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Summary Sheet

Charging Ahead with E-buses

Urban planning has been a difficult task for the past century. Satisfying contemporary concerns without compromising the flow of the city has been the primary obstacle in urban design. Recently, a growing urgency to develop renewable energy, and more significantly, apply it to regular living, has swept the conversation of urban planning throughout the world. One such example is the implementation of e-buses in a city's transportation system. We must analyze what the effects of a full fleet conversion to e-buses may look like in order to determine its viability as a long-term urban solution to these climate concerns, exemplified by our chosen cities of New York City, Beijing, and Tokyo.

The first and most direct implication of incorporating e-buses into a city's transportation network is its environmental effect. For this, we have to consider the decrease in private vehicle use, as well as the decrease in gaseous buses in the city. Modeled by a parabolic regression, we see the highs and lows of potential CO_2 emissions in the near future based on current trends, and by a restricted polynomial function, the predicted CO_2 emissions as a city's fleet of buses convert to electric. We generalize that a city's CO_2 emissions will be similar to global CO_2 emissions, and our model visually proves this behavior..

However, funding the gas to electric conversion will have a cost. We model this cost by using specific functions of a scenario (functions related directly to manually imputed variables) to capture the behavior of the economic effect of a full fleet conversion to e-buses. The cost, as represented by function outputs, will consider the total cost of this project, which can alter the viability of e-buses in different cities.

By comparing direct climate impact to cost, a relation function, we can produce 10 year plans for different cities (and thus varying inputs for both our climate and cost models) which concern the direct viability of a gas-to-electric bus fleet conversion for these cities. The cost for a full fleet conversion will be distributed over this 10-year period, and thus produce a very clear and precise conclusion about the economic requirements to implement such a project. We can better optimize this implementation by converting buses near the end of their lifetimes first.

Global impact from a full fleet conversion should produce the same behavior as local impact from a regional implementation of this transition. We achieve this result, and conclude that a global conversion of buses from gas to electric within the next 10 years will deviate negatively (that is, lower global warming) from current climate trends by 0.0005°C.

Keywords: Parabolic Regression, Restricted Polynomial Function, Relation Function, Full Fleet Conversion

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1 Introduction

1.1 Background

Starting from the Industrial Revolution in the mid-19th century, humans have had an increasing effect on climate. Greenhouse gas emissions from human sources have caused rapid global warming, especially prominent over the last half-century. One such result is the undeniable increase in global temperature since recorded human production of greenhouse gasses. Compared to 1950, our planet has warmed roughly 1.5°C [17]. Concerns have mounted over the past decade over the issue of global warming, and it has now found its way into recent urban plans. One of the most significant contemporary developments in slowing down global warming is the advent of electric vehicles. The conversation of incorporating electric vehicles into city transportation systems is growing more urgent, and plans for a gas to electric bus fleet conversion are currently underway.

We are asked to analyze the economic and climate effects of such implementation in a populous city, and determine its viability as a remedy to our global urban climate concerns. By further defining a possible 10-year plan to incorporate the e-bus fleet, we hope to turn an e-bus fleet conversion into an urban reality.

1.2 Problem Restatement

Question 1: Construct a model to aid cities in understanding the ecological consequences of transitioning to an all-electric bus fleet.
Identify a metropolitan area with a population of (at least) 500,000 people that does not currently have a fully electric bus fleet. Apply your model to your chosen location
Question 2: Money matters. Construct a model that focuses on the financial implications associated with a conversion to e-buses. Your model should factor in potential external funding covering up to 50% of the transition costs.
Apply your financial model to the same metropolitan area you used in the previous question.
Question 3: Transportation officials in metropolitan areas are exploring approaches in which they gradually change their fleet from combustion engine buses to electric ones. Assuming the goal is to have a fully electric fleet no later than 2033, utilize your previously developed models to craft a 10-year roadmap that urban transport authorities can leverage to plan their e-bus fleet updates.
Apply your models (or new model) to the same metropolitan area you used in the previous question and also apply it to two additional metropolitan areas of your choosing.
Question 4: Write a one-page letter to the transportation officials of one of your chosen metropolitan areas where you detail your recommendation for their transition to e-buses.

2 Problem Analysis

Question 1: In this first question, we are asked to construct a model of the ecological consequences during a transition from an all-gas bus fleet to an all-electric bus fleet. Practically, ecological effects can be simplified to greenhouse gas emissions, the direct cause of global warming and climate change. The two primary greenhouse gasses emitted by vehicles (powered by gas) are CO_2 and NO_x. However, in the past decade, NO_x levels have been steadily decreasing [20], and so, the effect of a NO_x decrease relative to current (that is, 2023) trends is insignificant. We will only analyze the effects of CO_2 to simplify our data and understanding of the effect of e-buses on the climate. There also exists an environmental effect of harvesting the materials needed to construct our fleet of electric buses – namely lithium. We must consider how impactful the process of producing lithium-ion batteries (from lithium mining) is on the environment, and consider this quantity when modeling the ecological impact of a gas-to-electric bus fleet transition. We are also asked to apply our model of CO_2 emissions to a metropolitan area, which we will choose as New York City; already high air pollution in the city gives us a more identifiable change in CO_2 emissions after applying our model.

Question 2: Question two asks for us to analyze the cost of implementing the gas-to-electric bus fleet conversion. An additional parameter – that up to 50% of our cost can be covered by external funding – is introduced. The first step in developing a solution is to find the function of cost without external funding. We must determine the general cost of a single bus conversion, extend it to the cost of the fleet, and then find the cost to run the fleet after the conversion compared to the cost to run the fleet on exclusively gas buses. Then, considering that the EPA offers around \$4 billion per year in grants, we expect a major urban project to consume around 5-25% of the \$4 billion in grants to satisfy the full 50% coverage [9]. We will use this to find the general cost of a full bus fleet conversion from gas to electric .

Question 3: Question three asks for us to develop a 10-year plan to complete the gas-to-electric conversion of a bus fleet, which, in our study, focuses on the New York City bus fleet. Knowing that the average lifespan of a gaseous bus is 12 years [1], we can optimally convert a gas bus to electric when it is about to be decommissioned. Our bus fleet data is reliant on records from 2021, which should produce the same 10-year result as 2023 because of minimal strides in the ecological developments in large metropolitan areas. Our ten year plan will simply build on our existing model of climate impact and cost, producing a consistent annual roadmap for costs and results during an implementation of a full bus fleet conversion.

Question 4: Question four asks us to write a proposal to a transportation official, which will incorporate the data we acquire from the previous questions. This is a formality, not too demanding on additional external information.

3 Methodology

Before our methodology, we selected three cities that we would focus on:

1. New York City: The largest city in the United States by population, and one that is also technologically developed, although somewhat lagging behind in public transportation.
2. Beijing: One of the largest cities in the world, and with a sizable bus population of over 20,000, Beijing was a prime candidate for seeing the implementation of our plan on a larger scale.
3. Tokyo: Also one of the largest cities in the world, Tokyo has a smaller bus population size but still affects a large amount of people.

Our methodology consists of two parts:

1. Overall climate impact: Using climate data, we modeled greenhouse gas and global warming growth rates over the past 60 years and measured the potential impact of our policies on the status quo. This included calculating the total amount of carbon dioxide reduction and temperature reduction based on that carbon dioxide reduction.
2. Overall cost: We created a model that, given variables such as cost per bus and external funding amounts, estimates the total cost of implementation of the plan. The plan also addresses immediate costs concerns and justifies calculating costs over the plan's timeline. We tested this model using a dozen cities, which showed that e-bus implementation is financially viable for most major cities across the globe.

4 Climate Impact Model

To start, we took CO_2 climate data from the National Oceanic and Atmospheric Administration to plot carbon dioxide levels in the atmosphere since 1958. Over the past 60 years, climate levels have increased by about 100 parts per million (ppm), resulting in drastic changes in the average global temperature. We also graphed global temperature change over the past 60 years compared to the baseline of the average global temperature from 1951 to 1980

4.1 Assumptions

Assumption 1: The behavior of global CO_2 emissions is the same as that of local CO_2 emissions – that is, a specific city's CO_2 emissions mimic global CO_2 emissions.

Justification: Trade winds are a natural phenomenon that occurs on Earth which carries and transports gasses in our atmosphere around the globe. Despite certain regions differing in CO_2 emissions by varying degrees of causes, CO_2 is generally evenly distributed across our atmosphere, where even CO_2 hotspots (like China or America) differ by less than 7% in CO_2 emissions compared to the lowest CO_2 emitters, like Antarctica [15].

Assumption 2: The range of an electric bus will be sufficient to run its route the whole day, and charge at night/off hours when there is a replacement bus available. Floating bus numbers in order to cover charging times will at most need to be $\frac{1}{8}$ of the total bus fleet size extra.

Justification: The average diesel bus has a range of 690 miles [18]. On the other hand, Proterra e-buses, which have already been implemented in multiple cities, have a range of 240 to 340 miles [19]. We also expect technology in the electric vehicle sector to continuously improve, potentially increasing the range of electric buses. Next, we did some quick calculations to predict the distance that buses have to travel every day:

There are at most 262 weekdays in a year, so if a bus drives on only weekdays, we can find the average mileage of a bus per day using $\frac{Mileage\ per\ year}{262\ driving\ days}$ (note that if a bus also drives on weekends their daily mileage will only decrease). The average public transportation bus drives 43,647 miles per year [23], which comes out to the average bus driving about 167 miles per day. The average e-bus has more than enough range to cover 167 miles per day, thus we can assume that there will be no issues with range except in extremely unusual circumstances.

Assumption 3: There will not be an increase in private vehicle use while a gas bus fleet transitions to all-electric.

Justification: The primary reason why people do not ride public transportation, or more specifically, buses, is because of inconvenience and delays [7]. Both electric buses and gas buses will run on existing routes, and both will have approximately the same range within city boundaries (assumption two), which implies that a bus's effective fuel medium does not play a part in the logistics of public transportation.

Assumption 4: For every electric bus added, an equivalent diesel/gas/hybrid bus will be removed from the fleet. That is, the bus fleet population will be constant over the 10 year plan.

Justification: We are studying the conversion to an all electric bus fleet, and should focus on the general broader picture. It would make our models more consistent to have a bus population that is not varying at large amounts. A change in bus population by significant amounts is also unrealistic, because a bus population too low could lead to decommissioning many bus routes from a bus shortage, and a bus population too high could be unnecessary.

Assumption 5: The amount of CO_2 released per electric bus will largely be based on the amount of lithium mined to create the lithium-ion battery of the Proterra ZX5 Max electric transit bus, which is the most recent and advanced electric bus.

Justification: The Max depends on a $738\ kWh$ battery [11]. Proterra's battery pack's gravimetric energy density ($\frac{Wh}{kg}$) goes up to 170 [19]. Since the density proportion is $\frac{Wh}{kg} = 170$, or $\frac{kWh}{kg} = 0.17$, we can find the mass of the Max's battery by setting $\frac{738\ kWh}{kg} = 0.17$. The mass is approximately $4341\ kg$. The battery is also made of nickel manganese cobalt, so we can do the following chemistry to find the amount of lithium in the battery:

$$\frac{total\ mass\ of\ LiNiMnCoO2\ (g)}{molar\ mass\ of\ LiNiMnCoO2\ (g/mol)} * grams\ of\ lithium\ in\ one\ mol\ of\ LiNiMnCoO2$$

$$\rightarrow \frac{4341000\ g}{195.50\ g/mol} * 6.94\ g/mol\ = 155\ kg\ of\ lithium$$

Note: For every metric tonne of mined lithium, 15 tonnes of CO_2 are emitted in the air [15].

$$155\ kg\ Li * \frac{0.001\ metric\ tonne\ Li}{1\ kg\ Li} * \frac{15\ tonnes\ CO_2}{1\ metric\ tonne\ Li} = 2.325\ metric\ tonnes\ CO_2$$

Therefore, for every Proterra ZX5 Max, 2.325 metric tonnes of CO_2 are emitted in the air.

Assumption 6: Positive results in one city will have a ripple effect across the globe.

Justification: It is reasonable to assume that changing only one city will have very little impact on the overall climate, especially with a change as restricted as converting only public transportation buses to electric. However, when cities show positive impact their methodology will typically be used in other cities as well, as already shown with certain e-bus movements occurring across the globe. Thus, we will be showing global CO_2 emission reduction changes by extrapolating our analysis to the entire world, to demonstrate the potential impact on the global climate.

4.2 Analytic Graphs and Models

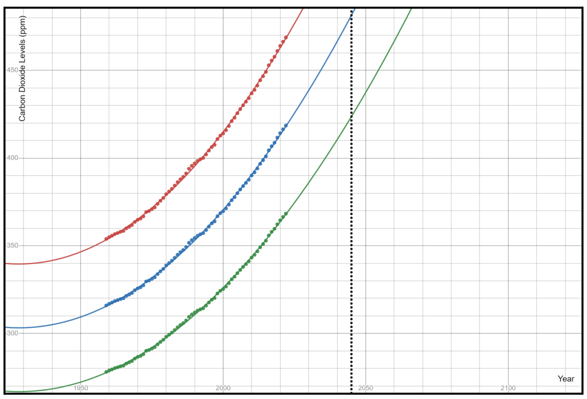


Figure 1: Quadratic regression analysis of the maximum (red), measured (blue), and minimum (green) CO_2 levels

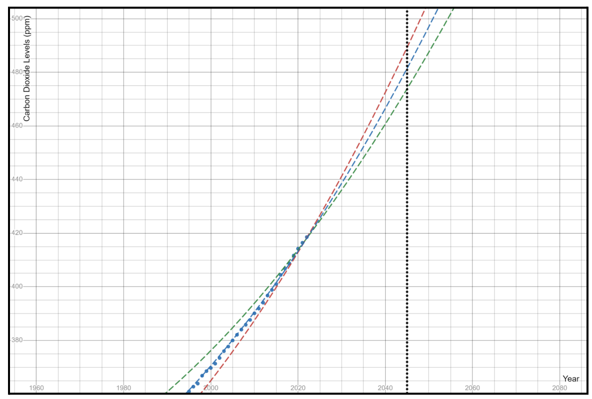


Figure 2: Current climate change growth rates based on quadratic regression curves from Fig. 1

For CO_2 levels, we initially graphed linear, quadratic, and exponential curves. It is also important to note that the data we chose included error estimations, which we factored in to create a high CO_2 level regression curve and a low CO_2 level regression curve. After graphing these models, we determined that the quadratic regression curves were the most accurate and best represented the data (note that the low and high curves were translated to match the measured data):

Normal curve (blue): $N(x) = 0.0130852x^2 - 50.4644x + 48958.5$

Low curve (green): $L(x) = 0.011515x^2 - 44.4087x + 43083.5 + 50.096$

High curve (red): $H(x) = 0.0146554x^2 - 56.5201x + 54833.6 - 50.01$

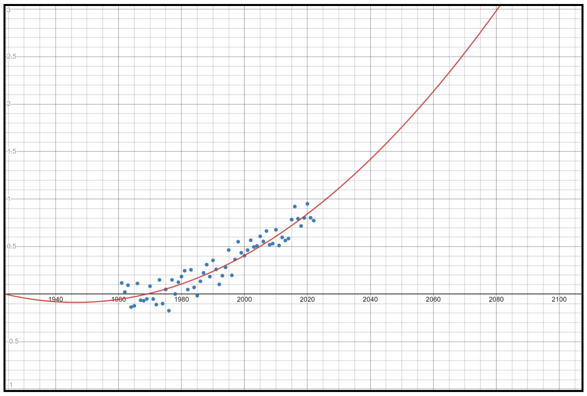


Figure 3: Average global temperature in Celsius compared to the baseline average global temperature in Celsius from 1951-1980

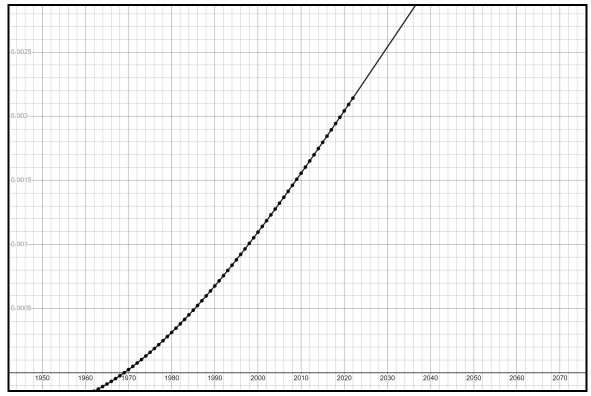


Figure 4: $\frac{T(x)}{N(x)}$

We chose a quadratic regression model for the global annual temperature change data. After modeling CO_2 levels and temperature, we were finally able to roughly estimate the temperature change per ppm increase of carbon dioxide.

Temperature increase per ppm increase of CO_2: $\frac{0.000172137x^2-0.670107x+652.072}{0.0130852x^2-50.4644x+48958.5}$

4.3 Ecological Relevance in NYC

In order to construct an ecological model relevant to NYC, we researched:

- types of MTA buses
    - how many of each bus are currently in use
    - how much CO_2 each bus roughly produces per mile
- average MTA bus mileage per year
- speed at which buses must be replaced to reach the quota of replacing all buses by 2033
- current MTA plans on transitioning

4.3.1 Types of MTA Buses

NYC maintains diesel, gas, hybrid, and electric vehicles. As of 2021, there were 3740 diesel buses (40’ buses, 60’ buses, and express buses are included), 1286 diesel/electric buses, 735 natural gas buses, and only 25 electric buses, with a total of 5786 buses [3]. According to UCSUSA, a nonprofit science organization, electric buses emit roughly 347g of carbon dioxide per mile, a diesel equivalent of 2,680g, a natural gas equivalent of 2,364g, and a diesel-electric hybrid equivalent of 2,212g [8].

4.3.2 Average Mileage

The average mileage of a transit bus is 4000 miles per month [21].

4.3.3 Average Speed of Transition and MTA Estimates

The MTA wishes to transition to a fully electric fleet by 2040. They aim to complete this in four stages. By the end of the first stage, in 2024, they plan to deploy 560 electric vehicles. By the end of the second stage, in 2029, they plan to deploy over 1000. By 2034, their third stage, they plan to deploy about 60% of the fleet, which is roughly equivalent to 3500. Finally, by 2039, they plan to retire around 2000 of the remaining non-electric fleet [16, 22].

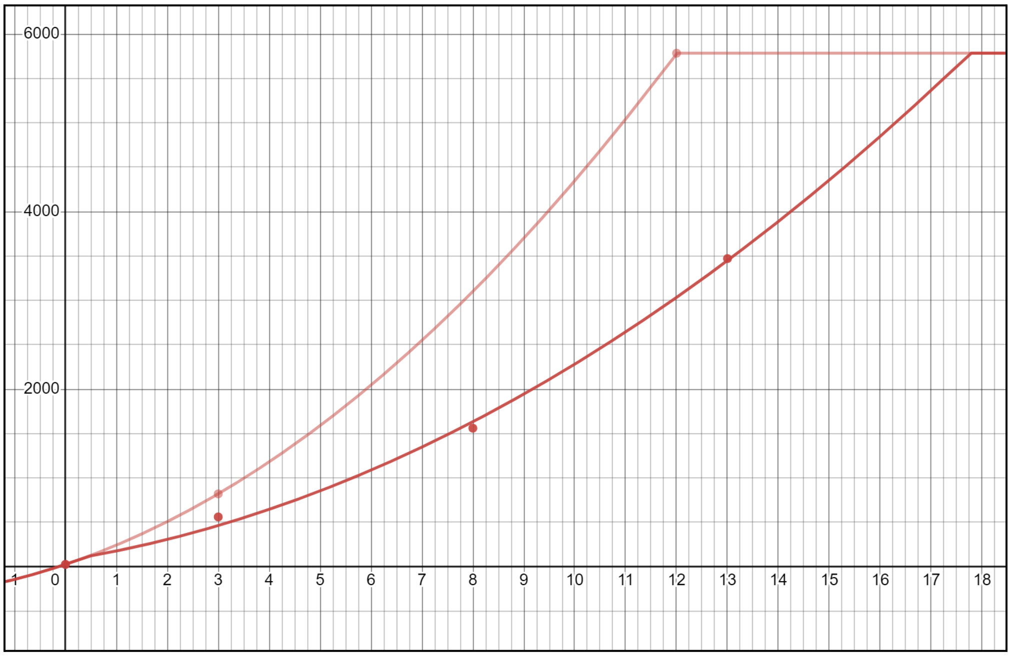


Figure 5: Electric bus fleet size versus time in years since 2021

Note: 2033, 10 years from 2023, is 12 years from 2021. You will see values of x up to 12 for this reason.

We used a polynomial regression model given the four stages in the MTA's timeline.

$F(t) = at^2 + bt + c$ where t represents the number of years since 2021

Using Desmos, we found that

$F(t) = 12.9352t^2 + 91.6575t + 71.627$ (See Figure 5- represented by the darker red function).

However, simply following the MTA's timeline is not in the goals of our study. To fully transition all 5927 buses, we need to follow:

$f(t) = 23.8981t^2 + 193.306t + 25$ (See Figure 5- represented by the lighter red function). Such that we can reach 5786 electric buses by 2033.

Thus, our plan requires that the rate at which electric buses are replacing diesel/gas/hybrid equivalent buses is equal to:

$$\frac{d}{dx}f(t) = 47.7962t + 193.306$$

Using this, we can construct a model representing the ecological impact of transitioning to an all electric fleet. This is developed from the assumption that all gas buses are converted to electric, therefore, the increase in electric buses is equivalent to the decrease in gas buses.

4.3.4 CO_2 versus time

We define the variables below to model our plan of CO_2 emissions by the MTA:

E_{NYC} = emission of CO_2 in metric tons per year by buses in NYC.
$T_{NYC} = 5786$ = total buses in NYC as of 2021
$T_{electric} = f(t)$ = total electric bus fleet
T_{diesel} = total diesel bus fleet
T_{gas} = total natural gas bus fleet
T_{hybrid} = total hybrid bus fleet
$g_{electric}$ = 347 g / mile
g_{diesel} = 2680 g /mile
g_{gas} = 2364 g / mile
g_{hybrid} = 2212 g / mile
t = years after 2021 (positive quantity)

As $f(t)$ approaches 5786, we must consider which type of bus is removed to make space for the electric buses. Instead of arbitrarily choosing, we made six models representing six possibilities in the order of removal

1. $T_{diesel} \rightarrow T_{hybrid} \rightarrow T_{gas}$ (in order of removal)

   T_{diesel} is restricted by the domain [0,3740]
   T_{hybrid} is restricted by the domain [0,1286]
   T_{gas} is restricted by the domain [0,735]
   t, years after 2021, is a positive quantity

   $$T_{diesel} = \{0 \le f(t) < 3740 : 3740 - f(t),\ f(t) \ge 3740 : 0\}$$

t years after 2021 is a positive quantity. As the amount of electric bus increases from 0 to 3740, the amount of diesel buses is represented by $3740 - f(t)$. *If f(t) is greater than the amount of diesel buses,* $T_{diesel} = 0$.

Let $h = 1286 - (f(t) - 3740)$

h represents the amount of hybrid buses remaining after all the diesel buses have been depleted.

$T_{hybrid} = \{T_{diesel2} \geq 0 : 1286,\ h > 0 : h,\ h < 0 : 0\}$

Once the diesel buses have been depleted, hybrid buses will start to deplete an amount of f(t) - 3740. To avoid negative numbers, we added a restriction such that when f(t) - 3740 is greater than 1286, or in other words when h < 0, T_{hybrid} *= 0.*

Let $c = 735 - (f(t) - (3740 + 1286))$

c represents the amount of gas buses remaining after all the diesel buses and hybrid buses have been depleted.

$T_{gas} = \{T_{hybrid} \geq 0 : 735,\ c > 0 : c,\ c < 0 : 0\}$

Once the hybrid buses have been depleted, gas buses will start to deplete an amount of f(t) - (3740+1286). To avoid negative numbers, we added a restriction such that when f(t) - (3740+1286) is greater than 735, or in other words when c < 0, T_{gas} *= 0.*

Finally,

$$E = \frac{4000\ mi}{month} \bullet \frac{12\ mo.}{yr.} \bullet \frac{1\ mt}{10^6\ g} \bullet (T_{electric}g_{electric} + T_{diesel}g_{diesel} + T_{hybrid}g_{hybrid} + T_{gas}g_{gas})$$

This order is represented by the red line. (Figure 6 see below)

2. $T_{diesel} \text{—>} T_{gas} \text{—>} T_{diesel}$ (in order of removal)

   **same operations as done above to avoid redundancy*

This order is represented by the orange line. (Figure 6 see below)

3. $T_{hybrid} \text{—>} T_{diesel} \text{—>} T_{gas}$

   **same operations as done above to avoid redundancy*

This order is represented by the green line. (Figure 6 see below)

4. $T_{hybrid} \text{—>} T_{gas} \text{—>} T_{diesel}$

   **same operations as done above to avoid redundancy*

This order is represented by the blue line. (Figure 6 see below)

5. $T_{gas} -> T_{diesel} -> T_{hybrid}$

   **same operations as done above to avoid redundancy*

This order is represented by the black line. (Figure 6 see below)

6. $T_{gas} -> T_{hybrid} -> T_{diesel}$

   **same operations as done above to avoid redundancy*

This order is represented by the purple line. (Figure 6 see below)

As observed, we found that the orange line, line two, suited best for the least emission of CO_2. The effect of transitioning to a fully electric fleet is tremendously good for the environment, compared to the emissions previously. With a fully electric fleet, emissions drop from 700,000 metric tons of CO_2 yearly (dashed black line) to approximately 100,000 metric tons yearly, nonetheless the order of transitioning. However, it is important to note that the removal of $T_{diesel} -> T_{gas} -> T_{diesel}$ has the best impact on the environment, indicated by its vast difference in CO_2 emissions yearly compared to the rest of the models.

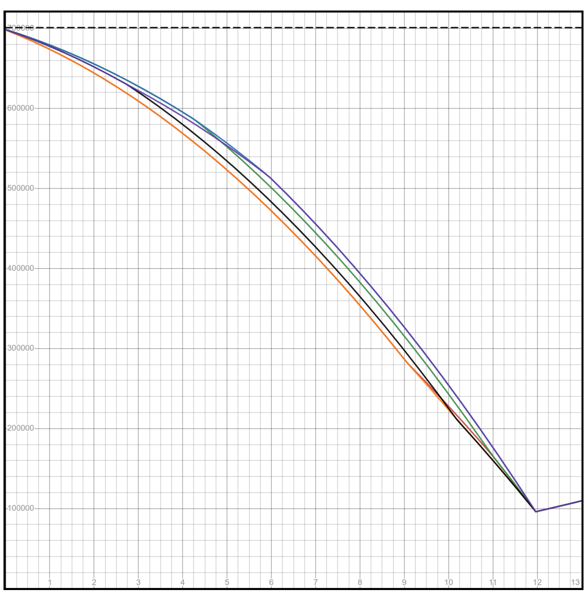


Figure 6: Metric tons of CO_2 released by MTA buses compared to years projected after 2021

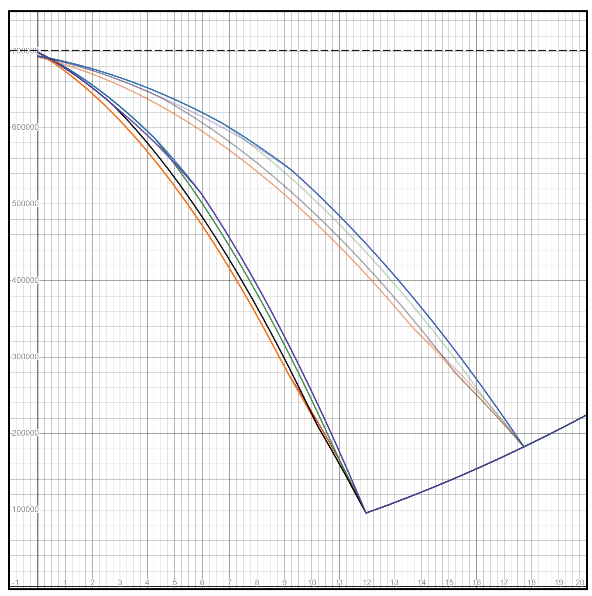


Figure 7: Comparing our plan with regard to the MTA's

Looking at the CO_2 emissions following $F(x)$ (see Figure 7), MTAs transition plan indicated by the translucent lines, rather than $f(x)$, our plan indicated by the darker lines, there is a drastic difference between our model for bus transition and the MTAs. The MTA will take around six years longer to completely replace their bus fleet with an electric bus fleet if they continue at the rate they are now.

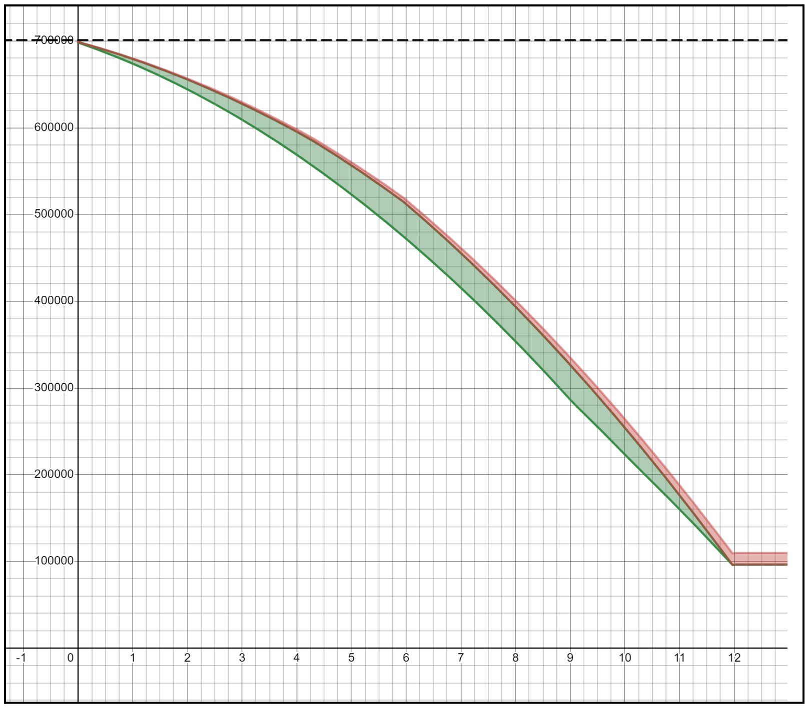


Figure 8: Lithium consideration

*The green shaded region is a simplification of the findings in Figure 6.

Recall from Assumption 5:

For every metric tonne of mined lithium, 15 tonnes of CO_2 are emitted in the air [15].

…

2.325 *metric tonne of* CO_2 is emitted from each bus battery

Thus,

$E_{lithium} = f(x) * 2.325$ (where $f(x)$ = electric bus fleet population)

$E_{total} = E_{NYC} + E_{lithium}$

*This increased hypothetical range of yearly carbon emissions is noted by the red shaded region.

The % difference between the emission rates without lithium considered, and with lithium considered, can be represented by the following:

$$\% \ Difference = \frac{|E_{total} - E_{NYC}|}{\frac{E_{total} + E_{NYC}}{2}}$$

*Note: we are using the maximum hypothesized values of each shaded region.

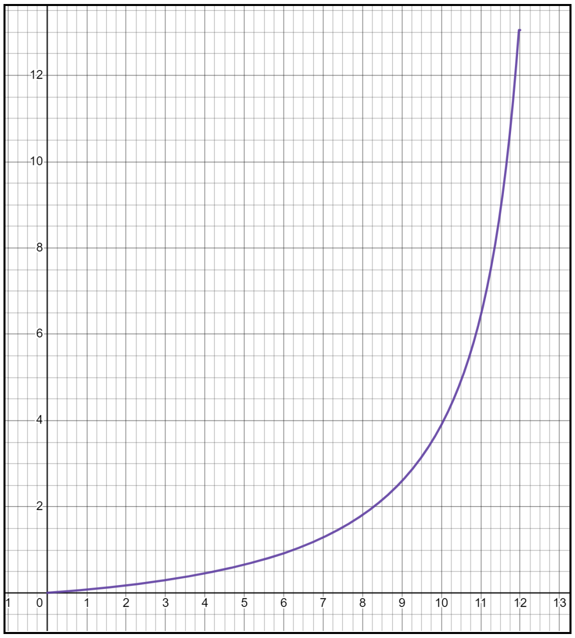


Figure 9: Years after 2021 vs. % difference of CO_2 emissions when lithium is considered

The % difference of E_{total} and E_{NYC} starts off slow, due to the slow production of electric cars, and exponentially increases. This exponential behavior could be explained by the behavior of $f(x)$ (see Figure 5). As $f(x)$ increases to 5786, the magnitude of $E_{lithium}$ increases, and E_{total} may differ from E_{NYC} up to over 12%. Thus, the influence of lithium should be considered.

4.4 Applications of Our Model on Metropolitan Areas

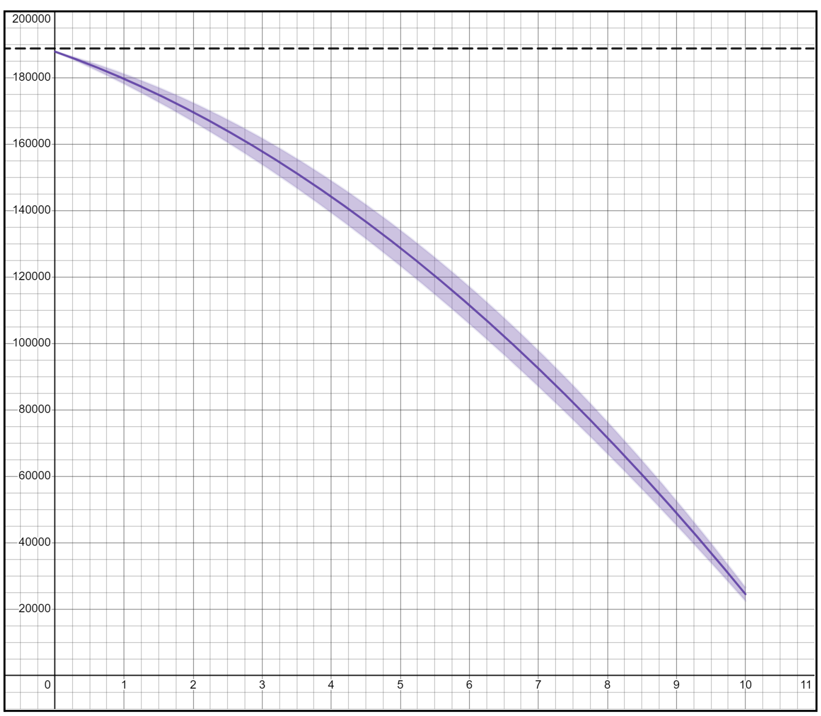


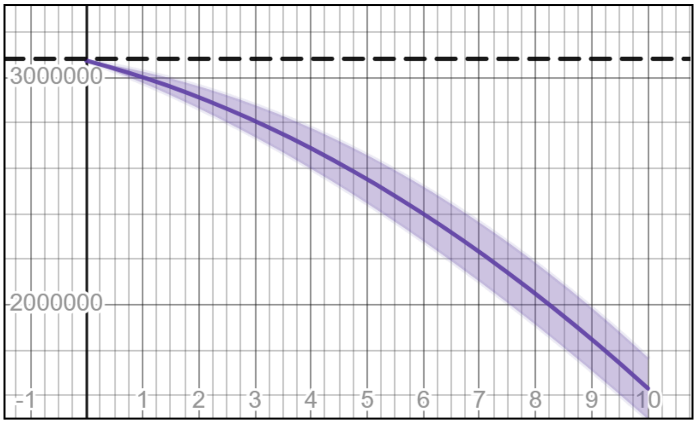
Figure 10: CO_2 emissions of buses in Tokyo

Our model also applies to Tokyo (5.5). Tokyo's Toei bus service, operated by the Tokyo Metropolitan Bureau of Transportation, has a fleet of 1467 buses. Using the operations similar to those discussed from 4.3.3 - 4.3.4, we were able to illustrate the emissions of CO_2 as t, in years since 2023, increases. This demonstrates the ecological impact with full conversion by 2033. Emissions start from around 190,000 metric tons of CO_2 yearly, and drop as low as 25,000 metric tons of CO_2 yearly.

The rate at which Tokyo must replace its buses with electric buses can be represented by the following:

$$scale\ factor \bullet \left(\frac{d}{dx}f(x)\right) \approx 16.1263t + 65.2209$$

$$(scale\ factor \approx 0.337397)$$



We also applied our model to Beijing, whose bus fleet population is at 23,948; they currently have ~11,000 e-buses. CO_2 emissions could drop by almost one half if they replace their remaining buses with e-buses. However, considering the scale of the operation, completing this would be extremely difficult, but its rewards are exceedingly good for the environment.

Figure 11: CO_2 emissions of buses in Beijing

The rate at which Beijing must replace its buses with electric buses can be represented by the following:

$$scale\ factor \bullet \left(\frac{d}{dx}f(x)\right) \approx 142.3660t + 575.7824$$

$$(scale\ factor \approx 2.978606)$$

4.5 Temperature Change in Regards to CO_2 Emissions

Recall Figure 3 and Figure 4 (page 8).

$\frac{T(x)}{G(x)}$ gives us the temperature increase per ppm increase of CO_2, where

$$\frac{T(x)}{G(x)} = \frac{0.000172137x^2 - 0.670107x + 652.072}{0.0130852x^2 - 50.4644x + 48958.5}$$

E = emissions of CO_2 in metric tons yearly

$\frac{1}{7.821 \bullet 10^9}$ = conversion from ppm to metric tons

$$\frac{T(2021+x)}{G(2021+x)} \bullet E \bullet \frac{1}{7.821 \bullet 10^9} \bullet \frac{3000000\ buses\ worldwide}{x\ buses}$$

(we used $\frac{T(2021+x)}{G(2021+x)}$ because $\frac{T(x)}{G(x)}$ starts at a different value of x: E is in terms of years since 2021, while $\frac{T(x)}{G(x)}$ is not).

For NYC, $x\ buses = 5927$

To simplify our operations,
Let,

$$n(x) = \frac{T(2021+x)}{G(2021+x)} \bullet E_{NYC} \bullet \frac{1}{7.821 \bullet 10^9} \bullet \frac{3000000 \; buses \; worldwide}{5927 \; buses}$$

$$E_{noConversion} = \frac{4000 \; mi}{month} \bullet \frac{12 \; mo.}{yr.} \bullet \frac{1 \; mt}{10^6 \; g} (25g_{electric} + 3740g_{diesel} + 1286g_{hybrid} + 735g_{gas})$$

(Recall equation from 4.3.4)

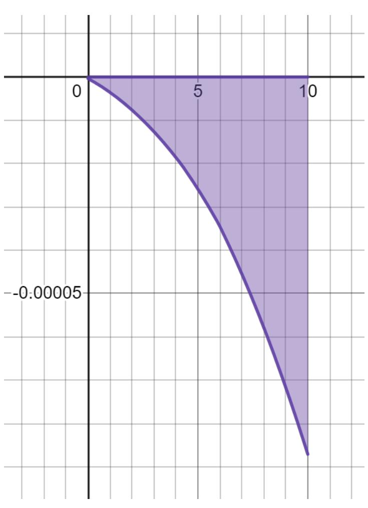
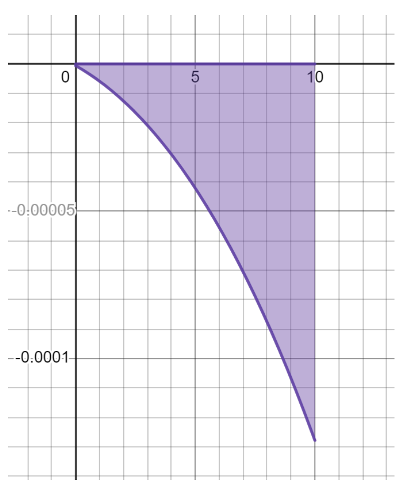
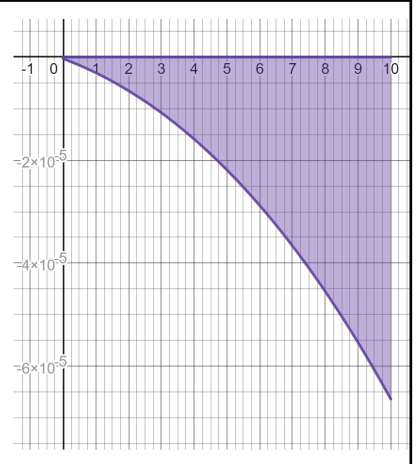
$$m_{noConversion}(x) = \frac{T(2021+x)}{G(2021+x)} \bullet E_{noConversion} \bullet \frac{1}{7.821 \bullet 10^9} \bullet \frac{3000000 \; buses \; worldwide}{5927 \; buses}$$

$$q(x) = n(x) - m_{noConversion}(x)$$

Now we can approximate the impact of these CO_2 emissions on a global scale. $n(x)$ represents the temperature contribution of the buses with gradual conversion to electric, and $m_{noConversion}(x)$ represents the temperature contribution of the buses with no conversion to electric. $n(x)$ should be smaller than $m_{noConversion}(x)$ because electric vehicles will emit less CO_2, and thus contribute less to the temperature globally. To determine if our understanding was correct, we used the following:

$$\int_{0}^{10} q(x)dx$$

Using the integral above, we were able to determine the temperature difference between our model (with conversion to electric buses), $n(x)$, and $m_{noConversion}(x)$. The findings are shown in the chart below. The negative sign of the temperature suggests that our model contributed less to the rising temperature, which is a positive outlook for the future.

New York City	Tokyo	Beijing
		
−0.000320419181302°C	−0.000755966774211°C	−0.000257144597674°C

4.6 Our 10-Year Roadmap

Based on our climate models above, we find that it would be effective to convert bus fleets over the next 10 years in each of the three cities of New York City, Beijing, and Tokyo to fully electric. This would be implemented through staggered replacement, with buses as they reach the end of their lifetime being replaced (or converted) into electric buses. Before the end of the 10-year plan, any remaining diesel buses will already be close to the end of their lifespans, and thus can also be replaced before the duration of the 10-year plan expires without losing efficiency.

5 Model of Cost

5.1 Assumptions

Assumption 1: The range of an electric bus will be sufficient to run its route the whole day, and charge at night/off hours when there is a replacement bus available. Floating bus numbers in order to cover charging times will at most need to be $\frac{1}{8}$ of the total bus fleet size extra.

Justification: The average diesel bus has a range of 690 miles (Environmental and Energy Study Institute). On the other hand, Proterra e-buses, which have already been implemented in multiple cities, have a range of 240 to 340 miles [19]. We also expect technology in the electric vehicle sector to continuously improve, potentially increasing the range of electric buses. Next, we did some quick calculations to predict the distance that buses have to travel every day:

There are at most 262 weekdays in a year, so if a bus drives on only weekdays, we can find the average mileage of a bus per day using $\frac{\textit{Mileage per year}}{262 \textit{ driving days}}$ (note that if a bus also drives on weekends their daily mileage will only decrease). The average public transportation bus drives 43,647 miles per year [23], which comes out to the average bus driving about 167 miles per day. The average e-bus has more than enough range to cover 167 miles per day, thus we can assume that there will be no issues with range except in extremely unusual circumstances.

Assumption 2: Floating bus numbers in order to cover charging times will at most need to be an extra $\frac{1}{8}$ of the normal bus fleet size

Justification: The charge time for an e-bus is also at most three hours [19], so a floating number of $\frac{1}{8}$ extra buses would also be able to cover charging time for full time bus services. Drive time to charging stations would be the same as a diesel bus driving to be refueled. Finally, charging would be done during off-hours, as e-buses have the range to last the entire day, potentially limiting the number of necessary extra buses.

Assumption 3: Buses will be replaced over the course of 10 years; when a diesel bus reaches the end of its lifetime it is replaced with an e-bus, thus reducing the upfront cost of payment for the city.

Justification: The average bus has a lifespan of 12 years [4], so over the course of 10 years the majority of buses will need to be replaced. Towards the end of the 10 years, the city government should have saved a significant amount of money, potentially from reduced fuel and maintenance costs, and thus would be able to pay upfront for the replacement of the few remaining buses.

5.2 Defining Variables

Let f = total fleet size
Let t = time (years) a bus is in service
Let v_e = electric bus cost
Let v_d = diesel bus cost
Let s = charging station cost per bus
Let m_e = total number of miles per year driven by the average electric bus
Let m_d = total number of miles per year driven by the average diesel bus
Let g_e = the fuel cost per mile for an electric bus
Let g_d = the fuel cost per mile for a diesel bus
Let u_e = maintenance/upkeep cost per year per electric bus
Let u_d = maintenance/upkeep cost per year per diesel bus
Let d = external funding (%)
Let e = electric vehicle-to-grid savings per year

5.3 Analysis of Cost with Expressions

(1) Total cost of vehicle replacement: $f \times (v_E - v_D)$
- Justification: The difference between an electric vehicle replacement versus a diesel vehicle replacement is the cost of replacing a bus with an e-bus instead of a diesel bus, which multiplied by the fleet will give the cost for replacing the entire fleet.

(2) Total cost of charging infrastructure: $f \times s$
- Justification: The total cost of charging infrastructure is the cost per bus for charging infrastructure multiplied by the number of buses.

(3) Electric bus fuel savings over diesel: $f \times ((g_e \times m_e) - (g_d - m_d)) \times t$
- Justification: The difference per year in fuel costs between an electric bus and a diesel bus is the difference between fuel cost per mile of electric buses multiplied by the number of miles the electric bus drives and the fuel cost of diesel buses multiplied by the number of miles the diesel bus drives. Then, the difference per year for the entire fleet is the difference per year in fuel costs for a single bus multiplied by the fleet size, and then multiplied by the lifetime of the fleet.

(4) Maintenance savings: $f \times t \times (u_e - u_d)$

(5) Electric vehicle to grid savings: $f \times e \times t$

Full cost of implementation: $d \times [(1) + (2)] + [(3) - (4)] - (5)$

$$d \times [(f \times (v_E - v_D)) + (f \times s)] + [(f \times [(g_e \times m_e) - (g_d \times m_d)] - (f \times e \times t)$$

5.4 Model Preconditions

Precondition 1: Public transportation buses last for 12 years [4].
Precondition 2: External funding is 50% of the upfront costs, or bus replacement and charging grid costs, as in previous projects funding has covered those two areas ([24], Question 2). Referring back to our problem analysis, we see that it is very plausible for half of the cost of our gas-to-electric conversion to be covered by external funding (not exclusive to **just** the EPA) as well.
Precondition 3: Electric vehicle-to-grid capabilities produce $6000 in savings per bus per year [14].
Precondition 4: We will use Proterra 40-foot bus prices at about $550,000 per bus [19].
Precondition 5: We will use a diesel bus price of $350,000 per bus [4].
Precondition 6: We will assume a charging station would be around $495,636 (charging station cost) + $202,811 (installation fee) for 8 buses [10].
Precondition 7: In the United States, fuel prices are $0.28 per mile and $0.59 per mile [23].
Precondition 8: Comparatively, outside of the United States,

$$\frac{US\ price\ per\ mile}{Outside\ US\ price\ per\ mile} = \frac{Gas\ price\ in\ US}{Gas\ price\ outside\ of\ US}$$

Thus, g_d and g_e can be found as the *outside US price per mile* variable, given gas prices of the locations inside and outside the United States [25].
Precondition 9: Maintenance for diesel: $0.64 per mile [2].
Precondition 10: Maintenance for electric: $0.88 per mile [10].
Precondition 11: The miles driven per bus is about 43,647 miles per year, the same for diesel and electric buses, assuming they drive the same routes. Note that once again electric bus range is a nonfactor except in extreme circumstances [23].

5.5 Implementation

We selected a dozen cities, including the three cities used in the climate model (New York City, Seoul, and Tokyo) to test the total conversion costs. Note that some figures are estimates, and that some cities may already have some electric buses, however those quantities are insignificant and already implemented electric buses will reduce initial costs.

City Name	Number of Buses	g_e (\$/mile)	g_d (\$/mile)	Total Cost ($)
Beijing	23,948	0.1179775281	0.5531569818	-6,752,899,042
Seoul	8,300	0.1856179775	0.643217693	-2,437,914,843
Delhi	7,135	0.1226966292	0.5746487424	-2,074,620,184
Shanghai	5,000	0.1179775281	0.5531569818	-1,409,908,769

New York City	5,927	0.28	0.59	-1,282,705,115
Manila	5,000	0.3051685393	0.5956287944	-1,030,915,238
Mumbai	3,228	0.1226966292	0.5746487424	-938,594,807.9
Jakarta	4,300	0.07550561798	0.237432784	-597,106,783.6
Tokyo	1,467	0.3240449438	0.5659496964	-265,162,338.1
Mexico City	720	0.1541573034	0.7015524718	-245,344,540
San Jose	900	0.28	0.59	-194,775,536.2
Dubai	1,518	0.07550561798	0.1023417173	-103,385,219.5

**Note that negative costs mean that money is saved using the plan.*

6 Model Sensitivities

Model sensitivities consider the change and viability of our models under changes in variables. They assess how well our models adapt to different scenarios and how generalizable our model is.

6.1 Ecological Models

6.1.1 Carbon Dioxide Model

Our carbon dioxide model relies on many different assumptions that allow us to expand a specific city's climate impact data into a global representation of the climate impact from a gas bus fleet to electric bus fleet conversion. In this context, our model is very flexible to variation. By altering the quantities associated with the T variables, that is, the total types of buses within a specific bus fleet, we alter the results within a 12 year interval (12 years past 2021, or 10 years past 2023). Our domains for respective T variables do need to be restricted to T itself, and so, though we must manually alter our variables and domains, our ecological model is fairly adaptive to different scenarios/cities. When we expand our model, for instance, to encapsulate the global data for buses (to expand T to 3 million buses), our carbon dioxide model changes an insignificant amount, varying our general functional behavior by very little.

6.1.2 Temperature Model

In our temperature model, we rely on a composite function between the aforementioned CO_2 model with the function for temperature increase per ppm of CO_2. As noted above, our carbon dioxide model is fairly adaptive to changes in T, or the dependent variable of the function, therefore our function for temperature increase per ppm of CO_2 will also be fairly adaptive. The dependent variable of our temperature model is ppm of CO_2, which is similar in behavior for all varieties of the CO_2 function parameters.

6.2 Cost Model

Our cost model relies on data which is generally consistent throughout all electric buses. Electric buses rely on a battery to be converted, and most buses all fall within a similar cost of conversion (no matter if the bus is diesel or gas). This means that the only varying quantity to consider in this model is primarily the number of buses the city aims to convert. No matter what our parameter (the number of buses to convert) is, the behavior of our function of cost should be the same universally.

7 Strengths and Weaknesses

7.1 Strengths

- Our models take into account several variables, especially within our CO_2 model, in order to be modified and generalized into different situations easily.
- Our functions directly relate to each other; that is, our function for temperature increase or change, varies with respect to CO_2 emissions, a result produced in another function. Errors that occur within encapsulating functions can be pin-pointed to a separate function's results.
- The restrictions placed on our functions produce a very legible and reaffirming result (i.e. we are able to take advantage of piecewise analysis rather than a singular regressive function that may fail to assess exact and attributable information at different inputs, or in the most case, years after 2021).
- Our 10-year plan, and its subsequent ecological results, somewhat reflect the current ongoing MTA plans for an e-bus fleet conversion – the behavior of both plans are similar, which provides a greater sense of our model's applicability to other city transitions.

7.2 Weaknesses

- Though having many variables increases our function's modularity, we lose concision and so, our functions themselves (the piecewise material that produces the figures throughout our report) become less and less readable.
- We have to rely on several estimates for varying quantities to produce the many constants which we use throughout our functions. Examples of this would be the estimated cost per electric bus, the estimated cost per gas bus, and the mileage of all types of buses (diesel, hybrid, and electric). These quantities, though we describe them in our models as constants, most definitely vary based on the weight of a bus, capacity of an electric battery, age of a bus, and quality of fuel.
- Our data for our models are dated to 2021, which means that our projection for transitioning begins before 2023; the missing data in these two years may or may not be accurate to our existing model's projections.
- We did not produce a minimum or maximum cost for a given city's transition like we did for the CO_2 projection off of current trends.

8 One Page Letter to Transportation Officials in New York City

Dear MTA Official,

Over the past 60 years, carbon dioxide emissions have increased drastically, resulting in increased global temperatures of over a degree Celsius. Without intervention, global temperatures will continue to rise at an even faster pace. The effects of global warming cannot be underestimated. Already, we are seeing unpredictable weather patterns, dangerously hot temperatures not exclusive to the summer, and even wildfire smoke from Canada.

A transition to a fully electric fleet of buses would be tremendously helpful for the environment. The implementation of a fully electric bus fleet will lower CO_2 emissions by 600,000 metric tonnes over a 10-year period. Nonetheless, this transition requires careful planning and attention to be properly executed.

One major concern that most metropolitan areas have for implementing electric buses in their cities is the potential costs associated with funding these technologies. However, we propose a 10-year solution that would not only revamp New York City's bus system to a fully-electric, climate-friendly method of transportation, but also would, according to our models, save the MTA over $1.2 billion that can be used to fund other environmental-friendly projects in the future.

The implementation of this project is fairly simple. Over the next 10 years, buses that need to be replaced at the end of their 12-year lifespan will be replaced by electric buses. This means that the only difference in costs at first will be the marginal difference between purchasing an electric bus and a diesel bus – a cost that will be compensated through years of cheaper fuel. Money that is saved by having electric vehicles on the road can be used towards the end of the plan, where a year before the 10-year mark, New York City should have enough money at hand to replace the few remaining diesel vehicles. Note that our plan also adds onto the current MTA's plan of electrifying the bus system, accelerating it, and thus

Furthermore, recent electric bus plans have also been funded with large amounts of federal and private grants. On June 26, 2023, the Biden-Harris Administration announced 130 awards totaling nearly $1.7 billion in funding for electric vehicles such as buses. Projects in cities such as Seattle and Chicago have received funding covering nearly their entire plans!

New York City has always been considered a world leader in innovation, and an investment in an electric bus fleet would continue that tradition. Success in the Big Apple, one of the largest and most diverse cities in the world, would inspire other cities to follow suit in an embracement of climate-friendly technology, especially because the implementation of a larger e-bus network will not be costly through our plan. Conversion of the entirety of the world's diesel buses to electric buses would lower the temperature of the planet by 0.0003°C over the next 10 years, which is massively significant in the context of this short-term period. This change can start with New York City. Rise to the occasion, and be the role-model for the world to follow.

Sincerely,
Team #14844

References

[1] Admin@roushcleantech. (2019, September 6). Fuel fact check: Do propane school buses actually have a shorter lifespan?. ROUSH CleanTech. https://roushcleantech.com/fuel-fact-check-do-propane-school-buses-actually-have-a-shorter-lifespan/

[2] Argonne National Laboratory. (n.d.). AFLEET Tool - Argonne National Laboratory. Afleet.es.anl.gov; United States Department of Energy. Retrieved November 14, 2023, from https://afleet.es.anl.gov/home/

[3] Capital Program Oversight Committee meeting - home | MTA. (n.d.-a). https://new.mta.info/document/42401

[4] Colorado Department of Transportation. (n.d.). Overview of Transit Vehicles. In codot.gov. Colorado Department of Transportation. Retrieved November 13, 2023, from https://www.codot.gov/programs/innovativemobility/assets/commuterchoices/documents/trandir_transit.pdf

[5] Day, L. (2022, April 19). This electric bus has a battery pack over 3 times bigger than a hummer EV's. The Drive. https://www.thedrive.com/news/this-electric-bus-has-a-battery-pack-over-3-times-bigger-than-a-hummer-evs

[6] Desmos Calculator. (2014). Retrieved February 22, 2015, from https://www.desmos.com/calculator

[7] Ecolane. (n.d.). 7 reasons why people stop using public transit. https://www.ecolane.com/blog/7-reasons-why-people-stop-using-public-transit

[8] Electric utility investment in truck and Bus Charging. (n.d.-b). https://www.ucsusa.org/sites/default/files/attach/2019/04/Electric-Utility-Investment-Truck-Bus-Charging.pdf

[9] EPA grants | US EPA - U.S. Environmental Protection Agency. (n.d.). https://www.epa.gov/grants

[10] Hanlin, J., Reddaway, D., Lane, J., Transit Cooperative Research Program Synthesis Program, Synthesis Program, Transit Cooperative Research Program, Transportation Research Board, & National Academies of Sciences, Engineering, and Medicine. (2018). Battery Electric Buses State of the Practice. In National Academies Press. Transportation Research Board. https://www.trb.org/Main/Blurbs/177400.aspx

[11] Hawkins, C. (2022, April 14). Proterra introduces ZX5 electric bus with 738 kilowatt hours of energy. Proterra. https://www.proterra.com/press-release/zx5-electric-bus-738kwh/

[12] How much CO2 is emitted by manufacturing batteries?. MIT Climate Portal. (n.d.). https://climate.mit.edu/ask-mit/how-much-co2-emitted-manufacturing-batteries

[13] Lan, X., & Scripps Institution of Oceanography. (2023, November 5). NOAA GLA DATA. Noaa.gov; National Oceanic and Atmospheric Administration. https://gml.noaa.gov/webdata/ccgg/trends/co2/co2_annmean_mlo.txt

[14] Lithium - historical statistics (data series 140). Lithium - Historical Statistics (Data Series 140) | U.S. Geological Survey. (n.d.). https://www.usgs.gov/media/files/lithium-historical-statistics-data-series-140

[15] Monastersky, R. (2014, December 18). Satellite maps global carbon dioxide levels. Nature News. https://www.nature.com/articles/nature.2014.16615

[16] MTA. (n.d.-b). https://new.mta.info/document/120411

[17] NASA. (2021, May 13). Watching the land temperature bell curve heat up (1950-2020) – climate change: Vital signs of the planet. NASA. https://climate.nasa.gov/climate_resources/266/watching-the-land-temperature-bell-curve-heat-up-1950-2020/

[18] Nunno, R. (2018, October 26). Fact Sheet | Battery Electric Buses: Benefits Outweigh Costs | White Papers | EESI. www.eesi.org; Environmental and Energy Study Institute. https://www.eesi.org/papers/view/fact-sheet-electric-buses-benefits-outweigh-costs#:~:text=Battery%2Dcharged%20vehicles%20typically%20have

[19] Proterra. (2020, September 15). The Proterra ZX5 Electric Transit Bus | Proterra. Www.proterra.com; Proterra. https://www.proterra.com/products/transit-buses/

[20] Study finds significant slowdown in decrease of nox emissions in US ... (2018, May 1). https://www.greencarcongress.com/2018/05/20180501-ncar/comments/

[21] Sunline Transit Agency Fuel Cell Electric Bus Progress Report - NREL. (n.d.-e). https://www.nrel.gov/docs/fy22osti/83559.pdf

[22] Transitioning to a zero-emissions bus fleet. MTA. (n.d.). https://new.mta.info/project/zero-emission-bus-fleet

[23] U.S. Department of Energy. (2020, November 14). Alternative Fuels Data Center. Afdc.energy.gov; U.S. Department of Energy. https://afdc.energy.gov/data/widgets/10309

[24] U.S. PIRG Education Fund, Environment America Research & Policy Center, Frontier Group, Horrox, J., & Casale, M. (2019). Electric Buses in America. https://pirg.org/wp-content/uploads/2022/07/US_Electric_bus_scrn-3.pdf

[25] Valev, N. (2023). Gasoline and diesel prices by country | GlobalPetrolPrices.com. GlobalPetrpPrices.com. https://www.globalpetrolprices.com/

[26] Zheng, M. (2023, June 21). The environmental impacts of lithium and Cobalt Mining. Earth.Org. https://earth.org/lithium-and-cobalt-mining/ [Original source: https://studycrumb.com/alphabetizer]