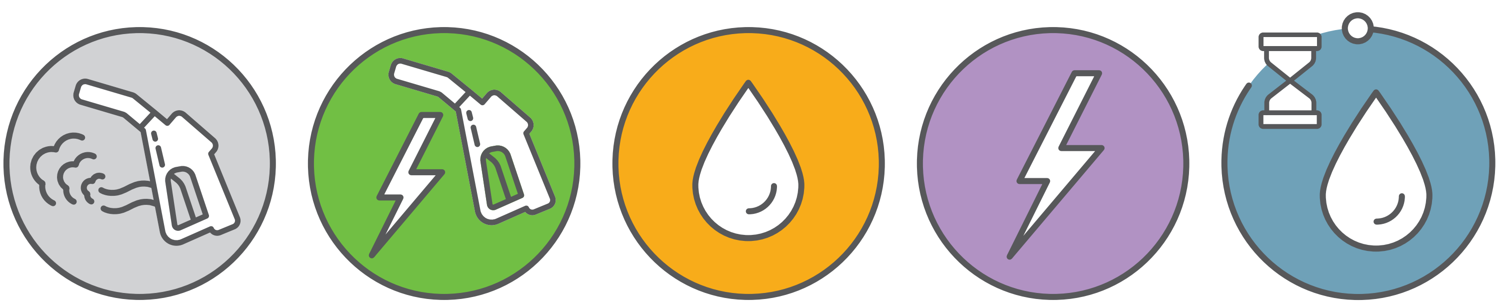
SR 21-284, Attachment 1

ZERO EMMISSION PROGRAM

Zero Emission Transit Bus Technology Analysis



REPORT PERIOD : JULY 2020 – DECEMBER 2020

Leading the way to a
ZERO EMISSION FUTURE.

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To ensure transparency and validation of the data, analysis methodology, and performance statistics results, AC Transit relied on academia for an independent review and analysis of the report. Stanford University's team is gratefully acknowledged and listed below:

Jimmy Chen is responsible for developing and managing the Stanford Energy Corporate Affiliate (SECA) program and establishing engagements for corporations and other organizations that have an interest in collaborating with Stanford on energy and energy-related research.

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Abstract

The Zero Emission Transit Bus Technology Analysis (ZETBTA) was initially intended to meaningfully analyze the various transit bus technologies that AC Transit operates. This report summarizes results of this study for the fuel-cell electric bus (FCEB), battery electric bus (BEB), diesel hybrid bus, and conventional diesel bus technologies. 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 will be 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, data integration and management, and transit deployment viability. 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 Rollout Plan to guide the implementation of ZEB fleets. This approach provided data results that helped assess which ZEB technology can best meet the operational requirements of the District while being financially efficient and sustainable.

Acronyms

Alameda-Contra Costa Transit District	AC Transit
Application Programing Interface	API
Battery Electric Bus	CARB
Business Intelligence	CCR
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
Liquid Hydrogen	LH_2
Low Carbon Fuel Standard	LCFS
Miles between Chargeable Road Calls	MBCRC
Miles per 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 each of the 5 Fleet Group Utilized in the Study	5x5

About AC Transit

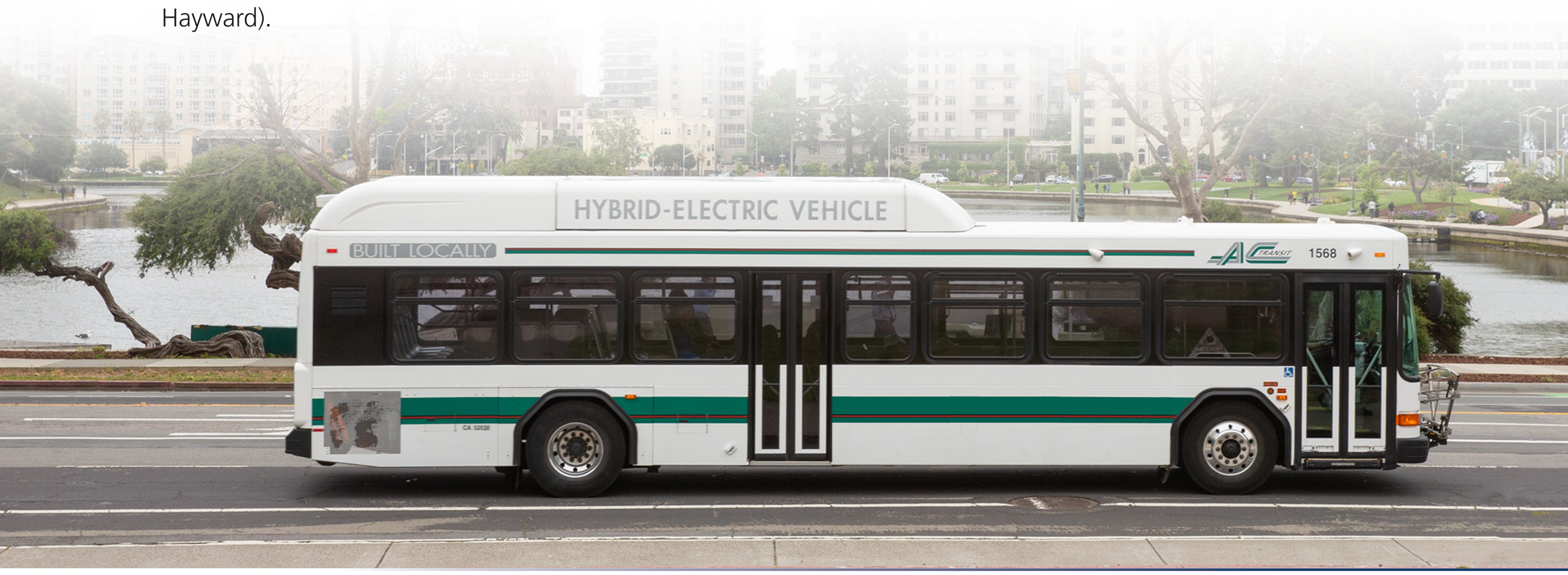
The Alameda-Contra Costa Transit District (AC Transit) is the largest public bus-only transit agency in California. Based in the San Francisco East Bay, AC Transit's General Office headquarters is in Oakland, Alameda County. AC Transit has been serving the East Bay since 1960, taking over from the Key System and its predecessors that carried passengers via buses, horse-drawn rail streetcars, electric streetcars, and ferries over the previous 100 years. AC Transit has a long-standing 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 has built a proud history of embracing clean technology in our efforts to serve the community better. We have long been a recognized leader in zero-emission buses, both nationally and internationally. The 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 with enhanced project delivery methods, and ongoing sustainable maintenance practices as each phase provide teachable moments on how to improve procurement, project delivery, operation, and performance of ZEB technology.

Our incredible team, funders, and partnerships have allowed us to remain a forerunner in proactively testing and comparing the cost and results of various conventional and zero-emission fuel technologies in a public transit environment. As we move towards converting to a zero-emission fleet, this report is the first step in gathering data to determine what transit bus technology and infrastructure best meets the needs of our service.

Service Profile

AC Transit operates 101 fixed routes with two main types 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

AC Transit has been building the most comprehensive ZEB Program in the United States that has expanded from hydrogen fuel-cell electric buses to battery electric buses. The program includes on-site hydrogen production and fueling, electric charging, on-site fleet maintenance, and workforce training. Currently there are 27 active ZEB's used in service, which include five (5) 40-foot battery electric buses, twenty-one (21) 40-foot fuel-cell electric buses, and one (1) 60-foot hydrogen fuel-cell electric demonstration bus. As we grow our ZEB fleet, so will the infrastructure required to re-energize each bus.

The District is deploying both ZEB technologies side-by-side at the Oakland (Division 4) facility. The Oakland facility has a hydrogen fueling station built in 2014 which has the capabilities of fueling thirteen (13) buses back-to-back and five (5) depot DC-fast charging stations installed in 2020 which can provide a maximum output of 125kW per charging station. The District also has designs and a plan in motion to build charging infrastructure for up to 50 buses. At the Emeryville (Division 2) facility, the agency recently expanded our hydrogen fueling capacity to accommodate 65 buses back-to-back and have plans to install up to 16 depot DC-fast charging stations.

In addition to deploying ZEB's, 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 ZEB's. As the District's ZEB fleet grows the 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.

Looking towards the future, AC Transit continues to pursue opportunities to fund and expand our zero emission programs. We have secured funding to purchase 43 more ZEB's: 23 40-foot battery electric buses and 20 40-foot fuel-cell electric buses with the latest advancements in zero-emission technology. By early 2023, we are expecting to have 70 ZEB's in service.

Transit Bus Technology Summary

AC Transit has now reached an exciting milestone in leading the way to a zero-emission future. This is the first publication of the Zero Emission Transit Bus Technology Analysis report. The report presents results of the data collected on energy, cost, and performance that is used to populate statistics in a set of common metrics such as cost, mileage, reliability, and availability. This report is our contribution to the industry, it will provide valuable information and experience as we prepare to embark on the journey towards transiting our fleet to 100% zero emission and serve as a roadmap for all those who follow.

Our goal with this report is to have true, side-by-side evaluation of ZEB technologies operated by the same agency, in the same service environment, from the same ZEB bus manufacturer and compare that to conventional fleets. The focus of this report is to compare capital cost, performance, and operating cost between ZEB types and to conventional diesel bus technologies operated by AC Transit. This report covers the 5X5 vehicles for the reporting period from July 2020 through December 2020.

5x5 matrix includes the bus grouping attributes and data summaries captured for the reporting period of this publication. Included are the deployment statistics that the buses were assigned to on the District's clean corridor routes that serve disadvantaged communities.

The figure below provides an overview of the 5 fleet groups utilized in the study. The data summaries conclude that during the review period, the FCEB had the highest fleet mileage (112,233), where the BEB had the lowest mileage (82,710). The BEB had the lowest cost per mile (CPM) when applying warranty and LCFS credits ($0.78), however the Legacy Fuel Cells had the highest CPM ($2.82) as they were outside the warranty period. The Diesel fleet was the most reliable (15,226 MBCRC) and available (94%), however produced the most carbon emissions (275 CO_2). The Legacy Fuel Cell fleet was the least reliable (3,024 MBCRC), and the BEB was the least available (57%). Additional details highlighting the matrix conclusions is found in the 5X5 data summary section in 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 (July - December 2020)					
Fleet Mileage	110,293	95,383	112,233	64,648	82,710
Cost/Mile	$0.93	$1.11	$1.51	$1.39	$2.84
Cost/Mile (w/ credits)	$0.88	$1.09	$1.11	$0.78	$2.82
Emissions (CO_2 Metric Tons)	275	183	0	0	0
Fleet Availability	94%	85%	90%	57%	84%
Reliability (MBCRC)	15,226	8,033	10,406	8,109	3,024

Bus Fleet Specifications

The buses selected for the evaluation are all forty-foot local route units ranging from the year 2010 to 2019. The mix includes fuel cell, battery electric, diesel, and diesel-hybrid technology. The group of buses represent the four propulsion technologies that many agencies are comparing performance against one another, but never all four technologies under the ownership of one agency. We included our legacy fuel cell in the evaluation to see how it holds up against the latest zero emission technology on the market.

The figure below provides additional specifications of the bus fleet groups utilized in the study. The matrix includes dates when the buses were placed into service, the cumulative life to date miles, and the design specification types of the twenty-five buses.

A keynote is that the District uses a typical lead time of eighteen (18) months from order date for a bus to be placed into service, this is 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
OEM Range Specification	480 miles	600 miles	300 miles	200 miles	220 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
Life to Date Miles	91,908	209,088	43,177	27,888	280,292

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, the District has a system of six stationary battery chargers to support our Battery Electric Buses (BEB) and a vapor compression hydrogen station to support Fuel Cell Electric Buses (FCEB). At the Emeryville Division, the District has recently updated to a liquid compression hydrogen station.

This evaluation utilized vehicles operated out of the Oakland Division because it is currently the District's only division equipped to support both Fuel Cell Electric Buses (FCEB) and Battery Electric Buses (BEB).

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	Upgraded 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	Six ChargePoint CPE250s	Messer IC-50 Ionic Compressor	Messer Dual ADC MP-100 Cryogenic Pumps
Related Hardware	Six - 100A/480V Circuits	Ambient Vaporizer	High Pressure Vaporizers
Operating Capacities			
System Capacity	62.5 kW combinable to 125kW	9,000 Gal LH_2 Storage 360 kg per day	15,000 LH_2 Storage 1,750 kg per fueling window
Daily Vehicle Capacity	12 per fueling window	13 per 12-hour window	65 per 12-hour window
Charge/Fueling Time	5.5 hours per charge	7.5 minutes per fill	6.5 minutes per fill
Fueling Location	West Wall of Facility	Fuel Island	Fuel Island

* Cost to upgrade the Emeryville hydrogen facility from vapor compression to liquid compression.

Battery Electric Infrastructure

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 this configuration, two chargers can be combined to charge a single vehicle at 125 kW. These chargers are currently covered by manufacturer warranty so there is no operations and maintenance (O&M) agreement in place.

BUILT:
2020

COST:
$896,937

Hydrogen Infrastructure

Oakland Hydrogen Station

The hydrogen station at the Oakland Division was built in 2014 at a total cost of $6,300,308. The station includes a 9,000-gallon of 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 using the District's solar assets as an energy source. 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 13 buses per 12-hour fueling window. The Oakland hydrogen station is maintained by a O&M contract with a vendor. The monthly cost of this O&M contract covering operations, preventative maintenance, corrective maintenance, and LH_2 tank maintenance is $15,577 which includes a $2,213 monthly allowance for corrective maintenance. Operations includes maintaining a remote monitoring and alarm system to support 24/7 operations by dispatching a technician upon alarm. Preventative maintenance includes regular and planned activities to any of the equipment on a weekly, monthly, or annual basis. Monthly inspections and certifications of liquid storage (hydrogen or nitrogen) are also included. The District plans to upgrade the Oakland hydrogen station with liquid pumps once funding is secured.

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 $5,100,000 for only the heavy-duty bus fueling portion of the project. In 2020, the station was upgraded at a cost of $4,424,644. Upgrades to the station includes a 15,000-gallon liquid hydrogen storage tank, dual ADC MP-100 Cryogenic Pumps, high pressure vaporizers, and 360 kg of high-pressure gaseous storage. Two dispensers were installed in the fuel island that are aligned with 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 a O&M contract with a vendor. The monthly cost of this O&M contract covering operations, preventative maintenance, corrective maintenance, and LH_2 and N_2 tank maintenance is $11,850 which includes a $750 monthly allowance for corrective maintenance. Operations includes maintaining a remote monitoring and alarm system to support 24/7 operations by dispatching a technician upon alarm. Preventative maintenance includes regular and planned activities to any of the equipment on a weekly, monthly, or annual basis. Monthly inspections and certifications of liquid storage (hydrogen or nitrogen) are also included.

BUILT:
2011
2020 UPGRADE:
$4,424,644

Facility Investment Projects

The District plans to build two additional BEB charging facilities over the next two years. In 2021, facilities for 22 additional charging stations will begin construction at the Emeryville (D2) facility. This project is fully funded and is currently in the design phase with completion planned during calendar 2022.

In 2023, the District is planning to construct a charging facility that will support 25 to 50 BEB charging stations. This facility will effectively be a BEB charging barn. It will feature overhead charging distribution and a parking deck for light duty vehicles on top. This project is in the planning phase and is already fully funded.

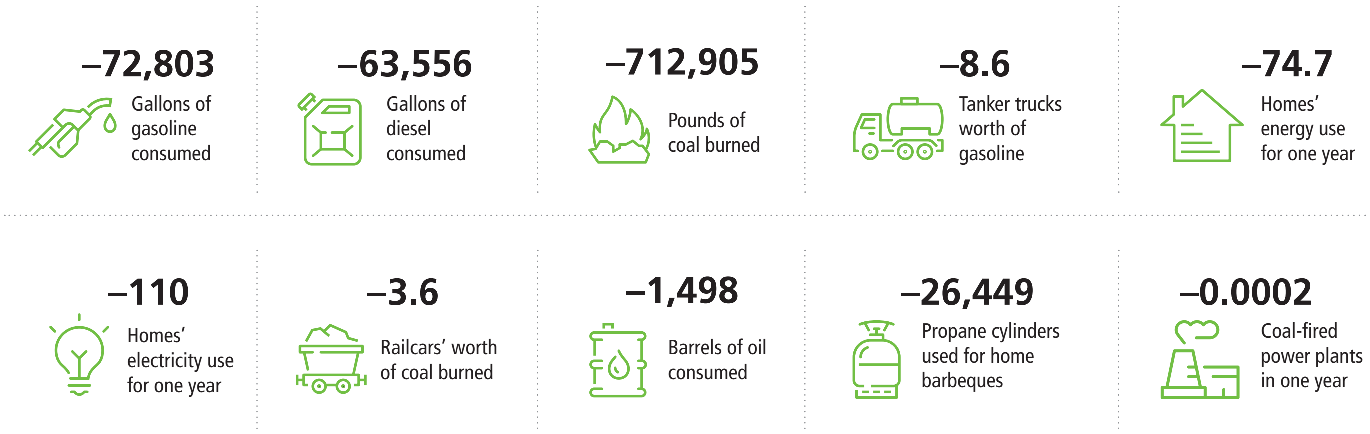
Figure 4: Facility Planned Projects

	BATTERY ELECTRIC BUS	**FUEL CELL ELECTRIC BUS**	
	Emeryville Facility	**Oakland Facility**	**Oakland Facility**
Facility Description			
Current Status	Future	Future	Future (Upgrade)
In Service Date	Planned 2021	Planned 2023	To Be Determined
Type of Fuel	Electric	Electric	Hydrogen
Technology	Distributed Charging	Distributed Charging	Liquid Compression
Core Hardware	TBD	TBD	Dual ADC MP-100 Cryo Pumps
Related Hardware	Electrical Service TBD	Electrical Service TBD	High Pressure Vaporizers
Fueling Location	South Wall of Facility	New Charging Bus Barn	Fuel Island
Operating Capacities			
Core Hardware	12-16 Charging Stations	25-50 Charging Stations	Dual ADC MP-100 Cryo Pumps
System Capacity	TBD	TBD	15,000 LH_2 Storage 1,750 kg per fueling window
Daily Vehicle Capacity	12-16 per fueling window	25-50 per fueling window	65 per 12-hour window
Charge/Fueling Time	TBD	TBD	6.5 minutes per fill

Environmental Impact

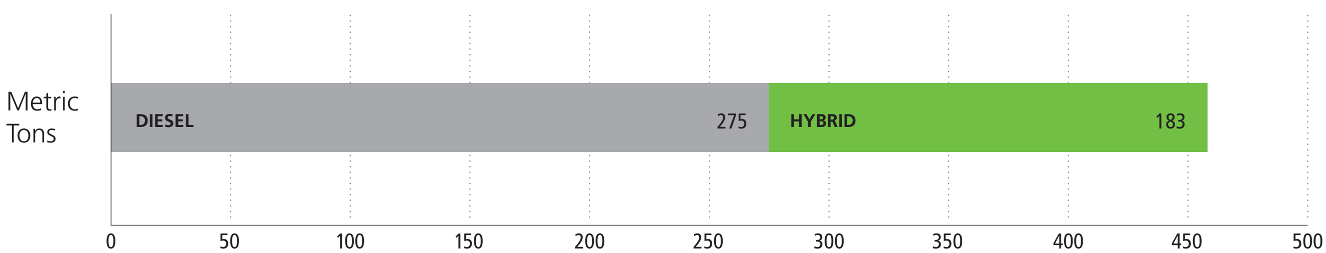
The District uses the 1600 series standard diesel bus fleet as the baseline control group and compares each other fleet to measure the environmental impact. Carbon dioxide (CO_2) is the primary greenhouse gas that is used for analyzing the environmental benefit in this study. The CO_2 comparison is measured 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 CO_2 reduction in various greenhouse gas equivalents.[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 458 CO_2 metric tons compared to the ZEB fleets (7000, 8000, Legacy Series) that had zero emissions.

Figure 6: Carbon Emissions (CO_2)



[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 would achieve 4,500 miles per month giving a test fleet a total of 22,500 miles per month. Mileage ran on zero-emission and diesel-hybrid buses can decrease in months when there are operator sign-ups (March, June, August, and December) as operators new to the division must be trained before they can drive these buses. This is not the case on the diesel bus as it is available at all District operating divisions.

The hybrid fleet had reduced mileage in October, November, and December due to availability problems. Low availability of the BEB fleet resulted in drastically reduced miles compared to the other fleets in the analysis. The Legacy FC fleet stayed consistent in the quantity of miles but below the expect total miles. The Diesel and FCEB fleet remained constant during the period.

Figure 7: Mileage by Technology (July 2020 – December 2020)

TECHNOLOGY	JUL	AUG	SEP	OCT	NOV	DEC
DIESEL	16,827	18,228	17,618	19,152	19,746	18,722
HYBRID	18,280	18,762	17,304	10,789	13,371	16,877
FCEB	16,939	19,516	18,787	20,127	20,932	15,932
BEB	13,768	14,504	9,875	12,147	6,439	7,915
LEGACY FC	12,565	12,776	13,288	13,334	14,953	15,794

Fuel Cell Powerplant Operating Hours

The fuel cell powerplant is a critical component to keep a hydrogen bus operational like the diesel engine is on conventional bus. The lifecycle of a fuel cell powerplant is best measured in hours of operation. The table below provides some insight to the age of our Legacy fuel cell fleet compared to the newer fuel cell fleet. The Legacy fleet has an average lifetime fuel cell operating hour of 25,763 compared to just 2,909 on the newer buses. At the end of this reporting period, three Legacy buses had exceeded 30,000 service hours without any major repairs or rehab maintenance. FC7 and FC12 have lower hours because they have spare replacement fuel cell powerplants that were installed after the original fuel cell was decommissioned. The buses participating in the study are highlighted in the following tables.

Figure 8: Fuel Cell Powerplant Operating Hours (Cumulative December 2020)

LEGACY FC	**Study Fleet**					**Additional Fleet**					
Bus ID	FC5	FC7	FC12	FC13	FC14	FC4	FC8	FC9	FC10	FC15	FC16
Hours	29,355	14,999	9,801	20,895	31,882	27,670	27,690	29,412	32,259	27,876	31,554
Average	21,386					29,410					
	25,763										

FCEB	Study Fleet					Additional Fleet				
Bus ID	7017	7018	7019	7020	7021	7022	7023	7024	7025	7026
Hours	4,095	4,126	4,234	4,346	3,392	1,660	1,962	2,142	1,362	1,767
Average	4,039					1,779				
	2,909									

Fuel Efficiencies

AC Transit utilized the Argonne National Laboratory GREET,[2] (Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation) model, 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 academia. It provides uniformity in deriving fuel economy equivalents based upon energy density as well as emission estimates by the type of fuel.

Figure 9: Fuel Efficiencies and Equivalents (July 2020 – December 2020)

TECHNOLOGY	Energy/Fuel	Fuel Efficiency	Efficiency Metric	Equivalent Efficiency	Equivalent Metric
DIESEL	Diesel	4.09	Miles/Gal	4.09	M/DGE
HYBRID	Diesel	5.30	Miles/Gal	5.30	M/DGE
FCEB	Hydrogen	8.15	Miles/Kg	9.06	M/DGE
BEB	Electricity	2.13	kWh/Mile	18.56	M/DGE
LEGACY FC	Hydrogen	5.01	Miles/Kg	5.57	M/DGE

AC Transit experienced the following relative fuel efficiencies using the GREET comparison model in the diesel equivalent format, the BEB buses were the most efficient in fuel economy at 18.56 M/DGE with the FCEB coming in second at 9.06 M/DGE.

Maintenance and Energy Costs

Cost per mile (CPM) is one of the industry standards used when calculating cost comparison between fleets. The method in which the CPM is calculated uses the actual vehicle mileage (Figure 7) and actual operating expenditures (Figure 13) captured within the reporting period. One being Labor and Materials (Maintenance) and the other Energy. For this analysis, energy can be diesel, hydrogen, or electricity which in most budgets would be labeled as fuel.

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.

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

Out of the three energy sources used by the District, the current hydrogen price creates the largest CPM cost increase. The District has been able to successfully manage the cost of electricity on PG&E's BEV-2 rate with its small fleet of 5 battery electric buses thus far.

Figure 10: Energy Rate (Fuel)

SOURCE	DIESEL	HYDROGEN	ELECTRICITY
Rate/Metric	$1.76/ Gal	$7.79/ KG	$0.22276/ KWH

The most cost effective for the reporting period was the diesel fleet with a $0.93 CPM. The ZEB technologies edged slightly higher with the BEB at $1.39 and FCEB at $1.51 CPM. The Legacy fleet was the most expensive with a $2.84 CPM. Hydrogen fuel currently has a high cost which significantly raises the CPM for the fuel cell bus fleet. 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 11: Operational Cost/Mile Totals (July 2020 – December 2020)

COST/MILE	DIESEL	HYBRID	FCEB	BEB	LEGACY FC
Maintenance	$0.54	$0.81	$0.56	$0.90	$1.29
Energy (Fuel)	$0.39	$0.30	$0.95	$0.48	$1.55
Total	**$0.93**	**$1.11**	**$1.51**	**$1.39**	**$2.84**

The fleets CPM can be adjusted with the applied warranties and Low Carbon Fuel Standard (LCSF) credits. The credits are a growing revenue source through the State and can only be applied to the ZEB fleet. For the report period, the adjusted CPM had the largest reduction in the BEB ($0.61) and FCEB ($0.40) fleet that can offset the maintenance and energy costs.

Figure 12: Operational Cost/Mile with Applied Credits (July 2020 – December 2020)

COST/MILE	DIESEL	HYBRID	FCEB	BEB
Applied Credits/ Warranties	$0.88	$1.09	$1.11	$0.78
CPM Reduction	$0.05	$0.02	$0.40	$0.61

When reviewing the energy cost across the test fleets, the FCEB was nearly triple the cost of the diesel, nearly quadruple that of the hybrid, and more than quadruple that of the battery-electric fleet. During the period, the battery electric and fuel cell had labor and material costs that mirrored the diesel fleet while the hybrid came in second to last place. The hybrid fleet was the least expensive energy cost to operate with the battery-electric fleet almost three thousand dollars higher. The legacy fuel cell fleet (with a fuel cell dominant design) was far more inefficient than the newer fuel cell fleet (with a battery dominant design), which is evident by the higher cost experienced by the legacy fleet in both categories maintenance and energy.

Figure 13: Maintenance & Energy Cost (July 2020 – December 2020)

TOTAL	DIESEL	HYBRID	FCEB	BEB	LEGACY FC
Maintenance Cost (L&M)	$60,014	$76,792	$62,516	$58,338	$106,581
Energy Cost (Fuel)	$43,017	$28,733	$107,137	$31,295	$128,431

Credits and Warranties

AC Transit has a warranty recovery program designed to identify warranty claims, record and enforce claims against manufacturers, coordinate repairs to the bus fleet, and processes reimbursements for repairs performed by District employees. 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. Note that the recoveries are not applied back to the asset which could lower the overall ZEB operating costs.

Figure 14: ZEB Recovery Total

TECHNOLOGY	WARRANTIES	CREDITS	TOTAL RECOVERY
FUEL CELL	$24,291	$76,489	$100,780
BATTERY ELECTRIC	$95,124	$41,058	$136,182

Low Carbon Fuel Standards (LCFS) Credit

In January 2020, the District hired a broker to collect and sell LCFS credits generated by the ZEB program and has claimed nearly $99,000 in clean energy credits so far this year. The amounts are differentiated by vehicle type, as shown in the table below. The revenue collected for the entire year is estimated to be about $118,000. The amount collected in the second half of the year (Q3 and Q4) is estimated to be $60,643.

Figure 15: Annual Energy Credits

VEHICLE TYPE	JAN - MAR	APR - JUN	JUL - SEP	OCT - DEC	ANNUAL
FUEL CELL	$55,224		$6,004	$15,261	$76,489
BATTERY ELECTRIC		$1,680	$35,910	$3,468	$41,058
TOTAL	**$55,224**	**$1,680**	**$41,914**	**$18,729**	**$117,547**

The revenue stream includes a brokerage fee and offsets from the District's other alternative energy sources such as solar panel facilities and hydrogen fuel stations. The District can count on this new revenue stream to increase as ZEB fleet increases over the next two years. In addition to reliable revenue growth, revenue generated from LCFS credits is flexible in how it can be used: to offset either capital or operating expenses (such as hydrogen and fuel expenses).

Fleet Availability

Fleet availability is a measurement of the vehicles readiness status for morning pull out at 7:00 a.m. The percentage is calculated by dividing the number of planned workdays by the number of workdays each vehicle was available for service. Training and special events are counted as available since the vehicle is 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 BEB fleet experienced long out-of-service periods due to high-voltage battery problems resulting in the vehicles 57% availability of the planned workdays. The Hybrid and Legacy FC fleets achieved an average availability of 85% due to defects that occurred throughout the test period. The Diesel and FCEB fleets both averaged over 90% availability. 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 16: Availability by Technology (July 2020 – December 2020)

TECHNOLOGY	JUL	AUG	SEP	OCT	NOV	DEC
DIESEL	95.48%	94.19%	94.00%	94.19%	98.67%	87.74%
HYBRID	92.90%	94.19%	96.67%	69.68%	72.67%	83.87%
FCEB	99.35%	89.03%	90.00%	94.84%	92.67%	77.42%
BEB	72.26%	74.84%	40.67%	69.03%	42.00%	45.81%
LEGACY FC	98.71%	80.65%	74.00%	78.06%	85.33%	89.03%

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 the vehicle from service until repairs are made. It is calculated as the count of a verified failure by the miles run during the same period.

Figure 17: Miles between Chargeable Road Calls (July 2020 – December 2020)

TECHNOLOGY	JUL	AUG	SEP	OCT	NOV	DEC
DIESEL	16,827	18,228	17,618	9,576	19,746	9,361
HYBRID	18,280	18,762	3,461	1,541	3,343	2,813
FCEB	16,939	6,505	9,393	3,354	20,932	5,311
BEB	6,884	14,504	9,875	3,037	6,439	7,915
LEGACY FC	2,513	2,555	1,476	2,667	4,984	3,949

Road call failures are categorized by system and component and used to direct maintenance activities to eliminate the root cause. The systems failures are defined as the following that include evaluation categories related to technologies.

- **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 18: Road Calls by System (July 2020 - December 2020)

SYSTEM	DIESEL	HYBRID	FCEB	BEB	LEGACY FC	TOTAL
Common System Failures	4	16	9	3	18	**50**
Engine/Fuel Cell System	2	8	5		6	**21**
Fuel System					15	**15**
High Voltage System			2	6		**8**
Transmission/Electric Drive				1	2	**3**
Total	**6**	**24**	**16**	**10**	**41**	**97**

The 1550 (Hybrid) fleet had 24 road calls, 12 of which were for passenger door and low voltage electrical system issues. Of the 8 engine-related calls, 4 relating to the diesel exhaust after-treatment system.

The 1600 (Diesel) fleet had 6 road calls with no concentration in any specific system.

The 7000 (FCEB) fleet had 16 road calls, 5 relating to the low voltage electrical system with no common failure points. Of the 4 Fuel Cell related failures, the H5 valve was replaced on 2 of the buses. As a note, two buses accounted for 11 of the 16 total calls.

The 8000 (BEB) fleet had 10 road calls, with half due to the high voltage batteries and state of charge issues.

The Legacy FC fleet had 41 road calls, of which 15 were fuel system or range related. There were 6 road calls for engine/fuel cell failures and 18 for common system failures, Doors and HVAC systems accounting for the majority.

Clean Corridor Deployments

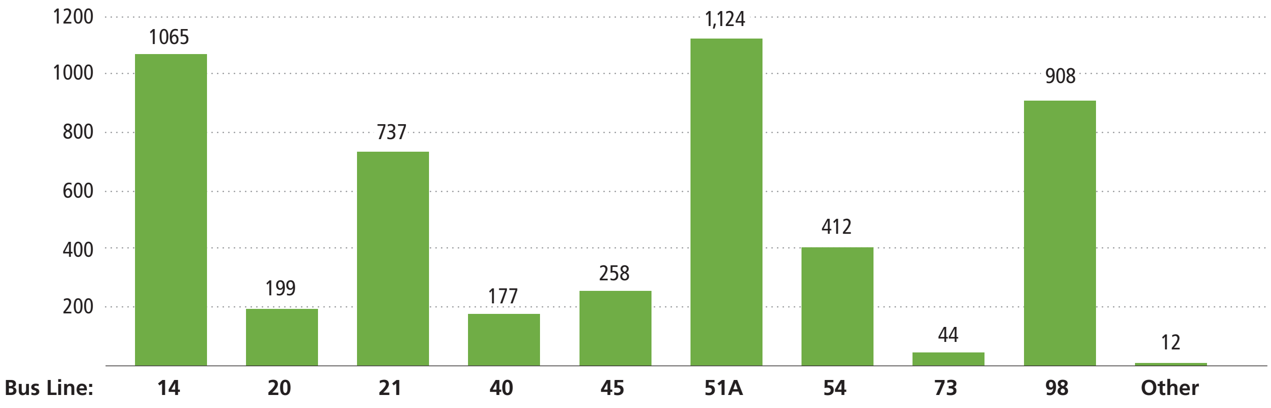
The State of California Legislature passed SB 535 in 2012 requiring 25 percent of investments from the Cap & Trade program be spent in Disadvantaged Communities (DACs). The legislation carried with it methodology for identifying those communities using information about income, race, pollution, and other 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. Figure 19 illustrates which lines had buses from this program deployed on them between July 1 and December 31, 2020. The results indicate that Lines 14, 21, 51A, and 98 were the primary lines covered in this program, with lines 54, 45, 40, and 20 used less often. All of these lines are included within the Clean Corridors program so compliance with DAC assignments is excellent. 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.

These lines for the core of the service network in East Oakland and have been operating with weekday schedules since August 2020 when the emergency service levels implemented in March 2020 were adjusted to return high-ridership lines to weekday service levels (from 7-day Sunday levels) to reduce pass-ups.

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 percent of the time and being in this program could lead to pass-ups given the 25 buses are all 40-foot coaches.

Figure 19: ZEB Deployments by Line



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, 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).

Total ZEB Workforce Development Production

To date, the District has successfully scheduled and produced over 22,051 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 20: 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 cour ses 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 ultimate 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 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, and poster training aids, related tool and diagnostic accessories as well. This one-of-a-kind training resource was funded by a California Air Resources Board grant. Working with the OEM, staff is learning how to convert this module into a primary training tool to teach a range of functions from preventive maintenance inspections to fault code troubleshooting exercises. This evolution is critical with ZEB fleet expansion as the demand for training will increase as will the need for practical instruction with technical processes.

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

Finally, the newest in-house development is in how training is delivered. Staff has successfully developed courseware designed for synchronous learning environments or online interactivity. 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 the table below) include the following: Digital Multimeter; High Voltage: Awareness and Safety; and Hydrogen: Safety, Fueling, and Storage. More courses are in development.

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 per each mechanic can best be shown in the table below. 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.

Figure 21: 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

AC Transit has spent the last twenty years learning-by-doing. This existential approach toward ZEB technology has yielded some of the best practices in the industry. Preparing mechanics will continue to evolve as experiences, training, and OEM partnerships burgeon.

Data Integration & Management Environment

AC Transit has developed a set of tools and processes in preparation for the ZEB program and its technology environment. The District recognizes the importance of advancing data quality, consistency, accuracy, reliability, and processes to address systems integration, security, compliance, regulatory requirements, decision-maker, and stakeholders' expectations.

The ZEB Data Integration and Management Environment (DIME) consist of 3 levels:

DIME facilitates accessing all the different data elements across multiple data sources, including a new Data Warehouse infrastructure to validate, manipulate and make all this information available to both internal and external customers. All the information contained in the reports is extracted directly from AC Transit's Enterprise Platform.

Data collection, transformation, and visualization of the energy and performance data are obtained directly from the District's various equipment and energy vendors, such as vehicle parameters; automatic vehicle location and speed; fluid consumption and mileage; charging station or utility usage; battery and fuel cell health, charging, status and throughput; asset and parts refits for reliability and other factors.

Figure 22: DIME Phase One

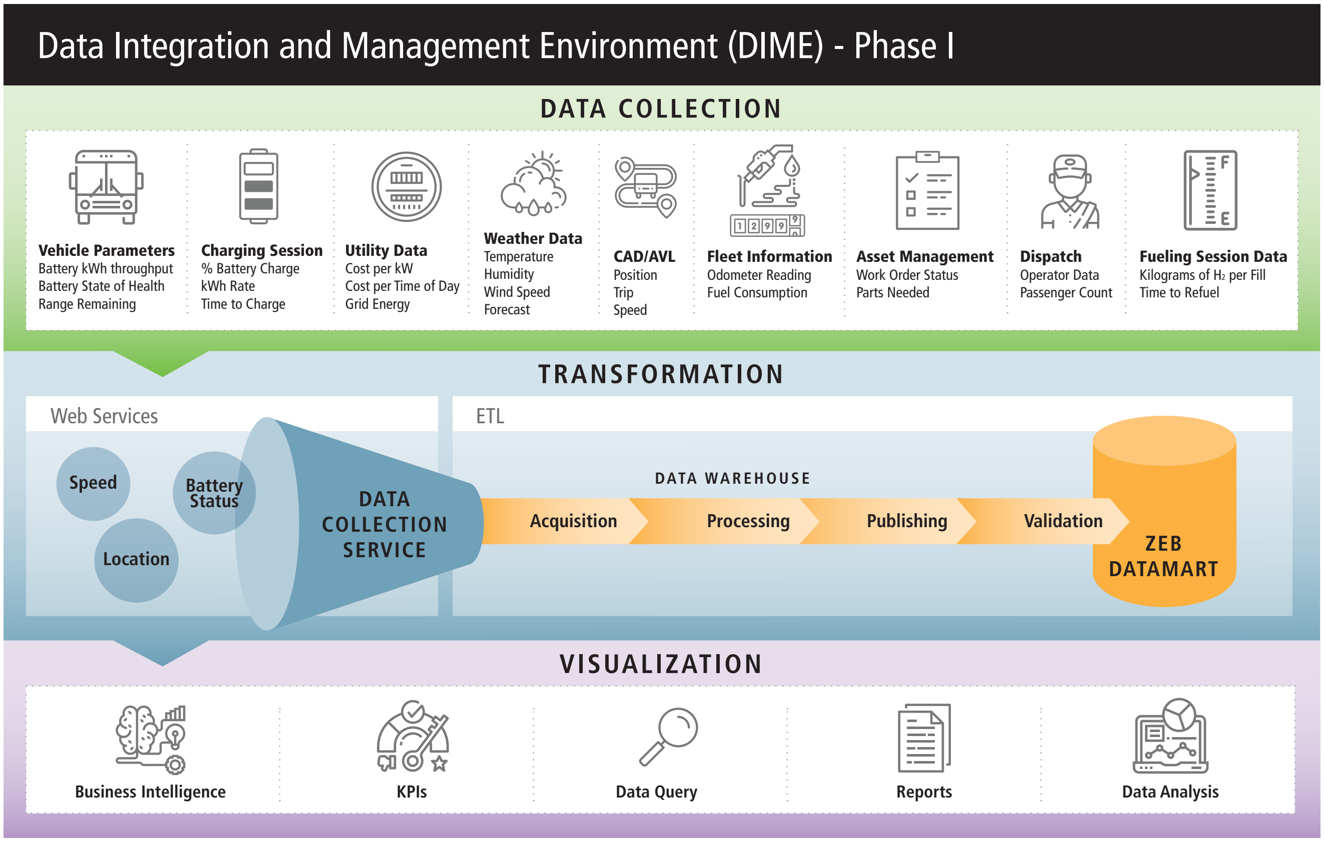


Figure 23: DIME Components

Component Glossary	
CAD/AVL	Computer Aided Dispatch/Automatic Vehicle Location – Collects real time information from vehicles
Asset Management	Centralized system that manages multiple resources in an organization
Web Services	Allow one system to communicate with another over the internet
ETL	Extract Transform Load – Set of processes that fetch data from multiple sources and consolidate it in one centralized location
Data Mart	Subset of processes inside the data warehouse that prepare the data for different customers/functional units
KPI	Key Performance Indicator – Visual representation that shows trends and patterns of the data being analyzed
Dispatch	Also known as Operations Control Center – Central coordination hub that ensures all services are running as expected

Data Collection

Data Collection layer eliminates manual steps and intervention in data ingestion from multiple systems to provide consistent precision. It integrates various external vendor Application Programming Interface (API) web services and multiple internal District systems. The Data Collection pipeline functions holistically as below.

- Identify various systems from where data will be collected, established, and test secured connectivity to their data collection API end points.
- Secure Configuration Management repository and update processes to the current administration and future enhancements
- Complete control of integration behavior and flow to accommodate each vendor's API requirements: Transport layer: TLS versions, Communication layer: Certificates.
- Authentication layer: Username/Password, OAuth, Session Token, data request Sync vs. Async, and fully integrated technology stack selection according to usage and need.
- Automated Self-Healing Data Collection processes and technologies that re-connect and re-process pending data collection automatically once an outage is resolved.
- Messaging tool to monitor and ensure expected data volume, velocity, and verity during Data Ingestion.
- Audit and Quality Assurance processes and tools to ensure robust and reliable connectivity and consistency in the overall Data Collection.
- Configuration to meet near future potential data growth with scalability, multi-platform support, and advanced security features considering ZEB technology and vendor partnerships are evolving trends.

Transformation

The Transformation layer addresses data extraction and transformation processes while maintaining the quality and availability of ZEB data. In this process, data is verified, cleaned, and stored on a secure Enterprise Datawarehouse SQL Server. This current layer functions and forthcoming roadmap features are listed below:

- Data Collection Service and related processes being rolled out to ensure data precision and accuracy.
- ZEB Data Model and Data Mart based on business requirements are being developed
- On-Demand data processing will also be integrated in future implementation phases

Visualization

Data has become one of the most strategic and critical assets for any organizational business decision makings. The Visualization layer encompasses data-driven decision analytics from accurate, reliable, and accessible enterprise data platforms. The forthcoming Cloud platform and Business Intelligence (BI) Visualization tools are to include the following features:

- The District is upgrading the existing Enterprise Datawarehouse to advance with cloud-based BI tool to offer modern data visualizations.
- Tools for users to request and check the delivery status of new BI datasets.
- Audit and monitoring tools for data and role-based access security
- BI and Visualization matrix for usage incorporating feedback for constant Improvement aligned with business needs and priorities to run Business Intelligence and Machine Learning models
- Capacity Planning and analysis of existing compute resources against current and forthcoming Business Applications, Vehicle events, IoT/sensors data feed, Enterprise Databases, Data Lakes, Data Warehouses, and Business Intelligence platforms
- End-to-end testing from Vehicle Data Collection to Business Intelligence, including workload stress tests synchronizing compute resources with data growth.
- On-Demand data visualization is on the roadmap for future development

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 there will be some initial results that do not reflect what will become a standard performance matrix. 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.

Next Steps

AC Transit will continue to deploy the ZETBTA control fleet and collect performance data to provide a follow up report for the review period of January to July 2021. This report is anticipated to have more robust data sets for the analysis as initial deployment "shake-out" challenges have been addressed and limitations related to the pandemic subside. Release of the report is targeted for the winter of 2021.

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Leading the way to a **ZERO EMISSION FUTURE.**