A COST BENEFIT ANALYSIS OF ELECTRIFICATION OF THE NEW YORK CITY METROPOLITAN TRANSPORTATION AUTHORITY BUS FLEET

by
Crystal Yeh

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I. Abstract

Cities and municipalities all over the world are currently considering the decarbonization potential of electrifying part or all of their public bus fleet. Bus fleets, with their planned routes, mileage, and life spans may provide an opportunity for electrification that is on par with light duty vehicle electrification. Currently, all electric buses have a higher up-front purchase or acquisition cost than their diesel counterparts of similar dimensions and manufacturers. This creates a need for fleet vehicle owners to weigh the costs and benefits of electrifying their fleet.

The New York City (NYC) Metropolitan Transportation Authority (MTA) is the United State's largest public transit authority. It has a combined fleet of 5757 buses. This paper considers the question: if the New York City Metropolitan Transportation Authority conducted a cost benefit analysis on converting their existent bus fleet to a partial or all electric bus fleet, would they find that the benefits of electrifying their bus fleet outweigh the costs?

Three scenarios were modelled in the research: The first model, the business as usual (BAU) model, considers the Total Cost of Ownership of the current fleet over the typical lifespan of a bus. The second model is a 50% adoption scenario which considers the costs and benefits of having an identically large fleet that was half identical to the BAU model, and half all-electric. The third model is a 100% adoption scenario, which considers the costs and benefits of an identically large fleet being all electric.

Model 1 results in levelized costs over the 12-year lifetime of $4,188,213,849 for the 5757 bus fleet, but no benefits other than avoiding the costs of electric buses. Model 2 resulted in levelized costs of $4,736,777,749, and benefits totaling $388,242,547. Model 3 resulted in levelized costs over of $5,284,423,736, and benefits totaling $656,517,051. Model 2 and 3 both showed that significant emission reductions were possible when electrifying the bus fleet.

II. Acknowledgement

I would like to acknowledge the guidance of my advisor Professor Austin Brown in the development and writing process of this paper. I would also like to acknowledge my capstone Professor Dan Zachary for his guidance.

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V. Background

In the US, transportation accounted for about 28.2 percent of total greenhouse gas emissions in 2018[1]. For this reason, the transportation sector has long been seen among policy makers as a key sector for national, state, and local decarbonization efforts. Furthermore, the effort to decarbonize the transportation sector provides a global opportunity for technology transfer initiatives. One of the most talked about innovations for the vehicle sector are battery electric vehicles (BEVs), a clean propulsion technology. Currently, much of the public conversation and academic research has been focused on the light duty vehicles (vehicles that weigh under 10,000 lbs) that individuals typically own. Medium duty vehicles (defined as weighing 10,001 and 26,000 lbs), which are typically used in the commercial and public fleet sector, provide a unique opportunity for decarbonization and vehicle electrification. Popular medium duty vehicles applications include buses, which are often used for school, corporate, and municipal transit; and also include delivery trucks and other short distance trucks used for commercial purposes.

One of the major barriers to adoption is that electric buses are a newer technology and purchase costs are higher than that of a diesel bus due to the lack of the economy of scale diesel buses have. However, operation and maintenance (O&M) and fuel costs tend to be relatively lower for electric buses. Electric buses also have associated marginal infrastructure costs to consider, such as the construction of refueling stations.

The New York City (NYC) Metropolitan Transportation Authority (MTA) is the United State's largest public transit authority with a fleet of subway train cars and buses. This paper will

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[1] *Sources of Greenhouse Gas Emissions | Greenhouse Gas (GHG) Emissions | US EPA*. (n.d.). Retrieved November 22, 2020, from https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions

explore the research question: if a cost benefit analysis were conducted involving the conversion of the NYC MTA existent bus fleet to a partial or all electric bus fleet, would the benefits of electrifying their bus fleet outweigh the costs? This research will have implications for not just the nation's largest public transit authority, but also can serve as a framework for other municipal public transit agency fleet owners to consider the costs and benefits of electrifying their public bus fleet.

i. Technology

Public transit buses usually have a similar chassis but can differ in their sizes and underlying drive train technologies. Buses have several options for their drive train. Diesel, compressed natural gas, hybrid electric, and battery electric (also known as "BEB" or "all-electric"). All but the first are usually considered by policy makers to be "cleaner" (lower emitting) options. Diesel buses are the oldest technology of these and still the most prevalent in most municipalities due to lower upfront purchase costs, economies of scale, and a fueling infrastructure built for it (diesel gas stations are found in 55 percent of retail fuel sites in North America[2]). Diesel buses are the most polluting of the drive train technologies. Exhaust from diesel buses typically contain carbon monoxide (CO), hydro-carbons (HC), nitrogen oxides (NOx), particulate matter (PM), carbon dioxide (CO_2), and sometimes sulfur dioxide unless using low sulfur fuel or scrubbers. Besides carbon dioxide, the primary greenhouse gas that contributes to anthropogenic climate change all of those pollutants can cause severe negative effects on cardiovascular and respiratory health, as well as being carcinogenic. According to the Center for Disease Control and Prevention (CDC) website; "adult exposure to diesel pollution

[2] *Fuel Locator | Diesel Technology Forum*. (n.d.). Retrieved November 28, 2020, from https://www.dieselforum.org/diesel-drivers/fuel-locator

contributes to 27,000 heart attacks, 14,500 hospitalizations and 2.4 million lost work days each year"[3].

Electric buses utilize an electric drive system in the form of battery-electric, hybrid-electric and fuel cell technologies. In this paper the terms "battery-electric", "BEB", and "all electric" will be used interchangeably. Battery electric buses have a similar chassis as their diesel counterparts, but their primary difference is that the electrochemical storage battery is the sole power source for the vehicle, which provides energy for propulsion through an electric traction motor as well as power all vehicle accessory systems. In terms of known benefits, they offer reduced or zero vehicle emissions, increased efficiency, reduced fuel use, quiet operation, enhanced performance, and usually lower maintenance costs. What is notable is that gas-powered vehicles typically have an energy conversion efficiency between 25-50%, whereas electric vehicles have an energy conversion efficiency upwards of 90%, which is partially due to the fact that only the later can recover energy while braking.[4]

There are existing precedents to municipalities electrifying their bus fleet both partially and fully. China's city of Shenzhen, for instance, was the first city to ever fully electrify their fleet, a process they began in 2011 and completed in 2017, electrifying over 16,300 buses (which is about 3 times the size of New York City's bus fleet)[5]. To accommodate the infrastructure necessary, the city built 510 bus charging stations and 8,000 charging poles. This bus

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[3] *Clean Diesel Bus Fleets | Health Impact in 5 Years | Health System Transformation | AD for Policy | CDC*. (n.d.). Retrieved November 28, 2020, from https://www.cdc.gov/policy/hst/hi5/cleandiesel/index.html

[4] *A Close-Up Look at Electric Vehicle Powertrain Components*. (n.d.). Retrieved November 28, 2020, from https://www.innovativeautomation.com/the-electric-vehicle-drivetrain/

[5] (N.d.). Retrieved November 28, 2020, from https://mp.weixin.qq.com/s?__biz=MzIyMzMzNjE3NA==&mid=2247489746&idx=1&sn=a8bb0210f150a93d80718a202018d42f&chksm=e81e9b53df6912452e156066766e8b8eaf8fc9107033b46df16eed95b538609ac0b8dee55feb&mpshare=1&scene=1&srcid=1228DNpV2EJVJ81zBrr0yjzT

electrification is estimated to replace 345,000 tons of fuel and reduce carbon dioxide emissions by 1.35 million tons[6].

ii. New York City Metropolitan Transportation Authority (MTA) Bus Fleet

New York City's Metropolitan Transportation Authority (NYC MTA) has the largest bus fleet in the United States of 5757 active buses as of 2019. It also boasts the greatest ridership in the nation at 2.2 million per average weekday, or 678 million annual ridership in 2019[7]. Compare this to the second largest bus system in the US, Los Angeles, which had an annual bus ridership in 2019 of 278 million, less than half of NYC's. There are also a whopping 234 local routes, 20 Select Bus Service, and 73 express bus routes in the five boroughs. Furthermore, the city reported greenhouse gas emissions of CO_2 equivalent of 563,826 tons. Of which about 30% are from emissions from the transportation sector.[8] For this reason, it is clear why policy makers would be interested in the potential for bus electrification for this fleet.

VI. Research Method

i. Methodology

The basic methodology of this paper was a cost benefit analysis. There were three modelled scenarios. The first model, the business as usual (BAU) model, considers the Total Cost of Ownership of the current fleet over the typical lifespan of a bus. The second model is a 50% adoption scenario which considers the costs and benefits of having an identically large fleet

[6] Ibid

[7] *Facts about New York City subways and buses*. (n.d.). Retrieved November 28, 2020, from https://new.mta.info/agency/new-york-city-transit/subway-bus-facts-2019

[8] *GHG Inventory—NYC Mayor's Office of Sustainability*. (n.d.). Retrieved November 28, 2020, from https://nyc-ghg-inventory.cusp.nyu.edu/

that was half identical to the BAU model, and half all-electric. The third model is a 100% adoption scenario, which considers the costs and benefits of an identically large fleet being all electric.

In the cost benefit analysis, for each modelled scenario, the costs are calculated, then the benefits are calculated. Then the three models will be compared and contrasted both quantitatively and qualitatively. The costs will be calculated through a Total Cost of Ownership analysis, which considers the lifetime costs of the fleet over the average lifetime of a bus. The benefits will attempt to quantify the avoided environmental costs and environmental health costs.

ii. Assumptions

The data collection process during the research revealed the need to use a mixture of values specific to the NYC MTA system and certain numbers that are just industry averages. For instance, the size of the NYC bus fleet (number of buses), the number of each type of bus, the length, the Vehicle Miles Travelled (VMT) per bus per year, and the greenhouse gas emissions of the NYC MTA bus system were all collected from public MTA websites and are specific to the transit system. However, certain assumptions such as the exact purchase cost per bus, vehicle O&M cost, fuel economy, fuel cost, and bus lifetime, were not readily available public data for the NYC MTA bus system. Therefore, industry averages were used for those numbers, specifically one pulled off of a study from the Journal of Transportation Research.[9]

Other assumptions include the assumption that Operator Labor costs remain constant between a diesel bus or electric bus fleet, and therefore will not be used in the cost calculations.

[9] Tong, F., Hendrickson, C., Biehler, A., Jaramillo, P., & Seki, S. (2017). Life cycle ownership cost and environmental externality of alternative fuel options for transit buses. *Transportation Research Part D: Transport and Environment*, *57*, 287–302. https://doi.org/10.1016/j.trd.2017.09.023

There is also an assumption of only considering ownership, with no consideration for leasing, which is not always realistic for some transit systems. Many transit systems do lease buses. NYC however, typically purchases its buses. A discount rate of 1% was assumed in the calculation of Net Present Value.

VII. Analysis and Results

i. Costs

a. Model 1: Business as Usual

The first model, Business as Usual, calculated the Total Cost of Ownership for the fleet owner, levelized over the 12 year life cycle of a typical bus. It started with using data from the publicly available MTA Capital Program Oversight Committee Meeting in January, 2019 that had the characteristics of the existing NYC MTA bus fleet. Table 1 below provides a summary.

Table 1. NYC Bus Fleet Bus Totals, by Type

NYC Bus Fleet	MTA Bus Total	Length (ft)
Standard		
Diesel	1453	40
CNG	644	40
Hybrid	1673	40
Articulate		
Diesel	868	60
CNG	105	60
Express	1014	45
Total	5757	285

The buses were broken down by type (diesel, CNG, hybrid) and by length because those dimensions affect the purchase cost, fuel cost, O&M costs, and fuel economy (MPGDE). CNG had lower fuel costs than diesel. Both hybrid and CNG have better fuel economies than diesel.

Larger buses have a poorer fuel economy than smaller buses (although they deliver more people, so they are an important asset in a public transit fleet).

As an assumption, the MTA bus total of 5757 was held constant for each model. The Total Cost of Ownership was calculated using purchase costs ($/bus), vehicle O&M cost, fuel economy, fuel cost, bus lifetime, and vehicle miles travelled per year. The table below summarizes the levelized costs for Model 1 over the average 12-year lifespan of a bus, showing both per bus costs and fleet costs. See Figure 2 in the Appendix for a detailed spreadsheet on the calculation methodology.

Table 2. Model 1 Levelized Costs

NYC Bus Fleet	NYCT DOB + MTA Bus Total	Per bus levelized cost over lifetime ($)	Fleet costs over lifetime ($)
Standard			
Diesel	1453	624,439	907,309,752
CNG	644	650,766	419,093,591
Hybrid	1673	877,521	1,468,092,895
Articulate			
Diesel	868	762,288	661,665,974
CNG	105	941,624	98,870,571
Express	1014	624,439	633,181,066
Total	5757	4,481,078	4,188,213,849

Figure 1. in the Appendices summarizes the spreadsheet used in the calculation. Understanding how the costs of Model 1, the Business as Usual scenario compares with the other models below is more useful for contextualizing the cost of fleet ownership.

b. Model 2: 50% Adoption Scenario

In this scenario, we consider the costs and benefits of replacing half of the 5757 bus fleet with BEBs, while half of the bus fleet retained the same costs. 2879 (rounded up from half of 5757) buses in the fleet were modelled as being replaced by BEBs. The table below summarizes the levelized costs for Model 2 over the average 12-year lifespan of a bus, showing both per bus costs and fleet costs. See Figure 3 in the Appendix for a detailed spreadsheet on the calculation methodology.

Table 3. Model 2 Levelized Costs

	Number of Buses	Per bus levelized cost over lifetime ($)	Fleet Costs ($)
50% Model 1 fleet	2878	624,439	2,094,106,925
50% Electric Fleet	2879	917,913	2,642,670,824
Model 2 Fleet costs	5757		4,736,777,749

For battery electric buses, purchase costs are higher than for diesel buses, however O&M and fuel costs are much lower, and the fuel economy of a battery electric bus is superior. One cost factor that heavily disadvantages electric buses is the marginal infrastructure cost. Using an electric fleet requires investment in refueling infrastructure in bus depots, which incurs a marginal cost for each bus added. Infrastructure and purchase costs are the reason that the levelized cost of owning an electric bus is so much higher than that of a typical diesel bus.

c. Model 3: 100% Adoption Scenario

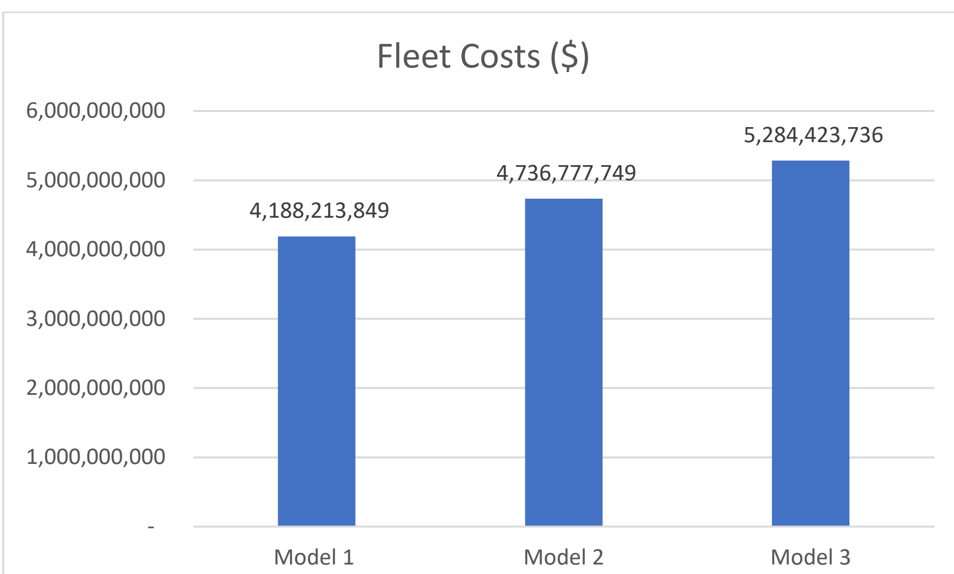
In this scenario, we consider the costs and benefits of replacing all of the 5757 bus fleet with BEBs. The table below summarizes the levelized costs for Model 3 over the average 12-year lifespan of a bus, showing both per bus costs and fleet costs. See Figure 4 in the Appendix for a detailed spreadsheet on the calculation methodology.

Table 4. Model 2 Levelized Costs

	Number of Buses	Per bus levelized cost over lifetime ($)	Fleet Costs ($)
100% Electric Fleet	5757	917,913	5,284,423,736

It is most helpful to contextualize the costs of the scenarios in comparison to each other. The Figure below summarizes the fleet costs for the three different modelled scenarios as they compare to each other.

Figure 1. Scenario Fleets Compares



Evidently, Model 2, the fleet that is 50% electric is more costly to the fleet owner than the fleet that is a more traditional mixture of diesel, diesel electric, and CNG. Furthermore, Model 3, the fleet that is 100% electric is more costly than the 50% electric fleet as well. Clearly, the cost analysis explains why not all fleet owners are planning to electrify their fleet, at least not not in its entirety. Battery electric buses are still an emerging technology in the mid duty vehicle sector, and the lack of existing infrastructure to accommodate its use creates marginal costs to fleet electrification.

ii. Benefits

The primary benefits of switching from a primarily Diesel to an Electric fleet are environmental. It can be thought of as two distinct categories: environmental health, which is focused on local pollution that tends to directly impact human health; and global anthropogenic climate change, which is focused on greenhouse gas emissions. There exists significant literature and debate regarding the quantification of environmental costs and benefits. For this study, the Social Cost of Carbon was used in the calculations of the benefits of switching to an electric fleet. For many fleet owners who live in a state or city with climate change related decarbonization policies, reducing carbon emissions is a crucial benefit of electrifying a fleet. This paper is using the Federal Government's Interagency Working Group on the Social Cost of Greenhouse Gases (IWG) High Impact Estimate (95th percentile estimate at 3% discount rate), which us $148 dollars per metric ton of CO_2. This indicates that for every ton of CO_2 emitted, there is a Social Cost to society in the form of marginal global warming of $148. Furthermore, an Argonne National Laboratory study was used to obtain lifetime mileage-weighted average air pollutant emission factors (in grams of pollutant emitted per mile) for the pollutants PM 2.5, SO_2

and NO_x[10]. Finally, an Environmental Protection Agency Office of Air and Radiation study was used to obtain total dollar value (in terms of health costs) per ton of directly emitted PM 2.5, SO_2 and NO_x for on-road mobile sources, using 2010 dollars and a 3% discount rate[11]. It is quite challenging to quantify environmental benefits, which is will further discussed in the Discussion section of this paper.

a. Model 1: Business as Usual

The benefits of the Business as Usual scenario for the purpose of this study are avoided costs of building new infrastructure to accommodate an electric bus fleet. The cost comparison above between the scenarios already factors that in. Calculating the benefits of the other two models provides a quantitative and qualitative comparison.

b. Model 2: 50% Adoption Scenario'

The benefits of Model 2 involve the calculation of displacing the emissions of half of the mostly diesel fleet with BEBs. Therefore, a calculation of the carbon emissions of 2879 diesel buses was done, and the carbon intensity and Social Cost of Carbon was used to calculate the benefits of avoiding the emissions of 2879 diesel buses. This is summarized in Table 5 below. See Figure 5 in the Appendix for a detailed spreadsheet on the calculation methodology.

Table 5. Model 2 Avoided Carbon Dioxide Costs

Model 2 Benefits	Avoided environmental cost per bus over 12 years	Fleet Avoided environmental cost over 12 years
Avoided Carbon Dioxide cost	41,702	120,061,226

[10] Cai, Hao. "Updated Emission Factors of Air Pollutants from Vehicle Operations in GREETTM Using MOVES." Argonne National Laboratory Energy Systems Division, 25 Oct. 2013.

[11] *US EPA*. (n.d.). Estimating the Benefit per Ton of Reducing PM2.5Precursors from 17 Sectors 1 Technical Support Document Estimating the Benefit per Ton of Reducing PM2.5Precursors from 17 Sectors. *U.S. Environmental Protection AgencyOffice of Air and Radiation*

The benefits of local pollution reduction of avoiding the PM 2.5, NOx, and SO2 emissions of 2879 buses were calculated using emission rates and damage per ton of emissions. Figure 6 in the Appendix illustrates the detailed calculation. The table below summarizes the Avoided Environmental Costs of the local pollutants and the carbon dioxide.

Table 6. Summary of Avoided Environmental Costs, Model 2

Model 2 Benefits	Fleet Avoided environmental cost over 12 years ($)
Avoided carbon dioxide cost	120,061,226
Avoided PM 2.5 Cost	174,610,428
Avoided SO_2 Cost	1,928,296
Avoided NOx Cost	91,642,597
Total	388,242,547

The purpose of Model 2 is to understand the costs and benefits to a fleet owner if just the costs of electrifying half of the fleet were considered, as well as what benefits can be reaped from electrifying half of the fleet.

c. Model 3: 100% Adoption Scenario

The benefits of electrifying the entire fleet are calculated as the avoided costs, or displacement, of the emissions of all of the original fleet. Therefore, a calculation of the carbon emissions of 5757 diesel buses was done, and the carbon intensity and Social Cost of Carbon was used to calculate the benefits of avoiding the emissions of 5757 diesel buses. This is summarized in Table 6 below. See Figure 7 in the Appendix for a detailed illustration on the calculation.

Table 7. Model 3 Avoided Carbon Dioxide Costs

Model 3 Benefits	Avoided environmental cost per bus over 12 years	Fleet Avoided environmental cost over 12 years
Avoided Carbon Dioxide	41,702	240,080,750

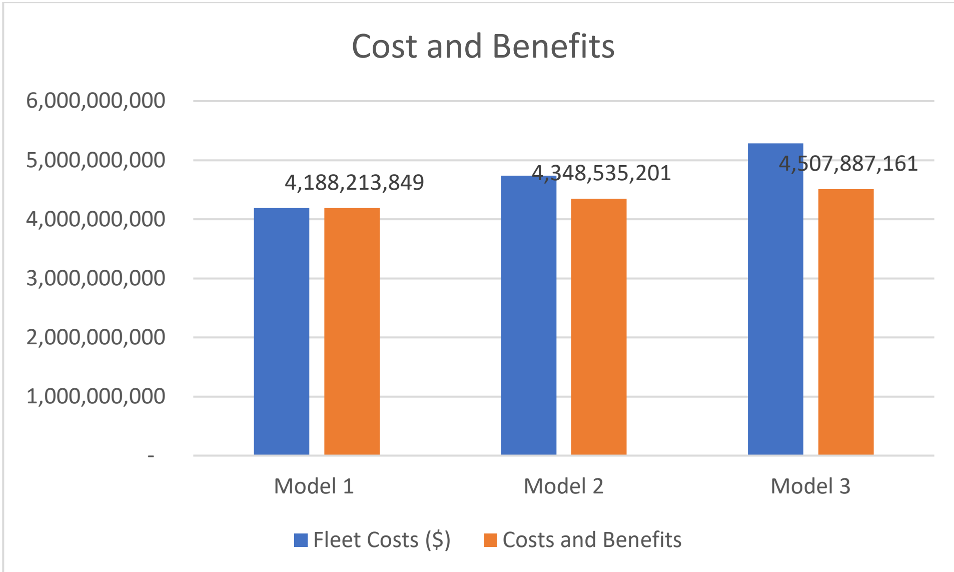
The benefits of local pollution reduction of avoiding the PM 2.5, NOx, and SO2 emissions of 5757 buses was calculated using emission rates and damage per ton of emissions. Figure 8 in the Appendix has a more detailed methodology. The table below summarizes the Avoided Environmental Costs of the local pollutants and the carbon dioxide.

Table 8. Summary of Avoided Environmental Costs, Model 3

Model 3 Benefits	Fleet Avoided environmental cost over 12 years ($)
Avoided carbon dioxide cost	240,080,750
Avoided PM 2.5 Cost	349,281,526
Avoided SO_2 Cost	3,857,262
Avoided NOx Cost	183,317,036
Total	776,536,575

What is the most helpful to consider from a fleet owners' perspective is the costs and benefits added together. Because benefits are avoided costs, they can be considered negative costs for this purpose. This is summarized in Figure 9 below.

Figure 9. Costs and Benefits Summary, across Models



When benefits are factored into the costs on a net basis, the net cost of the three different Models become very comparable to each other, with Model 2 being just 3% more costly than Model 1 and Model 3 being just 3% more costly than Model 2. Still, it is evident that a partial electrification scenario is more costly than business as usual, and a total electrification scenario is more costly still, although significantly mitigated when factoring benefits. What is not considered in this paper are policy goals. The fleet might have policy goals that would find the costs and benefits between the three Models would still warrant the electrification of a bus fleet.

VIII. Discussion

The purpose of this study is to help bus transit fleet owners consider the costs and benefits of electrifying their bus fleet. The reason the three models were chosen is that you have to consider the costs and benefits of the business as usual scenario in order to understand what happens when a business does not change their operations significantly. The purpose of Model 2 was that for many bus transit owners, electrification goals may often times be partial, in order to mitigate some of the costs of total fleet electrification, while also reaping the benefits of partial fleet electrification. Model 2's results may be useful for many municipalities that have a modest decarbonization goal over the next 12 years. The purpose of Model 3 is to consider the most aggressive electrification scenario, if a fleet owner were to own an all-electric fleet, holding constant the number of buses and vehicle miles travelled. Model 3's results could be useful for public transit fleet owners who live in municipalities that have more aggressive decarbonization policies, that could require from the top-down total electrification, regardless of the fact that it may be more expensive for the fleet owner, all benefits included. Despite the fact that this study showed that increased electric bus penetration is indeed more costly for the fleet owner than the business as usual, even considering the benefits, there are many real world policy scenarios where fleet owners do not operate solely with cutting costs in mind. Decarbonization goals may be the priority.

It is important to note that the scope of this research is very limited. Firstly, this study did not consider a year by year approach for modelling. Fleet owners typically retire and replace buses in their fleet year by year. This choice in modelling was not chosen due to inability to discover the appropriate data to make such accurate modeling. This means the modelling that was performed is not entirely realistic, as the buses in the fleet will have been purchased all in different years and retired in different years.

The value of the Social Cost of Carbon will always vary based on how it is modelled and who is doing the modelling. That's because carbon dioxide lacks clear marginal costs to any individual unit, be it fleet, city, country etc.; these costs are global. Therefore they need to be considered as a proportional fraction of carbon dioxide's global costs, as a unit of carbon dioxide has a unit of warming and therefore climate change effect. Furthermore, what discount factor you choose also affects the calculation significantly. The modelling of the Social Cost of Carbon is very controversial in the environmental economics community, the controversy of which will not be explored here.

IX. Conclusion

In conclusion, a fleet owner choosing to electrify their fleet should consider this study for a comparison of the costs and benefits. Evidently, electrifying half of a bus fleet is more expensive than the business as usual scenario of not doing so. Electrifying the entirety of a bus fleet is more expensive still than both scenarios. Fleet owners don’t necessarily make decisions solely based on costs and benefits aggregated. Public transit fleets are public private partnerships and oftentimes subjected to top down policy goals from the city or state government. Those policy goals may value decarbonization or reduction of local pollution efforts above pure considerations of costs.

X. References

i. Appendices

Figure 2

NYC Bus Fleet	NYCT DOB + MTA Bus Total	Length (ft)	Purchase Cost $/bus	Vehicle O&M cost ($/mile)	Fuel Economy (MPGDE)	Fuel Cost $/gallon of diesel equivalent	Bus Lifetime	Vehicle miles travelled per year per bus	Gallons of diesel needed per bus per year	Fuel cost per bus per year	Fuel cost per bus per year NPV	O&M costs per bus per year	O&M costs per bus per year NPV	Per bus levelized cost over lifetime	Fleet costs	Discount rate
Standard	3780															
Diesel	1453	40	485,000	$0.85	4.8	$2.30	12	7749	1614	$3,713.06	$4,189.00	$6,586.65	$7,431	624,439	907,309,752	1%
CNG	644	40	525,000	0.85	4.3	$1.50	12	7749	1802	$2,703.14	$3,049.62	$6,586.65	$7,431	650,766	419,093,591	1%
Hybrid	1673	40	758,000	0.74	5.76	$2.30	12	7749	1345	$3,094.22	$3,490.83	$5,734.26	$6,469	877,521	1,468,092,895	1%
Articulate	973															
Diesel	868	60	600,000	0.85	3.3	$2.30	12	7749	2348	$5,400.82	$6,093.08	$6,586.65	$7,431	762,288	661,665,974	1%
CNG	105	60	800,000	0.85	3	$1.50	12	7749	2583	$3,874.50	$4,371.13	$6,586.65	$7,431	941,624	98,870,571	1%
Express	1014	45	485,000	0.85	4.8	$2.30	12	7749	1614	$3,713.06	$4,189.00	$6,586.65	$7,431	624,439	633,181,066	1%
Total	5757									22498.80147	25382.65508	38667.51	43623.83794	4,481,078	4,188,213,849	

Figure 3

Number of BEBs	Purchase Cost $/bus	Vehicle O&M cost ($/mile)	Fuel Economy (MPGDE)	Fuel economy (Miles/kwh)	Fuel Cost $/gallon of diesel equivalent	Bus Lifetime	Vehicle miles travelled per bus per year	Gallons of diesel equivalent needed per bus per year	Fuel cost per bus per year	Fuel Cost per year NPV	O&M costs per bus per year	O&M costs per bus per year NPV	Per bus infrastructure cost	Per bus levelized cost over lifetime	Total Costs	Discount rate
2879	800000	0.6	22.1	0.55	2.1	12	7749	351	736	831	4649	5245	45000	917,913	2,642,670,824	1%

Figure 4

BEB	Length (ft)	Purchase Cost $/bus	Vehicle O&M cost ($/mile)	Fuel Economy (MPGDE)	Fuel economy (Miles/kwh)	Fuel Cost $/gallon of diesel equivalent	Bus Lifetime	Vehicle miles travelled per bus per year	Gallons of diesel equivalent needed per bus per year	Fuel cost per bus per year	Fuel Cost per year NPV	O&M costs per bus per year	O&M costs per bus per year NPV	Discount Rate	Per bus infrastructure cost	Per bus levelized cost over lifetime	Total Costs
5757	40	800,000	0.6	22.1	0.55	2.1	12	7749	$350.63	$736.33	831	4,649	5,245	1%	45000	917,913	5,284,423,736

Figure 5

Avoided Environmental Costs	Gallons of Diesel used by Model 1 by typical diesel bus	Carbon intensity of ULS Diesel (gCO2e/MJ)	Carbon intesity Diesel (lbsCO2e/dge)	Greenhouse gas emissions (CO2E lbs)	Greenhouse gas emissions (CO2E tons)	Social cost of carbon ($/CO2E ton)	Cost of GHG emissions	Avoided environmental cost per bus over 12 years	Fleet Avoided environmental cost over 12 years
Avoided environmental cost per bus per year	1614	101.65	29.09	46962.2	23.4811	148	3,475	41,702	120,061,226

Figure 6

Model 2 Avoided Pollutant Cost	Vehicle miles travelled per bus per year	Bus lifetime	Vehicle miles travelled fleet	Emission rates for urban buses (grams/mile)	Emissions over lifetime (grams)	Emissions over lifetime (tons)	Damage ($/ton emissions)	Cost to Society ($) over 12 years
Avoided PM 2.5	7749	12	267619464	0.5919	158403961	174.610428	1,000,000	174,610,428
Avoided SO2	7749	12	267619464	0.1127	30160714	33.2464862	58,000	1,928,296
Avoided NOx	7749	12	267619464	14.793	3.959E+09	4363.93319	21,000	91,642,597
total								268,181,321

Figure 7

Avoided Environmental Costs	Gallons of Diesel used by Model 1 by typical diesel bus	Carbon intensity of ULS Diesel (gCO2e/MJ)	Carbon intesity Diesel (lbsCO2e/dge)	Greenhouse gas emissions (CO2E lbs)	Greenhouse gas emissions (CO2E tons)	Social cost of carbon ($/CO2E ton)	Cost of GHG emissions	Avoided environmental cost per bus over 12 years	Fleet Avoided environmental cost over 12 years
Avoided environmental cost per bus per year	1614	101.65	29.09	46962.17	23.4810844	148	3,475	41,702	240,080,750

Figure 8

Model 3 Avoided Pollutant Cost	Vehicle miles travelled per bus per year	Bus lifetime	Vehicle miles tra	Emission rates for urban buses (grams/mile)	Emissions over lifetime (grams)	Emissions over lifetime (tons)	Damage ($/ton emissions)	Cost to Society ($) over 12 years
Avoided PM 2.5	7749	12	535331916	0.5919	316862961	349.281526	1,000,000	349,281,526
Avoided SO2	7749	12	535331916	0.1127	60331906.9	66.5045244	58,000	3,857,262
Avoided NOx	7749	12	535331916	14.793	7919165033	8729.38269	21,000	183,317,036
total								536,455,825

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XI. Biographical statement

The author of this paper possesses a Bachelor of Arts in Environmental Studies and Chinese (dual major) from Hunter College, the City University of New York. The author has four years of experience working in natural gas and electricity utility regulatory policy at the California Public Utilities Commission. In pursuit of her Masters of Science at Johns Hopkins University, she has completed courses in Transportation Policy in a Carbon Constrained World, Principals and Applications of Energy Technology, as well as several other relevant coursework.