



AC Transit Fuel Cell Electric Bus Progress Report

Data Period Focus: Jan. 2020 through Dec. 2020

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Introduction

This report presents early results from a deployment of fuel cell electric buses (FCEBs) operated by Alameda Contra-Costa Transit (AC Transit) in the east bay area of California. The ten FCEBs, produced by New Flyer, feature an electric drive propulsion system powered by a Ballard fuel cell system. The project team is collaborating with the U.S. Department of Energy (DOE) and DOE's National Renewable Energy Laboratory (NREL) to evaluate the buses in revenue service.

The goal of this evaluation is to compare the FCEB performance to that of conventional technology and to track progress over time toward meeting the technical targets set by DOE and the Department of Transportation (DOT). The FCEBs were delivered beginning in late-2019. The data period covers January 2020 through December 2020. NREL collects data on two different baseline bus fleets for comparison: five 2017 model year diesel buses and five 2016 model year diesel hybrid buses.

Each NREL evaluation tracks data and performance results for a specific transit agency operating a specific manufacturer's technology design. Results from different OEM designs will vary and are not necessarily representative of a specific technology. Results also will vary from agency to agency and even between facilities within the same agency. Readers should keep this in mind when using these results for decision making.

Results Summary

Bus fleets: This evaluation includes ten 2018 model year 40-ft FCEBs built by New Flyer with an electric propulsion system and a Ballard fuel cell system. The baseline buses are five 2017 model year Gillig 40-ft diesel buses and five 2016 model year diesel hybrid buses.

Bus use: AC Transit has split its FCEB fleet between two of its depots: Division 4 in Oakland (D4) and Division 2 in Emeryville (D2). At this point in the deployment, AC Transit is focused on operation of the FCEBs at D4. Because this results in differences in performance and cost between the two sets of FCEBs, NREL presents most of the results by sub-fleet.

Fuel economy: The FCEBs had an average fuel economy of 8.07 miles per kilogram of hydrogen, which equates to 9.11 mpdge. The diesel and hybrid buses had an average fuel economy of 4.14 mpg and 5.35 mpg, respectively. The FCEB fuel economy was approximately 2.2 times higher than that of the diesel buses, and 1.7 times that of the hybrid buses.

Results Summary (continued)

Fuel use and cost: During the data period, AC Transit fueled its FCEB fleet more than 1,700 times with an average fill amount of 15.44 kg. Daily dispensed hydrogen was 75 kg. The average cost of hydrogen was \$8.52/kg (\$7.79/kg plus sales tax). The diesel fuel cost for the data period was \$1.60/gallon. The FCEBs had an average fuel cost of \$1.06 per mile. The fuel cost for the diesel buses averaged \$0.39 per mile and the hybrid buses averaged \$0.29 per mile.

Availability: The average availability for the D4 FCEBs was 87.8%, while the D2 FCEBs averaged 60.6%. In comparison, the diesel buses averaged 95% and the diesel hybrid buses averaged 86% availability. Most unavailable time for the D4 FCEBs was due to general bus-related problems followed by fuel cell system issues (this category also includes balance of plant components). The D2 FCEBs had issues with the traction batteries and general bus-related problems. Most downtime for the diesel and hybrid buses was for general bus-related issues followed by time for preventive maintenance.

Results Summary (continued)

Maintenance cost: The cost to maintain the FCEBs in the data period was \$0.37/mile for the D4 FCEBs and \$0.80/mile for the D2 FCEBs. The higher cost for the D2 FCEBs was primarily due to the lower mileage accumulation. In comparison, the cost for the diesel fleet was \$0.35/mile and the hybrid bus fleet cost \$0.62/mile.

Propulsion-system maintenance was \$0.09/mile for the D4 FCEBs and \$0.30/mile for the D2 FCEBs. The comparative cost for the diesel buses was \$0.11/mile and the hybrid fleet was \$0.23/mile.

Note that the FCEB and diesel fleets of buses are under warranty and most repairs are covered by the OEM. The hybrid buses are out of the warranty period.

Fleet Profile

The Alameda-Contra Costa Transit District —AC Transit — offers public transit service in the East Bay of the San Francisco, California, area, including Oakland. The AC Transit service area of 364 square miles includes 13 cities and adjacent unincorporated areas in Alameda and Contra Costa counties. In 2006, AC Transit initiated its first three-FCEB pilot demonstration program to test the technology in transit service. Since that time, the agency has operated 24 FCEBs, 5 battery electric buses, and two hydrogen fueling stations.

AC Transit has split its FCEB fleet between two of its depots: Division 4 in Oakland (D4) and Division 2 in Emeryville (D2). At this point in the deployment, AC Transit is focused on operation of the FCEBs at D4. This results in differences in performance between the two sets of FCEBs. NREL provides results for most data parameters by sub-fleet with designations for division: D4 or D2.

Evaluation Buses

Vehicle System	FCEB	Diesel	Hybrid
Number of buses	10	5	5
Bus manufacturer/model	New Flyer, Xcelsior	GILLIG,	GILLIG,
Model year	2018	2017	2016
Bus purchase cost* (\$)	1.156 M	448,771	699,060
Length/width/height	41 ft/102 in./129.6 in.	40 ft/102 in./135 in.	40 ft/102 in./135 in.
Curb weight (lb.)	30,900	27,220	27,220
GVWR (lb.)	43,820	39,600	39,600
Hybrid system/ Transmission	Siemens ELFA2, Permanent Electronic Motor, 210 kW	Voith D864.6	BAE Systems HDS200
Fuel cell or engine	Ballard FCvelocity-HD85, 85 kW	Cummins ISL 280 hp @ 2,200 rpm	Cummins ISB 280 hp @ 2,200 rpm
Energy storage	A123 Systems, lithium-ion, 100 kWh	N/A	Lithium-ion, 12 kWh
Accessories	Electric	Mechanical	Electric
Fuel capacity	Gaseous hydrogen, 5 Type 4 composite cylinders, Agility Fuel Solutions, 37.5 kg at 5,000 psi	120 gal. diesel	120 gal. diesel

* Cost includes ACT equipment

Evaluation Buses

FCEB



Diesel



Hybrid



Infrastructure Description

AC Transit has installed hydrogen stations at each division, both designed and built by Linde LLC:

Emeryville (D2): The station, commissioned in August 2011, provides hydrogen from a combination of liquid hydrogen delivery and solar-powered electrolysis. In 2020, the station was upgraded at a cost of \$4.4 million. The upgraded station has a 15,000-gallon liquid hydrogen storage tank, dual cryogenic pumps, high pressure vaporizers, and 360 kg of high-pressure gaseous storage. Two dispensers are installed in the fuel island. The station also provides hydrogen at 700 bar pressure for a light-duty auto dispenser

Oakland (D4): The hydrogen station at D4, commissioned in December 2014, is similar to the D2 station, but does not provide higher pressure hydrogen for light-duty autos. An on-site electrolyzer is powered by a solid oxide fuel cell. Two dispensers are installed in-line with the diesel fueling island.

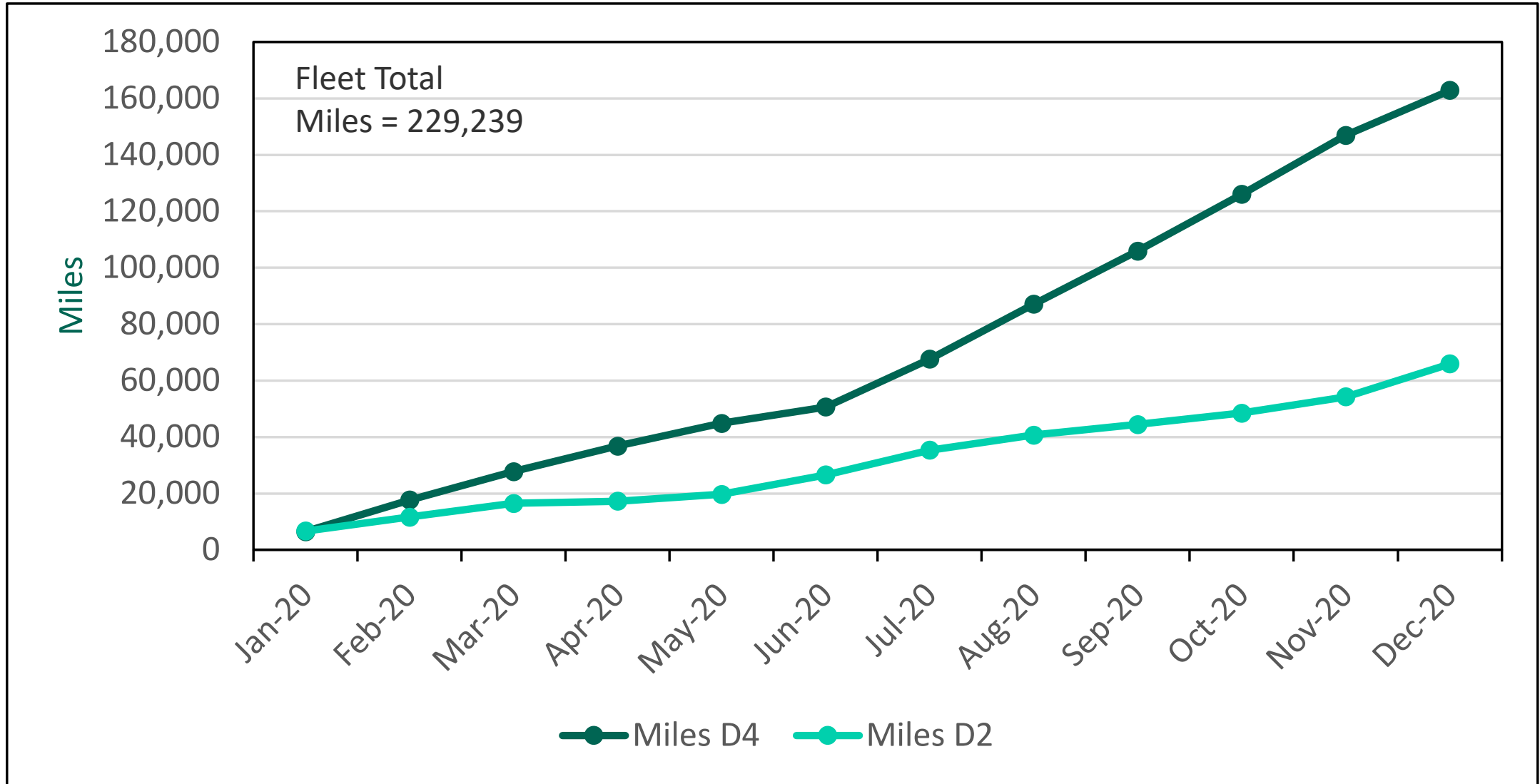
Data Summary

Data Item	FCEB D4	FCEB D2	Diesel	Hybrid
Number of buses	5	5	5	5
Data period	1/20–12/20	1/20–12/20	1/20–12/20	1/20–12/20
Number of months	12	12	12	12
Total mileage in data period	162,874	66,364	208,591	186,874
Average monthly mileage per bus	2,715	1,106	3,477	3,115
Total FCPP hours	16,580	7,018	—	—
Availability (85% is target)	88	61	95	86
Fuel economy (FCEB mi/kg)	8.09	8.00	—	—
Fuel economy (mpdge ^a)	9.14	9.04	4.13	5.35
Miles between roadcalls (MBRC) – bus ^b	6,032	4,424	23,177	5,496
MBRC – propulsion system only ^b	10,858	6,636	34,765	8,899
MBRC – FC System only ^b	20,359	11,061	—	—
Total maintenance (\$/mile)	0.368	0.800	0.348	0.616
Maintenance – propulsion system only (\$/mile)	0.086	0.304	0.112	0.228

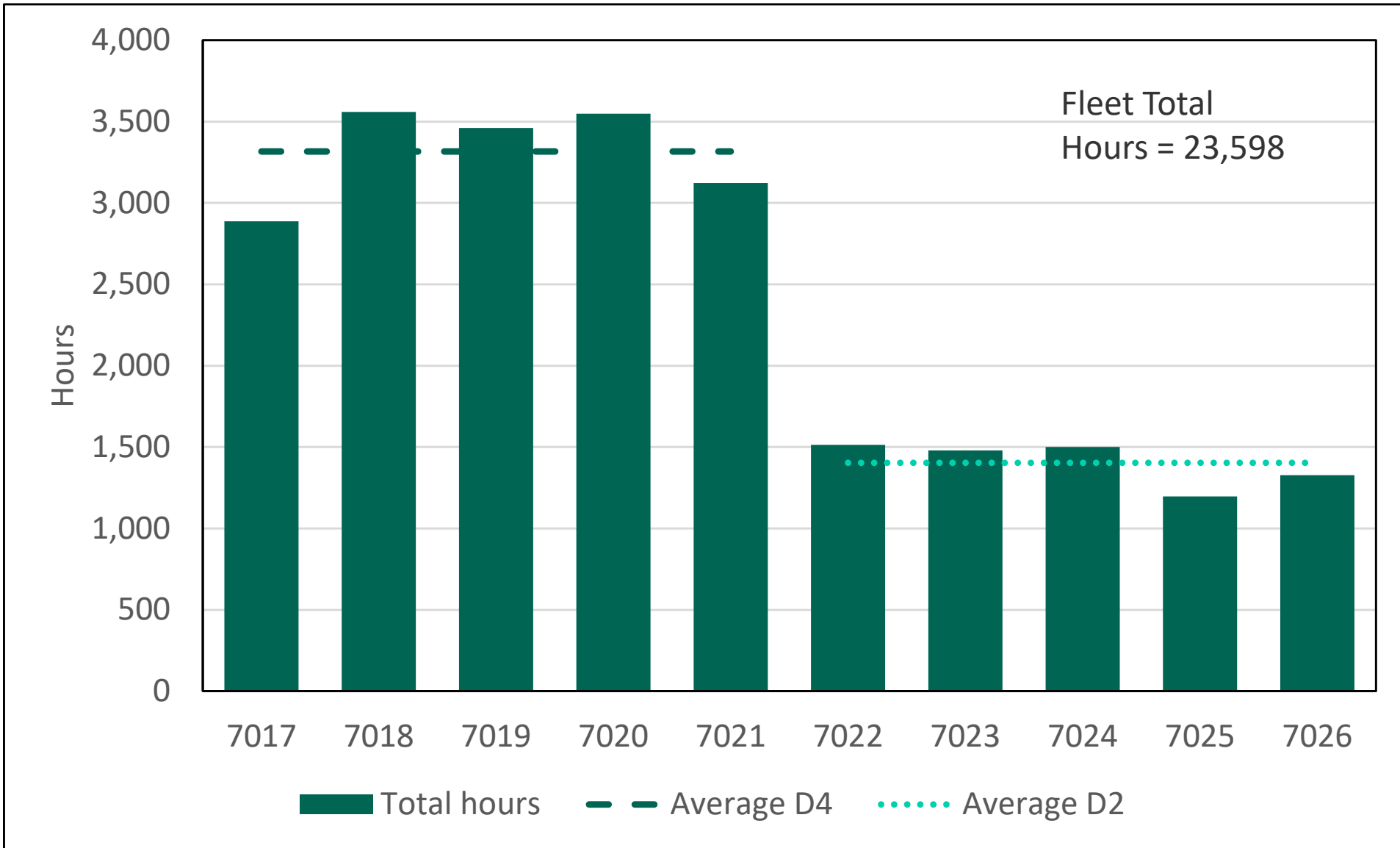
^a Miles per diesel gallon equivalent.

^b MBRC for the FCEB data cumulative from the clean point of January 2020 through December 2020.

FCEB Total Miles



FCEB Total Hours

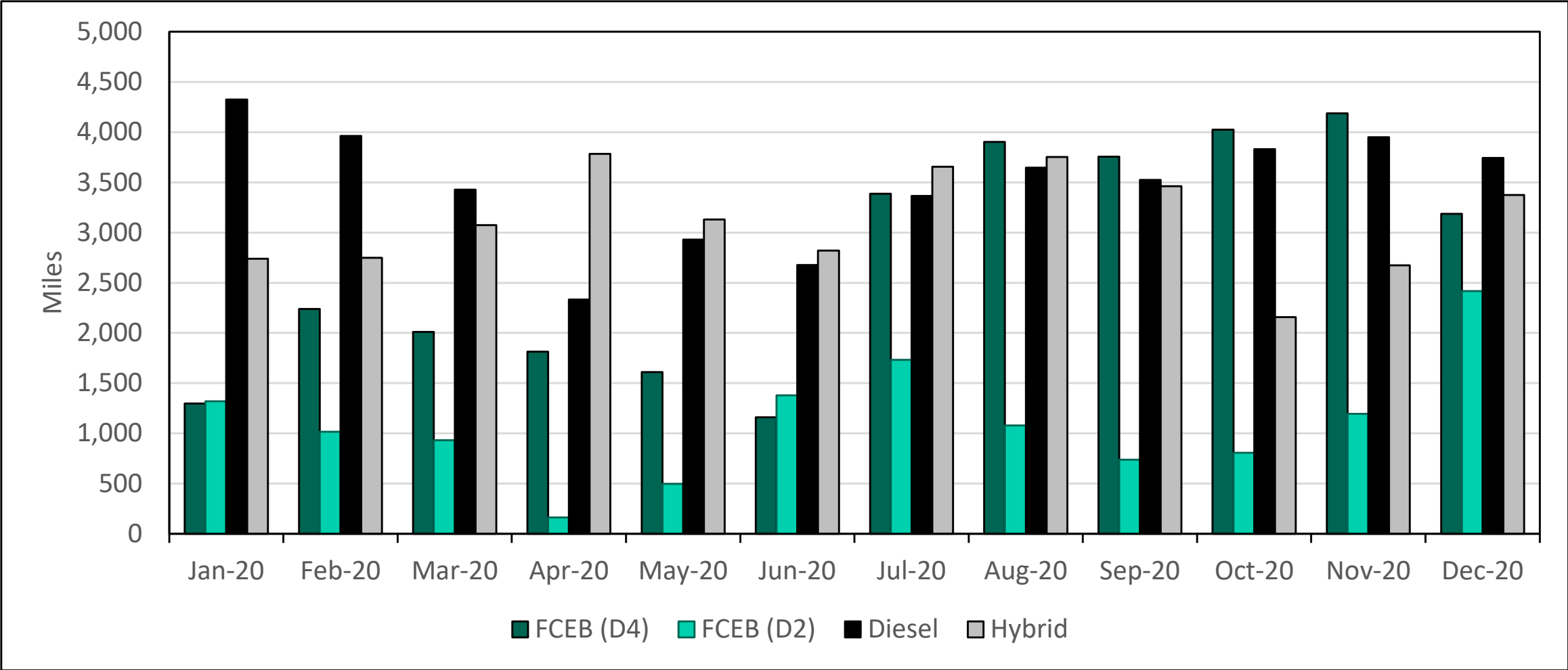


Fleet Average Monthly Miles by Bus

Bus	Miles	Bus Months	Average Monthly Mileage
7017	27,717	12	2,310
7018	34,725	12	2,894
7019	34,390	12	2,866
7020	34,982	12	2,915
7021	31,061	12	2,588
FCEB D4 Fleet	162,874	60	2,715
7022	13,829	12	1,152
7023	14,573	12	1,214
7024	13,947	12	1,162
7025	11,022	12	918
7026	12,993	12	1,083
FCEB D2 Fleet	66,364	60	1,106

Bus	Miles	Bus Months	Average Monthly Mileage
1601	43,772	12	3,648
1602	41,471	12	3,456
1603	42,403	12	3,534
1604	45,254	12	3,771
1605	35,691	12	2,974
Diesel Fleet	208,591	60	3,477
1556	42,375	12	3,531
1557	34,901	12	2,908
1558	40,875	12	3,406
1559	36,891	12	3,074
1560	31,832	12	2,653
Hybrid Fleet	186,874	60	3,115

Average Monthly Miles



Availability Analysis

Availability, which is a measure of reliability, is presented as the percentage of days the buses are actually available out of days that the buses are planned for passenger service. Buses available for service may have been used in passenger service, training, or for special events, or they may have been available but just not used. Buses unavailable for service may have had issues with the propulsion system (fuel cell system, electric drive system), general bus maintenance, or undergoing scheduled maintenance. Accidents are removed from the data—the bus is considered “not planned” during the repair time.

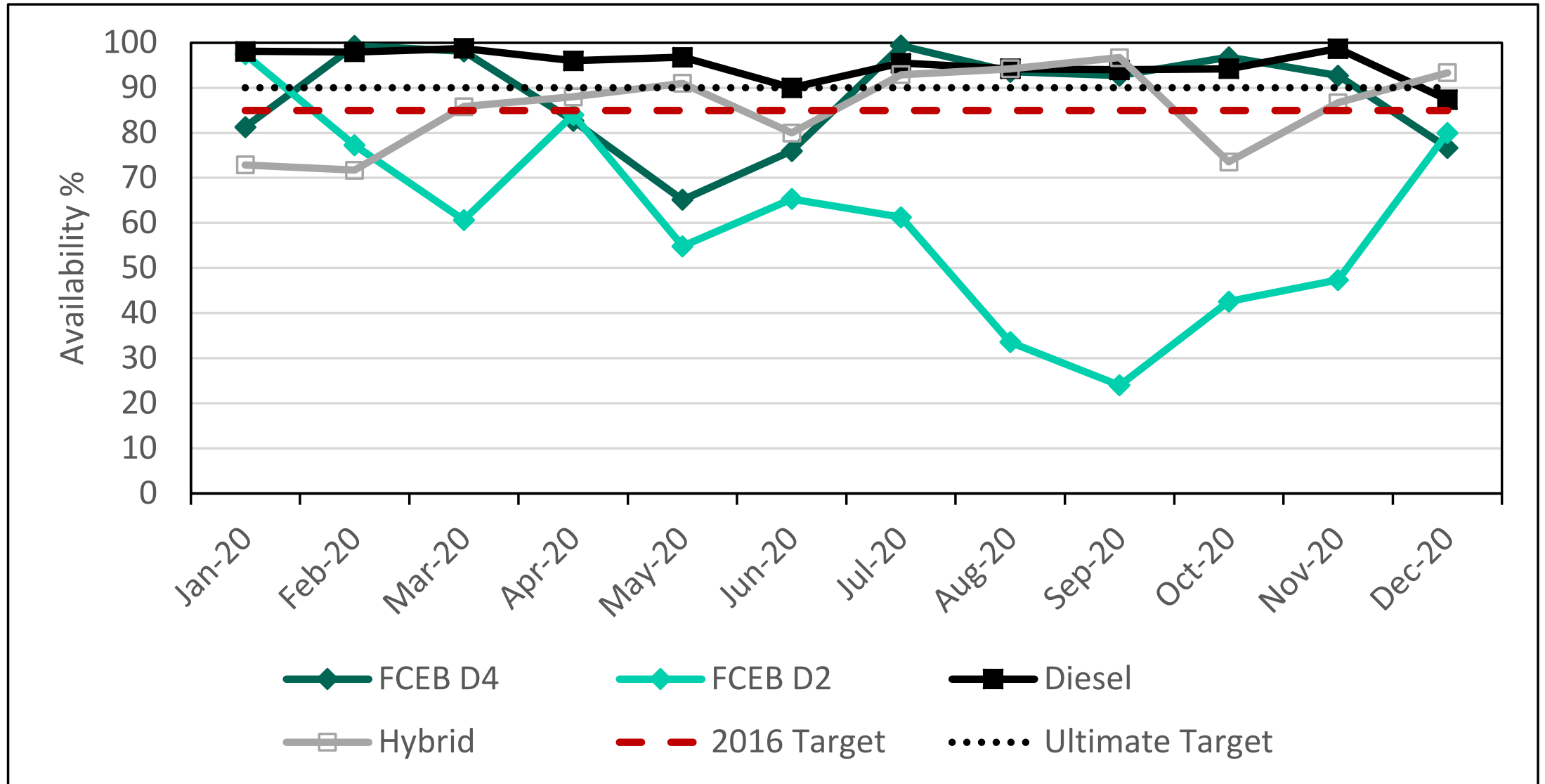
The data presented are based on availability for morning pull-out and don't necessarily reflect all-day availability. Transit agencies typically have a target of 85% availability for their fleets to allow for time to handle scheduled and unscheduled maintenance. For AC Transit, NREL calculates availability based on the planned service days, which are typically every day. AC Transit provides daily downlist for buses and a reason for unavailability.

NREL presents availability as a monthly average trend and as overall availability. Unavailable time is separated into several categories to show the primary reason for downtime. The fuel cell system downtime includes issues with the fuel cell stack and balance of plant components.

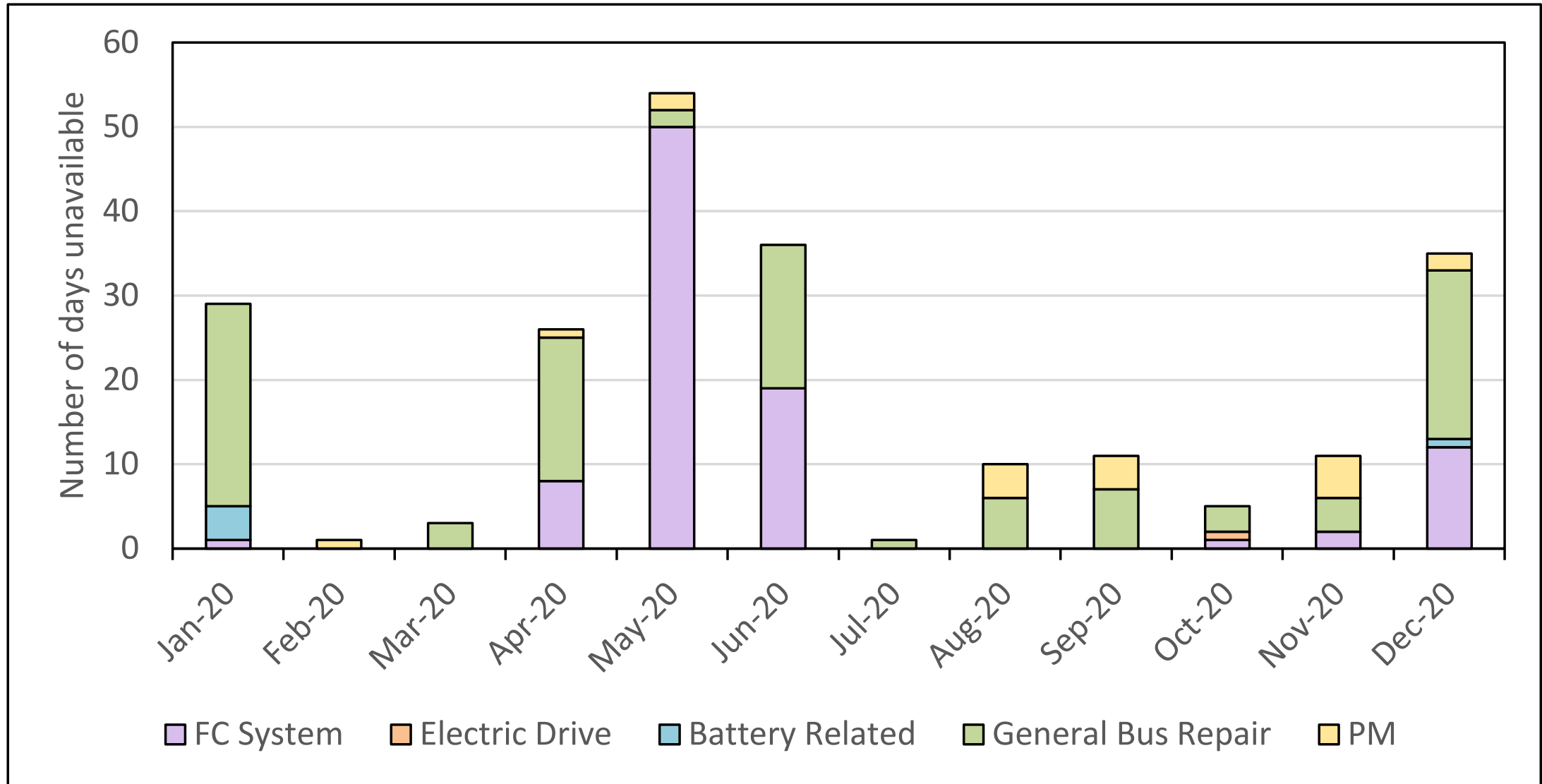
Availability Summary

Category	FCEB D4 # Days	FCEB D4 %	FCEB D2 # Days	FCEB D2 %	Diesel # Days	Diesel %	Hybrid # Days	Hybrid %
Planned work days	1,825		1,825		1,825		1,825	
Days available	1,603	87.8	1106.0	60.6	1,736	95.1	1,570	85.6
Days unavailable	222	12.2	719	39.4	89	4.9	255	14.4
Fuel cell system	93	5.1	149	8.2	—	—	—	—
Engine	—	—	—	—	12	0.7	34	1.9
Electric drive	1	0.1	49	2.7	0	0.0		
Batteries	5	0.3	322	17.6	—	—	—	—
Transmission	—	—	—	—	—	—	0	0.0
General bus maintenance	104	5.7	181	9.9	47	2.6	151	8.3
Preventive maintenance	19	1.0	18	1.0	30	1.6	70	3.8

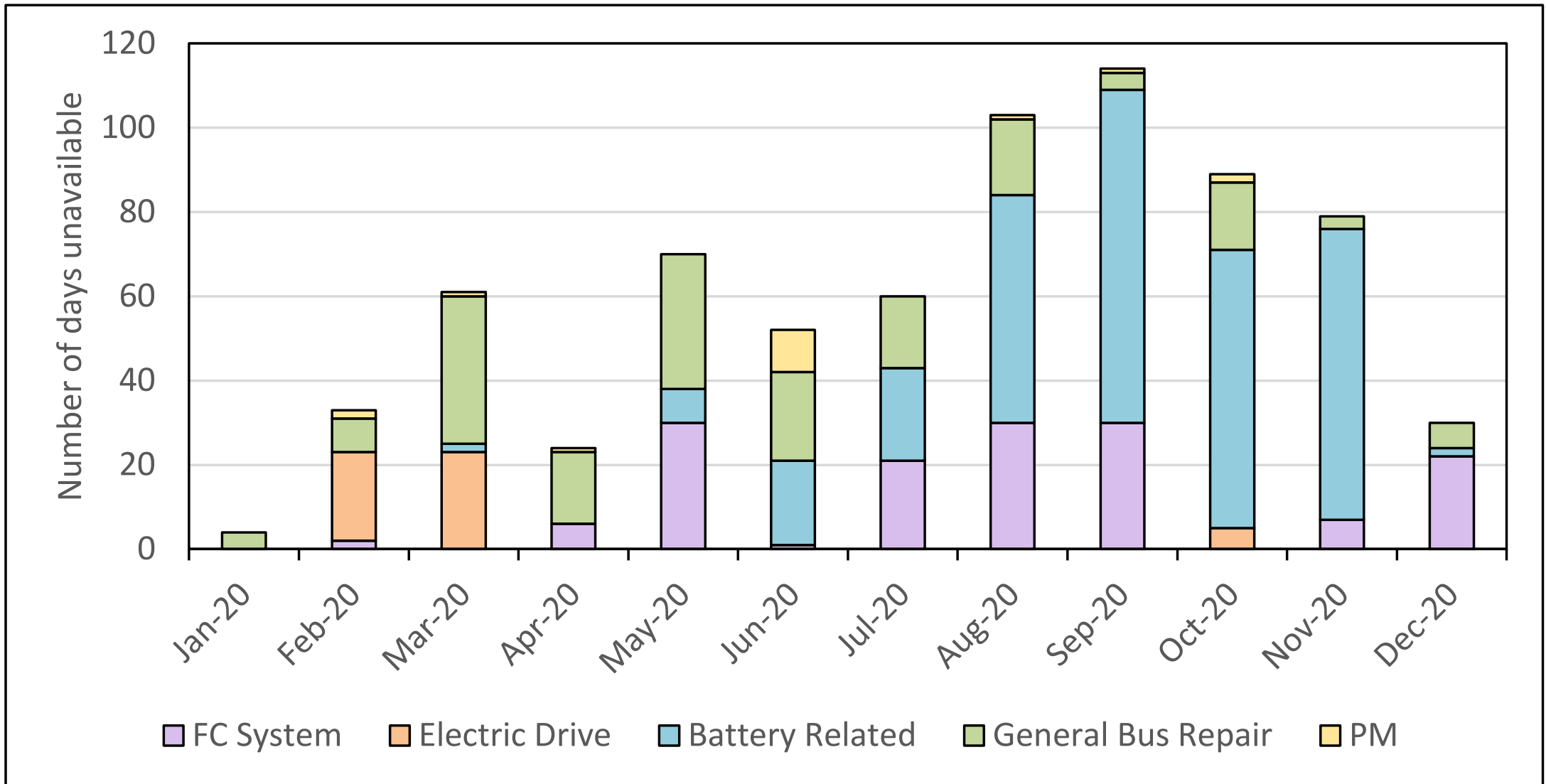
Monthly Availability



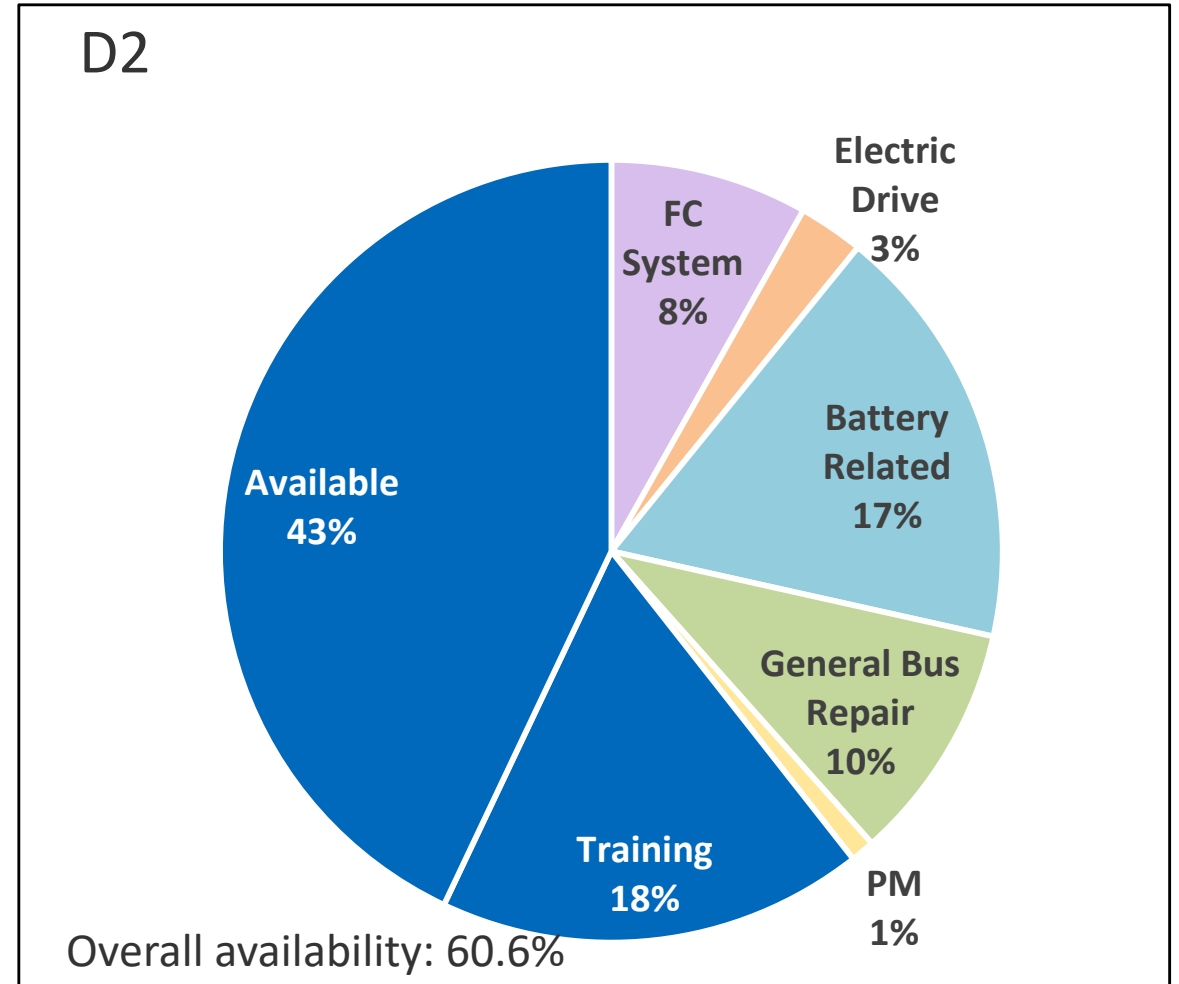
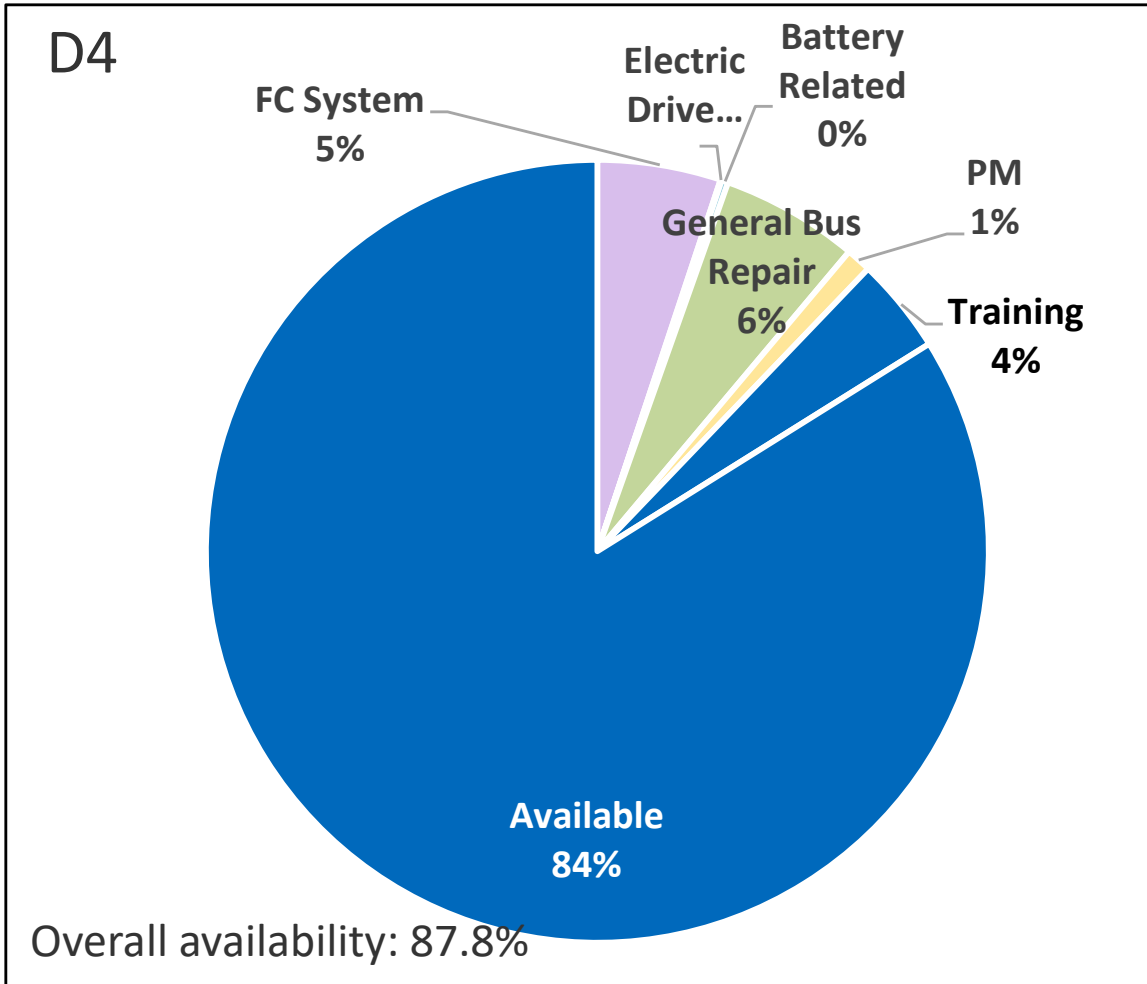
FCEB D4 Monthly Unavailability Reasons



FCEB D2 Monthly Unavailability Reasons



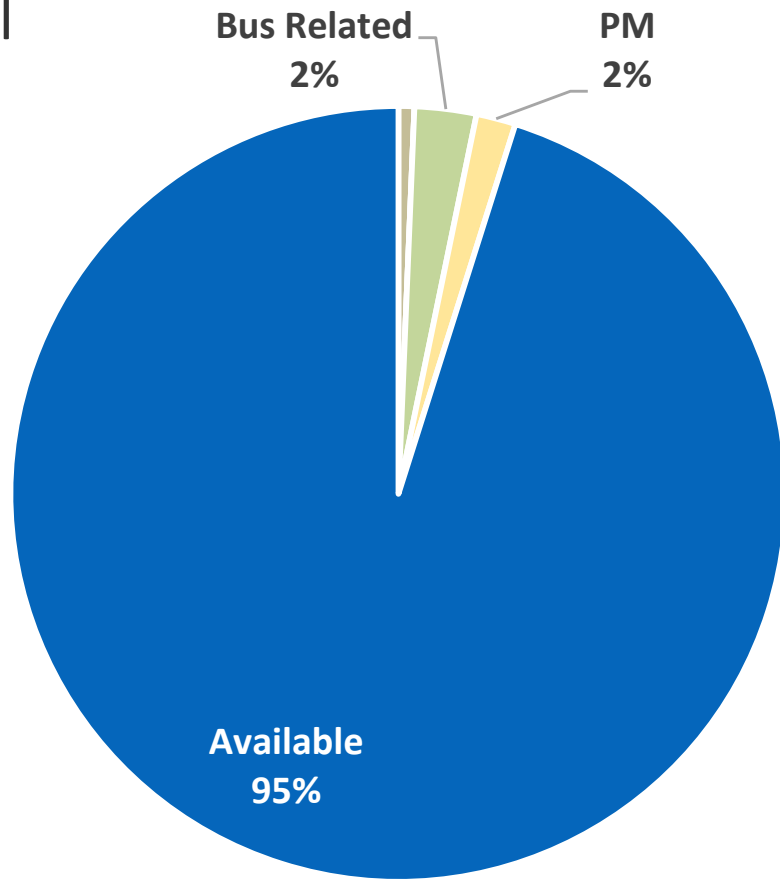
FCEB Overall Availability



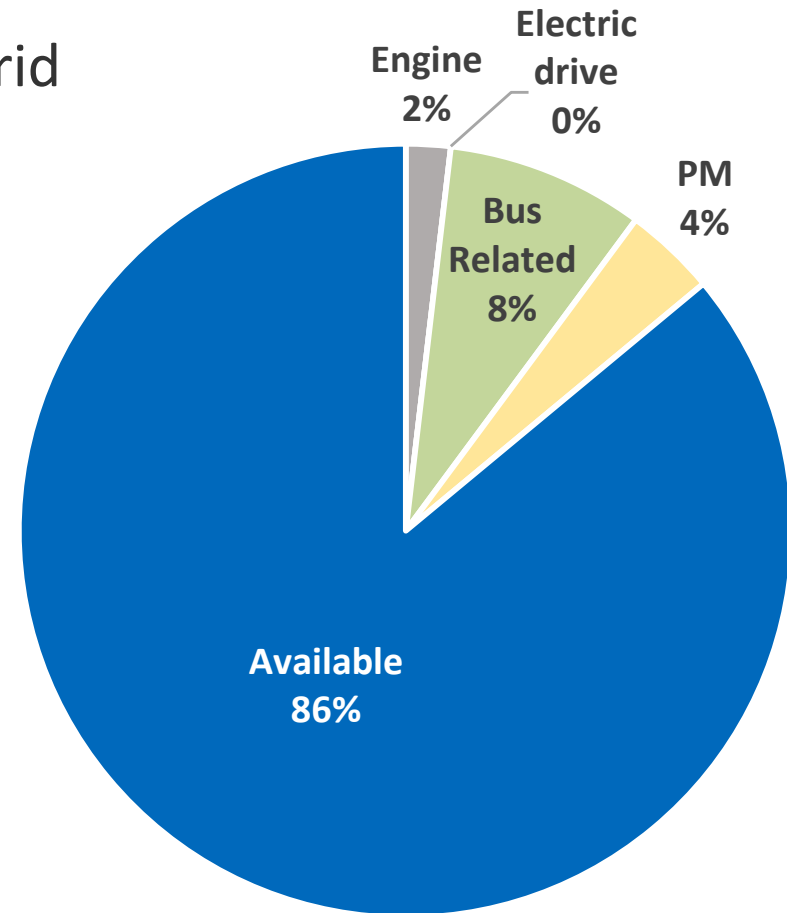
Training category = available, but used for training
Overall availability = available days + training days

Baseline Overall Availability

Diesel



Hybrid



Fuel Economy and Cost Analysis

AC Transit provides individual fueling records for the FCEB, diesel, and hybrid buses. Hydrogen is tracked in kilograms; 1 kg of hydrogen has essentially the same energy content as a gallon of gasoline. To compare the fuel economy of the FCEBs to that of the baseline buses, NREL converts kg hydrogen to diesel gallon equivalent (dge).

Conversions:

$$\text{kg H}_2 * 0.885 = \text{dge}$$

AC Transit provides the cost of hydrogen and diesel for each delivery. NREL calculates the cost per unit by month by combining all deliveries in that month.

The average cost of hydrogen during the evaluation period was \$8.52/kg. This is based on the negotiated price of \$7.79 per kg for hydrogen plus sales tax. The diesel fuel cost for the data period was \$1.60 per gallon.

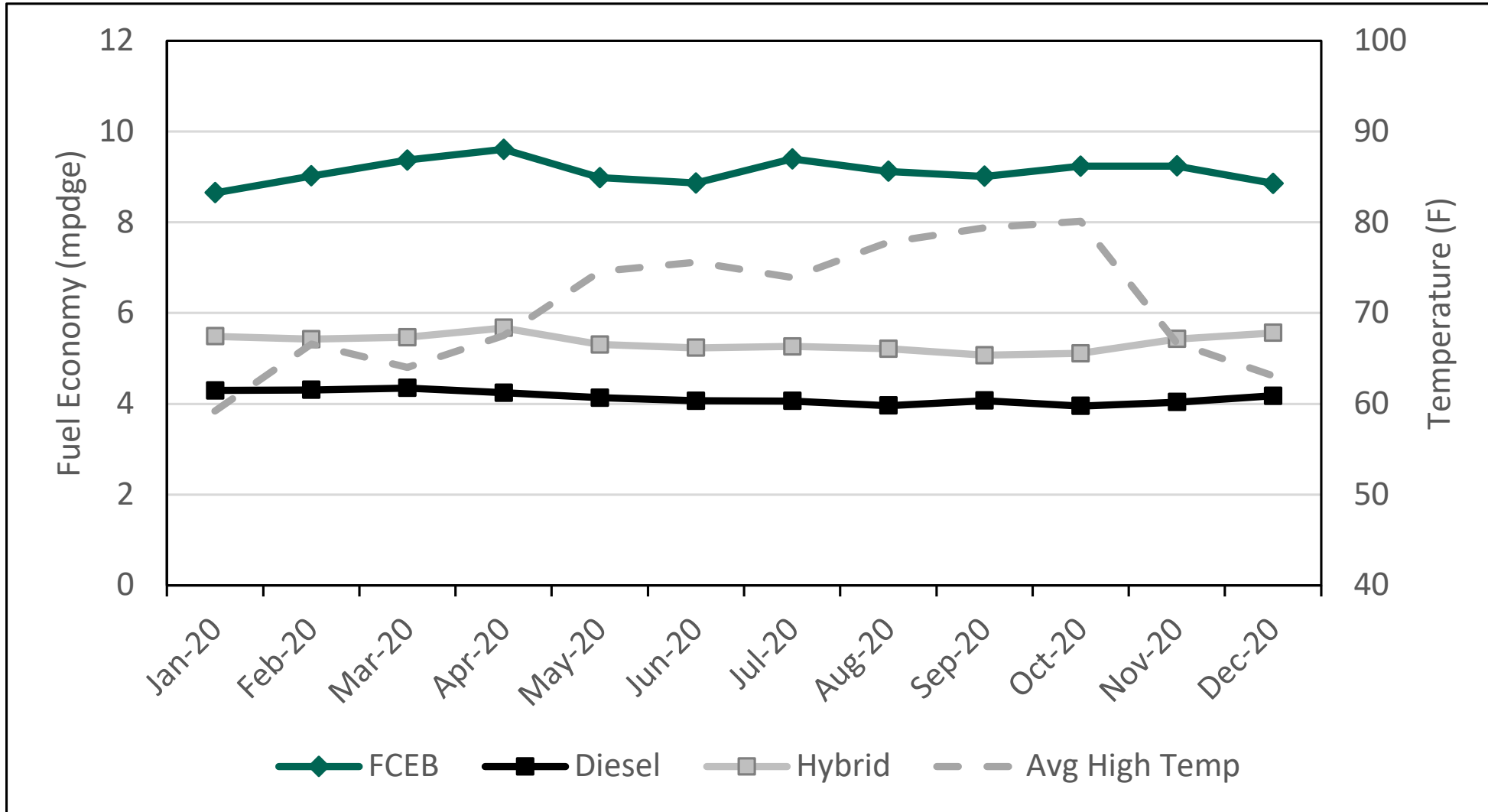
Fuel Economy by Bus

Bus	Miles	Hydrogen (kg)	mi/kg	Diesel gallon Equiv.	Fuel economy (mpdgc)
7017	26,683	3,430.9	7.78	3,036.2	8.79
7018	33,305	4,214.0	7.90	3,729.2	8.93
7019	32,588	3,945.9	8.26	3,492.0	9.33
7020	34,381	4,208.9	8.17	3,724.7	9.23
7021	30,298	3,637.7	8.33	3,219.2	9.41
FCEB D4 Fleet	157,254	19,437.4	8.09	17,201.2	9.14
7022	13,469	1,609.2	8.37	1,424.1	9.46
7023	14,137	1,831.7	7.72	1,621.0	8.72
7024	13,137	1,703.4	7.71	1,507.4	8.71
7025	10,341	1,281.1	8.07	1,133.7	9.12
7026	12,501	1,518.6	8.23	1,343.9	9.30
FCEB D2 Fleet	63,584	7,944.0	8.00	7,030.1	9.04

Bus	Miles	Diesel	Miles per gal
1601	43,409	9,958.3	4.36
1602	40,609	9,497.1	4.28
1603	41,197	9,711.9	4.24
1604	43,190	10,023.5	4.31
1605	35,563	10,161.0	3.50
Diesel Fleet	203,968	49,351.8	4.13
1556	42,244	7,558.2	5.59
1557	34,293	6,381.9	5.37
1558	39,570	7,524.4	5.26
1559	35,889	6,811.0	5.27
1560	31,012	5,932.6	5.23
Hybrid Fleet	183,008	34,208.1	5.35

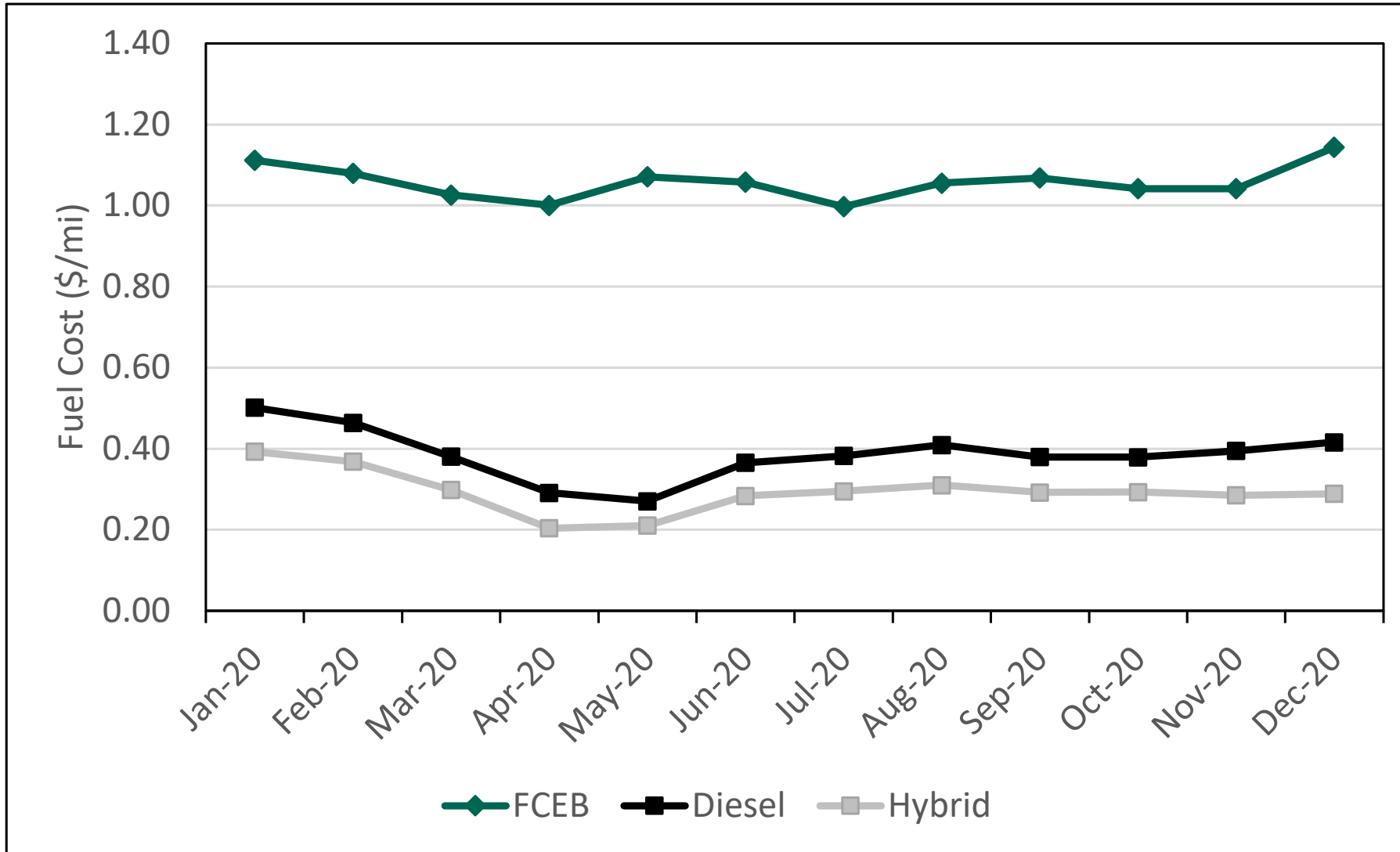
- FCEB fuel economy is 2.2 times that of the diesel buses and 1.7 times that of the hybrid buses.

Monthly Average Fuel Economy



Temperature at Oakland International Airport, data from NOAA: <https://www.ncdc.noaa.gov/cdo-web/datatools/lcd?prior=N>

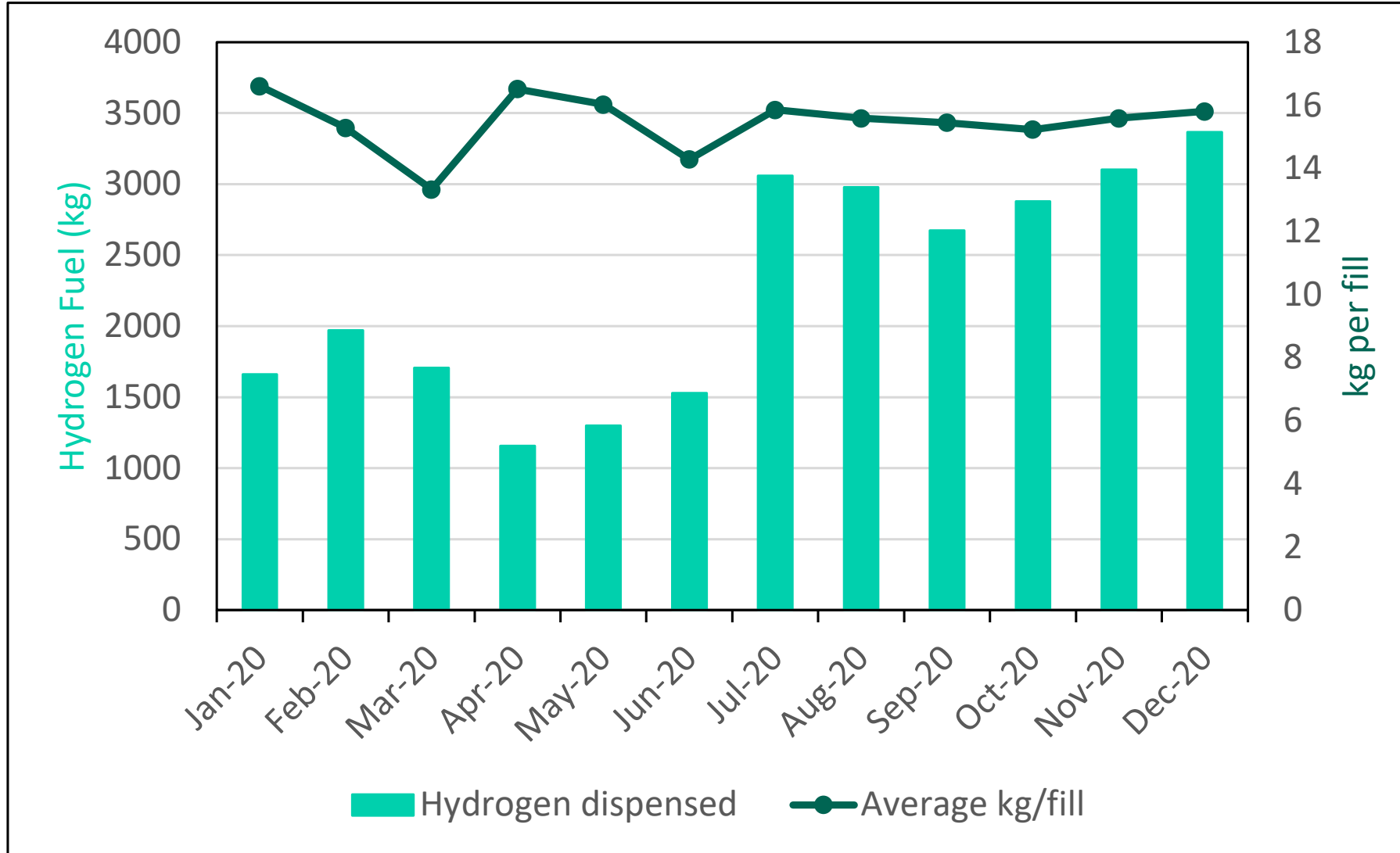
Monthly Average Fuel Cost Per Mile



- Average fuel cost
- H2 = \$8.52 /kg
 - Diesel = \$1.60 /gal

- Average cost per mile
- H2 = \$1.06
 - Diesel = \$0.39
 - Hybrid = \$0.29

Fleet Hydrogen Use



Overall
Daily kg Hydrogen: 74.8
H2 kg/fill: 15.44

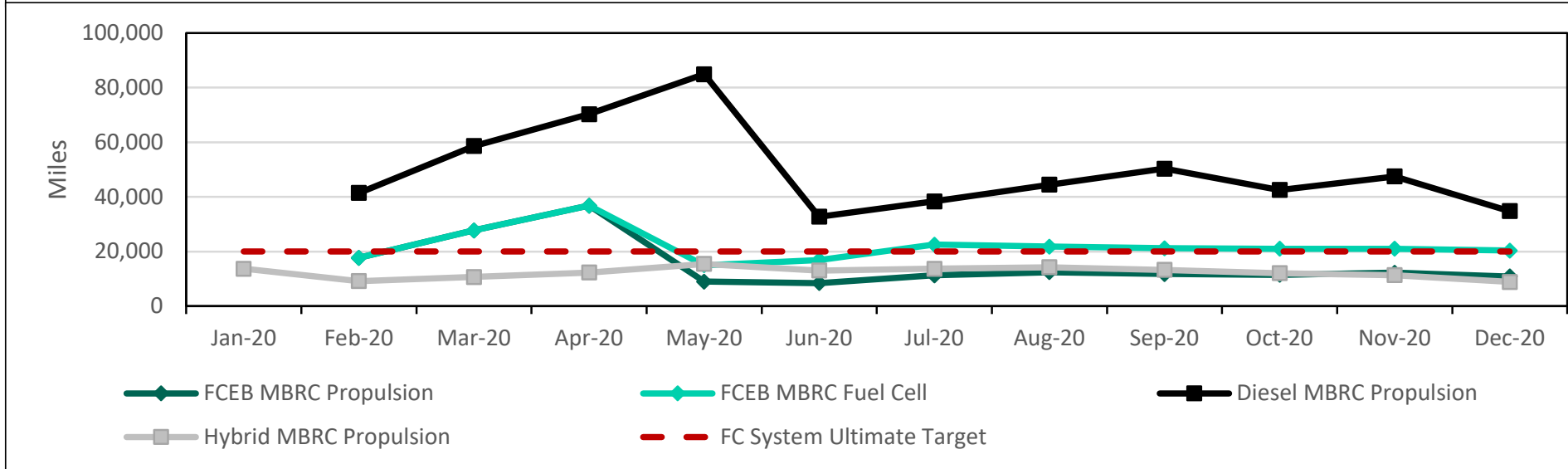
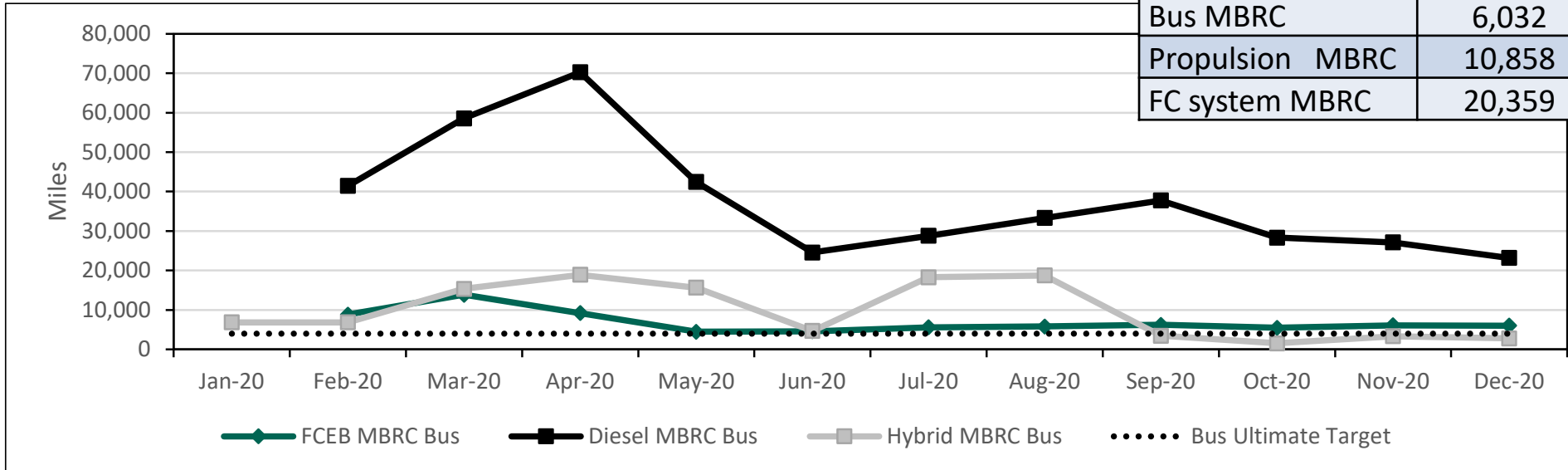
Roadcall Analysis

A roadcall or revenue vehicle system failure is defined as a failure of an in-service bus that causes the bus to be replaced on route or causes a significant delay in schedule. If the problem with the bus can be repaired during a layover and the schedule is kept, this is not considered a roadcall. The analysis described here includes only roadcalls that were caused by “chargeable” failures. Chargeable roadcalls include systems that can physically disable the bus from operating on route, such as interlocks (doors, air system), engine, or things that are deemed to be safety issues if operation of the bus continues. They do not include roadcalls for things such as problems with radios, fareboxes, or destination signs.

The transit industry measures reliability as mean distance between failures, also documented as MBRC. NREL tracks MBRC by total roadcalls, propulsion-related roadcalls, and fuel cell (FC) system-related roadcalls. Total roadcalls includes all chargeable roadcalls. “Propulsion-related roadcall” is a subset of total roadcalls and includes all roadcalls due to propulsion-related systems including the FC system (or engine for a conventional bus), electric drive, fuel, exhaust, air intake, cooling, non-lighting electrical, transmission systems, and hydraulics. The FC system-related roadcalls, a subset of the propulsion-related roadcalls, and MBRC are included for the FCEBs.

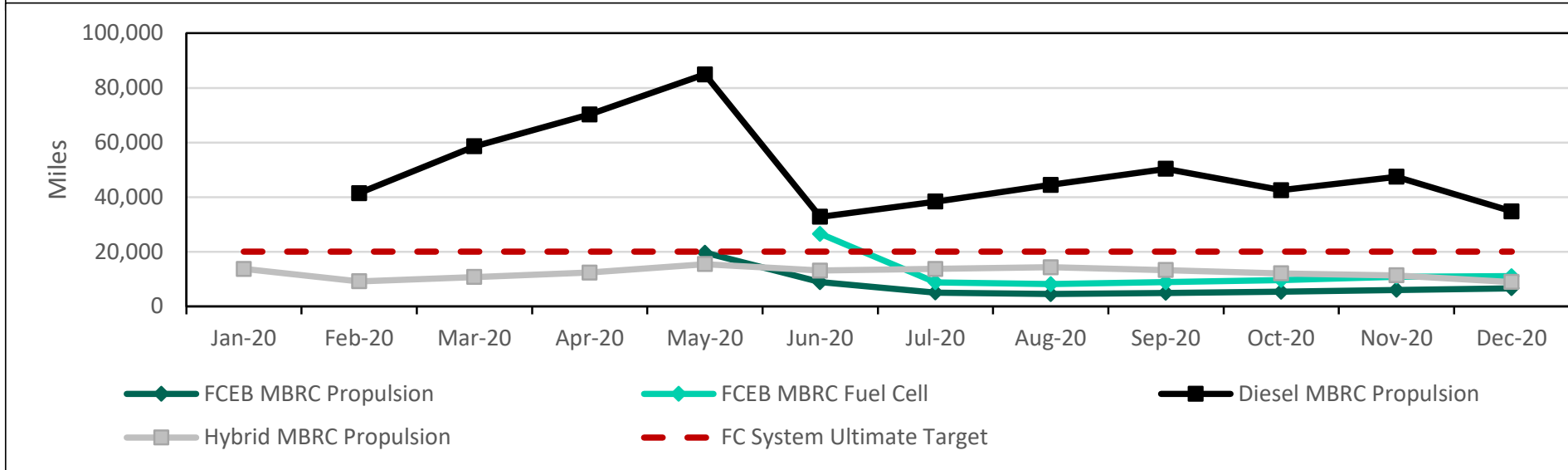
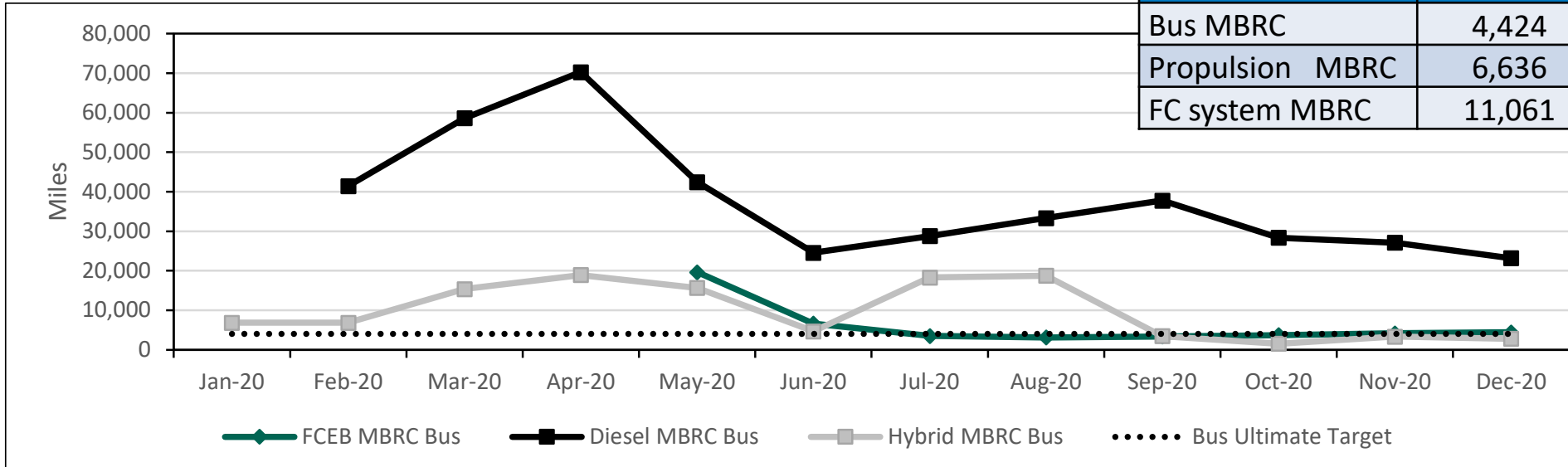
Cumulative MBRC: D4 FCEBs

	FCEB D4	Diesel	Hybrid
Bus MBRC	6,032	23,177	5,496
Propulsion MBRC	10,858	34,765	8,899
FC system MBRC	20,359	N/A	N/A



Cumulative MBRC: D2 FCEBs

	FCEB D2	Diesel	Hybrid
Bus MBRC	4,424	23,177	5,496
Propulsion MBRC	6,636	34,765	8,899
FC system MBRC	11,061	N/A	N/A



Maintenance Analysis

NREL collects all work orders for the evaluation buses to calculate a maintenance cost per mile. Costs for accident-related repairs which are extremely variable from bus to bus, were eliminated from the analysis. Warranty costs are not included in the cost-per-mile calculations because those costs are covered in the capital cost of the buses. For consistency, NREL uses a constant \$50 per hour. This does not reflect an average rate for AC Transit. Cost per mile is calculated as follows:

$$\text{Cost per mile} = [(\text{labor hours} * 50) + \text{parts cost}] / \text{mileage}$$

NREL calculates total cost per mile, scheduled maintenance cost per mile, and unscheduled maintenance cost per mile. NREL also categorizes maintenance cost by system to provide insight into which systems have the most costs for each technology.

The propulsion system costs are of particular interest. Propulsion-related vehicle systems include the exhaust, fuel, engine, FC system, battery modules, electric propulsion, air intake, cooling, non-lighting electrical, transmission systems, and hydraulics. These systems have been separated to highlight maintenance costs most directly affected by the advanced propulsion system changes for the buses.

Maintenance Analysis Results: FCEBs

Bus	Mileage	Parts (\$)	Labor hours	Scheduled Cost (\$/mi)	Unscheduled Cost (\$/mi)	Total Cost per Mile (\$)
7017	27,717	2,223.35	204.3	0.15	0.29	0.45
7018	34,725	2,663.25	187.8	0.15	0.20	0.35
7019	34,390	1,967.93	173.6	0.12	0.19	0.31
7020	34,982	2,508.78	192.4	0.16	0.19	0.35
7021	31,061	2,031.34	214.2	0.13	0.28	0.41
FCEB D4 Fleet	162,874	11,394.64	972.4	0.14	0.23	0.37
7022	13,829	1,649.97	182.1	0.16	0.61	0.78
7023	14,573	1,492.87	192.7	0.19	0.58	0.76
7024	13,947	864.42	165.3	0.21	0.45	0.65
7025	11,022	1,163.57	166.5	0.21	0.65	0.86
7026	12,993	2,566.81	200.7	0.18	0.79	0.97
FCEB D2 Fleet	66,364	7,737.63	907.3	0.19	0.61	0.80

Most parts costs are for filters, compressor oil, low-voltage batteries, and accessory components (radio, farebox)

Labor hours include time for PMs, bus component repairs, and help to manufacturers in troubleshooting issues

Cost per mile for the FCEB D2 fleet are artificially high due to low mileage.

Note: the FCEB fleet is still under warranty.

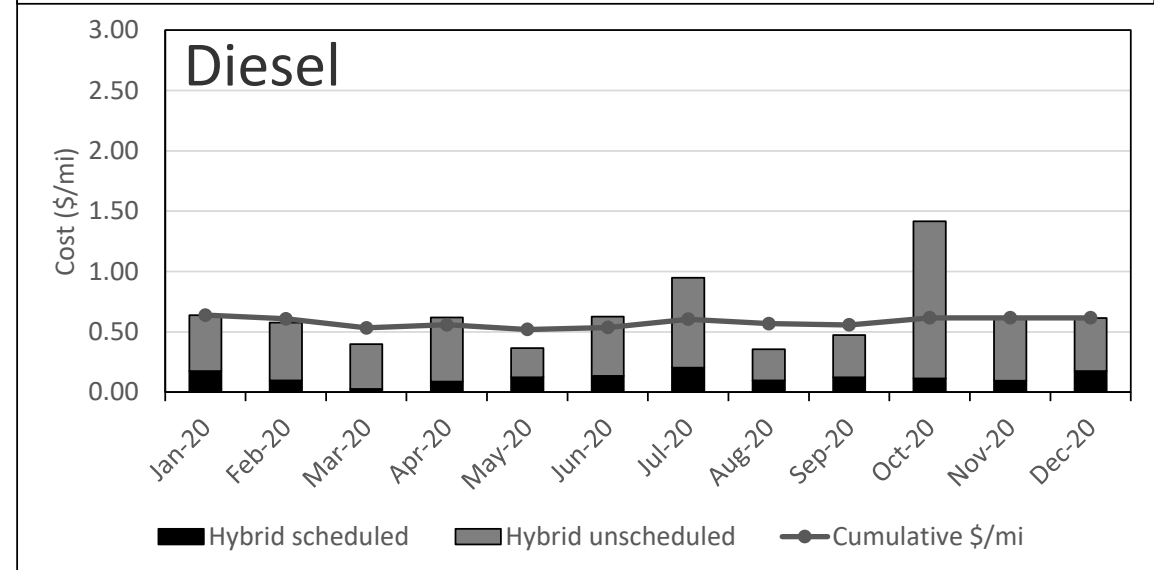
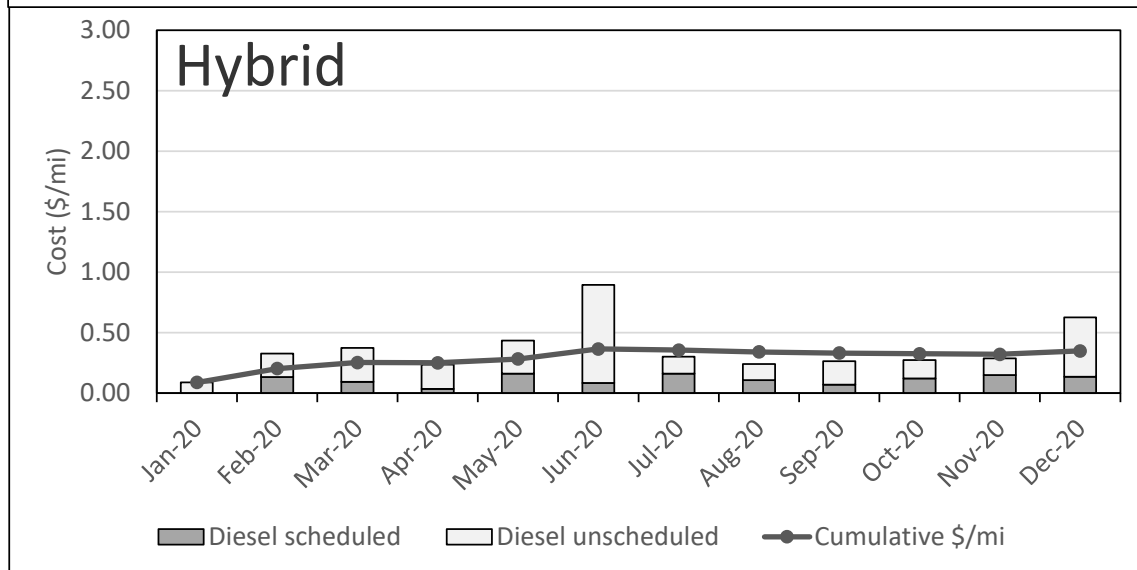
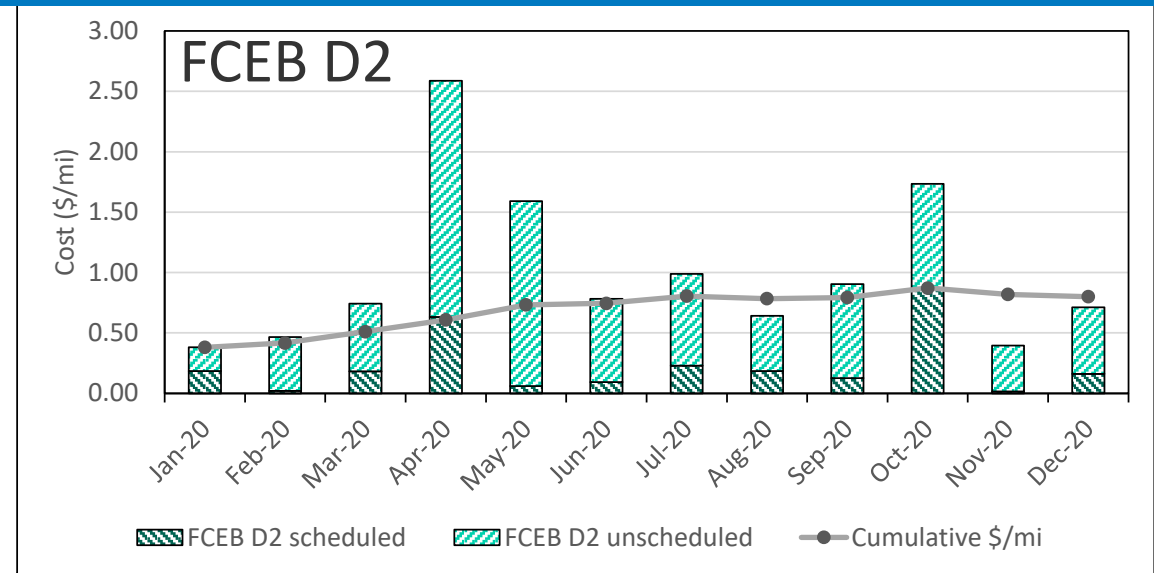
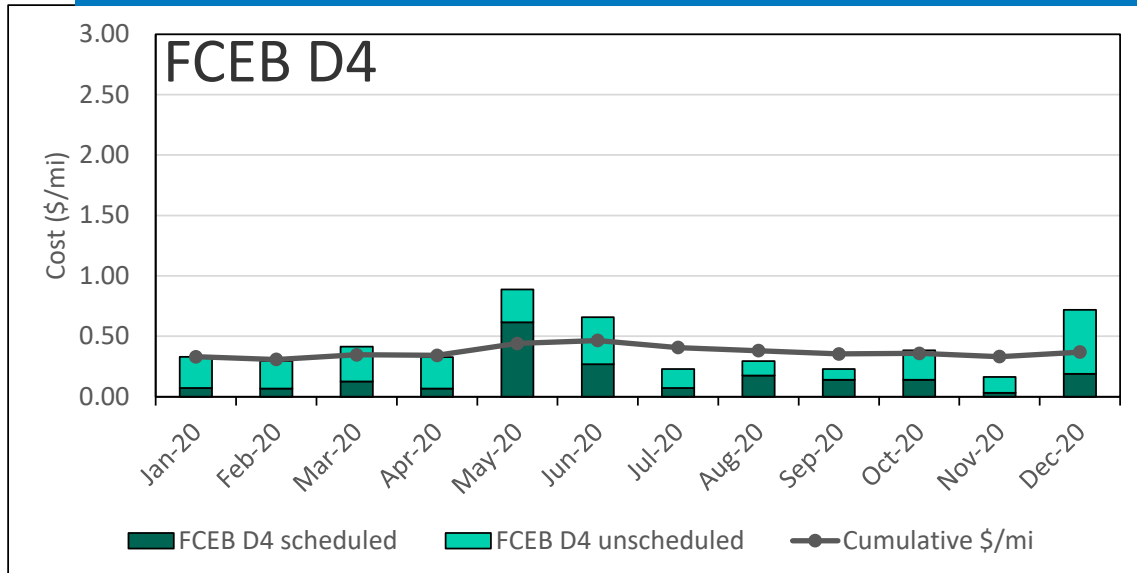
Maintenance Analysis Results: Baseline Fleets

Bus	Mileage	Parts (\$)	Labor hours	Scheduled Cost (\$/mi)	Unscheduled Cost (\$/mi)	Total Cost per Mile (\$)
1601	43,772	4,451.96	173.8	0.08	0.22	0.30
1602	41,471	3,419.21	181.5	0.10	0.20	0.30
1603	42,403	4,473.40	184.0	0.12	0.20	0.32
1604	45,254	5,114.57	184.9	0.10	0.22	0.32
1605	35,691	7,769.73	223.0	0.13	0.40	0.53
Diesel Fleet	208,591	25,228.87	947.2	0.10	0.24	0.35
1556	42,375	8,728.74	401.7	0.14	0.54	0.68
1557	34,901	10,274.59	347.9	0.12	0.68	0.79
1558	40,875	5,345.99	236.2	0.12	0.30	0.42
1559	36,891	3,728.25	255.6	0.12	0.33	0.45
1560	31,832	10,068.91	297.3	0.11	0.68	0.78
Hybrid Fleet	186,874	38,146.48	1,538.6	0.12	0.49	0.62

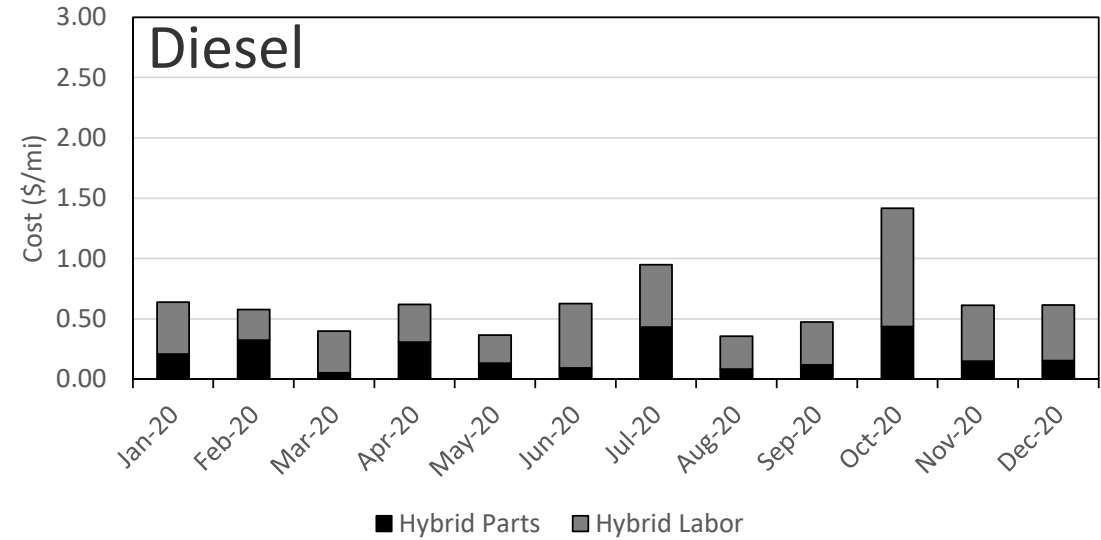
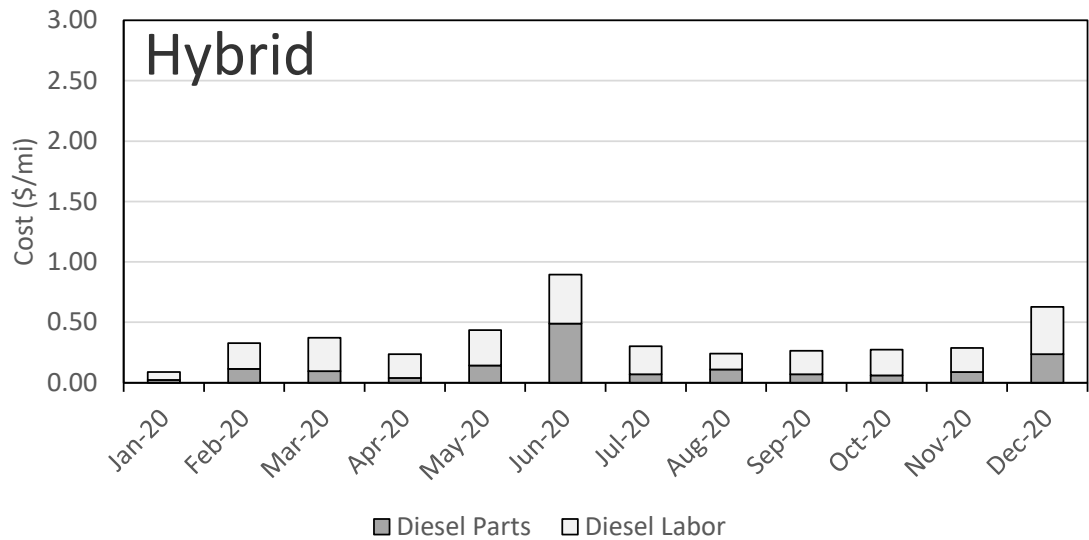
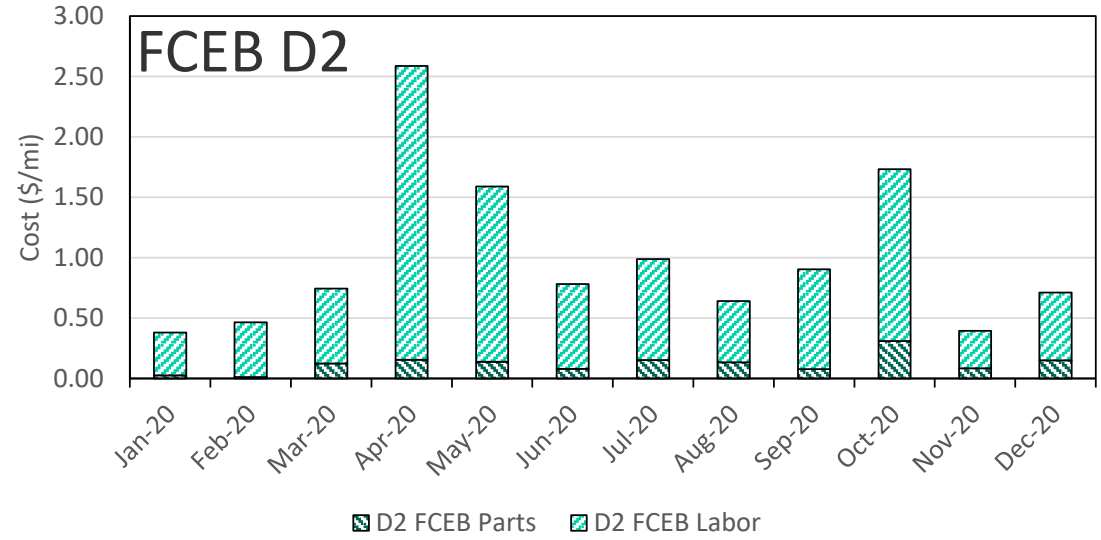
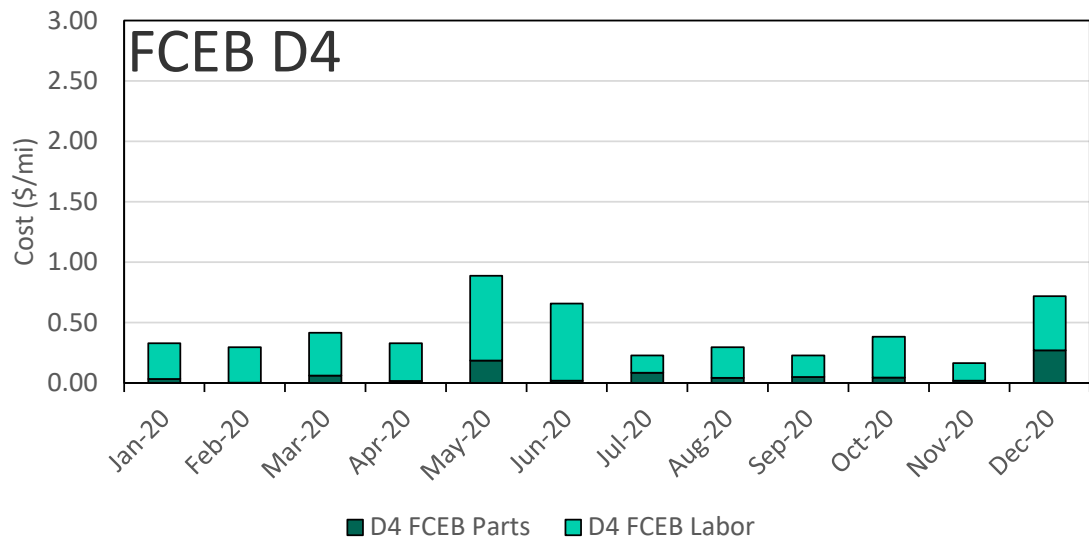
Parts costs for both fleets include consumables such as filters, oil, low voltage batteries, and diesel exhaust fluid. Unscheduled parts for the diesel fleet include an alternator, air dryer, and brakes; parts for the hybrid fleet include a differential, air compressor, fuel pump, fuel filter, coolant pumps, and NOx sensors.

Note: the diesel fleet is still under warranty, the hybrid fleet is not.

Scheduled and Unscheduled Maintenance Cost



Parts and Labor Maintenance Cost



Maintenance Cost by System

The vehicle systems include the following:

- Propulsion-related systems—Repairs for exhaust (including emissions equipment), fuel, engine, electric motors, fuel cell modules, battery modules, propulsion control, non-lighting electrical (charging, cranking, and ignition), air intake, cooling, hydraulics, and transmission
- Cab, body, and accessories—Includes body, glass, and paint repairs following accidents; body and sheet metal repairs on seats and doors; and accessory repairs such as hubodometers and radios
- PMI (preventive maintenance inspections)—Labor for preventive maintenance
- Brakes
- Frame, steering, and suspension
- Heating, ventilation, and air conditioning (HVAC)
- Lighting
- Axles, wheels, and drive shaft
- Air system, general
- Tires

Maintenance Cost per Mile by System

System	FCEB D4		FCEB D2		Diesel		Hybrid	
	Cost per Mile (\$)	Percent of Total (%)	Cost per Mile (\$)	Percent of Total (%)	Cost per Mile (\$)	Percent of Total (%)	Cost per Mile (\$)	Percent of Total (%)
Propulsion-related	0.086	23.3	0.304	38.0	0.112	32.3	0.228	37.0
Cab, body, and accessories	0.151	40.9	0.292	36.5	0.098	28.2	0.137	22.3
PMI	0.092	24.9	0.136	17.0	0.062	17.9	0.075	12.2
Brakes	0.001	0.2	0.005	0.7	0.034	9.9	0.033	5.3
Frame, steering, and suspension	0.019	5.2	0.022	2.7	0.012	3.4	0.033	5.3
HVAC	0.011	3.0	0.026	3.2	0.008	2.4	0.013	2.2
Lighting	0.003	0.9	0.003	0.3	0.003	0.9	0.003	0.4
General air system repairs	0.004	1.2	0.012	1.5	0.011	3.2	0.043	6.9
Axles, wheels, and drive shaft	0.000	0.1	0.001	0.1	0.005	1.3	0.052	8.4
Tires	0.001	0.2	0.000	0.0	0.002	0.6	0.000	0.0
Total	0.368	100.0	0.800	100.0	0.348	100.0	0.616	100.0

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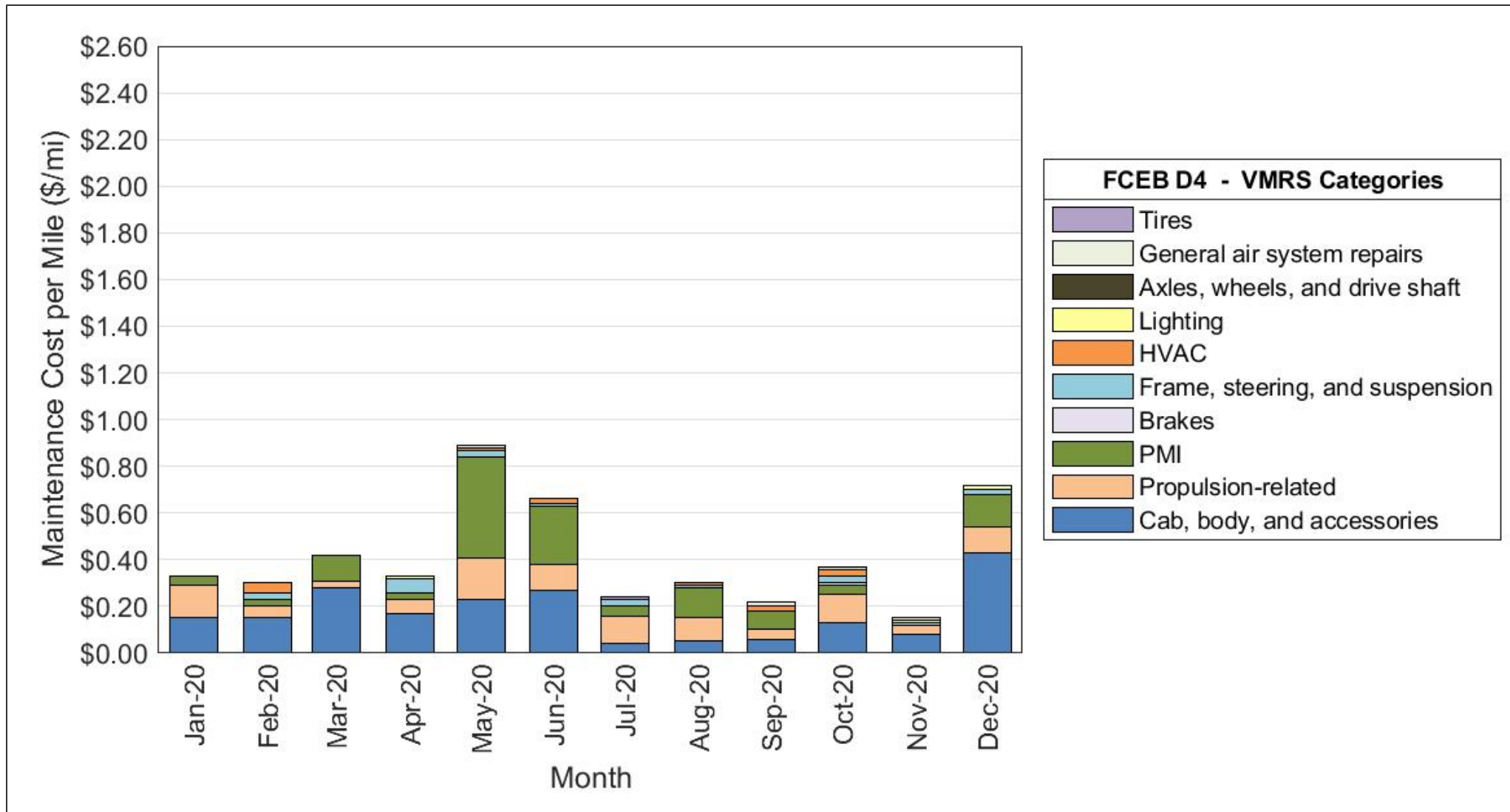
 Highest cost

 Second highest cost

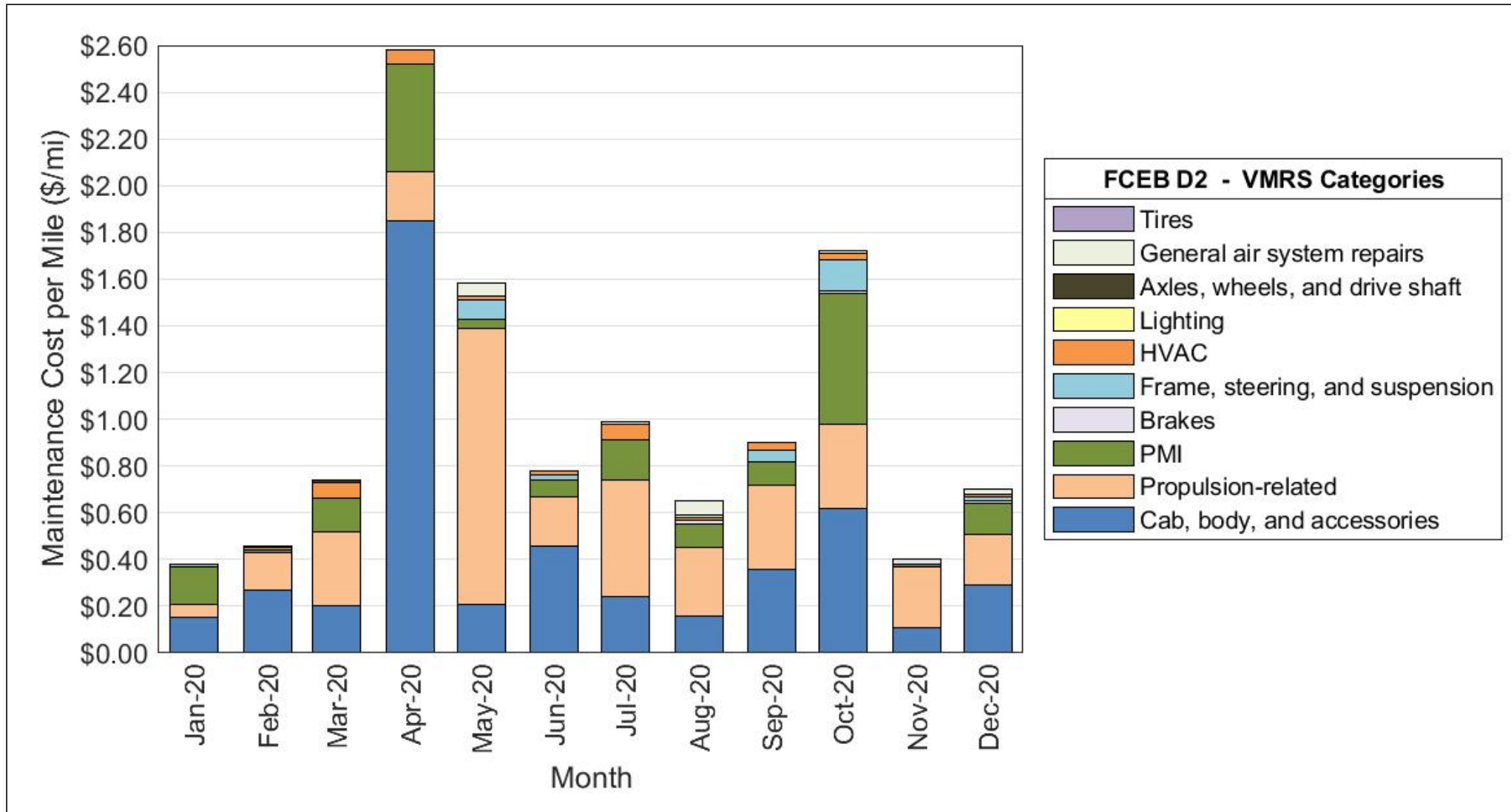
 Third highest cost

- For the FCEB D4 fleet the systems with the highest cost were cab, body, and accessories; PMI; and propulsion-related. For the FCEB D2, hybrid fleet, and diesel fleet, the systems with the highest cost were propulsion-related; cab, body, and accessories; and PMI.

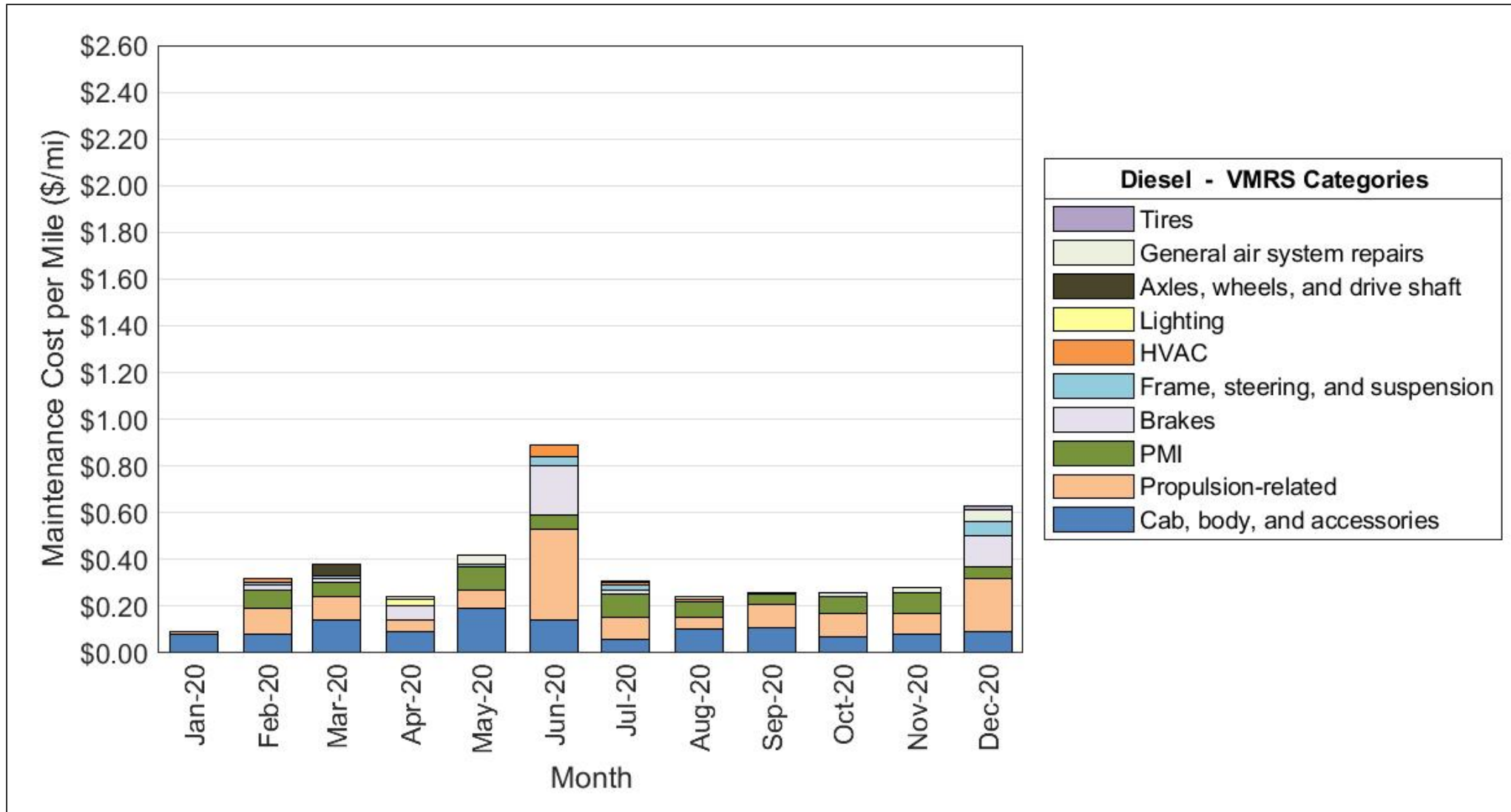
Maintenance Cost by System: FCEB D4



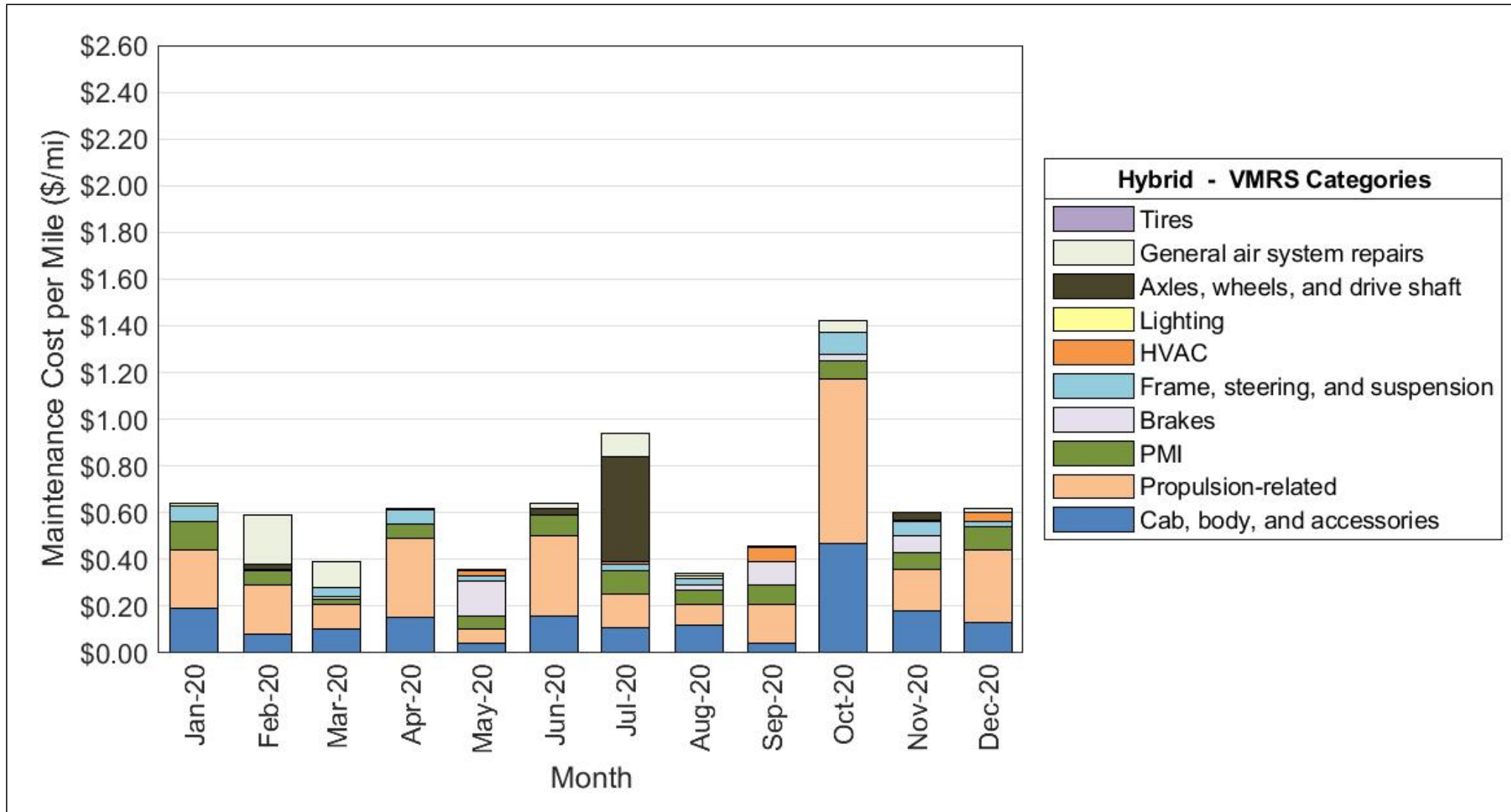
Maintenance Cost by System: FCEB D2



Maintenance Cost by System: Diesel Buses



Maintenance Cost by System: Hybrid Buses



Propulsion-Related Maintenance Costs by Subsystem

Maintenance System	FCEB D4	FCEB D2	Diesel	Hybrid
Mileage	162,874	66,364	208,591	186,874
Exhaust and Emission System	0.000	178.53	2,894.52	4,379.20
Fuel System	0.004	0.015	0.016	0.027
Powerplant System (Fuel cell System for FCEBs)	0.045	0.150	0.016	0.024
Electric Propulsion System	0.009	0.069	0.000	0.016
Non-Lighting Electrical System (General Electrical, Charging, Cranking, Ignition)	0.026	0.070	0.031	0.024
Air Intake System	0.000	0.000	0.002	0.009
Cooling System	0.002	0.000	0.026	0.073
Transmission System	0.000	0.000	0.000	0.002
Hydraulic System	0.000	0.000	0.002	0.000
Total Propulsion System	0.086	0.304	0.112	0.228

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Acronyms and Abbreviations

CNG	compressed natural gas	kW	kilowatt
dge	diesel gallon equivalent	kWh	kilowatt-hour
DOE	U.S. Department of Energy	lb.	pound
FC	fuel cell	MBRC	miles between roadcalls
FCEB	fuel cell electric bus	mi	mile
ft	feet	mpdge	miles per diesel gallon equivalent
FTA	Federal Transit Administration	mpgge	miles per gasoline gallon equivalent
gge	gasoline gallon equivalent	mph	miles per hour
GVWR	gross vehicle weight rating	NREL	National Renewable Energy Laboratory
hp	horsepower	PM	preventive maintenance
HVAC	heating, ventilation, and air conditioning	PMI	preventive maintenance inspection
in.	inch	psi	pounds per square inch
kg	kilogram		

Acknowledgments

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Appendix: Fleet Summary Statistics

Fleet Summary Statistics

	FCEB D4	FCEB D2	Diesel	Hybrid
Number of vehicles	5	5	5	5
Period used for fuel and oil analysis	1/2020-12/2020	1/2020-12/2020	1/2020-12/2020	1/2020-12/2020
Total number of months in period	12	12	12	12
Fuel and oil analysis base fleet mileage	157,254	63,584	203,968	183,008
Period used for maintenance analysis	1/2020-12/2020	1/2020-12/2020	1/2020-12/2020	1/2020-12/2020
Total number of months in period	12	12	12	12
Maintenance analysis base fleet mileage	162,874	66,364	208,591	186,874
Average monthly miles per vehicle	2,715	1,106	3,477	3,115
Availability	87.8	60.6	95	86
Fleet fuel usage in FCEB kg/diesel gal	19,437.4	7,944.0	49,351.8	34,208.1
Roadcalls	27	15	9	34
Total MBRC	6,032	4,424	23,177	5,496
Propulsion roadcalls	15	10	6	21
Propulsion MBRC	10,858	6,636	34,765	8,899
Fleet Miles/kg (FCEB) or miles/gal	8.09	8.00	—	—
Representative fleet MPG (energy equiv)	9.14	9.04	4.13	5.35
H2 cost per kg / diesel cost per gal	8.52	8.52	1.60	1.60
Fuel cost per mile	1.054	1.065	0.387	0.293
Total scheduled repair cost per mile	0.143	0.188	0.104	0.122
Total unscheduled repair cost per mile	0.226	0.612	0.244	0.494
Total maintenance cost per mile	0.368	0.800	0.348	0.616
Total operating cost per mile	1.422	1.865	0.735	0.909

Maintenance Cost Summary

Maintenance Cost Summary

	FCEB D4	FCEB D2	Diesel	Hybrid
Fleet mileage	162,874	66,364	208,591	186,874
Total parts cost	11,394.64	7,737.63	25,228.87	38,146.48
Total labor hours	972.4	907.3	947.2	1,538.6
Average labor cost (@ \$50.00 per hour)	48,619.50	45,363.00	47,359.00	76,930.50
Total maintenance cost	60,014	53,101	72,588	115,077
Total maintenance cost per bus	12,002.83	10,620.13	14,517.57	23,015.40
Total maintenance cost per mile	0.368	0.800	0.348	0.616

Propulsion System Maintenance Cost Summary

	FCEB D4	FCEB D2	Diesel	Hybrid
Total Engine/Fuel-Related Systems (ATA VMRS 27, 30, 31, 32, 33, 41, 42, 43, 44, 45, 46, 65)				
Parts cost	4,547.82	5,442.99	13,522.16	17,479.14
Labor hours	189.15	294.20	198.25	502.84
Average labor cost	9,457.50	14,710.00	9,912.50	25,142.00
Total cost (for system)	14,005.32	20,152.99	23,434.66	42,621.14
Total cost (for system) per bus	2,801.06	4,030.60	4,686.93	8,524.23
Total cost (for system) per mile	0.086	0.304	0.112	0.228

Maintenance Cost by Vehicle System

	FCEB D4	FCEB D2	Diesel	Hybrid
Exhaust and Emission System (ATA VMRS 43)				
Parts cost	0.00	0.00	2,403.51	5,215.23
Labor hours	0.0	0.0	30.3	92.5
Average labor cost	0.00	0.00	1,512.50	4,625.50
Total cost (for system)	0.00	0.00	3,916.01	9,840.73
Total cost (for system) per bus	0.00	0.00	783.20	1,968.15
Total cost (for system) per mile	0.000	0.000	0.019	0.053
Fuel System (ATA VMRS 44)				
Parts cost	0.00	178.53	2,894.52	4,379.20
Labor hours	14.5	16.0	10.0	12.5
Average labor cost	725.00	800.50	500.00	625.00
Total cost (for system)	725.00	979.03	3,394.52	5,004.20
Total cost (for system) per bus	145.00	195.81	678.90	1,000.84
Total cost (for system) per mile	0.004	0.006	0.016	0.027
Power Plant (Engine) (ATA VMRS 45)				
Parts cost	4,423.12	4,003.17	3,003.96	1,862.64
Labor hours	56.8	119.0	7.5	54.0
Average labor cost	2,841.50	5,951.00	375.00	2,700.00
Total cost (for system)	7264.6	9954.2	3379.0	4562.6
Total cost (for system) per bus	1,452.92	1,990.83	675.79	912.53
Total cost (for system) per mile	0.045	0.061	0.016	0.024

Maintenance Cost by Vehicle System

	FCEB D4	FCEB D2	Diesel	Hybrid
Electric Propulsion (ATA VMRS 46)				
Parts cost	3.59	19.02	0.00	462.20
Labor hours	28.3	91.5	0.0	50.0
Average labor cost	1,416.50	4,575.00	0.00	2,500.00
Total cost (for system)	1,420.09	4,594.02	0.00	2,962.20
Total cost (for system) per bus	284.02	918.80	0.00	592.44
Total cost (for system) per mile	0.009	0.028	0.000	0.016
Electrical System (ATA VMRS 30-Electrical General, 31-Charging, 32-Cracking, 33-Ignition)				
Parts cost	112.19	1,242.28	3,040.47	143.99
Labor hours	82.0	67.7	69.5	86.8
Average labor cost	4,099.50	3,383.50	3,475.00	4,341.50
Total cost (for system)	4,211.69	4,625.78	6,515.47	4,485.49
Total cost (for system) per bus	842.34	925.16	1,303.09	897.10
Total cost (for system) per mile	0.026	0.028	0.031	0.024
Air Intake System (ATA VMRS 41)				
Parts cost	0.00	0.00	506.92	1,354.90
Labor hours	0.0	0.0	0.0	5.5
Average labor cost	0.00	0.00	0.00	275.00
Total cost (for system)	0.00	0.00	506.92	1,629.90
Total cost (for system) per bus	0.00	0.00	101.38	325.98
Total cost (for system) per mile	0.000	0.000	0.002	0.009

Maintenance Cost by Vehicle System

	FCEB D4	FCEB D2	Diesel	Hybrid
Cooling System (ATA VMRS 42)				
Parts cost	8.92	0.00	1,423.84	3,986.41
Labor hours	7.5	0.0	78.0	194.5
Average labor cost	375.00	0.00	3,900.00	9,725.00
Total cost (for system)	383.92	0.00	5,323.84	13,711.41
Total cost (for system) per bus	76.78	0.00	1,064.77	2,742.28
Total cost (for system) per mile	0.002	0.000	0.026	0.073
Hydraulic System (ATA VMRS 65)				
Parts cost	0.00	0.00	248.93	74.56
Labor hours	0.0	0.0	3.0	0.0
Average labor cost	0.00	0.00	150.00	0.00
Total cost (for system)	0.00	0.00	398.93	74.56
Total cost (for system) per bus	0.00	0.00	79.79	14.91
Total cost (for system) per mile	0.000	0.000	0.002	0.000
General Air System (ATA VMRS 10)				
Parts cost	624.47	0.00	2,098.02	4,312.66
Labor hours	2.0	16.2	4.5	72.8
Average labor cost	100.00	808.50	225.00	3,641.50
Total cost (for system)	724.47	808.50	2,323.02	7,954.16
Total cost (for system) per bus	144.89	161.70	464.60	1,590.83
Total cost (for system) per mile	0.004	0.005	0.011	0.043

Maintenance Cost by Vehicle System

	FCEB D4	FCEB D2	Diesel	Hybrid
Brake System (ATA VMRS 13)				
Parts cost	0.00	0.00	5,322.87	2,167.48
Labor hours	3.0	7.0	37.0	78.8
Average labor cost	150.00	350.00	1,850.00	3,941.50
Total cost (for system)	150.0	350.0	7172.9	6109.0
Total cost (for system) per bus	30.00	70.00	1,434.57	1,221.80
Total cost (for system) per mile	0.001	0.002	0.034	0.033
Transmission (ATA VMRS 27)				
Parts cost	0.00	0.00	0.00	0.00
Labor hours	0.0	0.0	0.0	7.0
Average labor cost	0.00	0.00	0.00	350.00
Total cost (for system)	0.0	0.0	0.0	350.0
Total cost (for system) per bus	0.00	0.00	0.00	70.00
Total cost (for system) per mile	0.000	0.000	0.000	0.002
Inspections Only - No Parts Replacements (101)				
Parts cost	0.00	0.00	0.00	0.00
Labor hours	298.5	180.8	259.8	280.0
Average labor cost	14,925.00	9,042.00	12,991.50	14,001.00
Total cost (for system)	14925.0	9042.0	12991.5	14001.0
Total cost (for system) per bus	2,985.00	1,808.40	2,598.30	2,800.20
Total cost (for system) per mile	0.092	0.056	0.062	0.075

Maintenance Cost by Vehicle System

	FCEB D4	FCEB D2	Diesel	Hybrid
Cab, Body, and Accessories Systems (ATA VMRS 02-Cab and Sheet Metal, 50-Accessories, 71-Body)				
Parts cost	6,064.98	2,261.13	3,150.48	4,069.36
Labor hours	369.7	342.2	346.1	431.3
Average labor cost	18,487.00	17,110.50	17,305.00	21,563.50
Total cost (for system)	24,551.98	19,371.63	20,455.48	25,632.86
Total cost (for system) per bus	4,910.40	3,874.33	4,091.10	5,126.57
Total cost (for system) per mile	0.151	0.119	0.098	0.137
HVAC System (ATA VMRS 01)				
Parts cost	157.38	17.20	836.93	483.12
Labor hours	32.5	34.2	18.0	40.2
Average labor cost	1,625.00	1,708.50	900.00	2,008.50
Total cost (for system)	1,782.38	1,725.70	1,736.93	2,491.62
Total cost (for system) per bus	356.48	345.14	347.39	498.32
Total cost (for system) per mile	0.011	0.011	0.008	0.013
Lighting System (ATA VMRS 34)				
Parts cost	0.00	16.31	67.08	26.01
Labor hours	11.0	3.0	11.0	9.2
Average labor cost	550.00	150.00	550.00	458.50
Total cost (for system)	550.0	166.3	617.1	484.5
Total cost (for system) per bus	110.00	33.26	123.42	96.90
Total cost (for system) per mile	0.003	0.001	0.003	0.003

Maintenance Cost by Vehicle System

	FCEB D4	FCEB D2	Diesel	Hybrid
Frame, Steering, and Suspension (ATA VMRS 14-Frame, 15-Steering, 16-Suspension)				
Parts cost	0.00	0.00	78.44	3,180.72
Labor hours	63.0	28.7	48.5	58.5
Average labor cost	3,150.00	1,433.50	2,425.00	2,925.00
Total cost (for system)	3150.0	1433.5	2503.4	6105.7
Total cost (for system) per bus	630.00	286.70	500.69	1,221.14
Total cost (for system) per mile	0.019	0.009	0.012	0.033
Axle, Wheel, and Drive Shaft (ATA VMRS 11-Front Axle, 18-Wheels, 22-Rear Axle, 24-Drive Shaft)				
Parts cost	0.00	0.00	152.88	6,427.98
Labor hours	1.5	1.0	16.0	64.0
Average labor cost	75.00	50.00	800.00	3,199.00
Total cost (for system)	75.0	50.0	952.9	9627.0
Total cost (for system) per bus	15.00	10.00	190.58	1,925.40
Total cost (for system) per mile	0.000	0.000	0.005	0.052
Tires (ATA VMRS 17)				
Parts cost	0.00	0.00	0.00	0.00
Labor hours	2.0	0.0	8.0	1.0
Average labor cost	100.00	0.00	400.00	50.00
Total cost (for system)	100.0	0.0	400.0	50.0
Total cost (for system) per bus	20.00	0.00	80.00	10.00
Total cost (for system) per mile	0.001	0.000	0.002	0.000

Fleet Summary Statistics: SI Units

	FCEB D4	FCEB D2	Diesel	Hybrid
Number of vehicles	5	5	5	5
Period used for fuel and oil analysis	1/20-12/20	1/20-12/20	1/20-12/20	1/20-12/20
Total number of months in period	12	12	12	12
Fuel and oil analysis base fleet kilometers	253,069	102,326	328,246	294,514
Period used for maintenance analysis	1/20-12/20	1/20-12/20	1/20-12/20	1/20-12/20
Total number of months in period	12	12	12	12
Maintenance analysis base fleet kilometers	262,114	106,800	335,685	300,736
Average monthly kilometers per vehicle	4368.5629	1780.00113	5594.75827	5012.27214
Availability	87.8	60.6	95	86
Fleet fuel in FCEB kg/CNG L	19,437.4	7,944.0	186,816.9	129,491.7
Roadcalls	27	15	9	34
Total KBRC	9,708	7,120	37,298	8,845
Propulsion roadcalls	15	10	6	21
Propulsion KBRC	17,474	10,680	55,948	14,321
Representative fleet fuel consumption (L/100 km)	7.68	7.76	—	—
H2 cost per kg/ CNG cost per liter	25.73	26.00	56.91	43.97
Fuel cost per km	8.52	8.52	0.42	0.42
Total scheduled repair cost per km	0.654	0.661	0.241	0.186
Total unscheduled repair cost per km	0.089	0.117	0.065	0.076
Total maintenance cost per km	0.140	0.380	0.151	0.307
Total operating cost per km	0.883	1.159	0.457	0.568

Maintenance Cost Summary: SI Units

Maintenance Cost Summary

	FCEB D4	FCEB D2	Diesel	Hybrid
Fleet mileage	262,114	106,800	335,685	300,736
Total parts cost	11,394.64	7,737.63	25,228.87	38,146.48
Total labor hours	972.4	907.3	947.2	1,538.6
Average labor cost (@ \$50.00 per hour)	48,619.50	45,363.00	47,359.00	76,930.50
Total maintenance cost	60,014	53,101	72,588	115,077
Total maintenance cost per bus	12,002.83	10,620.13	14,517.57	23,015.40
Total maintenance cost per kilometer	0.229	0.497	0.216	0.383

Propulsion System Maintenance Cost Summary

	FCEB D4	FCEB D2	Diesel	Hybrid
Total Engine/Fuel-Related Systems (ATA VMRS 27, 30, 31, 32, 33, 41, 42, 43, 44, 45, 46, 65)				
Parts cost	4,547.82	5,442.99	13,522.16	17,479.14
Labor hours	189.15	294.20	198.25	502.84
Average labor cost	9,457.50	14,710.00	9,912.50	25,142.00
Total cost (for system)	14,005.32	20,152.99	23,434.66	42,621.14
Total cost (for system) per bus	2,801.06	4,030.60	4,686.93	8,524.23
Total cost (for system) per kilometer	0.053	0.189	0.070	0.142

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