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Zero-Emission Buses in the US: Understanding and Addressing Market and Policy Challenges

Leah Foecke Zachary Karson Thomas Tiberghien

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16. Abstract
As the US public transportation sector accelerates its shift from fossil fuels to zero-emission alternatives, transit agencies and transit bus manufacturers alike face significant uncertainty and instability. This report provides policymakers with updated insights into the US transit bus market, focusing on key industry dynamics, financial challenges with zero-emission bus (ZEB) acquisition, technological obstacles in deployment, and regulatory issues. The research relies on interviews with stakeholders, a detailed review of existing literature, and an analysis of US public transit data. Key findings reveal ongoing challenges related to costs, supply, reliability, and workforce development, all of which hinder the adoption of ZEBs. Specifically, challenges include the reality that purchase prices for zero-emission buses in the United States remain significantly higher than internal combustion engine (ICE) vehicles and have not declined as quickly as previously theorized. Additionally, the full-size ZEB market in the US has become highly consolidated, and most transit agencies lack capacity in terms of technical knowledge, staff, and funding required for a successful transition to ZEBs. Potential options to combat these challenges may include enhanced funding mechanisms, industry partnerships, facilitating access to supporting technologies and best practices, and undertaking initiatives to prepare the ZEB workforce. While more research is needed to support the sector's full transition to ZEBs, this report provides actionable insights policymakers can use in a rapidly evolving market to identify solution areas for further exploration and ease transit into a more sustainable future.

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Mineta Transportation Institute
College of Business
San José State University
San José, CA 95192-0219
Tel: (408) 924-7560
Fax: (408) 924-7565
Email: mineta-institute@sjsu.edu

transweb.sjsu.edu/research/2218

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Executive Summary

As the United States accelerates its transition to zero-emission buses (ZEBs) within the public transportation sector, opportunities and challenges have emerged that require careful consideration from policymakers, transit agencies, industry, and other stakeholders. This report provides an updated analysis of the US transit bus market, focusing on the dynamics of the ZEB manufacturing industry and the obstacles hindering widespread adoption of ZEBs.

The report highlights several critical challenges:

- **Industry Dynamics:** The ZEB market for full-size transit buses is relatively unstable and highly consolidated, with an effective duopoly in the battery-electric bus (BEB) segment and a monopoly in the fuel cell bus segment (FCEB) as of the writing of this report. The market for other types of ZEBs is relatively underdeveloped and unable to meet transit agencies' needs. Manufacturers are struggling to reliably and profitably supply the US market, facing underlying business case, regulatory supply chain, and macroeconomic challenges.

- **Business Case Challenges for Transit:** Industry dynamics are contributing to purchase prices for ZEBs that are significantly higher than for ICE vehicles, which have also not declined as quickly as previously theorized. For transit agencies, the ability to achieve total cost of ownership (TCO) savings is highly uncertain, and the funding landscape is primarily focused on capital expenditures, leaving significant uncertainty in the ability to fund incremental operating and maintenance costs.

- **Operational and Technological Hurdles:** Many transit agencies face a difficult choice between BEBs and FCEBs, with trade-offs in range, cost, reliability, operational requirements, and infrastructure requirements that make long-term planning and decision-making complex. For both technologies, transit agencies face significant operational challenges in deploying ZEBs, including the complexity of infrastructure project development for charging and fueling systems and training agency staff to optimally operate and maintain the vehicles to ensure reliability.

- **Policy and Regulatory Landscape:** Federal and state policies have played a crucial role in driving ZEB adoption, but they also contribute to market challenges. Regulations add layers of complexity and cost to an already economically challenging industry.

The report offers potential policy responses in several areas to address these challenges:

- **Enhancing Funding Mechanisms:** Policymakers could consider more holistic and innovative funding program designs to encourage volume purchasing, regional collaboration, reduced customization, and TCO optimization.

- **Industry Partnerships:** Policymakers could consider more robust partnerships with industry to address supply chain challenges, invest in research and development, collect and analyze ZEB performance data, and more thoughtfully allocate key risks associated with transition.

- **Technology Solutions and Best Practices:** Policymakers could facilitate the availability and use of supporting technologies, data, and learnings to smooth the transition for transit agencies, actions which could improve operational efficiency and enable cost-effective deployment even for transit agencies in remote locations or with fewer staff and resources.

- **Readying the Workforce:** Policymakers could implement new initiatives to upskill and reskill workers for this next generation of zero-emission mobility, with dedicated programs focused on public transit.

The objective of this report is to provide actionable insights to policymakers in a rapidly evolving market and help identify solution areas for further exploration. More research is needed in several key areas to support the sector's full transition to ZEBs.

1. Introduction

As the US public transportation sector seeks to accelerate its shift from fossil fuels to zero-emission buses (ZEBs), the stability of the US transit bus manufacturing industry continues to be at risk. Despite the once-in-a-generation disruptions caused by the zero-emission transition, many of the findings from the 2016 Mineta Transportation Institute report on this industry still apply today, including both market dynamics and structural policy obstacles (Czerwinski et al., 2016). The market has been impacted by counterbalancing forces in recent years, with unprecedented levels of federal investment on one hand and severe external shocks resulting from the Covid-19 pandemic on the other, leading to higher costs and longer lead times for delivery. The transition to ZEBs adds further complexity to an already challenging landscape, requiring manufacturers and transit agencies to navigate new technologies, regulations, and operational needs. Despite impressive progress from some transit agencies, the specific challenges related to transit fleet electrification are now drawing increased attention from policymakers as many transit agencies are struggling to meet their service improvement and emission reduction goals.

The purpose of this report is to provide policymakers with updated information on key trends in the US transit bus market, with a specific focus on ZEBs. The report includes an analysis of the challenges that transit agencies face in procuring and deploying ZEBs, the impacts of government policies on both manufacturers and transit customers, and potential solutions for policymakers and transit planners to consider for accelerating ZEB deployment. The focus of the report is on the key financial, economic, and commercial issues associated with transactions between transit agencies and ZEB manufacturers. The report takes a practitioner's perspective, grounded in the investigators' experience serving as a financial, strategic, and policy advisor to various federal, state, and local agencies for their infrastructure projects and programs. Many of the examples in the report come from California, given the investigators' experience working on the ground with transit agencies in that state and the relatively rapid progress on ZEB transition compared with other US states.

The methodology for the report includes a combination of formal interviews and informal conversations with a broad range of policymakers, transit agencies, manufacturers, and other subject matter experts; a literature review consisting of industry publications, transit agency ZEB rollout plans, and other policy reports; and an analysis of data from the Federal Transit Administration's (FTA) National Transit Database (NTD) and the American Public Transportation Association (APTA). Further details on the specific methods are included in Appendix A.

The report is organized in the following manner: Section 2 provides an overview of the ZEB market, including information on manufacturers and customers, the status of the ZEB transition, and key procurement and policy issues. Section 3 provides a detailed outline of challenges that the market faces, and Section 4 offers a range of potential solutions to address those challenges. Section

5 includes ZEB transition case studies, and finally, Section 6 provides concluding thoughts on the intended outcomes from this report and areas for further research.

2. ZEB Landscape and Background

This section provides a high-level overview of the zero-emission bus (ZEB) market for public transit agencies in the United States. For the purposes of this report, the term "ZEB" encompasses not only full-size zero-emission transit buses and motorcoaches but also cutaways and vans, as they are an important part of the public transit vehicle mix.

2.1 Introduction to Zero-Emission Buses

ZEBs are a category of buses that produce no tailpipe emissions, contributing to cleaner air and reduced environmental impact. While the last three decades have seen significant transformation of transit bus fleets to cleaner fuels, ZEB technology has proliferated within the last 5-10 years. This section provides a high-level overview of ZEBs, focusing on their characteristics, comparisons to ICE vehicles, and the various vehicle types and fuel options available in the US market.

Comparison of Vehicle Types

There is substantial variation between the different types of vehicles used to provide transit service. Transit agencies and other transportation providers vary the type of buses they deploy based on duty cycle, geography, and number of passengers using the service, among other factors. As such, transit vehicles can range from vans on one end of the spectrum to articulated buses on the other end. Table 1 shows standard bus types, their key features, and typical usage in a transit context.

Table 1. Common Transit Bus Types

Vehicle Description	Usage and Features
Standard or Conventional Transit Bus (Lighting eMotors, n.d.) Most common type of bus used for public transportation. Typically, these buses are 40 feet in length and can accommodate roughly 30 to 50 passengers. They are designed primarily for urban and suburban routes with frequent stops.	Ideal for regular city routes, short to medium distances, and areas with moderate to high passenger volumes. Features: • Single deck • Low-floor designs for easy passenger access • Equipped with multiple doors to facilitate rapid boarding and alighting
Articulated Transit Bus (Electrek, 2019) Consists of two rigid sections connected by a pivoting joint. These buses are typically about 60 feet in length and can carry more passengers than a regular bus (~100).	Suitable for busy urban routes with high passenger demand, including bus rapid transit (BRT) systems and routes with limited space for multiple-bus operations. Features: • Increased passenger capacity due to extended length • Flexible joint allows for easier maneuvering • Often equipped with three or more doors to manage high passenger flow
Motorcoach or Over-the-Road Bus (Ford, n.d.) Designed for long-distance travel and intercity transportation. These buses are usually around 45 feet in length and feature high-back seats with ample luggage space. Also called an "over-the-road" bus.	Best suited for intercity routes, long-distance travel, and tours, providing a comfortable and efficient transportation option for passengers traveling longer distances. Features: • Designed for comfort with amenities such as reclining seats, restrooms, and air conditioning • High passenger capacity, often accommodating 40 to 60 passengers • Built for highway travel with powerful engines and robust suspension systems
Cutaway (RDV Limousine, n.d.)	Typically used for demand-response transit services, feeder routes to main

Vehicle Description	Usage and Features
Smaller transit vehicle built on a van or truck chassis with a "cutaway" cab. These buses are typically 20 to 30 feet in length and can carry between 8 to 25 passengers.	transit lines, and areas with lower ridership. Features: • Compact size allows for flexibility in navigating narrower streets, windy rural roads, and mountainous roads. • Lower passenger capacity
Van (Cabot Coach Builders, n.d.) Small transit vehicle with a typical capacity of 8 to 15 passengers.	Typically used for paratransit and smaller transit services, feeder routes to main transit lines, and areas with lower ridership. Features: • Compact size allows for flexibility in navigating narrower streets, windy rural roads, and mountainous roads • Lower passenger capacity

Comparison of Fuel Types

Transit buses can be powered by a variety of fuel types. Before ZEBs were more widely available, many agencies turned from traditional fossil fuels to low-emission and hybrid fuels as a first step towards reducing emissions and addressing environmental concerns, or for other reasons, such as potential cost savings (United States Department of Transportation, Federal Transit Administration, 2022). The main types of traditional and low-emission fuels are:

- Traditional fuels: Gasoline and diesel have been the conventional choices for powering internal combustion engines in transit buses for many decades.

- Low-emission fuels: These include compressed natural gas (CNG), ethanol, liquefied petroleum gas (propane), liquefied natural gas, and biodiesel. Starting in the 1990s and 2000s, agencies began adopting these fuels for various reasons, including lowering emissions, before ZEBs were more widely available. In 1995, over 95% of transit vehicles were diesel-powered; this figure was just over 50% in 2015 (Hughes-Cromwick, 2018).

- Hybrid fuels: Hybrid vehicles combine a traditional internal combustion engine (gasoline or diesel) with a battery-powered electric motor. Transit agencies began experimenting with this technology around the same time as more widespread adoption of low-emission fuels in the mid 2000's according to APTA Fact Book data (Hughes-Cromwick, 2018), drawn to the benefits of improved fuel efficiency and reduced emissions.

There are two primary types of ZEBs: battery-electric buses (BEBs), which use electricity as fuel, and hydrogen fuel cell electric buses (FCEBs), which use hydrogen as fuel.

- Electricity: Electric vehicles are powered by charging an on-board battery with electricity. The electricity itself may vary in terms of its production method, upstream carbon emissions, and the speed at which it is delivered to the battery.

- Hydrogen: Hydrogen fuel cell electric vehicles use hydrogen as their power source. Like electricity, hydrogen may vary in its production method, upstream carbon emissions, and the speed at which it is delivered to the vehicle's on-board fuel tank. Hydrogen is an industrially produced gas which has a variety of uses apart from transportation. Much like fossil fuels, it is highly flammable. Hydrogen may be transported and stored either as a pressurized gas or liquid under appropriate conditions of pressure and temperature control, which require specialized equipment, such as compressors and chillers. However, the fueling interface between hydrogen storage and FCEBs is broadly similar to fossil fuels (particularly CNG), with a physical dispenser delivering the hydrogen into an on-board fuel tank.

ZEB Components

Although ZEBs generally have the same physical structure as their ICE counterparts, they differ in two main ways: (1) how energy is stored for use when the bus is operating; and (2) how propulsion occurs (in place of an internal combustion engine).

- BEBs use electricity stored in batteries to power a motor that propels the bus's wheels. This system is often supplemented with electricity produced by a regenerative braking system. BEBs are "fueled" by charging their on-board batteries. The key elements of a BEB powertrain include electric motor(s), batteries, a battery management system, control units, and inverters.

- FCEBs employ a propulsion system that combines hydrogen with oxygen through a "stack" of proton exchange membrane electrodes. This process generates only electricity, heat, and water. The electricity produced powers the bus wheels via an electric motor, air conditioning, and other accessories, and some electricity is sent to storage batteries. Like BEBs, FCEBs also use regenerative braking to produce additional electricity. FCEBs have a hybrid architecture, with a fuel cell supplying the necessary energy to operate the vehicle and batteries contributing to maximum engine power.

ZEBs share many similarities with ICE vehicles, but in addition to the key differences above, they are equipped with some different, advanced components that enable their operation using different fuel sources. These include:

- Power Electronics: These systems manage the flow of electricity between the power source and the motor, ensuring optimal performance.

- Battery Management System (BMS) and Hydrogen Storage: BEBs feature a BMS to monitor and optimize battery performance.

- Auxiliary Systems: Systems, such as air conditioning, heating, and power steering, operate on electricity from the main power source. Their energy consumption impacts the overall range of ZEBs, but physically both are similar or identical to the systems on ICE vehicles.

- Regenerative Braking: This system recaptures kinetic energy during braking and converts it back into electrical energy that can be used by the vehicle. Regenerative braking enhances efficiency by reducing the need to draw power from the main battery.

- Control System: This system integrates all components, managing their interactions for smooth and efficient operation. This includes software and hardware that monitor and control the powertrain, energy storage, and auxiliary systems.

Apart from these specialized components, ZEBs share most other structural and operational components with ICE vehicles, such as HVAC, signaling, passenger information systems, etc. Because the specialized components are largely internal, the passenger experience of riding a ZEB is very similar to riding an ICE vehicle—with the exception of lower noise and exhaust levels.

ZEB Infrastructure

Key components of ZEB infrastructure for a transit agency are electric charging stations for BEBs and/or hydrogen fueling stations for FCEBs, each with their own unique requirements and operational considerations. Deploying the infrastructure necessary to power ZEBs requires comprehensive planning and investment.

BEB charging infrastructure can vary depending on the needs of the transit agency. A primary source of variation is the interface between the bus and the external power source (outlined below). The selection of the type of charging technology or dispenser depends on factors such as fleet size, route characteristics, and available space, among others. The dispenser options include:

- Plug-in Charging: Mainly used at depots, this option is simple and widely available but may require more space and time for charging.

- Overhead Conductive Charging: Suitable for depots and on-route charging, this option allows for faster charging but may require more costly infrastructure investment.

- Wireless Inductive Charging: Another option for on-route charging, this technology offers convenience but may be less efficient and more expensive.

Apart from the charging interface, a typical BEB charging station comprises a transformer, switchgear, charger, and dispenser. The electric utility usually manages the installation and operation of the grid and transformer assets, while the transit agency is responsible for the switchgear and charger assets. Integrating BEB charging infrastructure into transit operations requires careful consideration of various factors, including route demands, bus service schedules, seasonal temperatures, passenger loads, available garage space, and utility rates. Transit agencies may adopt a mix of depot and on-route charging to meet their needs effectively. As power demands for BEBs can be significant, an analysis of current and future ZEB plans can be important for scalable solutions. Engaging with electric utilities can also provide insights into potential incentives and support programs for the installation of charging infrastructure.

Hydrogen fueling stations for FCEBs share similarities with compressed natural gas (CNG) fueling stations but include specialized components to manage hydrogen storage and fueling. These stations typically consist of:

- Hydrogen Delivery System: Hydrogen can be supplied externally or produced on-site; as of the writing of this report, most transit agencies are opting for delivered hydrogen due to the technical complexity of production.

- Storage Tanks: Used to store hydrogen between the time of production or delivery and use.

- Vaporizer: Used for liquid hydrogen to convert back to a gaseous form.

- Compressor and Chiller: Essential for maintaining the correct pressure and temperature.

- Dispensing System: Transfers hydrogen fuel from storage into the vehicle with particular speed and pressure specifications; for hydrogen, fuel is typically dispensed at a pressure of 350 bar (H35).

Planning for, designing, constructing, operating, and maintaining a hydrogen fueling station is a complex infrastructure project for most transit agencies. Typically, transit agencies require significant input from consultants, subject matter experts, and/or vendors during this process. Locating, sizing, specifying, and selecting equipment to meet a transit agency's requirements is complex and costly, with infrastructure costs generally far above those required for BEBs.

Beyond fueling and charging stations, ZEBs may require other infrastructure for efficient operation and maintenance of the fleet; in particular, transit agencies may need to build or retrofit maintenance facilities that accommodate the unique requirements of ZEBs, such as safety requirements for high-voltage systems.

Operations and Maintenance (O&M)

The operation and maintenance (O&M) of ZEBs involves several key considerations that are essential for ensuring these vehicles' reliability and efficiency. Below is a high-level description of key considerations that differentiate ZEBs from traditional ICE buses.

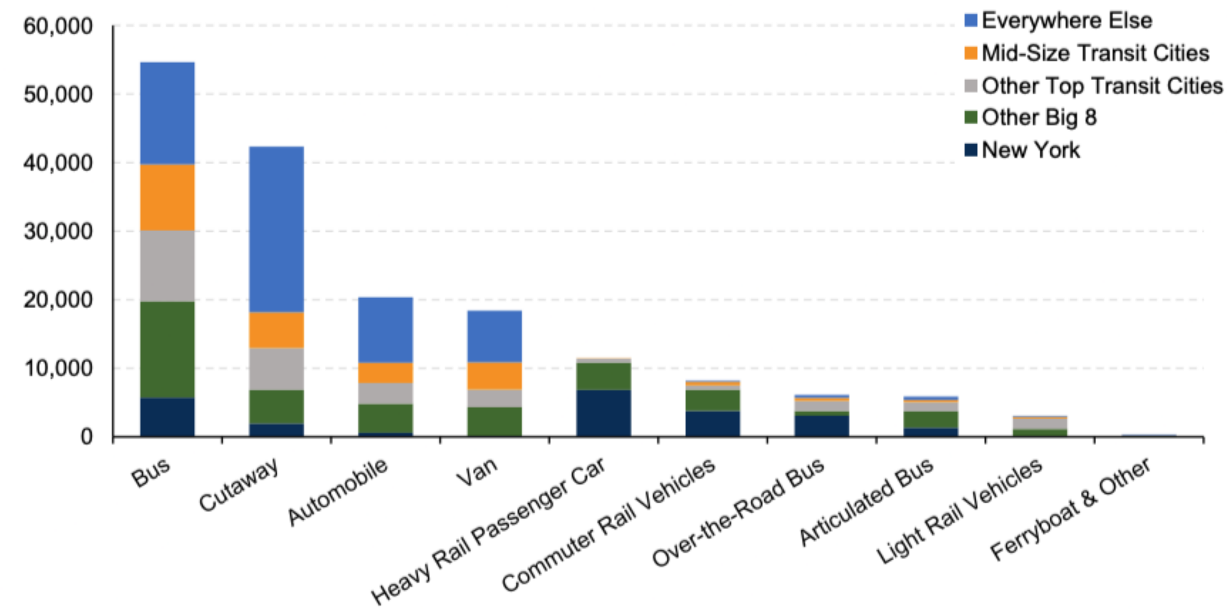
Table 2. Key Considerations

Key Consideration	Sub-section	Description of Key Considerations
Operations	High-Voltage Systems	ZEBs have high-voltage systems that require specialized skills for routine service and repairs. Maintenance teams for transit agencies may require certified electricians or OEM-provided technicians trained to handle these systems.
	Operational Range and Energy Management	Operators must be aware of current estimated operational range, which may diminish significantly during the lifetime of a vehicle, and power storage capacity; they must be able to effectively manage and monitor energy-related systems.
	Driver Behavior	Drivers must adapt to operating different vehicles, notably changing key driving behaviors that impact energy efficiency, such as learning to effectively operate regenerative braking systems.
Preventive Maintenance	Routine Inspections	Routine inspections will focus on high-voltage systems, battery health, and other critical components to ensure the buses remain in optimal condition, as opposed to typical focuses such as engine maintenance.
	Battery Health Monitoring	Regular battery health monitoring manages the degradation of BEB batteries. Periodic tests and measurements track battery capacity and identify any significant changes over time.
	Software Updates	Regular updates and maintenance of software systems is necessary to ensure they function correctly and efficiently. Notably, operators must ensure that updates do not impact key interfaces with other systems, such as charging or fueling equipment.
Emergency/ Unscheduled Maintenance	Response to Breakdowns	Transit agencies must have a plan in place for emergency repairs, including access to specialized technicians and necessary spare parts that they may not have access to on-site or on-staff.
	Specialized Repair Facilities	Given the specialized nature of ZEB maintenance, transit agencies may need to invest in dedicated repair facilities equipped with the necessary tools and equipment to handle high-voltage systems and other unique aspects of ZEBs or otherwise ensure off-site access to these facilities.

2.2 Zero-Emission Bus Customers and Deployers

The main entities purchasing ZEBs are the 2,000 urban and rural public transit agencies and over 4,000 non-profit transit providers spread throughout the U.S (Dickens, 2024). It is therefore critical to understand the transit agency context for the ZEB transition, given that they collectively define the demand side of the ZEB market, but also are responsible for the long-term successful deployment and operation of these vehicles. US transit agencies vary in size and types of service provided, resulting in different needs and priorities regarding ZEBs. This section explores this variation by dividing transit agencies into two broad categories: large transit agencies, which generally serve medium to large cities, and small transit agencies, which provide transit services in all other areas of the country, using smaller vehicle fleets to do so. The distinction between these categories is not clear-cut, as there are small agencies providing services in large cities and large agencies serving sparsely populated areas. However, this categorization helps illustrate the varying ZEB needs and deployment contexts for various agencies. Figure 1 below illustrates the concentration of each vehicle type in different transit markets, highlighting that a plurality of transit vehicles is concentrated in the “Big 8” transit cities, which are New York City, Los Angeles, Chicago, Philadelphia, Washington DC, Boston, Seattle, and San Francisco. These urban areas also rely largely on heavy and commuter rail vehicles, but the data shows that road-based transit vehicles are critically important outside of the Big 8. This dynamic supports this report’s focus on ZEBs, rather than rail-based modes, as the core of the zero-emission transition for most transit agencies in the country.

Figure 1. Active Transit Fleet by Type and Market



(US DoT, FTA, 2022)[1]

The rest of this sub-section describes the characteristics of different ZEB users by describing large and small transit agencies and their progress towards the zero-emission transition.

Large Transit Agencies

Large transit agencies in the US are concentrated in medium to large cities and provide the vast majority of transit services. For example, more than 40% of the nation's transit trips are conducted within the New York City urbanized area, despite that area only having 5.8% of the national population. Large agencies also depend more heavily on rail-based modes to provide transit service, which account for 20% of the vehicles that large transit agencies operate (United States Department of Transportation, Federal Transit Administration, 2022). Generally, these agencies have a diverse set of vehicles that allow them to cater to different circumstances within the areas they service. This means that they currently, or will in the future, use a large variety of ZEBs, including standard buses, articulated buses, motorcoaches, cutaways, and vans, in addition to the standard buses that are a cornerstone of their transit service.

Large transit agencies have been at the forefront of the ZEB transition. Many have already started procuring ZEBs and deploying the necessary infrastructure to run ZEB operations. These agencies can more easily take risks procuring some ZEBs since any initial deployment problems with ZEBs can be more easily covered using existing ICE vehicle fleets. In other words, starting to deploy a

[1] In the figure, "Everywhere Else" refers to areas generally covered by small transit agencies, while the other categories are covered by large transit agencies.

limited number of ZEBs is a much more limited risk for a larger fleet. In addition, these agencies' financial, knowledge-based, and personnel resources make them better positioned to navigate the ZEB transition than smaller agencies.

Small Transit Agencies

Small transit agencies are characterized not only by the size of their fleets and the number of people they service but also by their geographic distribution, the services provided, and their ZEB needs. Small transit agencies accounted for 2,441 of the 2,974 transit agencies listed in the National Transit Database (NTD) in 2022 (NTD, 2022).[2] These agencies cover large areas with sparser populations and operate with fewer vehicles. They provide proportionally more demand-response services, where vehicles are dispatched in response to specific customer requests, rather than following a fixed route or schedule.

Small transit agencies depend more heavily on smaller vehicles such as cutaways, vans, and even automobiles, as shown in Figure 1. In contrast to larger agencies, small transit agencies also typically employ relatively few staff, have small capital and operating budgets, and have limited access to specialized technical expertise. Another consideration when interpreting the relative progress of small and large transit agencies toward full zero-emission transition—as discussed in the next section—is that small agencies are subject to fewer reporting requirements and generally have lower capacity to report information about the services they provide. These limitations mean that it is difficult to precisely ascertain the extent to which small agencies have incorporated ZEBs into their fleets, adding a layer of uncertainty to this assessment.

Transit Agencies' Progress Towards Full Zero-Emission Transition

In the context of the ZEB market, understanding the nationwide transit bus fleet's composition by propulsion technology is crucial. As of 2022, the distribution of buses by emission category shows that traditional buses (diesel and gasoline) still dominate, making up 60% of the national transit bus fleet. Low-emission (compressed natural gas, ethanol, hydrogen, liquefied petroleum gas (propane), liquefied natural gas, and biodiesel) and hybrid fuels make up another 37% of the fleet. As shown below, zero-emission vehicles had an approximate market share of 3% in 2022.

[2] Note, however, that the NTD does not cover all transit agencies in the country; the number of small, "non-reporting" transit agencies not represented in this dataset means that the proportion of small agencies as a share of the total transit market is larger than this statistic may represent.

Table 3. Road Vehicles by Reported Fuel Type

Specification	Number of Vehicles
Zero-Emission	1,972 (3%)
Hybrid	9,642 (14%)
Low-Emission	15,407 (23%)
Traditional	39,909 (60%)
Total	66,920

(US DoT, FTA, 2022)

In 2021, the latest year for which data is available (and a year affected by the Covid-19 pandemic), ZEBs represented 8% of manufactured transit buses (514 ZEBs out of a total of 6,485 on-road vehicles). This statistic shows that ZEB procurement and deployment is accelerating relative to the current market share, but that, to achieve the ZEB transition, the ZEB market—both demand and supply—must grow by a factor of 12. Though the number of ZEBs procured and in service continues to rise every year, Table 3 shows that there is still a long way to go before a full transition.

Tables 4 and 5 give a broader picture of the size of the ZEB market compared to the on-road transit vehicle market using NTD data and information from a recent CALSTART report[3] (Hynes, Crippen, Lemons, & Varnell, 2024). Table 4 shows the stock of all vehicles available to transit agencies, and Table 5 displays the annual average flows of vehicles. Between 2014 and 2021, the average number of ZEBs procured by transit agencies has been 249, compared to an average number of 10,471 on-road transit vehicles (NTD, 2024). As noted above, this growth is primarily led by large transit agencies in major cities, which are increasingly integrating ZEBs into their fleets. Notably, although the share of "small" on-road transit vehicles is roughly 50% of the total national fleet, adoption of ZEBs has been faster for full-sized ZEBs than small ZEBs based on the data below.

[3] CALSTART's data collection process is robust: they gathered data primarily through local, state, and federal award documents, press releases, and author correspondence with 26 state Departments of Transportation and 85 transit agencies via email and phone interviews (Chard, R., Hynes, M., Lee, B., & Schnader, J., 2023). For ZEBs, these figures likely represent more complete estimates compared to the more limited view available through NTD data.

Table 4. Total On-Road Transit Vehicles in the US Market

Statistic	Number of Vehicles according to NTD	Number of Vehicles according to CALSTART
Full-sized[4] ZEBs	1,556	6,147
Small[5] ZEBs	629	1,010
Total ZEBs	2,185	7,157
Full-sized on-road transit vehicles	69,022	>59,000
Small on-road transit vehicles	61,730	>57,000
Total on-road transit vehicles	130,752	>126,000

Table 5. Annual Average Purchases of On-Road Transit Vehicles in the US Market

Statistic	Average Annual Vehicles according to NTD (2014-2021)[6]	Annual Vehicles according to CALSTART (2022 to 2023)[7]
Full-sized ZEBs	179	667
Small ZEBs	70	134
Total average ZEBs	249	801
Full-sized on-road transit vehicles	4,612	NA
Small on-road transit vehicles	5,859	NA
Total average on-road transit vehicles	10,471	NA

[4] "Full-sized" refers to conventional buses, motorcoaches, double decker buses, and trolleybuses.
[5] "Small" refers to cutaways and vans.
[6] Date ranges were selected due to NTD limitations of data past 2021.
[7] CALSTART reports how many ZEBs were added between 2022 and 2023.

2.3 ZEB Procurement Introduction

The topic of how transit agencies procure ZEBs is critical for understanding the market dynamics and context for the ZEB transition. While there is substantial overlap between ZEB and ICE vehicle procurement, with respect to the processes and strategies that both transit agencies and vendors employ, ZEB procurement introduces significant additional complexity. The interface between the ZEBs and the required equipment and infrastructure needed to fuel them heightens the importance of key decisions around choosing bus models and specifications. At the same time, the federal policies and regulations that govern bus procurements funded with federal aid constrain transit agencies' options in the ZEB market. This section discusses the issues around procurement in greater detail, including some of the methods that transit agencies use to acquire ZEBs today.

Transit agencies have a range of options available for how to procure buses. One conventional path is for a transit agency to develop a "Request for Proposals" (RFP) specific to its own needs and to conduct the competitive solicitation process itself to garner bids or proposals from interested vendors in a controlled, competitive environment. Transit agencies will often hire specialized consultants to develop the procurement documentation and/or consult available resources such as the American Public Transportation Association's (APTA's) "The Process of Transit Procurement" white paper (APTA, 2013) and Standard Bus Procurement Guidelines ("White Book") template (APTA, 2022); these resources assist transit agencies in compiling detailed bus specifications for procurement. Alternatively, there are several more "innovative" procurement methods that transit agencies frequently use to avoid the time- and resource-intensive process of running a competitive procurement. These methods vary in their familiarity to transit agencies and have unique advantages and disadvantages, as described below.

- Conventional RFP: As described above, a transit agency conducts its own competitive solicitation process to select a ZEB vendor. The main advantage of this method is that it allows a transit agency to define very specific needs and terms. The main disadvantage of this method is the relatively high transaction cost of developing and administering the RFP. For a smaller agency, an additional disadvantage is the inability to purchase sufficient quantities of ZEBs to benefit from any potential discount pricing. While this method is more frequently used by larger agencies, some small agencies also prefer to conduct their own RFP.

- State purchasing schedule: A state runs a competitive process to select one or more ZEB vendors as suppliers for the benefit of local transit agencies, effectively setting up a contract for an undefined quantity of vehicles, with defined pricing and terms, that transit agencies can use to purchase ZEBs without conducting their own procurement. Under the 2016 FAST Act, Section 3019 on Innovative Procurement, transit agencies may make purchases from any state's schedules—see FTA Circular 4220.1F, Chapter V, (Simpson, 2013) and FTA's Best Practices Procurement & Lessons Learned Manual (Federal Transit Administration, 2016) for more details. State purchasing schedules for ZEBs are available in multiple states, including California, Virginia, Washington, and Georgia. The main advantage of this method is that it allows transit agencies to contract directly with ZEB suppliers without the need for further competitive bidding. An additional advantage is the potential for discounted pricing due to larger total quantities of ZEBs being sold by a vendor, to multiple transit agencies, under the state purchasing contract. The main disadvantage is less flexibility around changing the specifications or scope of what is included in the purchase or the terms of the contract. Agencies large and small are using these contracts to buy ZEBs, often across state lines.

- Cooperative purchasing: Two or more transit agencies may establish a purchasing cooperative to aggregate demand and thereby receive more favorable pricing and terms from ZEB suppliers while sharing the burden of conducting a procurement. Agencies typically sign a cooperative purchasing agreement to formally join the cooperative, and one lead member of the cooperative conducts the competitive procurement(s) on behalf of the cooperative, making the resulting contract(s) with maximum prices available to cooperative members (who then can negotiate and execute purchase orders with the ZEB suppliers). Unlike state purchasing schedules, beneficiaries of the resulting contracts, along with minimum and maximum quantities for ZEBs, must be defined prior to the contract's award. The advantages and disadvantages of this method are similar to those defined above for state purchasing schedules. There are several such cooperative purchasing groups in the United States, the largest being the California Association of Coordinated Transportation (CALACT) with over 250 members (CALACT, n.d.).

- Joint procurement: This mechanism is similar to but distinct from cooperative purchasing in that two or more transit agencies enter into a single contract with a vendor for the delivery of goods and/or services. The main advantages of this method are lessening/sharing the procurement burden and increasing the chances of receiving a volume discount. The main disadvantages of this method are lesser flexibility for individual agencies and the amount of administrative effort required to execute the contract, which may still be significant.

- Sole source purchasing: Procurement regulations may allow transit agencies to purchase ZEBs directly from a supplier without a competitive process in certain unique and uncommon circumstances (typically when one or more of the following apply: (1) the item does not meet a certain micro-purchase threshold, (2) the item is only available from a single source, (3) the public exigency or emergency for the requirement will not permit a delay resulting from competitive solicitation, (4) funding agencies expressly authorize a noncompetitive proposal in response to a written request, or (5) after soliciting several sources, competition is determined inadequate, per 2 C.F.R. § 200.320(f)) (Code of Federal Regulations, 2024). The main advantage of this method is the speed of purchasing, but the main disadvantage is the likely high cost from a lack of competition and the potential for challenges on the sole source justification.

- Coordinated procurement: This is not a procurement "method" but rather a "strategy" in which two or more transit agencies agree to purchase the same type of ZEB, likely through a contract already established by a state purchasing schedule or cooperative purchasing entity. The benefits of this coordination strategy are discussed further in Section 4.

2.4 ZEB Policy Introduction

Over the last decade, policy has been the biggest driver of the transition to ZEBs. Federal and state policies are significantly impacting both the demand and supply in the ZEB market in the United States. While grants and financial incentives arguably play the most prominent role, purchase mandates and regulations also shape the market. Local policy can also help smooth the path toward ZEB deployment.

Federal Policy

While the number of ZEBs deployed by transit agencies in the United States has grown significantly over the last decade, federal policy governing the transit bus industry has not substantially changed. Buyers and suppliers of transit buses alike must comply with these regulations for any purchase involving federal funds. These issues are well documented in the 2016 Mineta Transportation Institute Report 12-66 (Czerwinski et al., 2016), including most notably Buy America, Altoona testing, minimum useful life, maximum spare ratios, and other procurement requirements, which are discussed in greater detail in Section 3. This 2016 report illustrates the impact of the federal regulatory regime on the vendor ecosystem, which faced waves of restructuring and consolidation resulting in only three main manufacturers serving the heavy-duty transit bus market (and only one engine supplier) at that time.

Perhaps one of the more significant changes in federal policy in recent years is simply the levels of funding available to transit agencies through the FTA programs that principally fund US transit buses. The Bipartisan Infrastructure Law significantly increased levels of formula funding for Urbanized Area Formula Grants (5307), Rural Areas Formula Grants (5311), and State of Good Repair Grants (5337), as well as for the competitive programs Bus and Bus Facilities (5339(b)) and Low- or No-Emission Bus Grants (5339(c)) (Federal Transit Administration, n.d.). For example, funding for the Low- or No-Emission Bus Grants Program increased 20-fold, from $550M per year to $1.1B annually (FTA, n.d.). Along with increased funding, the FTA also requires funding applicants to complete a zero-emission transition plan to build the planning foundation for capital purchases and projects. Although the increased funding levels have been a short-term boon to transit agencies, allowing them to better absorb the shock of the Covid-19 pandemic, maintain staff levels, and make high-priority capital investments, the federal government has not made any meaningful structural changes to transit funding policy in recent years.

Another significant and relevant federal policy development is a shift toward industrial policy to support the United States' clean technology manufacturing industry, characterized mainly by various forms of incentives in the Bipartisan Infrastructure Law, the Inflation Reduction Act, and other federal legislation. This has resulted in billions of dollars in grants and tax credits going to companies serving the automotive supply chain. While the primary target of these policies has been to accelerate the development of the zero-emission passenger electric vehicle industry, the heavy-duty battery-electric transit bus and truck markets will also likely benefit in the long-run from lower costs for batteries and other key components. However, it is still too early for these investments to be clearly observed in the economics of the US transit bus market.

Finally, the federal government has also taken a critical role in catalyzing the early development of a clean hydrogen production industry in the US The Bipartisan Infrastructure Law included an $8B hydrogen hub program to establish regional clean hydrogen networks, and the Inflation Reduction Act includes a substantial proposed tax credit for private companies to construct green hydrogen production facilities, per 26 US Code Section 45V (United States Department of Energy Office of Clean Energy Demonstrations, n.d.; Federal Register, 2023). These incentives help create the conditions for creating the economies of scale necessary to increase the availability and bring down the costs of hydrogen fuel, making it a more viable option for US transit agencies and other transportation use cases. As one of the seven awardees of the hydrogen hubs program, California has specifically cited the role that the hub can play in making clean hydrogen cost-competitive with diesel (Alliance for Renewable Clean Hydrogen Energy Systems, 2024).

State Policy

The most notable example of state policy leveraging major change in the ZEB market is the California Air Resources Board (CARB) Innovative Clean Transit (ICT) regulation, which implements a ZEB purchase mandate requiring that all new bus purchases by transit agencies in the state be ZEBs starting on January 1, 2029 (California Air Resources Board, 2019). The ICT has had a major catalytic effect on OEMs' investment in ZEB production and on transit agencies beginning the technical, operational, and financial planning processes to start converting their fleets. CARB's Advanced Clean Trucks (ACT) and Advanced Clean Fleets (ACF) regulations will also likely spur additional investment in zero-emission vehicle manufacturing and supply chains, with flow-down effects for the transit bus industry. To date, no other state has implemented a ZEB purchase mandate such as California's, although various other state legislatures have set similar policy targets to convert heavy-duty vehicle fleets to zero-emission. Similarly, California, Colorado, Connecticut, the District of Columbia, Hawaii, Maine, Maryland, Massachusetts, Minnesota, Nevada, New Jersey, New York, North Carolina, Oregon, Pennsylvania, Rhode Island, Vermont, Virginia, and Washington signed a Memorandum of Understanding committing to work towards 100% zero-emission new sales of medium- and heavy-duty vehicles by 2050 (Multi-State Medium- and Heavy-Duty Zero Emission Vehicle Memorandum of Understanding, 2020). While such targets do not send as strong a market signal as mandates, they can encourage transit agencies to begin setting their own targets, initiating planning processes, and applying for grants.

Another key area where states can impact ZEB deployment is through utility regulation. For BEBs, utilities play a critical role in the development of charging infrastructure projects and in the overall economics of deploying and operating BEBs. States, through their Public Utility Commissions, can require that utilities engage collaboratively in the early stages of planning a project and/or pay for certain "front of meter" portions of the total capital costs to bring power to a site. States can also create a different rate structure for certain types of customers (e.g., public transit agencies), reducing the per-kWh cost of electricity, and possibly reducing or eliminating "demand charges" to further encourage adoption of BEBs, as demonstrated by recent activity advancing potential solutions in New York (New York Public Service Commission, 2022).

States can also play a meaningful role in providing funding to transit agencies for ZEB acquisition, the installation of infrastructure, and the construction or retrofitting of facilities. State funding can be a significant part of the overall funding mix for transit agencies in some states (along with federal and local funding), and some states also have dedicated pots of funding for projects that reduce carbon emissions, such as various electrification programs through the Colorado Department of Transportation (Colorado Department of Transportation, n.d.) and numerous programs such as California's Clean Transportation Program (California Energy Commission, n.d.). States can also dedicate resources and personnel to providing technical assistance to transit agencies for ZEB planning and project development. Finally, states can exempt ZEBs from sales tax to improve the economics of ZEBs for transit agency purchasers.

Local Policy

Most public transit in the United States is locally controlled and substantially funded by local tax dollars. As such, local policymakers play an important role in making decisions about transit agency fleet conversion and ZEB infrastructure projects. In other words, on the demand side of the market, local policymakers who often sit on transit agencies' boards of directors help shape how quickly a transit agency converts its fleet by approving studies, procurements, and purchase orders. This approval process may sometimes pose a barrier, as the technology is still relatively new and unfamiliar to many officials.

City and county zoning, permitting, and right-of-way (ROW) processes and regulations may also come into play for specific infrastructure projects, and local officials can help accelerate project development by shaping those processes and regulations around the specific needs of a ZEB infrastructure project. In some cases, city regulations may need to be updated or made more flexible to accommodate ZEBs. One such example is the municipal gross vehicle weight (GVW) limits for local roads, which may be exceeded by ZEBs that are generally heavier than their diesel counterparts.

3. Observed Zero-Emission Bus Transition Challenges

Conversations with stakeholders and a review of relevant US transit data highlighted the challenges for the US's ZEB transition in four key categories: costs, market dynamics, operational performance, and organizational capacity. Key challenges and descriptive data characterizing the extent, nature, and causes of these observed challenges are summarized here.

3.1 Cost Challenges

The costs of vehicles and long-term deployment are among the most prominently observed constraints for stakeholders in the US's ZEB transition. Specific challenges within this thematic category are highlighted below.

Cost Challenge 1: High Purchase Prices

Purchase prices for zero-emission buses in the United States are significantly higher than ICE vehicles, and they have not decreased as quickly as previously theorized.

The upfront capital cost of zero-emission transit buses—both BEBs and FCEBs—is commonly cited as a barrier to deployment, both in conversations with transit operators and in industry publications (Hanlin et al., 2018).[8] The cost of ZEBs and ICE vehicles can vary depending on the size, capacity, layout, and add-ons ranging from software and additional mirrors to wheelchair lifts. However, the most important cost driver for ZEBs is the battery or fuel cell technology, as discussed in greater detail later in this section. Generally, FCEBs are more expensive than BEBs, which are in turn more expensive than ICE vehicles. Different sources provide varying cost estimates for the myriad fuel types, although generally BEBs can be up to twice as expensive as ICE vehicles, and FCEB prices can be higher still. Various recent price estimates by fuel type and vehicle length and type may be found in Table 11 in Appendix A. Considering the variability of these estimates, the current price of a full-sized (~40 foot) ICE bus is approximately $500k, while BEB prices are typically in the range of $800k–$1.2M, and FCEB prices are in the range of $1.2–$1.8M.

The phenomenon of higher costs for relatively newer technologies is by no means unique to the ZEB market. Economic logic would dictate that goods and technologies produced without the potential efficiencies of scale and with the burden of recouping major research, development, and commercialization costs would be more expensive than their legacy counterparts. For ZEBs, these

[8] For example, the Butte County, California Association of Governments (2023) cited in its zero-emission transit transition plan in that the current market cost of ZEBs that they see ranges between $0.75–$1.70M, which they estimate to be $0.25–$1.2M more expensive than traditional diesel buses. Similarly, the City of Beaumont Transit System (2023) compared ZEBs to their baseline technology of CNG in their transition plan, reporting that the market cost difference between ZEBs and CNG full-size buses is between $0.30–$0.37M, and $0.12–$0.2M for cutaway buses.

early-stage costs are often attributed to high component costs for batteries and fuel cells. For FCEBs, for example, the Department of Energy estimated in 2015 that the fuel cell system, battery system, hydrogen storage system, and total bus costs were such that the FCEB-specific components contributed about 25% of the total cost of the FCEB (United States Department of Energy Office of Energy Efficiency and Renewable Energy Hydrogen and Fuel Cell Technologies Office, n.d.). For BEBs, the battery technology may contribute closer to one-third of the total bus cost or more, although this figure may range dramatically based on the size of the battery selected, as demonstrated by the fact that costs are often quoted on a per-kilowatt-hour basis (Basma et al., 2022; California Air Resources Board, 2020).

Unfortunately, expectations of rapidly falling costs are not being realized from the perspective of most customers and market observers. For example, a 2016 fact sheet by the Sierra Club quoted BEB cost estimates of $480,000 by 2025, reaching or going beyond cost parity with a new diesel vehicle (Sierra Club, 2016). Similarly, 2019 National Renewable Energy Laboratory (NREL) estimates indicated an expected FCEB cost reduction to $850,000 within two years (Beshilas, 2019). According to ZEB Original Equipment Manufacturers (OEMs), breakthroughs related to higher energy density and lower costs for batteries have not continued after original progress in the mid-2010s. OEMs publicly disagreed about whether the costs of their vehicles would decrease closer to parity with ICE vehicles or if they planned to invest all savings from lower component costs and market maturation into higher battery capacity; this latter strategy would lead to higher value for money, but no major decreases in sticker prices for ZEBs (Center for Transportation and the Environment, 2021). According to interviewees, bringing the ZEB market to scale and maturity to benefit from greater efficiencies and competition can decrease prices, but they do not expect that scale alone can achieve price parity. Interviewees drew contrasts to other vehicle sub-markets, such as light-duty passenger vehicles and heavy-duty trucks, which they noted were much larger and better-resourced and thus more likely than the transit market to drive cost reductions in common components, such as vehicle batteries.

Given the consensus that market maturation alone is unlikely to eliminate higher ZEB costs, this section examines other factors that may be keeping ZEB prices elevated above ICE bus costs:

- First, most stakeholders in the ZEB transition acknowledge that general macroeconomic cost drivers and inflationary pressures, particularly in the post-Covid-19 world, play an important role. The costs of labor, key goods and materials, real estate, and more are all relevant in observed ZEB prices.

- Second, as described in a recent ZEB market sounding report by Caltrans, private sector stakeholders view transit agencies as largely price insensitive with respect to vehicle costs (IMG Rebel Advisory, Inc., 2024). In other words, agencies will still buy ZEBs despite the high prices. While potentially counterintuitive, this finding is reinforced by this report's interview findings, which indicated that stakeholders see substantial public funds flowing towards ZEB purchases, but less coordination or incentives that could bring down purchase costs or send a clear signal to the market that efforts to provide lower-cost products would lead to a competitive advantage.

- Third, the phenomenon of extensive customization of transit buses is also front of mind for many stakeholders in transit and the zero-emission transition (IMG Rebel Advisory, Inc., 2024). Customization can impact ZEB costs through two basic mechanisms. First, customers can directly increase the costs of the vehicle they are purchasing through optional add-ons, upgrades, or changes, which may require different or more expensive parts or materials as well as additional engineering and labor hours. Although quantifying the costs of customization is an inexact exercise, one analysis showed, for example, that California agencies buying the same BEB model paid widely varying prices between $800k–$1.3M (Shrode, 2023). Indirectly, the fact that most transit agencies are customizing their vehicles in non-negligible ways (e.g., requesting a different interior layout rather than a change in color) has fostered and reinforced a labor-intensive, small-scale, relatively high-cost manufacturing system for transit buses. This means that transit bus production is very different from, for example, highly automated and standardized passenger vehicle manufacturing.

- Fourth, policy and regulation are commonly cited key cost drivers. These factors are explained in more detail in the introduction to this report, but the most frequently mentioned examples include Buy America and FTA Altoona Testing requirements. Many stakeholders cite international price comparisons as convenient counterfactuals to US policy and regulations. While imperfect in their ability to quantify all contextual differences between national ZEB markets, these comparisons show that many non-US customers are paying substantially less for ZEBs—for example, BEB prices are in the range of 500,000 Euros in Europe, roughly half of the observed prices in the United States (Serrano & Ruiz, 2024). This difference is long-standing; evidence beginning in 2012 showed, for example, that BEB prices typically ranged between $550,000–$1,200,000 in the United States, while prices in China and Latin America ranged from $140,000–$350,000 and $260,000–$475,000, respectively (Allan et al., 2021). It is important to note that while policy and regulatory factors are the most obvious difference between US and international ZEB markets, the gap between US and international prices remains enigmatic; further research into the economic, competitive, regulatory, and other factors that may be preventing US transit agencies from procuring ZEBs at similar prices to agencies in Europe, China, or Latin America is urgently needed.

- Finally, some observers note that the relative immaturity of ZEB technology as compared to ICE vehicles, particularly uncertainty about life cycles and parts replacement, is causing a desire for stronger warranty terms from transit agencies (Smyth et al., 2020). The cost of this additional risk—which will likely be borne either by component suppliers or OEMs—is passed through to customers, increasing vehicle purchase prices.

Cost Challenge 2: Uncertain TCO Savings

Savings on the "total cost of ownership" of ZEBs compared to conventionally-fueled vehicles have been expected, but achieving these savings has proved difficult and uncertain for many agencies deploying ZEBs.

Despite the importance of upfront costs, as discussed in this report, many stakeholders in the ZEB transition appropriately focus on the lifecycle costs to purchase, own, operate, and maintain a vehicle; this single metric is typically referred to as the "total cost of ownership" (TCO). Many observers have theorized—and in some cases, measured—that the higher upfront purchase cost of a vehicle does not tell the full story of the financial impacts of ZEB deployment. While most commonly cited in reference to BEB deployment, the concept of potential TCO savings is broadly applicable when considering the costs of ZEB transition. Many TCO models, sensitivity analyses, and studies have been conducted focusing on the US ZEB transition, many of which predict meaningful cost savings for BEB deployment when compared to ICE deployment, but there is also substantial variability in these estimates (Ambrose et al., 2017; Portland General Electric, n.d.; Johnson et al., 2020). Studies related to FCEBs are fewer, generally showing a higher TCO than both BEBs and ICE buses (Chen, 2023).

Interviewees commonly cited four different cost categories that may impact the total cost of ownership for ZEBs compared to ICE vehicles.

- Maintenance costs: The cost of maintaining vehicles, including the time required to diagnose and repair, the cost of parts, and the frequency of required maintenance activities, will be different for ZEBs and ICE vehicles. While some types of maintenance will be less common and costly, large-scale, long-term maintenance cost data from a variety of contexts is not yet robust enough to draw concrete conclusions about potential maintenance cost savings of ZEBs.

- Fuel costs: The cost of hydrogen is unambiguously higher than for any conventional fuel, with transit agencies paying on average $9/kilogram for delivered liquid hydrogen in California (Villareal, 2024). Based on discussions with transit agencies and private market participants, these costs are expected to be at least 50% higher for agencies in remote areas far from fuel production and distribution. The cost of electricity can vary widely by geography and pricing structure; interviewees in particular note the high cost and uncertainty of time-of-use and demand charge-based pricing structures for electricity that many transit agencies experience, although electricity costs may be lower on a per-mile basis than ICE fuels. Both high electricity rates and complicated rate structures for pricing this electricity have been cited as key challenges for BEB deployment (Hanlin et al., 2018).

- Infrastructure costs: While this report is focused on zero-emission transit vehicles, the infrastructure required to fuel and maintain these vehicles is a critical part of the equation for many deployers. Legacy fueling and bus maintenance infrastructure is a known quantity and relatively much less expensive to procure, build, and maintain. In contrast, infrastructure for both BEBs and FCEBs can cost millions of dollars to install even for a small transit agency and many thousands to operate and maintain every year (Linscott & Posner, 2021). For agencies facing space constraints, these costs may also include land acquisition or leasing in order to site these new systems.

- Other "soft" transition costs: Many transit agencies cite other cost categories as smaller, but collectively important to their operating budgets. Many of these costs are relatively short-term transition costs, such as paying for consultant and technical assistance support, training, and grant writing. Others, such as the cost to insure more expensive vehicles and new high-cost infrastructure systems, persist indefinitely. This phenomenon has also been observed outside the US market (Pejcic et al., 2019).

For many interviewees and transit agencies, achieving theorized TCO savings is far from certain. These savings for any individual ZEB depend on many factors, ranging from energy prices to driver behavior to severe weather, making actual savings difficult to predict or budget for.[9] In a rigorous financial analysis of BEBs, Johnson et al. (2020) found that while on average transit agencies could expect to achieve a positive net present value from deploying a BEB, several factors, including the number of miles traveled, maintenance costs, upfront vehicle costs, the amount of grant funding that could be obtained, and electricity demand charges, were moderately or highly volatile and could drastically impact the relative costs and benefits of deployment.

Authoritative sources on the zero-emission bus transition have recognized this dynamic. For example, the TCRP Guidebook for Deploying Zero-Emission Transit Buses (Linscott & Posner, 2019) advises deploying agencies that "market immaturity makes cost savings difficult to prove, therefore, while operational and maintenance cost savings may ultimately be realized, use caution when making business decisions that rely on these potential cost savings" (p. 24). Similarly, NREL experts note that early in deployments, a lack of staff familiarity with the vehicles can increase the time required for training, diagnostics, and repairs; they note that based on meta-analysis results, ZEB propulsion systems can be less costly to maintain, but are often determined by specific circumstances, such as bus type, OEM support, maintenance practices, and more. While maintenance costs are expected to decrease over time as the technology becomes better known, NREL notes current evidence that the combined cumulative maintenance cost per mile was similar for ZEBs and non-ZEBs after 4–6 years (Jeffers, Kelley et al., 2022). In other words, current evidence does not typically demonstrate actual achievement of TCO savings.

[9] For example, the city of Glendora, California, noted in its transition plan (Schwartz, 2022), focused on transitioning from CNG and gasoline vehicles to BEBs, that lower maintenance and fuel costs may not materialize as expected due to the nascent nature of the technology, and that this uncertainty would be challenging for the transit agency to navigate during the transition period.

Cost Challenge 3: Mismatched Funding and Need

Existing funding sources are uncertain, competitive, and focus mostly on capital rather than lifecycle costs of operating ZEBs.

Notwithstanding the higher upfront vehicle purchase costs and total costs of ownership described in the previous sections, the observed impact of the ZEB transition on transit agencies, riders, and local communities depends on whether funding is available to adequately meet these needs. Stakeholders and interviewees observe a number of challenges related to the funding landscape for transit's zero-emission transition. Many transit agencies anticipate relying on discretionary state and federal programs because existing formula programs will be insufficient in meeting the full cost of transition.[10]

Given that many agencies will be relying on discretionary funding programs, a common theme in stakeholder observations was the impact of many or most of those programs relying on a competitive structure for allocating funding. For example, one of the cornerstone ZEB funding programs, FTA's Low- or No-Emission Bus program is drastically oversubscribed, with transit agencies applying for four times as much funding as was available in total in FY22, while the competitive portion of the Bus and Bus Facilities program received requests for 6.5 times as much funding as was available, with zero-emission projects making up 86% of these funding requests (Transportation for America, 2023).

Many transit agency transition plans required by the Innovative Clean Transit regulation in California mention competitiveness of transition funds as a "start-up and scale-up challenge," with particular urgency from very small and less well-resourced agencies.[11] In California, one further key source of uncertainty is the fact that some funding—notably, the credits that transit agencies can earn and monetize via the Low Carbon Fuel Standard (LCFS) regulation—is subject to market-based fluctuations. From a transit agency perspective, this means that the final funding amount is highly unpredictable, complicating long-term planning (Jeffers, Kelley et al., 2022). All of these factors are perceived as risks by stakeholders in the zero-emission transit transition.

In addition to the amount and method of allocation of funding, transit agencies also articulated the challenge of radically different funding approaches to capital and operational expenses. As discussed previously in this section, transit agencies are anticipating (and currently experiencing) transition costs that go far beyond purchasing different and more expensive vehicles. These other costs, particularly those related to fuel, labor, maintenance, ongoing training, and transition

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[10] For example, Sonoma County Transit (2023) noted the difficulty of covering the full estimated $60M cost of their zero-emission transition, a large funding need given the modest size of this agency.
[11] For example, the City of El Monte (2023) found it very challenging to successfully compete with larger agencies for funds. Transit agencies also expressed concern about the uncertainties associated with the funding sources they will be relying on. For example, the Shasta Regional Transportation Agency's (2023) transition plan notes the likelihood that programs could change significantly over time, while Unitrans mentioned that funding programs are often subject to broader economic conditions (University of California, Davis, 2022).

management, are typically labeled as "operational" costs and as such are not eligible for funding under most existing programs. This strategy of primarily funding up-front capital costs of vehicles and infrastructure would be well-aligned with agencies' funding needs if agencies could depend on operational cost savings associated with zero-emission buses. However, given the high uncertainty of TCO savings described above, many agencies are concerned about their ability to fund operational costs without new sources given the "color of money" issue described here.

3.2 Market and Supply Challenges

The ZEB market's supply side is also a significant topic of discussion among stakeholders. Specific challenges related to market characteristics and supply health are highlighted below.

Market Challenge 1: Consolidated and Unstable Market

The ZEB market in the US is relatively unstable and highly consolidated.

As recently as 2022, NREL researchers reported that at least ten OEMs were supplying BEBs and FCEBs in various sizes and lengths to the US market (Jeffers, Kelley et al., 2022). In the period up to 2022, the key suppliers of heavy-duty ZEBs in the US were Build Your Dreams (BYD), New Flyer of America, Proterra, and Gillig Corporation. As of 2022, these four companies had sold more than 190 ZEBs each, with varying market shares and product offerings. All other companies had sold fewer than 30 ZEBs each in the same period. Note, however, that the data in the table below is limited by the lack of data regarding zero-emission cutaways and vans, due to reduced reporting requirements from rural transit agencies. This lack of data generally means that much less is known about this portion of the market and the supplying manufacturers.

Table 6. US Sales and Market Share by Company, 2022

Manufacturer	US ZEB Manufactured, up to 2022	2022 US ZEB Market Share up to 2022
Proterra Inc.	587	38%
New Flyer (NFI)	394	25%
Build Your Dreams, Inc.	285	18%
Gillig Corporation	197	13%
Motor Coach Industries International	20	1%
El Dorado National	18	1%
Ebus, Inc.	15	1%
Van Hool N.V.	13	1%
Alexander Dennis Limited	2	0%
North American Bus Industries Inc.	1	0%
Total	1,559	100%

(National Transit Database, 2022) [12]

The data displayed in Table 6 above no longer accurately represents the ZEB market landscape in the US A number of recent, highly disruptive events have had major impacts on the options for purchasing new ZEBs, as well as repairing and supporting the ZEBs already on the road. At a high level, the market for full-size FCEBs (i.e., 30+ foot buses) can currently be described as an effective monopoly supplied only by New Flyer, while the market for full-size BEBs is an effective duopoly supplied by New Flyer and Gillig. Key disruptive events in the US ZEB market that led to this current state of play include:

- FTA limits on purchases of BYD buses using federal funds: The Fiscal Year 2020 National Defense Authorization Act added a new provision to public transportation law that limits the use of FTA funds to procure rolling stock from certain manufacturers with specific kinds of relationships to certain countries, including China. These restrictions applied two years after the passage of the legislation, taking effect in December 2021 (Federal Transit Administration, 2022). Although some purchases, including those made exclusively with state or local funds, are not impacted, this legislation introduced extreme limitations on BYD's ability to supply and compete in the US market (BYD, 2020). As a previously popular supplier and one of the largest ZEB manufacturers worldwide, this policy change proved highly impactful. BYD buses remain deployed by US transit agencies and can legally be purchased under some circumstances, but the scale of new BYD ZEB purchases

[12] This table was generated by counting the ZEBs per manufacturer on the 2022 NTD Revenue Vehicle Inventory dataset. Note that this does not include any vehicles where the fuel-type is unknown or not reported. Additionally, the manufacturer is not always known, resulting in numbers from individual manufacturers not adding up to 100%.

in the US market have decreased sharply as transit agencies no longer saw BYD as a viable supplier in most circumstances.[13]

- Nova Bus ends US manufacturing: In June 2023, the Volvo Group subsidiary Nova Bus announced that it would exit manufacturing for the US market, citing continued financial losses and a lack of profitability in the US, as compared to its successful Canadian business. The company intends to close its manufacturing facility located in Plattsburgh, NY by 2025 (PR Newswire, 2023). Similar to BYD, most transit agencies no longer see Nova Bus as a viable supplier in many circumstances.

- Proterra declares bankruptcy: In August 2023, electric bus manufacturer Proterra filed for bankruptcy, citing market and macroeconomic challenges (Duncan, 2023). The company said in its filings that it had delivered over 1,000 electric buses; a manufacturer of this scale leaves a meaningful gap in the US market. This announcement alarmed many market stakeholders and transit agencies. As of January 2024, Phoenix Motor—a current manufacturer of medium-duty transit vehicles—received court approval to acquire the transit portion of Proterra's business; the extent to which this acquisition will replace the portion of supply previously contributed by Proterra remains to be seen (*Mass Transit*, 2024).

- El Dorado National-California (ENC) exits transit segment: REV Group Inc. announced in January 2024 that the firm would be exiting the school and transit bus manufacturing markets in the United States, citing delays and price competition for critical components, the financial health of key suppliers, and difficulty competing with larger-scale firms (REV Group Inc., 2024). Since one of only two firms that was supplying FCEBs to transit agencies will be exiting the market, transit agencies report that they are effectively dependent on a single manufacturer, a condition many feel is precarious.

Collectively, the impact of these changes cannot yet fully be observed in market and purchase data due to lags in data collection and the gradual phase-out of previous market players from purchase data as they continue to deliver on previous purchase obligations. This data lag heightens the importance of qualitative data from market stakeholders and transit agencies, who report a significant sense of market instability and lack of choice. In effect, as of the writing of this report, stakeholders generally observe duopoly conditions in the market for full-size battery electric transit buses and describe the situation for hydrogen fuel cell electric buses as an effective monopoly.

Traditionally, many transit agencies have tended to demonstrate a strong preference for their incumbent bus supplier. This phenomenon may be due to the significant investments they have already made in staff training, tools, spare parts, and existing vendor relationships that may only

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[13] Note that while this information was accurate at the time of the writing of this report, significant elements of federal policy—including provisions of the NDAA—are subject to updates and reauthorization.

apply to a specific bus make and model. With ZEBs and the recent turmoil for suppliers in the US market, an additional concern for transit agencies lies with the financial health and stability of the vendor counterparty and their ability to fulfill warranties and supply spare parts over the entire useful life of the bus. This intense concentration is not common to all markets; in Europe, for example, OEMs' individual market shares are showing a continuous decline as the market diversifies (Serrano & Ruiz, 2024).

From the supply side, manufacturers are also reporting difficulties in reliably and profitably supplying the US market. This was displayed clearly at a February 2024 roundtable discussion hosted by the White House, FTA, and American Public Transportation Association (APTA). Discussion at this event focused on the financial viability and competitiveness for US bus manufacturing and ways to achieve a steadier and more competitive domestic market (The White House, 2024; American Public Transportation Association, 2024). Naturally, these phenomena are linked; underlying economic, regulatory, and structural challenges for manufacturers will often be experienced on the demand side as market instability.

Market Challenge 2: Lack of Robust Supply

The near-term supply of ZEBs for the US market is likely not robust enough to meet transit agencies' needs for sufficient choice and quantity.

The market disruptions described in the previous section present a concrete concern for transit agencies in terms of their ability to purchase and deploy ZEBs within a reasonable period of time. According to many transit agencies, policy and regulatory initiatives—including most notably the Innovative Clean Transit purchase requirement for California transit agencies—will put significant pressure on OEMs to produce ZEBs at an unprecedented rate. As APTA notes, transit agencies procure on the order of 4,500 heavy-duty transit buses annually (American Public Transportation Association, 2024). While the majority of these vehicles are not currently zero-emission, a growing share will be. Many transit agencies and stakeholders already experience backlogs or supply shortages and are increasingly concerned that an ever-smaller pool of OEMs will not be able to satisfy demand as it continues to grow.

The estimated size of the ZEB market varies based on the source, the data vintage, and the scope of which ZEBs are included. Section 3 contains estimates of the number of ZEBs currently deployed nationwide. For simplicity, this section will rely on a single estimate from CALSTART in 2023, which indicated that there was a total of 6,147 "full-size" ZEBs (>30 feet) (5,775 BEBs and 372 FCEBs) and 1,010 smaller ZEBs (<30 feet) deployed in the US

Comparing the number of ZEBs purchased per year to the total number of ICE buses purchased per year demonstrates the immense growth in the ZEB market that still needs to occur to reach a fully zero-emission US transit fleet. Although comparison of figures from varying sources is imperfect, the NTD Database indicates that there were 109,044 ICE transit vehicles operating as of 2022, meaning that ~6% of buses, cutaways, and vans operating transit service were zero-emission vehicles (National Transit Database, 2022). The remaining ~94% of the US transit fleet remains to be transitioned in future years.

On an annual basis, CALSTART data shows that between 2022 and 2023, a total of 801 ZEBs were purchased (Hynes, Crippen, Lemons, & Varnell, 2024). Meanwhile, NTD data between 2014 and 2021 shows that the average number of buses manufactured per year is approximately 10,471 buses, as shown in Table 7 below. Once again, comparing the order of magnitude of these two figures shows the needed growth in manufacturing capacity to satisfy the annual demand of US transit fleets, which is substantial. Table 7 also illustrates the importance of the small on-road vehicle market for transit agencies, where between half and two-thirds of vehicles manufactured for transit are not full-sized.

Table 7. US Transit Buses Manufactured Per Year

Year	Full-sized buses	Small on-road vehicles	Total on-road vehicles
2014	4,675	3,395	8,070
2015	4,960	3,748	8,708
2016	5,004	6,570	11,574
2017	4,586	7,518	12,104
2018	4,668	6,724	11,392
2019	5,424	9,521	14,945
2020	3,767	5,436	9,203
2021	3,813	3,958	7,771
2022	1,916	1,167	3,083
Average	4,612	5,859	10,471

(National Transit Database, 2022)

This concern about manufacturing capacity and ability to adequately supply the US market is commonly observed as long lead times or delays between order and delivery. Many agencies are reporting lead times of 12 months or more for vehicle production and delivery (Maryland Transit Administration, 2023). Based on its deployment experience to date, AC Transit uses an assumption of 18 months from order to service activation (AC Transit, 2021). From a national perspective, APTA generally cited a gap of 24 months or more between order and delivery of a ZEB in early 2024 (American Public Transportation Association, 2024). Some onlookers describe the root of these problems as Covid-19-related supply disruptions and shortages; however, as problems have not fully resolved as of the writing of this report several years after the peak of these disruptions, many hypothesize that the phenomenon of long lead times may be enduring.

Market Challenge 3: Regulatory and Policy Burdens

The regulatory and policy landscape in the US presents challenges for both the demand and supply sides of the market.

As discussed in the introduction to this report, numerous federal, state, and local policies—from the ICT regulation in California to the availability of funding through the federal Low- or No-Emission Bus program—are actively encouraging the transition to zero-emission transit vehicles. The evidence is clear that these policies and incentives are increasing demand for ZEBs. However, stakeholders have also observed a number of ways in which policies and regulations can lead to transition challenges.

First, many transit agencies are ambivalent about the concept of transit's position as a pathbreaker for the zero-emission transition for heavy-duty transportation. While some stakeholders clearly understand the commonly-cited reasoning, neatly summarized in the California Air Resources Board's "beachhead" strategy (e.g., predictable routes that are compatible with the technology's duty cycle capabilities, current industrial capacity, etc., as described in CALSTART (2022)), they also note weaknesses in this strategy. Many stakeholders note that transit agencies are not natural fits for "cutting edge" technology, given their limited resources, staff capacity, and challenges attracting and retaining employees with valuable technologically-focused skills; these workforce capacity challenges are discussed at length later in this report. Furthermore, many observers note the much smaller size of the transit bus industry as compared to other heavy-duty transportation sectors, with comparisons most often drawn with the trucking industry. As an illustration, compared to the estimated 4,600 transit buses that are manufactured annually (as cited above), the numbers of zero-emission trucks deployed annually through 2030 as a result of comparable fleet regulations is expected to grow from over 12,000 to over 130,000 (Kasdan & Steen, 2024). Many express concerns that the transit bus market is not large or profitable enough compared with other sectors to support the large-scale, expensive technological development, testing (e.g., Altoona testing), and early deployment required. In addition, many transit agencies point to the fact that shifting trips to transit from single occupancy vehicles already helps to reduce emissions, regardless of the bus fuel type.

Manufacturing and import restrictions are also impacting the US market in important ways. Interviewees often mention Buy America laws as a crucial factor in ZEB availability and cost, noting impacts both "upstream" on components sourcing and manufacturing and "downstream" in regulations on manufacturers such as BYD. A host of other laws and regulations, such as Cargo Preference restrictions that generally require products to travel on US-flagged ships (potentially adding to costs and delays), contribute to these dynamics in sometimes underappreciated ways (Moscoe & Henke, 2023).

Procurement is also a key regulatory lever often used to advance policy goals. In addition to typical procurement law, funding agencies, most notably the FTA, impose significant requirements on transit agencies in how agency funds are spent, as discussed further in Section 2. Some state funding programs include similar or the same procurement regulations, either because the FTA is considered the standard-bearer or because those programs are funded with a mix of state and federal dollars. Local governments are typically relatively more flexible in terms of procurement regulations enforced through funding, but also may impose another layer of oversight for transit agencies regarding how procurements are conducted (these are usually reasonable requirements necessitating a competitive bidding process for purchases above a certain dollar threshold).

Other policy and regulatory factors often only come to the forefront for transit agencies once they are well down the path to transition, as mentioned in Section 2. These factors may include local regulations concerning permitting or the development of infrastructure and energy storage, a lack of complete standards related to interoperability between vehicles and infrastructure, procurement regulations, and state-level inspection rules (Pejcic et al., 2019).

3.3 Operational Performance and Technology Challenges

After the initial purchase of ZEBs, stakeholders in the ZEB transition emphasize the importance of considering the long-term deployment success and ability of available technologies to meet operational needs. Specific challenges related to this topic are highlighted below.

Operational Challenge 1: Difficult Technology Choice

Many ZEB deployers find that making a technology choice between BEBs and FCEBs is complicated and fraught.

Most stakeholders view the two ZEB technologies currently available on the market—BEBs and FCEBs—as very different propositions with benefits and drawbacks. The key distinctions between these technologies are summarized in the introduction to this report; for transit agencies, key differentiators are typically range capabilities, cost, availability of fuel/energy, and infrastructure requirements. Many interviewees viewed the options as very different in their level of perceived risk and the extent to which they are "road-tested." Specifically, as of the writing of this report, many transit agencies see BEBs as more familiar and proven, and less expensive, as compared to FCEBs, with initial deployments strongly favoring BEBs (Jeffers, Kelly et al., 2022). Yet, several tradeoffs make this a challenging decision, including the ability to replace ICE buses on a 1:1 basis with ZEBs, considerations around reliable access to fuel, cost ranges, and differences in operational requirements.

As a result of these dynamics, many transit agencies comment that they would prefer to "wait and see" or hedge against the unknowns of both technologies. Currently, many transit agencies are planning to adopt a mix of BEBs and FCEBs rather than committing entirely to one technology (Jeffers, Kelly et al., 2022). The relative market share of each technology—which as of 2022, was over 96% BEBs for ZEBs currently deployed in the United States—is likely to change significantly over time (Chard et al., 2023). Some observers predict that eventually one technology is likely to become dominant, but until then, funders, policymakers, transit agencies, and even some market players are maintaining neutrality and hedging their bets. This strategy may protect against significant downsides of choosing a "losing" technology that becomes obsolete, but also creates challenges in collaboration and interoperability across fleets, and additional costs in procurement, training, maintaining spare parts inventories, and installing infrastructure for two technology types. The presence of two potential choices may even slow progress towards technological improvement if the (relatively small) transit industry must motivate further development and refinement of two different technologies.

Operational Challenge 2: Missing ZEB Models

Transit agencies have urgent needs for ZEBs with certain specifications that are not currently being met by the market.

Not all types of transit vehicles are currently available in zero-emission models for purchase. Stakeholders in the zero-emission transition are keenly aware that advancing new vehicle types, or vehicles with certain key specifications, to market is likely to be a slow and expensive process. This process requires developing, testing, and commissioning new technologies that are perceived to be on the "bleeding edge" of technology. Three key gaps in vehicle availability include the following:

- Cutaways: Numerous stakeholders, particularly smaller transit agencies, want to raise awareness of the existential problem posed by the lack of zero-emission cutaways on the market (particularly FCEBs, which are lagging further behind BEB cutaways). Transit agencies are particularly concerned about the uncertainty in cost, range, performance, and timing of availability and full testing for these vehicles (Morongo Basin Transit Authority, 2023; Schwartz, 2022; SunLine Transit Agency, 2020; Napa Valley Transportation Authority, 2023). These vehicles provide critical services, including paratransit and demand-response; for some agencies, cutaways are the only vehicles they operate. Note that the fragmentation of the cutaway market among smaller manufacturers and the lower reporting requirements for small and rural transit agencies limit visibility into the precise nature of the current market and challenges to meet demand.

- Over-the-road coaches: A subset of transit agencies require access to larger, longer-range coach-style buses, particularly to meet the needs of long, intercity routes. These routes provide key mobility services and potential reductions in vehicle miles traveled, but vehicle range and lack of availability of FCEBs in an over-the-road coach model are proving to be key barriers to deployment. For example, StanRTA (serving Modesto, California and Stanislaus County) notes that it will need motorcoaches that can guarantee over 250 miles on a single charge or tank; they are currently anticipating that they will not be able to deploy these vehicles until 2029 at the earliest (Stanislaus Regional Transit Authority, 2023).

- Longer-range ZEBs (particularly BEBs): Range anxiety is perhaps the most frequently mentioned operational challenge for ZEB deployers. Many transit agencies have service blocks that exceed the currently stated BEB ranges, requiring vehicles that can travel 150–200 miles with a single "tank" to avoid re-blocking service or procuring additional vehicles. For these reasons, procuring ZEBs with reliably longer ranges is likely a top priority for many transit agencies.

Operational Challenge 3: Lack of Operational Data

Transit agencies do not have the benefit of long-term, context-specific operational data to plan and make key decisions.

Despite well-structured and laudable efforts, such as NREL deployment evaluations and the AC Transit Five by Five study and follow-on progress reports (AC Transit, 2024), most transit agencies see the lack of reliable, long-term, large-scale data on ZEB performance as a persistent issue. For example, many agencies note that the projected ranges offered by manufacturers are unreliable in their view, as real-life conditions (such as cold, heat, heavy loads, hilly routes, or suboptimal driving technique) can significantly impact range (Yolo County Transportation District, 2023). This view is reinforced by NREL, who notes that BEB energy efficiency is sensitive to external factors ranging from heating and air conditioning loads to topography, and by TCRP, who advises in no uncertain terms that transit agencies cannot conduct route modeling only based on OEM energy efficiency and range estimates, as these are based only on ideal operating conditions and may not reflect the real-world demands of transit service (Linscott & Posner, 2021).

In addition to fuel efficiency and vehicle range, some transit agencies mention specific acute data needs that require further long-term evaluation. These topics include likely progressions of battery degradation over time, accuracy of state of charge measurements, mid-life refurbishment and replacement needs, and accurate comparisons of maintenance costs per mile. To make matters more complicated, as noted by TCRP, "…the capabilities and performance of an older ZEB model may have no bearing on how today's technology will perform in your service area," making the collection of accurate, long-term data applicable to a new deployment extremely difficult (Linscott & Posner, 2021, p. 21).

Transit agencies see these data needs as critical because they require large quantities of accurate and context-appropriate data to optimally (and cost-efficiently) manage a full ZEB fleet. For example, agencies and their consultants and advisors need accurate information to inform scheduling and routing, analyze the costs and benefits of technology purchases, inform driver and maintenance behavior, manage charging and fueling, and more. As one specific example of the key role of high-quality information, many transit agencies cite range decreases of 10–20% if a ZEB is driven ineffectively; the Center for Transportation and the Environment cites differences over 25%

(Linscott & Posner, 2021). This represents an incredibly large margin given the challenges with achieving sufficient range and managing fuel costs.

Operational Challenge 4: Rapid Technological Evolution

Relatively rapid evolution of zero-emission vehicle technologies and market offerings is challenging for transit agencies to manage.

Some experts in the ZEB field express the view that technological change in ZEBs is not likely to be particularly disruptive in the coming years due to the already widespread adoption of key norms and standards (e.g., uniform charging protocols). However, many transit agencies still view ZEBs as fast-changing. While the level of change may not be entirely unprecedented—as some agencies note, they have successfully adapted to new technology before, from compressed natural gas-fueled buses to use of significant on-board computers and technology—it is true that newer and changing technologies do present specific and novel risks to be managed.

For ZEBs, as mentioned above in the discussion of technology choice, a fear of technological obsolescence during the relatively long lifetime of a transit bus (12+ years for a full-size bus) is particularly salient. Transit agencies including Basin Transit, Placer County, and Needles Area Transit specifically noted the likelihood that technology will improve, which they perceive as both an opportunity but also a risk that they could invest in a current generation of ZEB technology which will soon be outdated (Morongo Basin Transit Authority, 2023; Placer County Department of Public Works, 2023; Needles Area Transit, 2023). In addition to the chance that they could miss out on the opportunity to deploy better or cheaper technology in the near future, some agencies also mention the more challenging risk that their buses could become difficult or impossible to procure spare parts for, or become unsupported by manufacturers, during the minimum useful life period during which they could not easily dispose of the vehicle.

In addition to these risks of obsolescence, many agencies draw attention to the significant investment of time and the potential need to engage expert help to stay up-to-date on technology options and best practices. Undertaking the recommended deployment process for the still-maturing ZEB industry and researching all currently available technologies and resources available at the federal, state, and local level can be an intensive activity for transit agencies. This challenge is closely related to capacity, knowledge, and workforce challenges addressed in detail later in this section.

Operational Challenge 5: Difficulty Scaling Up

Many transit agencies see challenges to full ZEB scaling and deployment beyond the pilot phase.

Agencies nearly uniformly expect to experience growing pains when moving from pilot-scale deployments to a full fleet transition. While in a pilot phase there may be capacity to absorb an unfamiliar maintenance problem, the ability to only run ZEBs on "easy" routes that are well-suited to ZEB capabilities, or the ability to use only newer ZEBs, new problems will arise after transit agencies have achieved a successful initial deployment. It has been previously recognized that large-scale deployments (consisting of 50 or more buses) are necessary to fully understand the technical and operational challenges of full fleet transitions (Center for Transportation and the Environment, 2021). Of course, at a national and international level, numerous deployments of this scale have been completed that transit agencies can learn from. However, it is important to note that transit agencies are extremely diverse in terms of routes, duty cycles, topography, weather, customer needs, employees' needs and preferences, legacy technology and practices, and more. Small transit agencies note that it is especially challenging to seamlessly translate the deployment experience of, for example, a large, urban, technologically sophisticated agency, to a small, rural one.

One key element of diversity between transit agencies that many feel is underappreciated is the role of organizational readiness, and particularly, the importance of a ZEB transition "champion" or leader (Bailey et al., 2020). While many agencies are extremely committed to zero-emission transition goals, they note that the experience of some early adopters is likely heavily influenced by the presence of a well-informed, enthusiastic champion—a characteristic that is difficult to create artificially. More broadly, the attitudes and beliefs of transit customers, local stakeholders, and transit agency staff can be more difficult to quantify than average local temperatures or route intensity, but no less important for the success of full ZEB adoption.

Finally, many agencies are acutely aware that their path to scaling up to a fully ZEB fleet will be an extremely long one. While a slow transition gives agencies time to learn and adapt, they will need to function in an environment of continuous change for a long period of time. During this transition period—which could easily be a decade or more—many agencies will be functioning using two or more fuel types, many different types of vehicles, and with staff who have varying levels of ZEB expertise. The potential challenges, from securing spare parts to ensuring continuous staff training, during this long transition period should not be overlooked (Pejcic et al., 2019).

Operational Challenge 6: Extensive Operational Changes

Deploying ZEBs is not a "plug and play" exercise, requiring sometimes dramatic changes in operations.

Transit agencies consistently call attention to the fact that their primary organizational mission—to provide transit service—necessitates maintaining a close focus on user experience, providing reliable service, and serving their communities. Because of the consistent focus on outcomes for users, transit agencies must carefully consider how the transition to ZEBs impacts every facet of their operations.

A primary concern during operations is vehicle reliability and operational capabilities. As discussed in previous sections, most stakeholders recognize the important role of vehicle range and the phenomenon of "range anxiety". Naturally, the need to replace ICE buses on a greater than 1:1

basis with ZEBs, to shorten routes, or require new operational practices to monitor state of charge or fueling status could be challenging for transit agencies. These changes can have implications in cost, scheduling, staffing needs, space requirements for additional vehicles, and more. Beyond range, stakeholders still express real concerns about ZEBs' reliability. These concerns are not unfounded; according to NREL, reliability for ZEBs (as measured by miles between road calls) is not yet on par with conventional ICE buses (Jeffers, Kelly et al., 2022). If buses are going out of service or requiring maintenance more frequently, agencies may struggle to maintain the 85% minimum level of availability that can be supported with an FTA-required 20% spare ratio (Jeffers, Kelly et al., 2022).[14]

At a more granular level, many interviewees note the day-to-day differences in ZEB maintenance that will need to be incorporated into their plans and procedures. For example, maintenance routines associated with fluids and filters for the propulsion system will change or be eliminated, it will become less common to reline brakes, and battery health and state of charge will need to be verified near-constantly (Pejcic et al., 2019). Conducting maintenance on this new equipment will also require securing consistent access to spare parts, about which many stakeholders express hesitation given recent supply chain challenges and delays. Anecdotally, many transit agencies describe being forced to take ZEBs out of service for many months due to maintenance problems, a lack of access to key parts, or insufficient support from vendors, an extremely concerning situation for deploying agencies. The importance of a well-developed supply chain for replacement parts and after-market support has also been identified as a key finding from the Low Carbon Vehicle Partnership in its studies of multiple ZEB deployments in the UK (Bailey et al., 2020).

As mentioned in the previous section on transition and scaling challenges, many agencies point specifically to challenges during the long transition period in which multiple technologies will likely be in use. During this time, many agencies will face space constraints for vehicle storage and fueling, and will be managing novel and complex on-site processes including construction, testing, and training, and more. As noted by Placer County, California, in its ICT transition plan, managing all these simultaneous and connected processes introduces significant risk to their transition program, as an issue in one transition plan component could have cascading impacts on other components (Placer County Department of Public Works, 2023).

Finally, although resilience is not a new operational challenge, many stakeholders are discussing the novel resilience challenges associated with ZEBs. For example, the City of Glendora noted that a power outage (relatively common in their area due to wildfire risk and excess energy use during heat waves) could mean that an agency was unable to provide critical transportation services (Schwartz, 2022). This sentiment is reinforced by the Shasta Regional Transportation Agency, who is subject to Public Safety Power Shutoffs and wildfires (Shasta Regional Transportation

[14] The FTA Rolling Stock Spare Ratio Policy is only specifically fixed to 20% of the number of vehicles operated in maximum fixed-route service for operators of 50 or more fixed-route revenue vehicles; for smaller operators, no specific limit is set, but the number of spare vehicles is expected to be reasonable (Federal Transit Administration, n.d.).

Agency, 2022). These agencies, among many others, are carefully considering the different and sometimes challenging proposition of electricity-dependent vehicles in this context. Given the diversity of transit agencies' local contexts, other resilience challenges could include the functioning of vehicles during extreme heat or cold, access to fuel for remote or isolated agencies, access to reliable vehicles for emergency activities such as evacuations, and more.

3.4 Capacity, Knowledge, and Workforce Challenges

The characteristics of transit agencies and other key stakeholders—specifically, their skills, resources, and capacity—are a key determinant of ZEB deployment success. Specific challenges related to this topic are highlighted below.

Capacity Challenge 1: Cross-Sector Coordination

The ZEB transition is inherently multi-sectoral and interdisciplinary, but information sharing and coordination can be difficult across many different stakeholders.

The ZEB transition involves not just public transit or transportation, but also energy, education, economic development, and more. It is also greatly impacted by policy, regulations, and resources from state, local, and federal governmental entities, private industry, not-for-profits, research entities, and educational institutions. This complexity requires significant coordination and knowledge sharing, but few robust, cross-sectoral channels exist. Stakeholders interviewed identified coordination challenges among funders at all levels of government that can lead to misaligned timelines and requirements, some level of duplication but also gaps, and significant work for agencies to apply for and manage funding through many different processes. As noted in Smyth et al. (2020), grant application timelines are typically spread throughout the year, a fact that greatly complicates transit agencies' application efforts given the need to plan for procurement to get accurate pricing, specifications for infrastructure, and more. This issue also extends beyond funding. For example, many transit agencies feel burdened by numerous and sometimes duplicative data requests from various partners and agencies related to their transitions. From the outside, some transit agencies' view is that relevant agencies are not necessarily working together, and there is no central entity coordinating this complex transition and collecting and disseminating relevant data about transit fleets and their ZEB transitions.

Similarly, many transit agencies do not see clear paths to coordinating with other non-transit stakeholders—for example, other public and private fleets in their region, or local energy producers—with whom collaboration and information sharing could be highly beneficial but is well outside these organizations' typical planning and project execution processes. Although some transit and transportation planning is done regionally, most required zero-emission transition planning is being conducted at an individual agency level. Some stakeholders identify this as a potential challenge—or at least, a missed opportunity—given the eventual need for not only individual ZEB deployment projects, but a functioning, interconnected zero-emission transportation network.

Capacity Challenge 2: Workforce Development and Training

Significant support is needed to develop and train a well-equipped workforce for the ZEB future.

The ZEB transition requires a skilled workforce on many fronts, ranging from ZEB operators to maintenance staff for vehicles and infrastructure, to trained emergency response personnel, to workers focused on automation and sophisticated manufacturing for ZEB components. Stakeholders recognize that ZEBs are both relatively new and technologically sophisticated and developing this workforce will require a mix of both attracting and retaining new workers (Metropolitan Atlanta Rapid Transit Authority, 2024). This challenge is overlaid on existing transit and manufacturing workforce pressures, which Humboldt Transit Authority describes as a long-term challenge to recruit and retain young and qualified workers to transit, particularly in rural areas (Humboldt Transit Authority, 2023). Public transit generally has problems with retaining workers. Interviewees emphasized that their inability to offer salaries competitive with other industries and a perceived lack of prestige for public transit occupations result in high turnover. Drivers and technicians can also be recruited by private sector fleets that can offer higher compensation, better benefits, or a more relaxed schedule.

Many stakeholders in the ZEB transition describe the current training system as a patchwork. Vehicle OEMs provide high-level vehicle training but are not set up to deliver ongoing training for more sophisticated operational and maintenance issues, train new employees as they join the organization, and offer ongoing workforce development. According to the FTA, workforce development efforts "lack coordination and consistent supporting resources," and require continuing support to coordinate still-evolving requirements, curriculum, and training tools (Center for Transportation and the Environment, 2021, p. 20). This sentiment is echoed by one of the undisputed pioneers in the zero-emission transition, Sunline Transit, who continuously advocates for greater funding for and focus on workforce training (SunLine Transit Agency, 2020). Crucially, when discussing workforce development and training, stakeholders emphasize that the role of organized labor and unions is key, and that developing collaborative working relationships focused on common goals would be beneficial.

Capacity Challenge 3: Lack of Knowledge and Resources

Most transit agencies lack capacity in terms of technical knowledge, staff and funding required for a successful transition.

Perhaps the most common uniting theme among stakeholders and transit agencies is concerns about a lack of capacity and resources to ensure a successful ZEB transition. Agencies recognize that the transition will be time- and resource-intensive, and some—especially small agencies—are concerned about their ability to conduct complex planning and modeling, make optimal procurement and project development decisions, and deploy sophisticated new technologies.

Extensive study is required for most transit agencies to determine their plans around developing ZEB infrastructure and facilities. Meanwhile, as discussed previously, transit agencies are also seeing very long timelines from the moment the purchase order is issued to ZEBs being delivered on their lots. Aligning the timelines of ZEB procurements with the planning and project development for infrastructure and facilities, while maintaining flexibility to adapt to delays, cost increases and other unforeseen challenges, is no trivial matter even for experienced and well-resourced teams and their consultants. As ZEB technology continues to slowly but steadily evolve, transit agencies must also weigh whether to wait for a ZEB with the promise of longer range and/or more reliable performance against other considerations, including the risk of cost increases or longer lead times in the future.

This final challenge reflects a blend of all those mentioned above including high costs, a quickly-changing market, navigating regulations and policy, making optimal technology choices, accessing sufficient data, disruptive changes in technology, new operational requirements, and workforce and training gaps.

3.5 Linking Challenges, Solutions, and Outcomes

The following graphics present a visual summary of the observed challenges identified in this section and the proposed solutions that aim to address these challenges (discussed in the following section). The diagrams illustrate the flow from the initial challenges through the specific problems they cause, leading to the solutions that can mitigate these issues, and finally, the outcomes that these solutions aim to achieve.

Each graphic is organized into four main sections:

- Challenges: The broad categories of difficulties faced by stakeholders in the ZEB transition.
- Problems: Specific issues or barriers within each challenge category that hinder progress.
- Proposed Solutions: The targeted actions or strategies designed to overcome the identified problems.
- Outcomes: The desired results or benefits that should emerge from successfully implementing the proposed solutions.

These graphics are intended to serve as a quick-reference tool to understand how proposed interventions can address existing barriers in the ZEB transition.

Figure 2. Cost Challenges

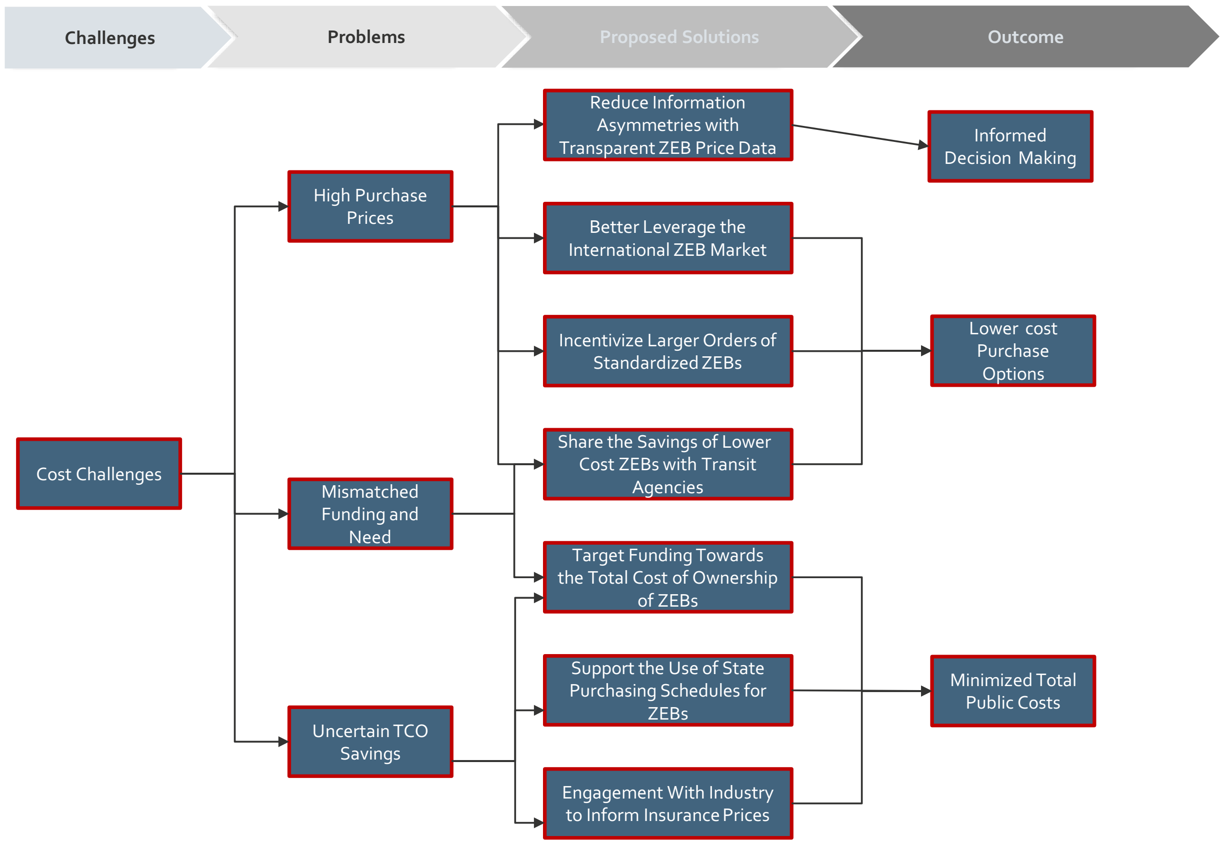


Figure 3. Market and Supply Challenges

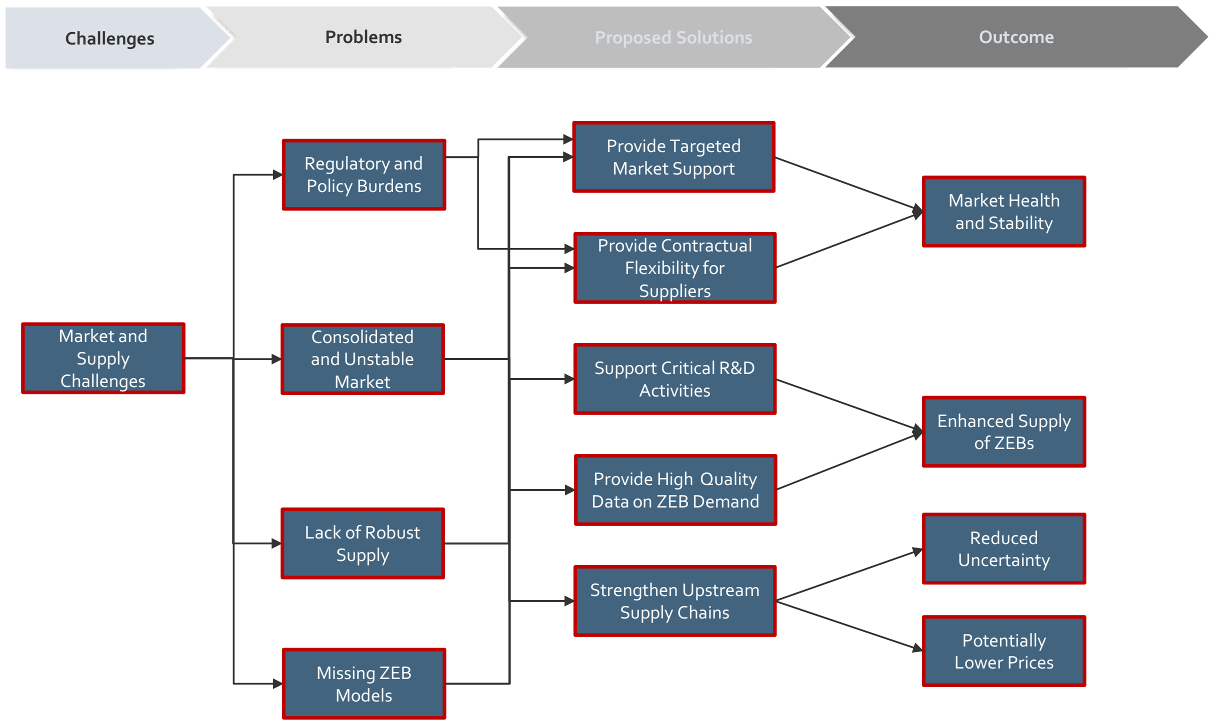


Figure 4. Operational Performance and Technology Challenges

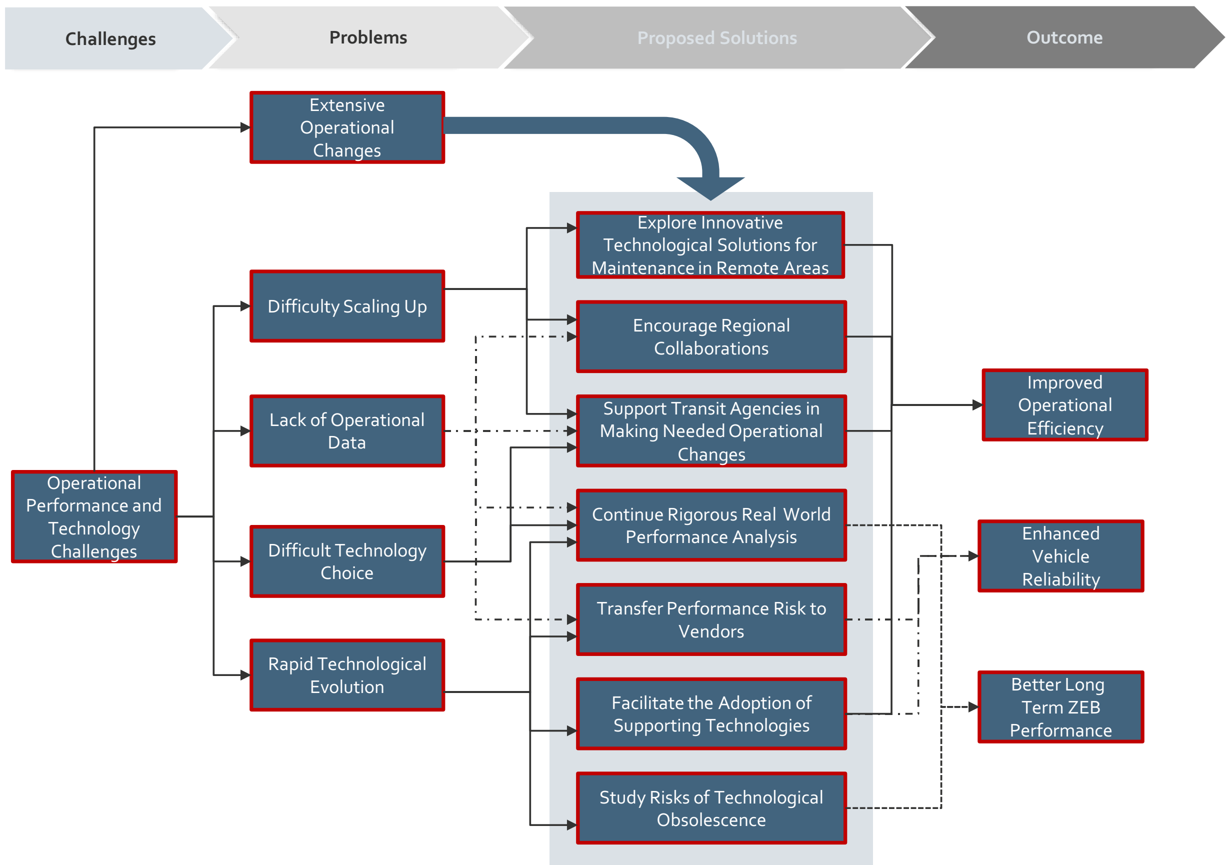
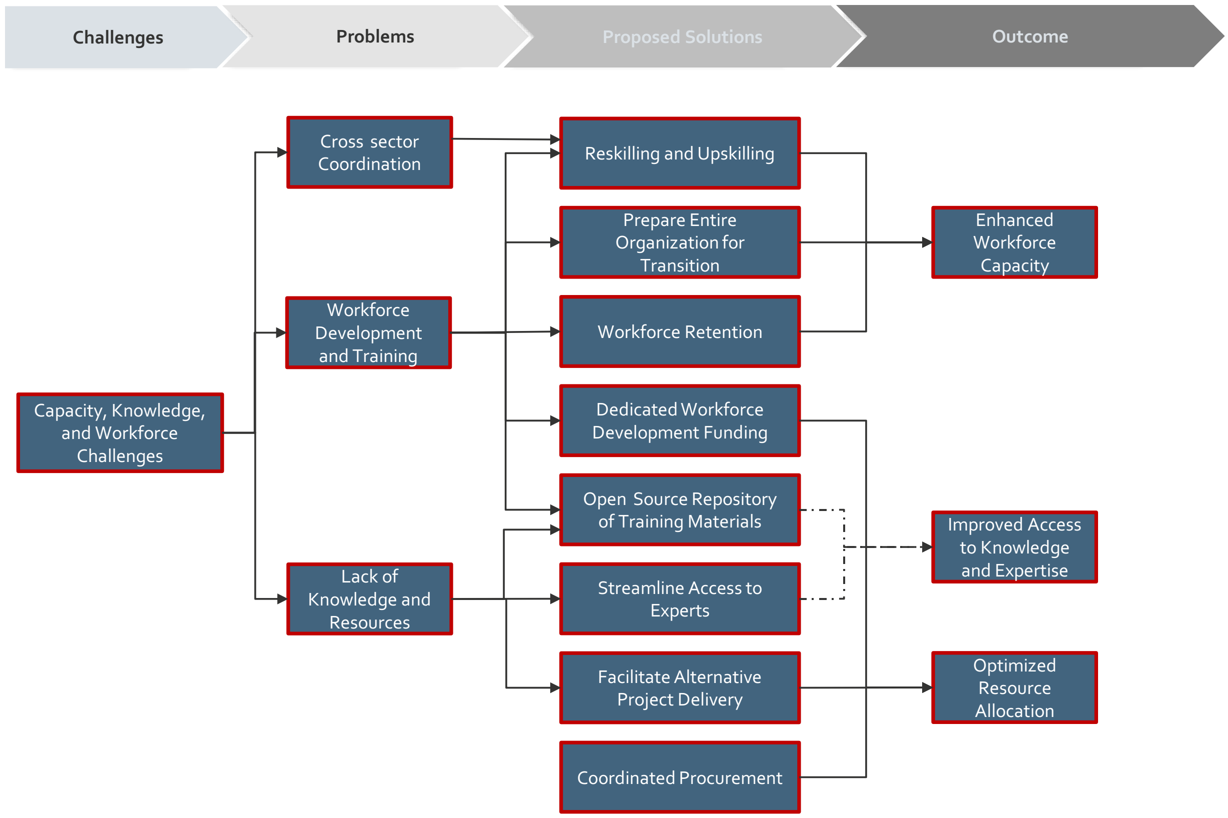


Figure 5. Capacity, Knowledge and Workforce Challenges



4. Potential Solutions to Zero-Emission Bus Transition Challenges

Through stakeholder interviews, a literature review, and analysis performed by the investigator team, potential solutions have been identified to mitigate the challenges described in Section 3 across the same four categories. The solutions are meant to be practical and realizable and are targeted toward a mix of federal, state, and local policymakers, as well as transit agency practitioners. These potential solutions are summarized in this section.

4.1 Solutions to Cost Challenges

Better Leverage the International ZEB Market

Related Challenges: High Purchase Prices | Consolidated and Unstable Market | Lack of Robust Supply | Regulatory and Policy Burdens

Analysis of the US ZEB market in this report and elsewhere raises difficult questions about whether the current market structure can facilitate robust competition, efficient production, and affordable pricing. Both expert opinion and observations of international markets point towards the lack of access to a wider market of international ZEB suppliers as a key challenge for US transit agencies. Recognizing that multiple policy goals must be balanced—including not only the efficient use of public funds and rapid transportation decarbonization but also promotion of US manufacturing interests—policymakers should investigate ways to better leverage the scale, efficiency, and cost benefits for transit agencies of accessing the international ZEB market. Most crucially, this would require revisiting the way in which Buy America rules are applied to ZEBs, while also investigating other potential barriers for transit agencies to take advantage of lower-cost purchase options. This action would not be without precedent; in 2022, for example, the FTA granted a partial, temporary Buy America waiver for vans and minivans based on the rationale that no Buy America-compliant options were available on the market. This waiver was facilitated by existing FTA policy, which allows waivers if the application of Buy America would either be inconsistent with the public interest, if the product is unavailable, or if a compliant purchase would increase the cost of rolling stock by more than 25% (Wanek-Libman, 2023; Federal Transit Administration, 2022).

Share the Savings of Lower-Cost ZEBs with Transit Agencies

Related Challenges: High Purchase Prices | Mismatched Funding and Need

The observation that financially constrained transit agencies are not displaying price-sensitive behavior in their ZEB purchases can be traced back to the incentives set up by existing funding programs. Currently, with the large majority of capital costs for a ZEB typically covered by discretionary funding sources, transit agencies have little incentive to seek out or select lower-cost options; nearly all savings will go to the funder, rather than the agency itself. While transit agencies are typically very good stewards of public funds, this structure leads them to optimize for their operational needs and preferences rather than lower costs, even when a different tradeoff might be more efficient. In order to better align incentives to bring down ZEB costs, funders—most importantly, the FTA—could allow transit agencies to share in the savings of purchasing lower-cost buses. This solution, which could be implemented in many different ways, could help combat vendor lock-in, further encourage standardization, and ensure that OEMs receive a clear market signal that encourages them to offer lower-cost options.

Incentivize Larger Orders of Standardized ZEBs

Related Challenges: High Purchase Prices | Rapid Technological Evolution | Lack of Knowledge and Resources

Current evidence indicates that scale alone—indicated both by the annual number of ZEBs purchased in the US market and the average number of vehicles per order—cannot bring ZEB prices to or below price parity with ICE vehicles. Nevertheless, moving towards larger orders of standardized ZEBs could lessen current cost and operational challenges. Uniting around shared ZEB specifications could enable manufacturers to produce vehicles more efficiently, reduce the labor and other costs associated with customization, and greatly simplify the resource-intensive process of developing detailed specifications and procuring ZEBs in line with those specifications. Understanding that moving towards more standardized vehicles can represent a tradeoff for transit agencies that may otherwise prefer to choose the features and configurations that their agency prefers, agencies may require a change in incentives to encourage them to move in this direction. These incentives could include funding bonuses, preferential consideration for funding (similar to the way FTA currently gives priority consideration in funding applications that use a joint procurement with at least three agencies), and a common specification in order to reduce customization (Wiard-Bauer & Lange, 2024). In addition to this change in incentives, policymakers would need to provide up-to-date, technically sophisticated, consensus specifications for transit agencies to use.

Reduce Information Asymmetries with Transparent ZEB Price Data

Related Challenges: High Purchase Prices | Consolidated and Unstable Market | Difficult Technology Choice | Lack of Knowledge and Resources

To support transit agencies and policymakers in making optimal decisions about ZEB purchase decisions, policymakers could focus on reducing information asymmetries by facilitating the provision of transparent cost and pricing data. This data could inform decisions on the costs of customizations, add-ons, and additional services, such as extended warranties, the tradeoffs inherent in standardization, and key cost drivers. To be useful, data would need to be sufficiently fine-grained and updated regularly, allowing stakeholders to understand relatively rapid changes in prices and the drivers of price differences. Even though ZEBs are purchased with public funds, detailed price information and the purchase orders and contracts associated with these purchases are often not publicly available, let alone aggregated for price comparison. One interim step towards greater transparency would be making FTA grant applications—particularly for the Low- or No-Emission Bus and competitive Bus and Bus Facilities program—publicly available online (Transportation for America, 2023). The current dearth of timely, accurate price information as a tool for transit agencies and policymakers prevents them from acting as informed consumers and puts these entities, which represent the public interest, at a disadvantage when purchasing from and negotiating with well-informed market players.

Target Funding Towards the Total Cost of Ownership of ZEBs

Related Challenges: Uncertain TCO Savings | Mismatched Funding and Need | Lack of Knowledge and Resources

Despite being positioned as trailblazers for the medium- and heavy-duty zero-emission transportation transition in the United States (particularly in key sub-markets such as California), transit agencies are inherently limited in their ability to reliably fund their ZEB transitions and manage the associated financial risks. While the high up-front capital costs of ZEBs have been widely discussed, US transit agencies call attention to the urgent need for support in managing uncertain ZEB operating costs. To address this issue, discretionary funding programs at the federal and state level could take a more holistic approach to funding the total cost of ownership of ZEBs, rather than almost exclusively funding up-front purchase costs. In the long term, some evidence shows that TCO for BEBs can be lower than for ICE vehicles when external costs such as air quality, noise, and greenhouse gas emissions are accounted for, such as in the case of an eight-year study of a deployment in Delft, Netherlands (Mathieu, 2018). The prospect of cost parity (or decreases) is currently much more remote for FCEBs and, for both technologies, is still largely theoretical. However, putting the focus on TCO for either technology would align incentives to reduce the total public costs of the ZEB transition, rather than focusing on the limited perspective of either the capital costs or the operational costs.

Ensuring that transit agencies have sufficient support not only to purchase but also to operate ZEBs could lessen the downside risk of higher-than-expected operating costs, which for transit agencies with minimal financial cushion could mean taking actions such as cutting transit service—a severe consequence for both transit-dependent communities and potential transit riders who might be dissuaded from increasing their transit use that could otherwise support emissions reduction goals. If policymakers accept the premise that TCO may be lower for ZEBs on average, but not necessarily for any given ZEB or transit agency, they may consider policy and funding ideas that would effectively "pool" the risk of TCO across transit agencies to limit the downside risk for any individual agency. The most familiar example of this mechanism is the way insurance functions to pool the cost risk of adverse events across many individuals. An entity such as the FTA could effectively play this role for the TCO cost risk of the ZEB transition, ensuring that any individual transit agency's risk of higher total costs is limited, but that collectively, the public can benefit from TCO savings.

Support the Use of State Purchasing Schedules for ZEBs

Related Challenges: Uncertain TCO Savings | Regulatory and Policy Burdens | Lack of Knowledge and Resources

One of the notable "soft" costs of transition is the cost of writing specifications for and procuring ZEBs and related goods and services. One well-known solution to this problem is transit agencies' ability to buy ZEBs off state purchasing schedules, removing the requirement for transit agencies to conduct a competitive procurement at all. While state purchasing schedules are imperfect—still, for example, facilitating extensive customization, and sometimes failing to adapt quickly enough to market conditions, available technology options, and market prices—they are often considered a best practice for efficient procurement (Schnader & Hamilton, 2020; Plotnick & Peirce, 2021). Alternatively, some stakeholders advocate for cooperative purchasing among transit agencies through organizations such as Sourcewell or the CALACT Purchasing Cooperative (Smyth, 2020; California Association for Coordinated Transportation, n.d.). This mechanism does not require explicit action by a state entity (unlike the state action required to establish a state purchasing schedule initially). However, it does have certain limitations, such as the requirement that the quantity of items being purchased be identified—a requirement that does not apply to state purchasing schedules (Symth, 2020). Please see Section 2 for further detail on these procurement methods. These methods should be encouraged and improved where possible, such as through market-responsive, technologically informed updates to the schedules (e.g., mechanisms for contract amendments in the case of new products coming on the market) as needed.

Engagement With Industry to Inform Insurance Prices

Related Challenges: Uncertain TCO Savings | Rapid Technological Evolution | Cross-Sector Coordination | Lack of Knowledge and Resources

Although comparatively smaller than other ZEB costs, such as vehicle purchase and fuel, the phenomenon of higher insurance costs for ZEBs may be worthy of further investigation. Although the fact will remain that insuring more expensive vehicles will be more costly, some stakeholders believe that observed insurance costs for ZEBs are also due to insurers' uncertainty and perceived risk. For example, while both hydrogen and diesel are both highly combustible, hydrogen may be perceived as riskier, and insurance for FCEBs may be priced accordingly. To ensure that insurance costs are as fair as possible, policymakers could consider initiating greater engagement and data sharing with the insurance industry to explore ways to reduce insurance costs.

4.2 Solutions to Market and Supply Challenges

Provide Targeted Market Support

Related Challenges: Consolidated and Unstable Market | Lack of Robust Supply | Regulatory and Policy Burdens

Policymakers often provide support to key industries to enhance market stability, attract new market entrants to increase supply and competition, and potentially allow firms to increase scale and efficiency in order to decrease costs and better meet market demand. Recent examples range from manufacturing incentives to bolster the domestic semiconductor industry via the CHIPS and Science Act and federal tax credits for investment in and production of solar energy (The White House, 2022; United States Department of Energy Office of Energy Efficiency and Renewable Energy Solar Energy Technologies Office, n.d.). While specific mechanisms and amounts of support should be carefully designed to ensure that they optimally meet the industry's needs and minimize negative market distortions, many tools are available. Among the most common are subsidies provided through the state or federal tax code (e.g., tax credits for certain eligible activities).

Other mechanisms of support for the US ZEB market could include support in navigating procurement and contracting, supporting workforce development activities, or programs to help project sponsors efficiently navigate permitting and utility hookups for physical facilities. Policymakers could investigate the specific challenges for upstream component suppliers, such as regulatory mandates, difficulty accessing key materials or labor, lack of sufficient transportation options, coordination and information-sharing challenges, and more. Depending on the nature of the specific industry needs, policymakers could deploy tools including but not limited to coordination support, incentives, low-cost financing, and more. A more robust supply chain for key ZEB components—which OEMs clearly state is primarily out of their control—could reduce uncertainty, smooth logistical hurdles, and potentially decrease prices.

Provide Contractual Flexibility for Suppliers

Related Challenges: Consolidated and Unstable Market | Lack of Robust Supply | Regulatory and Policy Burdens

Recent market engagement in the wake of US ZEB market tumult by key national transit actors including FTA, APTA, and the White House, highlighted immediate challenges for ZEB market players in an uncertain and inflationary environment (The White House, 2024). As recommended by these organizations, policymakers should provide needed flexibility to adapt contractual requirements—particularly the timing and inflation of payments—to provide further stability for the industry. At the same time, however, policymakers should interrogate the root causes of these challenges to understand why both customers and suppliers are struggling to thrive in the current marketplace.

Support Critical R&D Activities

Related Challenges: Consolidated and Unstable Market | Lack of Robust Supply | Missing ZEB Models | Rapid Technological Evolution | Cross-Sector Coordination

A key function for the public sector is to support activities that provide a public benefit but do not have a sufficiently compelling expected return on investment to encourage private sector action. Research and development (R&D) is a key subset of these targeted market support activities, in addition to those mentioned above. For example, public entities like the Advanced Research Projects Agency—Energy (ARPA-E) advances promising energy technologies that are too early in their development for private sector investment (ARPA-E, n.d.). In the ZEB context, R&D investment is urgently needed in multiple areas, including development and full commercialization of specialized zero-emission transit vehicles such as fuel cell electric bus cutaways and over-the-road coaches, and improvements in ZEB range and reliability. Particularly for activities that, in the near term, will primarily benefit the relatively small and less lucrative transit industry, incentives are not well-aligned with a robust R&D pipeline. To address this challenge, policymakers could make R&D investments in strategic areas like those mentioned above, either directly or indirectly, and claim greater agency over crucial technological advancements that their policy goals rely on. There are existing examples of this type of public investment in ZEB R&D. For example, the FTA-funded National Fuel Cell Bus Program developed and demonstrated early FCEBs for transit (Naylor, 2022). These actions would benefit not only transit, but also other sectors that will benefit from reliable and affordable zero-emission technologies.

Provide High-Quality Data on ZEB Demand

Related Challenges: Consolidated and Unstable Market | Lack of Robust Supply | Missing ZEB Models

In order to ensure that the supply of ZEBs meets the demand for ZEBs, a functioning market requires high-quality and timely flows of information. Although the legacy transit bus suppliers likely have a relatively clear picture of transit agencies' needs, gaps in this information, or a lack of widely available insights for other potential market participants, may contribute to potential market failures. As such, policymakers could endeavor to facilitate data collection and provision to ensure that industry has a clear picture of transit agencies' demand for ZEBs in terms of number of vehicles and timing of future purchases. This solution may be particularly important for sub-sectors such as cutaways and over-the-road coaches that are currently supplied by smaller, lower-resource firms that may not always understand the magnitude and specifics of demand for zero-emission vehicles.

4.3 Solutions to Operational Performance and Technology Challenges

Encourage Regional Collaborations

Related Challenges: Lack of Operational Data | Difficulty Scaling Up | Extensive Operational Changes | Workforce Development and Training | Lack of Knowledge and Resources

Transit agencies typically function as standalone entities with independent planning, purchasing, operational practices, and more. However, given the scale of the ZEB transition challenge relative to the size and resources available to a single transit agency, planning and executing a successful ZEB transition for every transit agency separately may be inefficient. Although many elements of autonomy can and will remain, policymakers could consider incentivizing and facilitating regional coordination among transit agencies to ease the challenge of the ZEB transition. In particular, working collaboratively on planning, procurement, workforce development and training, sharing information in a standardized manner, and developing large-scale infrastructure projects may be beneficial. An emerging strategy being explored to optimize maintenance processes and reduce operating costs and downtime for ZEBs is for multiple transit agencies in a region to coordinate around procuring the same ZEB make and model. The expectation is that a more uniform fleet will create efficiencies and economies of scale for spare parts, workforce training, and other aspects of maintaining the ZEB fleet. In practice, this often is difficult to implement due to timing constraints as well as transit agencies' preference for an incumbent supplier and/or certain custom configurations.

While some regional coordination within transit does exist, usually on an ad hoc basis, policymakers could encourage these activities by providing financial, coordination, and technical assistance resources. These ideas have been explored in more detail for some groups of transit agencies, such as the Northern Virginia Transportation Authority—an organization coordinating and representing numerous agencies—through its NoVa ZEB Strategic Plan (Northern Virginia Transportation Commission, 2024). These novel opportunities could be further explored and expanded in additional clusters of transit agencies throughout the country.

Transfer Performance Risk to Vendors

Related Challenges: Lack of Operational Data | Rapid Technological Evolution | Extensive Operational Changes | Lack of Knowledge and Resources

As discussed earlier in this report, the risks of the ZEB transition for a transit agency may include worse-than-expected performance in key areas such as range or distance between roadcalls, risks that issues cannot quickly and affordably be resolved, risks that technology could change or become obsolete, and more. While these risks are also relevant for ICE vehicles, a lack of data and less mature technology make them substantially more acute for ZEBs. One potential solution to this challenge would be to transfer greater responsibility for these key risks to vendors and manufacturers, rather than asking transit agencies to bear these risks. This concept would leverage the idea that vendors and manufacturers are in a much better position to accurately understand and influence the risk that their products do not perform as expected. This risk transfer can be accomplished through contractual terms such as service-level agreements, more often utilized for charging infrastructure equipment, but sometimes applied to vehicles as well (Bailey et al., 2020; Van Hool, 2022; Electric School Bus Initiative, 2023).

Other options for transferring risk may include extended warranties or contractual performance guarantees. Effectively, these mechanisms would require a vendor to accurately price and manage performance risks. An alternative solution that is currently available to transit agencies, although not widely utilized, is capital leasing of vehicles and other equipment (Plotnick & Peirce, 2021). In broad terms, leasing rather than owning a vehicle obligates the lessor to take responsibility for the vehicle's performance. It is important to note that this risk transfer will not be costless; policymakers should seek to ensure that the pricing for any form of performance guarantee is fair, that the competitive and market implications of such a requirement are carefully considered, and that performance guarantees are realistic in the context of a relatively unstable market.

Explore Innovative Technological Solutions for Maintenance in Remote Areas

Related Challenges: Difficulty Scaling Up | Extensive Operational Changes | Workforce Development and Training | Lack of Knowledge and Resources

For agencies in remote or rural areas, receiving a high level of quality support from the relatively small number of ZEB professionals that exist nationally in a reasonable amount of time will be very challenging. One potential solution to address the needs of these agencies, in addition to local workforce development and training solutions discussed later in this section, is exploring the use of virtual or remote resources for maintenance and troubleshooting. For example, a maintenance technician could connect with a ZEB maintenance expert remotely, allowing them to work together to solve common issues from afar. By providing the needed technology and coordinating the demonstration of this model, policymakers could effectively explore how best to support geographically remote agencies during the critical phases of their transitions.

Support Transit Agencies in Making Needed Operational Changes

Related Challenges: Difficult Technology Choice | Lack of Operational Data | Difficulty Scaling Up | Extensive Operational Changes | Workforce Development and Training

The scale of the operational differences between ZEBs and ICE vehicles raises the question of when transit agencies should attempt to integrate ZEBs into their current operational practices and when they should change operational practices to adapt to the reality of ZEBs. For example, some agencies could consider re-blocking select routes to avoid the need for costly extended-range vehicles or on-route fueling infrastructure. Like many decisionmakers, transit agencies may be susceptible to status quo biases and may not automatically consider which changes or tradeoffs may be in their agency's best interest. These decisions should be guided by high-quality evidence and best practices and led by transit agencies who best know their local context. Policymakers should encourage and support transit agencies in examining potential operational changes with an open mind, which may include ensuring access to high-quality data, technical assistance, financial support for key transition costs (typically represented by staff time, acquisition of new tools or software, or engagement of outside experts).

Facilitate the Adoption of Supporting Technologies

Related Challenges: Uncertain TCO Savings | Rapid Technological Evolution | Extensive Operational Changes | Lack of Knowledge and Resources

New technological tools and resources can be valuable resources for transit agencies in their transition. Many of these technologies, such as ZEB-specific routing software, driver feedback systems to understand operational efficiency, and effective charge management software, can reduce costs and operational barriers. However, many transit agencies, some of whom are already overwhelmed by the purchasing and deployment of vehicles, may miss this opportunity, or find that they do not have the knowledge or resources to effectively purchase and deploy them. In this context, policymakers could facilitate and appropriately fund the adoption of ZEB-supportive technologies. This facilitation could take the form of technical assistance to assess and plan for technology deployment, procurement assistance such as availability on state purchasing schedules, or engagement in setting standards for interoperability and use in transit, as applicable.

Continue Rigorous Real-World Performance Analysis

Related Challenges: Uncertain TCO Savings | Difficult Technology Choice | Lack of Operational Data | Rapid Technological Evolution | Extensive Operational Changes | Lack of Knowledge and Resources

As discussed previously, most transit agencies operate quite independently from one another. This independence also translates into a general lack of established channels for timely information sharing among agencies regionally and nationally. High-quality information that pertains to real-world operational conditions—particularly as transit agencies are on the front lines of deployment for ZEB technologies, some of which have not been operated in transit service for a full life cycle—is absolutely critical for effective operations and decision-making. Furthermore, accurate data about vehicle performance can assist policymakers and private industry in identifying key priorities for improvement, understanding risks, and more. Several examples of outstanding, rigorous data collection and sharing based on early ZEB deployments do exist, such as those provided by AC Transit and NREL ZEB deployment evaluations. (AC Transit, n.d.; National Renewable Energy Laboratory, n.d.). These efforts should be continued and, as possible, broadened to provide coverage of the full diversity of new technologies, operating conditions, and transit agencies.

Study Risks of Technological Obsolescence

Related Challenges: Regulatory and Policy Burdens | Rapid Technological Evolution

Technologies in every sector are continuously evolving. However, newer technologies that are encountering novel use cases and being observed in real-world conditions tend to evolve more quickly. While in general technological progress and innovation is a positive for all parties, the question of how to manage the previous generations of technology is also pertinent. For transit agencies bound by FTA Useful Life standards (Federal Transit Administration, 2007), the risk of technological obsolescence and being left with unsupported or inferior products for many years is meaningful. Policymakers could devote further study to the best ways to manage technological change in the transit sector, which may include options such as waivers to Useful Life standards to allow faster transitions or technology upgrades when efficient.

4.4 Solutions to Capacity, Knowledge, and Workforce Challenges

Reskilling and Upskilling

Related Challenges: Extensive Operational Changes | Workforce Development and Training

It is often easier for organizations to fill roles from within rather than hiring externally. Roles to operate, maintain and dispatch ZEBs and to design and build ZEB infrastructure projects are no different. While significant attention must also be paid to developing a pipeline of new talent, training existing workers for new skills is often the best solution for meeting the needs of the ZEB transition. Apprenticeships, on-the-job training, and rotational programs provide alternative pathways to ZEB technician and engineer roles than traditional educational routes. Developing the right type of program for each individual transit agency will depend on having a strong understanding of its workforce's specific skills, needs, and desires. Transit agencies are encouraged to conduct workforce assessments to better identify the right strategies for reskilling and upskilling workers and develop clear workforce development goals. Another best practice that policymakers could promote is for transit agencies to develop a dedicated workforce committee to include agency leadership and workers of various types to design and execute these workforce development initiatives. Going forward, it will be beneficial for the industry to adopt more standardized and transferrable accreditations and certifications that demonstrate that workers have received the adequate hands-on experience to be qualified for a specific ZEB role.

Open-Source Repository of Training Materials

Related Challenges: Workforce Development and Training | Lack of Knowledge and Resources

Rather than each agency developing its own courseware and training materials, this content could be made "open source" and available to all transit agencies within a region, state, or even nationwide. Developing high-quality courseware and on-the-job learning aids that have the potential to achieve the intended learning objectives can be time and resource intensive to develop. For ZEB operators and technicians, there is a need for "101-" and "201-"level trainings that are not specific to a particular ZEB make and model but that can be generally applicable. OEMs are struggling to be able to provide this type of foundational training to transit agency staff. An "open source" model can allow a baseline of content creation to be leveraged but with the ability for specific modules to be modified to better meet the specific needs of a transit agency or regional workforce. Where state and federal funds are being used for courseware creation and training, an "open source" model will lead to a more efficient use of public dollars.

Dedicated Workforce Development Funding

Related Challenges: Mismatched Funding and Need | Workforce Development and Training

Currently, most public dollars flowing toward ZEB workforce and training activities are a component of larger capital grants for bus purchases and infrastructure development. As such, these small "carve-outs" within the larger grant are paid less attention by applicants or funders, and the result is a less holistic and thoughtful approach. By establishing programs with dedicated funding for workforce and training activities, funders can recognize and elevate the importance of workforce development. As a result, programs are more likely to be innovative, strategic, and include robust evaluation and analysis.

Prepare Entire Organization for Transition

Related Challenges: Extensive Operational Changes | Workforce Development and Training

Critically, the transition to ZEBs demands organizational change and new forms of inter-disciplinary processes and cooperation. It is not sufficient to only train drivers, mechanics, and dispatchers; every staff member in a transit agency needs to be prepared for the resulting operational changes. This is particularly true around safety and emergency protocols, which significantly differ for ZEBs. A best practice is for leadership to ensure buy-in and understanding from everyone at the bus yard on these new processes, so that if a disaster were to occur, whoever was on the floor that day would know how to rapidly respond, potentially saving lives and avoiding severe property damage.

Facilitate Alternative Project Delivery

Related Challenges: Uncertain TCO Savings | Difficulty Scaling Up | Lack of Knowledge and Resources

Another solution to reduce the burden of ZEB transition on transit agencies is to encourage alternative project delivery strategies (where efficient) that share substantial risk and responsibility of ZEB infrastructure development and/or operations with private sector service providers, thereby largely eliminating the need for hiring or training workers with these capabilities. Many transit agencies are accustomed to using outsourcing contracts for bus operations and maintenance but are generally less familiar with other more innovative models such as "charging-as-a-service". Alternatively, and more ambitiously, policymakers could explore the concept of directly purchasing, installing, or operating equipment that transit agencies need for their ZEB transition (e.g., installing charging infrastructure on behalf of transit agencies for them to use).

Streamline Access to Experts

Related Challenges: Difficult Technology Choice | Rapid Technological Evolution | Difficulty Scaling Up | Extensive Operational Changes | Lack of Knowledge and Resources

A minimum level of knowledge is often needed to even know where to begin in transitioning toward ZEBs. Some transit agencies may struggle to even develop the RFP for hiring a consulting firm to engage for transition planning analysis, not knowing exactly what skills and experience might be needed. Clearly, transit agencies large and small will need access to experts in this sector at one point or another. A solution to mitigate this barrier and potential point of friction is to make it easier for transit agencies to access these subject matter experts. A state consulting bench, for instance, could make it much easier for a transit agency to identify and contract with a qualified contractor, without needing to undergo an extensive procurement and negotiation process.

5. Zero-Emission Bus Transition Case Studies

5.1 GreenPower

Overview

The GreenPower Motor Company was founded in 2010 with the mission to advance the adoption of electric vehicles by manufacturing affordable electric buses and trucks. GreenPower's product lineup includes a range of battery-electric vehicles designed for public transit, school transportation, cargo delivery, and shuttle services. With corporate headquarters in Vancouver, Canada and assembly facilities in California and West Virginia, GreenPower has positioned itself as an important player in the North American electric vehicle market. Despite an earlier deployment of 10 BEBs to the City of Porterville, the company has recently mainly catered to purchasers other than transit agencies, such as schools and universities.

Despite these strengths, GreenPower has faced several challenges in scaling its operations and fully capitalizing on the growing demand for electric buses. While the company has diversified its product offerings and customer base, its growth has been hindered by strategic decisions and external factors, such as required compliance with federal regulations and competition from more established manufacturers.

Key Challenges and Solutions

GreenPower's journey in the electric vehicle market has been marked by several challenges:

- Regulatory Compliance: GreenPower's reported refusal to conduct crash tests on their larger buses has limited their eligibility for federal funds, which are crucial for transit agencies to purchase new vehicles. Additionally, GreenPower's reliance on components manufactured in China has raised questions about their compliance with "Buy America" requirements, potentially complicating their customers' access to federal funding to purchase their products.

- Market Diversification: GreenPower's growth has been slower than anticipated, partly due to their focus on smaller transit vehicles and their reluctance to go through the testing process for some vehicles. This strategic decision has limited their penetration into the mainstream public transit market, where larger buses are in higher demand. As such, GreenPower has instead focused on serving customers outside of the transit space, such as schools and universities.

- Product Diversification: GreenPower has a diversified product lineup that includes vehicles for private sector applications, such as school buses and cargo delivery vans. This diversification has allowed GreenPower to tap into multiple revenue streams. Compared to some other ZEB manufacturers serving primarily the transit market, this means that GreenPower has less reliance on a single customer type.

- Strategic Partnerships: To address production challenges, GreenPower has entered into strategic partnerships, such as their collaboration with Forest River. This partnership allows GreenPower to leverage Forest River's market leadership in cutaway buses, integrating GreenPower's electric platforms with Forest River's body designs.

- Recurring Operating Losses: GreenPower has reported meaningful operating losses in recent years, despite growing revenues, indicating that they are facing some financial headwinds. In the year-end financial statements for FY24, the auditor's note indicated "substantial doubt" about its ability to continue operating as a going concern (i.e., the company's ability to meet its financial obligations) due to recurring operating losses and an accumulated deficit.

Key Takeaways for the US ZEB Transition

- Compliance with Federal Standards: For electric bus manufacturers, particularly smaller manufacturers supplying smaller transit vehicles such as cutaways, compliance with federal regulations, such as the "Buy America" program and Altoona testing requirements, may be barriers to accessing key markets, particularly within public transit.

- Market Diversification: Diversifying product offerings across multiple sectors, including public and private markets and potentially partnerships with other manufacturers, can help ZEB manufacturers mitigate risks and achieve more stable growth.

- Challenges in Production Expansion: Delays in building production infrastructure can hinder a company's ability to scale and meet demand, highlighting the importance of timely execution of expansion plans. Policymakers may consider ways to reduce the barriers to capacity expansions that would allow manufacturers to meet the US demand for ZEBs.

5.2 Santa Clara Valley Transportation Authority Advanced Transit Bus Vehicle-Grid Integration Project

Overview

The Santa Clara Valley Transportation Authority (VTA) Advanced Transit Bus Vehicle-Grid Integration (VGI) Project was an initiative undertaken between 2019 and 2020 aimed at enhancing the efficiency and sustainability of transit bus fleets through advanced grid integration and smart charging technologies. With a budget of $3M, this project focused on developing and demonstrating a comprehensive, integrated, charge management software platform that could reduce costs and support VTA's long-term electric bus infrastructure strategy. The primary objective of this project was to support VTA's goal of fully electrifying its bus fleet by 2040 by reducing the operational costs associated with electric bus fleets by optimizing the charging processes, thus mitigating the impact on the electric grid and ensuring that the buses could be charged during off-peak hours to minimize costs.

The VTA VGI project began to lay the foundation for future electric bus fleet electrification projects across California and beyond. By demonstrating the viability of smart charging and advanced energy management systems, the project provided a model for other transit agencies looking to transition to ZEB fleets. Specifically, the project reduced peak power demand by between 31–65%, saved over 25,500 gallons of fuel, and generated 84% lower carbon dioxide emissions, among other benefits.

Key Challenges and Solutions

- Technological Integration: Integrating new technologies from different vendors posed significant challenges. The project required the development of interfaces between various software platforms, including VTA's existing fleet management systems and the new energy management software.

- Infrastructure Delays: There were delays in receiving and deploying the necessary infrastructure, including buses and charging stations. These delays were exacerbated by the Covid-19 pandemic, which disrupted the supply chain and operational timelines.

- Energy Management: Optimizing the charging process was more complex than initially anticipated. Factors such as driver behavior, ambient temperature, and variations in energy consumption made it difficult to predict the exact energy needs of each bus for each route.

Key Takeaways for the US ZEB Transition

- Integrating Smart Charging into Fleet Management: To achieve cost savings and operational efficiency, agencies deploying BEBs should consider adopting charge management software. Specifically, transit agencies should ensure that they have access to integrated systems that monitor state of charge (SOC) and adjust charging times to lower utility rates, as seen with VTA's deployment.

- Potential for Cost Savings: By leveraging off-peak charging and optimizing energy consumption through vehicle-grid integration, transit agencies can significantly reduce electricity costs. This project highlighted how data-driven energy management systems can yield long-term financial benefits when scaling electric bus operations.

- Readiness of Technology: While smart charging and grid integration are promising, the VTA project revealed that some aspects, such as real-time optimization and predictive modeling, are still evolving. Agencies looking to adopt these technologies should anticipate ongoing improvements in hardware and software capabilities, and policymakers and researchers should consider ways that these capabilities can be further advanced.

5.3 Santiago de Chile's Deployment of Zero-Emission Buses

Overview

Santiago de Chile is a leading public transport system in Latin America regarding bus fleet electrification. Their transition began in 2017 with the ambitious goal of electrifying 25% of the city's bus fleet by 2025. By 2023, 30% of Santiago's buses were electric, and the city moved up its 100% electrification goal date from 2040 to 2035. With funding and financing support from the International Finance Corporation (IFC), the Inter-American Development Bank (IDB), and BancoEstado, the city procured 992 ZEBs, significantly reducing Santiago's carbon footprint. The buses operate under a 14-year bus supply leasing contract, separating fleet ownership from operation.

Key Challenges and Solutions

Santiago's fleet transition solution involved several innovative elements:

- Risk Sharing with Private Partners: The adoption of a novel concession model separated fleet ownership from operation. This model allowed private companies to own and maintain the buses while the operation was managed by different entities. Though not specifically designed to integrate ZEBs into the fleet, it aided the process of transition by sharing the financial and operational risks associated with the transition to electric buses with private partners.

- Disincentives for ICE Vehicles: The implementation of stringent emissions standards and taxes created a conducive environment for ZEB adoption by reducing incentives to buy ICE vehicles.

- Financial Guarantees: The Chilean government provided financial guarantees to private operators, ensuring that they would not bear the full risk of the substantial upfront investment required for ZEBs. This included guarantees that operators would be compensated in the event of financial losses or disruptions, which was critical in attracting private investment to the project.

- Technical Assistance: Collaboration with international organizations like IFC, IDB, and the C40 Cities Climate Leadership Group (C40) helped to mobilize funding and technical expertise. These organizations provided support in areas such as fleet management optimization, the design and deployment of charging infrastructure, and the development of financial models that ensured the ZEBs' economic viability over their full lifecycles.

Key Takeaways for the US ZEB Transition

- Unbundling Ownership and Operation: Separating the ownership of buses from their operation can ease the transition to electric buses by lessening the burden of high upfront costs and the risks associated with vehicle performance. This unbundling model worked well in Santiago because it transferred operational risk to the vendors, ensuring that transit agencies were less concerned about the performance and reliability of their ZEBs. A related risk transfer mechanism tailored to the US context is described in Section 4.

- Government Guarantees: As shown in the case of Santiago, government-backed guarantees can play a crucial role in attracting private investment by sharing potential downside risk associated with the ZEB transition. As mentioned in Section 3, while ZEBs may achieve a lower TCO, these savings are far from guaranteed. By offering guarantees to cover situations where the expected savings are not realized, ZEB transitions can be accelerated if stakeholders know that they are protected from financial losses if the transition does not deliver the anticipated cost benefits.

- Incentivizing ZEB Purchases: The US has implemented a range of policies aimed at reducing the cost of ZEBs for transit agencies, including grants, tax credits, and funding for infrastructure. However, the Chilean experience highlights another effective strategy: making ICE buses less attractive by increasing emissions standards and imposing taxes on polluting vehicles. This dual approach—both incentivizing ZEB purchases and disincentivizing ICE buses—could further accelerate the shift to cleaner public transport in the US, attacking the problem from both sides.

- Lack of Import Restrictions: The lack of import restrictions in the country made it easy for Santiago to import the lowest-cost ZEBs in the market from China, reducing the buses' capital cost.

- Reduced Total Cost of Ownership: The Zero Emission Bus Rapid-deployment Accelerator (ZEBRA) partnership, in collaboration with a local partner, conducted an in-depth TCO study (Zero-Emission Bus Rapid Deployment Accelerator, 2022). The study is based mainly on the information contained in the contracts signed for the provision of both diesel and electric urban buses. Results show that even with higher investment costs and equalizing the duration of the concession contracts, the adoption of electric buses in Santiago can be economically viable. The study projected a 32% reduction in TCO relative to ICE buses, primarily due to lower fuel and maintenance costs. Additionally, the regulatory environment in Chile includes penalties for higher emissions, further contributing to the cost-effectiveness of ZEBs in comparison to ICE buses. While these savings are not assured and may in part depend on policy factors such as relative fuel prices, this analysis illustrates the potential for TCO savings.

5.4 Canada Infrastructure Bank's Zero-Emission Buses Initiative

Overview

The Zero-Emission Buses Initiative by the Canada Infrastructure Bank (CIB) aims to support the transition to ZEBs across Canada by providing up to $1.5B in financing with the primary purpose of managing the upfront capital costs associated with the purchase of ZEBs and, in some cases, the necessary charging infrastructure. The initiative aligns with the federal government's goal to encourage the purchase of 5,000 ZEBs nationwide by local public transportation operators, reducing greenhouse gas emissions and promoting sustainable public transit. The initiative involves direct loans from CIB, which are designed to be repaid through operational savings generated by ZEBs compared to diesel buses. The Zero Emission Transit Fund complements this financing approach by providing grants for planning and capital projects, ensuring a comprehensive approach to fleet electrification. The collaboration between CIB and Infrastructure Canada aims to bridge funding gaps and accelerate the deployment of ZEBs, leveraging lifecycle operational cost savings to offset the higher upfront costs. Several municipalities in Canada have already received CIB financing. For example, the City of Edmonton received $14.4M to acquire 20 new ZEBs and to conduct a feasibility study on ZEB-related municipal building retrofits.

Key Challenges and Solutions

The primary challenge that the CIB aims to address through this initiative is the higher upfront costs of purchasing ZEBs compared to ICE buses. To overcome this hurdle, the initiative offers:

- Direct Loans: CIB provides financing for ZEBs based on expected operational savings from lower fuel and maintenance costs, which is meant to help bus operators better manage the increased capital expenditure per bus.

- Grant Funding: The Zero Emission Transit Fund supports planning and capital projects, reducing financial barriers and facilitating the transition to electric fleets.

- Collaborative Approach: Infrastructure Canada and CIB work together with organizations like the Canadian Urban Transit Research and Innovation Consortium (CUTRIC) to support the comprehensive needs of bus operators, including feasibility studies, infrastructure upgrades, and financing solutions. CIB and Infrastructure Canada primarily provide financial assistance, while CUTRIC provides technical support in the planning and implementation phases and expert guidance on fleet decarbonization, infrastructure requirements, and operational strategies.

- Risk Mitigation: The repayment of CIB loans is tied to actual cost savings, with CIB assuming the repayment risk if savings fall short of forecasts. This mechanism encourages ZEB adoption by reducing financial uncertainty for transit agencies.

Key Takeaways for the US ZEB Transition

- Integrated Funding Solutions: Combining direct loans with grant funding can address the high upfront costs of ZEBs and their associated infrastructure. This mechanism may be difficult to apply directly in the US context, where transit agencies traditionally do not borrow money to buy buses. However, it is interesting to note that financing-based mechanisms may more fully align transit agencies' incentives around demanding lower-cost buses. As explained in Section 3, in a situation where transit agencies receive public money to cover most of the purchase cost of ZEBs, there is less incentive for them to demand lower-cost market offerings. Financing solutions, although not currently part of the US transit landscape, could provide different incentives for both transit agencies and market players.

- Operational Savings-Based Financing: Operational savings from lower fuel and maintenance costs can make the financial case for ZEBs more compelling and can serve as a justification for adopting ZEBs. Demonstrating clear savings in fuel and maintenance could make the case for such investments more compelling to transit agencies and policymakers.

- Government-Private Collaboration: The CIB provided financing to manufacturers and to companies that lease zero-emission buses to transit agencies and schools, helping to support and develop the industry. More generally, collaborations between government entities and financial institutions can facilitate the development of a successful zero-emission public transit industry.

- Planning and Support Services: Providing comprehensive planning and support services, such as through CUTRIC's involvement in this case, can guide transit agencies through the complex process of fleet electrification. While the US has organizations like CALSTART that offer similar services, the CIB's approach ensures that every agency they collaborate with consistently receives the necessary support, rather than having to seek it out on an ad hoc basis. This systematic support model can help streamline the electrification process and reduce the burden on individual agencies.

5.5 Transition to Zero-Emission Buses in US Universities

Overview

Several universities in the United States have started to electrify their transit fleets as part of their broader commitments to sustainability and climate action. These initiatives generally start with the purchase of a small number of ZEBs, supported by various state and federal grants and university funds. These university fleet transitions demonstrate how ZEB adoption extends beyond traditional public transit agencies, highlighting the growing and diverse market for ZEBs. These cases also feature the role of voluntary, institution-driven initiatives in advancing the adoption of ZEBs.

Key Challenges and Solutions

The primary challenges faced by universities in transitioning to ZEBs are generally similar to those observed in public transit. The solutions and innovations highlighted by the case of universities' transition experiences include:

Financial Support: Universities have leveraged grants from state and federal programs, such as MassDEP, NYSERDA, and the FTA, to cover the initial costs of purchasing electric buses and installing charging infrastructure.

Internal Funding: Funds, such as Harvard's Green Revolving Fund, provide upfront capital for sustainability projects, including ZEB purchases and infrastructure upgrades.

Collaboration and Planning: Universities have consulted with other institutions and municipalities to learn from their experiences with ZEBs. For example, Harvard has worked with state and city transportation departments to align their electrification efforts with broader transportation goals by joining MassEVolves, an initiative that supports the work of organizations in Massachusetts that use zero emission vehicles for their operations.

Key Takeaways for the US ZEB Transition

Expanding Demand Beyond Public Transit: Universities represent an additional market for ZEBs, contributing to the overall demand and potentially influencing market dynamics. Policymakers could consider how adjacent sectors such as universities could help drive demand, cross-sector coordination, and innovation in the ZEB market.

Climate Pledges as Drivers: Institutional commitments to sustainability are significant drivers of ZEB adoption. These pledges create internal pressure to electrify transit fleets by making this a key component of broader environmental strategies. This voluntary approach, driven by institutional goals rather than regulatory mandates, can also advance ZEB adoption.

Small-Scale Initiatives: Universities' deployments demonstrate how starting with a few electric buses can be an effective approach to gradually transition to a fully electric fleet. This method allows for incremental learning and adjustments, which can be scaled up over time as more data and experience are gathered; however, the scale-up challenges noted in Section 3 may eventually be hurdles for universities as well.

Data and Insights from Universities: The data gathered from university fleet transitions could potentially provide insights for public transit agencies. Universities' environments offer a testing ground for strategies, and the lessons learned could inform larger-scale public transit deployment.

6. Summary & Conclusions

While the path to widespread adoption of ZEBs in the US is fraught with difficulties, it also presents a unique opportunity to implement lasting structural changes to address climate change, improve air quality, and foster sustainable public transportation.

The ZEB transition will require strategic action and coordinated efforts across multiple levels of government, as well as between policymakers, industry, advocates, and other stakeholders. By strengthening these partnerships to address ZEB-specific challenges, the sector will be better positioned to overcome an even broader set of issues affecting the future of public transit in the US that goes beyond just fleet transition.

This report is intended to advance these goals by putting forward a realistic accounting of observed challenges to the ZEB transition and recommendations for policymakers and practitioners with the potential to achieve significant impact. By examining and describing the rapidly evolving transit bus market in the US, with specific focus on ZEBs, this report highlights that barriers to transition exist in four key areas: industry dynamics, business case challenges for transit, operational and technological hurdles, and a policy and regulatory landscape that is not always well-aligned with the goals and needs of a successful ZEB transition.

An additional objective is to identify and inspire ideas for further research and analysis to promote transit fleet electrification—particularly around predicting the total cost of ownership (TCO) for ZEBs under different geographies and operational contexts, understanding long-term performance, optimizing fleet management strategies, investigating opportunities to improve supply chain reliability, and improving data collection and market intelligence for ZEB types other than full-size vehicles.

Although public transit fleet transition is a relatively small component of the overall energy transition in the US, it can play a meaningful role in driving new investment and producing new learnings for other heavy duty transportation vehicle manufacturing and supply chains. Success in the ZEB sector can drive technological advancements, spur the creation of innovative workforce training programs, and test industry engagement strategies and economic incentives that can benefit the broader transportation ecosystem.

The need to accelerate the ZEB transition is urgent, and meaningful market and policy shifts will likely be required to achieve these goals. Meaningful market and policy shifts, such as new funding mechanisms, supply chain interventions, and workforce development initiatives, will likely be required to achieve these goals. By leveraging the insights and recommendations outlined in this report, stakeholders can shape actionable strategies informed by both transit agencies' on-the-ground experience and relevant industry dynamics in order to advance this critical transition.

7. Appendix A

7.1 Stakeholder Discussions

The investigators completed over 15 semi-structured interviews with a variety of stakeholders, including representatives from the categories listed below. In addition, this report's insights pull from numerous informal conversations with stakeholders over a more extended period of time.

- Federal policymakers
- State policymakers (California) across several relevant agencies focused on transportation, energy, economic development, and other relevant topics
- Transit agencies
- ZEB and ZEB component OEMs
- Transit advocates and industry associations
- Other alternative fuels and public transit subject matter experts

7.2 Data Analysis Methodology

Data Cleaning

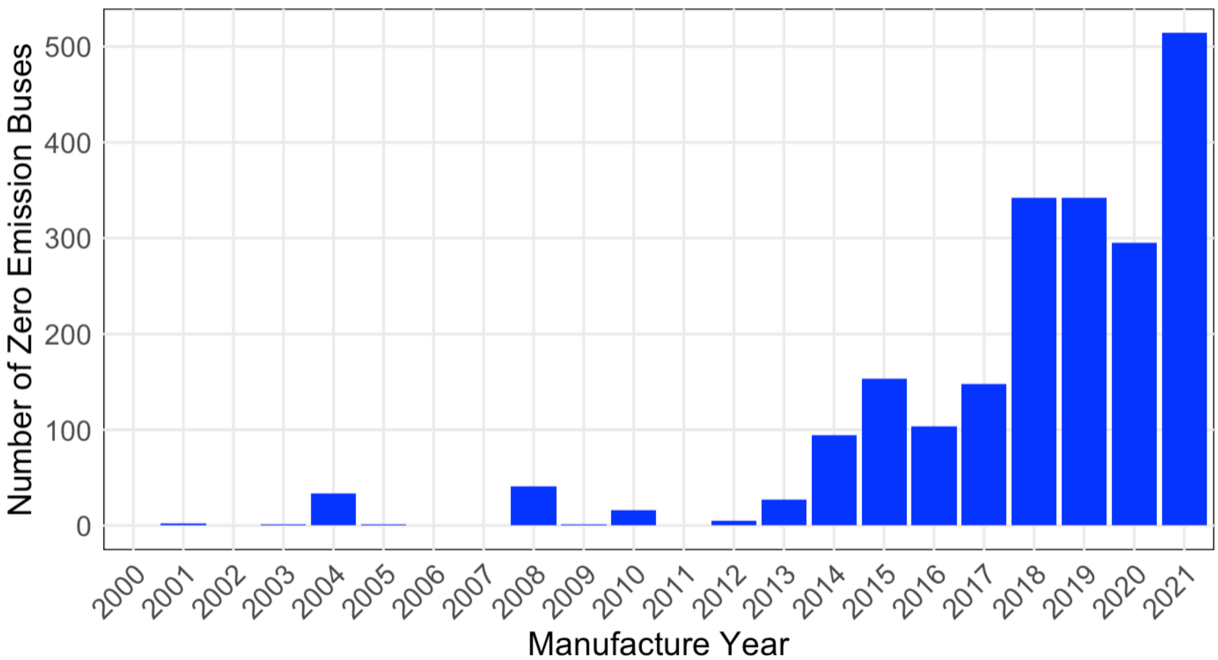
The data analysis was conducted using the R programming language on the R Studio IDE. The analysis started by loading and cleaning vehicle data from the National Transit Database. The cleaning was done by formatting the data to ensure consistency, such as by converting "Yes" and "No" data to True and False, and properly assigning NA (Not Applicable) to missing data. Since the analysis focused on buses, observations that relate to buses and ZEBs were identified with additional columns to make subsequent analysis easier. Data on modes of transport other than buses, such as trains and ferries, were filtered out. The result is a refined dataset highlighting the vehicles most relevant to the report, which was then used throughout the analysis. Both ZEBs and ICE buses are included in this refined dataset to be able to make inferences about ZEBs and the wider transit bus market. However, it is important to note that 17.2% of the vehicles in the bus dataset (22,523 out of 130,752) do not have fuel types reported. These observations are filtered out when comparing ZEBs and ICE buses in the rest of the data analysis.

ZEBs by Year

After refining the dataset to focus on buses, the data was further evaluated by examining the number of ZEBs by their year of manufacture. For each year, the total number of ZEBs was calculated and compared to the total number of buses produced. This allowed for the determination of the percentage of zero-emission buses each year, along with the calculation of the number of ICE buses for a more comprehensive understanding.

The first visual associated with the year-by-year data is a bar chart that shows how many ZEBs have been manufactured per year since 2000.

Figure 6. Number of ZEBs by Manufacture Year for Vehicles Reporting Fuel Type

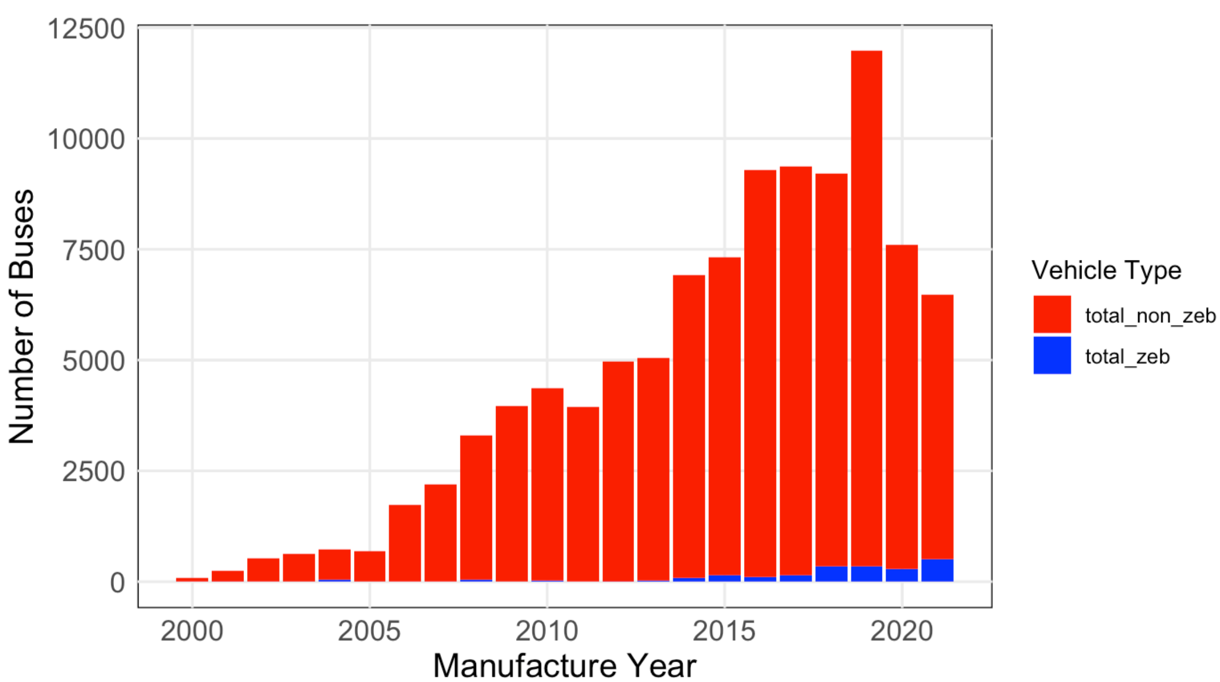


The percentage of ZEBs as a share of total buses for each year of manufacture was then determined to explore the relative growth of zero-emission technology within the bus industry over time.

Figure 7. Percentage of ZEBs by Manufacture Year for Vehicles Reporting Fuel Type

The final graph shows the overall composition of buses manufactured each year by separating them into two categories: ZEBs and ICE buses. This chart reveals not only the total production of buses but also the relative share of zero-emission vehicles over time in the transit fleet.

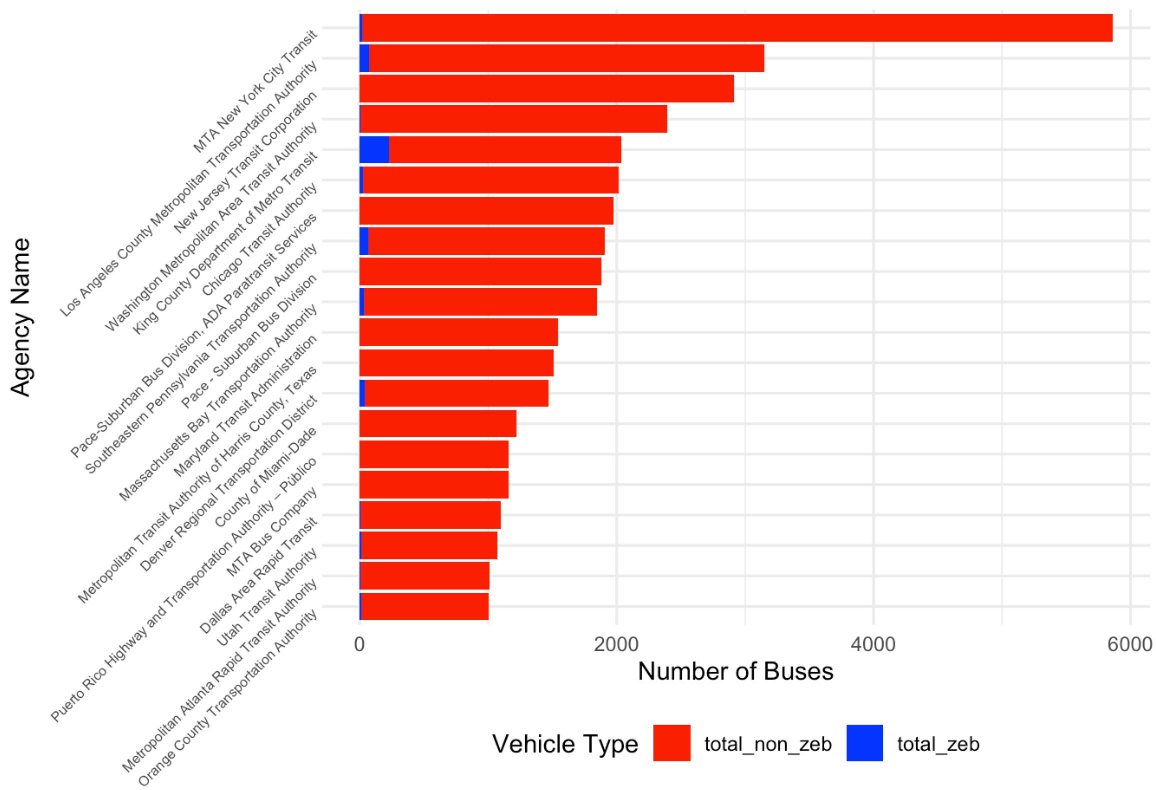
Figure 8. Total Buses by Manufacture Year for Vehicles Reporting Fuel Type



ZEBs by Transit Agency

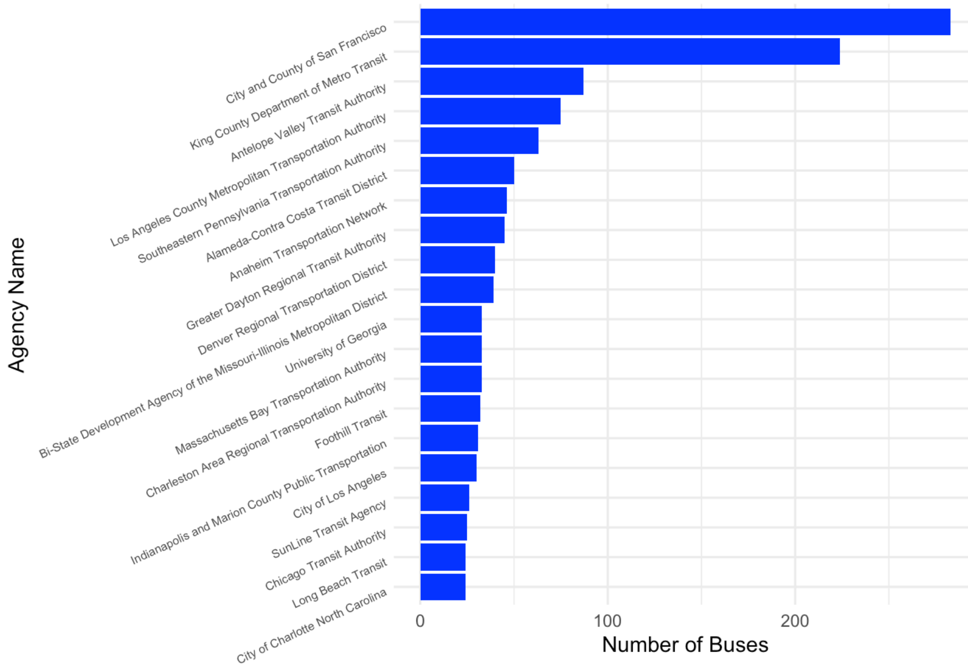
The following graphs examine the distribution of ZEBs across different transit agencies. By grouping the data by agency, the total number of ZEBs and ICE buses for each agency is calculated, and the top 20 agencies are identified based on the total number of buses in their fleet. This analysis provides a snapshot of how ZEB adoption is distributed among the largest transit agencies, highlighting the leaders in the transition to more sustainable transportation options.

Figure 9. Top 20 Agencies by Number of Buses



In addition to examining the overall bus fleet, the following graph also shows the top 20 agencies based on the total number of ZEBs in their fleet. This information is visualized using a horizontal bar chart that clearly displays the agencies with the highest number of ZEBs.

Figure 10. Top 20 Agencies by Number of ZEBs



ZEB Suppliers

An overview of all the suppliers of ZEBs breaks down their contributions and market share. The analysis groups the data by manufacturer and sums the total number of ZEBs they have produced, excluding trolleybuses from the primary ZEB count. The results are organized in a table that ranks manufacturers based on the number of ZEBs they have supplied.

Table 8. US Sales and Market Share by Company

Manufacturer	US ZEB Manufactured, up to 2022	2022 US ZEB Market Share up to 2022
Proterra Inc.	587	38%
New Flyer (NFI)	394	25%
Build Your Dreams, Inc.	285	18%
Gillig Corporation	197	13%
Other	27	2%
Motor Coach Industries International	20	1%
ElDorado National	18	1%
Ebus, Inc.	15	1%
Van Hool N.V.	13	1%
Alexander Dennis Limited	2	0%
North American Bus Industries Inc.	1	0%
Total	1,559	100%

Breakdown by bus type

The table below shows the distribution of bus types across different fuel types, with a specific focus on ZEBs. Excluding trolleybuses and filtering out buses with missing fuel type information, the remaining buses are categorized based on whether they are zero-emission or not.

The data is grouped by bus type and fuel type, distinguishing between the two ZEB fuel types (electric battery and hydrogen) and all other fuels. The analysis then sums the total number of buses for each combination of bus type and fuel type, providing a view of the types of buses that are most commonly being converted to zero-emission technology.

Table 9. Number of Buses by Vehicle Type and Fuel Type

Vehicle Type	BEBs	FCEBs	Other
Articulated Bus	163	2	5,812
Bus	1281	87	52,079
Cutaway	1	0	26,936
Double Decker Bus	2	0	220
Over-the-road Bus	21	0	6,069
Van	65	0	14,928

Urban and Rural Transit Agencies

To understand ZEBs' main customers, the analysis explored how their adoption varies across transit agencies serving urban, rural, and tribal communities. The total number of ZEBs are compared to the overall fleet size for each agency reporter type.

The analysis calculated the percentage of ZEBs within each agency type, revealing how these different communities incorporate zero-emission technology into their transit systems. The results are summarized in Table 10, highlighting the differences in ZEB adoption across urban, rural, and tribal transit agencies.

Table 10. Number of ZEBs and Total Buses by Reporter Type

Reporter Type	Total ZEBs	Total Buses	Percent ZEB
NA	3	3187	0.09
Rural	0	18,447	0.00
Tribe	0	777	0.00
Urban	2,182	10,8341	2.01

Table 11. Price Information from Various Sources for Different Vehicle Types and Fuel Types

Specification	Source	BEB Price (USD)	FCEB Price (USD)	ICE Vehicle Price (USD)
60-foot Bus	Lowell & Gupta, 2024	1.4M–1.6M	1.8M	-
45-foot Coach	Lowell & Gupta, 2024	1.2M–1.6M	-	-
40-foot Bus	Lowell & Gupta, 2024	800k–1.2M	1.2M–1.8M	-
35-foot Bus	Lowell & Gupta, 2024	800k–1.1M	-	-
30-foot Bus	Lowell & Gupta, 2024	800k	-	-
24-foot Bus (Cutaway)	Lowell & Gupta, 2024	220k	-	-
Bus, articulated (>=55')	National Transit Database, 2024	1.25M	2.1M	843k
Bus, double-deck (2 levels, one above the other)	National Transit Database, 2024	1.0M	1.9M	521k
Bus, intercity (>=32'6", 1 door, luggage bays)	National Transit Database, 2024	-	-	552k
Bus, suburban (>=27'6", 1 door, no luggage bays)	National Transit Database, 2024	-	-	358k
Bus, transit (>=27'6", 2 doors)	National Transit Database, 2024	900k	1.3M	536k
NA	Hughes-Cromwick, 2019	930k	-	-
40-foot Bus	Nunno, 2018	770k	-	445k
Standard Bus	Coren, 2017	750k	-	500k

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About the Authors

Leah Foecke, MS

Leah is a Manager at Rebel with over seven years of experience as an economic consultant and policy advisor. She brings experience advising clients at the national, state, and local level, with particular expertise in transit and transportation, zero-emission transition, and public-private infrastructure delivery. Prior to Rebel, Leah provided economic analysis, strategic advisory services, and monitoring and evaluation support to public and private sector clients as an economic consultant and held fellowships focused on climate and infrastructure with the City of Boston and the State of Massachusetts. She holds a master's degree in public policy from Harvard University's John F. Kennedy School of Public Policy and a bachelor's degree in economics and biology from the University of Wisconsin-Madison.

Zachary Karson, MS

Zachary Karson is a Manager at Rebel with experience advising both public and private clients on infrastructure projects and transactions in various sectors, including mass transit and mobility, renewable energy, broadband, water, and wastewater. Zachary focuses on financial analysis, risk analysis, procurement support, and assisting clients with key commercial and financial decisions. Zachary is also a registered Series 50 municipal financial advisor. Before working at Rebel, Zachary worked for various public and private organizations in the renewable energy sector. He holds a master's degree in public administration and a master's degree in business administration from New York University, and a bachelor's degree in political science and Spanish from Kenyon College.

Thomas Tiberghien, MS

Thomas is a Consultant at Rebel, where he brings his expertise in international development policy and quantitative research methods to advise clients on the acceleration of zero-emission bus adoption and infrastructure development. At Rebel, Thomas advises transit agencies on strategies to accelerate the transition to zero-emission buses. He also provides guidance to multilateral development banks and local governments on the development of infrastructure projects and public-private partnerships. Thomas holds a master's degree in International Development Policy from Georgetown University's McCourt School of Public Policy and a dual bachelor's degree in Mechanical Engineering and Applied Mathematics & Statistics from Johns Hopkins University.

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