ZERO EMMISSION PROGRAM

Zero Emission Transit Bus Technology Analysis

Volume 4

REPORT PERIOD : JANUARY 2022 – JUNE 2022

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Leading the way to a

ZERO EMISSION FUTURE.

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Author and Acknowledgements

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Abstract

The Zero Emission Transit Bus Technology Analysis (ZETBTA) is designed to meaningfully analyze the various transit bus technologies that AC Transit operates. This report, Volume 4, is the fourth edition of the study which concludes the two-year study with results from the fuel-cell electric bus (FCEB), battery electric bus (BEB), diesel hybrid bus, and conventional diesel bus technologies control fleet. There are five different technologies being evaluated: two different fuel-cell electric system designs, along with the other technologies. Five of each bus technology types are included in this study; hence the original nickname of the report was the 5X5 Transit Bus Technology Analysis. While AC Transit recognized the value of operating five different transit bus technologies by the same agency on the same routes in the same service environment, we realized that over 20 years of experience operating zero emission bus (ZEB) technologies afforded the opportunity to go much further. We integrated lessons learned and best practices gleaned from our extensive experience in deploying ZEB technologies, including developing innovative workforce training programs and data integration and management. When selecting cost and performance data to include in this analysis, AC Transit carefully considered key performance indicators (KPI) that align with our Strategic Plan and ZEB Transition Plan to guide the implementation of ZEB fleets. This approach provides data results that help assess which ZEB technology can best meet the operational requirements of the District while being financially efficient and sustainable.

Volume 4 of the Zero Emission Transit Bus Technology Analysis report is an enhanced version from the third publication. The additional results presented in this reporting period include the following that are key takeaways from the previous report:

1) The District updated its ZEB Transition Plan to meet requirements established in the Bipartisan Infrastructure Law (BIL) and type of technology replacement based on the ZETBTA cost/ performance data.
2) Workforce training has achieved over 25 thousand hours of instruction on ZEB technology and is moving forward with testing mixed reality systems (virtual and augmented reality) to engage workforce in the learning process.
3) Infrastructure upgrade at Oakland (Division 4) will create the capacity necessary to support our 2040 planned inventory.
4) Continued cost increases for the diesel, hydrogen, and electricity energy sources.
5) Summary comparison of the 4 volumes added to the appendix with a corrigendum on corrective action on data issues.

Acronyms

Alameda-Contra Costa Transit District	AC Transit/The District
Application Programing Interface	API
Battery Electric Bus	BEB
Business Intelligence	BI
California Air Resources Board	CARB
California Code of Regulations	CCR
Carbon Dioxide	CO_2
Cost per Mile	CPM
Data Integration and Management Environment	DIME
Direct Current – Fast Charging	DC-Fast Charging
Disadvantaged Communities	DAC
Division in Emeryville	D2
Division in Oakland	D4
Doctor of Philosophy	PhD
Environmental Protection Agency	EPA
Fuel Cell Electric Bus	FCEB
Gallon	Gal
Green House Gasses, Regulated Emissions, and Energy use in Transportation	GREET
Heating, Ventilation and Air Conditioning	HVAC
Key Performance Indicators	KPI
Kilogram	Kg
Kilowatt	Kw
Kilowatt-Hour	kWH
Labor and Materials	L&M
Learning Management System	LMS
Leland Stanford Junior University	Stanford University
Life-to-date	LTD
Liquid Hydrogen	LH_2
Low Carbon Fuel Standard	LCFS
Miles between Chargeable Road Calls	MBCRC
Miles per Diesel Gallon Equivalents	M/DGE
Operations and Maintenance	O&M
Original Equipment Manufacture	OEM
Pacific Gas & Electric Business High Use Electric Vehicle	PG&E's BEV-0
Personal Protective Equipment	PPE
Senate Bill	SB
Stanford Energy Corporate Affiliate	SECA
Structured Query Language	SQL
To Be Determined	TBD
Zero Emission Bus	ZEB
Zero Emission Transit Bus Technology Analysis	ZETBTA
24-Hours, 7 Days a Week	24/7
5 Buses of the 5 Fleet Groups	5x5

About AC Transit

The Alameda-Contra Costa Transit District (AC Transit) is the largest public bus-only transit agency in California. Based in the San Francisco Bay Area's East Bay, and headquartered in Oakland, AC Transit formed in 1960, assuming the storied transit routes of the Key System and its predecessors, which over the previous 100 years, carried passengers via horse-drawn rail streetcars, electric streetcars, ferries, and buses. AC Transit has an established commitment to preserving and improving the quality and quantity of transit service for 1.5 million East Bay passengers that populate our 364 square mile service area, which includes Alameda and Contra Costa counties' 13 cities and adjacent unincorporated areas of the East Bay.

AC Transit is a recognized leader in zero emission buses (ZEB), both nationally and internationally. Our transit district has been aggressively pursuing opportunities and determining the feasibility of reduced emission and zero emission technologies for nearly 20 years. AC Transit has improved the ZEB deployment process by enhancing project delivery methods and ongoing sustainable maintenance practices. Each phase of development offered our internal subject matter experts an opportunity for improved best practices on procurement, project delivery, operations, and ZEB technology performance. As a result, we have emerged as a vanguard in both testing and comparing the costs and results of various conventional and zero emission fuel technologies in a public transit environment. This report is the fourth volume of AC Transit's data gathering and research, which will determine which transit bus technology and infrastructure best meets the needs of our service.

Service Profile

AC Transit operates 129 fixed routes, with two primary forms of service: East Bay local service and Transbay express service. East Bay local service consists of regular routes, bus rapid transit routes, and supplemental school service. The service hours vary by line, with much local service operating every day from approximately 5:30 a.m. to midnight and All-Nighter lines operating from 1:00 a.m. to 5:00 a.m. Based on AC Transit's Clean Corridors Plan, the ZEB deployments are prioritized for disadvantage communities that stretch from the northern-most point of the District to nearly the southern-most part of Alameda County and touch all operating Divisions (Richmond, Emeryville, East Oakland, and Hayward).

Zero Emission Bus Program Overview

Spanning the past two decades, AC Transit has built the most comprehensive ZEB Program in the United States that has generated over 5 million miles and eliminated over 12,800 metric tons of CO2. The programs technology has expanded from a single hydrogen fuel-cell electric bus to a fleet of new generation hydrogen fuel cell and battery electric buses. Our ZEB infrastructure includes on-site hydrogen production and fueling, electric charging, on-site fleet maintenance, and workforce training.

ZEB Program Highlights:

Zero Emission Miles:
5 Million

ZEB Workforce Training:
25,414
Hours

CO2 Emissions Eliminated:
12,831
Metric Tons

Currently we have forty-three (43) ZEBs in service: thirty-six (36) FCEB [thirty (30) New Flyer and six (6) VanHool] and seven (7) BEB [five (5) New Flyer and two (2) Gillig]. As we grow our ZEB fleet, we will also need to build the infrastructure required to re-energize each bus.

AC Transit is deploying both ZEB technologies side-by-side at our Oakland (Division 4) facility. Built in 2014, the Oakland division's hydrogen station has the capability to fuel thirteen (13) buses consecutively. The six (6) depot DC-fast charging stations, installed in 2020, provide a maximum output of 125kW when two charging stations are conjoined. Our transit district's future design plans include the installation of charging infrastructure for up to fifty (50) buses. At the Emeryville (Division 2) facility, AC Transit recently expanded our hydrogen fueling capacity to accommodate sixty-five (65) buses consecutively, with design plans to install up to twenty-six (26) depot DC-fast charging stations.

AC Transit also participates in the California Low Carbon Fuel Standard (LCFS) market as a generator of credits based on green hydrogen production for bus use and through the deployment of ZEBs. As the District's ZEB fleet expands, our transit district will have a growing revenue source through the sale of LCFS credits that can be used to offset the fuel costs of the fleet.

The Agency continues to explore funding opportunities that will expand the zero-emission program. Our transit district has secured purchasing support for an additional forty-one (41) ZEBs that includes the combination of twenty-one (21) 40-foot battery electric buses and twenty (20) 40-foot fuel-cell electric buses that will have the latest advancements in zero emission technology. During the review period, we had 27 FCEBs in service.

Transit Bus Technology Summary

This is the fourth publication of the Zero Emission Transit Bus Technology Analysis report, representing data collected on energy, capital and operating costs, performance metrics, mileage, reliability, and availability from January 2022 through June 2022. This open-source report is AC Transit's contribution to the transit industry, offering an invaluable roadmap for agencies seeking to transition fleets to 100% zero emission.

The study reflects the transit industry's first ever, side-by-side evaluation of ZEB technologies by a single transit agency, in the same service environment using the same ZEB bus manufacturers, in a comparison to AC Transit's conventional diesel bus technologies.

The 5x5 matrix includes the bus grouping attributes and data summaries captured for the reporting period of this publication. Included in the report are the deployment statistics that the buses were assigned to using guiding principles of the District's Clean Corridor Plan that identifies routes serving disadvantaged communities.

Figure 1 (next page) provides an overview of the five (5) fleet groups utilized in the study and the summary statistics during the report period, the Diesel fleet had the highest fleet mileage (92,128), where the Legacy Fuel Cells had the lowest mileage (34,533). The BEB had the lowest cost per mile (CPM) when applying warranty and LCFS credits ($0.53), however the Legacy Fuel Cells had the highest CPM ($4.11) as they have been outside the warranty period. The BEB fleet was the most reliable (59,549 MBCRC) because the fleet only had one road call in the reporting period. Diesel had the highest availability (89%), however, produced the most carbon emissions (235 metric tons of CO2). The Legacy Fuel Cell fleet was the least reliable (3,139 MBCRC). The Hybrid Diesel fleet was the least available (51%). Additional details highlighting the matrix conclusions are found in the 5x5 data summary section of this report.

Figure 1: 5x5 Vehicle Matrix

FLEET	DIESEL (BASELINE)	DIESEL HYBRID	FUEL CELL ELECTRIC (FCEB)	BATTERY ELECTRIC (BEB)	LEGACY FUEL CELL
Series Grouping	1600	1550	7000	8000	FC
Technology Type	Diesel	Hybrid	Fuel Cell	Battery	Fuel Cell
Bus Qty	5	5	5	5	5
Manufacturer	Gillig	Gillig	New Flyer	New Flyer	Van Hool
Year	2018	2016	2019	2019	2010
Length	40′	40′	40′	40′	40′
Data Summary (January 2022 – June 2022)					
Fleet Mileage	92,128	54,660	88,188	59,549	34,533
Life-to-Date Mileage	757,363	1,235,654	452,103	272,046	1,423,925
Cost/Mile	$2.29	$3.11	$2.52	$1.61	$4.15
Cost/Mile (w/credits)	$2.25	$3.00	$2.20	$0.53	$4.11
Emissions (CO2 Metric Tons)	235	106	0	0	0
Fleet Availability	89%	51%	78%	66%	57%
Reliability (MBCRC)	10,236	5,466	6,299	59,549	3,139
MPG (DGE)	4.0	5.3	7.9	17.7	5.5

Bus Fleet Specifications

The buses selected are all 40-foot local route units spanning manufacturing years 2010 through 2019. The mix includes fuel cell, battery electric, diesel, and diesel-hybrid technology. The study's buses represent the four propulsion technologies currently under comparison at other transit agencies. However, our unprecedented distinction is that never before have all four technologies been critically tested under the ownership of one agency. AC Transit included our legacy fuel cell bus in the study to gauge its performance against the latest zero emission technology on the market.

Figure 2 below provides additional specifications of the study's bus fleet. The matrix includes the dates of activation of service, the cumulative life-to-date miles of the study, and the design specification types of the twenty-five (25) buses. It is important to note, AC Transit uses a typical lead time of eighteen (18) months from order date to service activation, and it's based on the average bus order, delivery, and acceptance timeline experienced during recent procurements.

Figure 2: Bus Specification Matrix

FLEET	DIESEL (BASELINE)	DIESEL HYBRID	FUEL CELL ELECTRIC (FCEB)	BATTERY ELECTRIC (BEB)	LEGACY FUEL CELL
Series Grouping	1600	1550	7000	8000	FC
Manufacturer	Gillig	Gillig	New Flyer	New Flyer	Van Hool
Bus Purchase Cost	$488,247	$699,060	$1,156,044	$938,184	$1,232,095
Energy/Fuel Capacity	120 gal	120 gal	38 kg	466 kw	40 kg
Range Specification	450 miles	500 miles	300 miles	180 miles	200 miles
Propulsion Design	Conventional Diesel	Diesel/ Battery	Battery Dominant	Battery	Fuel Cell Dominant
Battery Design	N/A	Lithium-Ion	Lithium-Ion	Lithium-Ion	Lithium-Ion
Engine/Powerplant	Cummins	Cummins	Ballard/A123	Xalt Energy	UTC/EnerDel
Transmission/Propulsion	Voith	BAE	Siemens	Siemens	Siemens
In Service Date	Jan 2018	Aug 2016	Jan 2020	May 2020	Aug 2011
Mileage since July 2020	439,796	327,484	368,476	240,579	227,448
Life-to-Date Mileage	757,363	1,235,654	452,103	272,046	1,423,925
Funding Source	Federal, Regional, Local	Federal, Regional, Local	State, Regional, Local	Federal, Regional	Federal, State, Regional

Facility Infrastructure Specifications

Zero emission technology buses operate out of both the Oakland (Division 4) and the Emeryville (Division 2) facilities. At the Oakland Division, AC Transit's infrastructure includes six (6) stationary battery chargers to support our Battery Electric Buses (BEB) and a vapor compression hydrogen station to support Fuel Cell Electric Buses (FCEB). Our transit district has recently updated to a liquid compression hydrogen station at the Emeryville Division. Currently, only the Oakland Division is equipped to support both Fuel Cell Electric (FCEB) and Battery Electric Buses (BEB) and therefore, the study is localized here.

Figure 3, below, provides an overview of the facility infrastructure that supports the ZEB fleets and includes summary statistics for the reporting period. Included in the study are the operating and maintenance (O&M) costs, availability, and reliability operating statistics. The biggest takeaway is that the BEB fixed electric charging facility was only available 23% of the time. A lack of a maintenance agreement with manufacture and the ongoing issue with power module failures contributed most of the charger down time. The district is currently working with ChargePoint on a 5-year warranty contract and to upgrade the 6 chargers with the newest power module available. The FCEB facilities achieved more than 96% availability. Costs for the DC fast charging equipment at the Oakland facility were covered under warranty. The costs for the FCEB equipment include the storage tank rental and maintenance activities. Additional information on the facility operating statistics is detailed in the following sections.

Figure 3: Existing Facility Matrix

	BATTERY ELECTRIC BUS	FUEL CELL ELECTRIC BUS	
	Oakland Facility	**Oakland Facility**	**Emeryville Facility**
Facility Description			
Current Status	Operational	Operational	Operational
In Service Date	2020	2014	Rehab 2020
Type of Fuel	Electric	Hydrogen	Hydrogen
Technology	Stand-Alone Chargers	Vapor Compression	Liquid Compression
Capital Cost (Build)	$896,937	$6,300,308	$4,424,644
Core Hardware	(6) ChargePoint CPE250s	IC-50 Ionic Compressor	Dual ADC MP-100 Cryo Pumps
Related Hardware	(6) 100A/480V Circuits	Ambient Vaporizer	High Pressure Vaporizers
Fueling Location	West Wall of Facility	Fuel Island	Fuel Island
Funding Source	Federal, Regional	Federal, State, Regional	State, Regional
Operating Statistics: January 2022 – June 2022			
Total O&M Cost	$0	$89,307.78	$71,351.04
Availability	22.7%	97.2%	96.7%

Battery Electric Infrastructure

BUILT:
2020
COST:
$896,937

Oakland Battery Electric Bus Infrastructure

The battery charging infrastructure at the Oakland (D4) Division was built in 2020 at a total cost of $896,937. The configuration consists of six stationary ChargePoint CPE250 chargers and one mobile CPE250 shop charger. The chargers operate at 62.5 kW in stand-alone mode. In paired mode, two chargers will combine to charge a single vehicle at 125 kW. The chargers had an initial one-year warranty provided by the bus OEM as part of the installation contract, that covered all repairs and parts needed to maintain the chargers.

Many of the fault issues were able to be corrected remotely however, the most common component related failure has been the power modules (two units are required for the 62.5 kw charge rate). To date all the power modules were repaired under warranty but had a cost avoidance of $10,500 dollars each. During the warranty period, $298,600 in repairs were performed by the OEM onsite. The cause of the failures were traced to the communications between the chargers and the bus during the charging process. The charger manufacture continues to work with the bus OEM to deploy coordinated software updates in both the bus and charger. Ensuring software updates on both sides of the plug are coordinated and vetted prior to deployment is critical for reliable operation. Language in purchasing contracts could include provisions for coordinated updates.

Repairs and monitoring of chargers covered under warranty were a priority and the vendor attempted to resolve issues quickly. After the warranty expired, requests for parts and transfer of some monitoring information were delayed since no formal agreement was in place. This vendor requires an extended warranty contract or else high parts costs and slow turnaround to repair requests can be experienced. An extended maintenance agreement – which is expensive and unreasonable – is being explored to help facilitate expedited parts and service requests. To facilitate our continued ZEB expansion, having our own fully trained technicians and receiving a robust training package from the infrastructure OEM is necessary to ensure repairs are prioritized and the equipment remains in a state of good repair.

Hydrogen Infrastructure

Oakland Hydrogen Station

The hydrogen station at the Oakland Division was built in 2014 at a total cost of $6.3 million. The station includes a 9,000-gallon liquid hydrogen storage tank, ambient vaporizers, an IC-50 ionic compressor, and 360 kg of high-pressure gaseous storage. The station also includes an electrolyzer that produces up to 65 kg of green hydrogen per day. Two dispensers were installed in the fuel island that are aligned with the diesel dispensers making the bus servicing process seamless. This station has a fueling capacity for thirteen (13) buses per 12-hour fueling window. The Oakland hydrogen station is maintained by an O&M agreement with a vendor. The cost of this O&M, covering operations, preventative maintenance, and corrective maintenance is $14,884 per month. This includes the $3,800 monthly cost of liquid hydrogen tank maintenance. Maintenance includes a remote monitoring and alarm system to support 24/7 operations, including the immediate dispatch of a technician upon alarm. Preventative maintenance is done to all equipment on a weekly, monthly, or annual basis. Monthly inspection and certification of liquid storage (hydrogen or nitrogen) is also included. The District plans to upgrade the Oakland hydrogen station with liquid pumps once funding is secured.

H_2

BUILT:
2014
COST:
$6,300,308

The Emeryville Hydrogen Station

The hydrogen station at the Emeryville Division was originally built in 2011 at a cost of $5.1 million for the heavy-duty bus portion of a project that also included a light-duty fueling component. In 2020, the station was upgraded at a cost of $4.4 million. Upgrades to the station include a 15,000-gallon liquid hydrogen storage tank, dual ADC MP-100 Cryogenic Pumps, high pressure vaporizers, and 1750kg of high-pressure gaseous storage. Two dispensers were installed in the fuel island alongside the diesel dispensers, making the bus servicing process seamless. The upgraded station can fuel 65 FCEBs in the 12-hour fueling window. The Emeryville hydrogen station is maintained by an O&M agreement with a vendor. The cost of this O&M covering operations, preventative maintenance, and corrective maintenance is $11,891 per month. This includes $5,950 for liquid hydrogen tank, and $600 nitrogen tank maintenance. Maintenance services provide a remote monitoring and alarm system to support 24/7 operations with the immediate dispatch of a technician upon alarm. Preventative maintenance is done to all equipment on a weekly, monthly, or annual basis. Monthly inspection and certification of liquid storage (hydrogen and nitrogen) is also included.

BUILT:
2011
2011 COST:
$5,100,000
2020 UPGRADE:
$4,424,644

Facility Investment Projects

AC Transit has design plans for two additional BEB charging facilities by the end of 2024. Infrastructure to accommodate up to twenty-six (26) additional charging stations is underway at the Emeryville (D2) facility. This project is in construction and is fully funded with completion forecast for mid-year 2023.

In 2023, the District is planning to construct a charging facility that will support twenty-four (24) BEB charging stations at the Oakland (D4) facility. The design is a BEB charging trellis with overhead charging distribution. This project is in the final design phase and is fully funded.

Daily H2 fueling capacities at the Oakland (D4) facility will increase from 13 buses to 75-150 buses per fueling window for FCEBs because of a core hardware upgrade from a traditional compression system with two dispensers to a two piston cryogenic pumps with four dispensers. The district is planning to add a future station at its Hayward (D6) facility to support the FCEB fleet. Hayward facility was selected for the next H2 station because of the relatively long routes and the significant deadhead component to many of the routes.

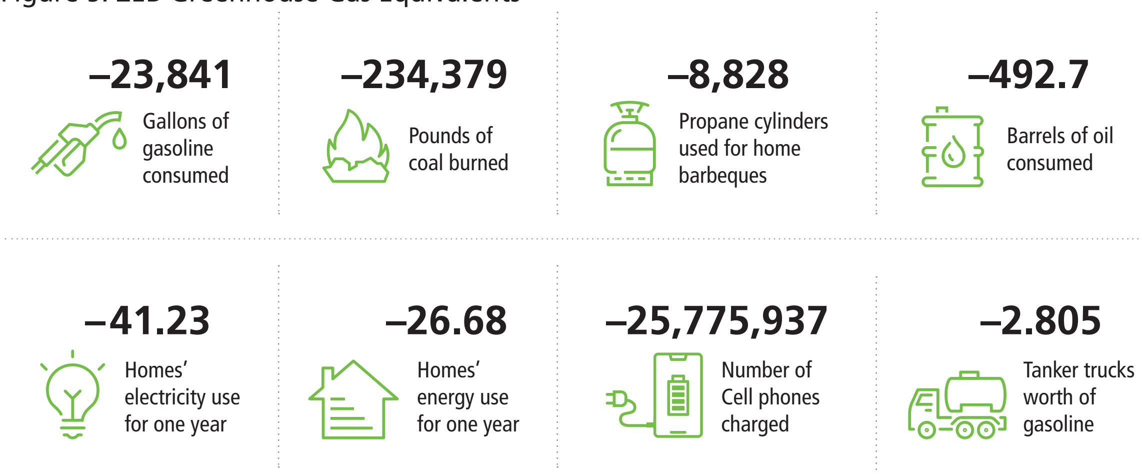
Figure 4: Facility Planned Projects

	BATTERY ELECTRIC BUS		FUEL CELL ELECTRIC BUS	
	Emeryville Facility (D2)	**Oakland Facility (D4)**	**Oakland Facility (D4)**	**Hayward Facility (D6)**
Facility Description				
Current Status	In Construction	In Design	In Design	In Planning
In Service Date	09/30/2023	12/31/2023	12/23/2023	12/31/2026
Type of Fuel	Electric	Electric	Hydrogen	Hydrogen
Technology	Distributed Charging	Distributed Charging	Liquid Compression	Liquid Compression
Core Hardware	ChargePoint Power Blocks	ChargePoint Power Blocks	Dual ADC 2-Piston Cryo Liquid Pumps	Dual ADC 2-Piston Cryo Liquid Pumps
Related Hardware	Dual Port Dispenser Charge Management System	Dual Port Dispenser Charge Management System	High Pressure Vaporizers 25K gal LH^2 Tanks Four Dispensers	High Pressure Vaporizers 25K gal LH^2 Tanks Four Dispensers
Fueling Location	South & East Wall of Facility	Bus Yard Overhead Trellis	Fuel Island	Fuel Island
Operating Capacities				
Core Hardware	26 BEB Distributed Charging Stations	24 BEB Distributed Charging Stations with Overhead Trellis	Dual ADC 2-Piston Cryo Liquid Pumps	Dual ADC 2-Piston Cryo Liquid Pumps
System Capacity	160 to 200 kW per pair of charging positions	160 to 200 kW per pair of charging positions	25,000 LH^2 Storage, 2 dispensers	25,000 LH^2 Storage, 2 dispensers
Daily Vehicle Capacity (By Design)	26 per fueling window	24 per fueling window	150 per 12-hour window	150 per 12-hour window
Daily Vehicle Capacity (Proven)	26 per fueling window	24 per fueling window	130 per 12-hour window	130 per 12-hour window
Charge/Fueling Time	TBD	TBD	6 to 8 minutes per fill	6 to 8 minutes per fill

Environmental Impact

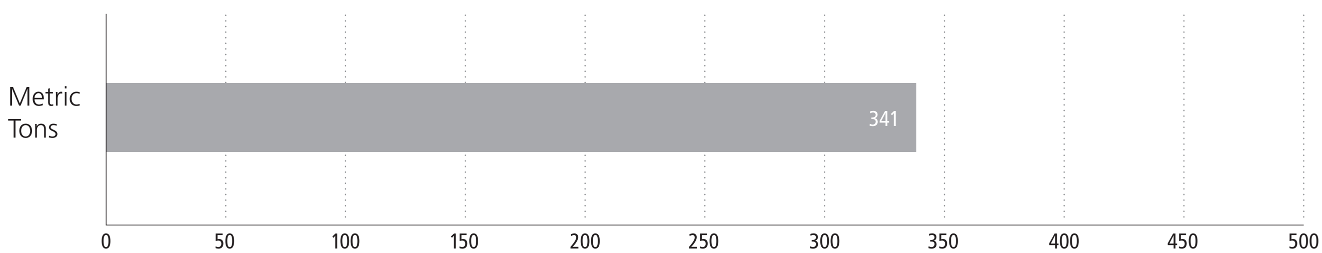
The District uses the 1600 series standard diesel bus fleet as the baseline control group and compares each other fleet to measure the environmental impact. Carbon dioxide (CO2) is the primary greenhouse gas that is used for analyzing the environmental benefit in this study. The CO2 comparison is measured in metric tons from tank-to-wheel that is calculated by using a carbon emission conversion methodology from the Environmental Protection Agency (EPA). The subsequent table demonstrates the ZEB CO2 reduction in various greenhouse gas equivalents based on 540 metric tons saved from the ZEB fleet deployments.[1]

Figure 5: ZEB Greenhouse Gas Equivalents



The following figure compares the carbon emissions by fleet technologies. For the reporting period, the diesel and hybrid vehicles combined to produce 341 CO2 metric tons compared to the ZEB fleets (7000, 8000, Legacy Series) that had zero tailpipe emissions.

Figure 6: Combined Diesel and Hybrid Carbon (CO2) Emissions (January 2022 – June 2022)



[1] EPA Calculator: https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator

5X5 Data Summaries

Fleet Mileage

An ideal mileage target is operating the bus approximately 150 miles per day over a 30-day period. A bus achieves 4,500 miles per month giving a test fleet a total of 22,500 miles per month. Zero-emission and diesel-hybrid bus mileage can decrease during March, June, August, and December, which are operator sign-up months. These decreases are primarily attributed to the training demands of new operators who are unfamiliar with the test fleet buses. This is not the case for diesel bus, which are available at all operating divisions.

Monthly mileage by technology is shown in Figure 7, below. Vehicle availability is directly correlated with mileage traveled, which is captured in the performance. Except for FCEB, fleet mileage reduced across all other technologies relative to previous reporting periods. The Legacy FC fleet mileage was suppressed due to limited availability of two (2) buses, additionally lower output of the aging fuel cells limited how and where this fleet could be deployed. Several drive motor failures and inventory supplier issues were the main contributing factor for the lower mileage on the hybrid fleet. Battery and faults in the high voltage system were a persistent issue on the FCEB fleet during this period. The BEB fleet was limited due to charging infrastructure and some issues related to the 24v bus charging system and vendor supply issues. The Diesel fleet mileage remained consistent during the evaluation period.

Figure 7: Mileage by Technology (January 2022 – June 2022)

TECHNOLOGY	JAN	FEB	MAR	APR	MAY	JUN	TOTAL
DIESEL	11,491	12,474	17,435	18,270	16,776	15,681	**92,128**
HYBRID	8,221	10,947	8,405	9,438	9,619	8,030	**54,660**
FCEB	14,396	12,844	14,042	14,320	17,576	15,009	**88,188**
BEB	10,080	10,454	12,464	12,328	7,215	7,009	**59,549**
LEGACY FC	6,472	5,157	4,915	6,469	5,648	5,873	**34,533**

Fuel Efficiencies

AC Transit utilized the Argonne National Laboratory GREET (Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation) model,[2] to construct Miles Per Gallon Equivalents (M/DGE) for the various energy fuels utilized. The GREET model has been adopted by government agencies, including the California Air Resources Board (CARB), industries, and academic institutions for its uniformity in deriving fuel economy equivalents, based on energy density, and emission estimates by type of fuel.

[2] Argonne National Laboratory: https://greet.es.anl.gov/

Figure 8: Fuel Efficiencies and Equivalents (January 2022 – June 2022)

TECHNOLOGY	Energy/Fuel	Fuel Efficiency	Efficiency Metric	Equivalent Efficiency	Equivalent Metric
DIESEL	Diesel	3.99	Miles/Gal	3.99	M/DGE
HYBRID	Diesel	5.25	Miles/Gal	5.25	M/DGE
FCEB	Hydrogen	7.09	Miles/Kg	7.88	M/DGE
BEB	Electricity	0.46	Mile/kWh	17.66	M/DGE
LEGACY FC	Hydrogen	4.98	Miles/Kg	5.53	M/DGE

AC Transit experienced the following relative fuel efficiencies using the GREET comparison model in the diesel equivalent format. The BEB buses achieved the highest fuel economy at 17.66 M/DGE, followed by FCEBs at 7.88 M/DGE. Another important metric the district is monitoring is the battery energy draw of drive motor on the BEB fleet. For this report period, 2.27 kWh/mile was the average for the BEB fleet.

Maintenance and Energy Costs

Cost per mile (CPM) is an industry standard when calculating cost comparison between fleets. Operating expenses are divided by the vehicles mileage to calculate the CPM. It is important that costs are viewed in two categories when comparing costs between fleet groups: Labor and Materials (Maintenance), and Energy. For this analysis, energy is diesel, hydrogen, or electricity, which is labeled as fuel in most budgets.

The fleet groups in this study use three type of energy sources required by the design of the bus technology. The energy rates are based on the purchased price of the diesel and hydrogen fuel where the electricity rate was based on the monthly utility bill consumption. The kilowatt-hour (kWh) and cost breakdown can be applied to the BEB fleet because a separate meter was installed at the charging station.

Out of the three energy sources used by AC Transit, the current price of hydrogen creates the largest CPM costs increase. Our transit district has been able to successfully manage the cost of electricity on PG&E's BEV-2 rate with the five (5) battery electric bus fleet thus far.

Figure 9: Energy/Fuel Rate (January 2022 – June 2022)

SOURCE	DIESEL	HYDROGEN	ELECTRICITY
Rate/Metric	$3.92 / Gal	$8.41 / KG	$0.214 / kWh

For the reporting period, the BEB fleet was the most cost effective at a $1.61 CPM which was helped by a favorable energy cost. The most expensive energy cost was in the Legacy FC fleet that had a $4.15 CPM. The Diesel fleet doubled its CPM to $2.29 due to very few items covered under warranty and an increase in diesel fuel costs. This was also similar with the Hybrid fleet as it experienced heavy repairs that pushed the maintenance costs and increased the CPM to $3.11. The Legacy fleet with the highest CPM at $4.15 continues to experience challenges with parts availability, declining fuel economy, and increasing repair frequencies. All energy costs had an increase in this report period, but diesel fuel saw the largest increase of almost 36% due to commodity shortages. Hydrogen with only a modest increase of 8% still had had the most impact to the CPM with the fuel cell bus fleets. It is expected that as the market continues to expand, the cost of hydrogen fuel may decrease lowering the CPM to a more favorable position.

Figure 10: Operational Cost/Mile Totals (January 2022 – June 2022)

COST/MILE	DIESEL	HYBRID	FCEB	BEB	LEGACY FC
Maintenance	$1.28	$2.37	$1.33	$1.15	$2.46
Energy (Fuel)	$1.01	$0.74	$1.19	$0.46	$1.69
Total	**$2.29**	**$3.11**	**$2.52**	**$1.61**	**$4.15**

When reviewing the energy costs on a per-mile basis across the test fleets, the FCEB was approximately 18% higher than the diesel fleet. During the period, the diesel and fuel cell were similar in labor and material costs. BEB technology was the least expensive for energy costs, totaling $27,354 at about $0.46 per mile.

Figure 11: Maintenance & Energy Cost (January 2022 – June 2022)

TOTAL	DIESEL	HYBRID	FCEB	BEB	LEGACY FC
Maintenance Cost (L&M)	$118,082	$129,653	$117,147	$68,504	$84,902
Work Orders	309	222	298	219	217
Labor Hours	727	733	668	435	515
Energy (Fuel)	$92,766	$40,285	$104,692	$27,354	$58,367

Credits and Warranties

AC Transit has a warranty recovery program, which identifies warranty claims, records, and enforces claims against manufacturers, coordinates repairs to the bus fleet, and processes repair reimbursements performed by employees in-house. The figure below summarizes the value of warranty claims recovered by ZEB battery and fuel cell technology fleet buses with additional details in the subsequent section.

Figure 12: ZEB Recovery Total (January 2022 – June 2022)

TECHNOLOGY	WARRANTY CLAIMS	WARRANTY RECOVERED	LCFS CREDITS	TOTAL RECOVERY
FUEL CELL	19	$28,074	$0	$28,074
BATTERY ELECTRIC	14	$50,049	$14,205	$64,254

Low Carbon Fuel Standards (LCFS) Credit

In January 2020, the District hired a third-party vendor to assist with the management of ZEB Program LCFS credits. To date, credits total nearly $184,000. The revenue collected for fiscal year 2022 is $39,794. The credits are differentiated by vehicle type and highlighted in the table below.

Due to expiration of the renewable hydrogen "fuel pathway" by the District's hydrogen supplier, offset to the hydrogen fuel costs was suspended. Under the LCFS program, it is the responsibility of the supplier to maintain the pathway to generate credits. The District is working with the supplier to resolve the issue to continue generating credits once the fuel pathway is (re)approved by the State.

Figure 13: Annual Low Carbon Fuel Standard (LCFS) Credits

TECHNOLOGY	2021				2022		TOTAL SINCE JAN 2020
	JAN – MAR	APR – JUN	JUL – SEP	OCT – DEC	JAN – MAR	APR – JUN	
FUEL CELL	$0	$0	$0	$0	$0	$0	$64,305
BATTERY ELECTRIC	$15,615	$12,872	$16,132	$9,456	$9,147	$5,059	$119,368
TOTAL	**$15,615**	**$12,872**	**$16,132**	**$9,456**	**$9,147**	**$5,059**	**$183,673**

The revenue stream includes a brokerage fee and offsets from AC Transit alternative energy sources such as the solar panel facilities. The transit district forecasts this new revenue stream to increase as ZEB fleet increases over the next two years. The LCFS credits can be sold to provide a reliable revenue stream which may be used to offset either capital or operating expenses (such as hydrogen and fuel expenses).

The FCEB fleet CPM is adjusted with the applied warranties and Low Carbon Fuel Standard (LCFS) credits. For the reporting period, Figure 14 provides the adjusted CPM where the FCEB and BEB fleets had the most reductions due to the offsetting LCFS and warranty credits.

Figure 14: Operational Cost/Mile with Applied Credits (January 2022 - June 2022)

COST/MILE	DIESEL	HYBRID	FCEB	BEB	LEGACY FC
Adjusted CPM	$2.25	$3.00	$2.20	$0.53	$4.11

Fleet Availability

Fleet availability is a measurement of the bus readiness, specifically, for morning pull out. The percentage is calculated by dividing the number of planned workdays by the number of workdays each bus was available for service. Training and special events are included in the available count because the vehicle is deemed operationally ready for service. The cause of the unavailability is categorized by system components to show issues and normalize routine scheduled maintenance and unscheduled repairs within the test fleets.

The FCEB fleet was considered available for 78% of the time during the period and had one bus account for almost half of the days due to a Vanner DC converter issue. The BEB fleet operated at 66% availability with more than half of the total days related to retrofit of the charger cabling and programming by the OEM. The Legacy FC fleet averaged availability of 57% due to low output power of the Fuel Cell of several units. The Hybrid fleet only averaged 51% because of two engine failures and supply chain issues. The Diesel fleet averaged over 89% availability with no pattern or chronic issues. The availability of all fleets continues to be impacted by delays in the supply chain. Since transit operators are allowed a 20% bus spare ratio, an availability rating of 85% or higher would not impact service delivery. However, an availability rating of 90% or higher is desirable and expected.

Figure 15: Availability by Technology (January 2022 – June 2022)

TECHNOLOGY	JAN	FEB	MAR	APR	MAY	JUN
DIESEL	77%	79%	88%	99%	95%	96%
HYBRID	50%	69%	49%	48%	48%	43%
FCEB	72%	71%	71%	71%	94%	89%
BEB	72%	70%	81%	69%	42%	61%
LEGACY FC	65%	43%	42%	69%	62%	59%

Reliability (Miles Between Chargeable Road Calls)

Miles Between Chargeable Road Calls (MBCRC) is a standard maintenance performance indicator that measures the vehicle miles between mechanical failures during revenue service. Road calls may cause a delay in service and necessitate removing buses from service until repairs are made.

Figure 16: Miles Between Chargeable Road Calls (January 2022 – June 2022)

TECHNOLOGY	JAN	FEB	MAR	APR	MAY	JUN
DIESEL	3,830	12,474	17,435	9,135	16,776	15,681
HYBRID	4,111	5,473	1,681	9,438	9,619	8,030
FCEB	4,799	12,844	3,511	7,160	17,576	3,752
BEB	10,080	10,45	12,464	12,328	7,215	7,009
LEGACY FC	2,157	2,578	1,638	6,469	2,824	5,873

Road call failures are categorized by system and component and used to direct maintenance activities to eliminate the root cause. Provided below are the road call categories that include the failures related to the components.

- **Common System Failures** – For this report, one broad category was designated for systems common to all buses: air system, low voltage electrical, brakes, steering, HVAC, etc.
- **Engine/ Fuel Cell** – Energy generating systems used to power or propel the vehicle. The fuel cell includes various balance of plant supporting and auxiliary components.

- **Fuel System** – Diesel and Hydrogen storage issues and faults.
- **High Voltage Systems** – Storage and distribution of high voltage electricity is utilized to power drive motors and store energy.
- **Transmission/ Electric Drive** – Systems to provide the power to the differential

Figure 17: Road Calls by System (January 2022 – June 2022)

SYSTEM	DIESEL	HYBRID	FCEB	BEB	LEGACY FC	TOTAL
Common System Failures	5	4	5	1	4	**19**
Engine/Fuel Cell System	3	5	6	0	5	**19**
Fuel System	1	0	1	0	1	**3**
High Voltage System	0	0	2	0	1	**3**
Transmission/Electric Drive	0	1	0	0	0	**1**
Total	**9**	**10**	**14**	**1**	**11**	**45**

For the reporting period:

- The Diesel fleet had Nine (9) road calls with three (3) related to the Engine systems, and the others not concentrated in any specific system.
- The Hybrid fleet had ten (10) road calls, five (5) of which were for engine issues with five (5) unrelated systems.
- The FCEB fleet had fourteen (14) road calls, six (6) relating to the fuel cell system and two (2) each related to high voltage system. The other road calls were unrelated common systems failures that were not related.
- The BEB fleet had one (1) road call related to a common system.
- The Legacy FC fleet had eleven (11) road calls, of which six (6) were fuel cell/fuel system and one (1) high voltage battery related with the remainder related to common system failures.

Clean Corridor Deployments

The State of California Legislature passed SB 535 in 2012 requiring 25 percent of investments from the Cap & Trade program be spent in Disadvantaged Communities (DACs). The legislation carried with it methodology for identifying those communities' using information about income, race, pollution, and other factors. The state routinely updates state-wide maps of communities they identify as DACs. The focus on investments in disadvantaged communities is aimed at improving public health, quality of life and economic opportunity in California's most burdened communities and at the same time reducing pollution that causes climate change. The 5X5 plan features lines only assigned to communities identified as DACs in the Clean Corridors Plan. Appendix A-5 illustrates which lines had buses from this program deployed on them between January 1 and June 30, 2022. The results indicate that Lines 14, 20, 21, 45, 51A, 90 and 98 had the highest number deployments within the Clean Corridors program which meet the compliance of the DAC assignments. These lines were chosen for the following reasons:

1) They serve disadvantaged communities that could benefit from reduced emissions from ZEB vehicles.
2) They operate out of Division 4.
3) They have high ridership.
4) With the exception of Line 40, they are typically assigned 40-foot buses.
5) They are generally flat, with only one line – 54 – heading into the Oakland hills. All other lines go no higher than the Macarthur/580 corridor.

The primary lines for the core service network in East Oakland have been operating with weekday schedules since August 2020. The adjustment was made from the emergency service (7-day Sunday levels) to reduce pass-ups as higher ridership returned to the lines.

The only change recommended by staff is to remove Line 40 from the deployment list for this program as it should be assigned 60-foot buses 100% of the time and being in this program could lead to pass-ups given the 25 buses are all 40-foot coaches.

Workforce Development

Moving to a ZEB fleet required changes to the District's multiple operating functions. Transitioning requires training employees to keep pace with changing technologies. AC Transit provides operational training for its bus operators, mechanics, and other support employees. The following describes the process for the planning and scheduling of training and the inter-agency cooperation with Original Equipment Manufacturers (OEMs). Emphasis herein is primarily focused on mechanic training. The shift from internal combustion engines and propulsion technologies to zero emission systems is more complicated for mechanics than it is for bus operators.

It is important to note however that every bus operator at a District ZEB bus location is trained prior to the fleet being deployed into revenue service. Training provides each employee with both academic and behind-the-wheel drive time experiences. Topics covered include awareness of high-voltage systems, dash controls and indicator lights, specific start-up and shut-down procedures, and defensive driving safety. Training meets regulatory requirements per California Highway Patrol, Motor Carrier Specialist inspections as is also defined in the California Code of Regulations (Title 13 CCR, § 1229, Driver Proficiency).

In alignment with its strategic goals, AC Transit is seeking state and federal advocacy programs to secure funding to support the planning, design, construction, and operation of a training center that will provide zero emission technological skills for operations and maintenance transit workers to serve as a career gateway and support a workforce development center for disadvantaged communities.

Total ZEB Workforce Development Production

To date, the District has successfully scheduled and produced over 25,414 hours of training in one or more of the nineteen (19) courses listed in the table below. Note that the courses are recorded alphabetically and by title in the first column. Secondly, the column entitled Hours represents the duration of each class. Finally, course content is developed for specific bus fleet(s) as is depicted in the third column.

Figure 18: ZEB-based Course Catalog

Course	Hours	Fleet
A123 Battery Training (Vendor)	8	Gillig Hybrid/ New Flyer FCEB
Ballard Fuel Cell - ZEB (Vendor)	24	New Flyer FCEB
Ballard Fuel Cell 1K hrs PMI	4	New Flyer FCEB
Digital Multimeter (Distance Learning)	4	ZEBs/Hybrid
Fuel Cell Power Plant - ZEB	8	New Flyer FCEB/ Van Hool FCEB
High Voltage Electrical Safety - ZEB (Vendor)	8	FCEB/BEB
High Voltage: Awareness and Safety (Distance Learning)	3	VH/New Flyer FCEB and BEBs
Hydrogen FC Safety and Familiarization - ZEB	8	Van Hool FCEB
Hydrogen Fuel Cell Bus Hands-On - ZEB	240	Van Hool FCEB
Hydrogen: Safety, Fueling, and Storage - ZEB (Distance Learning)	3	VH/New Flyer FCEB
Lithium Ion Battery Familiarization - ZEB	8	ZEBs/Hybrid
New Flyer BEB Orientation - ZEB (Vendor)	3	New Flyer BEB
New Flyer BEB Srv/Maintenance - ZEB (Vendor)	24	New Flyer BEB
New Flyer FC Orientation - ZEB (Vendor)	3	New Flyer FCEB
New Flyer FCEB Maintenance - ZEB (Vendor)	32	New Flyer FCEB
New Flyer FCEB Safety & PM - ZEB (Vendor)	8	New Flyer FCEB
New Flyer Safety/Fam. FCEB/BEB - ZEB	24	New Flyer Safety
Siemens ELFA - ZEB (Vendor)	8	VH/New Flyer FCEB and BEBs
XALT Battery - ZEB (Vendor)	16	New Flyer BEBs

Learning Management System

All training is planned and scheduled via a learning management system (LMS) located on the District's intranet site known as MyACT. This site serves as the main portal for transportation and maintenance department management to access available courseware, class schedules, and enroll staff. Moreover, the LMS provides users the functionality to query data, from researching staff attendance to classes completed per employee (including details related to bus types, routes, and/or by topics). This functionality is critical in being able to track training progress and to identify skill-set gaps that may warrant training campaigns as needed to ameliorate specific key performance indicators.

Maintenance Training Plan

Procuring fuel cell electric (FCEB) or battery electric (BEB) ZEBs requires coordination with internal stakeholders and OEMs, as well as prioritizing classes for specific employees based on high voltage exposure levels. The following outlines a general maintenance training plan.

Basic Courses: Familiarization and Safety

Training coordinates with OEMs and internal stakeholders to schedule staff to attend OEM bus familiarization and safety orientations. This is a standard, scheduled first-step practice when receiving any new bus (not just ZEBs). This training is foundational and impacts all mechanics and service employees (i.e., those who clean, fuel, and park).

Familiarization/safety orientation is an OEM-led class and content typically includes high voltage safety awareness, personal protective equipment (PPE), safety measures, and preventive maintenance. This course is presented to each shift at each affected operating division upon delivery of the bus. As this course is an overview, or high-level review, it is approximately three hours per session. In addition to mechanics and service employees, maintenance supervisory staff and maintenance trainers are required to attend.

Bus Component Courses

Additional OEM classes, beyond that of familiarization and safety include, but are not limited to, air systems, brakes, steering/suspension, door operations, electrical/multiplex systems (from schematics to ladder logics), computer and diagnostic systems, to include troubleshooting pathways. These bus component-based courses are scheduled for all mechanics at those locations where ZEB infrastructure and support exists. Courses entail moderate-to-high voltage level of exposure and therefore also, include maintenance trainers and maintenance supervisors. Often courses are scheduled quarterly and repeat as necessary. While these course topics are not specifically ZEB technologies, they are pertinent in that these are not static products/components. Performing preventive maintenance inspections and diagnostics on these products may impact or adversely affect ZEB functionality if not done correctly.

Advanced Courses

More advanced courses are initially taught by sub-component suppliers and scheduling is often coordinated through the OEM. For example, an OEM will work with staff to schedule the fuel cell manufacturer to teach the specifics of their product(s). Courses taught by sub-component suppliers usually address energy storage systems, electric-propulsion and/or fuel cell systems to name a few. Sub-component, supplier-led courses often include topics from safety and high voltage awareness to component functionality and troubleshooting diagnostics. As with Bus Component Courses the same operational staff are scheduled for these classes and training schedules are quarterly and repeat as necessary.

In-House Production

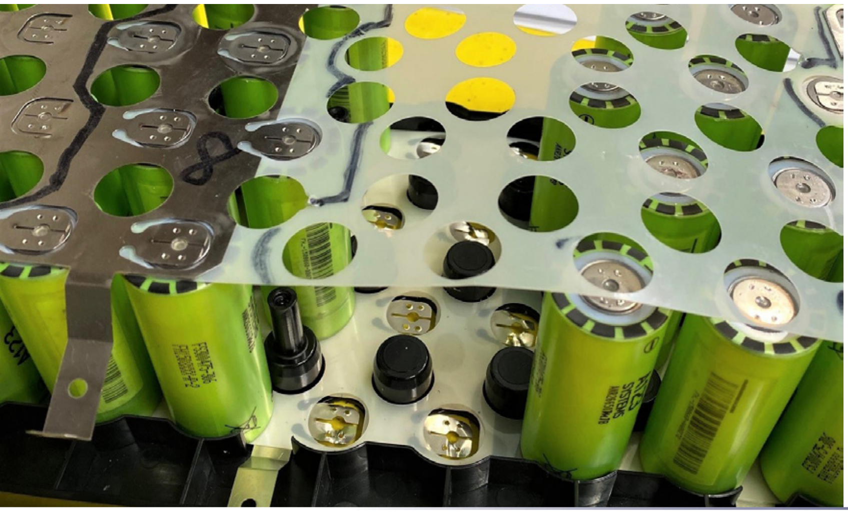
New technology requires strong partnerships with both OEM and sub-component suppliers. The learning curve is steep at first but flattens with practice and experience. The District's goal is for maintenance trainers to teach classes with less reliance on OEMs in the long run. To that end, some ZEB-based courses are now taught by staff and include the following topics: safety awareness for high-voltage systems and high-pressure hydrogen, operational start-up/shut-down and emergency procedures, familiarization with location and functions of major fuel cell and battery electric components, fueling of fuel cell and charging of battery electric buses.

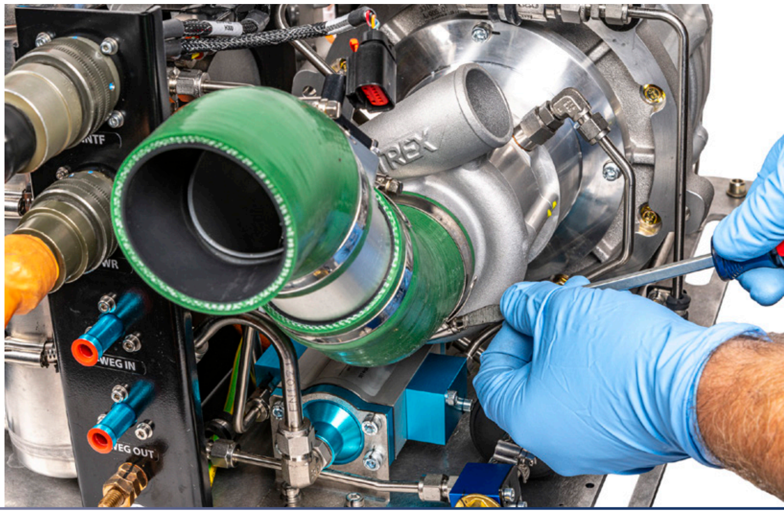
Working partnerships with OEMs has helped tremendously in gaining knowledge experience. These partnerships are structured pedagogically as well. OEMs often rely on training staff to learn how to translate engineering processes into mechanical procedures. The District has a rich history of acquiring training aides or modules used specifically to diminish these gaps between theoretical constructs and praxis.

The newest evolution in this effort is an actual OEM fuel cell module complete with air and coolant kits, poster training aids, related tool, and diagnostic accessories as well. This resource was funded by a California Air Resources Board grant and has literally been turned into one of the first-ever fully functioning fuel cell power plant training systems. This innovation in curriculum development engages mechanics, for example, to perform required preventive maintenance in 1,000 and 5,000-hour inspections. Mechanics can practice all the required steps on this training aid first, make mistakes safely, and turn each challenge into a teaching moment. And that's just the beginning, we anticipate developing fault code troubleshooting exercises as well. These innovations in teaching establish new skills and confidence, and dramatically decrease learning curves when performing the same tasks on live ZEBs. Future curriculum development will focus on creating similar training modules for energy storage, electric low floor axle, and hydrogen storage systems.

5-Week Technical Training Program

Another great example of in-house training can be found in the experiential, five-week technical (hands-on) fuel cell training program. This training is perhaps the most in-depth and notable course staff developed and helps mechanics' understanding and retention of the training as the individual learns by working alongside a zero emission trainer. Mechanics learn how to practice safety measures, perform preventative maintenance, advanced diagnostics, and troubleshooting. What makes this course unique is that it mimics the advantages of an apprenticeship model in that the mechanic learns by doing alongside an expert, repeatedly.





Synchronous Learning

Staff has successfully developed courseware designed for synchronous learning environments or online interactivity to deliver training. These live, interactive online classes enable maintenance trainers and mechanics from all operating divisions to engage together, virtually, and safely (especially during the current pandemic). Equally significant, mechanics can attend classes without having to leave their respective shops for the entire day. Training times are shorter, normally two to three hours, compared to more traditional in-person eight-hour classes. It should be noted that not all topics are well suited for this environment. Current courses (as identified in Figure 18) include the following: Digital Multimeter; High Voltage: Awareness and Safety; and Hydrogen: Safety, Fueling, and Storage. More courses are in development.

Mixed Reality Systems

Moving ahead, AC Transit will introduce a new, innovative learning methodology in implementing virtual and augmented reality systems (also known herein as mixed reality systems). Mixed reality systems will re-invent and re-invigorate workforce training by engaging staff in the learning process, in real-time. Learning-by-doing takes on new meaning as employees are immersed in actual work tasks, guided along the way by virtual, demonstrations. Mixed reality systems provide a virtual "live-assist" for on-the-job learning, making complex or multi-layered tasks less intimidating and cumbersome. Teaching becomes a live environment as the learner actively performs the tasks taught, at the same time. Mixed reality will transform traditional, one-dimensional, train-by-slide (decks) into a three-dimension, knowledge experience wherein learning becomes interactive to the object that is the focus of the training.

Virtual reality, for example, is ideal in preparing a new workforce to engage more frequently with high voltage systems. The application of a virtual reality headset offers the mechanic a chance to learn how to apply PPE, work on specific inspection steps (within an energy storage system) and make mistakes without consequence of injury to self, others, or damaging equipment. Implementing this mixed reality as a learning tool will reduce fear of shock, arch flash and other hazards as the process is practiced in virtually, and in a completely safe, world first. It's the perfect application to troubleshoot, test, and practice new steps that many would otherwise shy away from or avoid.

Similarly, augmented reality which incorporates mobile devices like smart phones, specialized glasses such as HoloLens or electronic tablets, introduces virtual objects or procedures into real world settings. Using special glasses, for example, would enable a mechanic looking at (or "pointing to") the fuel cell's air compressor and see, on screen (or, in the lens) a series of instructions to complete an inspection or removal process. All safety steps, inspection procedures, and recommended tools to perform the tasks correctly and accurately would display by voice command ensuring that work is completed at the pace of the worker or as led by a trainer.

The ZEB Evolution

Putting it all together, what does it take to work on ZEBs? There are as many theories about this as there are training programs. As technologies emerge so, too, do theories of requisite course criteria. At the highest level though, the District's workforce development can best be shown in Figure 19. The hours are estimates, but the training time invested is indicative of the evolution of a mechanic's proficiency working on either FCEBs and/or BEBs.

The District believes that implementing the training programs address the safety, reliability and sustain- ability of zero emission buses to fully deploy this technology in public transit.

To date, AC Transit has provided mechanics with 16 different zero emission training programs, totaling over 23,000 hours. Equally significant, staff has trained all drivers at multiple operating divisions deploying BEBs and FCEBs.

Figure 19: Mechanic Development

FCEB-BEB Courseware	Hours
Orientation and PPE/High Voltage	8
Energy Storage System	40
Power Train Technology	40
Fuel Cell	30
5-Week Technical Training Program	200

Conclusion

Conducting a study of this magnitude is not a simple task. Understanding there is a vast difference with technology maturity between the various fleets included in the study, AC Transit acknowledges initial results may not reflect what develops over time. Internal combustion engine transit bus technology has been evolving for over a century, zero emissions transit bus technology has been in demonstrations for about two decades and largely commercially available in the United States for less than that. As with any new advanced technology deployment, unexpected conditions may arise when buses are placed in service. What makes a tremendous difference, is the level of collaboration, support, and response from the bus and infrastructure manufacturer to resolve challenges and evolve the technology.

What we have outlined here is more than AC Transit's study for zero emission transition, but instead, a foundation for how we can transition together.

Next Steps

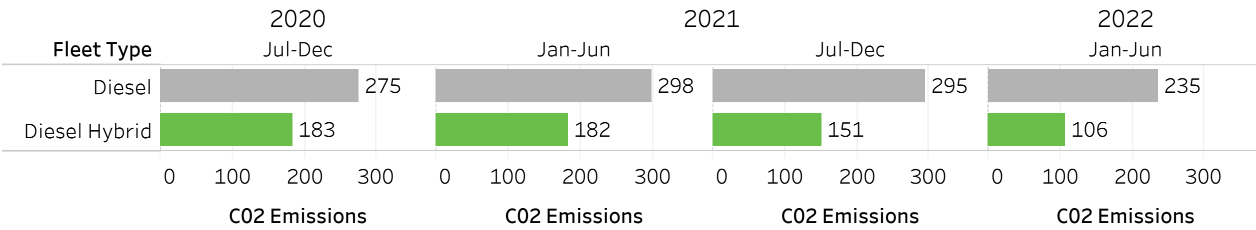
AC Transit will continue to deploy the ZETBTA control fleet and collect performance data to provide an annual report for the 2022 calendar year targeted for delivery in the summer of 2023. Workforce development will move forward with a mixed reality system that re-invents and re-invigorates the District's training program and engages staff with a real-time learning process.

Appendix: Data Summaries and Corrigenda

APPENDIX [A-1]

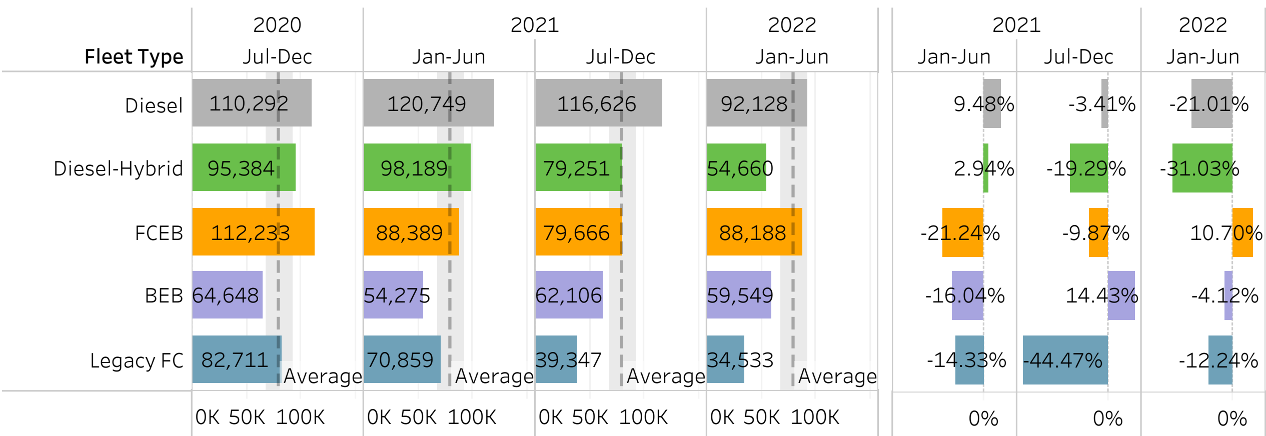
Fleet Type
Diesel Diesel-Hybrid FCEB BEB Legacy FC

Carbon Emissions (CO2) [FIG 6]

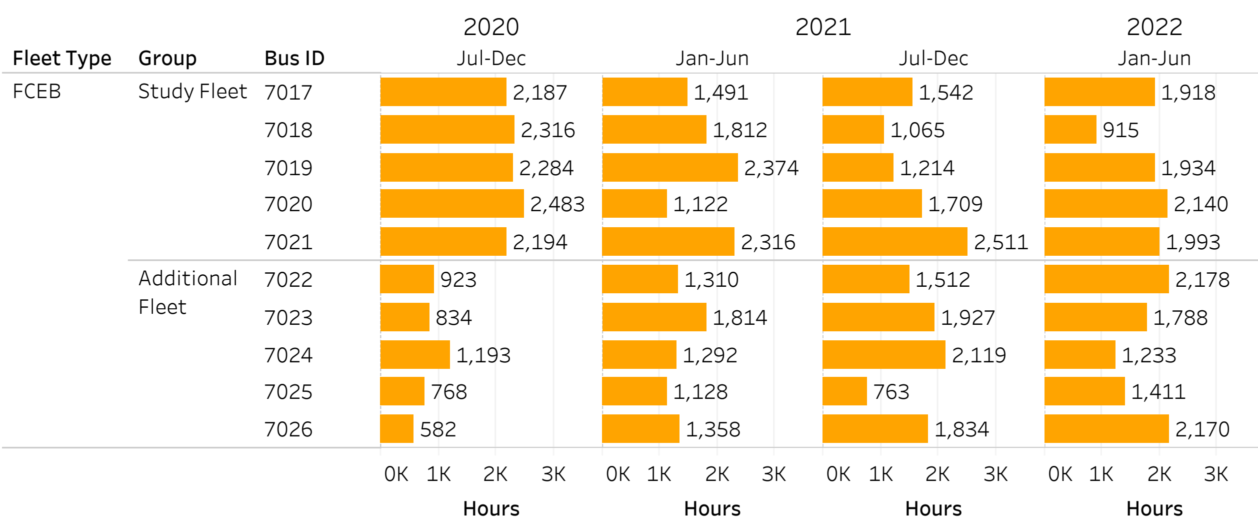


Fleet Miles [Fig 7]

6-mo % chg [Fig 7]



FCEB Operating Hours



APPENDIX [A-2]

ZEB Facility [Fig 3]

	2022		
Fleet Type	Battery Electric Bus	Fuel Cell Electric Bus	Fuel Cell Electric Bus
Facility	Oakland Facility	Oakland Facility	Emeryville Facility
Availability	97.2%	22.7%	96.7%

Fleet Type
Diesel | Diesel-Hybrid | FCEB | BEB | Legacy FC

Fuel - Equivalent Efficiency [FIG 8]

				2020	2021		2022
Fleet Type	**Energy/ Fuel**	**Efficiency Metric**	**Equivalent Metric**	Jul-Dec	Jan-Jun	Jul-Dec	Jan-Jun
Diesel	Diesel	Miles/Gal	M/DGE	4.09	4.13	4.02	3.99
Diesel-Hybrid	Diesel	Miles/Gal	M/DGE	5.30	5.49	5.33	5.25
FCEB	Hydrogen	Miles/Kg	M/DGE	9.06	8.76	7.89	7.88
BEB	Electricity	kWh/Mile	M/DGE	18.56	15.50	17.03	17.66
Legacy FC	Hydrogen	Miles/Kg	M/DGE	5.57	5.29	5.03	5.53

Energy/Fuel Rate [FIG 9]

	2020	2021		2022
	Jul-Dec	Jan-Jun	Jul-Dec	Jan-Jun
Diesel (Gal)	1.760	2.100	2.890	3.920
Electricity (KWH)	0.223	0.189	0.207	0.214
Hydrogen (Kg)	7.790	7.790	7.930	8.410

Cost Per Mile [FIG 10]

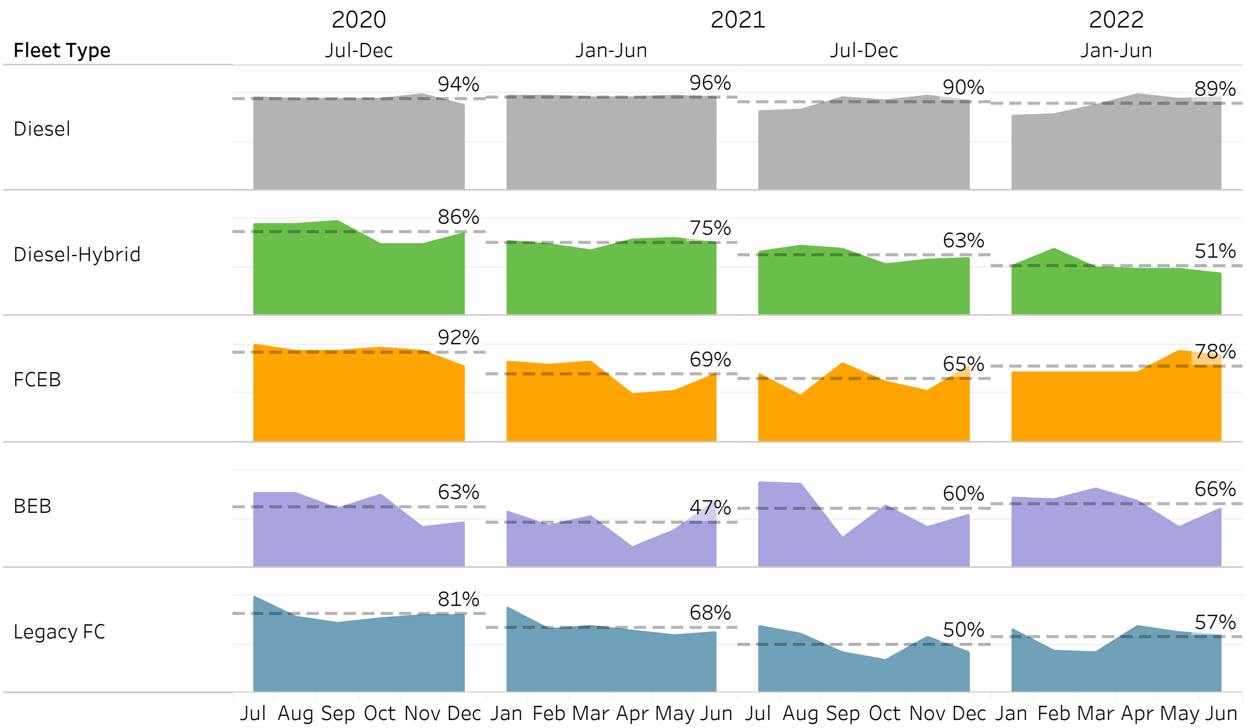
	2020	2021		2022
Fleet Type	Jul-Dec	Jan-Jun	Jul-Dec	Jan-Jun
DIESEL	$0.93	$1.41	$1.72	$2.29
HYBRID	$1.11	$1.80	$2.08	$3.11
FCEB	$1.51	$1.97	$2.14	$2.52
BEB	$1.39	$2.02	$1.60	$1.61
LEGACY FC	$2.84	$4.07	$4.75	$4.15

APPENDIX [A-3]

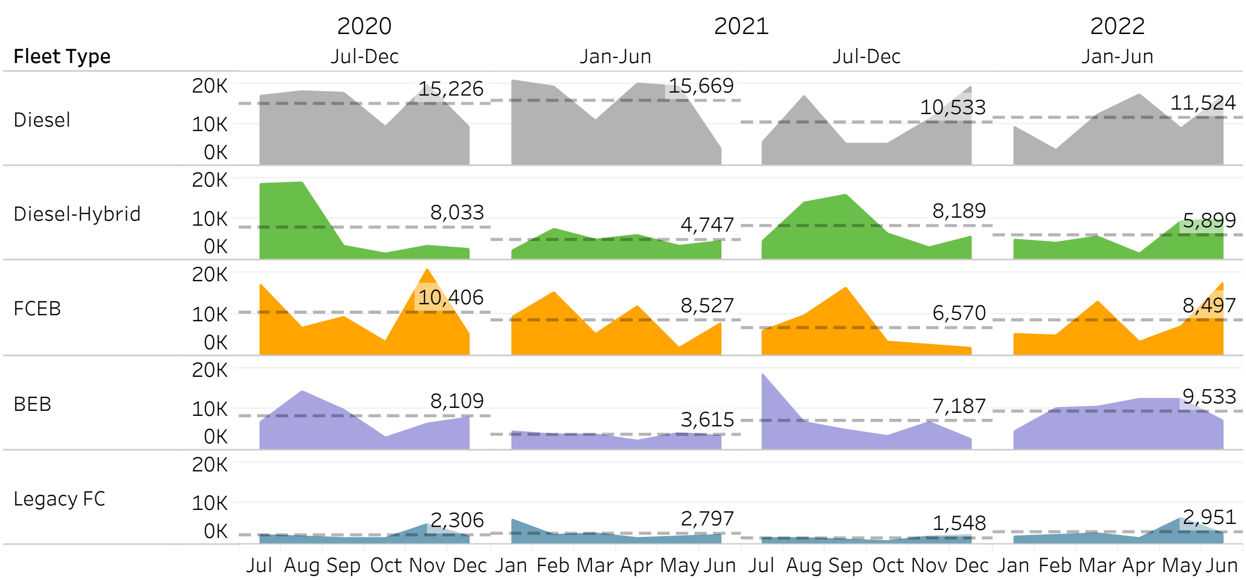
Fleet Type

Diesel | Diesel-Hybrid | FCEB | BEB | Legacy FC

Fleet Availability [FIG 15]



Miles Between Road Calls [FIG 16]

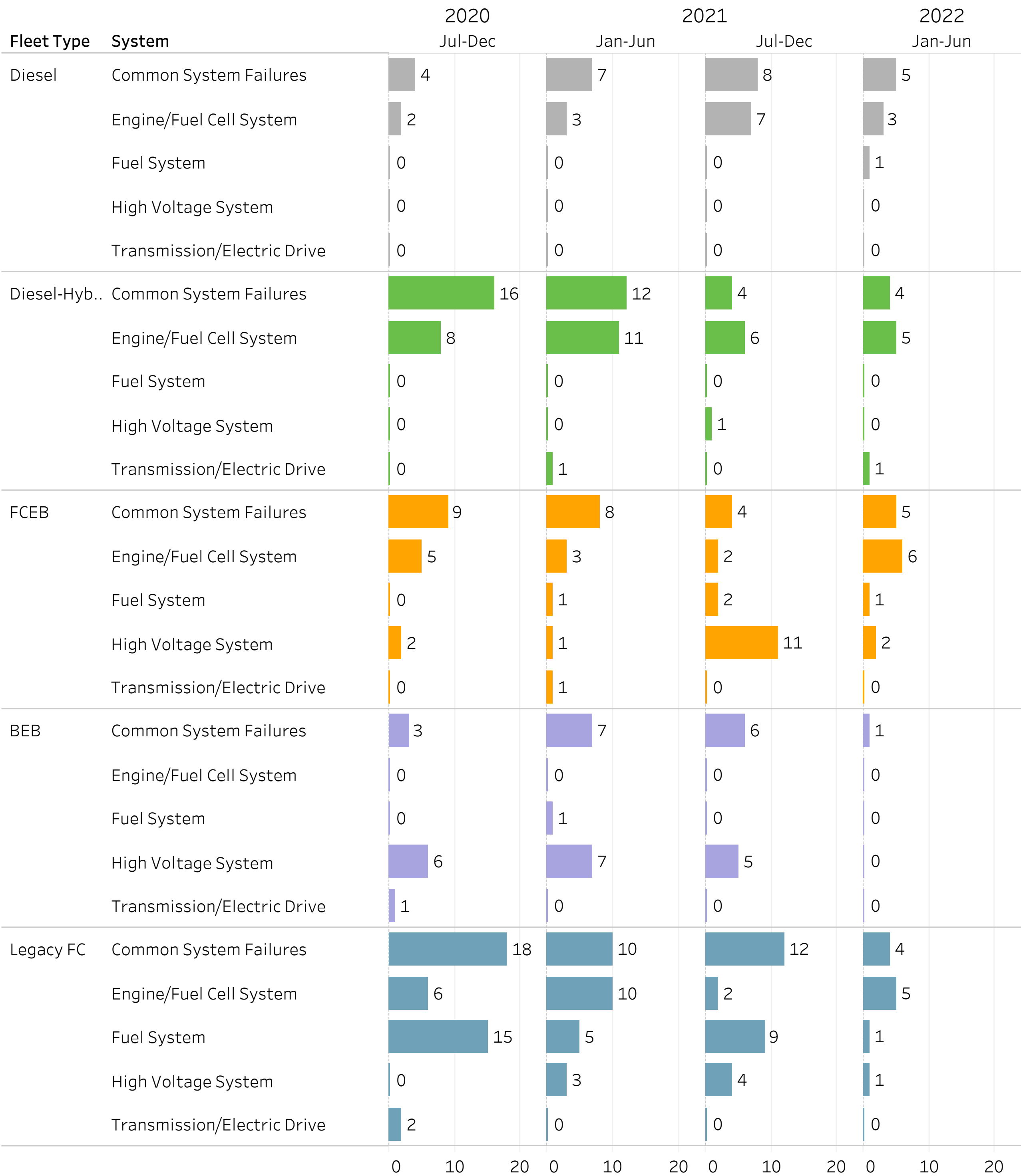


APPENDIX [A-4]

Fleet Type

Diesel · Diesel-Hybrid · FCEB · BEB · Legacy FC

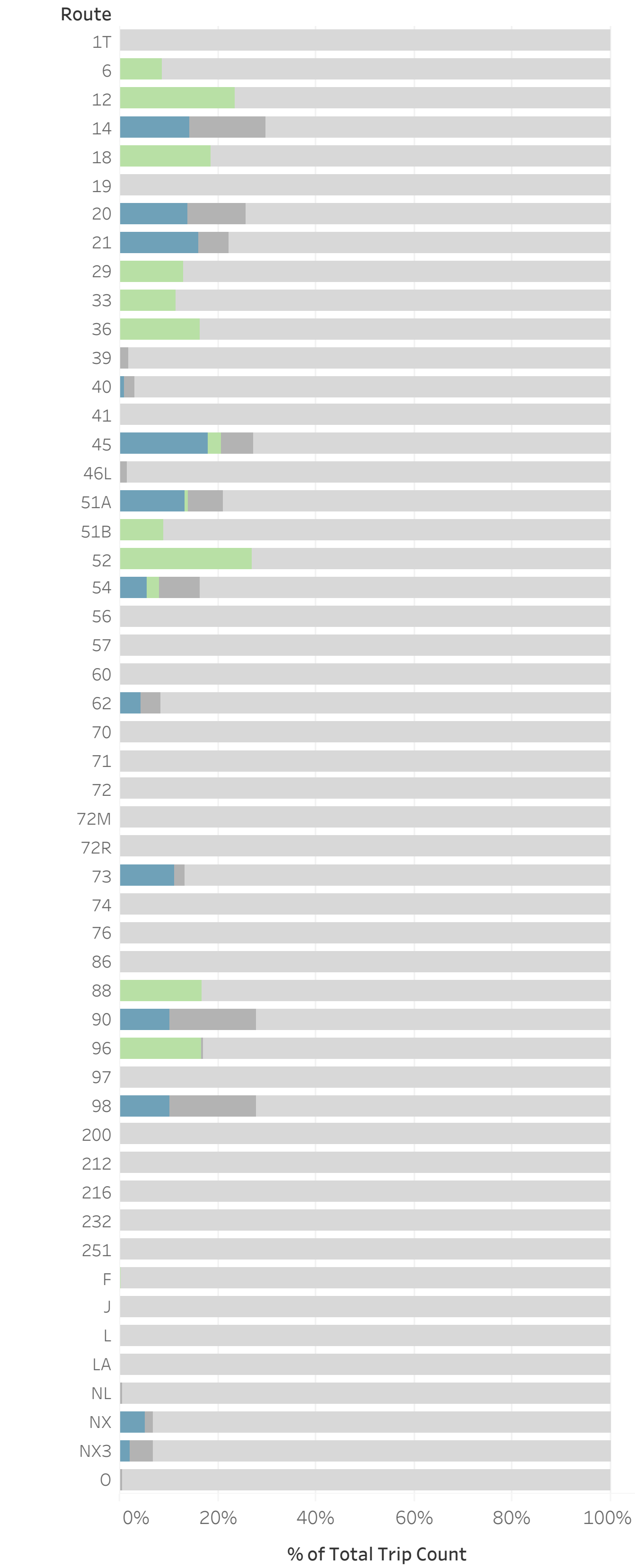
Road Calls by System [FIG 17]



APPENDIX [A-5]

Trips on Disadvantaged Corridors (DAC) across ZEB Fleet

% Trips on DAC Routes by Fuel Source



% 5x5 Trips Serving a DAC Route by Vehicle ID

ZEB Vehicle	Vehicle ID	DAC or Non-DAC: DAC Route	Non-DAC Route
5x5 ZEB Vehicles	0005	100.0%	0.0%
	0007	100.0%	0.0%
	0012	100.0%	0.0%
	0013	100.0%	0.0%
	0014	100.0%	0.0%
	7017	99.6%	0.4%
	7018	99.4%	0.6%
	7019	99.8%	0.2%
	7020	99.6%	0.4%
	7021	99.5%	0.5%
	8001	99.7%	0.3%
	8002	99.9%	0.1%
	8003	99.8%	0.2%
	8004	99.8%	0.2%
	8005	99.8%	0.2%
5x5 Fossil Fuel Vehicles	1556	97.2%	2.8%
	1558	97.0%	3.0%
	1559	96.4%	3.6%
	1560	98.5%	1.5%
	1601	98.6%	1.4%
	1602	97.6%	2.4%
	1603	97.8%	2.2%
	1604	98.7%	1.3%
	1605	98.0%	2.0%
Other ZEB Vehicles	0004	87.0%	13.0%
	0008	81.6%	18.4%
	0009	84.1%	15.9%
	0015	80.8%	19.2%
	7022	99.0%	1.0%
	7023	97.8%	2.2%
	7024	97.6%	2.4%
	7025	97.2%	2.8%
	7026	97.4%	2.6%
	7031	88.2%	11.8%
	7032	98.6%	1.4%
	7033	83.1%	16.9%
	7034	94.5%	5.5%
	7035	93.8%	6.2%
	7036	88.2%	11.8%
	7037	95.1%	4.9%
	7038	99.4%	0.6%
	7039	99.2%	0.8%
	7040	94.4%	5.6%
	7041	95.8%	4.2%
	7042	100.0%	0.0%
	7045	91.9%	8.1%
	7046	85.1%	14.9%
	7047	92.5%	7.5%
	7048	88.8%	11.2%
	7049	100.0%	0.0%
	7050	99.2%	0.8%
	8006	100.0%	0.0%
	8007	100.0%	0.0%

What is DAC?

Disadvantaged Communities (DAC) are areas that are more vulnerable to systemic and economic shocks and have historically faced the brunt of disinvestment. California SB 535 outlays how DAC are defined for the purposes of receiving investment priority from the State of California's cap-and-trade program. AC Transit's Clean Corridor Plan targets the deployment of zero-emission buses along routes that primarily serve DAC areas.

APPENDIX [A-6]
Summary of Volumes 1 through 4 (July 2020 - June 2022)

COST/MILE	DIESEL	HYBRID	FCEB	BEB	LEGACY FC	TOTAL
Vehicle Usage and Reliability						
Mileage	439,796	327,484	368,476	240,579	227,448	**1,603,783**
Life-to-date Mileage	757,363	1,235,654	452,103	272,046	1,423,925	**4,141,091**
Availability	92%	68%	73%	56%	64%	**71%**
Road Calls	40	69	63	36	107	**315**
MBCRC	10,995	4,816	5,849	6,502	2,146	**5,091**
Road Calls	40	69	63	36	107	**315**
Work Orders	1,268	1,195	1,348	1,109	1,320	**6,240**
Labor Hours	2,698	3,061	2,399	1,910	3,035	**13,103**
Energy and Efficiency						
Energy Consumption (Native)	108,297	61,175	47,396	534,006	45,668	—
Native Energy Units	gal	gal	kg	kWh	kg	—
Energy Consumption (DGE)	108,297	61,175	42,656	14,012	41,101	**267,241**
Fuel Efficiency (Native)	$4.06	$5.35	$7.77	$0.45	$4.98	—
Fuel Efficiency Units	mi/gal	mi/gal	mi/kg	mi/kWh	mi/kg	—
Fuel Efficiency (MPDGE)	4.1	5.4	8.6	17.2	5.5	**6**
CO2 Emissions	1,102	623	0	0	0	**1,725**
Costs and Credits						
Operating Cost	$687,490	$622,081	$731,318	$401,084	$855,048	**$3,297,020**
Energy Costs	$280,528	$149,153	$378,658	$111,405	$361,087	**$1,280,831**
Labor & Materials Cost	$406,962	$472,927	$352,660	$289,679	$493,961	**$2,016,189**
Labor Cost	$314,038	$355,575	$278,616	$221,486	$349,798	**$1,519,512**
Materials Cost	$92,924	$117,353	$74,044	$68,193	$144,163	**$496,677**
Warranties Recovered	$17,035	$13,049	$236,797	$230,907	$4,671	**$502,460**
LCFS Credits	$0	$0	$7,638	$98,132	$0	**$105,770**
Adjusted Operating Cost	$670,454	$609,031	$486,883	$72,045	$850,377	**$2,688,791**
Normalized Costs (Cost Per Mile)						
Operating CPM	$1.56	$1.90	$1.98	$1.67	$3.76	**$2.06**
Energy CPM	$0.64	$0.46	$1.03	$0.46	$1.59	**$0.80**
Labor & Materials CPM	$0.93	$1.44	$0.96	$1.20	$2.17	**$1.26**
Adj. Operating CPM	$1.52	$1.86	$1.32	$0.30	$3.74	**$1.68**

Note: Data reflect continuous collection for the period of July 1, 2020 through June 30, 2022.

APPENDIX [A-7]
Corrigenda

AC Transit's data integration and analytics models and processes have continuously improved since the start of the 5x5 study. As such, we have discovered erroneous data that we are obligated to report on. This section outlines the issues identified, steps taken to correct the issues, and any consideration on how the corrected data affects the interpretation of the results.

Vehicle availability

A vehicle may be unavailable to make morning pull-out due to various mechanical or non-mechanical reasons. When the cause did not originate from the vehicle itself, these instances are discounted from the numerator in this metric calculation. However, there were two issues that resulted in erroneous metrics being reported in Volumes 1, 2 and 3 for this indicator.

Issue 1: Ambiguous unavailability reason code

First, due to ambiguous terms used in the reason code for why a bus was unavailable, field staff sometimes incorrectly recorded the reason. For example, one reason code was "Bus Charging System." This was a term that could mean there was an issue with the high voltage system on the bus, or it could mean that the charging station was down. The result was that many records had an incorrectly assigned code for the reason the bus was down.

Corrective actions

Once this issue was discovered, staff reviewed the past two years of unavailability incidents and vehicle service notes to identify and correct erroneous data. In this process, staff renamed the ambiguous codes to make explicit which system was at fault for the vehicle being unavailable. For example, "Bus Charging System" was renamed to "Charging Station" to make it explicit that it was specific to the station and not the bus systems.

Issue 2: Incorrect unavailability reason code filtered out

A second issue was related to which system codes we chose to exclude from the metric calculation. We initially excluded three categories of system issues: Training, Special Events and Fuel Systems. However, closer inspection of these codes and further discussion with field staff brought to light that other codes should be filtered out, and that Fuel System reasons should be included.

Corrective actions

Staff updated the filters to the incoming data from the data warehouse using the correct system codes. The table below provides the correct System ID, System ID Reason Code, and whether that code contributes to the numerator in calculating this metric.

ID	System	Include In Numerator?
1	H2 Station	Exclude
2	General Bus and PMI Repairs	Include
3	Power Plant	Include
4	Drive System	Include
5	OEM/District Campaigns	Include
6	Training (Available)	Exclude
7	Special Event (Available)	Exclude
8	Fuel System	Include
9	PMI Inspections	Include
10	Charging Station	Exclude
14	Bus HV System	Include

Impact on findings

The combined impact of correcting these two issues is minimal on the final interpretation of the results. About 93% of all reported availability statistics in Volumes 1, 2 and 3 changed by less than 5 percentage points. The median percentage difference was 3.3%, and only impact worth noting is that the observed performance improved slightly for FCEB in Volume 1 results—from 57% available to 63% available. There are no other notable differences in the interpretation of the results.

Miles between Chargeable Road Calls (MBCRC)

Volume 1 reported the average monthly miles between chargeable road calls (MBCRC) in Figure 1 of the published report. Subsequent volumes reported the aggregate MBCRC metric, taking the total miles operated in the reporting period as the numerator and the total road calls in the reporting period as the denominator. The table below shows the reported versus revised MBCRC for Volume 1 by fuel technology.

TECHNOLOGY	Reported Avg Monthly MBCRC	Miles	Road Calls	Revised Aggregate MBCRC
DIESEL	15,226	110,292	6	18,382
HYBRID	8,033	95,384	24	3,974
FCEB	10,406	112,233	16	7,015
BEB	8,109	64,648	10	6,465
LEGACY FC	3,024	82,711	41	2,017

Corrective actions
Not applicable.

Impact on findings
This revision impacts the interpretation of the early results of the study. The revision deflates the performance of alternative fuel technologies relative to diesel fuel, and it bumps the ranking of Hybrid Diesel below that of BEB.

Operating costs and adjusted normalized operating costs

The last correction is due primarily to lag time in when data are collected and finalized versus when staff report the results of the study. Specifically, this occurred in the adjusted operating costs and subsequent mileage-normalized operating costs.

Operating costs are the sum of energy costs and maintenance costs. Adjusted operating costs are operating costs less energy credits and warranties recovered. Mileage-normalized operating costs, or cost per mile, are operating costs or adjusted operating costs divided by the total mileage in a reporting period.

Issue 1: Time lag in warranties, work orders and LCFS credit reporting
Although staff strive to report the most accurate, up-to-the-minute data, changes to the data may take place after publication. Warranties can take months to process. Work orders can re-open after being closed. Low-carbon fuel standard (LCFS) credits are not finalized until months later. Several warranties that were pending during earlier volumes eventually settled, which effectively drove down the costs of operation. However, work orders also reopened which drove costs up. And some LCFS credits were received after publication, driving effective costs down.

Issue 2: Incorrect time period reported for LCFS credits in Vol 1

The start of the 5x5 study was July 2020. However, the District had already started collecting LCFS credits prior to this period. The credits generated prior to commencing the 5x5 study were applied to Volume 1 cost reductions. This resulted in deflating the costs of FCEB by $68,851 more than what the actual costs incurred in this period. In other words, we said we received $76,489 in LCFS credits between July 2020 and December 2020 when in fact we received $7,638. That higher initial amount reflected actual LCFS credits received between January 2020 and June 2020. The same issue applies to BEB technology. We over-discounted the credits received by $11,206.

Issue 3: Downstream impacts on normalized cost per mile metrics

Since operating cost and adjusted operating costs are normalized for the miles operated in a specified time period, any changes to these underlying costs have downstream impacts on the normalized cost per mile metrics. The table below summarizes the difference between actual costs and reported costs per mile.

Corrective actions

District staff are working to standardize the way we factor in warranty costs to depict overall operating costs. This effort will conclude after the final publication of this report. Staff are seeking to understand ways to split warranty recoveries into two categories: (1) cost avoidance, which are repairs that were done to vehicles but are costs that we did not incur and (2) out-of-pocket repairs, which are those we performed in-house using our own labor and parts to later receive reimbursement. These reports do not make the distinction in the two kinds of warranties. In future reports, recovered costs associated with cost-avoidance warranties will be removed from consideration in reporting the adjusted operating costs.

District staff will continue to update and maintain reports that may change due to time lags. This is largely unavoidable, but using tools that are linked directly to our data warehouse, such as Tableau and Power BI, will ensure that the most accurate and up-to-the-minute data are accessible to data users.

Impact on findings

These changes were enough to trigger a reinterpretation of the results for the cost per mile for BEB technology, but only for the Volume 1 report. The results were not significant for other volumes, and the implicit ranking of these technologies in terms of costs was not altered. Appendix A-6 reflects a larger sampling period and offers a more certain grounding for the basis of decision-making.

Reported Cost per Mile			
	Vol 1	Vol 2	Vol 3
DIESEL	$0.88	$1.37	$1.70
HYBRID	$1.09	$1.78	$2.05
FCEB	$1.11	$0.58	$1.42
BEB	$0.78	$0.69	$0.57
LEGACY FC	NA	$4.07	$4.75
Actual Cost per Mile			
	Vol 1	Vol 2	Vol 3
DIESEL	$0.87	$1.39	$1.71
HYBRID	$1.10	$1.80	$2.07
FCEB	$1.23	$0.51	$1.39
BEB	-$0.53	$0.68	$0.61
LEGACY FC	$2.83	$3.93	$4.97
Difference (Actual - Reported)			
	Vol 1	Vol 2	Vol 3
DIESEL	-$0.01	$0.02	$0.01
HYBRID	$0.01	$0.02	$0.02
FCEB	$0.12	-$0.07	-$0.03
BEB	-$1.31	-$0.01	$0.04
LEGACY FC	NA	-$0.14	$0.22

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