Team Control Number
14610

2023
HiMCM
Summary Sheet

Problem Chosen
B

Summary

Amidst demanding societal and ecological changes, transportation reformation is essential in cultivating resilient global communities. As the prevalence of the climate crisis rises, transportation authorities from around the world are looking for effective and appealing solutions, such as battery-powered electric buses (BEBs). BEBs introduce an achievable step towards zero-emission urban bus transportation. The introduced problem aims to develop a model in which urban/metropolitan areas can predict the ecological and financial consequences of transitioning to all-electric bus fleets. This problem consisted of 4 segments: modeling the ecological consequences of a full BEB fleet while applying the model to a metropolitan area of at least 500,000 people. The second segment required modeling the financial implications of the transition and applying it to the same metropolitan area, developing a 10-year road map for 3 metropolitan areas, and writing a letter to advise transportation authorities in their transition to e-buses.

In modeling the ecological consequences of adopting a full fleet of electric buses, we evaluated societal, natural, and tropospheric conditional changes due to this transition to best advise transportation authorities. Among these ecological consequences, we found that societal noise, local pollutants, bus production, and battery disposal all accounted for significant conditional changes to the fragile urban ecological fabric. These conditional changes directly impact human health conditions, environmental health, and changes to tropospheric levels. It was found that diesel-fueled internal combustion buses emit significantly higher levels of the pollutants $PM_{2.5}$ and NO_X, each of which directly affects human health conditions by increasing the risk of cardiovascular disease, lung and breathing ability, as well as premature death. Amongst these impacts, pollutants contribute to significant environmental changes, altering acidity and nutrient balance in fragile natural ecologies. In addition, the urban ecological changes identified impact people of color at greater levels due to historical redlining practices that have deprived vulnerable communities of accessing resources that could protect them from the ecological impacts of transportation pollution and resource misuse.

We utilized the number of chargers found in the first part of the model to develop an effective financial model. This model included the raw cost of the bus and chargers, installation of chargers, electricity, and maintenance fees per mile. The increase in the price of electricity was found negligible and, therefore, not included in the model. The financial model was then used to develop a ten-year roadmap called *Zero*, an initiative aiming to achieve emission-free urban bus transportation in any global city.

Through the development of these models, HiMCM team 14610 was able to quantify and evaluate the effects of adopting a full fleet of electric buses in urban settings. In the future, further variable breakdown and city-specific data could contribute to the improvement of modern public transportation.

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1. Introduction

1.1 Background

Electronic buses (e-buses) are facing an uprising in urban areas due to increased attention to the current climate crisis. Cities are turning to buses to take over public transport sustainably. Some cities, including Bogota, New York, and Berlin, have begun small efforts to convert to e-buses. Not only is this an eco-friendly solution, but it is also cost-friendly as operational costs are low and government incentives including the Bipartisan Infrastructure Law. However, e-buses present some setbacks, including charging time, range limit, and initial cost – decreasing feasibility.

1.2 Problem Statement

This problem aims to model the possible implications of e-buses on metropolitan areas. This includes multiple e-buses: hybrid, battery, and fuel cell electric buses. As the problem requires, we considered metropolitan areas and their ecology when modeling ecological impacts. The problem requirements are as follows:

Question 1: Model the ecological consequences of converting to an all-electric bus fleet. Identify a metropolitan area with at least 500,000 people and implement your model in the city.

Question 2: Model the financial implications when transitioning to e-buses—factor in 50% financial coverage from external funding. Apply your model to the metropolitan area from question 1.

Question 3: Assuming metropolitan areas will go completely electric by 2033, develop a model to make a 10-year roadmap for urban transport authorities to plan e-bus fleet updates. Apply the model to 3 metropolitan areas, including the area from question 1.

Question 4: Write a one-page letter to the transportation officials in a metropolitan area in which you advise their transition to e-buses.

1.3 Assumptions

Assumption #1: All of the electric buses in the fleet will be long/extended range battery electric buses (BEBs). *Justification: Battery electric buses have many advantages/disadvantages when compared to other electrical buses, such as hydrogen fuel cell buses. While fuel cell buses are lightweight and can store energy for longer, battery electric buses are more energy efficient. Since energy efficiency plays a much larger role in our model, the battery electric bus was chosen to implement in the fleet.*

Assumption #2: All of the electric bus energy in Boston is generated from natural gas. *Justification: This assumption is justified because the majority of energy for the MBTA is generated from the ISO New England energy grid. The ISO New England grid produces 58% of its electricity with the help of natural gasses. Since all other sources of electricity are far less significant, we can assume 100% of the electricity consumed by electrical buses is generated from these natural gasses.*

Assumption #3: Electric vehicles (cars) and electric buses produce the same amount of carbon emissions per ton. *Justification: Both electric cars and electric buses are made of very similar materials such as steel, glass, wiring, and insulation. The main difference between a bus versus a car is the size.*

Assumption #4: All electric buses will be charged using only Level 3 plug-in charging systems. *Justification: Boston is constantly working towards energy efficiency, and level 3 plug-in chargers are the chargers that require the least amount of energy to function.*

2. Ecological Consequences

Ecological Consequences and Benefits of Adopting a Full-Electric Public Bus Fleet

When considering the ecological consequences and benefits of adopting a full-electric public bus fleet, consequences center around societal, natural, and tropospheric conditional changes. The following are categorized components of determining the ecological impacts of e-bus manufacturing and usage in an urban landscape.

2.1 Societal Noise Impacts

With an impact on societal conditions, a central component of urban ecology, societal noise levels produced by road traffic have been linked to increased risk of coronary heart diseases and contribute to both short-term and long-term human health issues. Anthropogenic (human-created) sounds contribute to a soundscape heavily valued in urban communities. However, the World Health Organization has identified traffic noise as a critical issue that can indirectly lead to conditional trauma, such as stress, and directly disturb the quality and quantity of sleep in urban communities that face deficits in sound pollution-filtering residential infrastructure. The World Health Organization recommends that safe noise levels in urban ecological settings not exceed 53 dB during the day and 45 dB at night. Generally, battery electric buses (BEBs) produce lower noise levels than internal combustion engine (ICE)-powered public buses. The presented component of the greater ecological consequences model introduces a quantitative analysis of the general increased risk of cardiovascular disease among individuals of any given population. The risk of cardiovascular disease has been proven to macroscopically impact society by increasing risk by 8% per 10dB increase above the weighted day-night recommended noise level (Babisch 2014). A conventional BEB produces 71.5 dB at 40 km/h, or approximately 25 mph, while an ICE bus produces 75.4 dB at the same speed and in the same testable setting (Misanovic et al., 2022).

The following model utilizes these measures under the assumption that standard bus speeds in urban areas are at a speed of 25 mph. This model does not consider stationary movement or movement at speeds other than 30km/h and 40 km/h.

- D_{speed} = *Decibel level at speed*: inputted variable accounts for sound pressure decibel levels of the bus at a standard speed.
- D_d = *Recommended decibel level during the day:* This is the recommended day decibel level according to the World Health Organization.
- D_n = *Recommended decibel level during the night:* This is the recommended night decibel level according to the World Health Organization.
- m_d = *Decibel rate of risk:* this component considers the rate at which increased risk occurs. This is the “per” in decibel level increase above the recommended amount. This value is 10 dB.

- m_{risk} = *Risk rate:* this is the percentage increase in risk by the decibel rate of risk. This value is an 8% increase per 10dB increase.
- r_{overall} = *overall risk of cardiovascular disease:* this the desired value used to quantify the societal risk of cardiovascular disease.

Equation 1: Overall Risk of Cardiovascular Disease

$$((((D_{speed} - D_n) / m_d) \times m_{risk}) + (((D_{speed} - D_n) / m_d) \times m_{risk})) / 2 = r_{overall}$$

$r_{overall}$ provides the overall risk of cardiovascular disease in a societal ecological setting for a specific bus type. The formula above would be conducted for both ICE and BEB buses, the difference describing the increased/decreased risk of cardiovascular disease when adopting ICE buses. This value can aid cities in better understanding how adopting a full-electric fleet of buses can decrease their risk of societal health issues, most significantly, cardiovascular disease.

2.2 Local Pollutants

The effect of local pollutants on urban ecologies centers around human, natural, and tropospheric conditional changes. To best quantify the comparative differences present in adopting fuel and engine-varying urban bus fleets, the presented component of a greater urban ecological impact study identifies engine and fuel-specific emission rates for significant air pollutants, including PM2.5 (particulate matter no larger than 2.5 microns in diameter) and NOx (nitrous oxides).

With emission rate data by mileage, a variable that is city and state-specific, the national average for urban, public bus transportation mileage, as well as city-specific active public bus quantities, can be used to determine the annual pollutant emissions caused by various bus types.

- P_{life} = *Life cycle of pollutant emissions:* A measure of the life cycle of pollutant emissions per mile in a vehicle. This considers production and active use emissions of the given pollutant.
- M_{annual} = *Average annual mileage:* the average annual mileage of the given vehicle. This value could be replaced with the national estimate gathered from the Alternative Fuels Data Center from the U.S. Department of Energy.
- B_{active} = *# of active buses:* the active number of buses in the given urban location.
- E_{annual} = *total annual emissions:* the total pollutant emissions (g) produced by buses in the given urban location.

Equation 2: Aggregated Annual Pollutant Emissions

$$E_{annual} = P_{life} \times M_{annual} \times B_{active}$$

Equation 2 can be used to calculate the total mass of pollutants produced by a vehicle. P_{life} is the mass in grams of pollutants produced per mile of urban buses. This value is based on state-specific data, results differing among states due to varieties in energy sources as well as estimated tailpipe and upstream emission and leakage levels. Due to the specificity of this value, four “extremes” including diesel and electric with 100% natural gas, landfill gas, and renewable energy sources, are being used to demonstrate the benefits and deficits of various bus systems and their respective fuel sources. Through the use of this component, cities can be aided in better understanding the quantity of pollutants being emitted by current and possible bus system configurations. If state or city-specific measures of pollutant emission rates are publicly available, results may be enhanced.

Specific pollutants used in our model include $PM_{2.5}$ (particulate matter smaller than 2.5 microns in diameter) and NO_X (nitrous oxides), which have been proven to significantly impact human health as well as natural and tropospheric conditions. $PM_{2.5}$ is the largest environmental health risk factor in the United States, being responsible for 63% of deaths from environmental causes, according to the Union of Concerned Scientists. Among the deaths and health issues caused by this deadly air pollutant, historically neglected communities of color have faced an inequitable exposure to transportation pollution. Historical redlining practices have deprived communities of color of resources essential for protection from the negative impacts of rapid urbanization and anthropogenic climate change. Through the use of electric public bus transportation with the use of renewable or sustainable forms of energy supplying electricity, traffic-induced air pollution can be decreased, and the negative health effects of particulate matter and toxic gasses can be reduced among the greater population primarily among people of color living in urban communities.

In addition to human health impacts such as premature death, nonfatal heart attacks, irregular heartbeats, aggravated asthma, decreased lung function, and difficulty breathing, $PM_{2.5}$ changes tropospheric and natural conditions. Fine particles can contribute to the haze effect and deficiencies in visibility, adjustments in acidity and nutrient balance of soil and water sources, negative impacts on sensitive ecosystems and agriculture, as well as deteriorated materials and infrastructure (Environmental Protection Agency, 2023). Nitrous oxides are a family of poisonous, reactive gasses that similarly endanger human health through the risk of respiratory and cardiovascular illness as well as contribute to acid rain, lack of visibility, and nutrient pollution. Impacts of traffic-induced air pollutants range from changes in human, natural, and tropospheric conditions, and can be significantly improved if generally reduced, a factor visible using Equation 2 to find annual emission output by bus and fuel type.

2.3 Bus Production

On average, electric cars generate 8.26 tons of carbon dioxide emissions (CO2e) per car through the manufacturing process overall. Out of this, 7 tons are contributed by the production of just the battery alone, while the rest of the 1.26 tons comprise of all the other materials required to make an electric vehicle. These materials would include high-strength steel, composite materials, plastics and polymers, glass, electrical components, and thermal insulation.

Electric cars weigh: 0.9 tons (0.0225 tons battery + 0.8775 tons of the rest of the car components).
Distribution of carbon emissions: 7 CO2e/1 battery + 1.26 tons CO2e/0.8775 tons e-car materials.

Then, to determine the amount of tons CO2e for 1 ton of electric vehicle materials. (Assumption #3), both electric cars and electric buses use the same materials. So the next step is

$$\frac{x\,CO2e}{1\,material} = \frac{1.26\,CO2e}{0.8775\,material}$$

After solving this equation, $x = 1.44$ tons CO2e, and therefore, 1.44 tons of CO2e is released per ton of electrical vehicle material used for manufacturing.

The next step is to apply this ratio to electric buses to determine how much carbon is emitted through the production of 1 bus. The battery of 1 electric bus produces 8.8 tons of carbon emissions (B, 2023). This would have to be added to the CO2e of the electric bus materials to generate the total amount of CO2e each electric bus releases during their manufacturing.

Electric buses weigh: 18 tons (0.55 tons battery + 17.45 tons electric bus materials)
The amount of carbon that the electric bus materials emits:

$$\frac{1.44\, CO2e}{1\, material} = \frac{x\, CO2e}{17.45\, material}$$

After solving this equation, x = 25.128 tons CO2e, and therefore, 25.128 tons of CO2e is released per 17.45 tons, or one bus worth, of electrical bus material used for manufacturing.

The next step is to apply this ratio to electric buses to determine how much carbon is emitted through the production of 1 bus. The battery of 1 electric bus produces 8.8 tons of carbon emissions.

$$25.128\, COe\ +\ 8.8\, COe\ =\ 33.928\, COe$$

Therefore, 33.928 tons of COe will be produced during manufacturing on electrical buses. This value can further be applied in an equation to calculate the total number of carbon emissions produced due to manufacturing all electrical buses in a given location.

- B_{total} = *# of buses:* The total number of electrical buses used in the given location.
- C_{total} = tons of carbon emission produced by manufacturing all electric buses in the given location

Equation 3: Overall Carbon Emissions Due to Manufacturing

$$B_{total} \times 33.928 = C_{total}$$

While converting to electric buses greatly reduces CO2 emissions, it's important to consider the ecological consequences of the production of them. During the driving life of an electrical bus, it does not emit any tail-pipe carbon emissions. However, the manufacturing of each bus releases a substantial amount of CO2e that must be considered when switching over to a completely electric bus transit system.

2.4 Battery Disposal

Electric bus batteries function optimally for 8-10 years, while the average useful life of a bus in the United States is 12 years. As a result, oftentimes, the batteries of buses are disposed of and replaced with new ones. When these old batteries are disposed of, a small but still significant amount of greenhouse gasses are produced. One idea proposed to prevent the greenhouse gasses emitted by the disposal of batteries is recycling and repurposing these batteries. In particular, a study observed the recycling of LFP, a battery type often found in e-buses. After the study was conducted, it was observed that additional emissions were unavoidable for recycled LFP batteries, and therefore, it is more sustainable to completely dispose of an old battery and use a new one. Since disposal is the most sustainable option for buses at the moment, we will base our environmental impact of batteries on the idea that when a battery becomes unusable, it will be completely disposed of and not recycled.

When batteries are disposed of in landfills, this results in hazardous compounds and toxic chemicals leaking into the soil. Using the metrics of a standard LFP battery and its chemical composition, the number of chemicals potentially leaking into the ground per battery can be calculated.

Weight of LFP electrical bus battery: 230Kg
Chemical composition of LFP battery:

Chemical Composition	Weight (%) of battery weight	Weight (kg) of chemical seeping
Ferrous Phosphate Litium	38.09	87.607
Carbon Black	0.62	1.426
Rubber, styrene-butadiene, fume	0.34	0.782
Polyvinylidene fluoride resin	1.04	2.392
Graphite	20.10	46.23
Phosphate (1-), hexafluoro-, lithium	1.10	2.53
Copper	9.22	21.206
Aluminum	4.00	9.2

Using the first two columns of this chart, the weight in kilograms of each chemical compound that can potentially seep into the ground when a battery is disposed of is calculated and placed in the third column.

With the third column values, an equation can be created calculating the total number of grams of each chemical compound potentially seeping into the soil after all batteries of electrical buses are disposed of in a given location.

- B_{total} = *# of buses:* The total number of electrical buses used in the given location.
- F_{total} = *kilograms of Ferrous Phosphate Litium:* the total kilograms of Ferrous Phosphate Litium produced by disposing all batteries of electric buses in the given location
- C_{total} = *kilograms of Carbon Black:* kilograms of Carbon Black produced by disposing all batteries of electric buses in the given location
- R_{total} = *kilograms of Rubber, styrene-butadiene:* kilograms of Rubber, styrene-butadiene, fume produced by disposing all batteries of electric buses in the given location
- P_{total} = *kilograms of Polyvinylidene fluoride resin:* kilograms of Polyvinylidene fluoride resin produced by disposing all batteries of electric buses in the given location
- G_{total} = *kilograms of Graphite:* kilograms of Graphite produced by disposing all batteries of electric buses in the given location
- PO_{total} = *kilograms of Phosphate (1-), hexafluoro-, lithium:* kilograms of Phosphate (1-), hexafluoro-, lithium produced by disposing all batteries of electric buses in the given location
- CU_{total} = *kilograms of Copper:* kilograms of Copper produced by disposing all batteries of electric buses in the given location
- A_{total} = *kilograms of Aluminum:* kilograms of Aluminum produced by disposing all batteries of electric buses in the given location

Equation Set #4: The Amount of Chemicals Leaking into the Soil Due To Battery Disposal

$$F_{total} = B_{total} \times 87.607\ kg$$

$$C_{total} = B_{total} \times 1.426\ kg$$
$$R_{total} = B_{total} \times 0.782\ kg$$
$$P_{total} = B_{total} \times 2.392\ kg$$
$$G_{total} = B_{total} \times 46.23\ kg$$
$$PO_{total} = B_{total} \times 2.53\ kg$$
$$CU_{total} = B_{total} \times 21.206\ kg$$
$$A_{total} = B_{total} \times 9.2\ kg$$

LFP batteries are extremely eco-friendly when compared to other battery types, because they don't contain heavy metals such as cobalt and nickel. However, they still contain some hazardous chemical compounds (as noted above) that should be taken into consideration. Furthermore, large amounts of most of these chemical compounds cause detrimental human health issues. Exposure to carbon black particles is related to irritation in the lungs and lung disease. Butadiene has been linked to irritation of eyes, nasal passages, throat, and lungs, and this chemical is also linked to cardiovascular disease. The consumption of Fluorosis is related to the forming of kidney stones, decreased birth rates, and impaired intelligence. Graphite inhalation can affect the lungs and cause graphite pneumoconiosis. High levels of phosphate cause algae blooms that produce algal toxins harmful to a human kidney and liver. Toxic concentrations of copper can cause abdominal pain and nausea. Excessive amounts of aluminum can lead to diseases in the bones, kidneys and brain.

2.5 Energy Efficiency

In this section of the model, a transit plan was created in order to maximize energy usage for the given metropolitan city. In order to maximize energy usage, the lowest energy consuming chargers for electrical buses, plug-in level 3 chargers, were the only chargers used (Assumption #4). To charge a battery electric bus with a level 3 plug-in charger system, 537 kWh is needed (the average was taken from 40-125 kW required for charging, and 250-660 kWh required for supplying energy to the battery) and each charge takes 5 hours. Taking this into consideration, a schedule needed to be created in order to make sure all buses would be charged only when they needed to, so no electrical energy would be wasted. To create a schedule multiple variables and values had to be calculated:

First off, the number of miles an electric bus would travel a day and how many miles a full tank would give a bus in order to determine how often a bus needed to be charged:

Average annual mileage of battery electric bus = 43,647 miles.
Number of miles able to be driven on a full tank = 275 miles.

Average mileage per day = 43647 / 365 = 119 miles
By dividing by the number of days, it was calculated that each transit bus would travel 119 miles each day.

Number of days bus could last ≈ 275/119
By dividing the number of miles given in a full tank by the number of miles driven everyday, it was calculated that each transit bus can drive for 2 days straight before needing to charge.

Taking the values above into consideration, a wave schedule in increments of five hours, since one charge takes five hours, was seen as the most optimal design to maximize energy efficiency. In particular, if an electrical bus stays in a charging port after it is completely charged a phenomenon called vampire draining will occur. In vampire draining, the battery will stop charging once it reaches its max. However, due to this, after a period of time it will lose small amounts of charge, and the charger will subsequently restart to bring the charge back to a full tank. While this may only waste small amounts of energy at a time, in the long-term and across all buses in a metropolitan city, this energy waste will add up. With a wave schedule in increments of five hours, buses are forced to leave after the five hour mark and vampire draining will not occur. In addition to this, a wave schedule will prevent time lost in which the transit buses are idle rather than on the road. With 5 hour increments, the buses will be on the road at all times unless they are charging. This maximizes the transit system quality and allows for low wait times in routes and increases passenger capacity to its optimal amount.

Given the buses ability to drive for 48 hours, the increments of 5 hour charging blocks need to fit into that comfortably. There are 9 waves of fleets that can fit into 5 hour blocks during a 48 hour (the max amount of time a bus can travel) increment. With 9 fleets, and 5 hours of charging for each one, a 45 hour cycle can be created. However, there are sometimes postponements, and this 45 hour cycle would leave no room for delays. This is why the schedule is built into a 50 hour cycle in order to leave time for mishaps.

Bus Transit Schedule

C = charging || W = working

Fleet #	Wave 1	Wave 2	Wave 3	Wave 4	Wave 5	Wave 6	Wave 7	Wave 8	Wave 9
0 - 5 hours	C	W	W	W	W	W	W	W	W
5 - 10 hours	W	C	W	W	W	W	W	W	W
10 - 15 hours	W	W	C	W	W	W	W	W	W
15 - 20 hours	W	W	W	C	W	W	W	W	W
20 - 25 hours	W	W	W	W	C	W	W	W	W
25 - 30 hours	W	W	W	W	W	C	W	W	W
30 - 35 hours	W	W	W	W	W	W	C	W	W
35 - 40 hours	W	W	W	W	W	W	W	C	W
40 - 45 hours	W	W	W	W	W	W	W	W	C
45 - 50 hours	W	W	W	W	W	W	W	W	W

Now that a schedule has been created, it can be utilized to understand how much carbon emissions are given off by the electrical buses when this system is in operation through a series of equations:

- B_{total} = *# of buses:* The total number of electrical buses used in the given location.
- B_{wave} = *# of buses per wave:* The total number of buses per wave.

- C_{fleet} = *amount charged per fleet:* The total amount of kWh used per fleet.
- C_{all} = *amount charged in total:* The total amount of kWh for all buses in the system.
- E = *amount of carbon emissions produced:* The total amount of carbon emissions produced in the system.
- Ch = *number of chargers:* The number of chargers that are needed to be implemented in the system.

Equation set #5: Total Number of Carbon Emissions generated from Charging/General Use

$$B_{total} / 9 = B_{wave}$$
$$B_{wave} \times 537 = C_{fleet}$$
$$C_{fleet} \times 9 = C_{all}$$
$$C_{all} \times 0.233 = E$$

OR

$$B_{total} \times 537 \times 0.233 = E$$

For financial model:

$$Ch = B_{wave} + 5$$

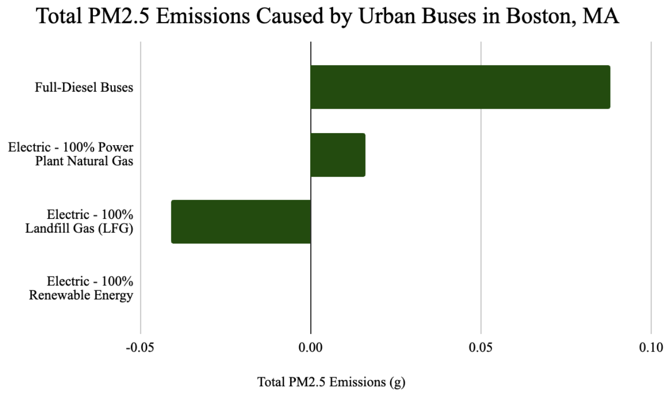
*While the first version of this algorithm may look complex and repetitive, all of the variables are needed. The variables that are not a vital part of this algorithm (the variables that are not part of the second algorithm) are extremely vital for the financial model in which we calculate the number of chargers that are implemented in the city as explained in the third algorithm.

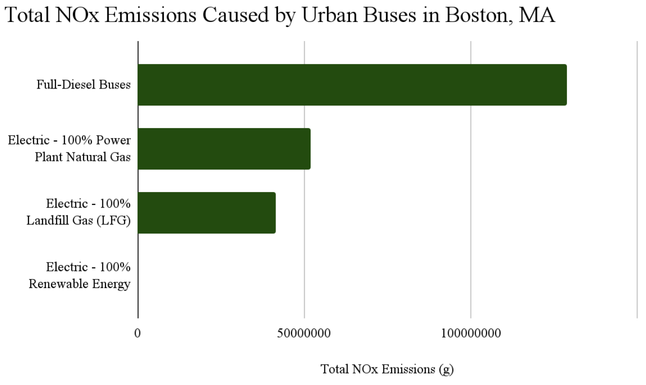
2.5 Applications in Boston, Massachusetts

- Societal Noise

Performing this component's formula with a focus on Boston, Massachusetts, at a speed of 25 mph in urban areas, shows **a 3.12% decreased risk of societal cardiovascular disease when adopting battery cell electric buses in Boston, MA, when compared to conventional internal combustion engine buses.**

- Local Pollutants


Total PM2.5 Emissions Caused by Urban Buses in Boston, MA


Total NOx Emissions Caused by Urban Buses in Boston, MA

$PM_{2.5}$ and NO_X emissions are significantly reduced when using electric energy sources in Boston, MA. Negative $PM_{2.5}$ emissions when using 100% landfill gas can be justified by considering that waste and biofuels can be utilized to reduce potential emissions. However, landfill gas produces significant amounts of NO_X emissions, therefore justifying our decision to apply renewable energy buses when possible.

- Bus Production

  In order to calculate the number of tons of carbon emission that the production of electrical buses would contribute to the city of Boston, the following equation needs to be applied:

  $$B_{total} \times 33.928 = C_{total}$$

  33.928 = CO2e for the production of 1 electric bus

  $$1055 \times 33.928 = 35794.04$$

  The city of Boston generates 35794.04 tons CO2e for the production of its buses.

- Battery Disposal

  Ferrous Phosphate Litium: $F_{total} = B_{total} \times 87.607\ kg$
  $\mathbf{92425.385\ kg} = 1055 \times 87.607\ kg$

  Carbon Black: $C_{total} = B_{total} \times 1.426\ kg$
  $\mathbf{1504.43\ kg} = 1055 \times 1.426\ kg$

  Rubber, styrene-butadiene: $R_{total} = B_{total} \times 0.782\ kg$
  $\mathbf{825.01\ kg} = 1055 \times 0.782\ kg$

  Polyvinylidene fluoride resin: $P_{total} = B_{total} \times 2.392\ kg$
  $\mathbf{2523.56\ kg} = 1055 \times 2.392\ kg$

  Graphite: $G_{total} = B_{total} \times 46.23\ kg$
  $\mathbf{48772.65\ kg} = 1055 \times 46.23\ kg$

  Phosphate (1-), hexafluoro-, lithium: $PO_{total} = B_{total} \times 2.53\ kg$
  $\mathbf{2669.15\ kg} = 1055 \times 2.53\ kg$

  Copper: $CU_{total} = B_{total} \times 21.206\ kg$
  $\mathbf{22372.33\ kg} = 1055 \times 21.206\ kg$

  Aluminum: $A_{total} = B_{total} \times 9.2\ kg$
  $\mathbf{9706\ kg} = 1055 \times 9.2\ kg$

- Electrical Efficiency

  There are 1055 transit buses in the city of Boston (NETransit), since the goal is to adapt the city to electric buses, there will also be 1055 electric buses in this model. Using these values, the algorithms explained in the general model can be applied:

$$1055 / 9 = 117$$
$$117 \times 537 = 62829$$
$$62829 \times 9 = 565{,}461$$
$$565{,}461 \times 0.233 = 132{,}002{,}66\ COe$$

For financial model:

$$Ch = 117 + 5 = 122 \text{ chargers}$$

**Used in the Boston financial model*

3. Money Matters: Financial Implications

3.1 Financial Model

Constants

- *Price Per Bus: $887,308.00*
- *Price of bus maintenance per mile: $0.64*
- *(U.S.A.-Specific) National average of singular urban transit bus mileage: 43647 miles*
- *Price of electricity per kilowatt hour: $0.1275*
- *Energy consumption per bus: 537 kWh*
- *Price of one charger: $40,000.00*
- *Price of charger installation per charger: $10,000.00*
- *Price of charger maintenance per year: $750.00*

Variables:

- Q_B = quantity of buses
- Q_C = quantity of chargers
- C_I = charging interval
- $R_{C,B} = Q_C / Q_B$ (ratio)
- T_I = (hours in a year / C_I) = total charging intervals

***Equation 4: Initial Year Total Bus Cost**:*

$$2P_T = 887{,}308+(0.64 \times 43647)+(0.1275 \times T_I \times 537)+(40{,}000 \times R_{B,C})+(10{,}000 \times R_{B,C})+(750 \times (R_{C,B}))$$

Equation 4 introduces the proposed system for calculating the cost of purchasing, employing, and maintaining an electric bus. This model relies upon several variables that are dependent on the location, such as the number of buses needed to fulfill the needs of the urban setting, as well as scheduled charging intervals under the assumption that buses charge every 50 hours, with one fleet charging at any given time. The equation is doubled to account for a 50% investment quantity from external groups, such as federal programs and private company programs. Constant values have been acquired through a technical report pursued by the National Renewable Energy Laboratory, which evaluates the financial costs of purchasing BEBs with a consideration of charging, maintenance, and energy-specific charge costs (Johnson et al., 2020). Through the use of this financial model, cities can better understand the efficacy of electric bus purchases and better plan the acquisition/replacement of BEBs over their desired period of time. In section 4, the use of this financial model is adjusted to account for a constant, gradual transition over 10 years in which diesel transit buses are replaced with promising battery electric bus fleets.

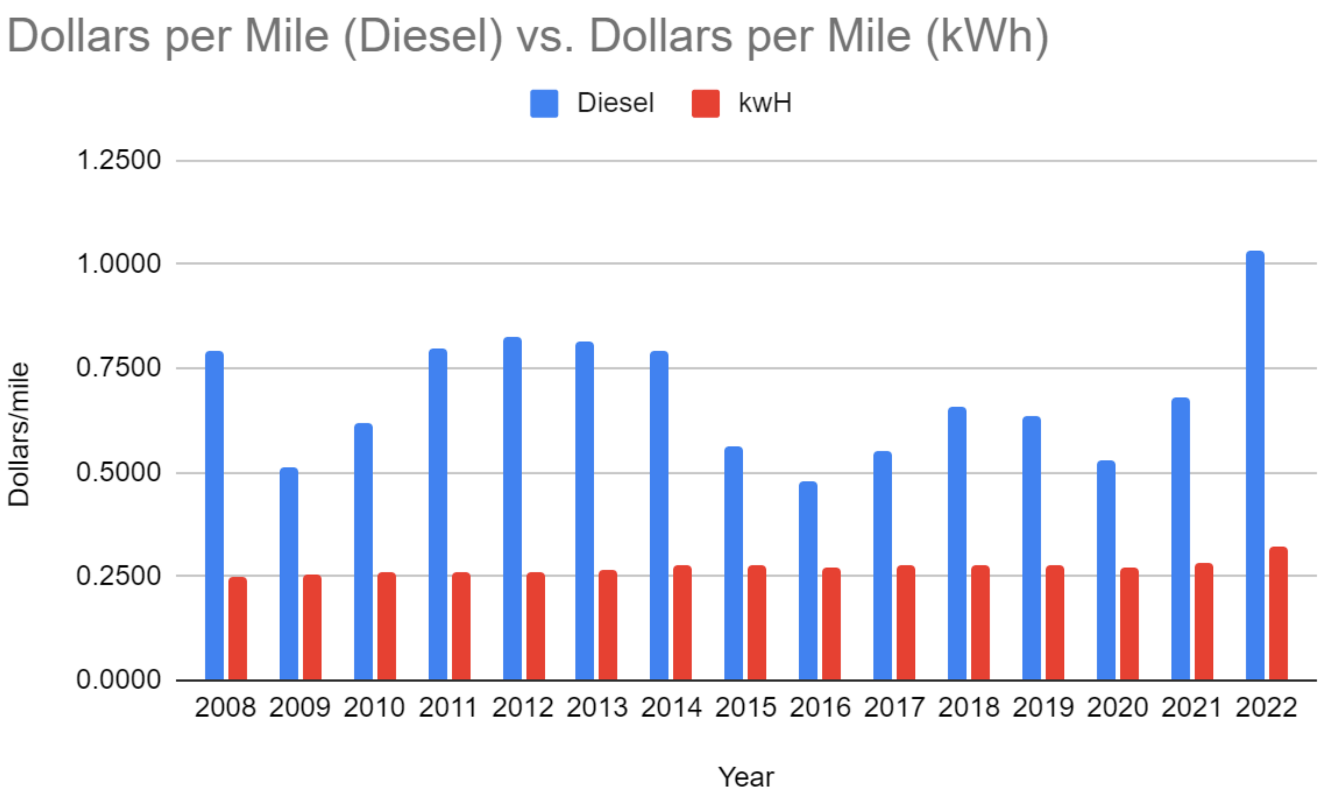
To tackle the financial model we began by identifying the cost of the variables listed under the part section. We proceeded to use that information to find the cost for one bus in a year. The table below expresses the financial model with Boston, Massachusetts-specific variables. A generalized model can be found in Equation 4.

Part	**Cost ($)**	**Quantity**	**Price (per bus per year: cost*quantity)**
Bus	887,308 per bus	1	887,308
BEB Maintenance	$0.64/mi	43647 miles/year	27,934.08
Electricity	$0.1275/ kWh	537 * (8760 hours/50 hours)= 94082.4 Note: To find the amount of times a bus is charged, we took the total amount of hours in a year divided it by the hours between every bus charge (50 hours).	11995.51
Price of charger	40,000	$\frac{122\ chargers}{1055\ buses}$ = 0.11563981042	4625.59
Charger installation	10,000	0.11563981042	1156.40
Charger maintenance	750	0.11563981042	86.73
External Funding (50%)			-466553.16
TOTAL COSTS:			**$466553.15**/bus per initial yr in Boston, MA.

Financial Results for Boston, MA:

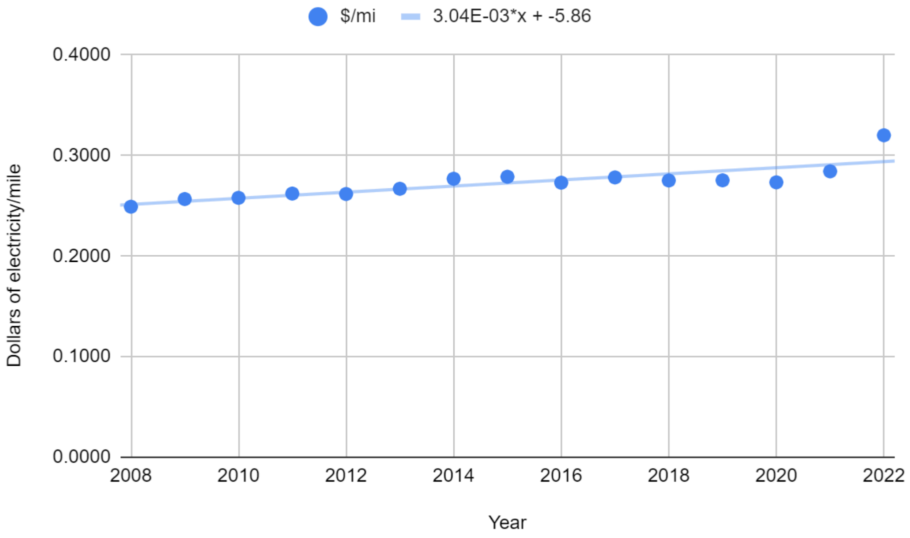
$466553.15/bus per initial year in Boston, MA.

3.2 Price Comparison



The graph above displays the cost of traveling one mile on a diesel bus versus on an electric bus. The national average of the price per gallon of diesel and the price per kWh of energy was used to calculate these numbers. From the years of 2008 to 2022, electricity costs significantly less in comparison to diesel. Proving it more cost-efficient over time.

3.3 Increase in Electricity



The graph displayed above showcases the increase in electricity prices over time. The U.S Energy Information Administration's data on the national average price per kWh was utilized to form this graph. The line of best fit showcases that the cost of electricity to travel one mile increases by $0.00304 each year.

This was not incorporated into the financial model as the time period used in the model, and the price delta were minute and therefore negligible.

4. *Zero*: 10-Year Roadmap

As stated in the problem, transportation officials have decided to pursue a 10-year gradual transition to electric urban bus transport. Therefore, the purchases of e-buses will be spread out over a span of 10 years.

Zero: Reaching Zero-Emission Public Bus Transit by 2033

Zero, an initiative taken to reach completely zero-emission public bus transport by 2033, introduces a gradual purchasing model in which transportation officials incrementally purchase e-buses every year to fully and efficiently replace ICE urban bus transport. The process is split into ten year-specific actions and their respective costs, considering initial purchasing price and maintenance and operation costs

4.1 General Model

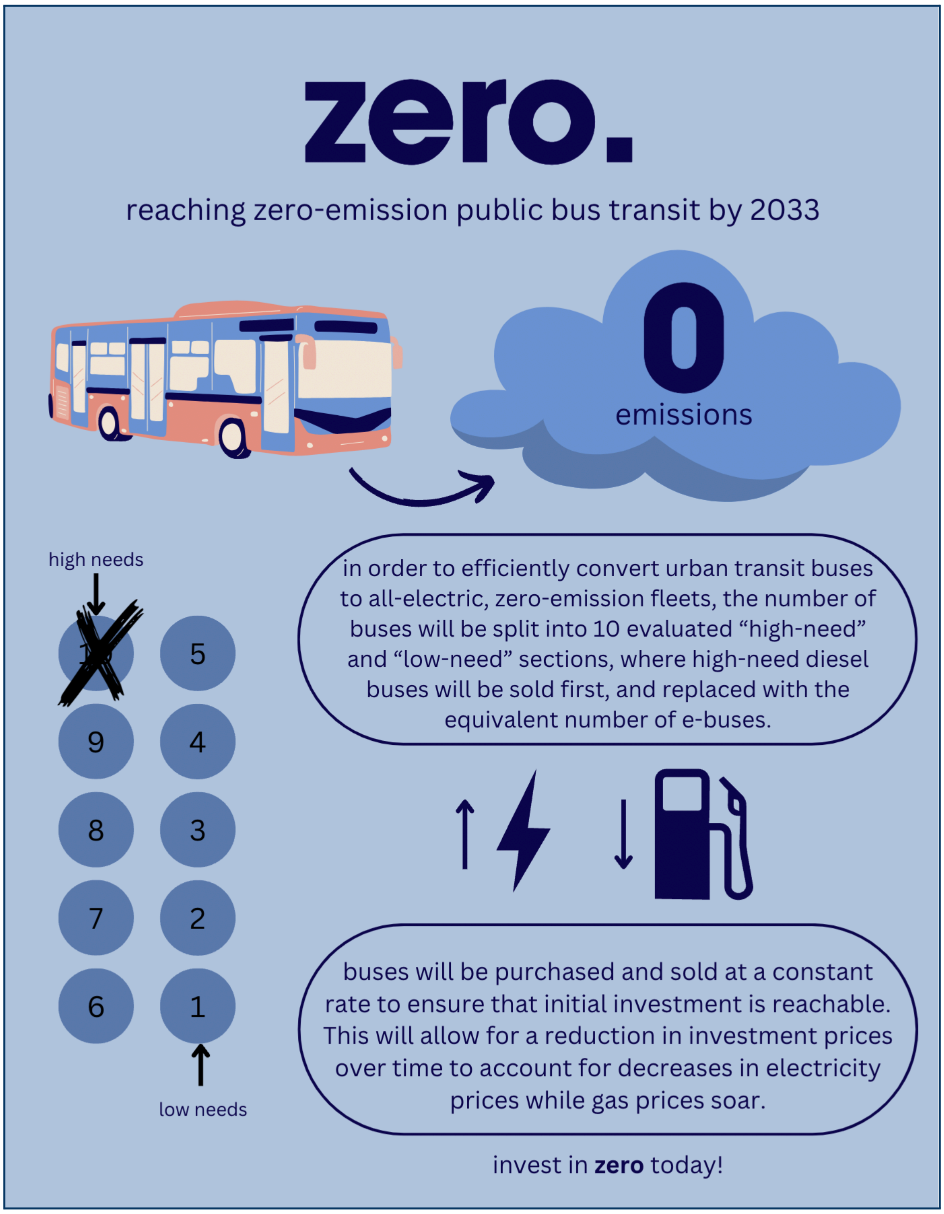
Variables:

- Q_B = *quantity of buses*
- P_B = *price per bus per year*
- P_R = *annual purchase rate* $(Q_B/10)$ *rounded*
  - *The purchase rate is the number of buses divided by 10. If the quantity of buses is not divisible by 10, the purchase rate will be rounded up, and during the last year (2033)* Q_B *modulo 10 would be subtracted from the annual purchase rate.*

Year	**Action: Replace diesel buses with e-buses**	**Cost**
2023-2032	$Q_B/10$	$P_R \times P_B - P_R \times 2500$
2033	$(Q_B/10) - (Q_B \bmod 10)$	$(Q_B/10 - Q_B \bmod 10) \times P_B - (Q_B/10 - Q_B \bmod 10) \times 2500$

We identified the buses needed to be purchased each year by taking the total number of buses required and dividing it by 10. However, as buses are replaced, each diesel/gas bus is auctioned off for ~$2500, which was incorporated into the cost equation.

4.2 Infographic



zero.

reaching zero-emission public bus transit by 2033

0 emissions

in order to efficiently convert urban transit buses to all-electric, zero-emission fleets, the number of buses will be split into 10 evaluated "high-need" and "low-need" sections, where high-need diesel buses will be sold first, and replaced with the equivalent number of e-buses.

buses will be purchased and sold at a constant rate to ensure that initial investment is reachable. This will allow for a reduction in investment prices over time to account for decreases in electricity prices while gas prices soar.

invest in **zero** today!

An infographic to educate communities about *Zero*, a zero-emission public transport bus initiative.

5. Model Applications

5.1 Boston, Massachusetts

- The Ecological Consequences model has been approached in section 2.5.
- Financial Model: Extended work can be seen in section 3.1
    - **\$466553.15/bus per initial yr in Boston, MA**
- 10-Year Roadmap:

Variables:

- $Q_B = 1055$
- P_B = \$466553.15
- P_R = *annual purchase rate* ($Q_B/10$) *rounded*
    - *The purchase rate is the number of buses divided by 10. If the quantity of buses is not divisible by 10, the purchase rate will be rounded up, and during the last year (2033)* Q_B *modulo 10 would be subtracted from the annual purchase rate.*

Year	Action: Replace diesel buses with e-buses	Cost
2023-2032	*Constant investment of $49,189,633.90 for the first nine years.*	*106* × $466553.15 - *106 × 2500 = $49,189,633.90 * 9 =*
2033	*Final year investment is less*	*101* × $466553.15 - *101* × 2500 = *$46,869,368.15*

- ***Total investment over the next ten years is $96,059,020.05 in Boston, Massachusetts.***

5.2 Fresno, California

First, the price of the bus in its initial year must be found to properly create a price estimate for the standard 10-year *Zero* transition plan.

Part	**Cost ($)**	**Quantity**	**Price (per bus per year: cost*quantity)**
Bus	887,308 per bus	1	887,308
BEB Maintenance	$0.64/mi	43647 miles/year	27,934.08
Electricity	$0.1275/ kWh	537*(8760hours /50hours)= 94082.4	11995.51
Price of charger	40,000	$\frac{15\ chargers}{126\ buses}$ = 0.11904761904	4761.90
Charger installation	10,000	0.11904761904	1190.48
Charger maintenance	750	0.11904761904	89.29
External Funding (50%)			-466639.63
TOTAL COSTS:			**$466639.63**/bus per initial yr in Fresno, CA.

Variables:

- $Q_B = 126$
- $P_B = \$466639.63$

Year	Action: Replace diesel buses with e-buses	Cost
2023-2032	*Constant investment of $6033815.19 for the first nine years.*	*13 × 466639.63 - 13 × 2500 =* ***$6,033,815.19 cost of initial year***

2033	*Final year investment is less.*	*7* × $466639.63 - *7* × 2500 = ***$3,248,977.41 cost of final year***

- ***Total investment over the next ten years is $9,282,792.60 in Fresno, California.***

5.3: Denver, Colorado

The price of the bus in its initial year will be found to properly create a price estimate for the standard 10-year Zero transition plan:

Part	**Cost ($)**	**Quantity**	**Price (per bus per year: cost*quantity)**
Bus	887,308 per bus	1	887,308
BEB Maintenance	$0.64/mi	43647 miles/year	27,934.08
Electricity	$0.1275/ kWh	537*(8760hours /50hours)= 94082.4	11995.51
Price of charger	40,000	$\frac{117\ chargers}{1028\ buses}$ = 0.11381322957	4552.53
Charger installation	10,000	0.11381322957	1138.13
Charger maintenance	750	0.11381322957	83.36
External Funding (50%)			-$466505.80
TOTAL COSTS:			$466505.8 /bus per initial yr in Denver, CO

Variables:

- $Q_B = 1028$
- $P_B = \$466505.80$

Year	**Action: Replace diesel buses with e-buses**	**Cost**
2023-2032	*Constant investment of $47,792,597.40 for the first nine years.*	*103 × $466505.80 - 103 × 2500 =* ***$47,792,597.40***
2033	*Final year investment is less.*	*101* × $466505.*80* - *101* × 2500 = ***$46,864,585.80***

- ***Total investment over the next ten years is $46,864,585.80 in Denver, Colorado.***

6. A Letter to the MBTA

Greetings Massachusetts Bay Transportation Authority,

Transportation reformation is essential in aiding environmental and social climates that face demanding anthropogenic changes. From harmful pollutant emissions to increasing health risks, transportation is the largest contributor to climate-induced health and environmental issues. It is crucial that transportation authorities, such as the MBTA, alter their actions and invest in green, sustainable infrastructure to reduce their negative effect on the urban ecology. Boston, Massachusetts is home to over 650,000 community members: mothers, fathers, teachers, engineers, doctors, but most importantly, people. As diverse communities of color face the effects of transportation pollution and climate-related impacts at a greater level, solutions must be introduced to reduce the inequities in current climate effects.

In this letter, the mathematically-supported benefits of adopting completely electric, renewable energy-powered urban transit buses are introduced, with an inclusion of initial cost estimates and a 10-year implementation roadmap according to our *Zero* initiative.

To begin, adopting electric buses has several ecological consequences. Within the fabric of an urban ecology, transportation-induced societal, natural, and tropospheric conditional changes can occur. We predict that relative to diesel-induced rates, societal risk of cardiovascular disease will decrease by 3.12%. By adopting battery electric buses, Boston, Massachusetts could reduce its net societal risk of cardiovascular disease, and save lives through the reduction of noise-related health issues. Electric buses generally produce lower sounds when compared with diesel buses at city-level speeds, and could significantly reduce health issues while retaining the highly-valued urban soundscape that makes Boston unique. In addition, adopting electric-powered buses significantly reduces the emission of local pollutants such as particulate matter smaller than 2.5 microns in diameter ($PM_{2.5}$) and nitrous oxides (NO_x), producing no tailpipe or upstream emissions when powered by sustainable and renewable energy. $PM_{2.5}$ is the largest environmental health risk factor in the United States, being responsible for 63% of deaths from environmental causes. Both pollutants have severe health effects such as cardiovascular disease, premature death, lung and breathing issues, and more. Among those affected by sound pollution and high pollutant levels, people of color are at higher risk due to historical redlining practices in which communities were provided with fewer resources, which now impacts diverse urban communities who lack access to sufficient transportation-induced effect protection. In order to reduce the effect of transportation-induced air pollution on human health, the MBTA must reconsider its current methods of transportation and consider adopting electric buses in replacement of the highly inefficient and dangerous diesel-powered internal combustion buses. Despite its reduction in environmental and health-related impacts, battery disposal and bus production practices must be considered, evaluated, and reviewed to ensure that climate effects are reduced rather than enhanced by electric bus adoption.

By splitting the 1,055 currently active buses into groups of 10, rated by highest and lowest need, diesel buses can be effectively sold while equal amounts of electric buses are purchased. This initiative is called Zero, which aims to transform modern bus transit solutions by using 100% renewable energy battery electric bus fleets that produce no emissions by 2033. This 10-year base plan could offer the MBTA effective solutions to approaching high costs of approximately $49,454,633.90 each year by taking advantage of increasingly affordable energy prices.

The people of Boston deserve better approaches to transportation infrastructure. It is up to the MBTA to adopt effective solutions to the issues that plague under-resourced communities.

Thank you,
HiMCM Team 14610

7. Conclusion

7.1: Strengths vs Weaknesses

Strengths:

1. The ecological consequences section of this model takes into account a variety of variables such as charging time, mileage for each charge, and the amount of buses that are operating at any given time. The schedule incorporates the number of fleets that will allow for optimal operating times so that there are enough buses in the city while reducing the amount of energy wasted on excess charging.
2. A specific bus and charger was chosen in order to make the whole system more accurate rather than the average of a lot of different chargers and buses. In this way, a more in depth system could be created where each and every aspect was directly linked to the chosen bus model and charger model.
3. Our entire model took heavy consideration of finances and was optimized in numerous ways to reduce costs as much as possible. This included utilizing and creating a schedule around the cheapest charger available (which was also the most environmentally friendly).

Weaknesses:

1. The background research that was done for a lot of the generalized equations was based on American statistics, so this model would only apply to cities in the U.S. This causes a drawback because it confines the model to only work for cities that follow the background statistics which are standardized for America.
2. The statistics used were a combination of a lot of different units that all had to be converted in order to connect with each other. This leaves more room for error when dealing with different components of an equation that didn't originally correlate with each other.
3. In the financial model, the decrease in battery price over time, which is an 8% decrease, is not included. This did not affect the model too much because the battery price was a part of the bus price, so accounting for this would include separating the price of the battery from the price of the bus.

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9. Appendices

Appendix 1: Societal Noise Calculations for Boston, Massachusetts.

			Societal Noise Costs
risk of cardiovascular diseases		BEB Noise (dB) at approx. 25 mph	71.5
recc. day ≤ 53dB	recc. night ≤ 45 dB	dB over recommended during day	18.5
8% increase in societal risk of cardiovascular diseases per 10 dB increase.		dB over recommended during night	26.5
		amount of 10dB increases (day /10)	1.85
		amount of 10dB increases (night /10)	2.65
		% of increased cardiovascular disease risk (day)	14.8
		% of increased cardiovascular disease risk (night)	21.2
		% of overall risk of cardiovascular disease with BEBs	18
			Societal Noise Costs
		ICE Noise (dB) at approx. 25 mph	75.4
		dB over recommended during day	22.4
		dB over recommended during night	30.4
		amount of 10dB increases (day /10)	2.24
		amount of 10dB increases (night /10)	3.04
		% of increased cardiovascular disease risk (day)	17.92

		% of increased cardiovascular disease risk (night)	24.32
		% of overall risk of cardiovascular disease with ICEs	21.12

Appendix 2: Boston Local Pollutant Emission Calculations

	Total PM2.5 Emissions (PM g / mi)	Average Annual Mileage	Number of Buses	Total Annual PM2.5 Emissions (g)
Full-Diesel Buses	0.088	43647	1055	4052187
Electric - 100% Power Plant Natural Gas	0.016	43647	1055	736761
Electric - 100% Landfill Gas (LFG)	-0.041	43647	1055	-1887951
Electric - 100% Renewable Energy	0	43647	1055	0
	based on California	*national average*		

	Total NOx Emissions (NOx g / mi)	Average Annual Mileage	Number of Buses	Total Annual NOx Emissions (g)
Full-Diesel Buses	2.8	43647	1055	128933238
Electric - 100% Power Plant Natural Gas	1.13	43647	1055	52033771
Electric - 100% Landfill Gas (LFG)	0.9	43647	1055	41442827
Electric - 100% Renewable Energy	0	43647	1055	0
	based on California	*national average*		