{(usage,final)} - F_{(usage,start)} = \sum_{i \in \mathbf{B}} \left(\frac{F_{o,i} + F_{m,i}}{L_i} * \Delta N_i \right)$$

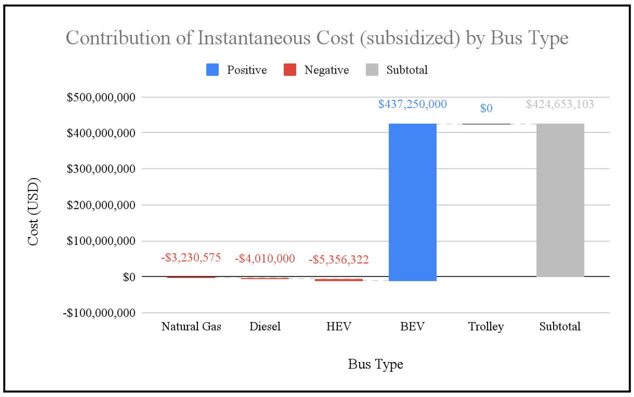


We find that transitioning to an e-bus fleet lowers the usage costs of the entire fleet by over **$11 million** per year.

Our **instantaneous cost**, or the cost to purchase new buses and dispose of old ones, are below:

$$F_{inst} = F_{retire} + F_{expand} = \sum_{i \in \mathbf{o}} (F_{(disposal,i)} * N_{(start,i)}) + F_{production,b} * N_{(final,b)}$$

With $S\%$ set as 50%, the instantaneous costs of transition are below:

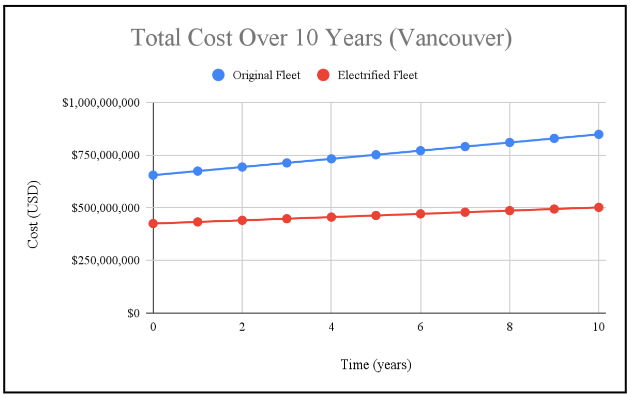


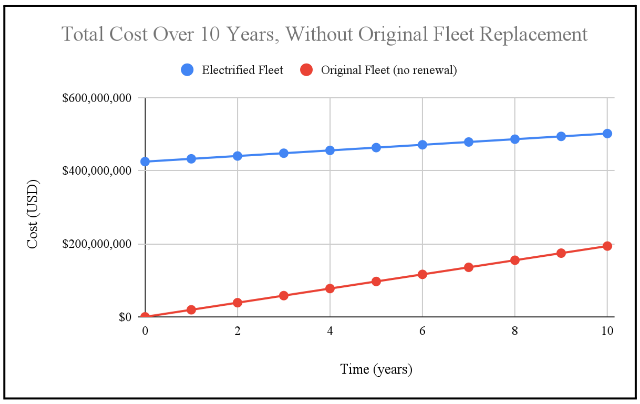
As expected, there is an extreme cost associated with purchasing a full fleet of BEVs, even when subsidized, reaching over **$400 million** for the city of Vancouver. It is important to note, however, that operating the original, non-electrified fleet would still eventually require the purchase of new buses to replace old ones, and it would cost roughly **$654,265,000** to replace all of Vancouver's initial fleet regardless.

Projecting the net expenses of a fleet T years after the transition, without considering inflation or changes in technology,

$$F_{(fleet)} = F_{inst} + F_{usage} * T$$

We projected the expenses for Vancouver's original fleet and its new electrified fleet over the next 10 years.

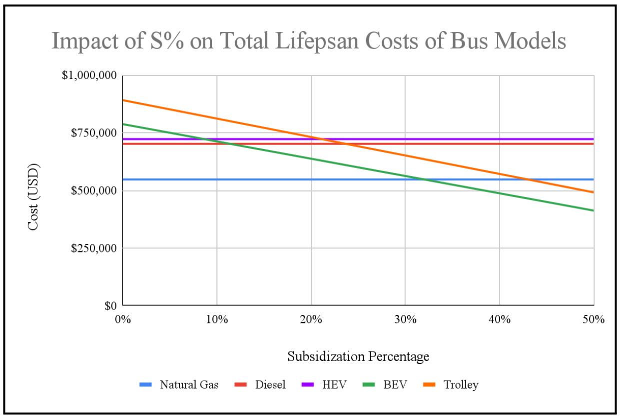


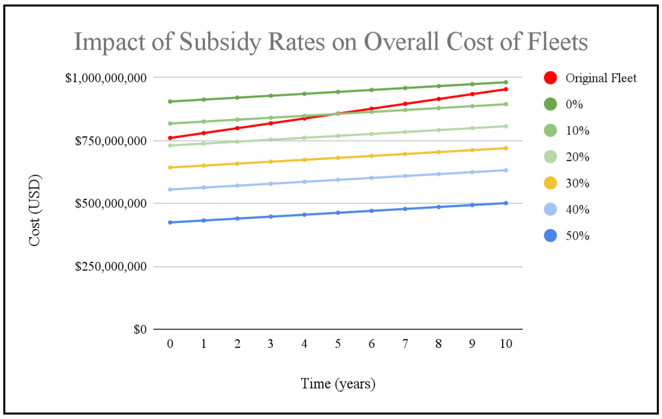


Assuming the entire original fleet is replaced at the start of our projections, our team found that the electrified fleet is both initially cheaper by roughly $200 million and less expensive to use per year by $11 million than the replaced fleet with an unchanged composition. If the original fleet is not renewed at the start, our electrified fleet will initially be a net loss of $400 million and save only $11 million per year, meaning that the fleet will still be a major expense for the city.

5.5 Sensitivity Analysis

Like our previous model, most of our variables are based on data and not assumed. However, one variable that can be changed is the percentage of external subsidies on electric buses, which can greatly impact the city's immediate expenses. Adjusting $S\%$ from 0% to 50%, we can see its impact on the lifespan costs of individual buses as well as the cost projections for Vancouver's bus fleets.





We can see that BEVs become the cheapest option over their lifespan with roughly 30% of purchase costs covered; the same applies to trolley buses at over 40% subsidized. For Vancouver's overall fleet transition, we find that switching to e-buses becomes cheaper than renewing Vancouver's original fleet once 20% of initial costs are covered. With 10% funding, the e-bus fleet becomes overall cheaper after roughly 5 years as well due to lower usage expenses. Thus, external funding plays a large part in making the transition to e-buses financially viable for Vancouver.

6 Roadmap Modelling (Requirement 3)

6.1 Variables

Variable	Definition	Variable	Definition
z	increment for buses replaced	w_C	weight of carbon emissions
o_y	number of buses replaced for year y	w_F	weight of financial costs
b_y	budget for year y	Inf_y	fuel inflation value for year y
I	evaluation index for transition plans	u_y	unspent budget up to year y
B	yearly additional budget		

6.2 Evaluation Factors

To help cities identify an optimal method to gradually transition their fleets, our team created an index considering both the total cost and total emissions of adopting an e-bus fleet over the next ten years. We first normalized the values of total cost and total emissions separately according to the following formula:

$$x_{norm} = \frac{x - x_{min}}{x_{max} - x_{min}}$$

where x represents F and C as the total cost or emissions over the next 10 years of a specific transition scenario, and their respective min and max are the minimum and maximum values of all considered scenarios.

The index that we use to measure to evaluate our transitions is simply the weighted arithmetic mean of our normalized values:

$$I = \frac{w_C * C_{norm} + w_F * F_{norm}}{2}$$

We set both w_C and w_F as 1 for now. The smaller this index is, the lower the overall cost and emissions are, and therefore the better.

6.3 Model Construction

Our team built an exhaustive simulation model to determine the most optimal process of fleet transition. Our program generates a list of every single possible combination of buses replaced (o_T) for each year (T) over the next ten years, where the total number of replaced sum to the total number of diesel, natural gas and hybrid buses in the original fleet, in increments of z. We round the amount of each bus model in the original fleet down to the nearest increment of z. These are then the constraints for o_T:

$$\sum_{T=1}^{10} o_T = N_d + N_h + N_n$$

$$o_T | z$$

Our program generates these permutations via a **depth-first search (DFS)** algorithm. We first replace diesel buses, then natural gases and finally hybrid buses. From there, we can apply our previous models to determine the instantaneous costs, both ecological and economical, of replacement, and also the operational and maintenance costs of that year of the current fleet, the number of buses that stay constant. The financial and economic costs of any given year are simply as follows, defined previously:

$$C_{transition,T} = C_{inst,T} + C_{usage,T}$$

$$F_{transition,T} = F_{inst,T} + F_{usage,T}$$

In a given year, our model accounts for projections regarding relevant fuel types [37] and also approximates technological improvements in electric buses, more specifically, their batteries: the bus part that has seen the most significant cost reductions over the past years [38]. We simply obtain these numbers from our research and apply them towards our consideration of operational and maintenance costs per bus. The price of an item (i) for any given year T is thus below:

$$F_{(i,T)} = F_{(i,2023)} * Inf_{(i,T)}$$

To prevent overspending and make transition plans more realistic, we implemented a yearly "budget" variable, a value that the city is not able to spend more than at any year. Each year, the remaining, unspent budget carries over to the next, while the next year's budget is added on. If any transition plan outspends their yearly budget, they are automatically eliminated.

$$b_T = u_T + B$$

$$F_{transition,T} \leq b_T$$

At the end of the 10 years, we can derive the total financial cost and emissions calculated from each year. We sum them to find the total, which we then apply to our evaluation factors above, in the end determining the most optimal way of transitioning a city's bus fleet to electric.

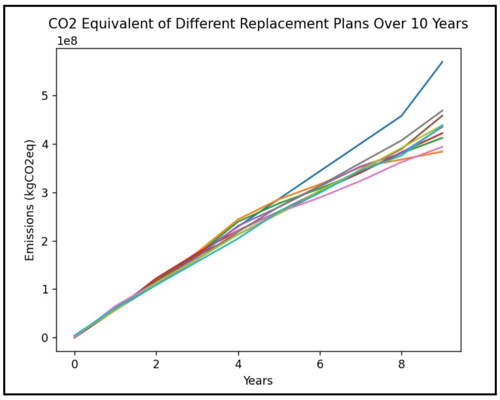
$$F_{transition} = \sum_{T=1}^{10} F_{transition,T}$$

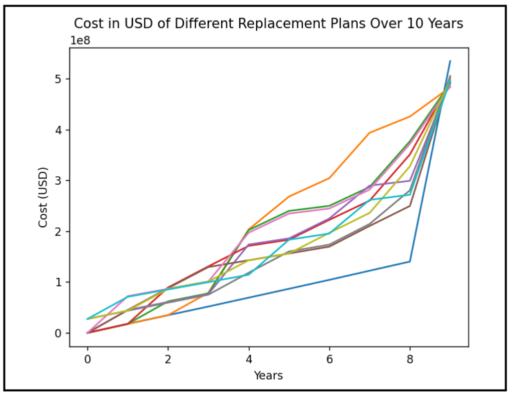
$$C_{transition} = \sum_{T=1}^{10} C_{transition,T}$$

6.4 Application and Results

a. Vancouver

Applying our model to the city of **Vancouver**, with z defined as 75 buses and B set as $50,000,000 a year, a selected graph of our DFS process is below, where each line represents a different fleet replacement plan:

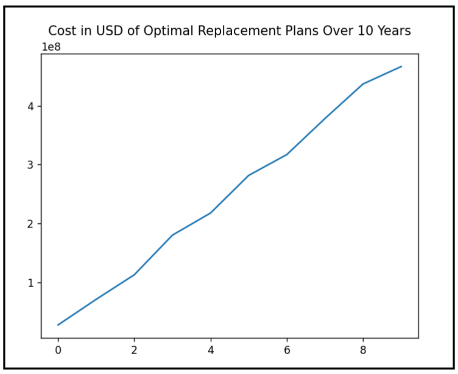


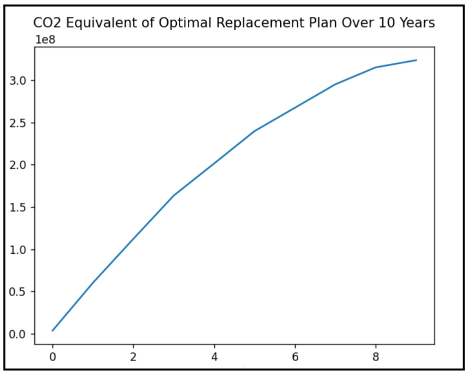


The optimal plan we identified was below:

Year	1	2	3	4	5	6	7	8	9	10
Buses Replaced	75	75	75	150	75	150	75	150	150	75

Its I, C_{norm}, and F_{norm} were all 0.0, meaning it was perfectly optimal by all metrics. It had the following projections:





We see relatively evenly distributed costs from the model as it tries to remain under yearly budgets.

b. Extending the Model

We also applied our model towards two other cities: **Boston, Massachusetts** and **São Paulo, Brazil.** Our team adjusted the electricity grid mix as well as all energy prices to fit local rates [41][42][43][44][45].

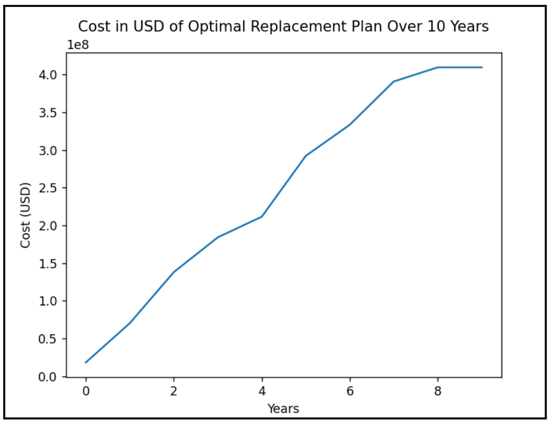
Boston has a primarily natural gas-based grid mix [40], altering values for our e-bus operation, and their fleet composition is as below [39].

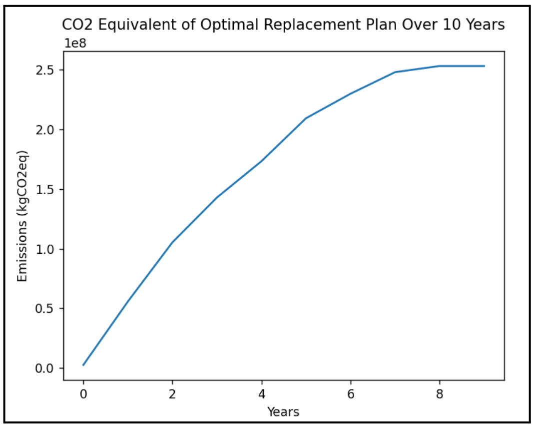
Bus type	CNG	Diesel	HEV	BEV	Trolley	Total
Initial # of buses	175	338	540	5	0	1058
Final # of buses	0	0	0	1058	0	1058

For Boston, with z defined as 50 buses and B set as $50,000,000, our optimal plan was as below:

Year	1	2	3	4	5	6	7	8	9	10
Buses Replaced	50	100	150	100	50	200	100	150	50	0

These are our obtained projections:





Boston incurs relatively constant costs over all 10 years with our plan during their transition, with their costs distributed to stay under budget.

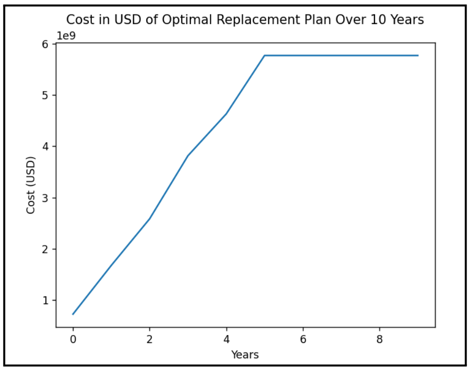
For **São Paulo's** bus fleet, we note that its size is significantly larger and it is currently nearly all-diesel [46].

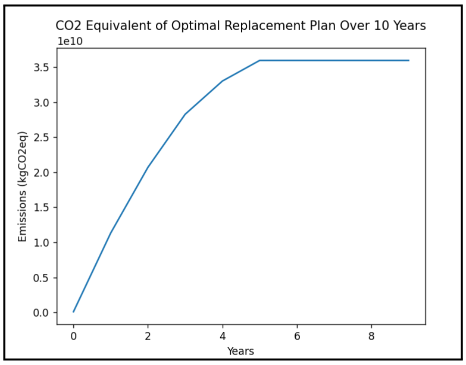
Bus type	CNG	Diesel	HEV	BEV	Trolley	Total
Initial # of buses	0	14502	0	0	201	14703
Final # of buses	0	0	0	14502	201	14703

Thus, we scale our starting parameters z and B up to 1000 and B $1,000,000,000, respectively. Our optimal plan is below:

Year	1	2	3	4	5	6	7	8	9	10
Buses Replaced	2000	2000	2000	3000	2000	3000	0	0	0	0

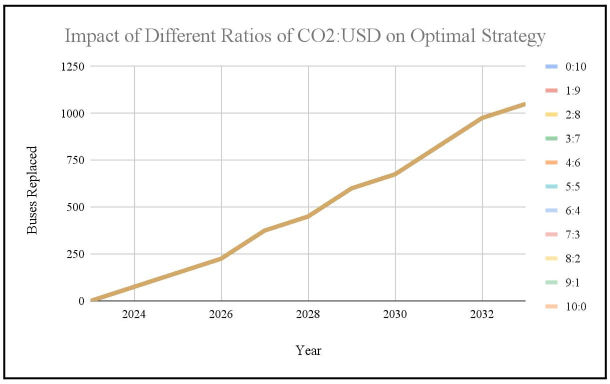
These are our projections for our plan:



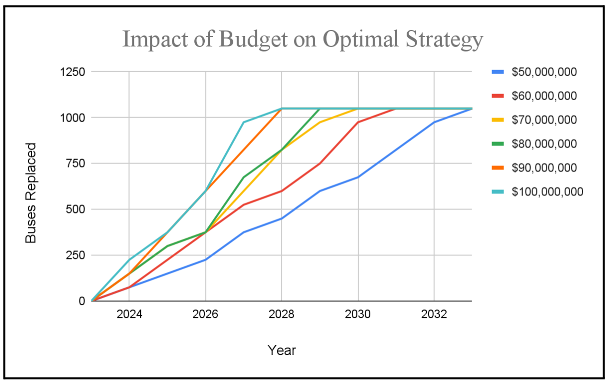


If São Paulo were to follow our plan, they would incur relatively high costs for the first 6 years of transition as they obtain e-buses before completing their swap, resulting in minimal costs for the rest of our considered timeframe.

6.5 Sensitivity Analysis



We conducted a sensitivity analysis on the ratio of our weights w_C and w_F for calculating our index in our Vancouver model, as shown above. We see that the final plan is completely identical across all weights, because our model is able to identify a plan that is simultaneously optimal for the budget constraints in both carbon emissions and financial costs. Therefore, our model is perfectly robust against shifts in our weights.



We also conducted a sensitivity analysis on the impact of Vancouver's yearly budget, or B, on their optimal strategy, adjusting it from $50 million up to $100 million. We note that with a greater yearly budget, cities should transition their fleet earlier as they can purchase more buses per year, resulting in increased carbon and financial savings. This is expected, as we've found that individual BEVs are simultaneously **cheaper and more environmentally friendly** than diesel, natural gas, and HEV buses, so the same should apply towards BEV fleets. Therefore, in Vancouver's case, with its cheap, clean electricity benefitting e-bus operation, **it is best for the city to transition as quickly towards a full e-bus fleet as budget allows.** This is **also the case** for **São Paulo** and **Boston**, even with slightly less clean electricity.

7 Strengths and Weaknesses

7.1 Strengths

Our model is highly adaptable across different bus fleets and situations, as we are able to modify the number of buses of each model to easily evaluate the environmental impacts of fleet compositions. We also separately calculate the emissions and costs from different life stages of a bus, meaning that if we were to expand our mathematical models of individual buses or modify certain formulae, the rest of our model would not be affected.

Our model can be tailored with parameters specific to the economic and environmental situations of each city, including grid mix, fuel prices, and trolley infrastructure.

Our model is based on comprehensive research and full life-cycle analyses, ensuring that we consider as many real-world aspects of emissions as possible.

Our presented roadmap is mathematically derived from permuting through thousands of possibilities of fleet replacement, ensuring that our roadmap is realistic and relatively optimal.

7.2 Weaknesses

Our model for individual buses requires a great amount of research to obtain variables for build materials, maintenance costs, and carbon emissions of different processes, some of which are based on assumptions previous researchers have made. Thus, our model has a larger chance of including inaccurate data.

Our roadmap model is very computationally intensive as we are calculating thousands of potential transition scenarios, which either require lower precision when dealing with larger bus fleets or exponentially increased runtime.

Our model does not consider some logistics behind a fleet transition—we did not include transport delays from adjusting to new technology, for example, or replacing buses that are already nearing the end of their lifespans first, since it is difficult to obtain quantitative data for these factors. Given more time, we can account better for the human aspect of fleet transition.

8 Conclusion

In order to best aid cities in determining the effects of transitioning to a fully electric bus fleet, our group constructed models determining both the ecological and financial ramifications of the entire life spans of various types of buses, incorporating life-cycle analysis to evaluate their impacts. By applying our individual models, we were able to create a simulation that calculates the most optimal plan of transition by permutating all possible plans of transition, specifically tailored to any individual city. We consider budgetary limitations as well as both financial and ecological aspects. After extensive sensitivity analysis, we conclude that the optimal plan for cities is to **transition to e-buses as early as possible**, which decreases both emissions and costs, best satisfying both criteria.

9 Letter to the Officials (Requirement 4)

Dear Transportations Officials of the City of Vancouver,

We understand that environmental friendliness is a priority for the city of Vancouver, and we believe transitioning to electric buses will further this effort. After conducting extensive research and making a model representing the impacts of various bus types, our group has come up with a recommended plan which we hope will allow your decision to transition to a fully electric bus fleet easier and smoother.

Our model can be split into two parts: determining ecological and financial impacts. The first part, ecological, is judged by the effective carbon emissions produced through four stages of a bus' lifecycle: production, operation, maintenance, and disposal. Our team individually modeled the environmental impacts of five types of buses currently employed by Translink in Vancouver, being compressed natural gas, diesel, hybrid, battery electric, and trolley electric. To accurately represent Vancouver's unique status in energy production, we took into account the hydro-based electricity grid mix, along with the fuel prices of the area.

The second part of our model covers your city's costs over the four aforementioned stages as well, specific to the city's direct financial costs. We especially paid close attention to maintenance costs, in which we considered Vancouver's wide-reaching trolley lines, and their respective maintenance rates and costs. We also took into account potential subsidies from the provincial government, up to 50%, covering production costs.

With this holistic, bottom-up approach, we were able to apply our models of individual buses to Vancouver's situation. We created a model which simulated all potential rates of fleet transition per year for Vancouver, and weighed each outcome against one another to derive a final, most optimal way of transitioning to an all-battery bus fleet, considering both financial and ecological impacts.

Assuming your department's budget per year is $50 million dollars, and that your department purchases buses in batches of 75, our recommended plan is as follows:

Year	1	2	3	4	5	6	7	8	9	10
Buses Replaced	75	75	75	150	75	150	75	150	150	75

Furthermore, after considering different potential budgets, along with applying our model onto different cities, we have determined that the optimal way of adopting an electric bus fleet is to conduct the transition as early as possible while remaining under your allocated budget. We found this to be the case as we determined e-buses to be both **cheaper to operate** and more **environmentally-friendly**.

If you were to adopt our plan, considering 50% external funding for purchasing e-buses, we estimate you will spend just under **$500 million** total on your bus fleet over the next ten years and produce just slightly over **300 million kilograms of CO_2 equivalent** emissions.

We hope that our findings will serve useful to your mission to make Vancouver a healthier, greener city for all its residents.

Sincerely,
Team #13694

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