# A Zero-Emission Transition for the U.S. Transit Fleet

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# List of Abbreviations

**AC Transit –** Alameda-Contra Costa Transit District

**AFL-CIO –** American Federation of Labor and Congress of Industrial Organizations

**BEB –** Battery electric bus

**BEV –** Battery electric vehicle

**CNG –** Compressed natural gas

**CTE –** Center for Transportation and the Environment

**DC –** Direct Current

**DOE –** United States Department of Energy

**EERE –** Office of Energy Efficiency and Renewable Energy

**EPA –** United States Environmental Protection Agency

**FAST –** Fixing America's Surface Transportation Act

**FCEB –** Fuel cell electric bus

**FCEV –** Fuel cell electric vehicle

**FHWA –** Federal Highway Administration

**FTA –** Federal Transit Administration

**FY –** Fiscal Year

**HVAC –** Heating, ventilation, and air conditioning

**IMI –** Integrated Mobility Innovation

**IRS –** United States Internal Revenue Service

**KPI –** Key Performance Indicator

**LA Metro –** Los Angeles County Metropolitan Transportation Authority

**LCFS –** Low Carbon Fuel Standard

**Low-No –** FTA Low or No Emission Vehicle Program

**Low-No-CAP –** FTA Low or No Emission Vehicle Component Assessment Program

**MOD –** Mobility-on-Demand

**NFCBP –** National Fuel Cell Bus Program

**NTD –** National Transit Database

**NTI –** National Transit Institute

**O&M –** Operations and Maintenance

**OCTA –** Orange County Transportation Authority

**OSU –** The Ohio State University

**RIN –** Renewable Identification Number

**SARTA –** Stark Area Regional Transit Authority

**STAR –** Strategic Transit Automation Research

**TVIDC –** Transit Vehicles Innovation Deployment Centers

**TTD –** Transit Trades Department

**TWU –** Transport Workers Union of America

**T&I –** United States House of Representatives Transportation and Infrastructure Committee

**USDOT –** United States Department of Transportation

**VTO –** Vehicle Technologies Office

**ZEB –** Zero-emission bus

**ZEV –** Zero-emission vehicle

# Executive Summary

The United States can transition its entire transit fleet to zero-emission vehicles (ZEV) by 2035, if federal support provides additional funding for vehicle and equipment procurement, technical assistance, and a comprehensive research and innovation program to accelerate transit vehicle technology development.

The following report offers a roadmap for federal lawmakers in support of this policy objective, including an accounting of estimated agency costs, key assumptions underpinning those figures, acknowledgement of limitations, and other considerations. Because the federal government has long been a primary funder of transit research, technology development, and vehicle procurement, it can uniquely accelerate transit's conversion to a 100 percent ZEV fleet.

To date, more than 1,300 zero-emission buses (ZEB) have been delivered or awarded to US transit agencies, representing roughly two percent of the US transit bus fleet. Costs for both battery electric buses (BEB) and fuel cell electric buses (FCEB) have decreased in the past decade with growing technology maturity and manufacturing scale. However, neither technology has reached cost parity with conventionally-fueled vehicles, and both still face technical constraints that limit wider adoption.

Though heavy-duty transit buses (30-foot to 60-foot) have thus far seen the highest penetration of zero-emission technologies in the national transit fleet, agencies of all sizes use other vehicles for both fixed-route and demand-response service. These include cutaway vehicles, vans, and other light-duty passenger vehicles. The Center for Transportation and the Environment (CTE) transition analysis accounts for all of them.

**The country can reach this full fleet transition objective by 2035, at a cost of between $56.22 billion and $88.91 billion.**

The cost analysis includes the incremental costs of ZEVs compared to conventionally-fueled vehicles (e.g., diesel, diesel-hybrid, compressed natural gas (CNG)), fueling infrastructure, direct technical assistance for transit agencies, and federal research and innovation support services using a combination of publicly available pricing and CTE project experience. "Low" and "high" estimates for each vehicle type are provided to capture the range of available models. A summary of the costs is shown in **Figure 1** and **Table 1** below.

CTE used a Mixed Fleet scenario to project costs, meaning agencies will employ both battery electric and fuel cell electric technologies according to service requirements. The Mixed Fleet scenario will be the most effective approach to a ZEV transition for transit systems in the US because it allows transit agencies to replace conventionally-fueled buses with ZEBs at a 1:1 ratio, keeping costs down and limiting the operational changes required to redesign service for range-limited vehicles.

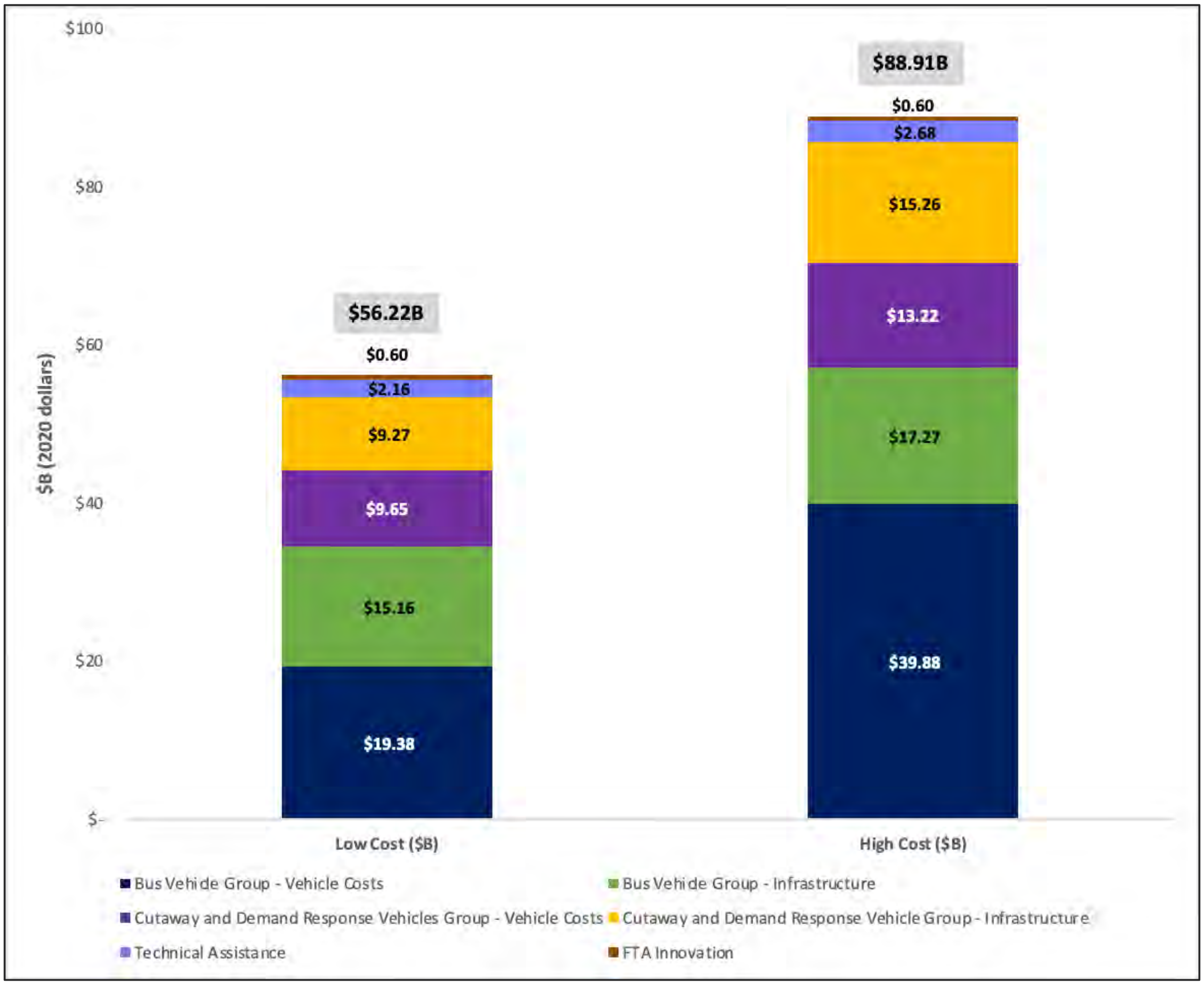


*Figure 1. Total Estimated Incremental Costs of the Mixed Fleet Scenario*

*Table 1. Summary of Estimated Incremental Costs of the Mixed Fleet Scenario*

| *Fleet Transition Costs* | Low Cost Estimate ($B) | High Cost Estimate ($B) |
|---|---|---|
| *Bus Vehicle + Infrastructure Transition* | $34.54 | $57.15 |
| *Cutaway and Demand Response Vehicle + Infrastructure Transition* | $18.92 | $28.48 |
| *Technical Assistance* | $2.16 | $2.68 |
| *Federal Transit Administration (FTA) Innovation and Bus Testing* | $0.60 | $0.60 |
| *Total* | **$56.22** | **$88.91** |

**Other assumptions and considerations informing CTE's estimates:**

- ***Fleet Sizing:*** Of nearly 2,800 reporting entities to the FTA, including state, local, and tribal governments, universities, non-profit organizations, and for-profit transit fleet operators who receive federal funding, these organizations operate roughly 70,000 transit buses. These agencies also operate roughly 40,000 cutaway vehicles (16-foot to 36-foot cabins built on truck chassis), and more than 45,000 transit vans and other passenger vehicles.

- ***Battery Electric vs. Fuel Cell Electric Technologies:*** Agencies operating in areas with lower population density will need more vehicles with greater range to support more challenging service requirements, and therefore will procure more FCEBs. CTE approximated splits between urban, suburban, and rural populations to determine the appropriate bus fleet mix. Overall, 73 percent of buses are converted to BEBs and 27 percent are converted to FCEBs in this scenario.

- ***Market Availability and Cost Reductions:*** Fuel cell electric cutaways and demand response vehicles for transit applications are limited; therefore, this analysis assumed those vehicles are 100% BEV, with fleet expansion required to meet service requirements. For the core analysis, CTE utilized current costs and did not project potential reductions over time. However, manufacturing scale and technology breakthroughs are expected to help the industry reach those objectives.

- ***Existing ZEV Fleet:*** FTA data does not track vehicle powertrain (e.g., battery electric, diesel, CNG), and reliable industry estimates remain incomplete and unreliable, so CTE did not have a reasonable basis for segmenting vehicles in the analysis. Because current ZEV adoption remains marginal relative to the overall national fleet, CTE assumed conversion of every vehicle. Existing infrastructure buildouts are also not included.

- ***Vehicle Costs:*** State procurement contracts for California, Georgia, and Virginia provided pricing for most vehicles. For vehicle types that were not in those contracts, CTE sourced costs from transit agency budgets, manufacturers' vehicle quotes, and publicly available documents. CTE established low and high average costs based on the available data.

- ***Asset Lifecyle:*** CTE set a 2035 full transition target based on federal requirements, setting a 12-year asset life for all buses (Bus Vehicle Group) in transit fleets, and time for program set-up. In the analysis, CTE replaced vehicles according to their earliest retirement date. Though other vehicles (e.g., cutaways) have shorter lifecycles, incremental costs of conversion are included only once per vehicle in the national fleet.

- ***Technical Assistance*:** Unique challenges posed by ZEV fleet deployments will necessitate robust technical assistance programming. CTE recommends that each transit agency with 10 or more vehicles develop a fleet transition plan to support future vehicle procurements and fueling infrastructure buildout. Likewise, agencies will need technical support for early vehicle deployments, and all fleet operators will need to build out capabilities for performance monitoring and data management.

- ***Infrastructure Sizing:*** Battery electric infrastructure costs include all engineering, design, materials, management, equipment, and construction costs. CTE included charger types (e.g., DC fast charger, level 2 charger) based on expected service requirements of each vehicle type (e.g., BEB, cutaway, van), and scaled them accordingly. Hydrogen fueling infrastructure costs are based off 50-bus increments nationwide, and maintenance facility upgrades are based off eight-bus increments nationwide.

- ***Hydrogen Competitiveness:*** FCEBs are currently more expensive than BEBs, though manufacturing scale is expected to reduce capital costs such that they are in line with BEBs. Because FCEBs will be necessary to replace conventionally-fueled buses with ZEBs in a 1:1 ratio due to their longer range, the federal government should ensure procurement of enough FCEBs to bring costs down.

- ***FTA Innovation and Bus Testing*:** Multiple technology breakthroughs are necessary to accelerate ZEB adoption, including battery and fuel cell technologies, auxiliary systems, automated vehicle technologies, and others. FTA maintains a research and innovation program, which is responsible for supporting transit technology and service delivery innovation. However, very little of its current funding supports vehicle technology development or ZEBs specifically. Likewise, the federal bus testing programs will need to grow to support new ZEB technologies, vehicle models, and market entrants. The national fleet transition cost estimates incorporate these requirements.

- ***Workforce Development:*** ZEV deployments impose new workforce development requirements, owing to different operational characteristics from conventionally-fueled vehicles. Transit operators, technicians, engineers, and planners need training in the sourcing, deployment, and management of ZEVs and supporting infrastructure. Sustained workforce development infrastructure will need to be in place to support the industry as it evolves.

- ***Manufacturing and Supply Chain*:** The CTE analysis assumes agencies will be able to replace all vehicles with ZEVs beginning in 2023. In reality, domestic ZEV manufacturers will require several years to reach a scale sufficient to meet demand associated with converting the entire US transit fleet. Any federal program for a national fleet transition will need to engage manufacturing stakeholders and ensure they can meet accelerated demand, possibly supporting them to help them achieve that capacity.

# Introduction

The on-road transportation sector currently accounts for 28 percent of all global greenhouse gas (GHG) emissions in the United States[1], larger than any other sector of the domestic economy. Because the federal government has been a primary funder of transit research, technology development, and vehicle procurement, it can uniquely accelerate transit's conversion to a 100 percent zero-emission vehicle (ZEV) fleet.

To date, more than 1,300 zero-emission buses (ZEB) have been delivered or awarded to US transit agencies, representing roughly two percent of the US transit bus fleet. Costs for both battery electric buses (BEB) and fuel cell electric buses (FCEB) have decreased in the past decade with growing technology maturity and manufacturing scale. However, neither technology has reached cost parity with conventionally-fueled vehicles, and both still face technical or economic constraints that limit wider adoption.

Though heavy-duty transit buses (30-foot to 60-foot) have seen the highest penetration of zero-emission technologies thus far in the national transit fleet, agencies of all sizes use other vehicles for both fixed-route and demand-response service. Battery-electric cutaway vehicles and transit vans are beginning to enter the US market, and other light-duty passenger vehicle models are becoming available in greater numbers each year.

Transit agencies, vehicle manufacturers, component and infrastructure suppliers, and other stakeholders have learned from ZEV deployments to date, and the industry better understands the challenges of scaling zero-emission technologies in transit operations than it did when federal funding for ZEB pilot projects began half a decade ago. Battery electric vehicles (BEV) have emerged as the most popular zero-emission alternative, but are still limited by transit service requirements. Extreme temperatures that require vehicle heating, ventilation, and air conditioning (HVAC) units to draw significant energy from batteries, longer routes in both duration and distance, and other operating characteristics restrict the routes on which agencies can deploy them. Battery and other component technologies will inevitably improve over time, increasing the viability of BEVs in transit service. Alternatively, integration of fuel cell technologies can mitigate range limitations.

Over the past 12 years, the Center for Transportation and the Environment (CTE) has built extensive knowledge through its experience supporting 71 unique transit agencies on more than 70 ZEB deployments and 25 ZEV transition plans across North America. These agencies represent nearly every geography, requiring CTE to understand the challenges of deploying ZEVs in all climates, and for service areas ranging from heavily urbanized to low-density suburban or rural. The expansive footprint of these deployments has also helped CTE appreciate the extent to which local factors, especially those involving state regulators, electrical utilities, and land considerations,

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[1] *Office of Transportation and Air Quality. "Fast Facts: U.S. Transportation Sector Emissions 1990-2018." United States Environmental Protection Agency. June 2020.*

impact ZEV fleet planning and decision-making. For more than two decades, CTE has worked directly with vehicle manufacturers and component suppliers to develop, integrate, and demonstrate new zero-emission technologies. This breadth and depth of experience informed the approach CTE applied to scoping the challenge of converting the entire US transit fleet to ZEVs on an aggressive timeline, and providing reasonable cost estimates for accomplishing it.

In any scenario, accelerating technology adoption would necessitate additional funding and regulatory changes. A full US fleet transition to zero-emission vehicles (ZEV) will require federal intervention to finance fleet procurement, local planning and deployment support, and technology development. **The country can reach this objective by 2035,** allowing time for passage of the next surface transportation authorization to provide federal funding and direction for the transition, as well as establishment or expansion of any federal programs. Transit agency procurement processes vary, and those that have yet to deploy ZEVs will need time to plan fleet conversions and engage local stakeholders (e.g., electrical utilities). Therefore, CTE assumed agencies would convert all new vehicles beginning in 2023, with 12 years for the transition to remain consistent with existing transit bus asset lifecycles.

The following sections offer a roadmap for federal lawmakers in support of this policy objective, including an accounting of estimated incremental costs over maintaining the existing non-ZEV fleet, key assumptions underpinning those figures, acknowledgement of limitations, and other considerations.

# Fleet Transition Costs and Assumptions

The costs to transition US transit vehicles to ZEVs include:

- Incremental costs of ZEVs compared to conventionally-fueled vehicles (e.g., diesel, diesel-hybrid, compressed natural gas (CNG)),
- ZEV fueling infrastructure (i.e., battery electric vehicle charging infrastructure or hydrogen fueling infrastructure),
- Technical assistance for transit agencies, and
- Federal research and innovation support.

All rubber-tired transit vehicles reported in the Federal Transit Administration's (FTA) National Transit Database (NTD) Vehicle inventory are included in this analysis, except for trolley buses, as those are already zero-emission. For NTD definitions of each vehicle type, see **Appendix A: National Transit Database Definitions.** Costs for zero-emission models of the vehicle types included in this analysis are shown in **Table 2**. "Low" and "high" estimates for each vehicle type are provided to capture the range of available models. Configurable options and extended warranties are not captured in the vehicle costs.

*Table 2. Vehicle Costs by Type Reported by NTD*

| Vehicle Type | Number of Vehicles (NTD, 2019) | Powertrain | Low Cost | High Cost |
|---|---|---|---|---|
| Bus (40' Transit Bus) | 55,625 | Diesel | $410K | $500K |
| | | Battery Electric | $660K | $800K |
| | | Fuel Cell Electric | $1.0M | $1.0M |
| Articulated Bus (60' Transit Bus) | 6,008 | Diesel | $740K | $1.0M |
| | | Battery Electric | $1.1M | $1.3M |
| | | Fuel Cell Electric | $1.5M | $1.5M |
| Over-the-Road Bus (Commuter coach) | 6,422 | Diesel | $330K | $610K |
| | | Battery Electric | $800K | $900K |
| Double Decker Bus | 209 | Diesel | $1.0M | $1.0M |
| | | Battery Electric | $1.4M | $1.4M |
| | | Fuel Cell Electric | $1.5M | $1.7M |
| School Bus | 98 | Diesel | $79K | $120K |
| | | Battery Electric | $290K | $380K |
| Van | 23,047 | Diesel | $40K | $77K |
| | | Battery Electric | $170K | $170K |
| Cutaway | 39,396 | Diesel/Gasoline | $88K | $240K |
| | | Battery Electric | $170K | $350K |
| Automobile | 7,275 | Gasoline | $18K | $24K |
| | | Battery Electric | $31K | $31K |
| Minivan | 12,981 | Gasoline | $30K | $37K |
| | | Battery Electric | $31K | $40K |
| Sport Utility Vehicle (SUV) | 562 | Gasoline | $30K | $37K |
| | | Battery Electric | $31K | $40K |

NTD vehicle types were categorized into the two groups for this analysis:

- **Bus Vehicle Group:** Bus, Articulated Bus, Over-the-Road Bus, and Double Decker Bus
- **Cutaway and Demand Response Vehicle Group:** School Bus, Van, Cutaway, Automobile, Minivan, and SUV

Cost estimates for configurable options for the vehicles are listed in **Table** 3.

*Table 3. Configurable Options for Vehicles*

| Item | Low Cost | High Cost | Unit |
|---|---|---|---|
| *Configurables/options* | $75K | $100K | per bus, regardless of powertrain |
| *BEB extended warranty* | $75K | $110K | per BEB |
| *FCEB extended warranty* | $17K | $25K | per FCEB |
| *FCEB mid-life fuel cell stack overhaul* | $40K | $40K | per FCEB |
| *Battery electric cutaway extended warranty* | $20K | $30K | per battery electric cutaway |
| *Diesel bus mid-life engine overhaul* | $50K | $50K | per diesel bus |

Fueling infrastructure cost estimates for both battery electric and fuel cell electric vehicles are listed in **Table 4**.

*Table 4. Fueling Infrastructure Installation Costs*

| Item | Low Cost | High Cost | Unit |
|---|---|---|---|
| Hydrogen Fueling Infrastructure | | | |
| *Maintenance facility upgrades* | $48K | $180K | per maintenance bay (assume 1 bay/8 buses) |
| *Electrical upgrades* | $100K | $100K | per station (each station serves 50 buses) |
| *Master planning* | $200K | $200K | per station (each station serves 50 buses) |
| *Design and engineering, permitting, construction, and equipment* | $4.4M | $5.1M | per station (each station serves 50 buses) |
| BEV Charging Infrastructure | | | |
| *BEB depot charging infrastructure design and engineering, permitting, construction, and equipment* | $250K | $280K | per BEB (Bus Vehicle Group) |
| *Cutaway depot charging infrastructure design and engineering, permitting, construction, and equipment* | $150K | $200K | per cutaway |
| *Demand response charging infrastructure design and engineering, permitting, construction, and equipment* | $70K | $60K | per demand response vehicle (Cutaway and Demand Response Vehicle Group) |

## Transition Planning, Technical Assistance, and Performance Monitoring

Transitioning fleets to ZEVs requires a fundamental change in a fleet operator's approach to the procurement of vehicles and the associated infrastructure to support them. Many fleet operators will require technical assistance for such a paradigm shift. CTE recommends that each transit agency with 10 or more vehicles develop a fleet transition plan to support future vehicle procurements and fueling infrastructure buildout. While these transition plans are not a static blueprint for ZEV implementation, they ensure that agencies have properly assessed the capabilities of battery electric and hydrogen technologies as they relate to current and future service requirements. These plans also ensure that agencies have evaluated the impact that these technologies will have on their operations and facilities.

These studies help agencies understand how much of their current bus service is feasible for the replacement of diesel or CNG vehicles with today's ZEV technologies. Identifying which daily vehicle schedules are not feasible with current BEV technology allows transit agencies to determine specific strategies to overcome limitations: identifying a block as feasible with slight technology improvements, adding on-route charging to a route to overcome range limitations, or, for buses, investigating FCEBs as an option to meet service requirements. Through transition planning, agencies can also assess whether long-term capital planning and operational requirements favor battery electric or hydrogen as a sole fuel source (assuming no mixed fleet). Other considerations include charging infrastructure requirements for BEVs, placement of hydrogen fueling equipment, fuel (e.g., electricity or hydrogen) cost modeling, and redundancy. Agencies that understand and internalize these considerations up front are more likely to make smart decisions in futureproofing facilities to reduce costs over the long-term.

Likewise, agencies will need technical assistance to support early ZEV deployments. This support will help the transit agency avoid common mistakes, support agency staff as they learn how to procure and manage the technology and ensure that initial vehicles are deployed successfully and meet the transit agency's specific needs. Eventually, agencies will develop their own internal capabilities and no longer need outside help.

In addition to general technical assistance, agencies also need help with performance monitoring and data management to ensure the success of their ZEV deployments. Tracking key performance indicators (KPIs), such as how various factors (e.g., driving style, route conditions, temperature, battery health) impact vehicle performance and energy efficiency, maintenance and operational data and costs, fuel consumption, and environmental benefits, allows transit agency staff to optimize vehicle usage and performance. These data also feed into planning future ZEV deployments.

A summary of recommended technical assistance costs is listed in **Table 5**. Multiple variables will affect the cost of technical assistance for a transit agency, including the number of vehicles, layout of facilities, technical capabilities of staff, agency size, infrastructure constraints, and number of fueling strategies to consider. The range of estimated costs for transition planning reflect these variables. Estimated costs for deployment support are a total budget assigned to each transit agency, irrespective of size. Estimated costs to support performance monitoring include costs to set up an internal data management program and annual reporting costs.

*Table 5. Costs for Recommended Technical Assistance to Support ZEV Transition*

| *Item* | Low Cost | High Cost | Unit |
|---|---|---|---|
| *Transition plan development* | $50K | $50K | Per small transit agency (10 <= x <= 50 vehicles) |
| | $150K | $200K | Per medium transit agency (50 < x <= 250 vehicles) |
| | $250K | $300K | Per large transit agency (> 250 vehicles) |
| *Deployment support* | $350K | $600K | Per transit agency |
| *Data management program start-up* | $50K | $50K | Per small transit agency (10 <= x <= 50 vehicles) |
| | $150K | $150K | Per medium transit agency (50 < x <= 250 vehicles) |
| | $200K | $200K | Per large transit agency (> 250 vehicles) |
| *Annual KPI reporting* | $60K | $60K | per transit agency per year |

## Analysis Approach

CTE evaluated three vehicle transition scenarios to illustrate a range of estimated costs. The scenarios represent different approaches to convert conventionally-fueled vehicles to ZEVs while meeting all service needs, based on the current capabilities of the technology.

As noted above, NTD vehicle types were categorized into the two groups for this analysis:

- **Bus Vehicle Group:** Bus, Articulated Bus, Over-the-Road Bus, and Commuter Coach
- **Cutaway and Demand Response Vehicle Group:** School Bus, Van, Cutaway, Automobile, Minivan, and SUV

**Table 6** describes the zero-emission conversion plan for each group of vehicles in each scenario.

*Table 6. ZEV Transition Scenarios*

| *Transition Scenarios* | Bus Vehicle Group Transition | Cutaway and Demand Response Vehicle Group Transition |
|---|---|---|
| *100% BEV w/ fleet expansion* | All buses are converted to depot-charged BEBs, with a 33% fleet expansion required to meet current service needs. Due to range limitations of BEB technology, BEBs cannot replace conventionally-fueled vehicles in a 1:1 ratio. | All cutaway and demand response vehicles are converted to depot-charged BEVs with a 50% fleet expansion required to meet current service needs due to range limitations of BEV technology. |
| *100% FCEB w/100% BEV Cutaway and Demand Response* | All buses are converted to FCEBs at a 1:1 ratio to current vehicles. | FCEVs of the cutaway and demand response vehicles for transit applications are limited and were not considered in this analysis. Therefore, this scenario uses 100% BEVs for the Cutaway and Demand Response Vehicle Group. |
| *Mixed Fleet* | Both depot-charged BEBs and FCEBs are used; 73% of current buses are converted to BEBs and 27% of current buses are converted to FCEBs. | Fuel cell electric vehicles of the cutaway and demand response vehicles for transit applications are limited and were not considered in this analysis. Therefore, this scenario uses 100% BEVs for the Cutaway and Demand Response Vehicle Group. |

**Figure 2** and **Figure 3** summarize the low and high estimates for the incremental costs for vehicles and infrastructure for all scenarios.

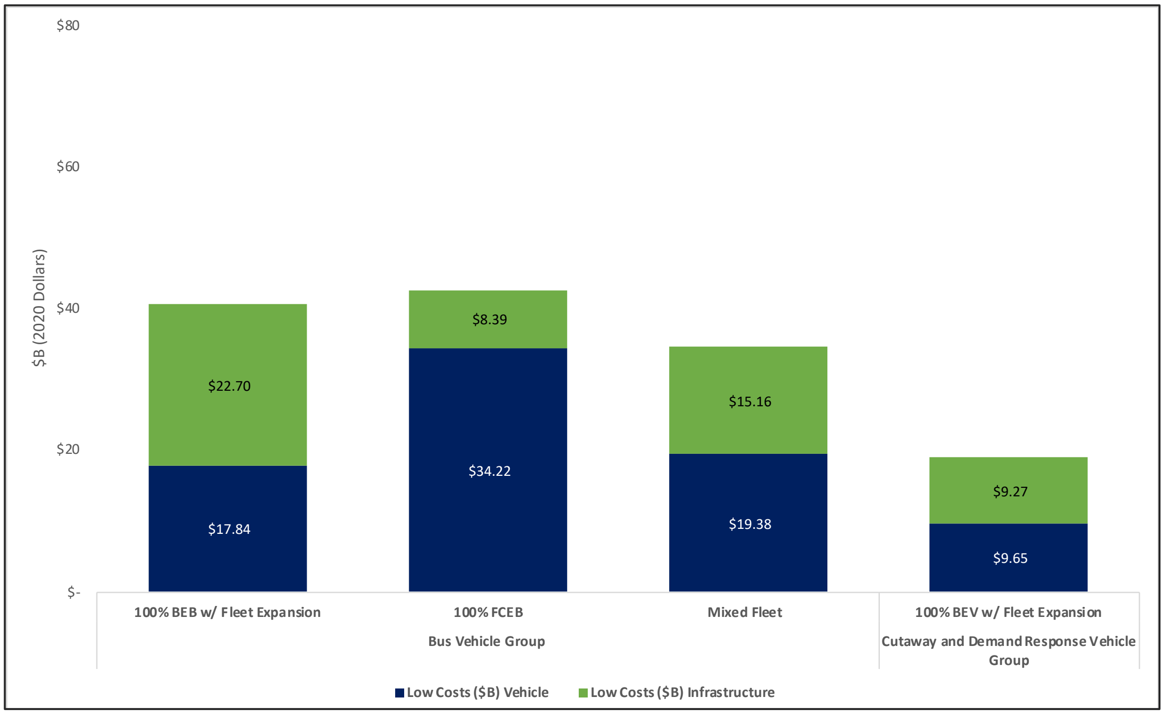


*Figure 2. Low cost estimate of incremental capital costs ($B) to transition all US vehicles for all scenarios*

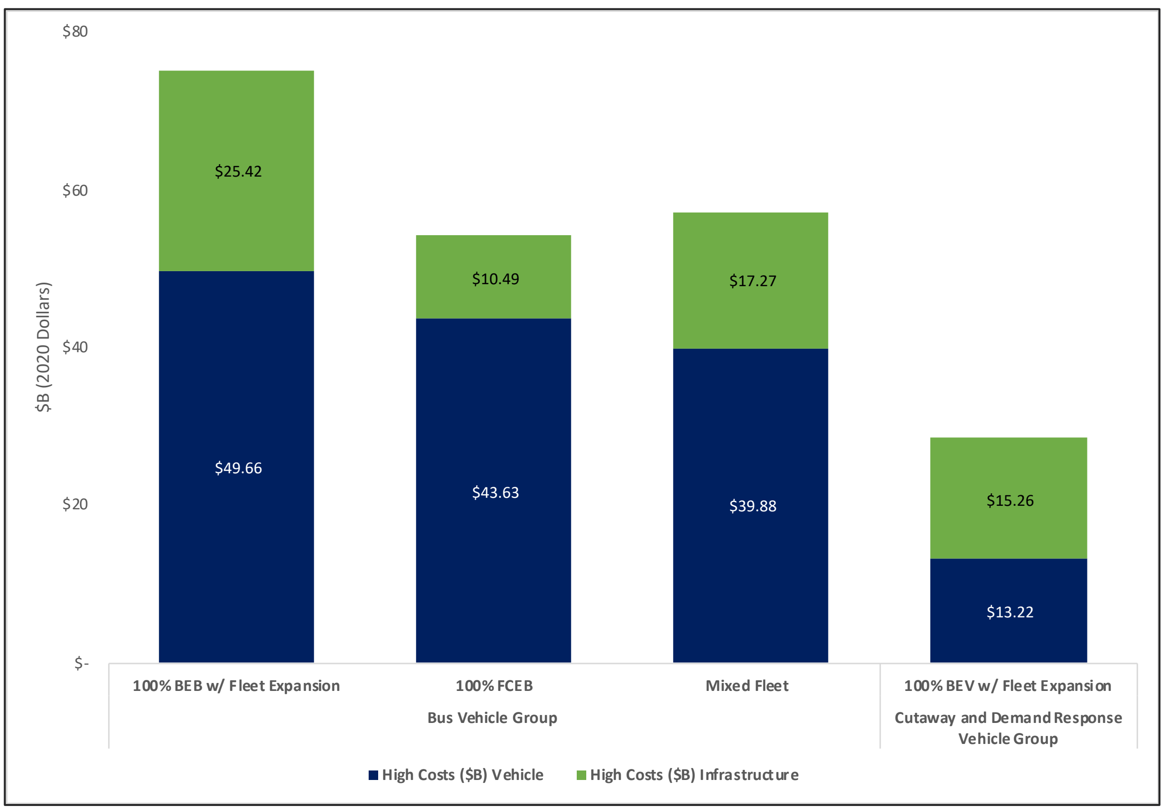


*Figure 3: High cost estimate of incremental capital costs ($B) to transition all US vehicles for all scenarios*

The Mixed Fleet scenario will be the most effective approach to a ZEV transition for transit systems in the US because it allows transit agencies to replace conventionally-fueled buses with ZEBs at a 1:1 ratio, which keeps costs down and limits the operational changes required to redesign service for range-limited vehicles. The Mixed Fleet scenario also preserves a competitive element between technologies in the market, reducing risks of stagnation among component suppliers and manufacturers. Technology advances in either the battery electric or fuel cell electric vehicle industries could change the optimal ratio of BEBs to FCEBs, leading to lower costs and improved operations. Finally, this approach allows agencies to diversify their fuel sources, which reduces systemic risks from fuel supply issues.

Using the Mixed Fleet approach, CTE believes the United States can achieve a 100 percent ZEV fleet transition by 2035 at a **total incremental cost of $56.22 billion to $88.91 billion**, including recommended technical assistance costs and innovation and bus testing costs. **Figure 4** and **Table 7** illustrate and summarize the estimated costs for this scenario.

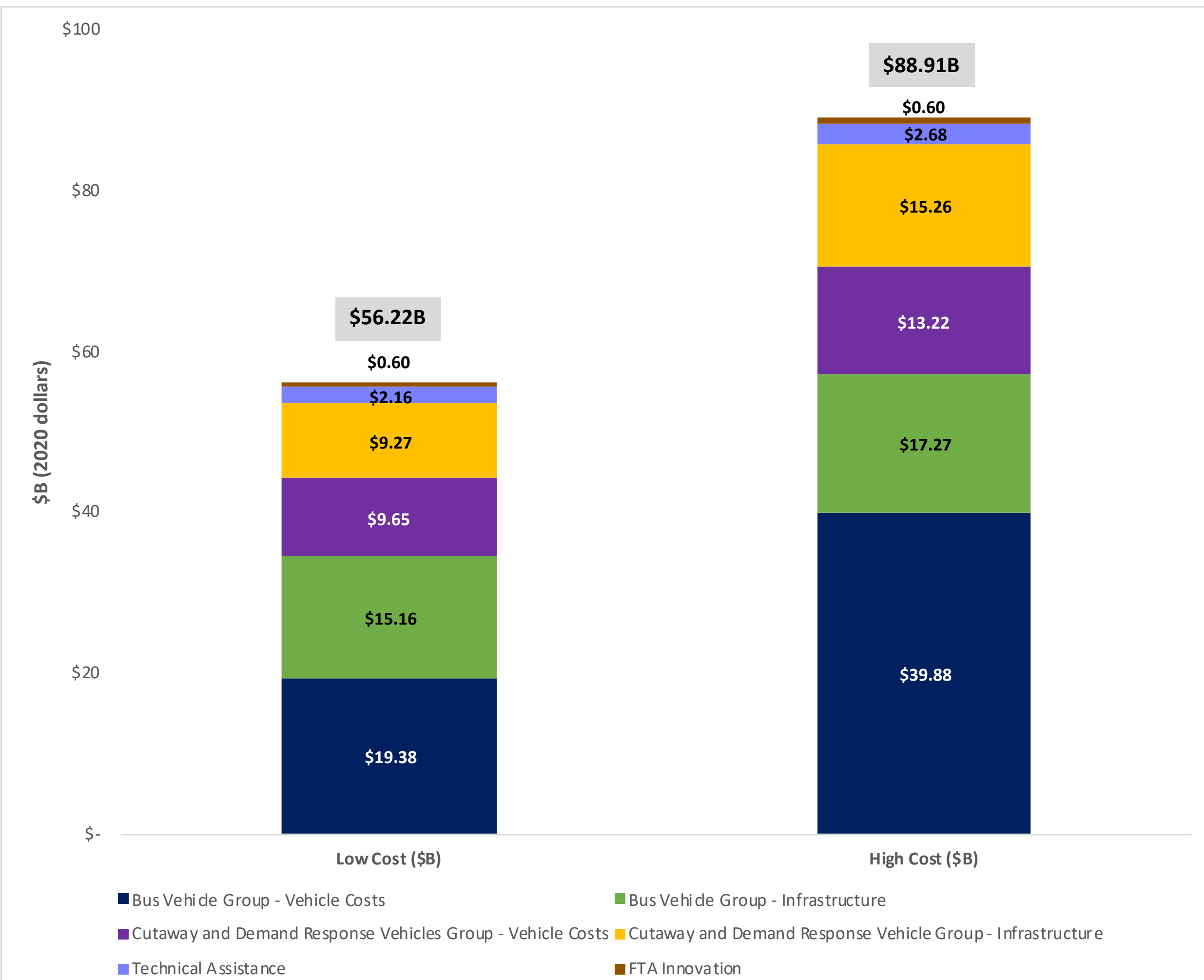


*Figure 4: Total estimated incremental costs of the mixed fleet scenarioTable 7. Total Fleet Transition Costs for the Mixed Fleet Scenario*

| *Fleet Transition Costs* | Low Cost Estimate ($B) | High Cost Estimate ($B) |
|---|---|---|
| *Bus Vehicle Group – Vehicles* | $19.38 | $39.88 |
| *Bus Vehicle Group – Infrastructure* | $15.16 | $17.27 |
| *Cutaway and Demand Response Vehicle Group – Vehicles* | $9.65 | $13.22 |
| *Cutaway and Demand Response Vehicle Group – Infrastructure* | $9.27 | $15.26 |
| *Technical Assistance* | $2.16 | $2.68 |
| *FTA Innovation and Bus Testing* | $0.60 | $0.60 |
| ***Total*** | **$56.22** | **$88.91** |

## Assumptions

- ***Fleet Sizing:*** Of nearly 2,800 reporting entities to the FTA, including state, local, and tribal governments, universities, non-profit organizations, and for-profit transit fleet operators who receive federal funding, these organizations operate roughly 70,000 buses. These include conventional transit buses, articulated buses, over-the-road coaches, and double-decker buses. These agencies also operate roughly 40,000 cutaway vehicles (16-foot to 36-foot cabins built on truck chassis), and more than 45,000 transit vans and other passenger vehicles.[2]

- ***Existing ZEV Fleet:*** FTA data currently does not track vehicle powertrain (e.g., battery electric, diesel, or CNG), and industry estimates remain incomplete and unreliable, so CTE did not have a reasonable basis for segmenting vehicles in the analysis. Because current ZEB adoption is somewhere between 1 and 2 percent, and other ZEV adoption is even lower, CTE assumed the entire national fleet requires conversion. Some agencies have already invested in some infrastructure buildouts to support ZEBs, but these are also not included.

- ***Vehicle Costs:*** State procurement contracts for California, Georgia, and Virginia provided pricing for most vehicles. For vehicle types that were not in those contracts, CTE sourced costs from transit agency budgets, manufacturers' vehicle quotes, and publicly available documents. CTE established low and high average costs based on available data. For more in-depth explanations of vehicle costs, see **Appendix B: Cost Assumptions.**

- ***Asset Lifecyle:*** CTE assumed a 12-year life for all buses (Bus Vehicle Group) in transit fleets. Federal funding requirements stipulate transit agencies must maintain new buses in revenue service for 12 years. Cutaways and other vehicles have a seven-year asset lifecycle, but incremental costs of conversion are included only once per vehicle in the national fleet (i.e., a vehicle replaced in 2025 was not included a second time in 2032). The drive systems in BEBs and FCEBs are expected to have longer lifecycles than those of diesel and CNG buses. While some transit agencies operate their conventionally-fueled buses for a few

[2] *2019 Vehicles. Federal Transit Administration. National Transit Database.*

years beyond asset lifecycle requirements, ZEBs offer the potential to be operated longer, which can reduce vehicles' total cost of ownership and could potentially lead FTA to increase the lifecycle requirements of the buses.

- ***Fleet Expansion:*** Due to BEV range limitations, a full ZEV fleet will either require additional BEBs, or a mix of BEBs and FCEBs. Because FCEVs are not considered in the Cutaway and Demand Response Vehicle Group, these segments of the fleet will inevitably require expansion to meet the transition target. **Table 8** shows estimated requirements for fleet expansion and a recommended optimal fleet mix for BEBs and FCEBs by transit agency type. The nationwide values are weighted averages based on the population percentage covered by each agency type. These population figures come from Pew's 2018 survey on urban, suburban, and rural communities. While these population splits are not a perfect framing of the national transit service profile, they allow CTE to approximate the operating requirements of all transit buses, cutaways, and other demand-response vehicles. CTE's experience has illustrated that denser urban environments remain better fits for BEVs, while lower density suburban and rural environments carry more strenuous operating requirements, and may be better suited for hydrogen fuel cell technologies.

*Table 8. Recommended Fleet Expansion and Mixed Fleet Vehicle Ratio*

| *Transit Agency Type* | Percent of US by Population[3] | BEV Fleet Expansion Requirement (Buses only)[4] | Feasible Fleet Mix (Buses only)[5] | |
|---|---|---|---|---|
| | | | BEB | FCEB |
| *Rural* | 14% | 1.5 | 5% | 95% |
| *Suburban* | 55% | 1.3 | 70% | 30% |
| *Urban* | 31% | 1.15 | 90% | 10% |
| *US Average* | 100% | 1.33 | 73% | 27% |

- ***Infrastructure Sizing:*** Battery electric infrastructure costs include all engineering, design, materials, management, equipment, and construction costs.[6] BEBs will use higher-powered Direct Current (DC) chargers (e.g., 150 kW) in a 2:1 or 3:1 vehicle-to-charger ratio. Battery electric cutaways will use DC chargers, allowing for faster charging times to meet the necessary duty cycle. However, it is likely that cutaway vehicles would be able to share one higher-powered DC charger in a 4:1 vehicle to charger ratio. Other vehicles (i.e., school buses, vans, automobiles, minivans, SUVs) will utilize Level 2 chargers in a 1:1 ratio. Hydrogen fueling infrastructure costs are based off 50-bus increments nationwide, and maintenance facility upgrades are based off eight-bus increments nationwide. The low cost assumption for the hydrogen fueling station corresponds to a liquid hydrogen fueling station, while the high cost assumption corresponds to a gaseous hydrogen fueling station.

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[3] *Parker, Kim et al., Demographic and economic trends in urban, suburban and rural communities. Pew Research Center. May 22, 2018. [pewsocialtrends.org/2018/05/22/demographic-and-economic-trends-in-urban-suburban-and-rural-communities/](pewsocialtrends.org/2018/05/22/demographic-and-economic-trends-in-urban-suburban-and-rural-communities/)*

[4] *Estimates are from CTE's ZEV transition planning for US transit agencies, as well as other publicly available transition plans*

[5] *Ibid.*

[6] *Ibid.*

For more in-depth explanations of infrastructure costs, see **Appendix B: Cost Assumptions.**

## Scenarios and Assumptions Outside the Analysis Scope

- ***On-Route Charging:*** CTE did not include on-route charging in the analysis scenarios, which imposes higher capital costs, but can mitigate BEB range limitations. For instance, with on-route charging infrastructure installed along bus routes, a transit agency committed to a BEB-only fleet may be able to meet more challenging service requirements without expanding that fleet. However, on-route charging stations may require both right-of-way acquisition and electrical upgrades to meet power demands, and lack operational flexibility if service changes due to their high installation costs.

  Unlike depot chargers, which can serve all BEBs (or other BEVs) parked at the depot, irrespective of service characteristics, on-route chargers can only serve vehicles on a route aligned with or near it. These characteristics make decisions to procure and install on-route charging infrastructure highly context-specific and challenging to scale in a generalized scoping analysis, even on an individual agency level. Instead, CTE uses FCEBs to mitigate BEB range considerations.

- ***Cost Reductions:*** For the core analysis, CTE utilized current costs, and did not project potential reductions or inflation over time. However, the Department of Energy (DOE) and the FTA have set a target for FCEBs of $600,000 per vehicle. It is not known when this target may be reached, but the availability of federal funding will accelerate the adoption of ZEV technologies, which may lead to reductions in vehicle costs due to economies of scale.[7] As shown in **Figure 5,** a scenario in which capital costs for both BEBs and FCEBs drop to $600,000 in 2028 (i.e., only 2023-2028 use current costs) would produce an *incremental low cost estimate of $42.39 billion and a high cost estimate of $60.02 billion*. Manufacturing scale and technology breakthroughs will help the industry reach that target.

- ***Infrastructure Cost Limitations*:** CTE did not include costs associated with land acquisition, electric utility infrastructure upgrades, new facilities to support depot charging, or hydrogen production and distribution to agency depots. These costs vary significantly by geography and are unknowable without extensive engineering and real estate analysis. Since these costs are not core requirements for fleet transition, they are not included in the analysis.

[7] *Eudy, Leslie and Matthew Post. Fuel Cell Buses in U.S. Transit Fleets: Current Status 2018. National Renewable Energy Laboratory. December 2018.*

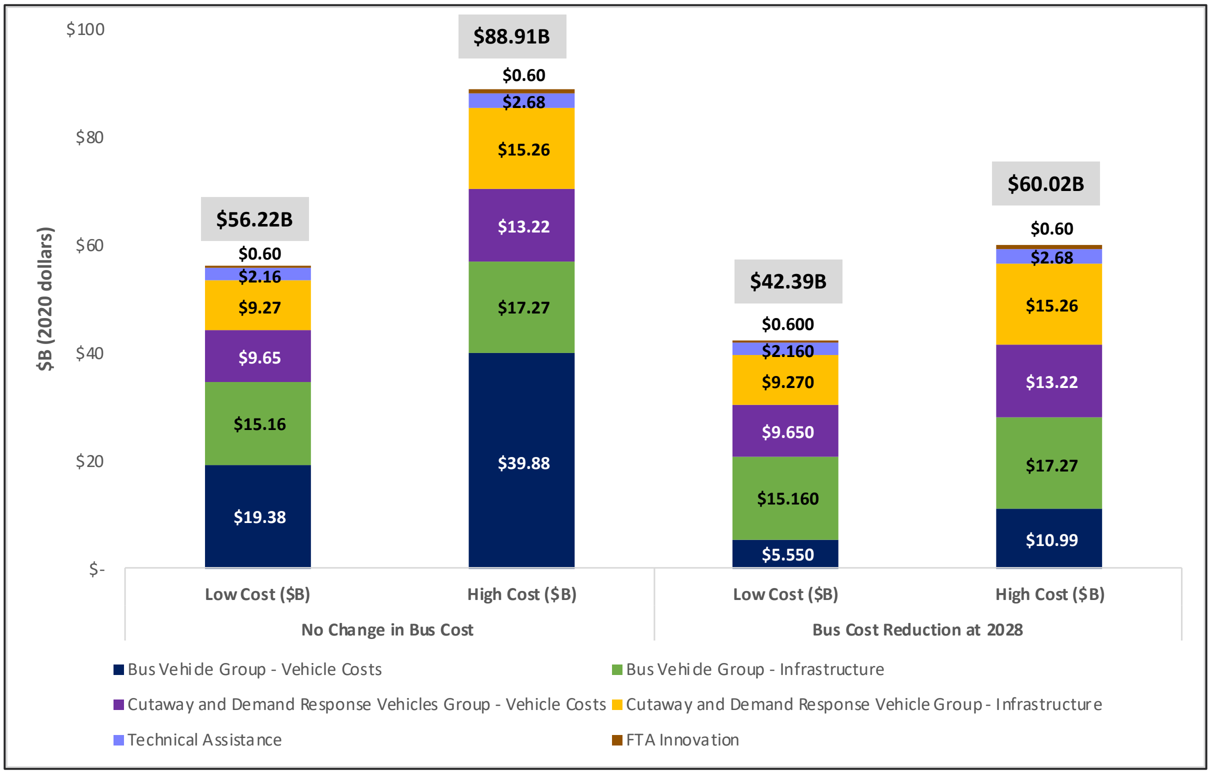


*Figure 5: Estimated incremental cost to transition the US transit fleet in a mixed fleet scenario, assuming a bus cost reduction in 2028*

- ***Operations and Maintenance (O&M):*** O&M costs are not included in the analysis, but extended warranties and mid-life overhauls are included in vehicle costs, if applicable. ZEVs should have lower maintenance costs compared to conventionally-fueled vehicles; however, the market is still maturing and those savings are unproven. Electricity costs to charge BEVs are highly variable across the country and can be higher or lower than diesel costs based on region. Hydrogen fuel costs are currently higher than diesel, ranging from $7.95 to $5.50 per kg in California.[8] [9] [10] These costs will be higher in markets outside of California, but increased demand and production with scale will likely reduce them.
  O&M costs for the Bus Vehicle Group in the three different transition scenarios, compared against diesel, are shown in **Figure 6**. These figures use operational data from actual ZEB deployments.[11] Due to the small number of BEB and FCEB deployments in the county, data availability is limited. As the market matures and transit agencies build technical capabilities to efficiently maintain their ZEB fleets, these costs should decrease and fall below those of diesel buses.

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[8] *US DRIVE. (November 2017). "Hydrogen Production Tech Team Roadmap." United States Dept of Energy*
[9] *Eichman, Joshua et al. (February 2016). "Economic Assessment of Hydrogen Technologies Participating in California Electricity Markets." National Renewable Energy Laboratory. NREL/TP-5400-65856.*
[10] *Melaina, Marc and Michael Penev. (September 2013). "Hydrogen Station Cost Estimates Comparing Hydrogen Station Cost Calculator Results with other Recent Estimates." National Renewable Energy Laboratory. NREL/TP-5400-56412.*
[11] *Operational & Maintenance costs from CTE data reporting efforts and NREL analyses.*

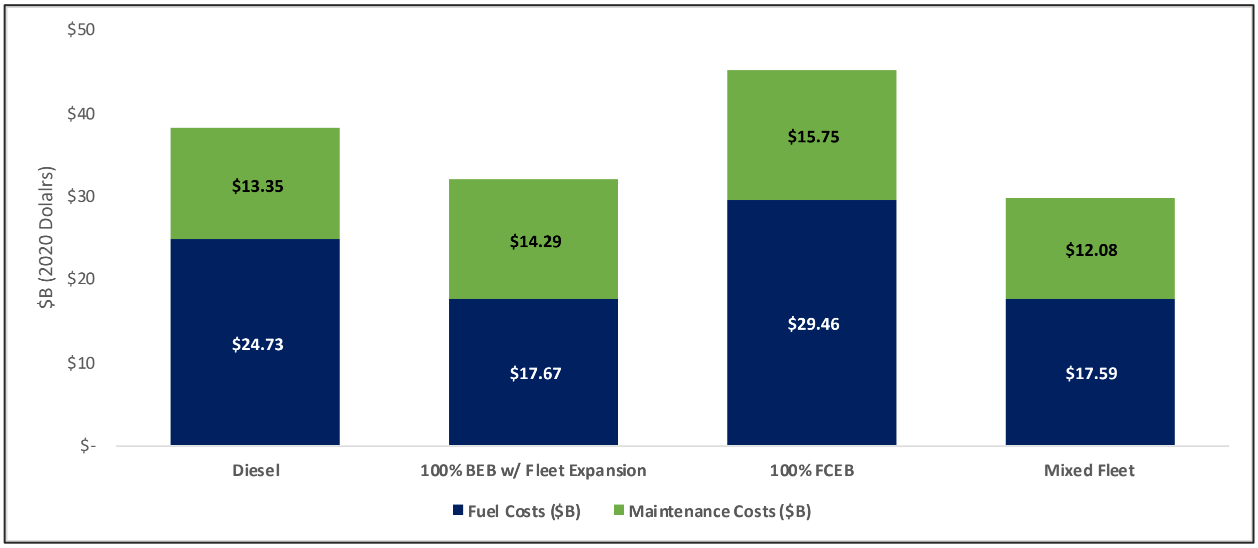



*Figure 6. Estimated O&M costs for the Bus Vehicle Group by analysis scenario*

- ***Supply Chain and Manufacturing Considerations:*** CTE's analysis relies on an industry capable of supporting 100 percent ZEV production in 2023. In reality, the manufacturing supply chain for zero-emission technologies has not sufficiently matured to meet that objective, but federal support for component manufacturing processes, tooling, facilities, and supply chains can accelerate the industry's ramp rate. Buy America requirements for domestically-manufactured vehicles and equipment dictate sourcing decisions, and therefore warrant additional federal support. This is especially true for buses, which feature more customization and share fewer component specifications with the wider automotive industry.

  The exact supply chain gaps and extent of federal support required are outside the scope of this analysis. However, the following components require manufacturing and supply chain scale-up, and would require additional assessment: Batteries, battery management systems, power conversion components (e.g., inverters and converters), traction motors, wiring harnesses, fast charging receptacles or rails, fuel cells, hydrogen storage cylinders, and fuel cell DC-DC converters.

- ***Spare Ratio:*** Though not governed by a formal statute or regulation, FTA maintains a recommended "spare ratio" to transit agencies with more than 50 buses that sets aside a percentage of their total fleet count as reserve rolling stock. FTA manages this policy via guidance circulars and grant selection criteria. Agencies out-of-line with recommendations will be less competitive in grant opportunities. It may be prudent for FTA to relax its spare ratio guidance, as transit agencies in very cold or very hot climates may need to retain more legacy diesel and CNG vehicles than they would normally in support of accelerating their transitions to ZEBs. Extreme temperatures force increased energy consumption via HVAC power loads, so BEBs may not be able to meet duty cycle requirements in those conditions. Therefore, agencies may need to occasionally deploy diesel or CNG vehicles during some periods of the year, until vehicle technologies improve to overcome climate-related challenges. Otherwise, agencies may be reticent to procure ZEBs without complete certainty they can serve as 1:1 replacements for retired vehicles. Changes to the spare ratio were not accounted for in this analysis.

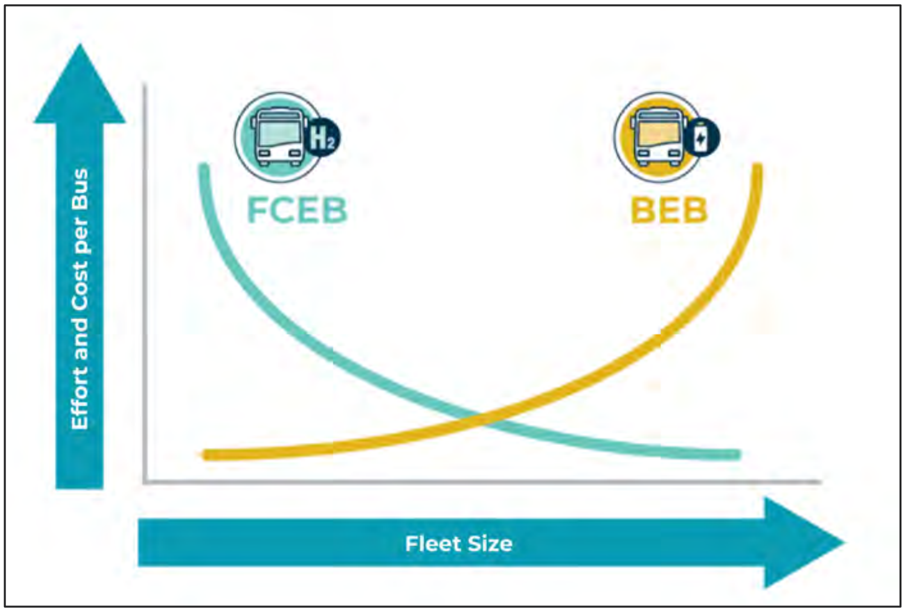
## Hydrogen Competitiveness

Based on fleet operating requirements, battery electric vehicles alone are not sufficient to meet the objective of a full national fleet transition to ZEVs, and any aggressive transit decarbonization strategy will need to incorporate them on a systemwide level. FCEBs are already in use at multiple transit agencies, such as the Alameda-Contra Costa Transit District (AC Transit) in Oakland, CA and the Orange County Transportation Authority (OCTA) in Orange, CA. Whereas BEBs encounter vehicle range limitations, FCEBs have demonstrated comparable service and range performance to diesel and CNG buses. FCEBs are demonstrating their ability to operate on any of the routes serving AC Transit and OCTA.

Though the first modern electric buses were FCEBs, far greater investment in battery electric technology and more procurement demand for BEBs have produced a situation where capital costs for FCEBs remain higher than those of BEBs, skewing demand in favor of battery electric variants. The FTA Low or No Emission Vehicle Program (Low-No) has also incentivized dozens of transit agencies to procure small numbers of ZEBs as pilot projects, and because BEBs impose lower startup costs at small scale, FCEBs have not enjoyed similar demand to mobilize that segment of the industry.

The cost and effort of an entry-level hydrogen station remains challenging for small scale operations. The conceptual graph in **Figure 7** illustrates the relative cost and effort of providing charging and fueling infrastructure for battery electric and fuel cell electric bus fleets. As fleets grow, the costs and complexity associated with incremental BEB charging infrastructure and associated facility and electrical infrastructure upgrades increase exponentially. Conversely, hydrogen fueling infrastructure scales efficiently, and therefore offers advantages over BEB infrastructure with larger fleets.

Federal support would ensure FCEBs reach cost parity with BEBs, which is expected through scaled manufacturing.




- **FCEB:** High initial cost for hydrogen fueling stations can be leveraged over many buses in larger fleets.
- **BEB:** More equipment and infrastructure required to support larger fleets

*Figure 7: Conceptual graph illustrating the relative cost and effort of deploying FCEB and BEB fleets.*

## Fuel Cell Bus Costs

The capital costs of FCEBs are directly related to volume production and demand. The first five buses at AC Transit were built at a per-unit cost of $3.2 million. Those costs rapidly declined to where AC Transit and OCTA were able to procure New Flyer's next-generation buses for less than $1.2 million apiece. New Flyer has since been awarded a California state contract to build additional buses of this same model for $1 million.

Maintenance costs for FCEBs are still high, but trends indicate further reductions as the technology matures. There are now at least five fuel cell manufacturers in North America manufacturing fuel cells for heavy-duty applications, and other companies in Asia and Europe are also building transportation fuel cells. Ballard fuel cells are currently powering New Flyer and ElDorado FCEBs in the United States, and several hundred buses in Europe and China, with more than 10 million miles of passenger service. Today, Ballard expects the cost to refurbish its 85-kW fuel cell stack at mid-life (in 2026/2027) to be as little as $30,000. It projects those costs will be $22,000 with the next generation fuel cell power module being introduced in 2021.

The cost of liquid fuel delivered to these stations is just under $8 per kilogram. Current prices are high, but growing demand and volume production are projected to reduce the price for renewable hydrogen to a cost of $5 per kilogram. The California Air Resources Board's (CARB) Low Carbon Fuel Standard (LCFS) program now allows transit agencies and other end users to claim approximately $1.40 per kilogram in credits, which owners can sell to non-compliant actors. The federal government provides Renewable Identification Number (RIN) credits for renewable pathways generating CNG, but not for hydrogen. Providing a similar federal benefit for hydrogen would increase its competitiveness both as a zero-emission option and as a fuel source generally.

A price of $5 per kilogram for renewable hydrogen is feasible, especially if there are long-term contracts for 2.5 tons or more of daily demand. Air Products estimates that with a pipeline supplying gaseous hydrogen to Los Angeles Metro's Carson Division (D-18), a hydrogen price of $1.35 to $2.70 per kilogram is possible if demand for 100 buses reaches 2.5 to 3 tons/day.

### The 100-Bus Initiative

CTE is working on a 100-Bus Initiative to form a consortium of transit agencies to purchase a collective 100 or more FCEBs in a single order. The primary objective of this effort is to drive down the capital cost of North American FCEBs to the point where they are commercially viable for agencies seeking zero-emission solutions. CTE believes that economies of scale for the bus OEMs and the supply chain associated with a 100-unit order will drive down the unit cost of the bus to approximately $850,000. At this price point, FCEBs become a viable complementary option to battery electric technology for transit agencies to meet zero-emission goals in the next 15 years. Other consortium objectives include lowering fuel costs through increased centralized production and higher density distribution methods, stimulating new hydrogen supply and service models (e.g., gaseous hydrogen pipeline), implementation at smaller transit agencies, validation of lifecycle costs for larger-scale deployments, and side-by-side showcase of both BEBs and FCEBs within a single agency's service to demonstrate optimal fleet mix. FTA can support this effort to establish FCEB commercial viability at lower prices by helping the industry organize and facilitate one or more joint procurements.

## Federal Transit Administration Innovation, Bus Testing, and Workforce Development

The US transit bus industry has long relied on federal support for technology development, as the domestic market has not been large enough to incentivize private investment of any significant scale. That federal support has helped the industry achieve major breakthroughs in the past decade, specifically in zero-emission technologies. Reaching a full fleet transition by 2035 will require both acceleration of transit technology development and federal testing capabilities to support new transit vehicle models and market entrants.

The FTA's primary funding mechanism for innovation programming, Section 5312, receives $28 million per year in authorized funding under the Fixing America's Surface Transportation (FAST) Act. Because this budget has to accommodate research and demonstration programs for all transit modes, it does not provide a dedicated funding stream supporting transit bus technology development. Though bonus appropriations have boosted this figure annually in support of innovation programs such as Mobility-on-Demand (MOD) Sandbox and Integrated Mobility

Innovation (IMI), nearly all of that funding has supported new mobile applications and ridesharing integration, not vehicle technologies.[12] [13]

Lack of federal funding for transit vehicle technology development will need to change in support of zero-emission fleet transition targets. While exact industry needs are unknowable, there is precedent for a multi-year program specifically targeted at development of advanced vehicle technologies for transit buses. Congress authorized the National Fuel Cell Bus Program (NFCBP) in 2005, which was largely responsible for launching the US ZEB industry. The program funded Proterra's creation and incentivized existing manufacturers to develop their own electric powertrains. This program provided $90 million over seven years, and its success serves as a model for further federal support to the industry.[14]

North American transit bus manufacturers have focused most of their research and development resources on delivering increases in battery capacity, leaving fewer resources for complementary technologies that can increase vehicle energy efficiency and therefore accelerate ZEB adoption. For instance, today's HVAC technology is inefficient, consuming roughly as much energy as vehicle operation itself in extreme temperatures.[15] These energy requirements limit the ability of agencies to deploy BEBs in colder climates, requiring they either use diesel-powered heating units, or incur additional infrastructure expenses (e.g., on-route charging) to meet basic service requirements.

Moreover, electric drive components (e.g., steering and braking) for transit buses are relatively new to the market and immature compared with products available in the light-duty vehicle and even medium- and heavy-duty truck markets.[16] Their effective integration will increase vehicle energy efficiency through elimination of mechanical parts and reduce maintenance costs. Electric drive also facilitates drive-by-wire capabilities, which are necessary for vehicle automation.

Beyond safety, automation offers significant energy efficiency benefits through driver assistance, and reduced capital costs at bus depots. Through its post-deployment KPI monitoring activities, CTE has observed that ZEBs can experience significant variability in energy consumption from the driver behind the wheel. Inefficient driving behavior, particularly acceleration and braking, can reduce vehicle range by more than 25 percent.[17] Poor use of the regenerative braking system in ZEVs minimizes potential gains. Automation would both reduce this variance and increase vehicle range. At the bus depot, automation may allow transit agencies to procure fewer chargers and

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[12] *Mobility on Demand (MOD) Sandbox Program. Federal Transit Administration. July 16, 2020. https://www.transit.dot.gov/research-innovation/mobility-demand-mod-sandbox-program.*

[13] *Integrated Mobility Innovation. Federal Transit Administration. March 16, 2020. https://www.transit.dot.gov/IMI.*

[14] *Ricketson, Sean. National Fuel Cell Bus Program 2005-2018. Federal Transit Administration. https://www.hydrogen.energy.gov/pdfs/review18/ia008_ricketson_2018_o.pdf.*

[15] *Data from CTE-supported deployments.*

[16] *Transit Bus Automation Project: Transferability of Automation Technologies Final Report. Federal Transit Administration. (September 2018)*

[17] *Data from CTE-supported deployments.*

minimize any expansion requirements of a BEB-only fleet. Many agencies install chargers on a 2:1 or 3:1 ratio with BEBs, expecting to plug them in for overnight refueling. Automation would enable more efficient use of chargers without requiring personnel to physically move vehicles around the yard. The technology would also enable tighter parking arrangements, which would help agencies pursuing a BEB-only strategy, as the charging infrastructure for a full fleet will have a large footprint.

FTA created the Strategic Transit Automation Research (STAR) program in 2018 to explore these benefits, and drive industry innovation through research and demonstration funding.[18] However, since publishing the STAR plan in early 2018, that program has not received adequate funding to advance development of automation technologies in the transit bus industry. CTE is supporting the first automated transit bus demonstration in North America, partially-funded through a $2 million IMI grant award to the Connecticut Department of Transportation. However, this is the only transit bus project that has received funding to date, and FTA has not provided a timeline for funding further opportunities. Progressing from prototypes and demonstration projects to scaled production of automated transit buses will require greater federal focus and dedicated funding.

CTE worked with US House of Representatives Transportation and Infrastructure (T&I) Committee staff to include an amendment in the Moving America Forward Act (H.R. 2) that would establish a new program modeled on the NFCBP for transit bus technology development. The amendment received support from multiple labor groups, including the Transportation Trades Department (TTD), American Federation of Labor and Congress of Industrial Organizations (AFL–CIO), and Transport Workers Union (TWU). If passed, the legislation would authorize $100 million over five years ($20 million per year) for advanced transit bus technology development, including automation and driveline component engineering aimed at increasing energy efficiency and accelerating ZEB adoption.[19] However, a more aggressive approach to transitioning the national vehicle fleet would require additional funding to incentivize manufacturer investment and accelerate technology development. Including scope for HVAC, reducing bus weights through innovative engineering, and other components would warrant expanding the program to $30 million annually.

## Bus Testing Program

Federal funding also needs to support the establishment of proving grounds for connected and automated transit vehicle technologies, buildout of other component testing capabilities, and operation of these facilities. The three existing federal bus testing centers at Penn State-Altoona, Auburn University, and the Ohio State University (OSU) will fill this crucial role for the industry. Though these university testing centers receive annual federal funding for bus and component testing, existing levels are insufficient to meet industry needs at the current and expected rates of

[18] *Strategic Transit Automation Research Plan. Federal Transit Administration. Federal Transit Administration. (January 2018)*
[19] *Moving America Forward Act, H.R. 2, 116th Congress (2020)*

technology change. This change also means increasing growth in new vehicle models and components, and with them more demand for federal testing capacity. Moreover, multiple foreign manufacturers have already indicated they intend to establish domestic manufacturing operations and enter the US zero-emission transit bus market.

Penn State-Altoona has operated with $3 million in authorized Section 5318 funding annually since 1998, plus occasional bonus appropriations ($2 million in Fiscal Year (FY) 18, $1 million in FY19, and $0 in FY20). This authorized level for operations funding needs to increase by $2 million (to $5 million total) annually, and should be supplemented by $7.5 million in capital funding to upgrade Altoona's facilities in support of zero-emission vehicles. This funding totals $31.5 million over 12 years.[20]

Both OSU and Auburn University have both received annual operations funding through the FAST Act authorization, but federal match requirements for potential customers have precluded any testing by bus manufacturers, suppliers, or transit agencies to date. OSU and Auburn University have also received a combined $11 million in federal appropriations to build out their testing facilities, but lack of direction from FTA has stifled their spending of that funding to date.

In 2018, CTE won one of two FTA awards for the Transit Vehicle Innovation Deployment Centers (TVIDC) program, which, among other objectives, aimed to build industry consensus around how to best direct the Low or No Emission Component Assessment Program (LowNo-CAP) bus testing centers. CTE convened a year-long industry panel comprised of 14 transit agencies of all geographies and sizes, all major US bus manufacturers, the three federal bus testing centers, Calstart, and the American Public Transportation Association.

Recommendations from the TVIDC industry panel endorsed designating OSU as the nation's primary transit vehicle test bed for automated and connected vehicle technologies and supported Auburn's proposal to install a climatic test chamber equipped with a heavy-duty, two-axle chassis dynamometer for controlled environment component testing on full buses. Manufacturers on the panel suggested availability of this equipment would incentivize them to use the facilities even for their own private testing. Auburn would require $64 million in capital funding to build out this facility and related infrastructure, and an additional $3 million annually to support operations. This funding totals $100 million over 12 years.[21]

OSU would need $25 million in initial capital funding, with an additional $90 million in operations and future capital funding to support a buildout of its full bus, component, and connected and automated vehicle technology testing facilities. This funding totals $115 million over 12 years.[22]

[20] *Penn State-Altoona capital planning and operations estimate.*

[21] *Auburn University capital planning and operations estimate.*

[22] *The Ohio State University capital planning and operations estimate.*

The total required increase in funding for the federal bus testing centers over 12 years would be $246.5 million. **Adding this to the $30 million per year program for transit bus technology development brings the overall 12-year research and innovation requirement to roughly $600 million, or $50 million per year.**

## ZEV Workforce Development

Deployment of ZEVs imposes new workforce development requirements owing to different operational characteristics from conventionally-fueled vehicles. Transit operators, technicians, engineers, and planners need training in the sourcing, deployment, and management of zero-emission vehicles and supporting infrastructure. Zero-emission transitions of all fleets require some degree of workforce training, but safely managing high-voltage systems is the greatest concern within the industry. Sustained workforce development investments will need to be in place to support the industry as it evolves.

Transit agencies currently rely on manufacturers to provide training for vehicle O&M, but this training lacks standardization across the industry, with varying approaches from OEM to OEM and no certification mechanism. The National Transit Institute (NTI) at Rutgers University receives $5 million in authorized Section 5314 funding annually to build and coordinate these types of workforce development programs but has neither a mandate nor dedicated funding to add ZEVs and supporting technologies to its scope.

Multiple transit agencies have launched nascent ZEB workforce development programs, with two—SunLine Transit in Palm Springs and the Stark Area Regional Transit Authority (SARTA) in Canton, Ohio—receiving center of excellence designations from FTA in support of their efforts. The TVIDC industry panel also discussed strategies for expanding workforce development programming to meet the industry's growing need, including how to leverage the existing programming established at SunLine and SARTA. Rather than directly injecting federal funds to support buildout of these centers of excellence and others aiming to build similar programs, including AC Transit and the Los Angeles County Metropolitan Transportation Authority (LA Metro), the panel recommended FTA amend the LowNo program to incentivize incorporating workforce development. It could do this either by making workforce development a competitive criterion for grant selection, reducing local match requirements for that programming, or both. The panel also wanted to see any curricula and certifications program coordinated through NTI.

If Congress pursues a method of distributing ZEV funding to transit agencies outside of the LowNo program, it will need to ensure workforce development programming are requirements of that program, and that NTI and the other local or regional workforce development centers are equipped to coordinate and execute that programming. Ostensibly, these resources could also support transit agencies that do not operate heavy-duty transit buses, as well as other public agencies beginning to deploy medium- and heavy-duty trucks with similar supporting infrastructure and high-voltage requirements.

# Other Federal Policy Considerations

Other federal policy changes can accelerate zero-emission technology development, increase resources available to agencies for infrastructure and vehicle deployment, and mitigate planning challenges.

FTA awards billions of dollars annually in capital improvement grants including New Starts, Small Starts, and Bus and Bus Facilities and can set program criteria to incentivize or compel the incorporation of zero-emission technologies. The FTA Low-No program is authorized for $55 million annually under the FAST Act as a subsection of Bus and Bus Facilities, and appropriations brought the total program funding to $130 million in FY20. Congress can restrict this program to ZEVs and use it as a primary funding mechanism through changes in the next surface transportation authorization. H.R. 2 proposed increasing funding for this program to $375 million in FY21 and steadily escalating it to $500 million in FY25.[23] These annual funding levels would not be sufficient to meet the rapid fleet transition objectives laid out in this report, but represent the most straightforward path to reaching it.

Other US Department of Transportation (USDOT) agencies, namely the Federal Highway Administration (FHWA), award hundreds of millions of dollars in discretionary grant funding annually for capital improvement and innovation projects, and can set new selection criteria to provide more opportunities for ZEB projects. Congress can also create these criteria in the next surface transportation authorization.

The US Department of Energy likewise awards hundreds of millions of dollars annually through its Office of Energy Efficiency and Renewable Energy (EERE), Vehicle Technologies Office (VTO), and Hydrogen and Fuel Cell Technologies Office. For instance, in its 2020 funding opportunity, VTO made roughly $5 million available for transit projects, of $139 million total.[24] Requiring that additional program grant funding go toward transit applications can supplement FTA Research and Innovation funding. CTE is not providing a target for additional funding through non-FTA funding sources, but leveraging these programs would accelerate zero-emission transit technology development and deployment.

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[23] *Moving America Forward Act, H.R. 2, 116th Congress (2020)*

[24] *Fiscal Year 2020 Advanced Vehicle Technologies Research. FOA # DE-FOA-0002197. Department of Energy. https://www.energy.gov/sites/prod/files/2020/07/f76/FY20_VTO_2197_selections_table-for_release.pdf*

## Additional Recommendations and Next Steps

The federal government can take steps across multiple agencies to facilitate commercialization and accelerated deployment of FCEBs. Some of these steps are regulatory, and others would require legislation:

- **EPA**: Adopt regulations with zero-emission targets for vehicle OEMs and fleet operators.
- **DOE**: Provide expanded research funding for materials science and technology enhancements of component systems. Improved ground and vehicle storage for both liquid and gas supplies are of particular importance. Funding to improve the efficiencies and durability of fuel cells, balance of plant, energy storage, and power control systems is needed, as well as investments in support of research to improve compression and liquid pumping technologies, critical to more efficient hydrogen fueling station operations.
- **DOE**: Support for fast-tracking codes and standards to facilitate advances in safety, systems design, and new product development.
- **DOE**: Restore funding in support of vehicle integration and deployment of prototypes and small-fleet demonstrations to provide evidence of successful component designs and vehicle integration that improves performance and efficiency.
- **USDOT**: Provide manufacturing subsidies to assist OEMs to build at scale with improved productivity and high standards of quality control.
- **USDOT**: Large-scale pilot deployments of 100 to 200 buses at multiple operating divisions, to demonstrate and prove the required logistics of effectively and efficiently managing larger fleets of ZEBs.
- **USDOT**: Provide transit agencies with the flexibility to sell capital equipment to private entities, who could leverage tax credits to lease back the equipment at a more affordable cost to the public agency. This could reduce the risk to these agencies of procuring new technologies.
- **USDOT**: Exempt ZEBs from counting toward an agency's spare ratio through at least 2030. This change would allow agencies to retain more conventionally-fueled vehicles as spares in instances where strenuous operating conditions may otherwise challenge regular operations.
- **USDOT**: Offer RINs for hydrogen fuel, comparable to CNG, and LCFS credits to subsidize renewable and low carbon-intensity hydrogen, leveling the playing field in competition with petroleum and carbon-based conventional fuels.
- **IRS**: Provide tax benefits to private fuel suppliers to incentivize infrastructure investments and construction. Provide similar benefits to private investors to purchase rolling stock and expensive vehicle component systems (e.g., fuel cells, batteries, storage systems), enabling them to lease back to transit agencies at reduced cost and risk.

Finally, Congress should establish an industry working group that includes vehicle manufacturers, component suppliers, transit agencies, electric utilities, and other industry stakeholders to assess in greater detail what federal support may be necessary to accelerate fleet transitions to 100 percent ZEVs. This group's scope of analysis would include current and accelerated manufacturing capabilities, technology readiness and necessary breakthroughs, standards development, infrastructure scaling requirements, regulatory challenges, workforce needs, and other supporting topics.

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# Appendix A: National Transit Database Definitions

*NOTE: All definitions are sourced from the Federal Transit NTD Glossary, with terms corresponding to the agency's national fleet vehicles report.*

**Articulated bus:** Extra-long (54 ft. to 60 ft.) buses with two passenger compartments. The rear body section is connected to the main body by a joint mechanism that allows the vehicles to bend when in operation for sharp turns and curves and yet have a continuous interior.

**Bus:** Rubber-tired passenger vehicles powered by diesel, gasoline, battery or alternative fuel engines contained within the vehicle. Vehicles in this category do not include articulated, double-decked, or school buses.

**Cutaway:** A vehicle in which a bus body is mounted on the chassis of a van or light-duty truck. The original van or light-duty truck chassis may be reinforced or extended. Cutaways typically seat 15 or more passengers, and typically may accommodate some standing passengers.

**Double decker bus:** High-capacity buses having two levels of seating, one over the other, connected by one or more stairways. Total bus height is usually 13 to 14.5 feet, and typical passenger seating capacity ranges from 40 to 80 people.

**Minivan:** A light duty vehicle having a typical seating capacity of up to seven passengers plus a driver. A minivan is smaller, lower and more streamlined than a full-sized van, but it is typically taller and has a higher floor than a passenger car. Minivans normally cannot accommodate standing passengers.

**Over-the-road bus/coach:** A bus characterized by an elevated passenger deck located over a baggage compartment.

**School bus:** Passenger vehicles designed or used to carry more than ten passengers in addition to the driver; and used primarily for the purpose of transporting pre-primary, primary, or secondary school students either to such schools from home or from such schools to home.

**Sport utility vehicle (SUV):** A high-performance four-wheel drive car built on a truck chassis. It is a passenger vehicle which combines the towing capacity of a pickup truck with the passenger-carrying space of a minivan or station wagon. Most SUVs are designed with a roughly square cross-section, an engine compartment, a combined passenger and cargo compartment, and no dedicated trunk. Most mid-size and full-size SUVs have three rows of seats with a cargo area directly behind the last row of seats. Compact SUVs may have five or fewer seats.

**Van:** An enclosed vehicle having a typical seating capacity of 8 to 18 passengers and a driver. A van is typically taller and with a higher floor than a passenger car, such as a hatchback or station wagon. Vans normally cannot accommodate standing passengers.

# Appendix B: Cost Assumptions

## Vehicle Costs

| NTD Vehicle Type | Source |
|---|---|
| *Bus (ZEV)* | California Department of General Services, “Zero Emission Transit Buses (ZEBs), New Flyer" Contract ID 1-19-23-17B https://caleprocure.ca.gov/PSRelay/ZZ_PO.ZZ_CTR_SUP_CMP.GBL?Page=ZZ_CTR_SUP_PG&Action=U&SETID=STATE&CNTRCT_ID=1-19-23-17B |
| | California Department of General Services, “Zero Emission Transit Buses (ZEBs), Proterra, Inc" Contract ID 1-19-23-17C https://caleprocure.ca.gov/PSRelay/ZZ_PO.ZZ_CTR_SUP_CMP.GBL?Page=ZZ_CTR_SUP_PG&Action=U&SETID=STATE&CNTRCT_ID=1-19-23-17C |
| | Commonwealth of Virginia, Transit Buses, CNG, Diesel, Hybrids, GILLIG, LLC, Contract E194-75548 MA2274, 2020 |
| | Commonwealth of Virginia, Transit Buses, CNG, Diesel, Hybrids, New Flyer, Contract E194-75548-MA2275, 2020 |
| | State of Georgia; Supplemental Mass Transit Vehicles and Transportation Related Vehicles, 99999-01-SPD0000152, June 28, 2018, https://solutions.sciquest.com/apps/Router/ShoppingDashboardUserDetails?tmstmp=1607069954552 |
| *Bus (non-ZEV, BEB, FCEB)* | State of Georgia; Supplemental Mass Transit Vehicles and Transportation Related Vehicles, 99999-01-SPD0000152, June 28, 2018, https://solutions.sciquest.com/apps/Router/ShoppingDashboardUserDetails?tmstmp=1607069954552 |
| *FCEB Target Cost* | Eudy, Leslie and Post, Mathew, Fuel Cell Buses in U.S. Transit Fleets: Current Status, NREL/TP-5400-72208, December 2018 https://www.nrel.gov/docs/fy19osti/72208.pdf |
| *Articulated Bus (ZEV)* | California Department of General Services, “Zero Emission Transit Buses (ZEBs), New Flyer" Contract ID 1-19-23-17B https://caleprocure.ca.gov/PSRelay/ZZ_PO.ZZ_CTR_SUP_CMP.GBL?Page=ZZ_CTR_SUP_PG&Action=U&SETID=STATE&CNTRCT_ID=1-19-23-17B |
| | California Department of General Services, “Zero Emission Transit Buses (ZEBs), Proterra, Inc" Contract ID 1-19-23-17C https://caleprocure.ca.gov/PSRelay/ZZ_PO.ZZ_CTR_SUP_CMP.GBL?Page=ZZ_CTR_SUP_PG&Action=U&SETID=STATE&CNTRCT_ID=1-19-23-17C |
| *Articulated Bus (non-ZEV)* | Commonwealth of Virginia, Transit Buses, CNG, Diesel, Hybrids, New Flyer, Contract E194-75548-MA2275, 2020 |
| *Over-the-Road Bus (ZEV)* | California Department of General Services, “Zero Emission Transit Buses (ZEBs), Proterra, Inc" Contract ID 1-19-23-17C https://caleprocure.ca.gov/PSRelay/ZZ_PO.ZZ_CTR_SUP_CMP.GBL?Page=ZZ_CTR_SUP_PG&Action=U&SETID=STATE&CNTRCT_ID=1-19-23-17C |

| *NTD Vehicle Type* | Source |
|---|---|
| *Over-the-Road Bus (ZEV)* | State of Georgia; Supplemental Mass Transit Vehicles and Transportation Related Vehicles, 99999-01-SPD0000152, June 28, 2018, https://solutions.sciquest.com/apps/Router/ShoppingDashboardUserDetails?tmstmp=1607069954552 |
| *Over-the-Road Bus (non-ZEV)* | AC Transit Adopted Budget Fiscal Year 2020-2021, http://www.actransit.org/wp-content/uploads/FY2020-21-Adopted-Budget-Book.pdf. |
| | State of Georgia; Public Mass Transit and Transportation Related Vehicles, 99999-01-SPD0000138, 10/31/2019, https://solutions.sciquest.com/apps/Router/ShoppingDashboardUserDetails?tmstmp=1607069954552 |
| *Double Decker (ZEB)* | Foothill Transit, "In Depot Charging and Planning Study," https://ww2.arb.ca.gov/sites/default/files/2020-09/C_Burns_McDonnell_Foothill%20Transit_ROP_ADA08182020.pdf |
| *Double Decker (non-ZEV)* | AC Transit Adopted Budget Fiscal Year 2018-2019, http://www.actransit.org/wp-content/uploads/FY18-19-Adopted-Budget-Book.pdf. |
| *School Bus (ZEV)* | Electric School Bus Purchase Order from CTE client |
| | Burgoyne-Allen, Phillip and O'Keefe, Bonnie, "From Yellow to Green - Reducing School Transportation's Impact on the Environment," August 2019, https://bellwethereducation.org/sites/default/files/Bellwether_WVPM-YellowToGreen_FINAL.pdf |
| *School Bus (non-ZEV)* | Burgoyne-Allen, Phillip and O'Keefe, Bonnie, "From Yellow to Green - Reducing School Transportation's Impact on the Environment," August 2019, https://bellwethereducation.org/sites/default/files/Bellwether_WVPM-YellowToGreen_FINAL.pdf |
| | State of Georgia; GA School Buses Related Equip, 99999-SPD-G20160601, 6/30/2019, https://solutions.sciquest.com/apps/Router/ShoppingDashboardUserDetails?tmstmp=1607069954552 |
| *Van (ZEV)* | Commonwealth of Virginia VA State Contract, DGS, 194-75548 |
| | Correspondence with zero-emission van vehicle OEMs |
| *Van (non-ZEV)* | State of Georgia; Public Mass Transit and Transportation Related Vehicles, 99999-01-SPD0000138, 10/31/2019, https://solutions.sciquest.com/apps/Router/ShoppingDashboardUserDetails?tmstmp=1607069954552 |
| | Commonwealth of Virginia, Contract E194-85672, 6/1/2020 |
| *Cutaway (ZEV)* | SunLine Transit Agency, "Zero-Emission Bus Rollout Plan," September 2020, https://ww2.arb.ca.gov/sites/default/files/2020-09/SunLine_ROP_ADA09082020.pdf |

| NTD Vehicle Type | Source |
|---|---|
| *Cutaway (ZEV)* | State of California Air Resources Board. (2018). Staff Report: Initial Statement of Reasons - Public Hearing to Consider the Proposed Innovative Clean Transit Regulation A Replacement of the Fleet Rule for Transit Agencies: Appendix K. Retrieved from https://www.arb.ca.gov/regact/2018/ict2018/appkstatewidecostanalysis.xlsx?_ga=2.48303334.1749999270.1571069223-138148794.1501775822 |
| | Blanco, Sebastian, Lion Electric Bus Now Ready For Your City's Pre-Order, May 30, 2018, https://www.forbes.com/sites/sebastianblanco/2018/05/30/lion-electric-bus/#117ced372827 |
| | Correspondence with zero-emission cutaway vehicle OEMs |
| *Cutaway (non-ZEV)* | State of Georgia; Public Mass Transit and Transportation Related Vehicles, 99999-01-SPD0000138, 10/31/2019, https://solutions.sciquest.com/apps/Router/ShoppingDashboardUserDetails?tmstmp=1607069954552 |
| *Automobile (non-ZEV)* | Commonwealth of Virginia VA State Contract, DGS, 194-75548 |
| | Commonwealth of Virginia, Contract E194-85672, 6/1/2020 |
| *SUV (ZEV)* | Commonwealth of Virginia, Contract E194-85672, 6/1/2020 |
| *SUV (non-ZEV)* | Commonwealth of Virginia, Contract E194-85672, 6/1/2020 |
| *Minivan (ZEV)* | Assumed same costs as ZEV SUV |
| *Minivan (non-ZEV)* | Assumed same costs as non-ZEV SUV |
| *BEB Extended Battery Warranty* | California Department of General Services, "Zero Emission Transit Buses (ZEBs), New Flyer" Contract Contract ID 1-19-23-17B https://caleprocure.ca.gov/PSRelay/ZZ_PO.ZZ_CTR_SUP_CMP.GBL?Page=ZZ_CTR_SUP_PG&Action=U&SETID=STATE&CNTRCT_ID=1-19-23-17B |
| | California Department of General Services, "Zero Emission Transit Buses (ZEBs), Proterra, Inc" Contract Contract ID 1-19-23-17C https://caleprocure.ca.gov/PSRelay/ZZ_PO.ZZ_CTR_SUP_CMP.GBL?Page=ZZ_CTR_SUP_PG&Action=U&SETID=STATE&CNTRCT_ID=1-19-23-17C |
| | Commonwealth of Virginia, Transit Buses, CNG, Diesel, Hybrids, GILLIG, LLC, Contract E194-75548 MA2274, 2020 |
| | Commonwealth of Virginia, Transit Buses, CNG, Diesel, Hybrids, New Flyer, Contract E194-75548-MA2275, 2020 |
| *FCEB Extended Battery Warranty* | Pro-rated estimate of BEB ESS Extended Warranty for average FCEB battery size (100 kWh) |
| *Cutaway Extended Battery Warranty* | Pro-rated estimate of BEB ESS Extended Warranty for average battery electric cutaway battery size (120 kWh) |

## Fueling Infrastructure Cost Assumptions

| Item | Source |
|---|---|
| BEB Charging per vehicle | CTE Industry Experience in Developing ZEB Transition Plans for transit agency clients; assumes a 3:1 ratio of 150 kW DC chargers to buses. Costs including design and engineering, permitting, construction, and equipment. |
| | City of Santa Monica's Big Blue Bus, "Zero-Emission Bus Rollout Plan," September 2020, https://ww2.arb.ca.gov/sites/default/files/2020-09/Santa%20Monica%20BBB_ROP_ADA08052020.pdf |
| | Foothill Transit, "In Depot Charging and Planning Study," August 2020, https://ww2.arb.ca.gov/sites/default/files/2020-09/C_Burns_McDonnell_Foothill%20Transit_ROP_ADA08182020.pdf |
| | SunLine Transit Agency, "Zero-Emission Bus Rollout Plan," September 2020, https://ww2.arb.ca.gov/sites/default/files/2020-09/SunLine_ROP_ADA09082020.pdf |
| | North County Transit District, "Zero-Emission Bus Rollout Plan," September 2020, https://ww2.arb.ca.gov/sites/default/files/2020-09/NCTD-%20ROP%20_Reso_ADA08122020.pdf |
| | OmniTrans, "Zero-Emission Bus Rollout Plan," September 2020, https://ww2.arb.ca.gov/sites/default/files/2020-09/Omnitrans_ROP_ADA08262020.pdf |
| | San Joaquin RTD, "Zero-Emission Bus Rollout Plan," June 2020. https://ww2.arb.ca.gov/sites/default/files/2020-09/SJRTD_ZEB%20ROP_ADA08122020.pdf |
| | AC Transit, "Zero-Emission Bus Rollout Plan," June 2020, https://ww2.arb.ca.gov/sites/default/files/2020-09/AC%20Transit%20ZEB%20Rollout%20Plan_ADA06102020.pdf |
| | CTE Industry Experience in Developing ZEB Transition Plans for transit agency clients |
| Level 2 Charging infrastructure and installation | CTE Industry Experience in Developing ZEB Transition Plans for transit agency clients; assumes a 1:1 ratio of level 2 AC chargers to vehicles. Costs including design and engineering, permitting, construction, and equipment. |
| | Nicholas, Michael, "Estimating Electric Vehicle Charging Infrastructure Costs Across Major U.S. Metropolitan Areas," August 2019, https://theicct.org/sites/default/files/publications/ICCT_EV_Charging_Cost_20190813.pdf |
| | Cost quotations from Electric School Bus project for CTE client |
| Cutaway Charging Infrastructure and Installation | CTE Industry Experience in Developing ZEB Transition Plans for transit agency clients; assumes a 4:1 ratio of 150 kW DC chargers to cutaways. Costs including design and engineering, permitting, construction, and equipment. |

| *Item* | Source |
|---|---|
| *FCEB Station Design, construction, and materials* | Argonne National Laboratory, "Heavy-Duty Refueling Station Analysis Model (HDRSAM) V 1.3," September 2017, Accessed at https://hdsam.es.anl.gov/index.php?content=hdrsam.<br><br>Capital costs including design and engineering, permitting, construction, and equipment. Low costs assume a liquid refueling station capable of supporting a fleet of 50 FCEB with 100% utilization and an average fill of 20.6 kilograms (1030 kg daily) was assumed. Station configuration is 350 bar dispensing via liquid hydrogen pump and vaporization with no precooling. Components include liquid tank, liquid pumps, high-pressure vaporizers, gaseous buffer storage and dispensers.<br><br>High costs assume a delivered gaseous hydrogen station capable of supporting a fleet of 50 FCEB with 100% utilization and an average fill of 20.6 kilograms (1030 kg daily). Station configuration is 350 bar cascade dispensing with precooling. Components include low pressure gaseous storage, gas compressors, cascade buffer storage, refrigeration equipment, and dispensers. |
| *FCEB Station Electrical upgrades* | CTE Industry Experience in Developing ZEB Transition Plans for transit agency clients |
| *FCEB Station Master Planning* | CTE Industry Experience in Developing ZEB Transition Plans for transit agency clients |
| *FCEB Station Maintenance Facility Upgrades* | CTE Industry Experience in Developing ZEB Transition Plans for transit agency clients. Low costs correspond to upgrade requirements for transit agencies currently operating CNG buses. High costs correspond to upgrade requirements for transit agencies not currently operating CNG buses. |
| | GETbus, "Zero-Emission Bus Rollout Plan," September 2020, https://ww2.arb.ca.gov/sites/default/files/2020-09/ICT_GET%20ROP_ADA08282020.pdf. |

## Vehicle Operational and Maintenance (O&M) Cost Assumptions

| Item | Source |
|---|---|
| *BEB O&M Costs* | CTE's Key Performance Indicator (KPI) performance monitoring activities for transit agency clients |
| | Eudy, Leslie and Post, Mathew, Zero-Emission Bus Evaluation Results: Long Beach Transit Battery Electric Buses, FTA Report No. 0163, April 2020, https://www.transit.dot.gov/sites/fta.dot.gov/files/2020-05/FTA-Report-No.-0163.pdf |
| | Eudy, Leslie and Post, Mathew, Zero-Emission Bus Evaluation Results: County Connection Battery Electric Buses, NREL/TP-5400-72864, December 2018, https://www.nrel.gov/docs/fy19osti/72864.pdf. |
| | Eudy, Leslie and Post, Mathew, Foothill Transit Agency Battery Electric Bus Progress Report, NREL/PR-5400-75581, March 2020, NREL/TP-5400-72864, December 2018, https://www.nrel.gov/docs/fy20osti/75581.pdf |
| *FCEB O&M Costs* | Eudy, Leslie and Post, Mathew, SunLine Transit Agency American Fuel Cell Bus Progress Report, NREL/PR-5400-71312, April 2020, https://www.nrel.gov/docs/fy20osti/71312.pdf |
| | Eudy, Leslie and Post, Mathew, Zero-Emission Bus Evaluation Results: Stark Area Regional Transit Authority Fuel Cell Electric Buses, FTA Report No. 0140, October 2019, https://www.transit.dot.gov/sites/fta.dot.gov/files/docs/research-innovation/134491/zero-emission-bus-evaluation-results-sarta-fta-report-no-0140_0.pdf |
| | Eudy, Leslie and Post, Mathew, Zero-Emission Bus Evaluation Results: Orange County Transportation Authority Fuel Cell Electric Bus, FTA Report No. 0134, May 2018, https://www.transit.dot.gov/sites/fta.dot.gov/files/docs/research-innovation/132691/zero-emission-bus-evaluation-results-orange-county-transportation-authority-fuel-cell-electric-bus.pdf |
| *Diesel O&M Costs* | U.S. Energy Information Administration, "Petroleum and other Liquids; Weekly Retail Gasoline and Diesel Prices," https://www.eia.gov/dnav/pet/pet_pri_gnd_a_epd2d_pte_dpgal_a.htm |
| | U.S. Department of Energy, Alternative Fuels Data Center, https://afdc.energy.gov/conserve/mass_transit.html |

## Other Cost Assumptions

| Item | Source |
|---|---|
| *General* | No changes in prices over time; no escalation or reduction of 2020 pricing and no inflation |
| *Technical Assistance* | CTE's experience providing technical assistance to transit agency clients, including transition planning, deployment support, and performance monitoring |