Update of Investigation into Changes in Fuel Economy and Vehicle Range Related to Change in Ambient Temperature for Battery and Fuel Cell Electric Buses

THE MIDWEST HYDROGEN CENTER OF EXCELLENCE
A Key Initiative of the Renewable Hydrogen Fuel Cell Collaborative

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Disclaimer

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Executive Summary

This report updates findings from a 2019 study into the effects of changing weather on zero-emission bus performance.[1] The report relies on data that was made available to the Study Team from transit agencies that have deployed hydrogen fuel cell electric, battery electric, CNG, and diesel buses.

This update expands on the original report by including data for additional transit agencies that deploy battery electric buses. The evaluation in this report of the relationship between change in ambient temperature and the efficiency — and thus range – for these buses is also improved by the use of data for additional control variables that can also affect fuel economy. The inclusion of factors such as vehicle length, curb weight, and battery size in a statistical model for vehicle fuel efficiency allowed the Study Team to better understand the effect of change in ambient temperature on zero-emission buses.

The Study Team collected data from ten transit agencies, some of which deploy more than one fuel technology in their bus fleets. Altogether, data was obtained from nine agencies that deploy battery electric buses, two agencies that deploy fuel cell electric buses, and one agency that deploys both CNG and diesel buses. The CNG and diesel bus analyses were included to provide insight into what to expect from traditional transit vehicles during changes in weather. The agencies were in variable climate conditions, ranging from hot (southern California) to cold (northern Minnesota), and included one from Canada. Of the battery electric bus transit systems, one used "on-route" recharging systems and three used diesel fuel-fired heaters to warm the passenger cabin.

The results of the updated analysis showed that for temperature drops from 50-60° to 22-32° Fahrenheit, battery electric buses lost around 23.8% efficiency on average, compared to efficiency losses of 19.3% for fuel cell electric buses, 4.2% for CNG buses, and 0.3% for diesel buses. For battery electric and fuel cell electric buses, this was, respectively, an improvement from the 32.1% and 28.6.% loss in efficiency over this drop in ambient temperature since the initial report.

In conjunction with fuel capacity for the different bus types, these efficiencies translated into losses in range going from 50-60°F to 22-32°F of 21.0% for battery electric buses, 13.0% for fuel cell electric buses, 4.0% for CNG buses, and 0.3% for diesel buses. For battery electric and fuel cell electric buses, this was, respectively, an improvement from the 37.8% and 23.1% decrease in range over this drop in ambient temperature since the initial report.

The following table shows the effects of temperature change on range for the ten transit agencies evaluated based on the data that was collected. Some agencies in more southerly climates did not experience average daily outdoor temperatures that were near or below freezing. Similarly, a handful of agencies in more northerly climates did not experience ambient temperatures near or above

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[1] The initial report can be found at: Henning, Mark; Thomas, Andrew R.; and Smyth, Alison, "An Analysis of the Association between Changes in Ambient Temperature, Fuel Economy, and Vehicle Range for Battery Electric and Fuel Cell Electric Buses" (2019). *Urban Publications*. 0 1 2 3 1630. https://engagedscholarship.csuohio.edu/urban_facpub/1630.

80° F over the period of time for which data was available. Two transit agencies, SunLine and the Toronto Transit Commission, deployed more than one vehicle model for a given type of fuel technology. These models are distinguished in the table below.

Mean Range in Miles per Daily Vehicle Assignment at Selected Ambient Temperatures

Vehicle Type	Agency (Location)	Ambient Temperature (F)							
		10°	*20°*	*Freezing*	*40°*	*50°*	*60°*	*70°*	*80°*
Battery Electric Bus (BEB)	CAT Bus (Clemson, SC)	N/A	N/A	135	147	160	171	172	155
	DART – Delaware (Wilmington, DE)	N/A	N/A	128	142	166	197	194	188
	Duluth Transit (Duluth, MN)	121	124	133	162	187	190	189	172
	Lane Transit District (Eugene, OR)	N/A	N/A	139	140	157	166	144	N/A
	MBTA (Boston, MA)	N/A	61	64	71	80	110	114	98
	Mountain Line (Missoula, MT)	105	119	135	148	186	190	198	N/A
	SunLine (Thousand Palms, CA)	N/A	N/A	N/A	N/A	138	134	136	121
	TriMet (Portland, OR)	N/A	N/A	69	75	86	101	100	97
	Toronto Transit Commission – New Flyer (Toronto, ON)	143	152	162	164	167	171	175	159
	Toronto Transit Commission – Proterra (Toronto, ON)	116	122	140	143	151	171	N/A	N/A
Fuel Cell Electric Bus (FCEB)	SARTA (Canton, OH)	202	213	223	245	262	278	268	254
	SunLine – ENC (Thousand Palms, CA)	N/A	N/A	N/A	N/A	286	298	279	269
	SunLine – New Flyer (Thousand Palms, CA)	N/A	N/A	N/A	N/A	255	268	283	278
Diesel and CNG Buses	SARTA – CNG (Canton, OH)	419	468	466	453	489	462	424	418
	SARTA – Diesel (Canton, OH)	528	535	539	540	539	527	505	474

1. Introduction.

A. Background.

The purpose of this report was to continue an investigation into how zero-emission bus performance responds to changes in ambient temperature. The report relies on selected data that was made available to the Study Team, as set forth below. The initial report we conducted in 2019 analyzing the effects of ambient temperature change on zero-emission bus performance (hereinafter, the "2019 Report")[2] only considered ambient temperature in explaining variation in fuel efficiency, and by extension vehicle range. This update to the 2019 Report considered additional factors as control variables that can further isolate the effect of temperature variation on fuel efficiency. These factors included vehicle length, vehicle curb weight, reporting service for energy use and mileage data per daily vehicle assignment, nameplate battery capacity for battery electric vehicles, the presence of a fuel-fired heater to warm the passenger cabin, and whether snow fall of greater than 2 feet annually occurred within an agency's operational footprint.

This is not an exhaustive list of factors that may affect fuel efficiency and vehicle range. For instance, it does not include other factors such as road grade, average travel speed, and driver behavior – all of which are also known to account for variations in fuel economy for transit bus fleets.[3] Nevertheless, as is shown below, trends may be determined from the available data that may be of interest to transit agencies considering transitioning to zero emission fleets.

B. Terms and Definitions.

As described in the 2019 Report, fuel efficiency stated in terms of miles-per-gallon (or equivalently miles-per-kWh, miles-per-kg of hydrogen, etc.) can be misleading when evaluating improvements in efficiency. This is because equal increases in a measure of efficiency such as miles-per-gallon (MPG) are not equal in terms of fuel savings. For example, a vehicle improving in efficiency from 9 to 10 MPG would use 1.10 fewer gallons of fuel over 100 miles, whereas another vehicle improving from 49 to 50 MPG would use 0.04 fewer gallons over the same distance. To better understand how much more or less fuel is consumed as temperature varies, we therefore report fuel efficiencies in terms of kWh-per-mile when evaluating battery electric buses (BEB), and kg-per-mile when evaluating fuel cell electric buses (FCEB). Fuel conversion factors used for these analyses came from the Vehicle Technology Office within the U.S. Department of Energy.[4]

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[2] *Id.* The 2019 Report includes a more in-depth discussion of the terms, definitions and methodologies.

[3] *See* de Abreu e Silva, J., Moura, F., Garcia, B., & Vargas, R. (2015). Influential vectors in fuel consumption by an urban bus operator: Bus route, driver behavior or vehicle type? *Transportation Research* Part D, 38, 94–104. https://www.sciencedirect.com/science/article/abs/pii/S1361920915000358

[4] *See* State & Alternative Fuel Provider Fleets: Fuel Conversion Factors to Gasoline Gallon Equivalents. https://epact.energy.gov/fuel-conversion-factors

2. Methodology

A. Data Sources and Collection

The data used in this study constitute a convenience sample. The authors leveraged existing professional relationships to obtain records of daily fueling and miles traveled per vehicle. Table 1 includes the transit agencies, along with characteristics for their vehicles, that were not only willing to share their fuel economy performance data with the study team, but also those with a system of daily, per vehicle information collection in place that allowed them to do so.

Table 1. Vehicle Characteristics for Participating Agencies

Agency	Vehicle Type	Location	Vehicle Length	Mfg.	Battery Size/ Tank Capacity	Onboard Diesel Heater	On-route Charging
CAT Bus[5]	BEB	Clemson, SC	40 feet	Proterra	440 kWh	no	no
DART[6]	BEB	Dover, DE	35 feet	Proterra	440 kWh	no	no
DTA[7]	BEB	Duluth, MN	40 feet	Proterra	440 kWh	yes	no
LTD[8]	BEB	Eugene, OR	40 feet	BYD	324 kWh	yes	no
MBTA[9]	BEB	Boston, MA	60 feet	New Flyer	450 kWh	no	no
Mountain Line[10]	BEB	Missoula, MT	35 feet	Proterra	440 kWh	no	no
SunLine[11]	BEB	Thousand Palms, CA	40 feet	BYD	324 kWh	no	no
TriMet[12]	BEB	Portland, OR	40 feet	New Flyer	200 kWh	no	yes
TTC[13]	BEB	Toronto, ON	40 feet	Proterra New Flyer	440 kWh 400 kWh	yes	no
SARTA[14]	FCEB	Canton, OH	40 feet	ENC[15]	50 kg	N/A	N/A
SunLine	FCEB	Thousand Palms, CA	40 feet	ENC New Flyer	50 kg 38 kg	N/A	N/A
SARTA	CNG Diesel	Canton, OH	40 feet 35 feet	Gillig	145 dge 121 gallons	N/A	N/A

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[5] Clemson Area Transit

[6] Delaware Transit Corporation,

[7] Duluth Transit Authority

[8] Lane Transit District

[9] Massachusetts Bay Transportation Authority

[10] Missoula Urban Transportation district (Mountain Line)

[11] SunLine Transit Agency

[12] Tri-County Metropolitan Transportation District of Oregon

[13] Toronto Transit Commission

[14] Stark Area Regional Transit Authority

[15] ElDorado National California

The data range for this update covers the beginning of 2019 through February 2020. Daily average ambient temperature data used in our analyses were gathered from the websites of authoritative government scientific agencies. For the United State this was the U.S. National Oceanic Atmospheric Administration (NOAA),[16] while for Canada it was the Department of Environment and Climate Change.[17]

Another important parameter to establish in evaluating the association between ambient temperature and fuel efficiency was a *base temperature* that relates well to most climate conditions across North American, and the U.S. in particular. *Base temperature* is the outside temperature at which no heating or cooling is necessary to maintain comfort conditions.[18] According to NOAA, 65° F is the temperature at which energy usage for heating and cooling is typically minimized in the United States.[19]

B. Research Methods and Analysis.

The Study Team used a statistical regression to evaluate the effects of outdoor temperature on the efficiency of FCEBs and BEBs in the data sample, controlling for other factors that could also influence efficiency.[20] These factors included vehicle length, vehicle curb weight, reporting service for energy use and mileage data per daily vehicle assignment, nameplate battery capacity for battery electric vehicles, the presence of a fuel-fired heater to warm the passenger cabin, and whether snow fall of greater than 2 feet annually occurred within an agency's operational footprint. The goal was to develop a model, using the existing data, to roughly predict median temperature effects related to fuel efficiency.

Estimated fuel efficiency for vehicles in the data set was converted to expected vehicle range at different outdoor temperatures given the usable fuel capacity for different vehicle types presented in Table 1. The following assumptions were made in establishing fuel efficiency, which in turn were used to estimate vehicle range:

- Usable hydrogen for calculating vehicle range for fuel cell buses is based on 95% tank capacity.[21]

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[16] National Oceanic and Atmospheric Administration. National Climate Date Center. *Climate Data Online Search*. https://www.ncdc.noaa.gov/cdo-web/search

[17] Government of Canada. Environment and Climate Change Canada. *Historical Data.* https://climate.weather.gc.ca/historical_data/search_historic_data_e.html?searchType=stnName&timeframe=1

[18] ASHRAE, 2001: 2001 ASHRAE Handbook: Fundamentals. American Society of Heating, Refrigerating and Air-Conditioning Engineers, 544 pp.

[19] National Oceanic and Atmospheric Administration. National Climate Date Center. *What are Heating and Cooling Degree Days*. https://www.weather.gov/key/climate_heat_cool

[20] A quantile regression model was fit to the data using the statistical software package STATA. Such a model is robust to violations of the normality and constant variance assumptions that must be met under a standard linear regression model. For more on quantile regression, *see* Hao, L., Naiman, D. Q. (2007). Quantile-regression model and estimation. In *Quantile regression* (No. 149). SAGE. https://www.sagepub.com/sites/default/files/upm-binaries/14855_Chapter3.pdf

[21] *See* NREL's Fuel Cell Buses in U.S. Transit Fleets: Current Status 2018. https://www.nrel.gov/docs/fy19osti/72208.pdf

- Usable energy for calculating vehicle range for battery electric buses is based on 80% nameplate battery capacity.[22]
- Usable capacity for calculating vehicle range for CNG buses is based on 75% tank capacity.[23]
- Diesel buses had a net usable fuel capacity of 114 gallons.[24]

3. Results and Analysis

A. Association of Change in Temperature to Fuel Efficiency Decline

The following are the results of the analyses undertaken upon applying the statistical model to the data. Table 2 sets forth the effects on fuel efficiency due to changes in temperature, controlling for the other factors listed previously, such as vehicle length and curb weight. Altogether, these explanatory variables accounted for around 75% of the variation in fuel efficiency based on a statistical measure of goodness-of-fit.[25] The resulting effects were separated by fuel technology. For temperatures below the 65° F base temperature, the blue column describes the percent change in fuel consumption associated with a 1° F decrease in ambient temperature. For temperatures *above* the 65° F base temperature, the red column describes the percent change in fuel consumption associated with a 1° F increase in ambient temperature.

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[22] *See* https://www.proterra.com/understanding-range-clarity-behind-the-calculations/

[23] Based on assessment of usable capacity as a proportion of nominal capacity for CNG tanks in Table 5.1 of U.S. Department of Transportation. NHTSA. (2016). *Commercial Medium- and Heavy-Duty Truck Fuel Efficiency Technology Study – Report #2*. https://www.nhtsa.gov/sites/nhtsa.dot.gov/files/812194_commercialmdhdtruckfuelefficiency.pdf

[24] *See Gillig Low Floor Coach Service Manual*. (2007). https://www.bidnet.com/bneattachments?/449042500.pdf

[25] The R-squared statistic was used to quantify this goodness-of-fit between fuel efficiency and the explanatory factors in the regression model.

Table 2. Relationship Between Ambient Temperature and Fuel Efficiency

Vehicle Type	Below 65° F, a 1° F **decrease** in ambient temperature was associated with the following median change in fuel consumption:	At or above 65° F, a 1° F **increase** in ambient temperature was associated with the following median change in fuel consumption:
Battery Electric	.85% increase	.69% increase
Fuel Cell	.69% increase	.42% increase
CNG	.15% increase	.03% increase
Diesel	.01% increase	.72% increase

On average, the largest relative increase in fuel consumption as outdoor temperature decreased below 65° F was among the battery electric buses in the sample, followed by fuel cell, CNG, and then diesel buses. For both the battery electric and fuel cell buses, the magnitude of this increase in fuel consumption during falling temperatures below the base temperature was smaller than that seen in our 2019 Report. In that report, we found among both BEBs and FCEBs a relative increase in fuel consumption of nearly 1% per 1° F drop in ambient temperature during periods of colder weather.[26]

The largest relative increase in fuel consumption in the sample, on average, as outdoor temperature increased *above* 65° F, was among the diesel buses, followed by battery electric, fuel cell, and then CNG buses. For both battery electric and fuel cell buses, the magnitude of this increase in fuel consumption during rising temperatures above the base temperature was also smaller than that seen in our initial report. We found in that paper a relative increase in fuel consumption among BEBs and FCEBs of around 1.0% and 0.5%, respectively, per 1° F rise in ambient temperature during periods of warmer weather.

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[26] *See* Henning, et al, *supra*, note 1.

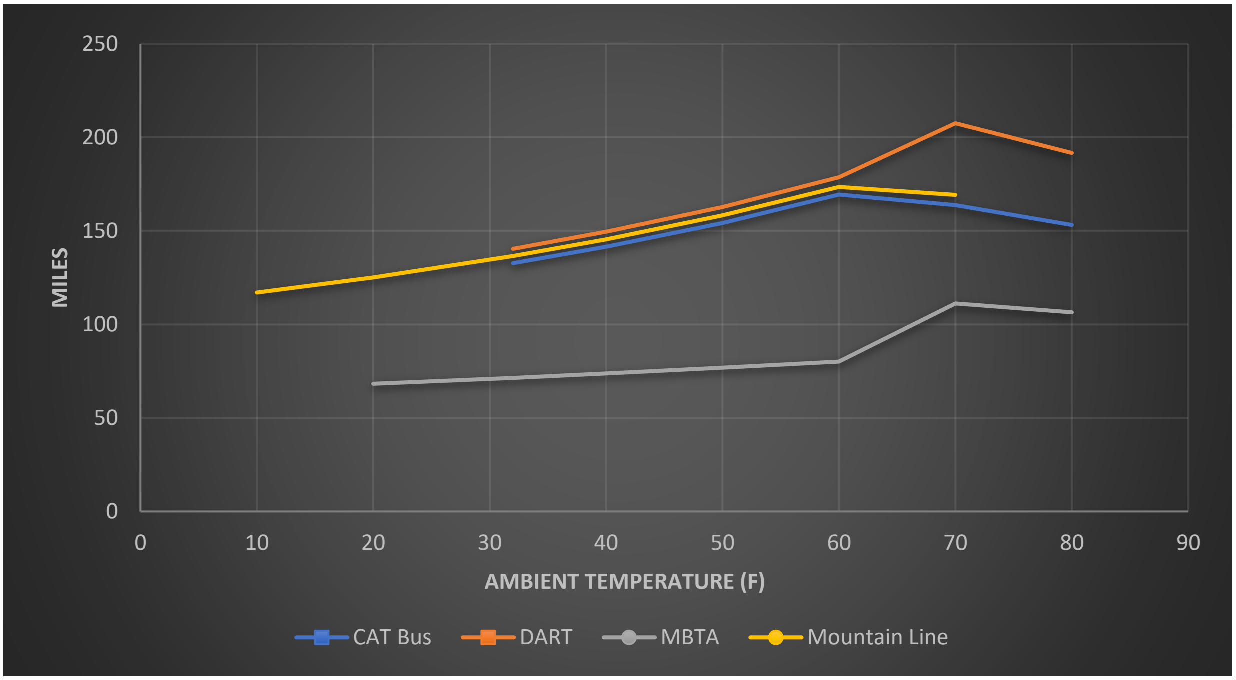
B. Association of Change in Temperature to Fuel Efficiency Decline

Point estimates of vehicle range at various ambient temperatures can be constructed by plugging in temperatures-of-interest into the statistical model and relating the resulting fuel efficiency estimate to usable tank capacity, where

$$Range = Usable\ capacity\ \div Fuel\ efficiency.$$

Figures 1 through 4 chart the median range for buses in our dataset at selected ambient temperatures based on this modeling of the data. Transit agencies are grouped in these figures according to similar vehicle characteristics. For example, some battery electric buses deployed by these agencies have relatively larger batteries and thus the ability to store more energy. In this regard we differentiated between agencies using BEBs with a 400 kWh or greater battery and those that did not. Similarly, for some BEBs the presence of a fuel-fired heater to heat the passenger cabin and the use of on-route charging, where batteries are smaller by design, are also known to affect vehicle range. The Study Team considered these important distinguishing factors when grouping vehicles in the context of range comparisons.

Figure 1. Range vs. Temperature for BEBs with 400 kWh or Greater Battery (all-electric heater)[27]



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[27] MBTA's buses are 60-foot articulated buses that carry heavier loads on average than the BEBs with similarly sized batteries represented in Figure 1. An independent analysis by the *Boston Globe* of MBTA's same BEBs found vehicle ranges similar to those estimated here by the Study Team (60 miles during a 20-degree day and 110 miles in "nice weather"). *See* Vaccaro, A. (2020, September 16). Electric buses still a ways off for MBTA. *Boston Globe*. https://www.bostonglobe.com/2020/09/16/metro/electric-buses-still-ways-off-mbta/

Figure 2. Range vs. Temperature for BEBs with 400 kWh or Greater Battery (diesel heater)

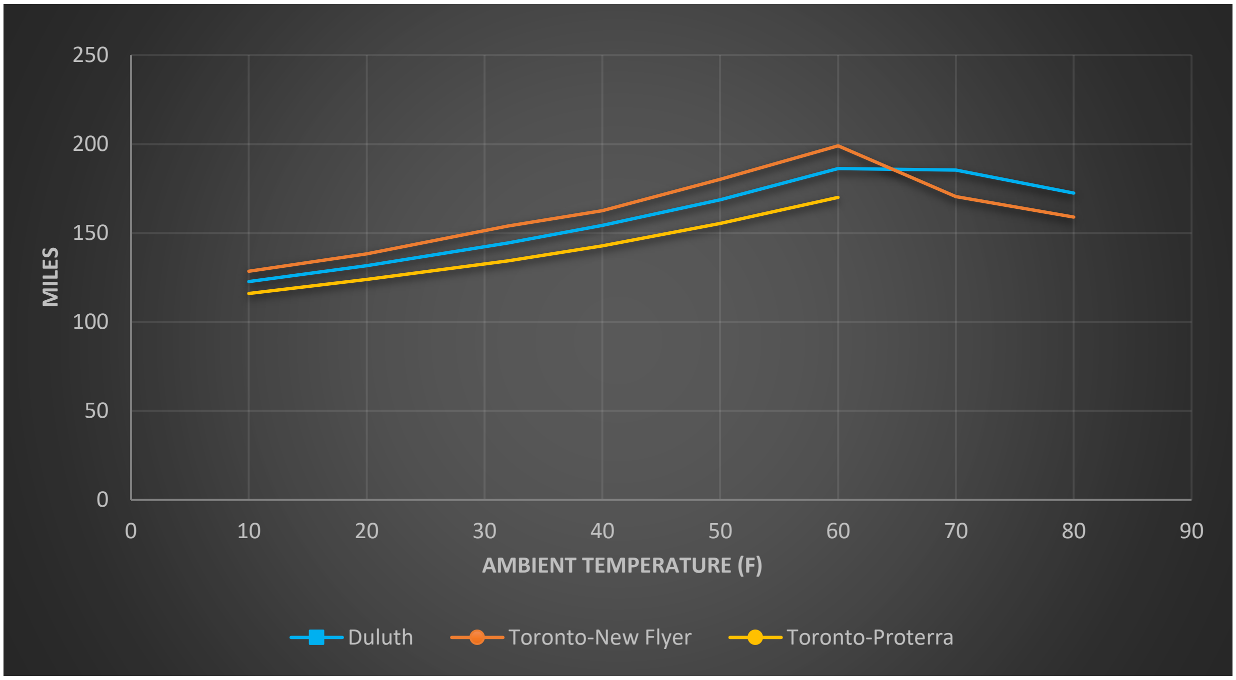
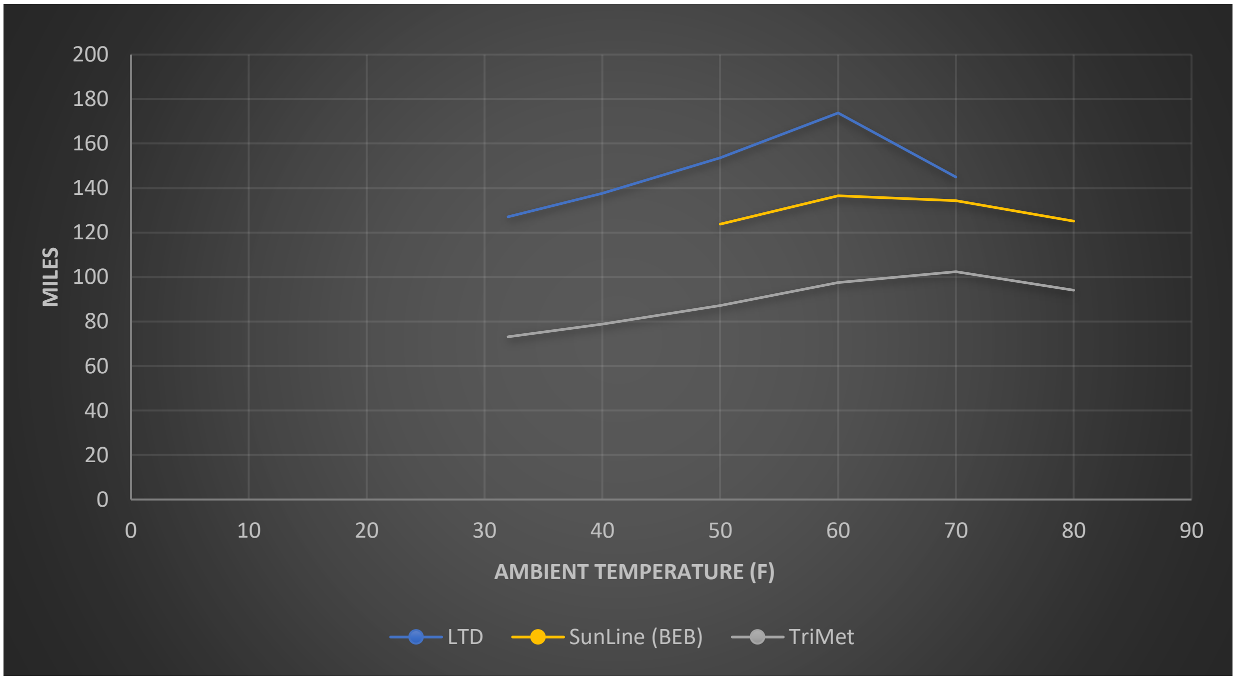
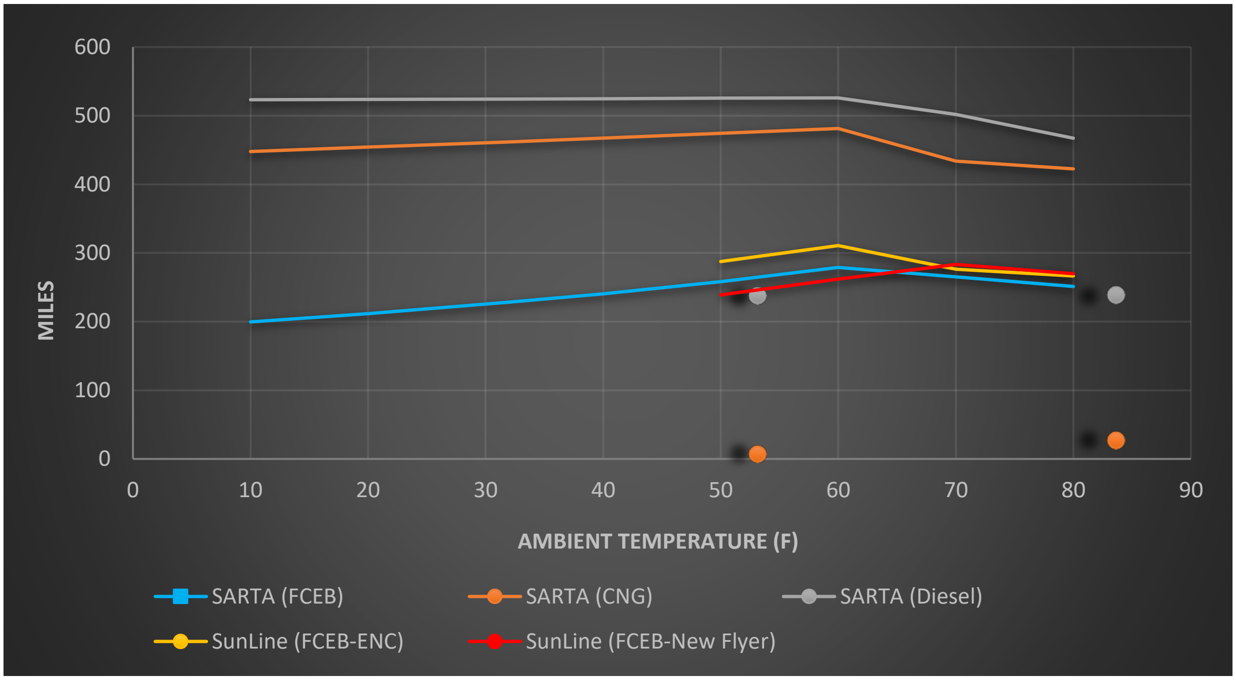


Figure 3. Range Versus Temperature for BEBs with Less than 400 kWh Battery



Note: LTD's BEBs use an on-board diesel heater to warm the passenger cabin while SunLine's and TriMet's do not.

Figure 4. Range Versus Temperature for Fuel Cell Electric, Diesel, and CNG Buses



C. Fuel Efficiency Uncertainty

In addition to point estimates of median fuel efficiency, the statistical model allowed us to describe the uncertainty of fuel efficiency at different ambient temperatures. That is to say, for a given outdoor temperature, what range of values for fuel efficiency might be expected in most cases? We chose to specify 99% uncertainty intervals. We would expect 99% of future observed fuel economies to lie between these lower and upper bounds. Figures 5 and 6 illustrate this fuel efficiency uncertainty at different outdoor temperatures by fuel technology based on the data obtained by the Study Team.

Figure 5. Fuel Efficiency Uncertainty for Battery Electric, CNG, and Diesel Buses (in kWh per mile)

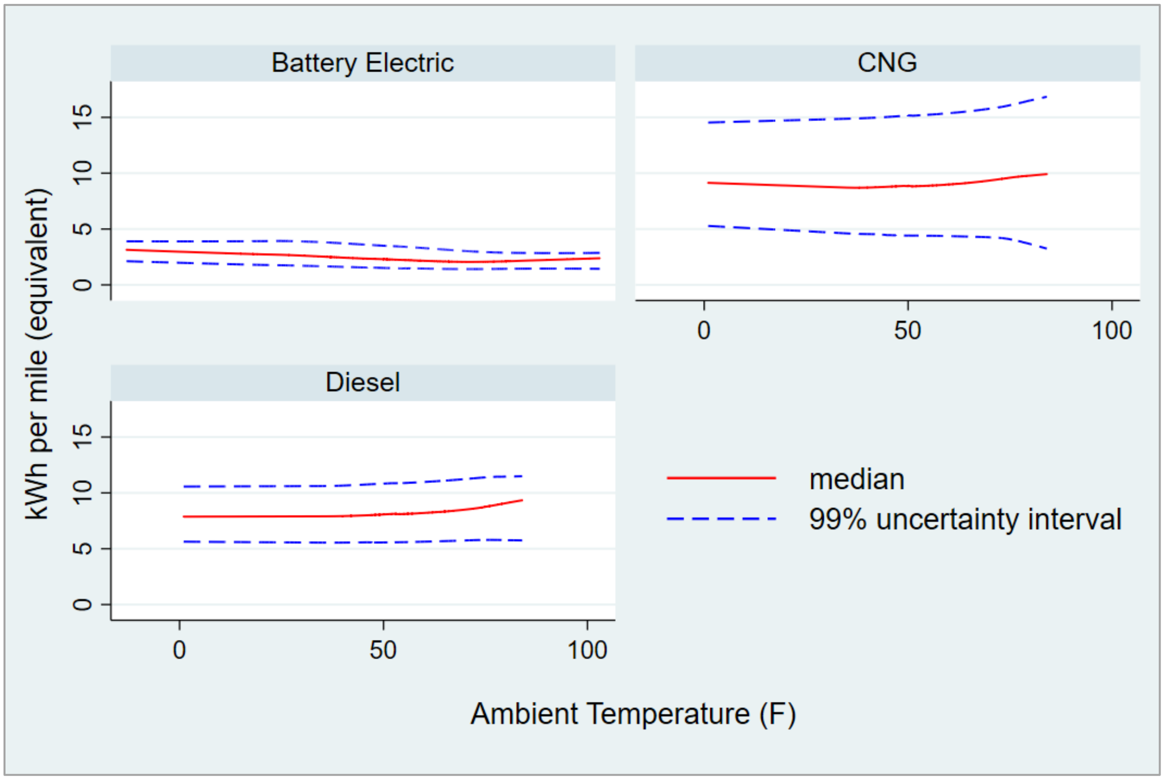
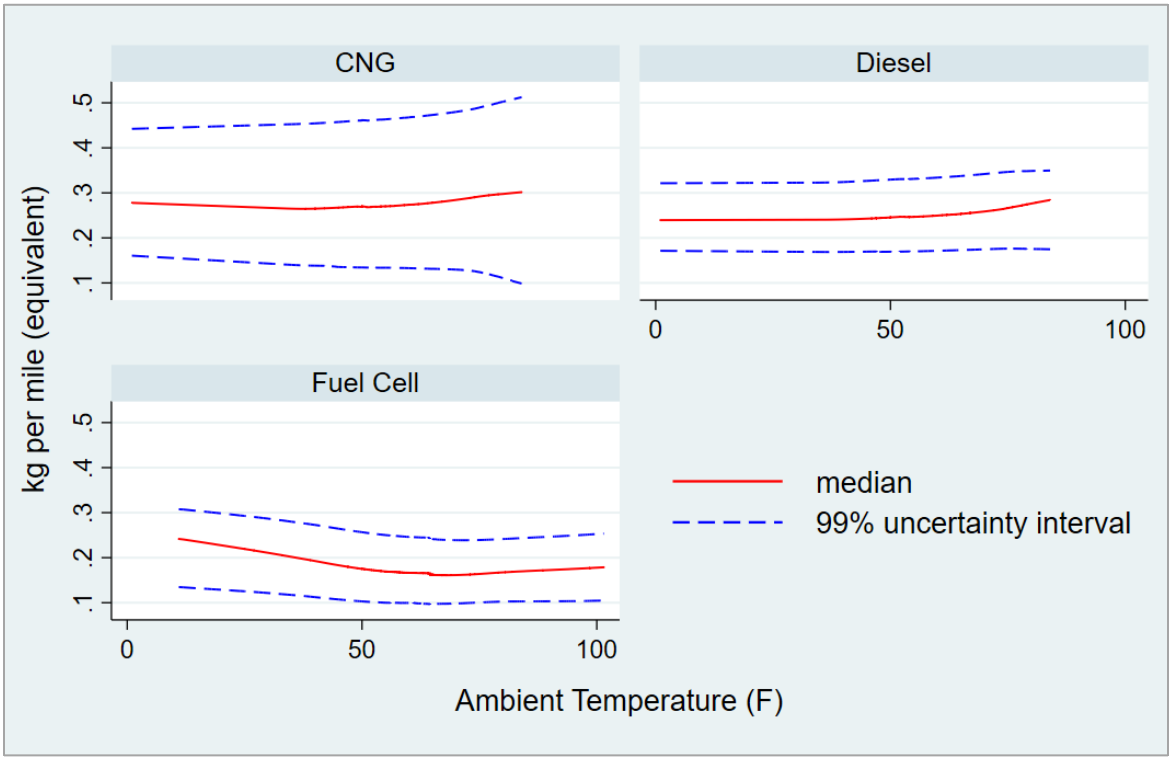


Figure 6. Fuel Efficiency Uncertainty for Fuel Cell, CNG, and Diesel Buses (in kg of H2 per mile)



Figures 5 and 6 indicate that battery electric buses had the narrowest uncertainty intervals and thus the lowest fuel efficiency uncertainty while CNG buses had the widest uncertainty intervals and therefore the highest fuel efficiency uncertainty. Fuel cell and diesel buses appeared to have comparable fuel efficiency uncertainty. On average, across all ambient temperatures in the dataset, we would expect median fuel efficiency by fuel technology to vary 99% of the time no more than the amounts seen in Tables 3 and 4 based on this analysis.

Table 3. Variation in Median Fuel Efficiency Across All Temperatures (Battery Electric Bus Comparison)

Fuel Technology	Expected Variation
Battery Electric	+/- 0.8 kWh per mile
Diesel	+/- 2.6 kWh-equivalent per mile
CNG	+/- 5.2 kWh-equivalent per mile

Table 4. Variation in Median Fuel Efficiency Across All Temperatures (Fuel Cell Electric Bus Comparison)

Fuel Technology	Expected Variation
Fuel Cell	+/- 0.08 kg of H_2 per mile
Diesel	+/- 0.08 kg of H_2-equivalent per mile
CNG	+/- 0.16 kg of H_2-equivalent per mile

4. Conclusion

This analysis reinforces findings from our 2019 Report evaluating the relationship between ambient temperature and fuel efficiency for zero-emission buses (ZEB). Additional control variables were included in this update to isolate the fuel efficiency effects associated with temperature variation. Below 65° F in particular, ZEB fuel efficiency, and by extension range, seems more sensitive to temperature variation compared to fossil-fuel based vehicles, resulting in relatively higher fuel consumption as temperatures drop. This can be explained, in part, by the far greater amount of waste heat that fossil vehicles generate for propulsion compared to BEBs and FCEBs, which can be recycled and used for heating the passenger cabin. The magnitude of the increase in fuel consumption for both ZEB types, however, was smaller for this study update compared to that found in the 2019 Report. This could be due in whole or in part to the inclusion of additional control variables in our current statistical model that also explain variation in vehicle fuel efficiency. It could also be due to improvements over time in how agencies and their drivers operate the vehicles so as to minimize fuel consumption.

Interestingly, we found no evidence that fuel efficiency and range uncertainty were higher for ZEBs compared to the fossil-fuel based buses. Indeed, the greatest fuel efficiency and range uncertainty across all ambient temperatures was among the CNG buses. Fuel efficiency uncertainty for the buses in this study seemed relatively stable for both ZEB types in both warmer and colder weather. The agencies deploying these ZEBs could therefore expect that while average fuel consumption is likely to increase during cold weather, the “give or take” of a few kWh of electricity or kg of hydrogen would be more or less constant.

While we included additional factors in our modeling of fuel efficiency in this study update, additional key factors were not included and should be evaluated in future work. Among these are driver behavior and how the buses are used. Anecdotal information from transit agencies indicates that there is a period of familiarization when ZEBs are deployed during which drivers learn how to cover the same route and distance using less fuel. The magnitude of this effect is not fully understood. It could possibly interact with ambient temperature so that driver behavior varies with seasonal conditions in a way that minimizes fuel consumption.