Transit Bus Technology Roadmap

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Introduction

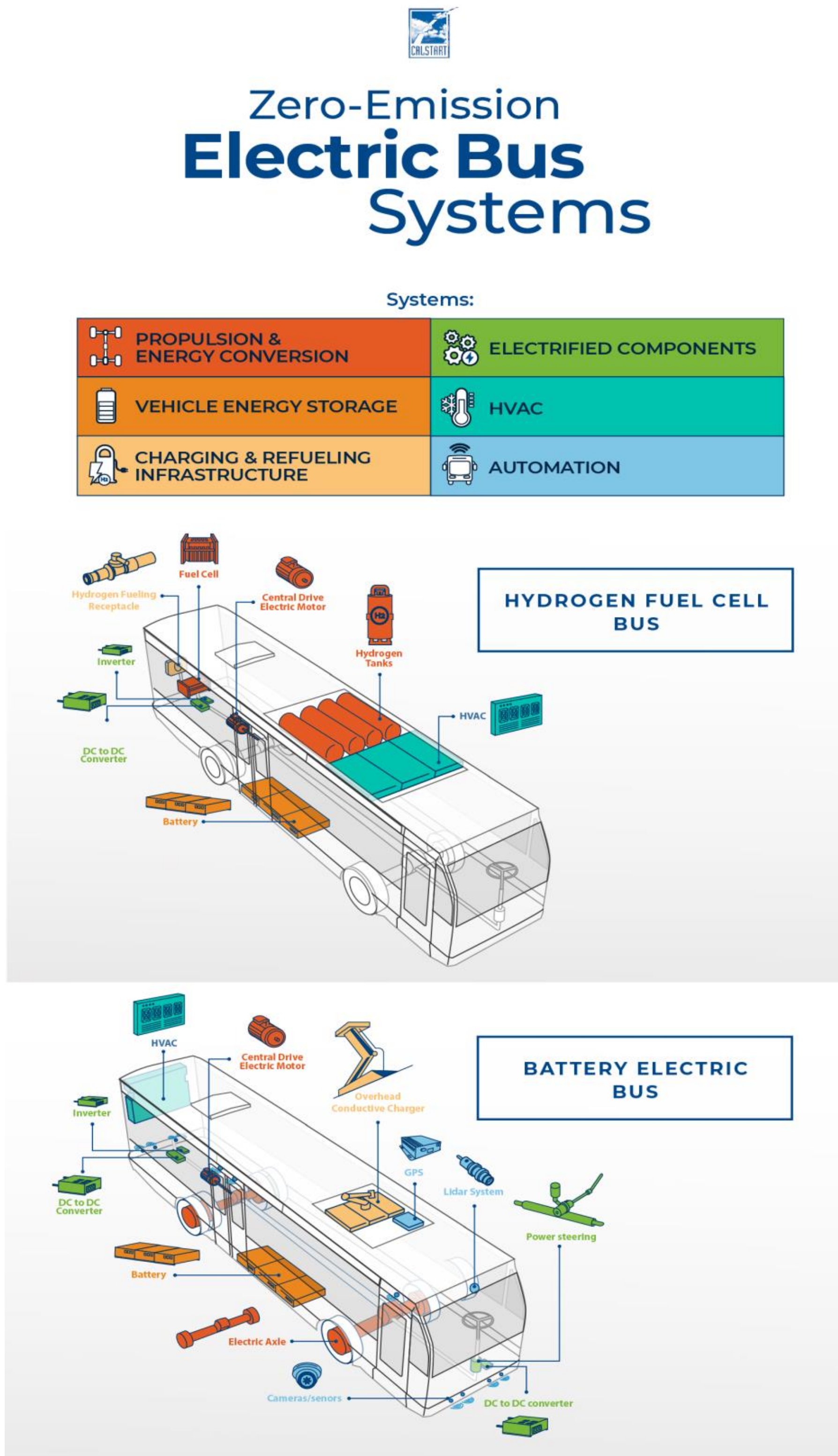
The Low or No Emission Vehicle Program (Low-No)[1] has enabled the rapid growth of the zero and near zero transit bus sector in recent years. Between September 2018 and September 2019, zero emission bus deployments increased by 36% and as of September 27, 2019, there were 2255 zero emission buses that had been deployed, purchased, or received funding in the United States[2]. Bus deployments occurred in every region of the United States and many transit agencies purchased their first zero emission bus. Europe has also experienced strong growth in zero emission buses and has deployed 2200 buses[3]. In addition, purchases of low emission electric-hybrid buses have continued at a strong pace.

This growth in Low-No bus deployments has been fueled by several factors including decreasing costs of battery electric and fuel cell propulsion systems, major technological improvements to components, and financial support from Federal and state governments. However, the electrification of buses has created unique technological challenges for buses. Some components, systems, and sub-systems were designed to be operated alongside an internal combustion engine and are not designed to work with electrified propulsion systems. In addition, some Low-No bus technologies are in the early stages of commercialization and have not yet reached technological maturity. Lastly, the challenges that extreme environmental conditions, like cold weather, hot weather, and hilly routes, pose to low and no emission bus performance continues to drive the need for technological solutions. These technological challenges must be addressed to improve bus performance, increase user acceptance, and sustain strong growth in Low-No transit bus deployments.

This Roadmap identifies key technology sectors that need further development and demonstration to support the commercialization and fleet-wide mass deployment of Low-No transit buses. Critical technology adoption areas will be reviewed to give the reader an understanding of the current technology advancements and further development needs. This Roadmap will focus primarily on enabling technologies that will further develop the market for Low-No buses and their associated infrastructure solutions. Many of the advanced technologies and components featured in this report will also be applicable to the clean heavy-duty truck market. This Roadmap aims to provide a technological needs assessment for advancing the commercialization of Low-No buses and to guide future demonstrations and research in the Low-No transit bus sector.

[1] Low or No Emission Vehicle Program 5339(C), https://www.transit.dot.gov/funding/grants/lowno
[2] Fred Silver, John Jackson, and Bryan Lee. (2019) "Zeroing in on ZEBs: The Advanced Technology Transit Bus Index." *CALSTART*. Available at: https://calstart.org/zeroing-in-on-zebs-2019/
[3] Mark Kane. (2019). "Europe: 2,200 EV Buses Deployed - Two-Orders Of Magnitude Behind China." *Inside EVs*. Available at: https://insideevs.com/news/377417/europe-2200-ev-buses-behind-china/

Main Technology Pathways



Systems	Research Needs
Vehicle Energy Storage Systems	• **High pressure gaseous hydrogen storage*** • Incremental improvements to battery capacity, efficiency, and cycle lifetime • New battery chemistries • Ultracapacitors and flywheels
Propulsion and Energy Conversion	• Next generation lower cost fuel cells • Electrified axles and in-wheel motors • Next generation power switches
Electrified Components and Enabling Technologies	• More durable compressors and pumps • New DC-to-DC converter designs to improve efficiency • More reliable inverter cooling systems
Heating, Ventilation, and Air Conditioning	• **Integrate heat pumps into bus systems*** • **Develop a Clean Emission Protocol for fuel-fired heaters*** • Determine energy savings from improved insulation
Automation	• **Develop a Next Generation smaller bus (that is Buy America and NHTSA compliant)*** • Automatic braking systems on larger buses • Full automation of a 40-foot bus
Charging and Refueling Infrastructure	• **Demonstrate microgrids and other grid resiliency technologies*** • Develop higher power DC fast inductive charging • Transit bus export power and bi-directional vehicle-to-grid integration protocol • Ultracapacitor flash charging • Develop on-site hydrogen production technologies

* This is a priority technological research need that will be discussed in more detail

Low-No Bus Technological Needs Assessment

Low-No bus technology has rapidly matured over the last decade. Low-No transit buses are no longer experimental and are now considered to be early market commercialized technology. Despite this progress, Low-No buses still face moderate user acceptance issues due to technological challenges with components and bus sub-systems. Overcoming these technological challenges will be vital for driving the Low-No bus market towards technological and commercial maturity and encouraging transit agencies to adopt these buses. Some technological advances will have a disproportionate impact on bus performance. CALSTART has identified several high-priority technological challenges that address critical concerns and limitations in Low-No buses. The following are the most urgent and highest impact technological advances for zero emission buses.

Microgrids and Grid Resiliency

Low-No buses are reliant on electricity or hydrogen as their source of fuel. This poses unique fuel supply risks to transit agencies. If electric supplies were disrupted, transit agencies would not be able to charge their battery electric buses. Some fleets have attempted to mitigate this problem by adopting hydrogen fuel cell bus fleets. However, since electricity is needed to produce, store, and dispense hydrogen, an outage would also affect hydrogen fuel cell bus fleets. This is especially true if hydrogen production, which is very electricity-intensive, is conducted on-site. As a result, an event that disrupts electricity supplies, like a grid outage or a natural disaster, would effectively disable any zero emission bus fleet and force the transit agency to halt transit service until power could be restored, regardless of which fuel they use. In addition to being inconvenient, this is problematic because city officials might use transit bus fleets to evacuate people from natural disasters. If a Low-No bus fleet were to fail under these circumstances, it would represent a critical reputational risk to the industry.

To mitigate these concerns, resilient charging and fueling infrastructure needs to be developed and deployed. Resilient infrastructure needs to be able to provide sufficient power during outages and must be able to withstand major natural disasters. These systems would need to include a microgrid that can disconnect from the utility grid and power the facilities during an electricity disruption using on-site distributed energy resources. A microgrid would need to have the capacity to power vehicle charging equipment in the event of an outage. A microgrid serving a hydrogen facility would need to provide power to the compressors, chillers, and hydrogen fueling dispensers at a minimum. A microgrid can also play a role in demand management and help transit operators reduce operational costs by engaging in peak shaving.

CALSTART is currently working on a microgrid feasibility study for the Stark Area Regional Transit Authority. This planned microgrid will provide backup power for the hydrogen production and dispensing equipment and can provide up to 24 hours of protection against a grid outage or failure. Santa Clara Valley Transportation Authority has also developed a microgrid to power their bus charging activities. Thus far, these microgrids have been deployed at bus depots that have relatively small electric bus fleets. However, microgrids that are capable of serving larger fleets will need to be developed. Further efforts need to be undertaken to demonstrate an emissions-free microgrid that has the capability to provide resiliency to large bus fleets in the event of a disaster.

Next Generation Small Zero Emission Automated Bus

The development of transportation network companies (TNCs) and ridesharing services have greatly altered the transportation industry. The rise of TNCs has changed rider preferences for the method of transportation they use, causing public transportation ridership to decrease in recent years. This has led to an increase in vehicle miles traveled and an increase in traffic congestion. The development of connected and automated single occupancy vehicles will likely exaggerate this trend towards lower ridership unless public transportation adapts.

Transit agencies also need to use automation and connectivity to provide an attractive alternative to TNCs and increase shared ridership. According to the results of a recent FTA industry inquiry, the perceived best business model for higher levels of automation is in the use of on demand smaller bus operation, often referred to as micro transit[4]. Next generation buses can use these features to improve rider experience and offer new public transit services to riders. Automated and connected buses provide an opportunity to improve transit service. Automated and connected technology can be used to provide services like ridesharing and dynamic routing services where the bus uses real-time geospatial information to optimize its route and minimize the amount of time it spends in traffic. Buses can also be integrated with other forms of public transportation and provide first-mile/last-mile services to public transportation hubs. Presently the small automated buses being tested in North America are limited to 15 mph and have NHTSA Safety exemptions. Going forward these buses need to be safe in mixed traffic at higher speeds and operate without safety exemptions, as well as being Buy America and Americans with Disabilities Act compliant. Market research needs to be conducted to determine which automation and connectivity services will be attractive to the public and will boast ridership. Further efforts will be needed to develop and refine these technologies.

CALSTART is playing a major role as an accelerator of the next generation zero emission automated bus. The Los Angeles Department of Transportation and CALSTART were recently awarded an Automated Driving System Demonstration Grant from the FTA to demonstrate a bus with sensors which can provide additional safety and driver collision avoidance assistance. The LA Department of Transportation has already installed the Mobileye Shield Plus sensor system on their buses, which prevents accidents by warning drivers when there is a threat of collision and if the bus is at risk of drifting out of its driving lane[5]. Since the bus driver remains in control of all driving functions, the use of this driver assistance technology constitutes Level 0 automation. These systems are enablers for increasing levels of automation on larger buses.

CALSTART's Connected and Automated Transportation Users Forum (CATUF) is currently working on specifying a zero emission autonomous small transit vehicle. Through CATUF, CALSTART is working with thirteen transit agencies to describe a transit vehicle that will meet their needs, be zero emission, achieve SAE Level 4 autonomy, comply with Buy America and ADA requirements, and function in all climate conditions[6]. CALSTART is working with transit agencies to specify appropriate automation features and on-demand services for riders. CATUF is also working on specifying automated disability, fare payment, lane keeping, parking assistance, vehicle avoidance & braking, and cybersecurity services

[4] National Archives and Records Administration. (2018). "Research Program: Automated Transit Buses." Federal Register. Available at: https://www.federalregister.gov/documents/2018/01/16/2018-00615/research-program-automated-transit-buses
[5] Mobileye. https://www.mobileye.com/us/fleets/products/mobileye-shield-plus/
[6] CALSTART. "CALSTART to Explore New Automated Vehicle Technologies Aimed at Boosting Transit Ridership and Cutting Emissions." Available at: https://calstart.org/catuf-matthew-lesh/

to its bus. As a follow-on to this work, there is a need to fund the development and demonstration of vehicle protypes and then pilot deployments of up to 39 vehicles (3 vehicles per transit operator in CATUF).

High Pressure Gaseous Hydrogen Storage

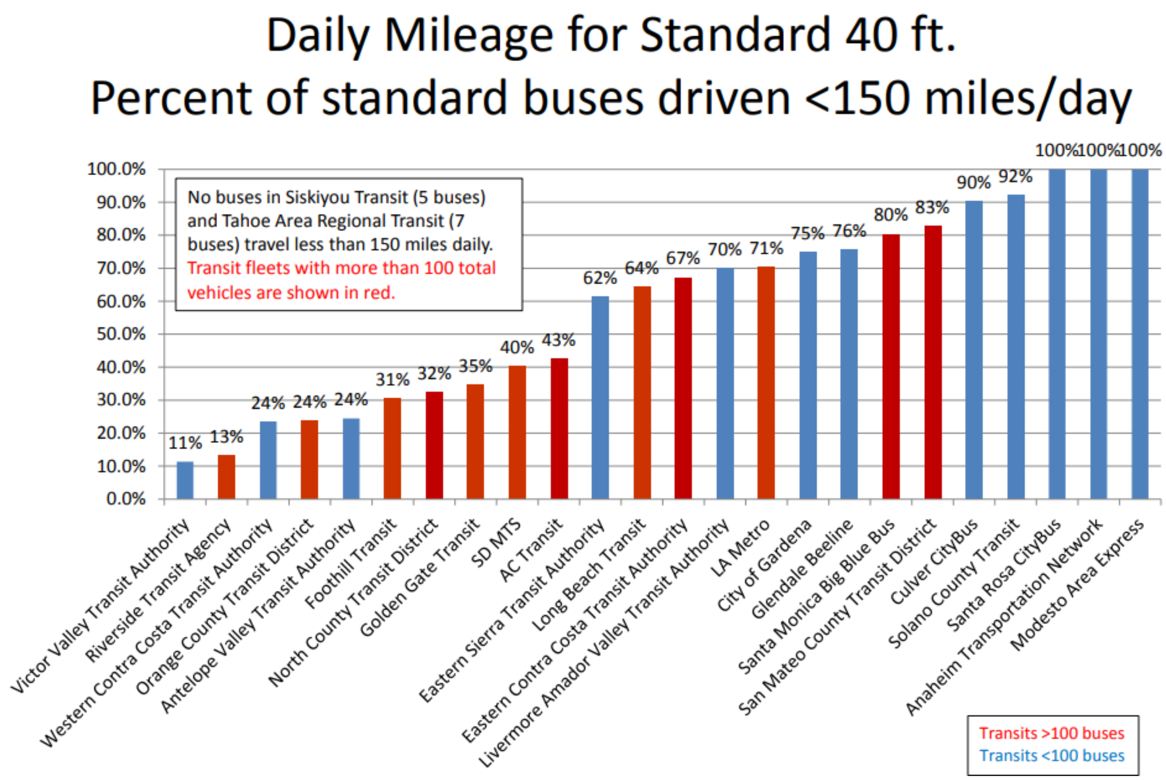
Fuel cell electric buses use hydrogen as their primary source of power. For vehicle applications, the typical storage solution for hydrogen is in a gaseous form at 350-700 bar pressures. Currently, transit buses fuel at 350 bar and many fuel cell buses can obtain a range of 300-350 miles, which is sufficient for many transit functions. However, some transit agencies operate their transit buses for up to 20 hours per day or run long-distance intercity bus service. As a result, some transit operators require buses with ranges up to 500 miles per fueling.

To obtain longer ranges, transit operators could potentially use 700 bar fueling for transit buses. This transition to 700 bar fueling will require several advances. Light-duty fuel cell vehicles already use 700 bar fueling to store small quantities of hydrogen. However, 700 bar fueling is not standard practice for heavy-duty vehicles where larger scale hydrogen storage is required. Research will need to be conducted to understand the ramifications of 700 bar fueling for onboard hydrogen storage tanks on heavy-duty vehicles. Fast filling hydrogen at high pressures also causes the hydrogen to rapidly heat up, which can threaten the integrity of the tank if not properly managed. Modifications can be made to hydrogen refueling infrastructure to mitigate these concerns. For 700 bar fueling, the hydrogen must be precooled to -40°C before it can be dispensed into a vehicle. The precooling system is expensive (costing $100,000-$200,000 per dispensing hose) and is energy intensive, adding about $0.50 per kg of hydrogen. Further research needs to be conducted to understand the implications that 700 bar fueling will have for storage tanks and hydrogen fueling infrastructure. Efforts will need to be undertaken to reduce the costs associated with precooling.

Standards will also need to be developed for 700 bar fueling for heavy duty vehicles[7]. SAE J2601 provides standards for 700 bar fueling for light duty vehicles that have a capacity of less than 10 kg of hydrogen. SAE J2601-2 provides standards for 350 bar fueling for heavy duty vehicles but only optional standards for 700 bar fueling for heavy duty vehicles. As a result, there is a gap in the standards for high pressure hydrogen fueling for buses. This gap will need to be filled to facilitate the standardization of 700 bar fueling equipment and fueling procedures.

The development of 700 bar fueling for buses and heavy-duty vehicles will allow buses to carry more hydrogen, which will improve range and performance of the bus. In California, there are multiple transit operators that have extended routes. For example, Victor Valley Transit Authority has some routes that are up to 400 miles long. As a result, developing 700 bar fueling is important for serving extended routes. Furthermore, the hydrogen truck sector is also attempting to standardize hydrogen fueling at 700 bar. As a result, the development of 700 bar fueling for transit buses would allow bus and truck hydrogen fueling infrastructure to be interoperable.

[7] Hydrogen Europe." Refueling Stations." Available at: https://hydrogeneurope.eu/refueling-stations



Source: California Air Resources Board[8]

High Efficiency Heating Systems

HVAC plays an integral role in the rider's experience and comfort. However, HVAC and especially heating, is responsible for a significant amount of energy consumption on a bus. Traditional transit buses have HVAC systems that are powered by fossil fuels and can divert waste heat from combustion to heat the bus. Low-No buses do not have this resource available to them and usually power their HVAC system with electric resistance heating from the vehicle's battery or fuel cell. This forces the HVAC system to compete with the propulsion system for power from batteries or the fuel cell. This parasitic load has dramatically decreased the range and performance of zero emission buses especially in cold climates. In extremely cold conditions, the heating system can consume more power than the vehicle propulsion system. Due to size, weight, and structural concerns, it is not practical to mitigate this problem by adding more batteries to the bus to provide additional energy capacity.

Heat pumps provide an alternative to using electric resistive heating. Heat pumps capture heat from air outside of the bus and transfer heat to the inside of the bus. Heat pumps are very useful because they can produce heat even when the exterior temperature is colder than the interior temperature. Since heat pumps transfer heat instead of generating it, they use significantly less energy than other forms of heating which can help to mitigate the problem of HVAC parasitic load. Heat pumps are currently being used in European markets and heat pumps that use carbon dioxide (R744 refrigerant) as the medium to transfer heat are becoming increasingly popular. The introduction of heat pumps to the transit sector has

[8] California Air Resources Board. (2016). "Transit Agency Survey Preliminary Results." ACT Workgroup Meeting. Available at: https://ww3.arb.ca.gov/msprog/bus/transit_survey_summary.pdf

been limited in the United States and bus manufacturers have limited experience working with this technology. As a result, heat pumps are in the early stages of commercialization and more work needs to be done to integrate this technology into bus systems. Smaller fuel cells may also be used in a battery electric bus to produce heat. A fuel cell heater can produce electricity for electric resistance heating and be designed in a way that recovers the fuel cell waste heat for optimal efficiency. Partners and funding are needed to demonstrate advanced high efficiency heating systems.

Fuel-fired Heaters

While heat pumps are an attractive solution for heating, this technology has limits. Since heat pumps move heat from the exterior environment to the interior of the bus, they will not be effective in extremely cold climate conditions, like those found in the northern and northeastern regions of the United States. As a result, many transit operators in cold climate regions may be installing fuel-fired heaters (using fossil fuels like diesel, propane, or compressed natural gas) on their zero emission buses to provide heating. By using these heaters, at least during the coldest months of the year, they hope to maximize passenger comfort and bus performance.

The use of fuel-fired heaters poses several challenges for transit buses. Fuel-fired heaters produce greenhouse gases, particulate matter, and NOx emissions which reduces the environmental and public health benefits of the bus. These emissions raise legitimate questions about whether a bus using a fuel-fired heater is really a “zero emission” bus, which can cause reputational harm to the Low-No bus industry. Currently, there are few regulations on the use of fuel-fired heaters. Some states have restrictions on the climate conditions under which fuel-fired heaters can be used. Under federal law, fuel-fired heaters are unregulated. As a result, there are no regulations that limit emission levels from fuel-fired heaters. This has raised concerns that emissions from a fuel-fired heater can be substantial. Since many diesel and compressed natural gas buses use aftertreatment and ultra-low NOx technologies, there is a risk that a fuel-fired heater can potentially produce a disproportionately large amount of emissions. Further research needs to be conducted on fuel-fired heaters to benchmark the amount of emissions they produce. A Clean Emission Protocol and an emissions standard also need to be developed for fuel-fired heaters to minimize the amount of emissions they release and ensure that they do not produce large quantities of emissions. Funds are needed to perform emissions testing on fuel fired heaters and work with the supplier to develop a clean emission protocol that can guide future fuel-fired heater deployments.