BUS ELECTRIFICATION

Accelerating the Electrification of Bus Service in the Boston Metro Area

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SUPPORTING ORGANIZATIONS

350 Mass · ACE alternatives for community & environment · Cambridge Bicycle Safety · clf Conservation Law Foundation · EDF Environmental Defense Fund · ELM Environmental League of Massachusetts · Green Energy Consumers Alliance · GreenNewton · GreenRoots · International Brotherhood of Electrical Workers · LivableStreets Connecting People + Places · Transportation for Massachusetts · MASSPIRG · Newton EV Task Force

LIST OF ACRONYMS

AFLEET: Alternative Fuel Life-Cycle Environmental and Economic Transportation Tool

AVERT: Avoided Emissions and Generation Tool

CNG: Compressed Natural Gas

CO2: Carbon Dioxide

DEQ: Diesel Emissions Quantifier Tool

DOE: Department of Energy

EPA: Environmental Protection Agency

GHG: Greenhouse Gas

GWSA: Massachusetts Global Warming Solutions Act

THE MBTA: Massachusetts Bay Transportation Authority

PM: Particulate Matter

TCO: Total Cost of Ownership

ZEV: Zero Emission Vehicle

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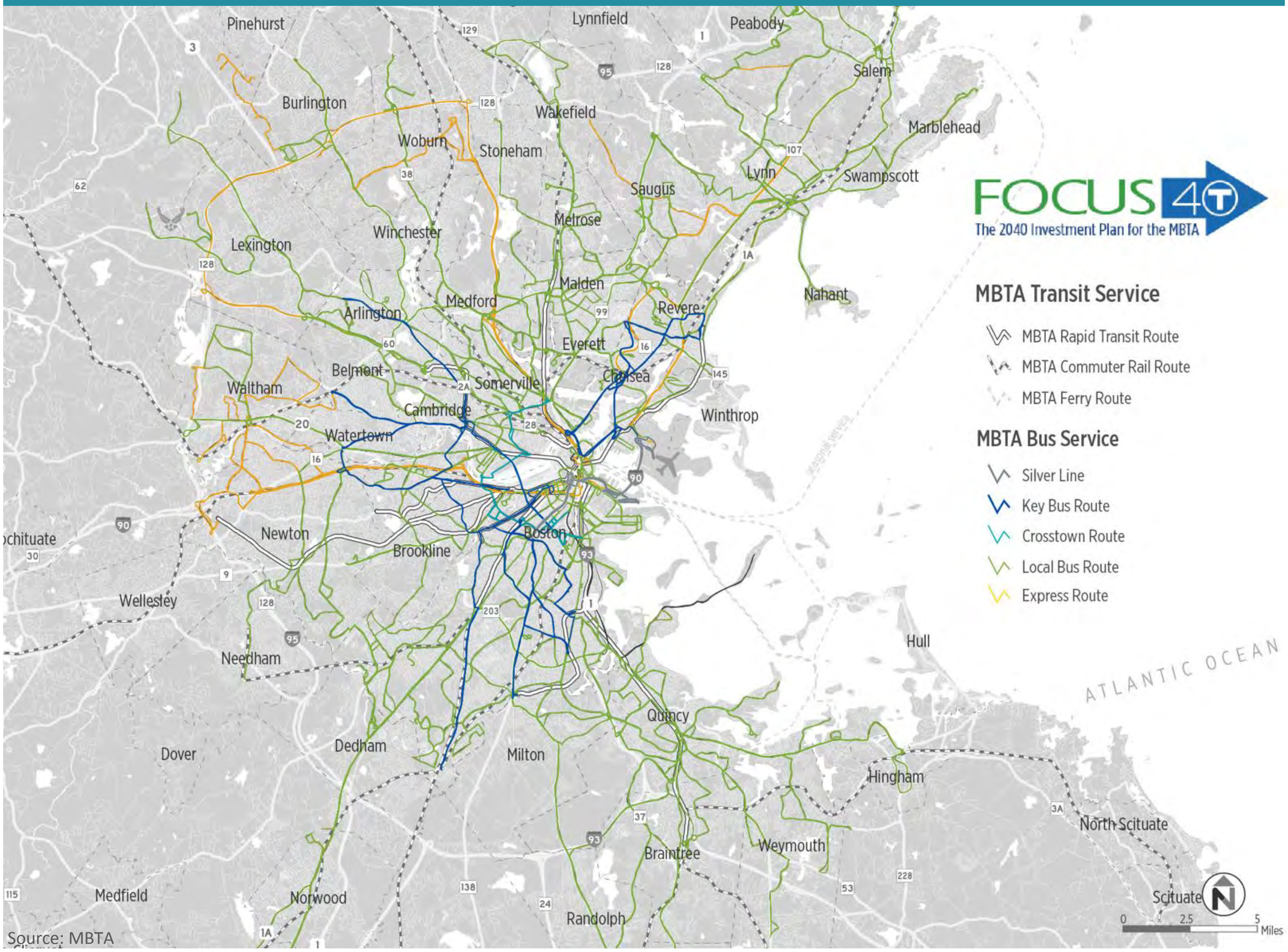
Figure 1: Map of the MBTA's bus routes[1]



Source: MBTA

EXECUTIVE SUMMARY

The Massachusetts Bay Transportation Authority (the MBTA) operates one of the largest transit agencies in the country, with over 170 bus routes in 44 towns and cities[2] in the Greater Boston region and an average of 410,000 weekday bus trips.[3] This report analyzes the economic, environmental, and public health benefits of electrifying the MBTA's fleet of more than 1,150 buses, and calls on the MBTA to publicly commit to a facilities and fleet management plan that would fully electrify MBTA's bus fleet by 2030 while centering equity and people in the process by prioritizing garage upgrades and bus electrification for routes serving low-income neighborhoods and communities of color.

The MBTA's fleet is currently comprised primarily of diesel, diesel-hybrid, and compressed natural gas (CNG) buses, and purchases in the last four years have emphasized replacing aging diesel buses with diesel-hybrids. In April 2021 the MBTA released a fleet and facility plan update that states that the agency intends to continue to purchase diesel hybrid buses while gradually converting its bus fleet to zero emission technologies over the next two decades. According to the update, the MBTA will purchase close to 400 diesel hybrid buses in the next six years.[4] In contrast, the MBTA plans to purchase just 120 electric buses in that time. This slow and insufficient investment in electric buses is further dependent on the pace of facility modernization efforts. Unfortunately, the MBTA electrification plans will begin by replacing existing electric trolley buses with 35 electric buses, a move that will not replace any fossil fuel buses or reduce pollution or overall emissions. In addition to resulting in no reduction of greenhouse gas (GHG) or particulate emissions, it also places these new buses in some of the most affluent, lowest-pollution areas that the MBTA serves, rather than in environmental justice communities with higher rates of pollution and respiratory illnesses.

Our organizations recognize the shared values held by the MBTA — we agree that the goal should be a zero emission fleet and that the MBTA should prioritize delivering high-quality service to transit critical communities with high percentages of low-income residents and households of color,[5] — but in this report we offer a different vision for the MBTA's future that speeds up the electrification process and centers equity in the planning efforts by prioritizing garage updates and bus routes serving low-income neighborhoods and communities of color. Rather than first replacing already electrified trolley buses with electric buses while adding more diesel hybrid buses to the fleet, as is the current pathway, the MBTA should identify solutions that prioritize upgrades to garages and the electrification of routes that serve the highest percentage of low income residents and people of color, who bear the brunt of transportation related pollution and are more likely to be transit dependent.

Using Argonne National Laboratory's 2019 Alternative Fuel Life-Cycle Environmental and Economic Transportation (AFLEET) modeling tool, the Environmental Protection Agency's (EPA's) Avoided Emissions and Generation Tool (AVERT), EPA's Diesel Emissions Quantifier tool, and data provided by the MBTA, this report compares the cost, public health, and climate impacts of three different fleet scenarios:

1. **Current fleet composition** — A mix of diesel, diesel-hybrid, compressed natural gas (CNG), twenty-eight electric trolley buses, five battery electric buses;
2. **Business-as-usual** — Older, retirement age buses are replaced with diesel hybrids resulting in a fleet that is primarily diesel-hybrid with 175 CNG buses; and
3. **Full electrification** — The entire bus fleet is replaced with zero emission electric buses.[6]

Our analysis shows that fully electrifying the MBTA's buses would reduce the fleet's GHG emissions by 97%, save the MBTA more than $175 million in lifetime operating costs, and save area residents approximately $9 million per year in avoided healthcare costs as result of reduced smog and other transportation-related air pollution. (See Table 1, below.) The report then offers a fleet management plan that would transition the MBTA to a fully electrified fleet over the next ten years by expanding and upgrading the existing trolleybus network and ramping up the procurement of battery electric buses to phase out internal combustion buses over the next decade. Furthermore, this plan is designed to prioritize environmental justice communities and to ensure that electrified service is of at least as high quality as non-electrified service.

Table 1: Electrification Benefits Summary

Metric	Current Fleet Composition	Diesel-Hybrid Scenario	Full Electrification Scenario
Fleetwide Lifetime TCO	$1,258,998,969	$1,227,108,685	$1,052,440,099
Fleetwide Annual CO_2 Emissions (tons)	74,883.87	53,183.33	1,764.24
Annual Avoided Health Costs	NA	$6,317,081.60	$9,079,253.60

Recommendations

Recognizing these benefits and the need for further new bus procurement and electrification planning, our organizations urge the MBTA to take the following steps toward full electrification of its transit bus fleet:

1. **Commit to full bus fleet electrification by 2030.** Los Angeles (2030), San Francisco (2035), and Chicago, New York, and Seattle (all 2040) have already committed to full electrification and taken concrete steps to begin that transition.[7] A gradual shift to electric buses and trolleys over the next ten years is well within the MBTA's reach. Publicly committing to electrifying the fleet by 2030 would provide clear objectives and timelines as the public works with the MBTA to achieve equitable and productive interim steps.
2. **Stop internal combustion engine bus purchases no later than 2023.** The MBTA should commit to ending the purchase of internal combustion engines no later than 2023, which would provide a gradual ramp up toward full electrification and ensure forward-looking bus procurement policies. Postponing the phaseout of fossil fuel bus purchases beyond 2023 would unnecessarily delay the economic, climate, and public

health benefits of electrification. Commitments to stop purchasing fossil fuel buses have already been made by cities such as Seattle (by 2020),[8] San Francisco (by 2025),[9] and Los Angeles (by 2025), and by California's state-wide commitment (2029).[10]

3. **Release a 2030 fleetwide electrification plan by June 2022.**
   Fleet electrification will require broad commitment within the MBTA, and engagement with the public, utilities, state and federal offices, and manufacturers of electric buses and related charging infrastructure. The MBTA should create a detailed bus fleet electrification plan that includes a thorough network wide route analysis to identify electric bus technology options, battery specifications, and charging strategy. The plan should lay out a firm implementation schedule with interim electrification targets and be finalized by June 2022 through a robust and equitable public input process. These steps would help provide a transparent roadmap and allow the public to effectively engage with the MBTA throughout the electrification planning process.
4. **Prioritize low-income and communities of color in its electrification planning.**
   The burden of air pollution and climate change is disproportionately carried by low-income people and communities of color. These communities must be first in line when it comes to the deployment of zero emission electric buses. Electrification planning, buildout of charging infrastructure, and garage modernization should be done in conjunction with local residents and community groups, especially those that are most affected by transportation pollution.
5. **Create an effective charging strategy to expand and build a reliable electric bus network.**
   The MBTA should explore both in-route charging (IRC) and overnight garage charging for electric buses, and in-motion charging (IMC) for trolleys to provide added range resiliency and to ensure the smoothest possible transition to an electric fleet. The electrification plan should include outreach to utilities to discuss any electrical upgrades necessary to accommodate transit bus charging, and to design and implement optimal electricity rates.
6. **Accelerate bus facility modernization and replacement.**
   All of the MBTA's nine bus garages are beyond their useful life or are functionally obsolete.[11] The MBTA's facilities plan lists 2038 as the tentative year for modernization of all existing garages.[12] As the pace of bus facility modernization efforts will govern the pace of bus electrification, the MBTA should adopt an aggressive timeline for garage replacement by advancing the planning, design, and construction of Quincy, Arborway, and Fellsway facilities simultaneously. The MBTA should also advance the modernization of the Southampton and Cabot facilities, instead of relegating them for replacement ten plus years out, as currently planned. These core facilities have the largest capacities and serve a high percentage of low-income residents and people of color. The MBTA should identify MBTA and MassDOT properties that can be used as swing space as these facilities are rebuilt. All new garages starting with Quincy in 2024 must start housing an electric bus fleet from day one.
7. **Make job retraining opportunities available to current employees.**
   As part of the electrification process, the MBTA should provide opportunities for current bus drivers and fleet maintenance staff to update their skills to operate and maintain the growing electric bus fleet while providing new greener jobs and training opportunities for workers from disadvantaged communities.

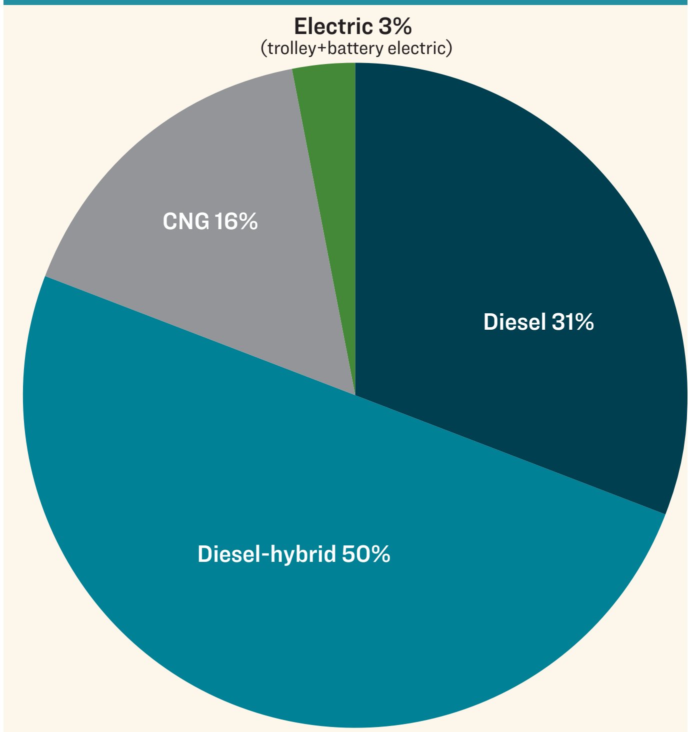
INTRODUCTION

A. The MBTA Bus Fleet

With more than 170 bus routes,[13] an average of 410,000 weekday bus trips[14] and a fleet of more than 1,150 buses,[15] the Massachusetts Bay Transportation Authority ("the MBTA") operates one of the largest bus transit systems in the United States. Fossil fuel buses currently make up approximately 97% of the fleet: 338 (approximately 31%) are diesel vehicles, 540 (50%) are diesel-hybrid vehicles, 175 (16%) are compressed natural gas ("CNG") vehicles, 28 (2.5%) are electric trolley buses, and only five (0.5%) are battery electric buses.[16]

Since first purchasing diesel-hybrid vehicles in 2010, the agency has converted roughly half of its bus fleet to diesel-hybrids, in an attempt to reduce emissions and lower fuel consumption,[17] but has stopped short of a meaningful procurement shift toward electric buses.

Figure 2: Current MBTA Bus Fleet Composition by Vehicle Fuel Type



In 2019, the MBTA started testing five zero-emission, battery-electric buses on the Silver Line.[18] New bus procurements over the past several years, however, have largely been diesel-hybrids.[19] This recent update indicates that the MBTA plans to add close to 400 diesel-hybrids while procuring only 120 electric buses in the next six years. All electric bus purchases remain dependent on the pace of facility modernization efforts. Although we recognize that the MBTA's aim is to eventually electrify its fleet by 2040, it has not yet made a firm electrification commitment along any timeline. This report evaluates a future fleet where the MBTA continues to purchase diesel-hybrid buses to demonstrate the missed opportunity that such a middle ground plan would represent by forgoing the opportunity to reduce its climate emissions, save the agency money, and improve the air quality and the health of area residents.

The MBTA has stated publicly its interest in advancing sustainability goals, especially as they relate to combating climate change and mitigating its effects.[20] In its 2017 Sustainability Report, the MBTA explained, "[o]ur goal is to make sustainability not just a program at the MBTA, but a core value that is at the heart of our mission and influences the way we do business."[21] Our organizations recognize that the COVID-19 global pandemic created an economic crisis that deeply impacted the ridership and financial stability of transit agencies across the country. As the MBTA creates a forward looking vision for bus service in Greater Boston, we encourage the MBTA to take into account the climate and public health benefits of electrification as part of any financial calculus and explore all avenues for state and federal funding. Making firm electrification commitments — and engaging the public in developing a plan to meet those commitments — will demonstrate strong climate leadership, secure a viable economic future for the MBTA, and help ensure an equitable transition for those most adversely affected by transportation related emissions.

With many opportunities to offset transit costs through federal funding, grants available should be considered alongside these fleet metrics. The Low-No Emission Vehicle Program "provides funding to state and local governmental authorities for the purchase or lease of zero-emission and low-emission transit buses, including acquisition, construction, and leasing of required supporting facilities."[22] This annual funding that disbursed $182 million in grants in 2021[23] can be used by the MBTA to support new electric bus purchases. For trolleybuses, there is an opportunity to receive Fixed Guideways Funding which has a yearly funding availability of $2.3 billion. Fixed Guideway Funding can be used to fund both new systems as well as extensions to existing networks.[24] The MBTA should create a dedicated planning team to leverage the millions of dollars of new investments that will be available for electric transit buses and charging infrastructure through the federal infrastructure plan and surface transportation reauthorization.

B. Types of Electrification

Historically, public transit systems were electrified almost as soon as Frank Sprague invented the trolley pole in 1888. Overhead wires powered streetcars around the country, and later trolleybuses as well. However, in most cities around the country, these streetcar and trolleybus systems were removed in favor of diesel buses. Boston is an exception, having kept both streetcars in the form of the light rail service on the Green Line and Mattapan Line and trolleybuses in Cambridge, Watertown, and Belmont. The MBTA should expand its existing trolleybus network as part of a broader transit electrification effort that will improve air quality and reduce transportation-related climate emissions in the metro Boston region.

There are several options for bus fleet electrification, each with its own advantages and optimal use case. In the long run, the MBTA will need to optimize a mix of electric technologies, including both battery electric buses, which will likely include buses that utilize overnight charging and those with additional in route charging capabilities, and trolley buses that are capable of In-Motion Charging (IMC) to allow extended range off-wire. As discussed below, the MBTA should commit to rapidly phasing out diesel, hybrid, and CNG buses in favor of trolleys and electric buses based on the characteristics of each route.

1. Trolleybuses: In-Motion Charging Extends Range Beyond Overhead Wires

URBAN TRANSPORT MAGAZINE, MARK DONAGHY

The MBTA has a fleet of 28 trolleybuses. As MBTA electrifies its fleet, it should invest in modern trolleys that use In-Motion Charging (IMC) technology.[25] IMC trolleybuses have both trolley poles for a direct wire connection and batteries to be able to operate off of the wires for a substantial distance. First developed during the 1990s, initial IMC trolleys had a small battery to allow a trolleybus to make a short detour in case of obstruction to the right-of-way or small, unpowered sections of wire. With improvements to battery technology, however, IMC trolleys are now capable of off-wire ranges as long as 22.1 miles.[26] This capability gives them a high level of flexibility, both for detours as well as for regular service.

IMC trolleys have obvious advantages over conventional diesel or dual-mode diesel-trolleybuses (such as the Silver Line fleet between South Station and Logan Airport):

- The route need not be completely wired. Outlying portions of a route that may see branched service, and areas lying further from main power feeds, can be run on battery power. Wires can be constructed where it is most efficient: where power and right-of-way are available and service most dense.
- There are few issues with range anxiety or cold weather since the buses spend most of their time connected to the power grid. Buses can use overhead wires for propulsion, battery charging, and climate control, and minimize non-propulsion battery use on other portions of the route.
- There is no need for charging downtime since recharging occurs while the bus is in revenue service.
- Smaller battery size reduces the curb weight of buses. Since road wear is largely a function of weight, an increase of just 20% of a vehicle's weight can double damage to roadways.
- Compared to both overnight and In-Route Charging, IMC buses have lower electric demand peaks, because their charging is spread throughout the service day instead of concentrated during short, high power, charging sessions. A lower peak electric demand allows for smaller power feeds, less expensive charging infrastructure, and lower electric utility demand charges. The advantages are mainly useful on high-use trunk lines. Electric buses' comparatively smaller need for infrastructure makes them more advantageous in lesser-traveled corridors.
- Extending the routes will require some additional infrastructure costs, but new overhead wire costs only between $1 and $3 million per mile, depending on available power supplies.[27]

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In the North American context, the largest current fleet using IMC technology is in Dayton, Ohio. Dayton is by far the smallest city in the United States with a trolleybus network, dating back nearly 100 years. Yet instead of talking of scrapping its wires, the Greater Dayton Regional Transit Authority has optimized them using IMC buses. These buses operate under the wires for most of their routes, but can then (in the Dayton context) operate up to 15 miles without wires, letting the agency extend its routes without extending the infrastructure. Before updating its fleet, Dayton tested IMC buses and electric-diesel hybrids, much like the current (and aged) MBTA Silver Line fleet, and found that the IMC buses were far superior.[28] In addition to Dayton, King County Metro in Seattle and SFMTA in San Francisco, the two largest trolleybus operators in the country, use IMC technology to extend the range and functionality of their electric trolley bus fleets, all of which have had short-range IMC technology for several years. While the aforementioned cities have more extant miles of trolleywire today, the MBTA had 37 trackless trolleybus lines at its peak. There are several trunk routes in the MBTA system that are particularly well-suited to IMC technology.

2. Battery Electric Buses

Battery electric buses today can travel from 150 miles to 275–300 miles on a single charge.[29] And though electric buses currently have a higher up-front purchase price than fossil-fueled buses, the lifetime costs are significantly lower due to significant savings on maintenance and fueling costs, even without assigning any dollar value to massive reductions in local and global air pollution.[30]

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a. In-route charging: Extending electric service beyond the densest routes

While trolleys with in-motion charging systems work well in areas with large numbers of buses running down specific shared "trunk" corridors, the larger fixed costs of charging infrastructure make it less suited to areas further from the urban core.

Electric buses that utilize In-Route Charging (IRC) can work better for suburban routes. IRC buses are essentially battery electric buses with an additional fast charge apparatus on the roof that allows for regular "top-up" charging during the course of the day, increasing cold-weather performance.[31] It is also possible to produce heat with an auxiliary diesel, biofuel, or alcohol-fuel heater, but these systems increase the cost and complexity of both vehicles and maintenance while doing less to reduce GHG emissions. Under the IRC model, charging stations are installed at strategic points along a bus route, most often the terminal stops at either end of the route. This allows the bus to charge its batteries whenever it is stopped at a terminal station: driver breaks, scheduled dwell times, and early arrival time all present opportunities for the bus to recharge. Proper planning can reduce the overall cost of charging stations by citing in route charging stations at terminals used by multiple bus lines.

b. Overnight Charging

While many urban and some suburban routes would be best electrified with in-motion charging trolleys and battery electric buses that utilize in-route charging, electric buses that rely on overnight charging at the depot should also play an important role in system-wide electrification. Express commuter buses make relatively few stops and provide a direct-to-downtown service pattern primarily for rush hour commuters without serving major off-street terminals. These routes have a relatively short service span, with significantly reduced midday service, which means the buses can more easily return to a garage to recharge in the midday as well as overnight. Thus, the limitations of overnight charging operations are less applicable to these routes. Several outlying suburban routes do not serve major terminals where it would make sense to install charging infrastructure.

Several urban routes serve corridors that can't easily be wired and terminals which do not have the space for top-up charging. For instance, the route 111 bus runs between on-street terminals in Chelsea and Everett to a small terminal in Downtown Boston and most of its route is on the Tobin Bridge, where it would be nearly impossible to install overhead power. Despite being one of the busiest routes in the MBTA network, it is a likely candidate for electric buses that rely on overnight charging. Likewise, the 70 bus runs from multiple on-street terminals in Waltham to a small, on-street layover in congested Central Square in Cambridge, and neither terminal is well-suited for overhead chargers.

C. Bus Fleet Electrification Delivers Equity, Climate, and Public Health Benefits

Transportation accounts for 42% of statewide carbon dioxide emissions and is a leading source of local air pollution[32] that disproportionately impacts environmental justice populations. Transitioning to an electric bus fleet would benefit those most burdened by air pollution, improve public health, and lower greenhouse gas emissions.

Electrification of MBTA's bus fleet will bring Massachusetts closer to its emission reduction goals. In March 2021, Massachusetts passed a new law, "An Act Creating a Next Generation Roadmap for Massachusetts Climate Policy," that updates goals for greenhouse gas reductions related to the 2008 Global Warming Solutions Act.[33] It commits Massachusetts to achieve net zero emissions by 2050 and sets interim benchmarks to reduce emissions by 50% by 2030 and 75% by 2040. Additionally, in July 2020 Massachusetts signed a multi-state memorandum of understanding (MOU) that calls for 30% of new trucks and bus sales to be zero-emission by 2030 and entirely zero-emission by 2050.[34] Further, Governor Baker's Commission on the Future of Transportation recommends that all new vehicles sold in Massachusetts be fully electric by 2040 and all buses purchased with state resources be electric by 2030.[35]

Electric buses have significantly lower life cycle global warming emissions than their fossil fuel counterparts. One study concluded that, based on the mix of fuels in the 2016 electricity grid, an electric bus produced 1,078 grams CO_2e per mile, compared to the 2,212 grams CO_2e per mile emitted by a diesel hybrid bus.[36] Converting to electric buses would lead to considerable greenhouse gas emissions reductions, and these reductions will grow larger over time as more of the fleet shifts to electric buses and the electricity grid becomes cleaner.

Fleet electrification supports transportation equity and public health benefits. The MBTA bus network is more heavily used by minority and low-income riders than any other mode of transportation.[37] An analysis shows that 77.2% of all MBTA bus routes are minority lines and 66% are low-income routes.[38] Communities along these routes are often dependent on bus service for their transit needs and experience higher air pollution levels. On average, residents of color in Massachusetts are exposed to vehicular pollution that is 26 to 36% higher than the exposure to white residents.[39]

Even short-term exposure to vehicular emissions and fine particulate matter can have adverse health effects, including increased incidence of cardiovascular diseases such as heart attacks, as well as asthma attacks, and other lung and heart ailments.[40] This disparity in exposure to air pollution has been linked to higher rates of COVID-19-related infections and risks in communities with greater populations of people of color or low-income residents.[41] This extra burden has quantifiable implications for the people who rely on the MBTA in their daily lives.

Children are especially vulnerable and may bear a double or triple burden.[42] In 2017, the Massachusetts Department of Public Health found that more than 15% of Boston's elementary and middle school aged children had asthma, which is the leading cause of school days missed and the third leading cause of hospitalizations for children under 15, and that in Boston, black children are 5.5 times more likely, and Hispanic children were 4.1 times more likely, than their white peers to be hospitalized for asthma.[43] These health inequities make it critical that MBTA accelerate the electrification of its bus fleet. Electrifying its bus fleet, beginning with routes that run through communities of color and low- and moderate-income neighborhoods, would dramatically reduce the air pollution in these areas, thus beginning to alleviate the disproportionate burden these communities shoulder as a result of transportation related pollution.

Climate legislation passed in March 2021 for the first time included the definition of environmental justice and environmental burdens in the statute, recognizing the disproportionate impact of high pollution levels on environmental justice populations. The MBTA should center equity in its electrification planning processes. This means prioritizing deployment of zero-emission electric buses in neighborhoods like Roxbury, Dorchester, Mattapan, Chelsea, Lynn, Revere, and Quincy that are already disproportionately burdened by pollution and congestion and are more likely to be transit dependent. The MBTA should engage with communities in a meaningful and transparent manner at the outset of the planning process to identify and address neighborhood concerns.

D. Report Findings

As explained previously, the modeling for this report compares three different visions for MBTA's future fleet: a) the current fleet make-up comprised of diesel, diesel-hybrid, CNG, and electric buses; b) a scenario that reflects recent purchasing of mainly diesel-hybrid buses; and c) a fleet with battery electric buses.[44] See Table 2 below. For modeling purposes, this report uses battery electric buses for the zero emission technology used, but electrified trolleys provide similar public health and climate benefits by eliminating tailpipe emissions.

Table 2: Number of Vehicles of Each Fuel Type by Modeling Scenario

Fuel Type	Current Fleet	Diesel-Hybrid Scenario	Full Electrification Scenario
Diesel	502	0	0
Diesel-hybrid	572	1074	0
CNG	175	175	0
Electric	5	5	1254

Through an analysis of the results using national modeling tools, this report arrives at three main conclusions:

First, converting MBTA's bus fleet to electric vehicles would result in substantial cost savings, mainly through a reduction in annual fuel and maintenance costs. The MBTA would save more than $174 million in lifetime total ownership costs for its bus fleet as compared to continuing to replace buses with diesel-hybrids. See Table 1. These savings would more than offset the high upfront costs of purchasing new vehicles, such that the MBTA would realize greater financial savings the faster and more robust its transition to electric buses is. The cost savings estimates referenced in this report were generated using Argonne National Laboratory's 2019 Alternative Fuel Life-Cycle Environmental and Economic Transportation ("AFLEET") Tool. This report compares the total cost of ownership under each scenario, factoring in bus mileage, fuel and electricity usage, and purchase and operating costs, as well as additional information such as insurance and registration costs.[45]

Second, electrification would result in significant reductions in CO_2 emissions, with greater reductions in more accelerated electrification scenarios. Using data provided by the MBTA to calculate on-road reductions, as well as the EPA's Avoided Emissions and Generation Tool (AVERT) to calculate emissions from increased electricity use from electric vehicle charging, we found that electrification would result in more than 51,000 tons, or roughly 0.05 MMT, of avoided annual CO_2 emissions as compared to a diesel-hybrid replacement plan. This analysis incorporates applicable grid generation mix in the Northeast region of the United States, as determined by AVERT's marginal emission factor for the region.

Third, converting from fossil fuel buses to electric buses would significantly improve the air quality of the region, thus reducing public health costs and potentially saving lives. Using the EPA's Diesel Emissions Quantifier (DEQ) tool, which quantifies avoided public health costs as a result of reduced $PM_{2.5}$ emissions, we estimate that full electrification would result in more than$9 million annually in avoided healthcare costs in the Boston area. The tool uses indicators such as reductions in emergency room visits, hospitalizations, and missed days of work to estimate these public health savings.

LIFE CYCLE COST SAVINGS FROM MBTA BUS FLEET ELECTRIFICATION

The MBTA will realize considerable cost savings as it electrifies its fleet. Our modeling indicates accelerated electrification leads to greater cost savings, and that these savings will continue to grow over time as annual operation and maintenance[46] savings accrue year-over-year. Although electric buses entail a higher upfront cost, they offer substantial savings in fuel and maintenance costs compared to diesel, diesel-hybrids, and CNG buses, resulting in overall total cost of ownership savings over the typical twelve-year lifespan of an MBTA bus.[47]

To understand the feasibility of battery-electric buses (both overnight garage charging and in-route charging varieties) as well as electric trolleybuses, the legacy system of diesel and diesel hybrid buses should be understood first. Both diesel and diesel hybrid buses are highly sensitive to diesel prices, and thus when computing an overall cost, there are wide variances depending on fuel price projections. Electric buses, by comparison, have lower maintenance costs than diesel or hybrid buses due to a much lighter engine, less wear and tear on the brakes, regenerative braking which reduces fuel costs, and fewer moving parts.

As seen in Table 3 and 4, our AFLEET modeling shows that the lifetime total cost of ownership of an electric bus is around $95,000 less than that of a diesel hybrid bus and would result in significant fleetwide[48] cost savings.[49] These savings increase the faster the transition to electric buses, as annual maintenance and fuel (electricity) savings increase year over year with electric buses.

Table 3: Per Bus Lifetime Total Cost of Ownership by Fuel Type[50]

Fuel Types	Purchase Price (USD)	Lifetime Fuel Costs (USD)	Lifetime Maintenance Costs (USD)	Lifetime TCO (USD)
Diesel	$300,000	$286,240	$210,373	$840,396
Diesel-Hybrid	$510,000	$188,560	$319,060	$934,675
CNG	$360,000	$204,676	$338,397	$843,908
Electric	$650,000	$79,891	$109,957	$839,266

Source: Argonne National Laboratory's AFLEET modeling tool.

The full electrification scenario would result in an estimated $175 million in lifetime savings in fuel, operation and maintenance costs as compared to the diesel-hybrid scenario.[51]

Table 4: Fleetwide Lifetime Costs Cross-Scenario Comparison			
Fleetwide TCO and Savings	**Current Fleet Composition**	**Diesel-Hybrid Scenario**	**Full Electrification Scenario**
Fleetwide Lifetime TCO (USD)	$1,258,998,969	$1,227,108,685	$1,052,440,099
Electrification Savings Compared to Diesel-Hybrid Scenario (USD)	NA	NA	$174,668,586
Electrification Savings Compared to Diesel-Hybrid Scenario (%)	NA	NA	14.23%

CO_2 EMISSIONS REDUCTIONS

We are in the midst of a global climate crisis. As a coastal state, Massachusetts's 1,500 miles of coastline are particularly vulnerable to sea level rise and more extreme weather patterns.

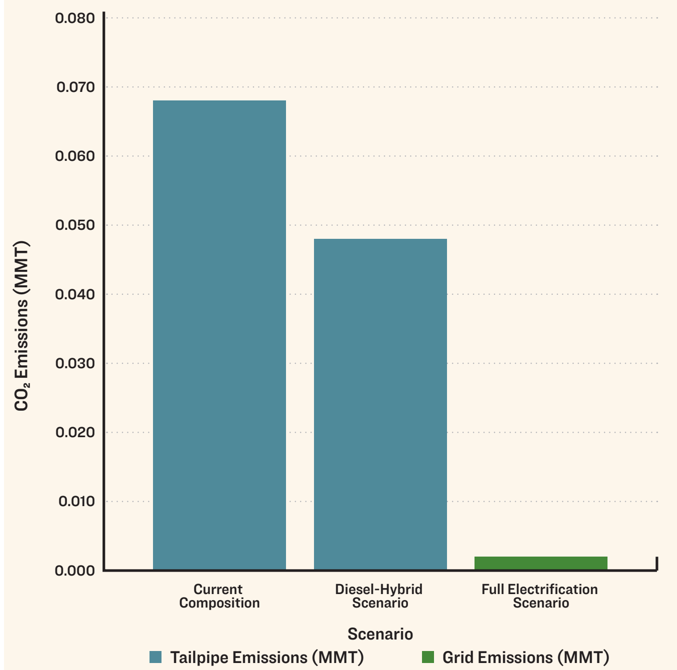
Decarbonizing our transportation sector, starting with our transit and public fleets, will move the Commonwealth closer to its climate goals. Electric buses and trolleys have significantly lower global warming emissions than their fossil fuel counterparts and will become exponentially cleaner as the electric grid gets powered by clean and renewable sources of energy.[52]

Diesel-hybrid vehicles simply do not offer emissions reductions comparable to those of an electric vehicle. Based on fuel efficiency, advanced hybrid buses may only reduce GHG emissions by 30% from diesel vehicle levels,[53] whereas electric vehicles entirely eliminate tailpipe GHG emissions.

Transit agencies across the U.S. have made commitments to lowering their emissions and electrifying their bus fleets. In 2018, San Francisco announced plans to fully electrify its 800-bus fleet by 2035.[54] Chicago followed suit in April 2019, committing to converting its 1800-bus fleet entirely to electric vehicles by 2040.[55] Los Angeles made a similar commitment in 2019, purchasing 130 electric buses that year and announcing plans to fully electrify its 2,300-bus fleet by 2030.[56] New York City announced the deployment of fifteen electric buses in 2019 as well, with a commitment to purchasing 500 buses over the next five years.[57]

In its June 2020 response to our records request, the MBTA provided emissions data for the current bus fleet. Using this data, we calculated tailpipe emissions for each bus type as well as fleetwide tailpipe emissions for the diesel-hybrid and full electrification scenarios. The MBTA's data only provided tailpipe emissions, so we also applied MBTA's electric bus electricity usage data to AVERT's marginal emission factor for the Northeast region to calculate the CO_2 grid emissions of increased electric bus charging.

Figure 3: Fleetwide Annual CO_2 Emissions[58]



Our analysis demonstrates massive reductions in both tailpipe and grid emissions under the full electrification scenario. Tailpipe emissions (74,876.83 tons of CO_2 per year in the current fleet; 53,176.30 tons per year for the diesel hybrid scenario) were entirely eliminated by electrifying the fleet. The grid emissions associated with charging even a fully electrified fleet (1,764.24 tons of CO_2 per year) are negligible when compared to the other scenarios. As Massachusetts's grid transitions to renewable energy to achieve its GWSA goals, these grid emissions will drop.

The results of removing heavily polluting internal combustion engine vehicles from the road are dramatic. Replacing the older, mostly diesel target buses with diesel-hybrid buses results in considerable tailpipe emission reductions, as diesel-hybrid buses do emit fewer pollutants than diesel buses. But electrification goes further, completely eliminating tailpipe emissions.

A bus fleet with a higher proportion of electric vehicles produces fewer tailpipe emissions. Although grid emissions increase as more electric vehicles are added and require charging, the additional emissions are negligible compared to those reduced from the tailpipe. As of 2019, the MBTA estimates its fleetwide CO_2 tailpipe emissions to be almost 75,000 tons, or 0.068 MMT. Our calculations for its current CO_2 grid emissions are roughly seven tons or 0.0000064 MMT. Converting more of its fleet to diesel-hybrid vehicles, as was modeled in the diesel-hybrid scenario, reduces combined emissions by almost one-third. In the full electrification scenario, tailpipe emissions are zero and, although adding over 1,000 electric buses and trolleys increases grid emissions, they are far lower than those produced by the current fleet and by the diesel-hybrid scenario. The diesel-hybrid scenario is only nominally better for CO_2 reduction and climate change mitigation than the current fleet composition.

The social cost of carbon, developed by an Interagency Working Group comprised of experts from more than a dozen federal agencies and offices, provides an estimate of the global economic damage, in dollars, caused by each incremental ton of CO_2 emitted into the atmosphere.[59] Originally developed to help federal agencies quantify the value of future reductions in carbon dioxide emissions that result from their decisions, the tool estimates impacts such as drought, wildfires, decreased agricultural productivity, and sea level rise, among others. Although there is significant variation in the dollar estimates for future emissions reductions depending on the discount rate used, using a discount rate of three percent, the social cost of each incremental ton of CO_2 emitted into the atmosphere in 2030 is $62.[60] Fully electrifying the MBTA's fleet by 2030, would reduce the MBTA's CO_2 emissions by more than 73,000 tons per year compared to the current fleet. Using a three percent discount rate, these reductions would avoid more than $4.5 million in annual global economic damages, and more than $54 million across an assumed 12 year average lifetime for the fleet — annual savings which would increase as the social cost of each ton of CO_2 emitted into the atmosphere rises in successive years.

PUBLIC HEALTH SAVINGS

Transportation plays a major role in air pollution. EPA estimates that nationally, on-road vehicles emitted 114,000 tons of particulate matter ($PM_{2.5}$) in 2017.[61] On-road vehicles in Massachusetts alone produced over 1,785 tons of $PM_{2.5}$ in 2017,[62] and the five counties[63] the MBTA serves (Suffolk, Middlesex, Norfolk, Essex, and Plymouth) accounted for 58.78% of these emissions.[64] Drivers and other workers face a higher risk of negative health impacts from long-term exposure of diesel pollution. A 2010 report by the Clean Air Task Force found that transit buses are polluted by their own tailpipe exhaust.[65] In Boston transit buses the mean peak $PM_{2.5}$ exposure was found to be 14 times that in outdoor air. The same study found that concentrated trails of diesel soot from transit buses also permeates the vehicles behind and reduces air quality among community sidewalks.[66]

Particulate matter can irritate and damage the respiratory system. Those exposed may experience a variety of symptoms, some mild, like a cough or trouble breathing, and some more critical, like decreased lung function and cardiovascular disease.[67] Vulnerable populations, such as children, the elderly, people who work outside, and those with existing respiratory or cardiovascular issues can be harmed at very low levels of $PM_{2.5}$ exposure.[68] Racial and socio-economic factors play a role, as well; a 2018 study published in the American Journal of Public Health found that low-income Americans carried 1.35 times higher burden for $PM_{2.5}$ air pollution than did the overall population, and non-white Americans had 1.28 times higher burden.[69] Black Americans, specifically, carried a 1.54 times higher burden than did the overall population.[70] A recent study found that ozone and fine particulate matter from vehicle emissions in 2016 claimed approximately 620 lives in Massachusetts.[71]

According to a 2017 report from the Massachusetts Department of Health, children in the Boston area have higher rates of hospitalizations and emergency department visits due to asthma than children statewide. The same report found that, in 2012, Boston's healthcare charges associated with pediatric asthma were $38.7 million.[72]

As illustrated in Tables 5 and 6 below, this report uses the AFLEET model to calculate annual per-bus tailpipe emissions of a variety of pollutants, specifically, CO, NO_X, $PM_{2.5}$ and PM_{10}, VOCs, and SO_X. The full electrification scenario would greatly reduce pollutants across the board, in some cases up to 100%.[73] The diesel-hybrid scenario resulted in considerable pollution reduction — as would be expected by any fleet modernization — but not to the extent of full electrification.

Table 5: Annual On Road Emissions

Pollutant	Current Composition	Diesel-Hybrid Scenario	Full Electrification Scenario
CO (lbs)	1287.40	1118.40	0.00
NO_x (lbs)	560.80	100.20	0.00
PM_{10} (lbs)	38.40	21.60	18.60
$PM_{2.5}$ (lbs)	20.60	5.00	2.40
VOCs (lbs)	56.80	11.20	0.00
SO_x (lbs)	2.20	1.20	0.00

Table 6: Percent Reduction In On Road Emissions as Compared to Current Fleet Composition

Pollutant	Diesel-Hybrid Scenario	Full Electrification Scenario
CO	13.13%	100.00%
NO_x	82.15%	100.00%
PM_{10}	44.01%	51.56%
$PM_{2.5}$	76.21%	88.35%
VOCs	80.28%	100.00%
SO_x	45.45%	100.00%

A reduction in particulate matter and other pollutants from transit buses would have a quantifiable effect on the area's air quality, potentially saving millions of dollars a year in healthcare costs. This report uses the U.S. EPA's Diesel Emissions Quantifier tool to calculate the avoided healthcare costs associated with changes in fine particulate matter emissions ($PM_{2.5}$). This tool calculates a monetary value for avoided instances of certain air quality related health impacts, including upper and lower respiratory symptoms, asthma attacks, nonfatal heart attacks, hospital admissions, emergency room visits, and missed days of work, among others.[74] Using the EPA tool and its underlying data, we calculate that the full electrification scenario would save area residents over $9 million per year in reduced healthcare costs compared to the current fleet composition. See Table 7.

Table 7: Annual Avoided Healthcare Costs[75]

	Diesel-Hybrid Scenario	Full Electrification Scenario
Annual Cost Benefits (USD)	$6,317,081.60	$9,079,253.60

Although the diesel-hybrid scenario would see significant emissions reductions as well, bus replacement with diesel-hybrid vehicles would not realize the same public health benefits as electrification. Compared to the $9 million in avoided healthcare costs associated with the full electrification scenario, the fleet composition of the diesel-hybrid scenario would only save $6.3 million annually.

OUR PROPOSALS

We propose the following measures to build a reliable electric bus network. The two portions of the MBTA which currently run electric trolley buses or dual-mode buses are an excellent fit for existing in-motion charging trolleys. We propose that they be used as a foundation from which to expand the MBTA's zero-emission bus network. These trolley networks would use the existing overhead wire system, so would not require any major capital outlay beyond vehicle acquisition. Furthermore, our proposed improvements occur on many of the highest-traffic and highest-priority corridors, and thus overlap with areas targeted for further service under MBTA's Bus Network Redesign, including the 71,72,73 routes from Harvard Square, the Silver Line, and the 22, 23, 28, and 29 in Roxbury-Dorchester-Mattapan.[76]

- Replace the current trolleys (routes 71, 72, and 73) with In-Motion Charging (IMC) trolleybuses which can operate past the end of the overhead wire network to further extend the range of electric service to all buses using the Harvard Square tunnel with minimal additional infrastructure.
- Replace the Silver Line SL1, SL2, and SL3 dual-mode buses with In-Motion Charging trolleys, utilizing the existing Silver Line overhead wire.
- Build an In-Route Charging (IRC) network for electric buses based on Quincy Center and design the Quincy garage to be fully electric. Based on the experience with in-motion charging trolleys, consider strategic extensions of the overhead catenary wire network over time to further increase the trolley network.
- Identify other routes that could switch over to in-route charging or overnight charging electric buses in the next 2-3 years.
- Commit to all new bus procurements being electric by 2023 and to full bus network electrification by 2030.

The Silver Line

The distance from the end of the wire at Silver Line Way to the Airport and back is about six miles, which is **well within the range of in-motion charging trolley buses** and the SL2 is shorter still. At 11 miles, the distance covered by the SL3 to Chelsea is slightly longer. This is still within the range of an in-motion charging trolley, but adding a short segment of wires to the Chelsea portion of the route would allow the buses to operate even more reliably. This wiring would be relatively uncomplicated as the Chelsea route segment operates in a separated right of way.

Electrifying SL3 is particularly important as it serves two Environmental Justice areas, Chelsea and East Boston, with large populations of people of color. Both areas have significantly lower incomes, fewer transportation options, and higher rates of asthma and other respiratory illnesses. Diesel exhaust from trucks and buses is a major contributor to these illnesses. Rather than replacing electric trolleys with battery electric buses in higher-income areas, our proposal would prioritize getting zero-emission transportation options to the communities that suffer the most from transportation related pollution.

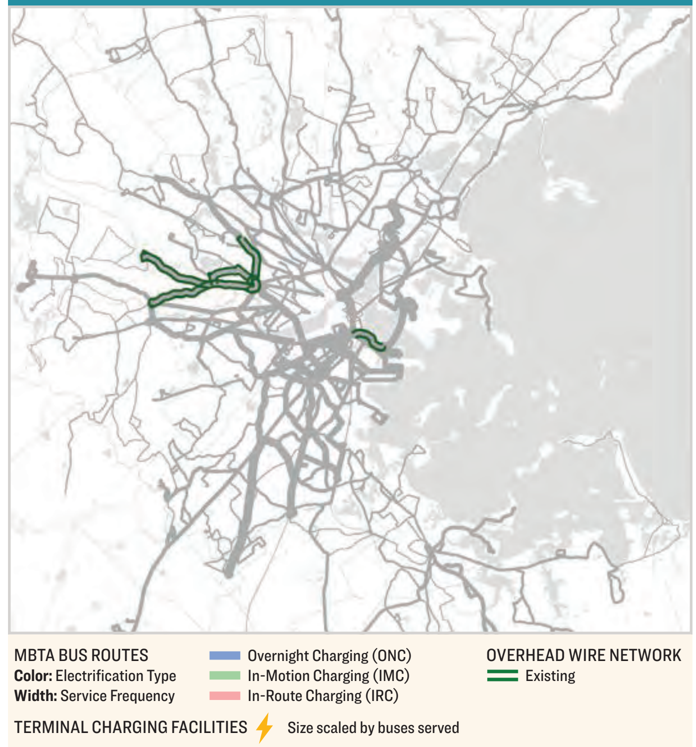
Harvard-based Buses (The existing trolleybuses: 71, 72, 73)

For the buses serving the Harvard tunnel, the IMC conversion calculus is even more favorable. Today, buses entering the Harvard tunnel from the west — the 71 and 73 on Mount Auburn Street — operate on electric power, while buses coming from the north (other than yard pull-outs for the electric trolley bus routes and the 72) use diesel propulsion. While the MBTA has stated its intent to replace electric trolleybuses with battery-electric buses, the timeline is unclear; moreover, such a move would be counterproductive, increasing potential carbon emissions due to the onboard diesel heating systems.[77] Rather, the MBTA should convert the current electric trolleybuses to IMC buses.

By converting the existing trolleybuses to IMC buses, the current operation of the fleet could be optimized, allowing buses to use battery storage to bypass any problems with overhead wire or gaps in overhead during construction, especially the planned construction on Mount Auburn Street. A new IMC fleet would also allow the MBTA to establish level boarding in the Harvard bus tunnel if the buses were equipped with left-side doors. In early stages of electrification expansion, Harvard-based diesel routes could be switched to IMC trolleybuses, allowing a significant expansion of the electric fleet with zero additional infrastructure.

The additional routes covered by the buses would require a larger fleet and outstrip the capacity of the current storage North Cambridge carhouse, but there is ample room at the MBTA-owned Watertown Yard at the end of the 71 route to house additional buses, and since IMC buses do not require overhead wire at depots, this would require minimal additional expense, while freeing up space at existing bus yards which currently store the diesel fleet and reducing deadhead operation to the start and end of the route served.

Figure 4: Existing Extent of MBTA Electrification



A. A Phased Approach

We propose a phased approach to bus electrification, using electric bus technologies and charging infrastructure that are most appropriate for each route and corridor. This would begin where the MBTA has existing electrification infrastructure and plans for new bus garages, and then expand based on a combination of the ease of electrification and characteristics of the routes. This phased approach imagines that the network would be fully electrified within 12 years of the beginning of such a plan so that the new diesel-hybrid buses currently in procurement would be the last diesel buses the MBTA purchases. By using a combination of different electric technologies, it would allow the agency to implement the one which works best for a particular route.

PHASE ONE

Just as the MBTA has started testing battery electric buses, they should begin testing IMC trolley buses and IRC technology for battery electric buses. Replacing the current trolleybus fleet with a fleet of IMC buses would allow the MBTA to leverage its existing electrified transit infrastructure to double the number of zero-emission buses on the road with minimal capital outlay for infrastructure. The purchase of each type would provide a good sample of experience to make the decision on which way to go for an emissions-free future. The existing network based at Harvard gives the agency the opportunity to test IMC trolley buses on several of the MBTA-designated Key Routes that carry the most passengers. The network using the Seaport Transitway is also a good testing opportunity for IMC. Because these buses would operate using the existing power infrastructure, there would be no need to convert existing garage space to service a new type of vehicle or install extensive charging infrastructure.

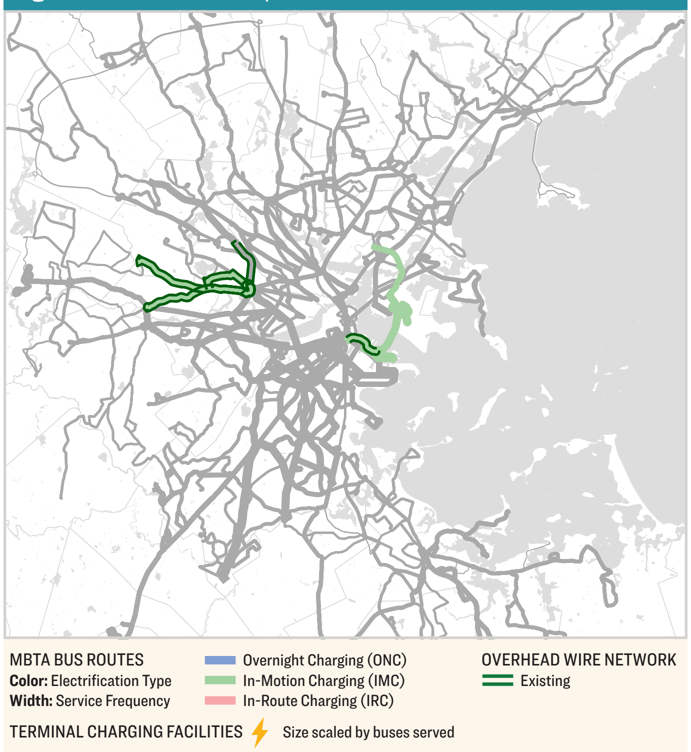
PHASE 1 ROUTES: SL1, SL2, SL3, 71, 72, 73;

PHASE 1 BUSES: Approximately 80 (8% of the fleet);

PHASE 1 PASSENGERS SERVED DAILY: Approximately 35,000 (8% of bus ridership);

PHASE 1 TIMEFRAME: 12 months (vehicle acquisition).

Figure 5: Phase One Proposal



PHASE TWO

Phase Two assumes the completion of any rehabilitation of the overhead wire network in Cambridge and Watertown and would allow the full conversion of all routes operating through the Harvard Tunnel. These include routes 74, 75, 77, 78, and 96. In addition, the Route 57, which runs from the Route 71 terminal in Watertown to Kenmore, would be able to convert some of its service to electrified IMC by extending Route 71 buses to Kenmore (the 57 runs with more frequency than the 71, particularly at rush hour, so it would be difficult to convert all trips to IMC without additional infrastructure).

In addition, Phase Two institutes In-Route Charging for battery electric buses using the new Quincy Garage (which is currently in design by the MBTA) as a base of operations. Having outgrown the current Hancock Street garage, the MBTA is preparing to break ground on a state-of-the-art facility at 599 Burgin Parkway that will be built to accommodate an all-electric bus fleet. Installing IRC infrastructure at Quincy Center's busway would make all-electric operations possible on an earlier timeline, as IRC top-ups at the station busway would supplement the garage charging. Similar IRC infrastructure at the Braintree Busway could serve to expand service, including to the 226 route.

Phase Two would also see Route 111 electrified since it is a route serving a dense environmental justice area with high pollution rates. If it is difficult to install charging infrastructure and have enough space to charge vehicles at the terminals of this route, it would be a good candidate for the early implementation of Overnight Charging battery electric buses. These buses could be charged at existing MBTA facilities in Everett or Charlestown, or located overnight at the new capacity in the Quincy Garage.

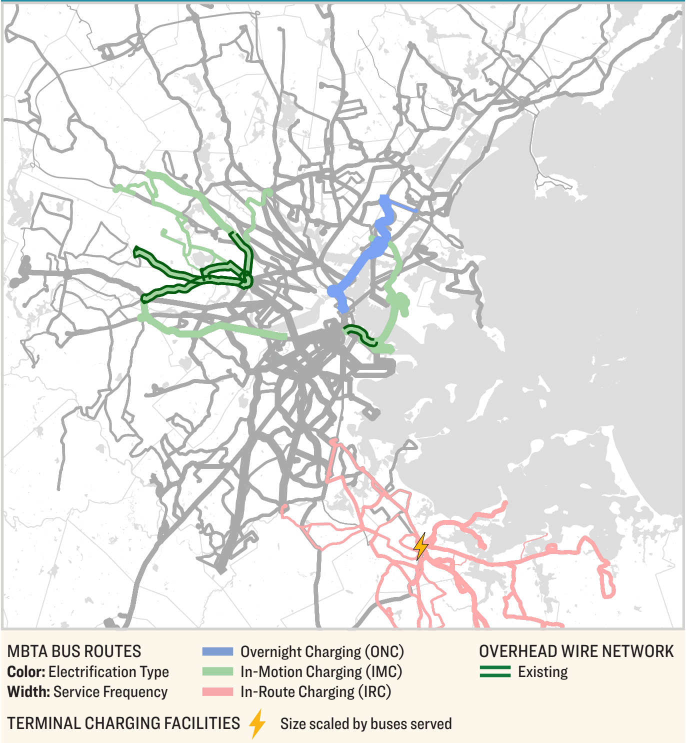
PHASE 2 ROUTES: Routes 57, 74, 75, 77 78, 96, 111, 200-series (210, 211, 212, 214, 215, 216, 217, 220, 221, 222, 225, 226, 230, 236, 238, 245);

PHASE 2 BUSES: Approximately 130 buses (12%), with 120 in Quincy and the remainder split between North Cambridge and Watertown Yard;

PHASE 2 PASSENGERS: Approximately 46,000 (12%);

PHASE 2 TIMEFRAME: 2 to 4 years (vehicle acquisition and Quincy Garage construction, potentially sooner for Harvard-operating routes).

Figure 6: Phase Two Proposal



PHASE THREE

The goal of this phase is to electrify buses serving some of the most transit-dependent parts of Boston in Dorchester, Roxbury and Mattapan. Electrification of these routes would be based on the experiences gained in earlier phases, and decisions regarding electrification type would be made accordingly. This phase assumes that a new bus facility is located at the current Arborway Yard site, and that it is a fully electric facility serving up to 200 vehicles. The routes served in this phase are designed to be electrified with minimal infrastructure since they are served by five major transit terminals with either IRC charging at terminals or IMC networks:

- Ruggles
- Forest Hills
- Nubian
- Ashmont
- Mattapan

For IRC buses, this would allow top-up charging to take place with a small number of chargers, especially since many of these routes run between two of these terminals. If IMC is selected, these routes could be electrified with a small amount of overhead wire, which could tie into existing 600V DC traction power available at each of these transit nodes. These routes represent several of MBTA's busiest bus routes.

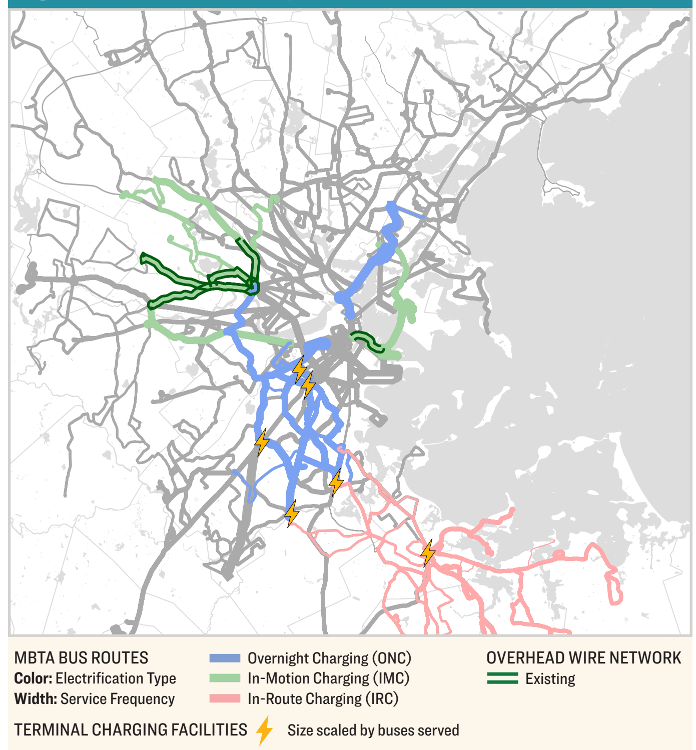
PHASE 3 ROUTES: 14, 15, 19, 22, 23, 28, 29, 31, 39, 45, 66;

PHASE 3 BUSES: 180 (18% of the fleet, many of them 60-foot vehicles);

PHASE 3 PASSENGERS: Approximately 78000 (20% of bus ridership);

PHASE 3 TIMEFRAME: 3 to 5 years (Electrification construction, garage modifications, and vehicle acquisition).

Figure 7: Phase Three Proposal



PHASE FOUR

Assuming satisfactory implementation of IMC and IRC buses in Phases 1 through 3, Phase 4 would extend electrification to targeted neighborhoods with high bus ridership and to environmental justice communities. Specifically, it would electrify additional buses in Roslindale, Hyde Park and Dorchester, as well as routes between Sullivan Square and Malden.

PHASE4 ROUTES: 16, 21, 32, 35, 36, 37, 38, 40, 50, 101, 104, 105;

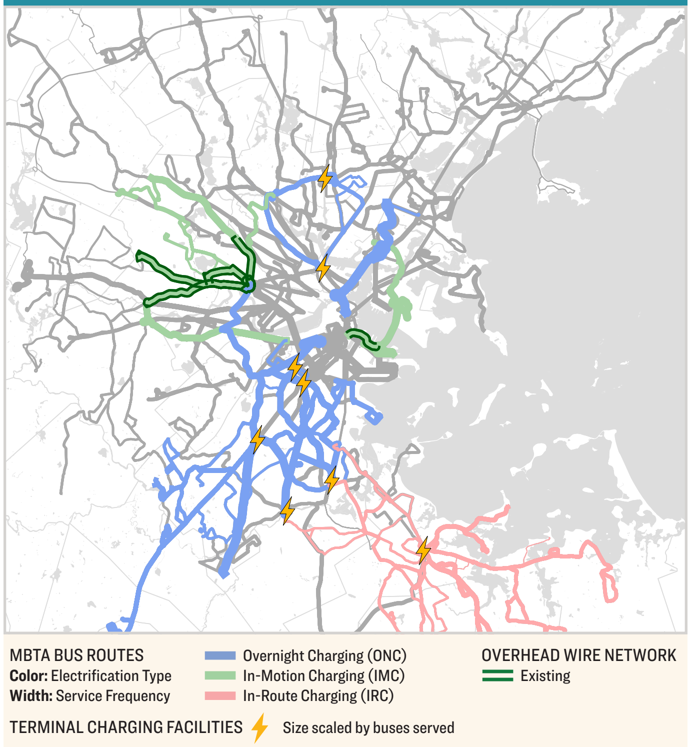
PHASE 4 BUSES: 80 (8% of the fleet);

PHASE 4 PASSENGERS: Approximately 43,000 (10% of bus ridership);

PHASE 4 TIMEFRAME: 3 to 6 years (Electrification construction, garage modifications, and vehicle acquisition).

Combined, Phases 1 through 4 would electrify approximately **40% of MBTA's fleet**, which would serve more than **50% of MBTA bus ridership.**

Figure 8: Phase Four Proposal



PHASE FIVE

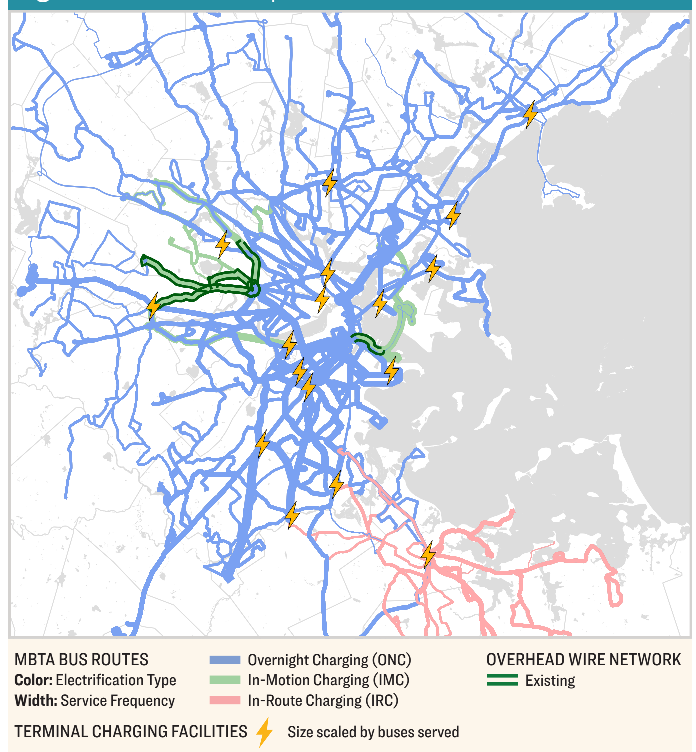
Phase Five would be a longer term project to electrify the remaining MBTA routes. Electrification type would depend on the experience of previous phases and technological changes. Some routes, especially express buses with long routes and suburban services which do not serve major transfer nodes, will likely require overnight charging buses (many express buses are idle during the midday and can charge then). Other routes may be best integrated into the IMC system.

This phase would include charging stations or IMC networks at most of the major bus terminals in the system, including:

- Alewife
- Watertown
- Kenmore
- Lechmere
- Maverick
- City Point
- Orient Heights
- Wonderland
- Lynn

It is anticipated that this system would be built out by 2030, allowing the entire MBTA fleet to be converted to electric buses at that time.

Figure 9: Phase Five Proposal



CONCLUSION

Our organizations call on the MBTA to seize the opportunity afforded by renewed federal investment in public transit, and in electric buses and charging infrastructure in particular, to demonstrate real leadership when it comes to addressing historic transportation inequities and reducing the local and global impacts of transportation pollution. Through a decade-long process of community engagement, planning and investment in garages, charging infrastructure, and zero-emission electric buses and trolleys, the MBTA can save itself money, save Boston metro area residents more than $9 million per year in avoided healthcare costs, and reduce climate polluting greenhouse gas emissions by more than 73,000 tons of CO_2 per year.

At the outset of this effort, the MBTA should engage in a transparent, public process that centers equity and values the health of its riders. Any economic forecasts of costs should account for the healthcare costs of riders from *not* electrifying the MBTA's bus fleet. That human cost — in missed days of work and school, hospital visits and trips to the doctor — should be part of the calculus. Moreover, future plans for garage and bus upgrades should account for, and correct, historic racial disparities in transportation-related pollution.

The MBTA's April 2021 Fleet and Facility Update acknowledges three key factors: **1)** the need to transition to a zero-emission fleet; **2)** the ability of current technologies to allow that transition to begin today; and **3)** the importance of serving transit critical communities by upgrading facilities with routes serving high percentages of households of color and low income households.[78] That report includes MBTA's data on the communities it serves, broken down by specific bus garage, with information on bus capacity, location, ridership, percentage of low income households along routes served out of that garage, and percentage of households of color along routes by each garage.[79] Yet when MBTA identifies which garages will receive priority upgrades, it fails to align its stated priorities with its planned facilities improvements.[80]

Our organizations stand ready to work with the MBTA to find the right path toward full fleet electrification while addressing the inequitable impacts of transportation pollution. As part of this process, we call on the MBTA to publicly commit to transition its fleet to fully electrified buses and trolleys by 2030, end the purchase of internal combustion engine buses no later than 2023, and prioritize garage updates and bus electrification in low income neighborhoods and communities of color.

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36. Union of Concerned Scientists, "Electric vs. Diesel vs. Natural Gas: Which Bus is Best for the Climate?" (July 19, 2018), https://blog.ucsusa.org/jimmy-odea/electric-vs-diesel-vs-natural-gas-which-bus-is-best-for-the-climate/.

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41. Office of Massachusetts Attorney General Maura Healey, "COVID-19's Unequal Effects in Massachusetts," (2020), https://www.mass.gov/doc/covid-19s-unequal-effects-in-massachusetts/download.

42. Centers for Disease Control and Prevention, "Most Recent National Asthma Data," (2018), https://www.cdc.gov/asthma/most_recent_national_asthma_data.htm.

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44. This framework allows a representative snapshot comparison of the benefits of electrification. Although the fleetwide benefits will change based on the total number of buses in service and the speed at which MBTA electrifies, the report has made conservative assessments to guard against overly optimistic projections for the steady decline in electric battery prices.

45. The data we input into this model were largely derived from the MBTA public records requests so the results are tailored specifically to the MBTA and the metro area it serves.

46. We adjusted AFLEET's default maintenance valuation to better reflect national averages. AFLEET's original valuation set electric buses' maintenance costs at 93.8% that of diesel buses' costs ($0.938/mile vs. $1.00/mile) To ensure our adjustment was conservative and objective, we used the highest value of the research we had collected: electric buses' maintenance costs were set to 52.6%that of diesel buses' costs, ($0.332/mile vs. $0.631/mile), per the results of a 2020 University of Texas Study. See Quarles, N., et al, "Costs and Benefits of Electrifying and Automating Bus Transit Fleets," (2020), https://www.caee.utexas.edu/prof/kockelman/public_html/TRB18AeBus.pdf. See also Horrox, J. & Casale, M., Frontier Group & U.S. PIRG Education Fund, "Electric Buses in America," (2019), https://uspirg.org/sites/pirg/files/reports/ElectricBusesInAmerica/US_Electric_bus_scrn.pdf (diesel maintenance costs at $1.53/mile, vs. electric maintenance $0.55/mile, 35.94% that of diesel maintenance costs); U.S. Department of Transportation Federal Transit Authority, "King County Metro Battery Electric Bus Demonstration," (2017) https://afdc.energy.gov/files/u/publication/king_county_be_bus_preliminary.pdf (diesel maintenance costs at $0.44/mile, vs. electric maintenance $0.18/mile, 40.90% that of diesel maintenance costs); Regional Transportation Commission of Washoe County, "Electric Bus Initiative – Benefit-Cost Analysis" at Appendix D, (2016), https://www.rtcwashoe.com/wp-content/uploads/2017/04/2016-Tiger-Grant-BCA.pdf (diesel maintenance costs at $1.00/mile, vs. electric maintenance $0.44/mile, 44.00% that of diesel maintenance costs); Aber, J., Columbia University, "Electric Bus Analysis for New York City Transit," (2016), http://www.columbia.edu/~ja3041/Electric%20Bus%20Analysis%20for%20NYC%20Transit%20by%20J%20Aber%20Columbia%20University%20-%20May%202016.pdf (electric maintenance costs at as little as 50% that of diesel maintenance costs).

47. MBTA, Focus 40 State of the System Report: Bus, (Dec. 2015), https://static1.squarespace.com/static/57757a3cff7c50f318d8aae0/t/5bb522bc652dead51cf88250/1538597569137/Bus+SoS+Report+-+Final+Accessible_121815.pdf.

48. Fleetwide costs were calculated as a sum of the total costs of ownership per bus of each fuel type and multiplied by the number of buses of each fuel type represented in each scenario. See Table 3.

49. As explained above, our modeling, conducted in late 2020, relied primarily on AFLEET's available baseline data for most inputs, including bus purchase prices, insurance and other fees. For more information on AFLEET, including a mid-2021 update, see https://greet.es.anl.gov/afleet_tool. The American Public Transit Vehicle Association publishes an annual public transit vehicle database with a wealth of information in it on vehicle purchases by transit agencies across the country, which show averages that are slightly different than those used in this report but reflect comparative price differences between bus types that are similar to those listed in AFLEET. https://www.apta.com/research-technical-resources/transit-statistics/vehicle-database/. Average purchase price data compiled from the APTA report are included in two tables in the Methodology Appendix of this report.

50. Total cost of ownership, as calculated by AFLEET, includes the columns seen above for purchase price, maintenance, and fuel, as well as additional inputs on vehicle purchase price depreciation, insurance costs, and license and registration costs.

51. For our modeling of future bus procurements, we used AFLEET's national average information for bus purchase prices. In response to a public records request, the MBTA reported purchase prices for all bus types well above national averages, and in cases like the diesel-electric hybrid buses it intends to rely on in the future, prices above $1 million per bus, which appear to be among the most expensive diesel buses reported by any agency in APTA's annual transit vehicle report. See *supra*, note 47. The MBTA declined to provide an explanation for this price disparity, which it is not obligated to do under Massachusetts public records statutes. Without an explanation as to why MBTA's historic purchase prices appeared far higher than national averages, and without any understanding as to whether those inflated purchase prices would be agreed to by the MBTA for future purchases, this report utilized more conservative purchase prices from AFLEET, which similarly show current a price premium for electric buses, followed by (in descending order) diesel hybrids, CNG, and diesel buses.

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56. Kyle Hyatt, "Los Angeles' order of 130 electric buses in largest in US history," Road Show (Nov. 19, 2019), https://www.cnet.com/roadshow/news/los-angeles-bus-byd-largest-ever/.

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58. Fleetwide annual CO_2 emissions (beginning in 2020) include both on-road and grid emissions, as calculated using the MBTA-provided data and EPA's Avoided Emissions and Generation Tool ("AVERT") respectively.

59. Interagency Working Group on Social Cost of Greenhouse Gases, "Technical Support Document: Social Cost of Carbon, Methane, and Nitrogen Oxide Interim Estimates Under Executive Order 13990," (February 2021), https://www.whitehouse.gov/wp-content/uploads/2021/02/TechnicalSupportDocument_SocialCostofCarbonMethaneNitrousOxide.pdf?source=email.

60. *Id*. at 4. These dollars are reported in 2007 dollars.

61. EPA, "2017 National Emissions Inventory (NEI) Data," (April 2020), https://www.epa.gov/air-emissions-inventories/2017-national-emissions-inventory-nei-data.

62. *Id*.

63. This report's modeling relies on a county-by-county estimation of health costs. See Methodology Appendix.

64. EPA, "2017 National Emissions Inventory (NEI) Data," (April 2020), https://www.epa.gov/air-emissions-inventories/2017-national-emissions-inventory-nei-data.

65. Clean Air Task Force, "A Multi-City Investigation of Exposure to Diesel Exhaust in Multiple Commuting Modes," (2010), https://www.catf.us/wp-content/uploads/2019/02/CATF_Pub_Diesel_Exhaust_Exposure_Investigation.pdf

66. *Id*.

67. EPA, "Health and Environmental Effects of Particulate Matter," (2019), https://www.epa.gov/pm-pollution/health-and-environmental-effects-particulate-matter-pm; EPA, "Particle Pollution and Your Health," (2003), https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P1001EX6.txt.

68. *Id*.

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75. The annual avoided health costs were calculated using EPA's Diesel Emissions Quantifier tool and manual calculations with its underlying data. The tool uses public health indicators such as reductions in emergency room visits, hospitalizations, and missed days of work, among other factors, to estimate these public health savings as an annual dollar amount.

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77. MBTA, "Bus Fleet Update," (Sept. 23, 2019), https://cdn.mbta.com/sites/default/files/2019-09/2019-09-23-fmcb-K-bus-fleet-update-accessible.pdf

78. MBTA, "Bus Transformation Update Part 1: Fleet and Facility Update," at 3-6, 8 (April 2021), https://cdn.mbta.com/sites/default/files/2021-04/2021-04-26-fmcb-6-bus-transformation-update.pdf.

79. *Id*. at 9.

80. *Cf*. *id*. 9 ("prioritization criteria and existing facilities") with *id*. at 14 ("facilities modernization implementation plan").

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