Watts on Wheels!

Summary Sheet

The rising climate crisis begs the need to phase out fossil fuels. The ecological and financial implications of fossil fuel dependency are far outweighed by the effects that cleaner energy options offer. Currently, common lifestyle elements of daily life are being replaced with eco-friendly options. In a metropolitan setting, public transportation is integral to the systematic functions of society. Buses are a prime example of transportation that is undergoing the transition from fossil fuel dependence to electricity. In this paper, we will create a model that represents the ecological and financial consequences of the transition from diesel to electric buses.

To address the ecological impacts of transitioning from a diesel to an all-electric fleet of buses, a mathematical model was created to assess the amount of CO_2 emissions and noise pollution created by both types of buses. The model used to calculate CO_2 emissions, referred to as Model 1.1, analyzes sources of CO_2 production during the life cycle of both types of buses. Model 1.1 takes into consideration the CO_2 emitted during the production, use, maintenance, disposal, and recycling of buses. Once this model was created, the corresponding values for each component in the equation could be inputted, resulting in the total CO_2 emissions for a given bus.

In Model 1.2, a separate mathematical model was created to evaluate the noise pollution created by diesel and electric buses. In this model, the type of vehicle, engine type, speed, and decibels were converted into perceived sound. Ambient noises, such as pedestrians, were excluded in this model as the sounds remain constant despite the transition of bus models.

After collecting the data from using Model 1.1 and 1.2 for diesel and electric buses in a given city, the difference between CO_2 emissions and noise pollution for the two types is used as a strategy to aid in educating cities about the benefits of transitioning to an electric, eco-friendly bus fleet. These models were applied to three metropolitan areas: Washington, D.C.; Denver, Colorado; and Chicago, Illinois. Through this difference, government officials and residents would be able to visualize the ecological benefits of electric buses.

When identifying the financial implications of the transition from diesel to electric buses, referred to as Model 2, the following components were identified: initial purchases, cost of supplying energy, maintenance, operating, legal, and recycling fees. The sum of each of these factors was compared between diesel and electric buses to display the financial benefits of the transition over time.

The results of Models 1.1 and 1.2 show that dependent on the variables of a given area, carbon emissions and noise pollution will decrease at a linear rate. In Model 2, the high initial costs of the transition make diesel buses a more economical option in the short term. However, due to the lower annual costs of electric buses, the transition will save municipalities money over time. Each of these models is represented with graphs to provide visual aids of their efficacy.

In the future, this model can be improved to include these factors to create a more accurate representation of the ecological and financial benefits of the transition from diesel buses to an all-electric fleet.

Keywords: bus transit, diesel, electric vehicle, carbon footprint, life cycle analysis

Letter to a Transportation Official

November 10, 2023

Dear Shoshana M. Lew,

To put it simply, public transportation makes the world go ‘round. Each route a transit bus passes through forms crucial connections between people and space that may have never existed before. Due to your expertise in transportation in Denver, Colorado, we are sure that you are highly familiar with the importance of public transportation. However, the consequences that come with traditional transportation systems are also harming the people you serve.

Climate change, global warming, and carbon emissions are ever-growing concerns around the world. Unfortunately, one of the major contributors to this problem is transportation. In the United States, 29% of carbon emissions are the result of transportation[1]. A significant portion of this statistic is made up of the emissions from diesel buses.

Fortunately, there is a solution to this problem. Electric buses serve the same functions as diesel buses - but with the added benefit of being eco-friendly and cheaper for the city to operate in the long term. In this letter, we will propose a recommendation for the transition of Denver's bus system from a diesel to an all-electric, zero-emission fleet.

Currently, the Denver Public Transit System has 1080 diesel buses in its fleet, with only one or two electric-battery buses here and there. The consequences of not transitioning the existing model can be quantified through two angles: the ecological and financial burdens on our community.

By transitioning to an all-electric bus fleet over 10 years, 8964.069 tons of carbon dioxide will be removed from pollution each year. It is well known that in communities with high levels of CO_2 emissions, children are more prone to asthma. In addition, over the same 10 years, 8005.516 kiloliters of water will also be saved each year.

While the ecological benefits of this transition are obvious, the financial burdens tend to discourage city leaders from pursuing this plan. Although the upfront acquisition costs of buying electric battery vehicles may seem significantly higher than those of purchasing diesel buses, the return on investment over ten years is significantly greater. As fossil fuels become scarce, the rate of diesel is increasing, while electricity costs are decreasing. By taking the cost from manufacturing to the end life of a bus, the return on investment of electric battery buses is about 62% higher than maintaining the diesel infrastructure.

With Regards,
Team #14625

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[1] US EPA. (2022, May 19). Carbon Pollution from Transportation — US EPA. US EPA. https://www.epa.gov/transportation-air-pollution-and-climate-change/carbon-pollution-transportation

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1 Introduction

1.1 Background

The evils of global warming have been on an unprecedented rise. According to the American Lung Association, 26 percent of air pollution comes from diesel-fueled vehicles. The consequences of carbon emissions can be reflected in the health of humans, animals, and the environment (National Institute of Environmental Health Sciences, 2022). Fortunately, we hold the power to mitigate its consequences by transforming diesel-based public transit buses into electric battery-powered buses. Phasing out diesel buses to battery electric buses holds promising improvements in many aspects of a metropolitan city.

We aim to develop a model to quantitatively analyze the ecological and financial benefits of transitioning to an all-electric bus fleet model.

1.2 Problem Restatement

Fossil fuel dependency is cause for concern not only environmentally, but financially as well. The rise of electronic buses aims to solve this issue in the transportation sector by offering an eco-friendly and economical mode of transit due to the low carbon emissions and fuel costs associated with electric vehicles.

The goal of this paper is to create two distinct models that can identify the ecological consequences and financial implications of the transition from diesel to all-electric buses within a given metropolitan area. By applying our models to three metropolitan areas: Washington, D.C.; Denver, Colorado; and Chicago, Illinois, we will be able to prove the positive effects of this transition in a real-world setting.

1.3 Assumptions

Assumption 1: All non-electric buses within a metropolitan area are diesel-powered.

- This factor keeps the CO_2 emissions created by non-electric buses constant when comparing them with electric buses.

Assumption 2: No infrastructure will be built or destroyed for diesel buses.

- Existing infrastructure may be used for other vehicles, such as trucks and construction vehicles.

Assumption 3: No additional diesel buses will be manufactured unless one breaks down.

- Since the purpose of this model is to analyze the transition of diesel to electric buses, extraneous diesel buses will be unnecessary.

Assumption 4: The noise pollution for diesel and electric buses is significant for speed levels between 0-50 km/h.

- As the speed of buses increases, the difference between the dBA of diesel and electric buses becomes less significant, because the sound generated by the tires exceeds the sound that is generated from the vehicle systems (Borén, 2019).

Assumption 5: Each electric bus needs one charger.

- To prove the efficacy of the transition, we chose the worst-case scenario for a bus-to-charger ratio. In reality, it would not be economically nor spatially feasible to buy one charger for every electric bus.

Assumption 6: The average life for each type of bus is the same.
- To maintain consistency when calculating [...], we made this assumption based on the information provided by the APTA procurement guidelines (APTAAdmin, n.d.).

Assumption 7: The price of diesel used is the average in the region.
- We chose the average cost of diesel so that it is representative of the entire region.

Assumption 8: All the electric buses of a region are the same model.
- If a region does not have any electric buses, all succeeding buses will be the most prominent electric buses on the stock market due to their relevance. If a region has existing electric buses, the same model would be used in calculations.

2 Part One: Ecological Model

2.1 Brief Overview

In this section, we aim to quantify and compare the ecological impact of internal combustion engines (ICE) and battery-electric buses (BEB) throughout y years. The emission of each type of vehicle was determined from the different stages of the Life Cycle Assessment.

The Life Cycle Assessment is a systemic approach to evaluating the ecological impact of a product from the start to the end of its production, operation, and disposal. Performing an LCA test provides insights to policymakers, businesses, leaders, and other organizations to make thoughtful decisions about implementing structures. While most LCAs calculate total ecological effects over a bus' whole life, our models calculate ecological effects per year in order to compare the differences in ecological effects over a period of time. (see Figure 1). Some basic assumptions were made to make the analysis comparable, as numerous factors can impact a vehicle's ecological impact:

Assumption 1: All ICE use the same type of diesel as each city will establish contracts with specific bus companies.

Justification: In December of 2022, 77% of all transit buses used diesel-powered engines. This means that a majority of buses use diesel-powered engines, and therefore it is safe to assume that all of the buses in use are diesel-powered.

2.1.1 GREET Model

The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model is a tool created by the U.S. Department of Energy's Bioenergy Technologies Office that examines the life-cycle impacts of vehicle technologies, fuels, products, and energy systems. For any given energy and vehicle system, GREET can calculate total energy consumption (non-renewable and renewable), emissions of air pollutants, emissions of greenhouse gases, and water consumption. Continually updated by world-class researchers at ANL, GREET provides reliable calculations of life-cycle energy and emissions related to transportation and accounts for a wide range of conventional and emerging energy systems and vehicle technologies (GREET: The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model, 2018).

GREET was used in this project to calculate emission values of CO_2 and water use in production of various parts involved in bus manufacturing.

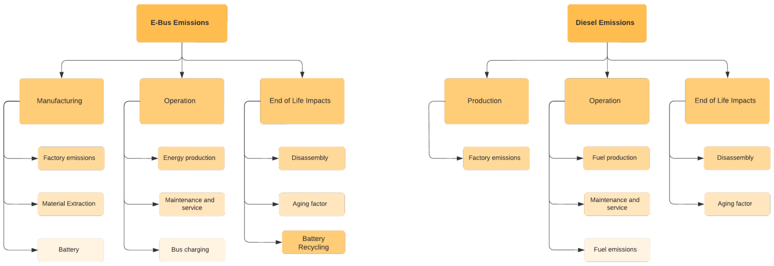


Figure 1: Life Cycle Assessment Electric vs. Diesel Parameters

2.1.2 Variable Identification

Variable Symbol	**Definition**
$CO_{2Emissions}$	Total CO_2 Emissions of buses (kg) in one year
n	Number of buses
CO_{22pg}	$\mathrm{CO}_2 Emissionspergallon$
MPG	Miles per gallon
MPY	Miles per year
F_{comp}	CO_2 Emissions of a particular component (kg/kg)
LCD_{comp}	Life Cycle distance of a component (miles)
k	Change in buses per year
F_{ADR}	$\mathrm{CO}_2 footprintofdisposalandrecyclingphasefromGREET(kg)$
$W_{vehicle}$	Weight of vehicle (kg)
E_{consum}	Rate of consumption (kWh)
B_{cap}	Battery capacity (kWh)
B_{deg}	Battery degradation (decimal percent)
CO_{2pk}	CO_2 Emissions per kWh

2.1.3 Manufacturing Emissions

The CO_2 footprint for the production phase was calculated for electric buses using Eq. (1). This calculation was only used for electric buses as we assume all ICE buses have already been manufactured and are currently in use; therefore, we do not have to take into account the manufacturing emissions of pre-existing buses. The calculation considers the respective weight of the parts, produced for the specific vehicle configuration. Then, it is multiplied by the footprint value of that specific part obtained from the GREET database. This is done for all the parts included in the production of each bus model, and a sum of all the part's emission values is done to compute the total emission value of production.

$$CO_{2Production}(kg) = [\Sigma(F_{comp} * W_{comp})] \tag{1}$$

This equation can account for any combination of parts that a city identifies in each type of bus; as long as it is present in the GREET database. In our analysis, we use parts identified by García et al. (2022), where these parts are the most common in all bus types. These parts are split into ICE- and BEB-bus types to display some parts that are only present in one type of bus or another (see Appendix 1: Parts Usage).

2.1.4 Usage Emissions

To quantify the CO_2 emissions from fuel combustion and production, two separate equations were made, one for diesel buses and one for electric buses.

Diesel Bus Usage Emissions

Eq. (2), shown below, calculates the total CO_2 emissions from diesel bus use by multiplying CO_2 emissions per gallon of diesel by gallons per mile (also equal to 1MPG) by the total miles per year. This equation, by using MPY and MPG, takes into account changes in bus routes and distances traveled per year, as well as changes in efficiency throughout a bus' life (MPG will decrease as a bus ages).

$$CO_{2use}(kg) = CO_{2pg} * \frac{1}{MPG} * MPY \tag{2}$$

Electric Bus Usage Emissions

Eq. (3), shown below, calculates the total CO_2 emissions from electric bus use by multiplying MPY by energy consumption rate per mile (in kWh) by the inverse battery capacity by the CO_2 production of each kWh. The inverse battery capacity is used to model the degradation of a battery over y years by a set percent. This percent is described as a decimal 0-1, where 99% would be 0.99. When a battery ages, more energy is required to travel the same distance, which is why the inverse of the degradation factor is needed. This equation takes into consideration different CO_2 production for different sources of energy, as CO_2pk is the carbon dioxide emission of the electricity source per kWh. This equation does not take into account any tailpipe emissions, as EVs are previously defined as zero-emission vehicles (Zhang et al., 2019).

$$CO_{2use}(kg) = MPY * E_{consump} * \frac{B_{cap} * (2 - B_{de_g^y})}{Bcap} * CO_{2pk} \tag{3}$$

2.1.5 Maintenance Emissions

In order to calculate the CO_2 emissions from part maintenance in a bus, Eq. (4), as shown below, was developed. This equation multiplies the CO_2 emission per part by the number of times the part must be replaced in a year (modeled by miles per year divided by the life cycle distance of a part) and then adds together all values for appropriate parts. In our analysis, we used three specific parts from the list in Appendix 1: tires, engine oil, and coolant. This equation does not change based on bus type, only the parts would change per bus type (BEBs do not have engine oil).

$$CO_{2maintenance}(kg) = \Sigma(F_{comp} * \frac{MPY}{LCDcomp}) \tag{4}$$

This equation takes into account changes in bus distance, as MPY can change year to year. It also takes into account any combination of parts that a city may want to model in their equation, making it highly versatile.

2.1.6 End-Of-Life Emissions

Eq. (5), shown below, is used to calculate End-Of-Life CO_2 emissions from diesel buses. Electric buses have a lifespan between 12-15 years, so therefore, if we must consider a period of 10 years, only diesel buses would accrue this specific category of emission. End-of-life emissions are calculated by multiplying the CO_2 emission per kg value of recycling (gathered from the GREET model) by the weight of the vehicle, in kg.

$$C_{O2ADR}(kg) = F_{ADR} * W_{vehicle} \tag{5}$$

This equation takes into account the weight of the vehicle as well as the individual recycling emission component of the vehicle. This ensures that the equation can be applied to a variety of models of buses (Pelletier et al., 2019).

2.1.7 Total CO_2 Emissions

To make two final equations, Eq. (1), (2), (3), and (4) were combined into one equation. However, to account for the number of buses, this value was multipled by n buses. In addition, the manufacturing and end-of-life emissions are only calculated by the change of buses each year, therefore, this value is not multipled by n, it is multiplied by k, or the number of buses that are changed to BEB each year.

$$CO_{2Emission}(n_{diesel}) = n_{diesel}*((CO_{2pg}*\frac{1}{MPG}*MPY)+[\Sigma(F_{comp}*\frac{MPY}{LCD_{comp}})])+k*(F_{ADR}*W_{vehicle}) \tag{6}$$

$$CO_{2Emission}(n_{electric}) = n_{electric}*((MPY*E_{consump}*\frac{B_{cap}*(2-B_{deg}^{y})}{Bcap}*CO_{2pk})+[\Sigma(F_{comp}*\frac{MPY}{LCD_{comp}})])$$

$$+\mathrm{k}*(\mathrm{F}_{ADR} * W_{vehicle})$$

(7)

It is important to note that we only calculated CO_2 emissions because all other pollutants make up a total of less than 1% [cite] of total emissions, therefore, we focused on making an equation to model CO_2 emissions as it is the most prevalent greenhouse gas in bus emissions.

2.1.8 Water Consumption

In order to model water consumption, you would use the equations from Eq. (6) and Eq. (7), substituting any CO_2 value for water usage (obtained from GREET model). The following equations were developed:

$$Wa_{usage}(n_{diesel}) = n_{diesel} * ((Wa_{pg} * \frac{1}{MPG} * MPY) + [\Sigma(F_{comp} * \frac{MPY}{LCD_{comp}})]) + k * (F_{ADR} * W_{vehicle}) \tag{8}$$

$$Wa_{usage}(n_{electric}) = n_{electric} * ((MPY * E_{consump} * \frac{B_{cap} * (2 - B_{de_g^y})}{Bcap} * Wa_{pk}) + [\Sigma(F_{comp} * \frac{MPY}{LCD_{comp}})])$$

+k*(F$_{ADR} * W_{vehicle}$)(9)

2.1.9 Noise Pollution

Traffic noise is a prevalent issue in urban and residential areas. A survey by the World Health Organization in 2011 indicates that at least 1 in 5 adults will experience sleep disturbance due to high traffic noise levels. The levels of noise pollution an individual experiences vary based on their proximity to major roads, varying traffic flows, and other factors. Understanding the exposure to noise pollution is essential as various emerging studies link high exposure to noise pollution to long-term health cardiovascular, and mental health, sleep disturbance, cognitive problems, and other health challenges (National Institute of Environmental Health Sciences, 2022). Evaluating electric vehicles and diesel-fueled buses' noise pollution levels is essential to determining the impact on the long-term health of residents.

Objective: The model below determines the noise production of diesel-based and electric bus fleets and performs a spatiotemporal approach to evaluate the benefits of electric bus fleets over diesel buses.

Assumption: Several studies in the past have attempted to determine the reduction of traffic noise pollution due to the implementation of electric buses. To develop a model for metropolitan areas, the following assumptions were made based on previous experiments: As the speed increases, the difference between diesel and electric bus dBA becomes less significant, because the sound generated by the tires exceeds the sound that is generated from the vehicle systems. The difference is significant for speed levels between 0-50 km/h, ideal for urban landscapes with congested traffic flow (Ka Ho Tsoi et al., 2023). The difference past 50 km/h is negligible. The noise generated during acceleration and deceleration periods and overall differences in road characteristics of the buses are not being considered in this model due to the variability in the type of bus, driving style, type of bus, etc.

$$L_{diesel}(v) = k_{diesel} * v + L_{ambient} \tag{10}$$

$$L_{electric}(v) = k_{electric} * v + L_{ambient} \tag{11}$$

In this case, v represents the bus speed in miles per hour (mph) or kilometers per hour (km/h), and $L_ambient$ represents external sounds such as pedestrians, street sounds, etc.

3 Part One: Ecological Model Analysis and Application

3.1 Sensitivity Assessment

In order to demonstrate the effect of each variable on Eq. (6) and Eq. (7), and by extension Eq. (8) and Eq. (9), a sensitivity assessment was done. This sensitivity assessment took the averages of all the values to begin and then changed each variable to the min and max range to determine its effect on the change in CO_2 emissions per year. The percent change was then calculated, and is shown in the following table:

Variable	**Percent Change**
CO_{2pg}	116.15
MPG	-95.07
MPY (diesel)	796.02
LCD_{comp}	-0.05
F_{adr}	-1.73
$\mathrm{W}_{vehicle}$	-0.45
$\mathrm{E}_{consump}$	-12.07
CO_{2pk}	-54.02
MPY (electric)	-33.09
B_{cap}	0.00
B_{deg}	0.00

This analysis clearly shows that miles per year of diesel buses has the most significant change in the model. This means that the miles per year should be carefully inputted to accurately represent the data. Miles per gallon and CO_2 emissions have the following highest percent change, meaning they also play an important factor in the model. In addition, both battery capacity and the battery degredation factor had a zero percent change, meaning they had no effect on the model. When working with the equations in the future, both of these values will be kept the same between all applications as it does not have an effect on the output.

3.2 Energy Production

While testing the sensitivity analysis, one important discovery arose: CO_2 emissions for electricity varies greatly based on where the electricity comes from. For example, if natural gas is used, it gives a value of 0.4532 kg per kWh, if coal is used, it gives a value of 1.0544 kg per kWh, and if any renewable resources is used, such as solar power, it gives a value of 0 kg per kWh. Figure (insert number here) below show the change due to differing energy sources.

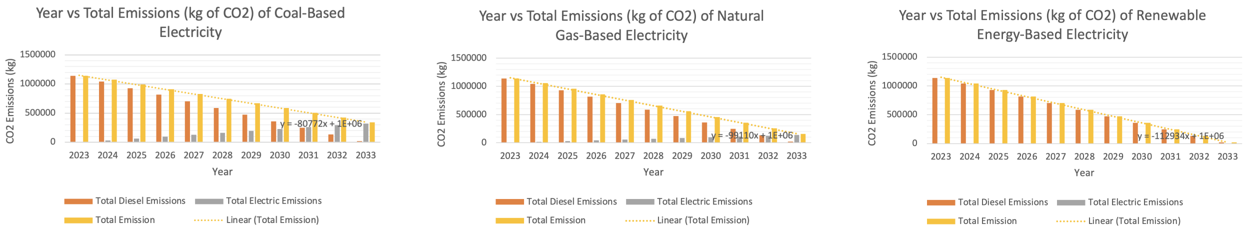


Figure 2: Changes in CO2 Emissions In Regards to Energy Types

These differences highlight the importance of a city being able to use energy that is supplied from renewable sources. Even if a city does use a source that has a high CO_2 emission rate, such as coal, it still does result in a decrease in total carbon dioxide emissions. However, this change is amplified when using renewable energy by almost 40%.

3.3 Metropolitan Application

In order to apply the models above, the following values were used:

Variable	**Value**
n_{diesel}	58
$n_{electric}$	14
k	5.8
MPG (diesel)	3.6
MPY (diesel)	26460.44828
MPY (electric)	15150.14286
$E_{consump}$	1.69
CO_{2pk}	0.172337856
CO_{2pg}	11.844597
Wa_{pk}	0.274243822
Wa_{pg}	11.2730547
$W_{vehicle}$	12000

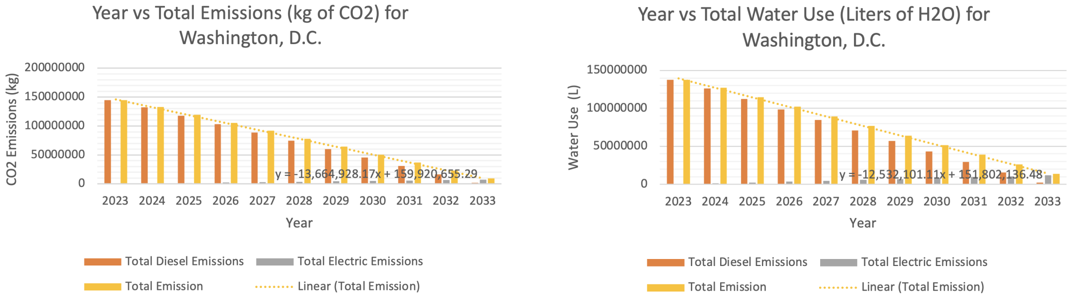


Figure 3: Washington, D.C. CO2 Emissions and Water Use

Note: CO_{2pk} and Wa_{pk} were weighted averages of the types of energy sources in Washington, D.C. based on data in 2021.

After inputting these values of variables into the equations for ecology impacts, the following graphs were created:

Overall, each year in a ten year period, 13664.928 tons of CO_2 will be reduced from emissions and 12532.101 kiloliters of water will be saved.

4 Part Two: Financial Model

Implementing a transition to all zero-emission vehicles requires a multi-faceted approach to analyze the cost benefits in comparison to maintaining the all-diesel bus system for the next 10 years. The Life Cycle Assessment approach must be taken to compute the cost at different stages of a vehicle's development. Our model focuses on the three main stages of the transition process: acquisition, operational, and end-of-life expenses. There is a potential external funding that will cover up to 50% of the transition costs. Therefore, by analyzing the return on investment, the profit timeline can be understood as well.

Also known as the Life Cycle Cost, the first step is to understand the different components that contribute to the costs over the entire life span of an electric and diesel bus. The flow chart in Figure [...] shows the different factors that affect costs.

1. **Acquisition Costs** are costs that come with the initial bus purchase. This includes the cost of the buses and the cost of the chargers.
2. **Manufacturing and Installation Costs** are costs associated with manufacturing and installing costs of the buses, chargers, and their respective components.
3. **Ownership Costs** are costs that comply with the law. For example, vehicular insurance, accident insurance, inspections, etc. would be considered in this parameter.
4. **Operating Costs** are costs of the materials and goods needed to keep the bus running over its life span.
5. **Maintenance Costs** are costs related to the materials and procedures that maintain the bus and ensure long-term survival (i.e. repairs).
6. **End-of-Life Costs** are costs that come with the disposal of the bus. However, the salvage cost is the residual cost which should be subtracted from the final cost as that money remains throughout the life span.

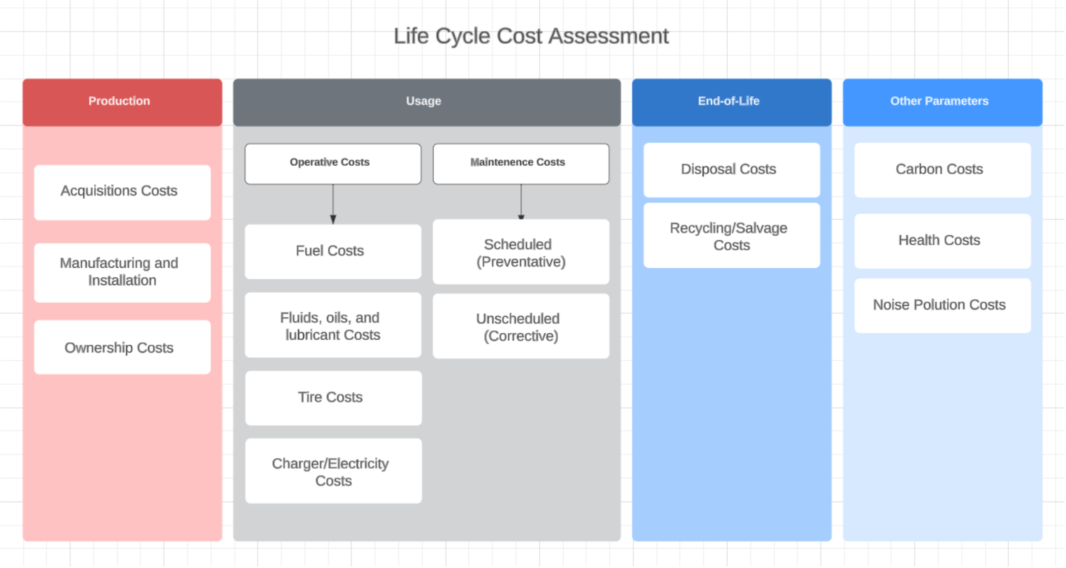


Figure 4: Life Cycle Cost Assessment Parameters

7. **Other Costs** are external costs that may affect the public. Mainly related to carbon emissions, these costs are expected to be significant over the long-term implications of electric buses.

4.1 Parameter Equations

After understanding the factors and the parts of each parameter, a mathematical model can be made by deriving equations for each factor. The final equation will be a sum of the equations. The general equation for diesel and electric buses will be the sum of costs for each category:

$$C_{total} = C_A + C_L + C_O + C_M + C_E + C_S \tag{12}$$

where C_{total} is the total life cycle cost, C_A is the acquisition costs, C_L is the cost related to law, C_O is the operating costs, C_M is the maintenance costs, C_E is the end-of-life costs, and C_S is the societal costs. Note that the time value of money is not considered in the equation because of the assumption that it will not have a significant impact in comparing costs (Zhang et al., 2021).

To incorporate time and analyze the cost for the ten-year model, the equation would be:

$$C_{total} = N_{bus} \cdot [C_A + C_R + Y \cdot [C_L + C_O + C_M + C_S]] \tag{13}$$

where N_{bus} is the number of buses and Y is the number of years. As we assumed that no electric buses would need to be recycled before the end of the ten-year plan, the recycling costs would only apply to diesel buses. Additionally, we assumed that no diesel buses would be added which is why the acquisition cost would not be included in the final C_{total} for the diesel buses during the transition. However, this model gives a general equation to compare the entire life cycle costs of diesel and electric buses (Furch et al., 2022).

In some cases, the data set may not include the cumulative costs for each variable. Therefore, it is important to understand the specific equations of each variable to end up with equations that are specific to the diesel and electric buses.

C_L, which represents law costs, can be represented as the following:

$$C_L = Y \cdot [C_{SI} + C_{AI} + C_{RT}] \tag{14}$$

C_{SI} represents annual insurance, C_{AI} is the accident insurance, and C_{RT} is the road tax. The operating costs are the sum of energy, material, and battery costs. Energy costs that are specific to diesel and electric buses:

$$CE_{diesel} = Y \cdot AC \cdot d_{total} \cdot P_{diesel} \tag{15}$$

$$CE_{electric} = Y \cdot AC \cdot d_{total} \cdot P_{electric} \tag{16}$$

where CE is the energy costs, AC is the average consumption per km, P is the price per unit of energy, and Y is the total kilometers traveled in the years. This can be manually found by multiplying annual kilometers driven by the number of years. Additionally, there are extra material costs that include tires, lubricant oils, etc that apply to both electric and diesel vehicles:

$$CM = Y \cdot C_{OL} \cdot P_{OL} + \frac{Y \cdot 4 \cdot P_{tire}}{L_{tire}} \tag{17}$$

where C_{OL} is the consumption of oils and lubricants in L per km, P_{OL} is the price of oils and lubricants per L, P_{tire} is the price of one tire, and L_{tire} is the average life of one tire in km.

However, there are extra battery costs that come with electric buses, which are known as accumulator batteries:

$$C_B = \frac{Y \cdot P_{batt}}{L_{batt}} \tag{18}$$

where P_{batt} is the price of a battery and L_{batt} is the life of the battery in km.

Lastly, there are maintenance costs. These include repairs and schedule changes to maintain the life of an electric bus. However, repairs that are unscheduled are hard to predict which is why they will not be included in the equation:

$$C_{main} = \frac{Y \cdot [P_{material} + P_{labor}]}{T} \tag{19}$$

where $P_{material}$ is the cost of the material during the maintenance, P_{labor} is the price of labor for the maintenance, and T is the time between maintenance schedule

4.2 Return on Investment

The return on investment (ROI) can give insight into the profits that come from transitioning from diesel buses to electric buses. The general equation to find ROI is below:

$$ROI = \frac{Profit \cdot 100}{Investment} \tag{20}$$

which gives the percent of ROI in a specified time frame. The general equation can be modified to find the ROI comparing diesel and electric buses:

$$ROI = \frac{Y \cdot [CA_{diesel} - CA_{electric}]}{C_{diesel} - C_{electric}} \tag{21}$$

5 Part Two: Financial Model Analysis

5.1 Sensitivity Test

After completing a sensitivity test that changed the number of buses, total miles, cost of electricity, and cost of diesel, all with ranges of minimum to maximum real-world value found, the following percent changes occurred:

Variable	**Percent Change**
Total # buses	4781.81
Total miles	3292.97
Electricity cost	0.03
Diesel fuel cost	32.78

This sensitivity test shows that the total number of buses has the most effect on the model. Total miles also has a very large effect on the model, whereas electricity cost only changes the model by 0.03%, meaning that the change in cost is so small it almost has no effect. Total miles and total # of buses have a 10-fold impact over diesel fuel cost, ultimately revealing that the cost of electricity and fuel do not have as large of an impact as the number of buses or miles traveled.

6 Part Three: Applications

6.1 10 Year Plan

Currently, a majority of metropolitan cities have a zero-emission plan in place to convert their buses. However, our task is to develop a 10-year transition model for public transport authorities in other cities. There are multiple ways to approach the phasing out and implementation process based on the resources and infrastructure available in a city, however, we propose a generalized, incremental model that city leaders can adopt and modify based on their needs and goals.

If a city has x number of diesel-based buses, the goal is to replace $x/10$ buses per year, and $x/120$ per month. As diesel buses are being phased out, the salvage cost per bus must be taken into consideration, as well as the cost to implement an incremental level of charging infrastructure and upfront purchase costs of BEBs. This will provide the average acquisition cost, which then can be added to the operational costs described in the previous section to project the overall cost of the transition project.

We assumed that no additional charging and storage garages were built as the availability of construction, labor, space, and other factors vary dramatically between cities and cannot be easily quantified. Therefore, we propose a model where the storage spaces for public buses remain consistent, and as diesel buses are phased out, BEB buses take up the storage spaces, and charging infrastructure is added there.

In this section, we will create a 10-year road map for the transition from diesel to an all-electric fleet of buses for Washington D.C., Denver, CO, and Chicago, IL.

According to a 2022 Transit Authority Report, there are 1600 diesel operational buses in the city of Washington D.C.

6.1.1 Washington, D.C.

Transition trajectory:

- 1664 BEBs introduced and 1664 diesel buses replaced by the end of 2033.
- Around 160 buses are targeted each year.
- Initially, 160 diesel buses are salvaged, and the storage spaces are upgraded to support BEB. As the initial batches of BEB are in function, the next round of diesel buses are phased and the infrastructure for the next round of electric buses is implemented.

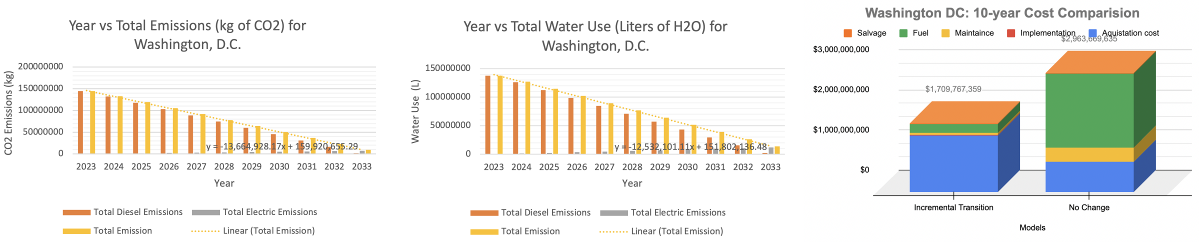


Figure 5: Washington, D.C. Environmental Effects and Cost with and without Electric Bus Implementation

6.1.2 Denver, CO

Transition trajectory:

- 1044 BEBs introduced and 1044 diesel buses replaced by the end of 2033.
- Around 104 buses are targeted each year.
- Initially, 104 diesel buses are salvaged, and the storage spaces are upgraded to support BEB. As the initial batches of BEB are in function, the next round of diesel buses are phased and the infrastructure for the next round of electric buses is implemented.

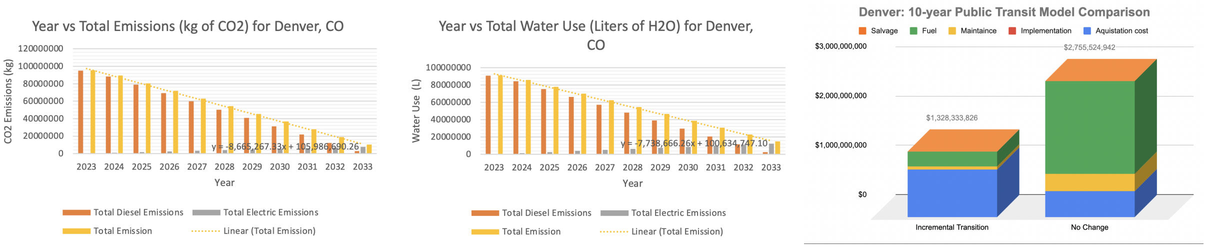


Figure 6: Denver, CO Environmental Effects and Cost with and without Electric Bus Implementation

6.1.3 Chicago, IL

Transition trajectory:

- 1848 BEBs introduced and 1848 diesel buses replaced by the end of 2033.
- Around 185 buses are targeted each year.
- Initially, 185 diesel buses are salvaged, and the storage spaces are upgraded to support BEB. As the initial batches of BEB are in function, the next round of diesel buses are phased and the infrastructure for the next round of electric buses is implemented.

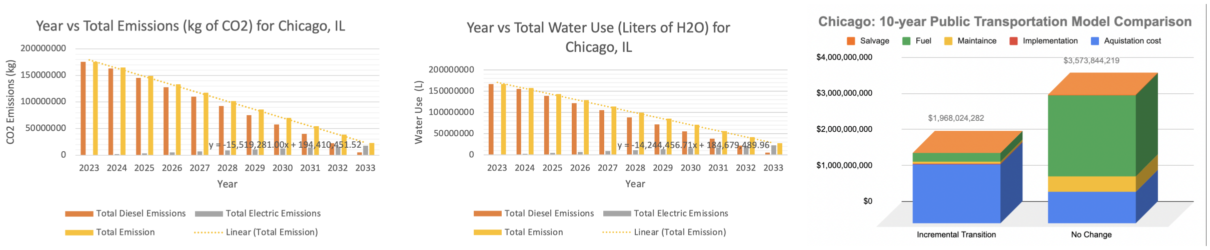


Figure 7: Chicago, IL Environmental Effects and Cost with and without Electric Bus Implementation

Refer to Appendix 2 for the final 10-year plan for each city

7 Conclusions

The transition from diesel to electric buses is vital in the fight against climate change. Through the use of our models, we can prove that over a given period of time within an area, the ecological and financial benefits of electric buses will surpass those of diesel buses.

The strengths of our model include addressing multiple sources of vulnerability when implementing electric buses. Throughout this model, we considered several areas which could contribute to carbon emissions, noise pollution, and finances. Through this, we were able to make sound conclusions about the positive impacts of electric buses due to the thoroughness of our model. Another source of strength in our model is the incorporation of national databases and outside studies, which include compilations of peer-reviewed and valid data.

Sources of weakness in our model include the lack of inclusion of factors such as inflation and the degradation rate of batteries. When such factors were tested, they resulted in insignificant differences when compared with and without them. However, accounting for values such as inflation is important when making calculations farther into the future because the value of a dollar is important when analyzing financial implications. Last but not least, many of the values used in this model vary based on time of year, ridership levels, policy measures, and more.

In the future, these models can be expanded to include the impact of the transition on human health in more depth. To aid in helping the public understand why this transition is critical, including relevant such as health and wellness is useful in doing so. and environmental health impacts. The effects on animal life and other biodiversity are also crucial when considering transition.

Overall, it is evident that battery-electric buses have ecological and financial benefits compared to existing diesel buses. Communities across the world should invest towards transitioning to a greener and brighter future.

8 Appendices

8.1 Appendix 1: Parts Usage

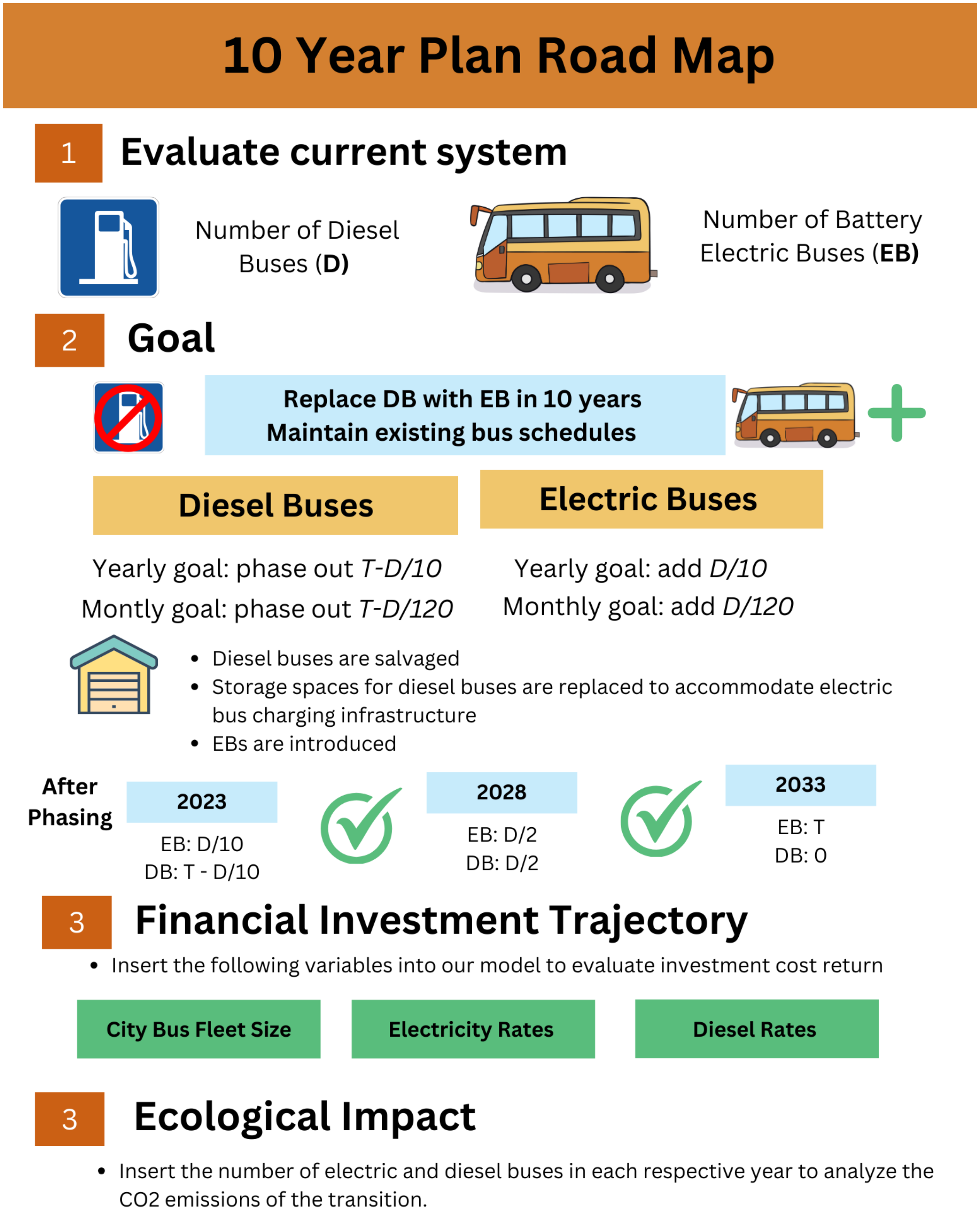
Part	F_{comp} **(diesel, kg)**	W_{comp} **(diesel, kg)**	F_{comp} **(electric, kg)**	W_{comp} **(electric, kg)**
Chassis	2.63	26.6	2.6	36.1
Powertrain	2.51	30.9	3.96	1.8
Transmission	3.75	5.7	3.26	3.5
Body	8.63	36.8	9.48	44
Power Electronics	-	-	2.41	6.8
Motor	-	-	2.57	7.8
Battery	-	-	42.13	17.8

Table 1: Parts for use

Part	F_{comp} **(diesel, kg)**	F_{comp} **(electric, kg)** heightTires
3.59	3.59	
Coolant	1.66	1.66
Engine Oil	3.12	-

Table 2: Parts for maintenance

8.2 Appendix 2: Final 10-Year Plans; General Model and Specific Models



10 Year Plan Road Map

1 Evaluate current system

Number of Diesel Buses **(D)**

Number of Battery Electric Buses **(EB)**

2 Goal

Replace DB with EB in 10 years
Maintain existing bus schedules

Diesel Buses	**Electric Buses**
Yearly goal: phase out *T-D/10*	Yearly goal: add *D/10*
Montly goal: phase out *T-D/120*	Monthly goal: add *D/120*

- Diesel buses are salvaged
- Storage spaces for diesel buses are replaced to accommodate electric bus charging infrastructure
- EBs are introduced

After Phasing

2023		**2028**		**2033**
EB: D/10 DB: T - D/10	✓	EB: D/2 DB: D/2	✓	EB: T DB: 0

3 Financial Investment Trajectory

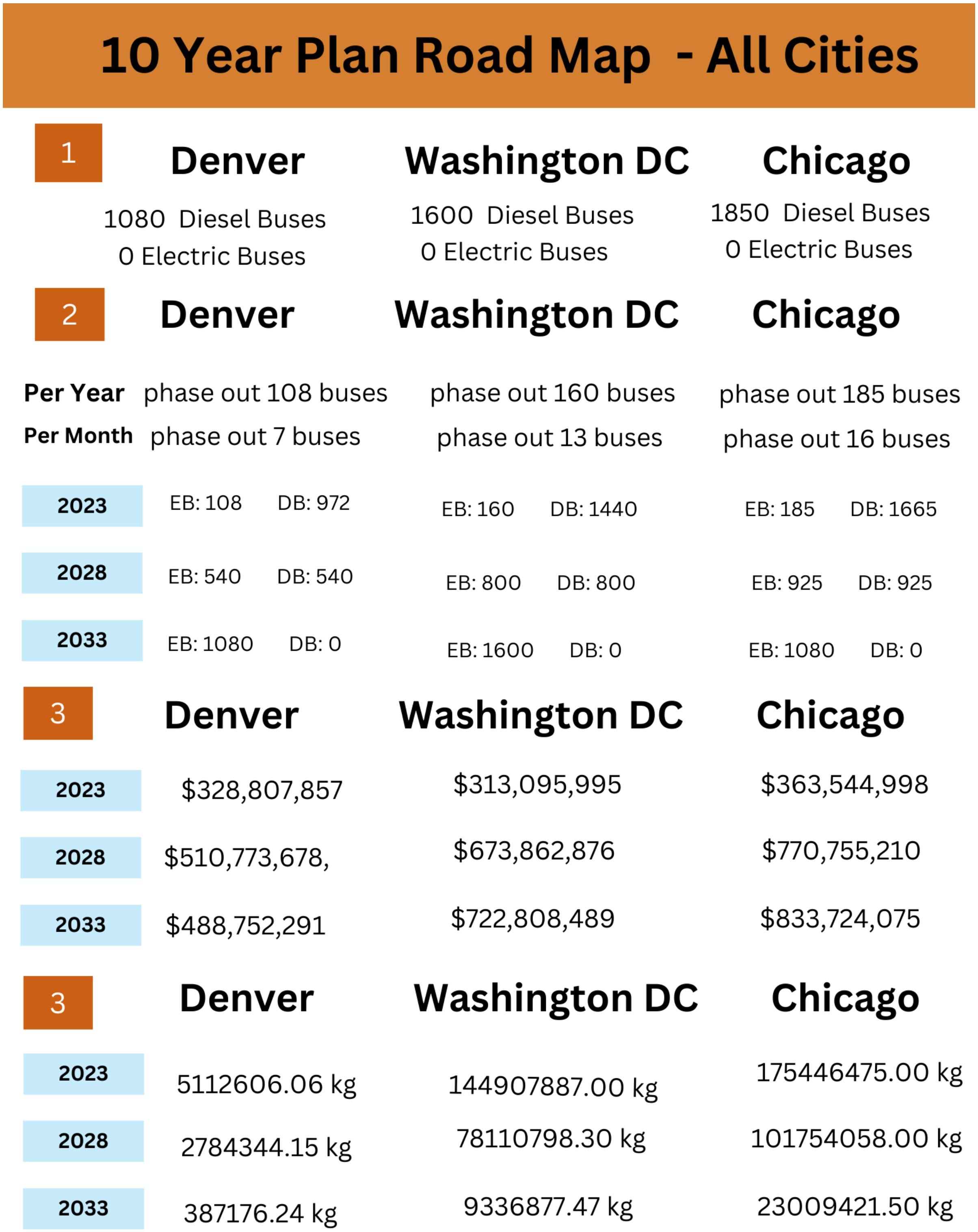
- Insert the following variables into our model to evaluate investment cost return

City Bus Fleet Size **Electricity Rates** **Diesel Rates**

3 Ecological Impact

- Insert the number of electric and diesel buses in each respective year to analyze the CO2 emissions of the transition.

Figure 8: General 10-year Plan



10 Year Plan Road Map - All Cities

1	Denver	Washington DC	Chicago
	1080 Diesel Buses 0 Electric Buses	1600 Diesel Buses 0 Electric Buses	1850 Diesel Buses 0 Electric Buses

2	Denver	Washington DC	Chicago
Per Year	phase out 108 buses	phase out 160 buses	phase out 185 buses
Per Month	phase out 7 buses	phase out 13 buses	phase out 16 buses
2023	EB: 108 DB: 972	EB: 160 DB: 1440	EB: 185 DB: 1665
2028	EB: 540 DB: 540	EB: 800 DB: 800	EB: 925 DB: 925
2033	EB: 1080 DB: 0	EB: 1600 DB: 0	EB: 1080 DB: 0

3	Denver	Washington DC	Chicago
2023	$328,807,857	$313,095,995	$363,544,998
2028	$510,773,678,	$673,862,876	$770,755,210
2033	$488,752,291	$722,808,489	$833,724,075

3	Denver	Washington DC	Chicago
2023	5112606.06 kg	144907887.00 kg	175446475.00 kg
2028	2784344.15 kg	78110798.30 kg	101754058.00 kg
2033	387176.24 kg	9336877.47 kg	23009421.50 kg

Figure 9: Caption

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