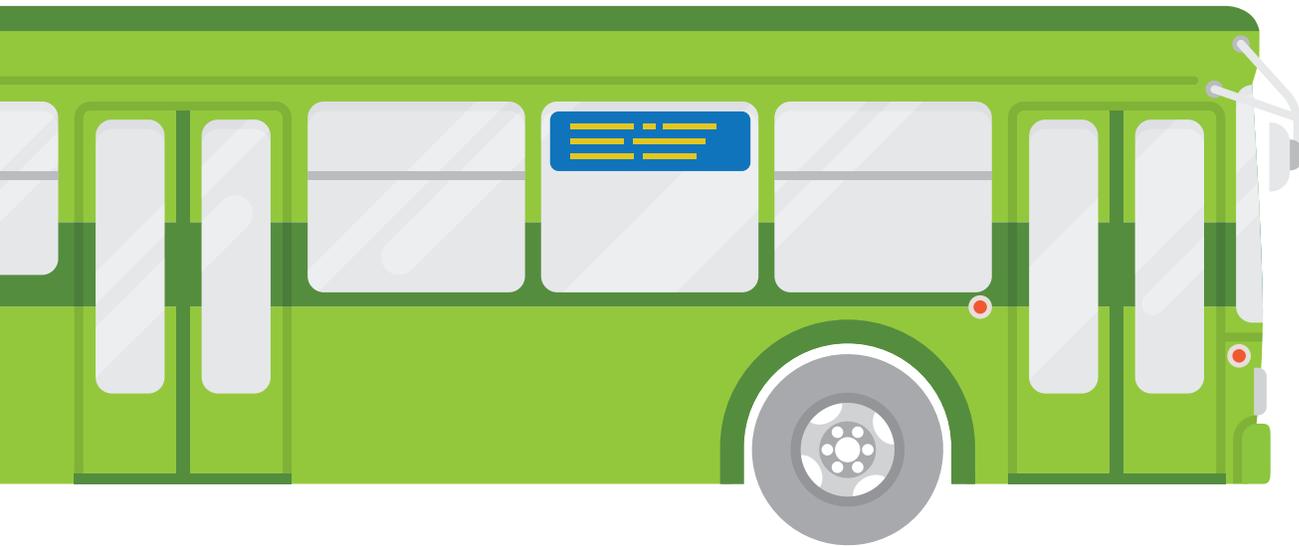


POLICYMAKER GUIDE

Which Alternative Fuel Technology is Best for Transit Buses?



The choice of which fuel technology to use for transit buses is an important issue for public transit agencies in terms of budget impact, operating performance, bus purchasing decisions and related refueling and depot infrastructure, as well as greenhouse gas and air pollutant emissions. Alternative fuel technologies such as natural gas and electric buses are attractive to transit agencies given the fast turnover of buses (12 years), federal incentives, and in some cases, policymaker and public pressure to meet societal economic and environmental goals.

This study found that among the choices available to transit agencies, battery electric buses are the best option due to low life cycle agency costs and environmental and health impacts from greenhouse and air pollutant emissions.

Although there are still some barriers, such as low range, to their adoption, electric buses should be considered in both short-term experimentation and long-term planning for public transit agencies.

The research summarized in this guide was sponsored by the Richard King Mellon Foundation.

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About The Team



Carnegie Mellon University
Scott Institute
for Energy Innovation

Over the coming decades the world must make fundamental transformations in how energy is used and produced. This will require new science, technology and public policy innovations. That's the role of **Carnegie Mellon University's Wilton E. Scott Institute for Energy Innovation**. The Scott Institute works through CMU's academic units to find solutions for the nation's and world's energy challenges through research, strategic partnerships, public policy outreach and education. The complex challenges that it addresses include:

- **How to use and deliver the energy we already have with greatly improved efficiency**
- **How to expand the mix of energy sources in ways that are clean, reliable, affordable and sustainable**
- **How to create innovations in energy technologies, regulations and policies**

The **Traffic21 Institute** at CMU is a multidisciplinary research center focused on addressing the problems facing the transportation system in the Pittsburgh region as a first step to applying the learned solutions both nationally and globally.

The purpose of this policymaker guide is to provide a fuller picture of both total agency costs and social costs for alternative fuel technologies for transit buses in order for policymakers and other interested parties to make better-informed decisions.

This policymaker guide was developed by a team led by Stephanie Seki and Chris Hendrickson with Deborah Stine providing editorial guidance. Those authoring the paper contributing to this guide include researchers from Carnegie Mellon University who participated in the Traffic21 project. These researchers include: Fan Tong, Chris Hendrickson, Allen Biehler, Paulina Jaramillo and Stephanie Seki. The Port Authority of Allegheny County, Pittsburgh's public transportation provider, also contributed information and guidance on the work. Additional development and reviews of this guide were provided by: Courtney Ehrlichman, Amanda King, Jenni Miller and Richard Stafford. The paper used to inform this policymaker guide is: Tong, F., C. Hendrickson, A. Biehler, P. Jaramillo and S. M. Seki. Life Cycle Economic and Social Costs of Alternative Fuel Options for Transit Buses. Under review at Transportation Research Part D, 2016.

QUESTIONS?

Please contact Dr. Chris Hendrickson, director of **Traffic21**, at cth@cmu.edu or Dr. Deborah Stine, associate director for policy outreach of the **Scott Institute**, at dstine@andrew.cmu.edu.



Executive Summary

Executive Summary

This policymaker guide focuses on transit buses, which are used over short distances with fixed routes and frequent stops. The contribution of public transit buses to air pollution emissions in a city is a visible and constant issue for public transit agencies around the country. This policymaker guide evaluates alternative fuel technologies for transit buses based on agency costs and environmental impacts, considering buses that have a turnover of 12 years. Agency costs include those related to bus purchase, operation and maintenance, fuel procurement and refueling and depot infrastructure. Social costs are the environmental and health impacts from criteria air pollutants (CAPs) and greenhouse gas (GHG) emissions, as described in Table 1.

In 2013, the American Public Transit Association estimates that there were 65,950 transit buses in the United States.¹ According to our analysis, these buses used approximately 0.4% of the energy consumed by on-road vehicles in the United States.² The fuel used in transit buses can contribute to unintended environmental consequences. Therefore, the Environmental Protection Agency (EPA) regulates tailpipe CAP and GHG emissions.³ The National Research Council (NRC) found in 2010 that the social costs from on-road vehicle use were approximately \$110 billion dollars.⁴ Transit buses would have been responsible for \$440 million in social costs if we assume energy consumption and social costs are proportional.¹ It is therefore important for transit agencies to consider alternative energy sources to fuel their buses.

IN 2013, THE AMERICAN PUBLIC TRANSIT ASSOCIATION ESTIMATES THAT THERE WERE 65,950 TRANSIT BUSES IN THE UNITED STATES.¹ ACCORDING TO OUR ANALYSIS, THESE BUSES USED APPROXIMATELY 0.4% OF THE ENERGY CONSUMED BY ON-ROAD VEHICLES IN THE UNITED STATES.²

TABLE 1. Environmental and health damages. Reference websites are included.

Environmental Measure/Model for Greenhouse Gases		Description
Greenhouse Gases (GHGs) ^{5,6}	CO ₂ – Carbon Dioxide CH ₄ – Methane N ₂ O – Nitrous Oxide	Greenhouse gases when released into the atmosphere are well mixed, and independent of the source location. At elevated levels, they are found to be contributors to global warming. GHGs are estimated over the life cycle of bus operation. Emissions are estimated with GHG inventories, process data, vehicle test reports and other data sources. <i>Learn more from the Environmental Protection Agency at: www.epa.gov/ghgemissions/overview-greenhouse-gases</i>
Global Warming Potential (GWP) ⁷	20-YEAR CO ₂ – 1 CH ₄ – 87 N ₂ O – 268 100-YEAR CO ₂ – 1 CH ₄ – 36 N ₂ O – 298	Global warming potential is a metric to convert non-CO ₂ emissions (measured in mass units) to CO ₂ -equivalent emissions based on the equivalency of cumulative radiative forcing. Methane and nitrous oxide have higher warming potentials than CO ₂ , but also vary with time. Methane has a higher potential for warming in the short term (20-year) than the long term (100-year). The Intergovernmental Panel on Climate Change (IPCC) in Assessment Report 5 (AR5) established the values. <i>Learn more from the Environmental Protection Agency at: www.epa.gov/ghgemissions/understanding-global-warming-potentials; www.ipcc.ch/report/ar5/wg1</i>
Social Cost of Carbon (SCC) ⁸	• \$13-\$120 per metric ton • \$41 per metric ton (median value) 2015 dollars	The social cost of carbon monetizes the marginal damages of CO ₂ emissions using integrated assessment models. The range of SCC estimates reflects assumptions on discount rate and model choice. <i>Learn more from the Environmental Protection Agency at: www3.epa.gov/climatechange/EPAactivities/economics/sc</i>
Environmental Measure/Model for Criteria Air Pollutants		Description
Criteria Air Pollutants (CAPs) ^{9,10}	NO _x – Nitrogen Oxides CO – Carbon Monoxide VOCs – Volatile Organic Compounds PM – Particulate Matter SO ₂ – Sulfur Dioxide	Criteria air pollutants are found to contribute to environmental and health damages. The type of pollutant and the location of the emission are important considerations. There are federal criteria standards for the pollutants to protect the environment and human health. Emissions are estimated using the Environmental Protection Agency's (EPA) National Emission Inventory (NEI), EPA's Continuous Emissions Monitoring System (CEMS) and the GREET Model. <i>Learn more from the Environmental Protection Agency at: www.epa.gov/criteria-air-pollutants</i>
APEEP/AP2 ¹¹	NO _x VOCs PM _{2.5} SO ₂	APEEP/AP2 is an integrated assessment model of the environmental and health damages (social cost) attributed to CAP emissions. The damages are estimated per unit of CAP emission for each contiguous United States county. <i>Learn more at: sites.google.com/site/nickmullershhomepage/home/ap2-apeep-model-2</i>
Estimating Air Pollution Social Impact Using Regression (EASIUR) ¹²	NO _x PM _{2.5} SO ₂	The EASIUR model estimates health damages (social cost) attributed to CAP emissions using a chemical transport model. The estimates can be made on a 36 x 36 km scale (typically smaller than a county). <i>Learn more at: barney.ce.cmu.edu/~jinhyok/easiur</i>

| Executive Summary

In this guide we summarize work that estimated agency costs and social costs for eight alternative fuel technologies for transit buses: conventional diesel, diesel hybrid-electric bus, compressed natural gas (CNG), liquefied natural gas (LNG), battery electric bus (BEB) with rapid-charging (on road), BEB with slow-charging (overnight in garages), B20 (20% biodiesel, 80% diesel) and B100 (100% biodiesel). Figure 1 describes the pathways and the fuels that they use. The Traffic21 Institute evaluated and compared the eight bus options in 40-foot and 60-foot bus lengths, specifically for the Port Authority of Allegheny County based on the following criteria:

- **Capital investment in buses**
- **Capital investment in garage and refueling infrastructure**
- **Climate change impacts from greenhouse gases (GHGs), estimated as damages in dollars**
- **Air quality impacts from criteria air pollutant (CAP) emissions, estimated as damages in dollars**
- **Operation and maintenance of the systems and other practical considerations**

Previous studies on alternative fuel technologies for transit buses have focused on lifetime agency costs. While some studies considered either GHG or CAP emissions from buses, these studies did not compare or add the social costs to agency costs as a way of ranking alternative fuel technologies. The previous work is summarized in Table 2.

We find that rapid-charging battery electric buses (BEBs) have the lowest life cycle costs when compared to conventional diesel buses, as shown in Figure 2, for the scenario with 80% federal funding for bus purchasing costs. The other alternative fuel pathways have nearly equal or higher life cycle costs compared to conventional diesel. Even considering sensitivities in fuel costs, infrastructure costs, discount rate and lifetime of the buses, BEBs remain the least expensive cost option when federal funding is available. However, battery electric buses have limited driving range and require new charging infrastructure, so they may be preferable as a long-term rather than short-term option. As batteries improve over time, they will allow for a longer driving range and lower purchase costs of BEBs. In the meantime, the electricity grid used to fuel the vehicle will become cleaner (less coal intensive) in response to policy pushes and favorable economics of natural gas and renewable power plants. As BEBs become more advantageous, transit agencies can prepare by planning for infrastructure changes in garages and/or en route, working with the utility to prepare for larger electricity loads, and by learning from early adopter agencies.

FIGURE 1.
Alternative fuel bus
pathways and fuel
descriptions.

Data Source: Tong et al.²

ACRONYM KEY:

B20	A blend of 20% biodiesel and 80% petroleum diesel
B100	Biodiesel (pure)
BEB	Battery electric bus
CAP	Criteria air pollutant
CNG	Compressed natural gas
GHG	Greenhouse gas
HEB	Hybrid-electric bus
LNG	Liquefied natural gas
O&M	Operation and maintenance

* The primary fuel is used to power and operate the bus. A secondary fuel is only used under certain drive cycles or driving conditions.

^ Electricity is considered a fuel.

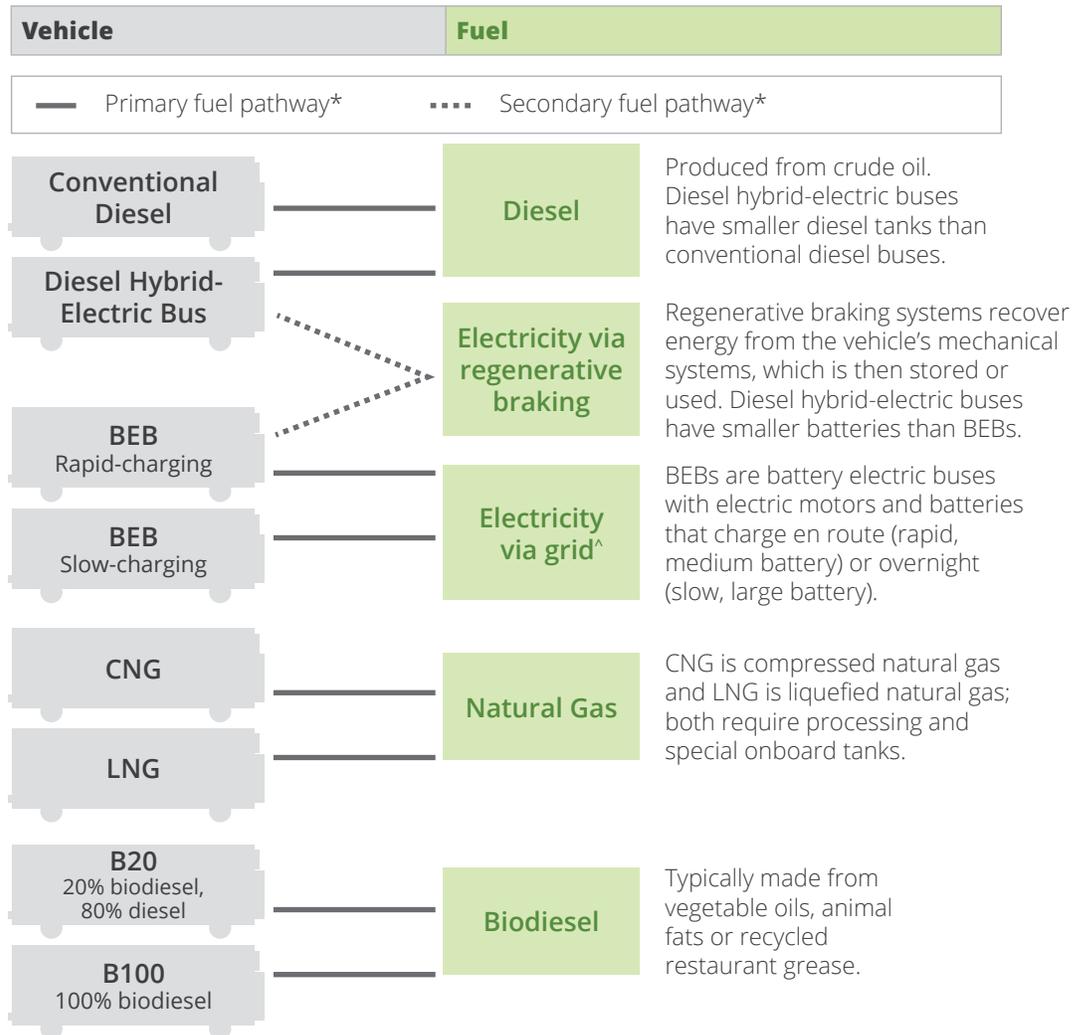
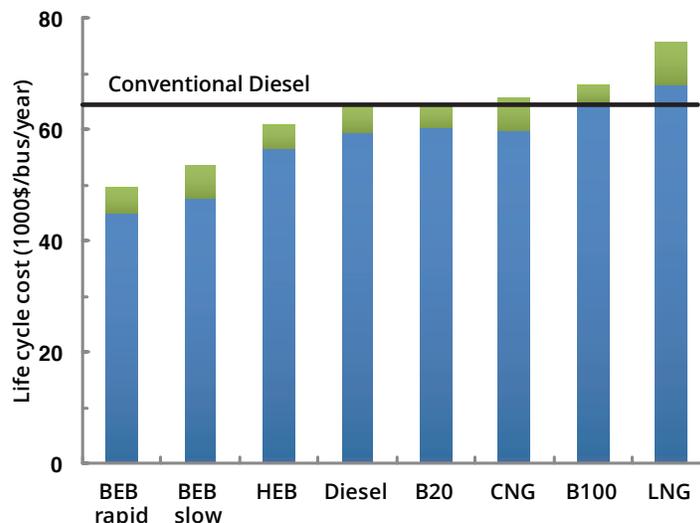


FIGURE 2.
Life cycle costs in 1000\$/bus/year
assuming 80% federal funding
for bus purchases.

Comparing the alternatives to conventional diesel, BEBs have the lowest costs. Other alternatives have equal or larger costs compared to conventional diesel. BEB: Battery electric bus, Diesel: Conventional diesel, B20: 20% Biodiesel, HEB: Diesel hybrid-electric bus, CNG: Compressed natural gas, B100: 100% Biodiesel, LNG: Liquefied natural gas. Data Source: Tong et al.²

KEY:

■ Agency Costs
■ Social Costs



Executive Summary

TABLE 2. Summary of previous studies on alternative fuel options for transit buses in the United States.

Study	Cost Components [^]	Fuel Options	Conclusions
Lowell et al. (2007) ¹³	<ul style="list-style-type: none"> Vehicle costs: <i>Purchase, fuel, O&M (not fuel)</i> Labor 	<ul style="list-style-type: none"> Diesel Diesel HEB CNG Hydrogen fuel cell electric bus Hydrogen fuel cell hybrid bus 	The net present value of projected total life cycle costs of fuel cell electric buses and fuel cell hybrid buses are higher than diesel, CNG, or diesel HEB buses for all scenarios considered.
Clark et al. (2007) ¹⁴	<ul style="list-style-type: none"> Vehicle costs: <i>Purchase, fuel, O&M (not fuel)</i> 	<ul style="list-style-type: none"> Diesel Diesel HEB CNG 	Diesel is the most economic option. However, when only 20% of bus cost is incurred, the four bus options have similar costs.
Clark et al. (2008) ¹⁵	<ul style="list-style-type: none"> Infrastructure <i>Stations</i> Emission estimates in Clark et al. (2007) 	<ul style="list-style-type: none"> B20 	This report updated the results in Clark et al. (2007) using (higher) fuel costs in 2008. CNG buses are the most economic technology in four fuel price scenarios, and diesel HEBs are the least economic technology.
Clark et al. (2009) ¹⁶	<ul style="list-style-type: none"> Vehicle costs: <i>Purchase, fuel, O&M (not fuel)</i> Infrastructure <i>Stations & garages</i> 	<ul style="list-style-type: none"> Diesel (<i>pre-2007 and 2007</i>) Diesel HEB Gasoline HEB CNG 	Each technology has the potential to be the best option. Key factors include bus speed, annual mileage, cost assumptions, fuel prices and purchase incentives, which may impact the comparison.
Johnson (2010) ¹⁷	<ul style="list-style-type: none"> Vehicle costs: <i>Purchase, fuel, O&M (not fuel)</i> Infrastructure <i>Stations & garages</i> 	<ul style="list-style-type: none"> Diesel CNG 	CNG is profitable for large transit bus fleets (>75 vehicles) unless one or more factors, such as diesel prices, CNG bus maintenance costs, bus annual mileage and vehicle incremental costs become unfavorable.
Science Applications International Corporation (2011) ¹⁸	<ul style="list-style-type: none"> Vehicle costs: <i>Purchase, fuel, O&M (not fuel)</i> Infrastructure <i>Stations & garages</i> 	Diesel, Biodiesel, Gasoline, Ethanol, CNG, LNG, Hydrogen ICE, Propane, Dimethyl ether, Electric trolleybus, BEB, Diesel HEB, Hydrogen fuel cell electric bus	This is a guidebook that includes estimates for 13 different fuel/powertrain types. It also has an accompanying spreadsheet-based life cycle costs model, FuelCost2.

Study	Cost Components [^]	Fuel Options	Conclusions
Gladstein Neandross & Associates (2012) ¹⁹		<ul style="list-style-type: none"> • Diesel • CNG 	Converting a single bus depot to support the use of CNG buses could be economically feasible.
Lowell (2012) ²⁰	<ul style="list-style-type: none"> • Vehicle costs: <i>Purchase, fuel, O&M (not fuel)</i> 	<ul style="list-style-type: none"> • Diesel • CNG 	CNG has a payback period of five to eight years, and has 14% reduction in comparative annual fuel costs.
McKenzie and Durango-Cohen (2012) ²¹	<ul style="list-style-type: none"> • Infrastructure <i>Stations</i> • Separate emission estimates 	<ul style="list-style-type: none"> • Diesel • Diesel HEB • CNG • Hydrogen fuel cell bus 	Alternative fuel buses can reduce operating costs and emissions, but the increase in infrastructure requirements is an important factor to consider.
Trillium CNG (2014) ²²	<ul style="list-style-type: none"> • Vehicle costs: <i>Purchase, fuel, O&M (not fuel)</i> • Infrastructure <i>Stations & garages</i> 	<ul style="list-style-type: none"> • Diesel • CNG 	The payback periods of a small (50 vehicles) and a large (200 vehicles) fleet are 3.7/5.7 years and 2.0/4.0 years (without/with federal funding for bus purchase).
Ercan et al. (2015) ²³	<ul style="list-style-type: none"> • Vehicle costs: <i>Purchase, fuel, O&M (not fuel)</i> • Infrastructure • Social costs <i>GHGs & CAPs</i> 	<ul style="list-style-type: none"> • Diesel • Diesel HEB • B20 • CNG • LNG • BEB 	In congested, urban areas, the BEB should be the preferred bus. The hybrid bus is most balanced over the given scenarios because it has lower bus capital investment than a BEB.
Bi et al. (2016) ²⁴	<ul style="list-style-type: none"> • Vehicle costs: <i>Purchase, fuel, O&M (not fuel)</i> • Infrastructure <i>Chargers</i> • Social costs <i>GHGs & CAPs</i> 	<ul style="list-style-type: none"> • Diesel • Diesel HEB • Plug-in charging BEB • Wireless charging BEB 	The wireless charging bus has the lowest life cycle cost. It has lower use-phase carbon emissions because it has a smaller, lighter battery than a plug-in charging bus.

[^]These papers have different details in estimating these cost components.

*Acronyms explained: HEB, hybrid-electric bus; CNG, compressed natural gas; LNG, liquefied natural gas; BEB, battery electric bus; B20, a blend of 20% biodiesel and 80% petroleum diesel; B100, biodiesel (pure); O&M, operation and maintenance; GHG, greenhouse gas; CAP, criteria air pollutant.



Overview

Who Manages Transit Bus Fleets?

Transit buses are used over short distances with fixed routes and frequent stops. These bus systems are managed by public transit agencies, which may also be responsible for other transit modal systems (i.e., light rail, ferries, etc.). In 2013, the American Public Transit Association estimates that there were 65,950 transit buses in the United States.¹ According to our analysis, these buses used approximately 0.4% of the energy consumed by on-road vehicles in the United States.²

FIGURE 3. Total number of transit buses in the United States by fuel type 2007 to 2013.
 *Biodiesel was counted in the "Other" category till 2008. **Fuel sources 2012 data was not available and the data were averaged from 2012 and 2013. "Other" includes propane, bio/soy fuel, biodiesel in 2007, hydrogen, methanol, ethanol and various blends. Data Source: Alternative Fuels Data Center. www.afdc.energy.gov/data/10302.



What Types of Alternative Fuel Technologies are Available to Fuel Transit Buses?

More than 58% of transit buses in the United States are fueled with ultra-low sulfur diesel.¹ Although transit agencies are still primarily dependent on conventional diesel, agencies are active adopters of alternative fuel options, which have been increasing since 2007.²⁵ Bus fleets turn over every 12 years so there is built-in transition ability. Figure 3 shows the number of buses by fuel type currently operated by United States transit agencies. The most common alternative fuel is the fuel group that comprises compressed natural gas (CNG), liquefied natural gas (LNG) and blends. Note, however, that the data is skewed regionally because transit agencies in California are more likely to have alternative fuel buses than other states.²⁶

MORE THAN 58% OF TRANSIT BUSES IN THE UNITED STATES ARE FUELED WITH ULTRA-LOW SULFUR DIESEL.

Transit agencies seek more efficient, less expensive fuel options for high-mileage transit buses. They are also often obligated to seek fuel diversity and promote environmental sustainability.²⁷ The alternative fuels evaluated here are compared to conventional diesel, and include: diesel hybrid-electric bus, natural gas, 20% biodiesel (B20) and 100% biodiesel (B100) and battery electric buses with slow-charging (overnight in garages) or rapid-charging (en route) capabilities. Transit agencies make decisions on which type of bus to purchase by evaluating a number of important factors.

How do Transit Agencies Fund and Plan for New Buses and Infrastructure?

The typical life span of a transit bus is 12 years. Transit agencies, such as the Port Authority of Allegheny County in the Pittsburgh region, may use federal funding to cover up to 80% of the bus purchase costs. Planning for new bus purchases can start many years before the buses are needed, based on fleet turnover requirements. As a result, new bus options are constantly being tested by the agencies. New buses must meet the basic needs of the transit agencies, including: size, capacity, range, durability and noise concerns, in addition to fuel economy. Fuel economy and mileage range statistics for the alternative fuel options are shown and compared in Figure 4 and Figure 5.² BEBs have much shorter ranges than the other bus fuel options, but have significantly better fuel economy. The current limited range for BEBs is an operational issue for transit agencies as it is likely to be smaller than the daily mileage of transit buses. Shorter-range buses result in more frequent charging requirements (disrupted schedules), and possibly additional charging locations that can contribute to higher costs. The shorter 40-foot buses also have comparatively better range and fuel economy than 60-foot buses because of their lighter weight.

Some alternative fuel technologies for transit buses will require significant changes to garages to accommodate new refueling infrastructure. Natural gas-based fuels require different refueling infrastructure than diesel. Two primary infrastructure issues related to natural gas are complying with fire code requirements and the selection of fast versus slow refueling equipment.¹⁹ Similarly, electric buses require new charging outlets and possible upgrades to transformers to handle charging loads. Federal funding can be used for both new garage infrastructure requirements as well as the purchase of new buses.

PLANNING FOR NEW BUS PURCHASES CAN START MANY YEARS BEFORE THE BUSES ARE NEEDED, BASED ON FLEET TURNOVER REQUIREMENTS. AS A RESULT, NEW BUS OPTIONS ARE CONSTANTLY BEING TESTED BY THE AGENCIES.

Overview

FIGURE 4. Typical range for alternative bus fuels (in miles), for the 40-foot (blue) and 60-foot (green) bus sizes. Range is calculated using fuel economy, fuel tank/battery size and usable fuel per tank/battery. Data Source: Tong et al.²

KEY:

- 40-foot bus
- 60-foot bus

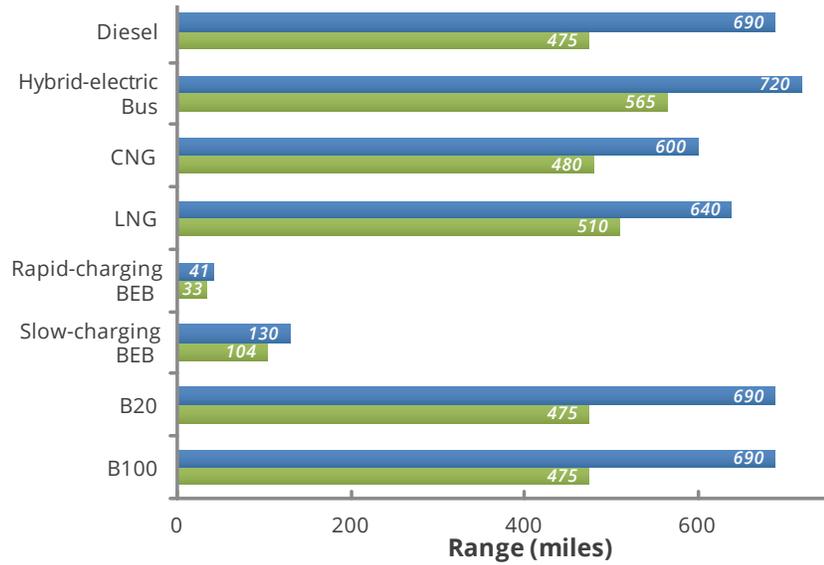
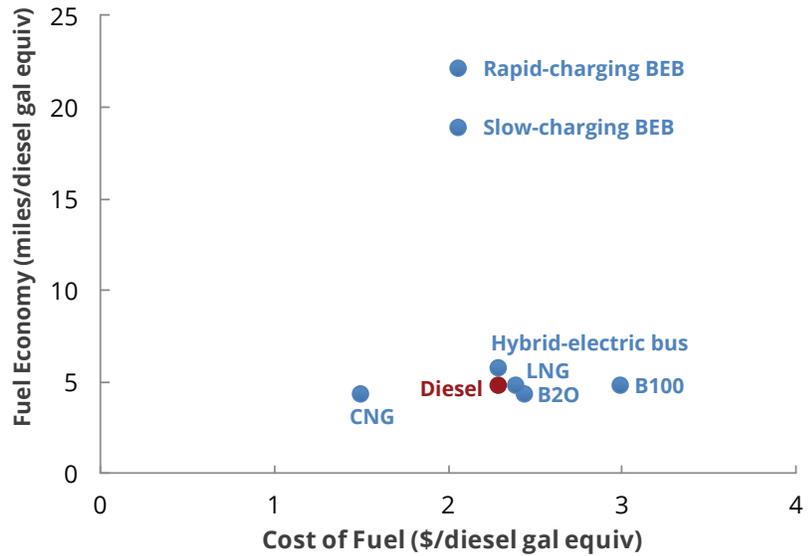


FIGURE 5. Typical fuel economy and fuel cost for alternative bus fuels for a 40-foot bus. A 60-foot bus would have poorer fuel economy and the same cost of fuel per fuel type. Data Source: Tong et al.²

ACRONYM KEY:

- B20** A blend of 20% biodiesel and 80% petroleum diesel
- B100** Biodiesel (pure)
- BEB** Battery electric bus
- CNG** Compressed natural gas
- LNG** Liquefied natural gas



How are Environmental Impacts Estimated?

Transit buses that run on alternative fuels have the potential to reduce petroleum consumption and reduce the social costs associated with emissions to the environment. We focus on two main environmental impacts: GHG emissions that contribute to climate change and CAP emissions that impact the environment and human health. The specific emissions considered are:

- **GHG emissions: carbon dioxide (CO₂), methane (CH₄) and nitrous oxide (N₂O)**
- **CAP emissions: nitrogen oxides (NO_x), carbon monoxide (CO), volatile organic compounds (VOC), particulate matter (PM) and sulfur dioxide (SO₂)**

WE FOCUS ON TWO MAIN ENVIRONMENTAL IMPACTS: GHG EMISSIONS THAT CONTRIBUTE TO CLIMATE CHANGE AND CAP EMISSIONS THAT IMPACT THE ENVIRONMENT AND HUMAN HEALTH.

Emissions are estimated using peer-reviewed publications,^{6,10} which built bottom-up emissions inventories for the life cycle fuel of the bus operation. The life cycle of the bus operation includes energy extraction, production and delivery of the fuel, and bus operation (tailpipe exhaust, tire and brake wear). We also include the manufacture of lithium-ion batteries for BEBs as they are an additional component. The emissions are then monetized per unit of bus distance/operation to estimate social cost (environmental and health impact).

Monetizing environmental impacts is controversial and has significant uncertainty. The methods of monetization are different for GHG and CAP emissions. GHG emissions are estimated in CO₂-equivalent units, using a Global Warming Potential (GWP) from the recent Intergovernmental Panel on Climate Change (IPCC) assessment report.⁷ The emissions are monetized using a Social Cost of Carbon (SCC) value developed by a United States interagency work group.⁸ CAP emissions are air pollutants that can impact the environment and human health, but these impacts are specific to the locations of emissions, unlike GHGs, which are well mixed in the atmosphere regardless of location. The study used two state-of-the-art models for estimating the social cost of CAP emissions, the Air Pollution Emission Experiments and Policy (APEEP/AP2)¹¹ analysis model and the Estimating Air pollution Social Impact Using Regression (EASIUR)¹² model. The environmental measures used in this study are described in more detail in Table 1.



Which Alternative Fuel Technology is Best for Transit Buses?

Which Alternative Fuel Technology is Best for Transit Buses?

Costs consist of life cycle agency costs and social costs. Life cycle agency costs include: bus purchase costs, fuel costs, operation and maintenance (O&M) costs and infrastructure costs. Social costs are due to climate change (from GHGs) and air pollution (from CAPs). Life cycle agency costs and social costs are added to produce total annualized costs per bus. This analysis uses some data specific to the Port Authority of Allegheny County, but all methods can be applied to other bus agencies. Social costs are location-specific, and are modeled for Allegheny County, Pennsylvania. The model is available and can be modified for decision makers' use.

What are the Total Agency Costs for the Alternative Fuel Technologies?

IF COSTS WERE EVALUATED ON A PER PASSENGER BASIS, THE 60-FOOT BUS MAY BE MORE COST-EFFECTIVE, PARTICULARLY DURING RUSH HOUR.

Total life cycle agency and social costs for each alternative fuel bus are shown in Figure 6 for 40-foot (top) and 60-foot (bottom) buses.² Two adjacent bars are shown for each fuel alternative — the left bar shows costs assuming external funding pays for 80% of bus purchase costs (federal funds to support public transit agencies) and the right bar shows costs assuming no external funding. Social costs are shown in light red and blue at the top of the bars. For 40-foot buses, the social costs are between 3% and 7% of the agency cost with no external funding, and between 5% and 11% with external funding. For 60-foot buses, the percentages are between 3% and 6% with no external funding, and between 5% and 12% with external funding.

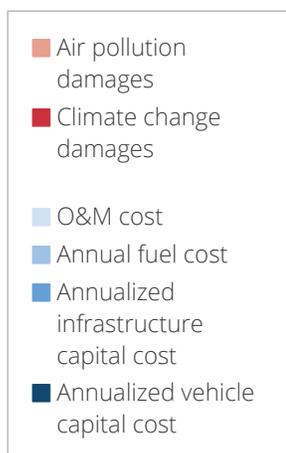
For a 40-foot bus, without funding, the life cycle costs for the alternative fuel technologies are equal to or higher than conventional diesel. In the scenario with external funding, the rapid-charging BEBs, slow-charging BEBs and hybrid-electric buses have costs lower than conventional diesel. All other fuel alternatives have equal or higher costs compared to conventional diesel. For a 60-foot bus, BEBs are only less expensive than conventional diesel in the case of external funding, and all other alternatives have higher costs. The 60-foot bus has a higher purchase price and lower fuel economy than its 40-foot counterpart, which contributes to higher fuel cost. However, the 60-foot bus can carry more passengers. If costs were evaluated on a per passenger basis, the 60-foot bus may be more cost-effective, particularly during rush hour.

For both bus sizes, the diesel hybrid-electric bus and LNG buses have higher costs than conventional diesel (without external funding). For the diesel hybrid-electric bus, the purchase costs are larger than all the other non-BEB buses. When accounting for external funding, the diesel hybrid-electric bus becomes cheaper than conventional diesel from the agency perspective. LNG has slightly higher bus capital costs, more extensive and expensive infrastructure upgrades and higher social costs than conventional diesel. Even with external funding, it is still a higher cost option.

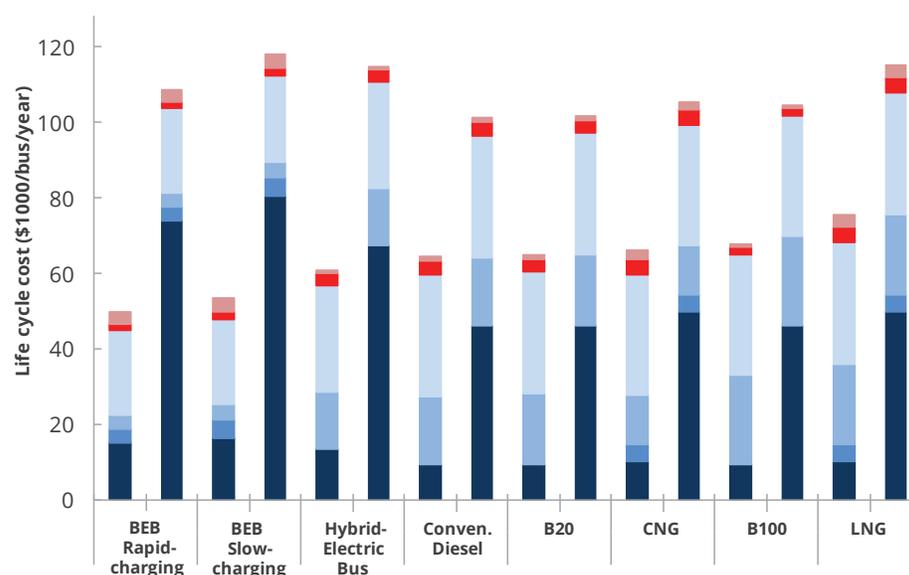
Sensitivity to the assumed parameters is described in Table 3 and the results are shown without and with federal funding in Figure 7. BEBs remain the least-cost option even considering uncertainty in the parameters. Some sensitivity evaluated includes accounting for different grid electricity emissions and prices, which vary region to region and could change over time. Fuel economy of the alternative fuel systems can also vary across regions along with weight of passenger loads, road type, speed and weather conditions.

Two primary issues in considering BEBs are addressing the short- and long-term infrastructure investment needs and the currently limited battery capacity, which does not meet the mileage requirements of typical daily bus use.

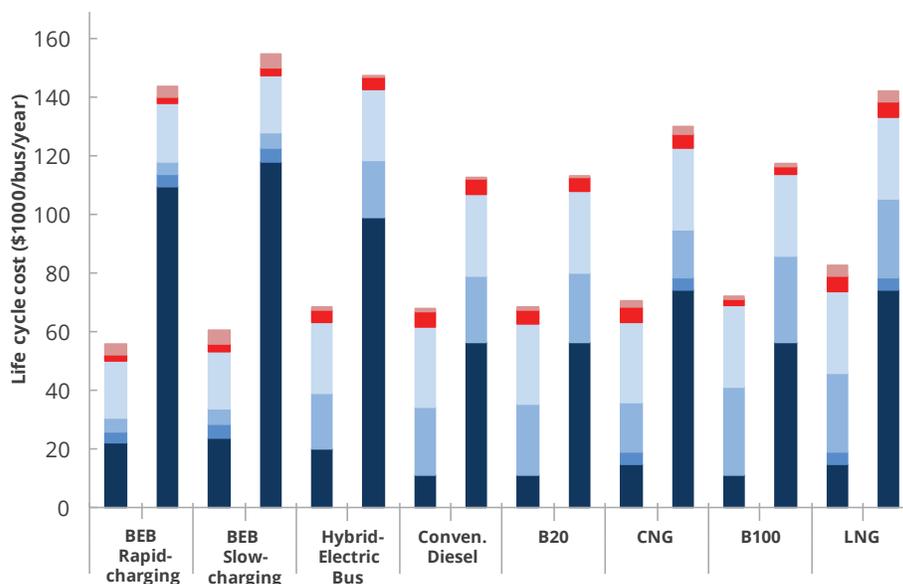
FIGURE 6. Annualized agency and social costs for a 40-foot transit bus (top) and a 60-foot bus (bottom). The bars on the left assume 80% of the bus purchase costs are paid through external funding. The bars on the right assume no external funding. The results assumed a 12-year lifetime, and a 1% discount rate. The climate change damages assume a 100-year GWP, and the air pollution damages are estimated using the AP2 model. Data Source: Tong et al.²



40-FOOT BUS



60-FOOT BUS



Which Alternative Fuel Technology is Best for Transit Buses?

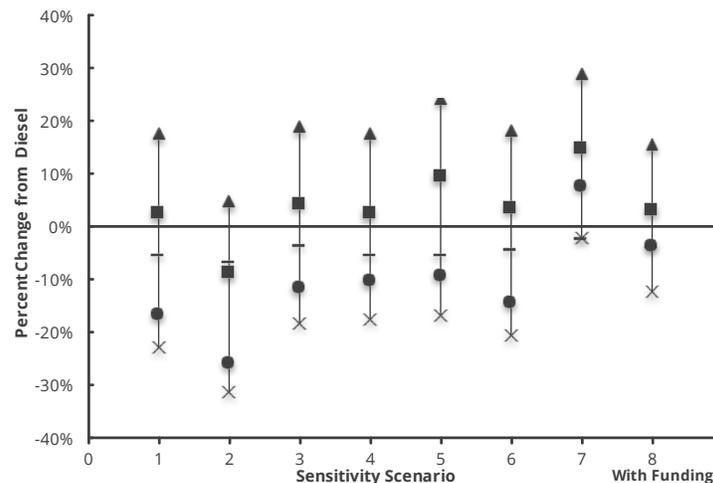
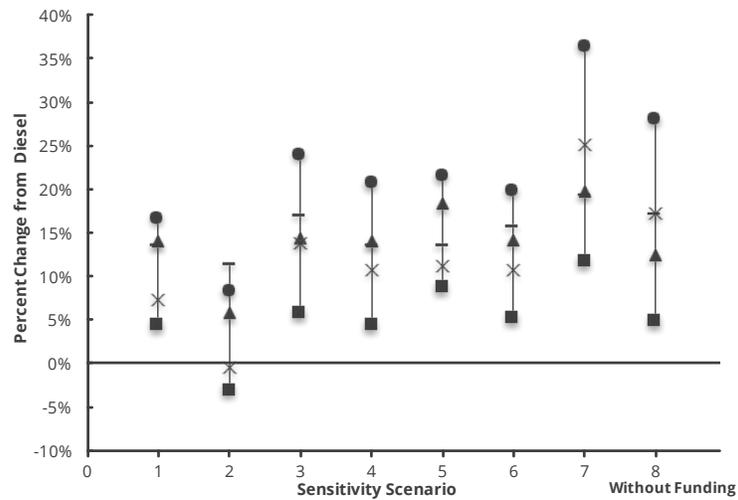
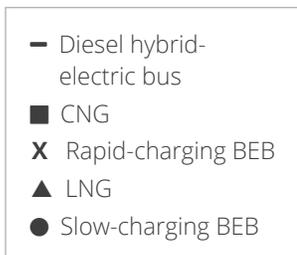
TABLE 3. Model assumption scenario descriptions for the sensitivity analysis.

Data Source: Tong et al.²

Scenario Number	Description
1. Baseline	Annual mileage of 37,761 miles/year and 1% discount rate
2. Higher diesel price	Diesel price \$1/gallon higher than the baseline
3. Reduced annual mileage	Annual mileage reduced to 30,000 miles/year
4. Doubling electricity price	Double electricity price from the baseline
5. Doubling infrastructure cost	Double the per bus infrastructure cost from the baseline
6. Higher discount rate	Increase discount rate to 3%
7. Combine 3, 4, 5, 6	See above
8. Combine 2, 3, 4, 5, 6	See above

FIGURE 7. Sensitivity to parameter changes for the alternative fuel options without (top) and with (bottom) federal funding.

Percent change is shown for total cost when compared to conventional diesel. Scenarios 1 through 8 are described in Table 3. B20 and B100 were removed for figure clarity as they are only sensitive to a max of 3%. Data Source: Tong et al.²



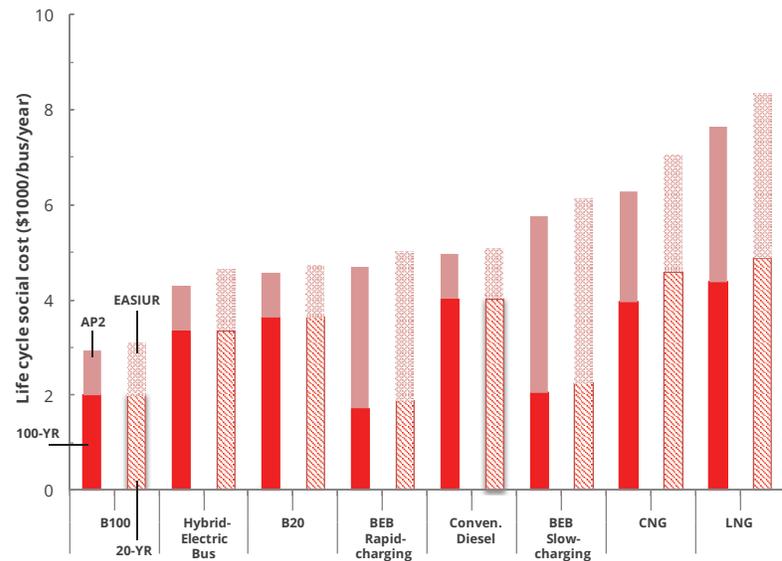
What are the Environmental and Health Impacts of the Alternative Fuel Technologies?

Although the environmental and health impacts are not large enough to change the total life cycle costs comparison, understanding these impacts separately from agency costs can be useful in informing the selection of an alternative fuel. Figure 8 shows only the climate change and air pollution damages for the alternative fuel bus options using both the AP2 and EASIUR models (refer to Table 1 for explanation). Damages from B100, B20 and diesel hybrid-electric buses are less than conventional diesel for both 40-foot and 60-foot buses. Rapid-charging BEBs have generally equivalent social costs to conventional diesel. Slow-charging BEBs, CNG and LNG buses all have higher social costs than conventional diesel for both bus sizes. Estimates from the EASIUR model are slightly higher than AP2, but they generally follow the same comparison pattern.

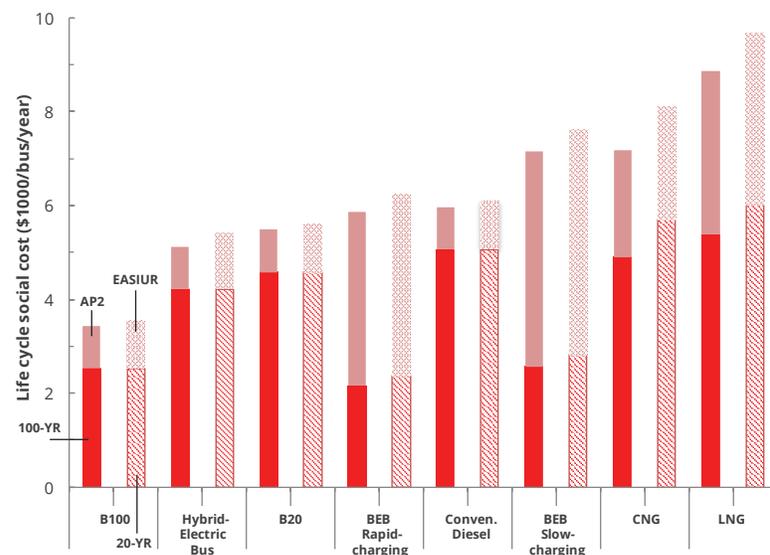
FIGURE 8. Life cycle social costs for a 40-foot (top) and a 60-foot transit bus (bottom). The left bars were estimated using the AP2 model and a 100-yr GWP (lower estimate), and the right bars were estimated with the EASIUR model and a 20-yr GWP (higher estimate). Lower dark red bars are climate change damages and upper light red bars are air pollution damages. Data Source: Tong et al.²



40-FOOT BUS



60-FOOT BUS



| Which Alternative Fuel Technology is Best for Transit Buses?

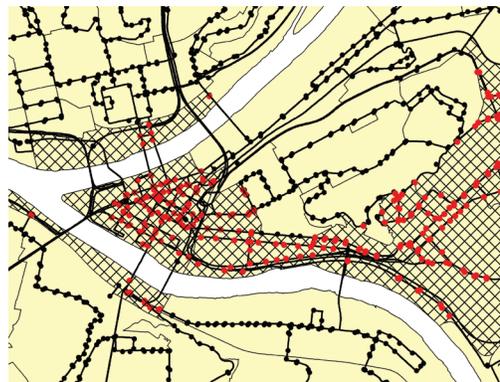
A FULL REPLACEMENT OF DIESEL BUSES WITH BEBS WOULD PROVIDE THE BIGGEST AIR POLLUTION IMPROVEMENTS IN TERMS OF BUS TAILPIPE EMISSIONS.

Slow-charging BEBs, CNG and LNG buses have higher social costs because they rely more on grid electricity, which has high SO₂ and NO_x emissions. LNG and CNG fuel processing requires considerable use of electricity, and BEBs charge and store grid electricity as their “fuel.” The social costs of BEBs are lower than CNG and LNG because BEBs are much more efficient. These social costs are important to consider when purchasing alternative fuel buses. There still remains uncertainty around the emissions and damage estimates for climate change and air pollution. However, the uncertainty is unlikely to change the relative ranking and contribution to the overall costs of the alternatives.

How Much do Transit Buses Contribute to Emissions in Hot Spot Areas?

In some cases, transit agencies may be particularly concerned about the emissions directly from buses in hot spot areas, which may have higher population density and denser bus traffic. In Pittsburgh, the Port Authority of Allegheny County operates 100 bus routes. There are 83 bus routes that serve the downtown area, and 89 bus routes that serve both downtown and Oakland neighborhoods. We chose the downtown (Central Business District) area and Oakland as hot spots, along with the North Shore, South Shore and Bluff neighborhoods next to and across the rivers from downtown. These hot spots are shown in the hatched area in Figure 9.

FIGURE 9. Port Authority of Allegheny County's transit bus routes in Pittsburgh, PA are black solid lines. Stops in the shaded hot spot areas are red dots. The hot spot areas are Downtown (Central Business District), North Shore, South Shore, Bluff and Oakland neighborhoods. Data source: Tong et al.²



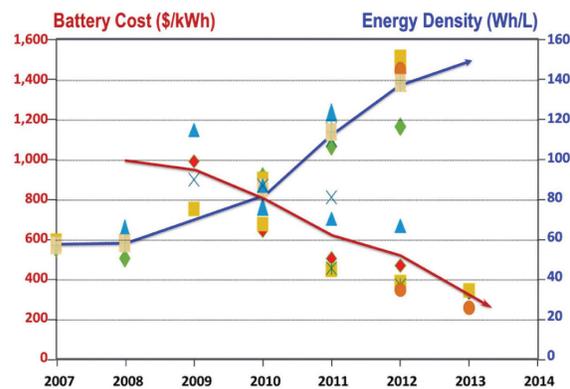
Within a year, 94% of all the bus trips travel through the hot spot areas, and roughly 10% of the Port Authority's bus mileage is within these areas. Using the total fleet mileage and the average fleet bus emissions factors²⁸, we estimate that 135 metric tons of NO_x and 2.2 metric tons of particulate matter of diameter 2.5 micrometers or smaller (PM_{2.5}) were emitted by buses in 2015, of

which 10% were in the hot spot area. Some alternative fuel buses offer CAP emission reductions compared to the current fleet of buses. A full replacement of diesel buses with BEBs would provide the largest air pollution improvements in terms of bus tailpipe emissions over the entire Port Authority operating area, and particularly in the hot spot areas.

Estimating emissions at a more detailed scale also allows the Port Authority to understand the contribution of their buses to overall air pollution with better spatial resolution. A previous study estimated 224 tons of PM_{2.5} emissions were released from mobile sources in 2009 in Allegheny County. Port Authority buses contributed only approximately 1% of the PM_{2.5} mobile emissions in the county that year.²⁹ Bottom-up estimates for hot spot areas can provide a more detailed look at emissions, which could influence the decision to purchase alternative fuel buses.

What are Other Important Factors to Consider?

FIGURE 10. Declining cost of plug-in electric vehicle batteries with rising energy densities from the United States Advanced Battery Consortium. Source: US Department of Energy (DOE) energy.gov/sites/prod/files/2014/02/f8/everywhere_road_to_success.pdf



Given the clear advantage of BEBs in this analysis, it is important to consider two factors closely related to the costs and usability of this fuel type. BEBs rely on rechargeable batteries, which currently provide a range of around 30 to 130 miles. Although the current range could not meet the needs of most typical bus routes without impacting the operation and planning (see Figure 4), battery technology

has been improving while costs for batteries have also been decreasing for battery electric vehicles as shown in Figure 10.³⁰ Improvements in battery performance should translate to a longer range for BEBs, but the timing on these developments is uncertain. For this reason, we recommend observing and learning from other transit agencies that adopt BEBs, and testing the buses before full implementation to ensure the buses meet agency needs.

In addition to improvements in battery technology, there will be changes in the electricity grid in the future due to federal and state energy policies. The United States Environmental Protection Agency's (EPA) Clean Power Plan (CPP) and state-level Renewable Portfolio Standards (RPS) may both contribute to more renewable energy sources, and fewer coal-fired power plants.^{31,32} In the Midwest/Mid-Atlantic region, the United States Energy Information Administration projects a 26% decline in direct CO₂ emissions from changes to the electricity grid from 2015 to 2030, as shown in Figure 11.³³ With a reduction in the CO₂ emissions, there would be a direct reduction in the social cost. All fuels that rely heavily on the electric grid would experience a decrease in total cost due to reduced social costs.

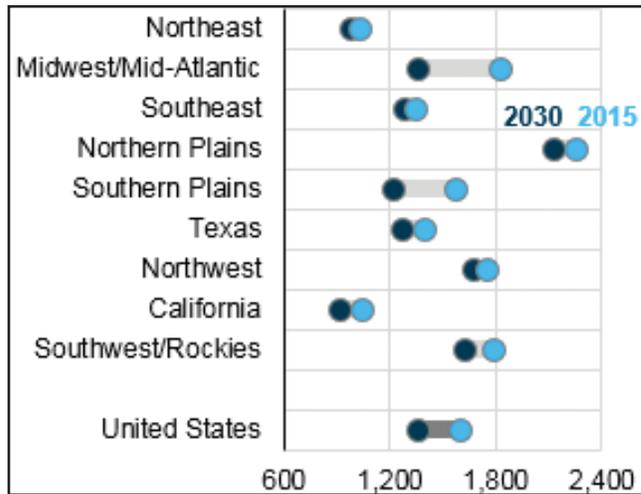
WE RECOMMEND OBSERVING AND LEARNING FROM OTHER TRANSIT AGENCIES THAT ADOPT BEBS, AND TESTING THE BUSES BEFORE FULL IMPLEMENTATION TO ENSURE THE BUSES MEET AGENCY NEEDS.

| Which Alternative Fuel Technology is Best for Transit Buses?

Electricity Market Regions

FIGURE 11. Carbon dioxide emissions rate by region in 2015 and 2030. Units: pounds of CO₂ per megawatt hour (fossil generation only).

Pennsylvania is in the Midwest/ Mid-Atlantic region, which is estimated to see a 26% decrease in CO₂ emissions. Data Source: United States Energy Information Administration.





Findings

Findings

This guide has presented life cycle agency and social costs, as well as other practical challenges for eight alternative fuel technologies for transit buses. Table 4 outlines the pros and cons of each option. The lowest cost alternative fuel bus option is a BEB when compared to conventional diesel. Rapid and slow-charging BEBs should be considered when external funding for bus purchases is available. Although BEBs are the best option from a total life cycle cost perspective, there are range and infrastructure issues that would require additional consideration and likely more time for development.

THE LOWEST COST ALTERNATIVE FUEL BUS OPTION IS A BATTERY ELECTRIC BUS WHEN COMPARED TO CONVENTIONAL DIESEL.

TABLE 4. Pros and cons of each alternative fuel technology transit bus.

Transit Bus Option	Pros	Cons
Conventional Diesel	<ul style="list-style-type: none"> Existing technology (high reliability) Lowest bus purchase cost No new infrastructure needed 	<ul style="list-style-type: none"> Large GHG emissions
Diesel Hybrid-Electric Bus	<ul style="list-style-type: none"> Lower environmental impacts than conventional diesel Very good driving range No new infrastructure needed 	<ul style="list-style-type: none"> High bus purchase cost
BEB Rapid-charging	<ul style="list-style-type: none"> Quiet while running High vehicle efficiency, low electricity cost and low O&M cost Reduce GHG emissions significantly 	<ul style="list-style-type: none"> Very high bus purchase cost Very poor driving range Major infrastructure upgrades Larger CAP emissions Low reliability (evolving tech)
BEB Slow-charging	<ul style="list-style-type: none"> Quiet while running High vehicle efficiency, low electricity cost and low O&M cost Reduce GHG emissions significantly 	<ul style="list-style-type: none"> Very high bus purchase cost Poor driving range Major infrastructure upgrades Larger CAP emissions Low reliability (evolving tech)
Compressed Natural Gas (CNG)	<ul style="list-style-type: none"> Lowest cost of fuel (\$/dge) Fuel can be produced in PA Moderate bus purchase cost 	<ul style="list-style-type: none"> Major infrastructure upgrades Larger GHG & CAP emissions
Liquefied Natural Gas (LNG)	<ul style="list-style-type: none"> Fuel can be produced in PA Moderate bus purchase cost (higher than diesel, but lower than other alternatives) 	<ul style="list-style-type: none"> Major infrastructure upgrades Largest GHG & CAP emissions Highest total cost
B20 (Biodiesel)	<ul style="list-style-type: none"> Minor infrastructure upgrades Reduce GHG emissions 	<ul style="list-style-type: none"> Biodiesel not readily available Higher cost of fuel (\$/dge)
B100 (Biodiesel)	<ul style="list-style-type: none"> Minor infrastructure upgrades Reduce GHG emissions 	<ul style="list-style-type: none"> Biodiesel not readily available Highest cost of fuel (\$/dge)

ACRONYM KEY:	
\$/dge	Cost per diesel gallon equivalent
B20	A blend of 20% biodiesel and 80% petroleum diesel
B100	Biodiesel (pure)
BEB	Battery electric bus
CAP	Criteria air pollutant
CNG	Compressed natural gas
GHG	Greenhouse gas
HEB	Hybrid-electric bus
LNG	Liquefied natural gas
O&M	Operation and maintenance

A horizontal illustration of a landscape on a green background. A white dashed line represents a road. Above the road, from left to right, there is a red barn with a white roof and a silo, a green bus, and a cluster of city buildings including a brown one, an orange one, and a blue one. There are also several green trees and white streetlights scattered across the scene.

Recommendations

Recommendations

Based on the findings from this project, Carnegie Mellon University researchers believe that battery electric buses will soon become the least costly transit bus option, but improvements to the range of the buses and agency planning for infrastructure modifications will be necessary before this is possible. Figure 12 outlines the short- and long-term planning strategies a transit agency could take in preparation for battery electric bus integration.

FIGURE 12. Short- and long-term strategies for transit agency investment in alternative energy sources for transit buses.

🕒 Short-Term Strategies

WAIT AND OBSERVE.

Transit agencies should learn from the implementation experience of alternative fuel buses, particularly battery electric buses operated by early-adopter agencies.

PLAN AHEAD.

The investment in alternative fuel buses likely requires changes to the garage infrastructure and may require changes to operation scheduling. Anticipating and planning for these changes could help with the transition to alternative fuel buses.

TEST THE OPTIONS.

Before making the investment, plan on testing the buses and the potential infrastructure to ensure it meets agency needs.

UPDATE STUDIES.

As more and better data on costs, performance and emissions become available, update this type of study to ensure that decisions are based on the most current information.

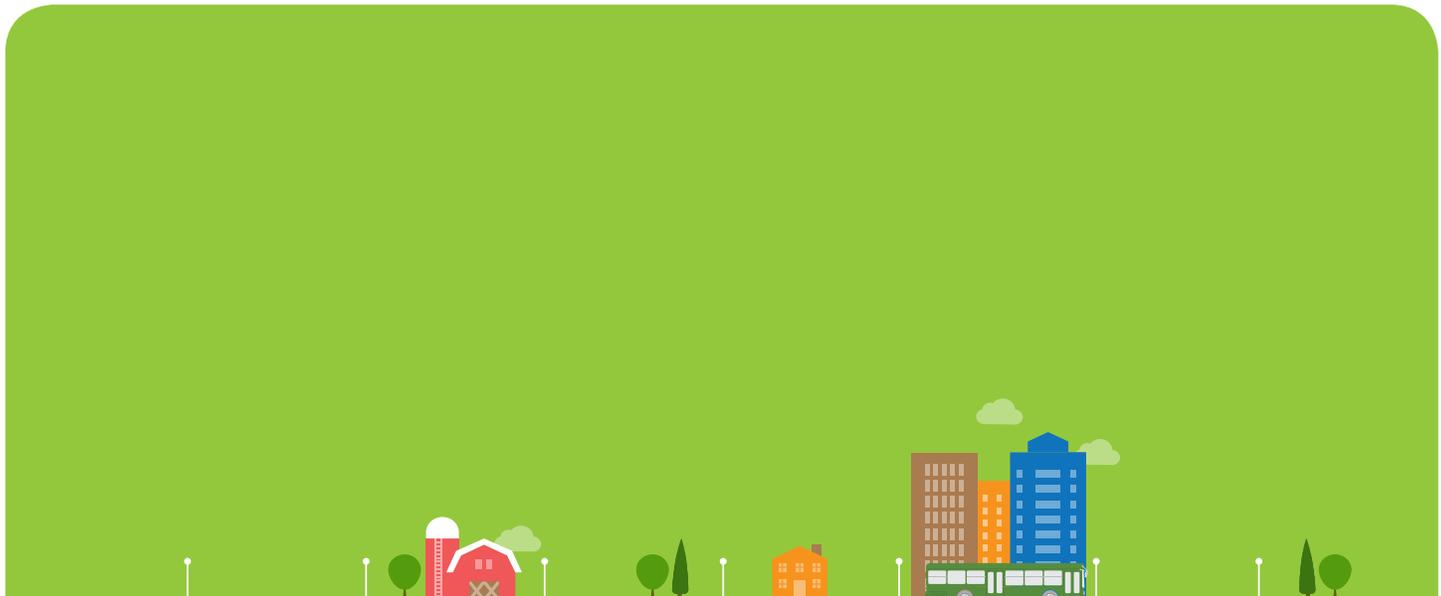
🏠 Long-Term Strategies

INVEST IN BATTERY ELECTRIC BUSES.

In the long term, battery electric buses should become less expensive and have longer range. The benefits of reduced emissions from a cleaner grid and the use of external funding for capital investments further make BEBs an attractive option.

INVESTIGATE RENEWABLE ENERGY SOURCES.

With a switch to battery electric buses, a large contributor to the life cycle emissions is from grid electricity. Although the grid in Pennsylvania is likely to become cleaner, having independent, renewable energy sources at Port Authority facilities could be a favorable option from an emissions standpoint.



Acronyms

Acronyms

APTA	American Public Transit Association
APEEP/AP2	Air Pollution Emission Experiments and Policy model
B20	20% Biodiesel
B100	100% Biodiesel
BEB	Battery Electric Bus
CAP	Criteria Air Pollutant
CH₄	Methane
CNG	Compressed Natural Gas
CO	Carbon Monoxide
CO₂	Carbon Dioxide
CPP	Clean Power Plan
DOE	Department of Energy
EASIUR	Estimating Air pollution Social Impact Using Regression model
EIA	Energy Information Administration
EPA	Environmental Protection Agency
GHG	Greenhouse Gas
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation model
GWP	Global Warming Potential
HEB	Hybrid-Electric Bus
LNG	Liquefied Natural Gas
N₂O	Nitrous Oxide
NO_x	Nitrogen Oxide
NRC	National Research Council
O&M	Operation & Maintenance
PAAC	Port Authority of Allegheny County
PM_{2.5}	Particulate Matter with diameter less than 2.5 micrometers
RPS	Renewable Portfolio Standard
SCC	Social Cost of Carbon
SO₂	Sulfur Dioxide
VOC	Volatile Organic Compound



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Heinz College
5000 Forbes Ave.
Pittsburgh, PA 15213
412-268-9505
traffic21.heinz.cmu.edu

Carnegie Mellon University
Scott Institute
for Energy Innovation

Scott Hall
5000 Forbes Ave.
Pittsburgh, PA 15213
412-268-7434
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