An Analysis of the Association between Changes in Ambient Temperature, Fuel Economy, and Vehicle Range for Battery Electric and Fuel Cell Electric Buses

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Disclaimer

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Executive Summary

This report evaluates the effects of changing weather on zero emission bus performance. The report relies on selected data that was made available to the Study Team from transit agencies that have deployed hydrogen fuel cell and battery electric zero emission buses.

All transit buses, regardless of fuel source, experience some loss of range in extreme weather. As transit agencies plan to replace their traditional diesel-fueled buses with zero emission buses, they will need to consider the effects of extreme weather on the new buses replacing their existing fleets. This report collects zero emission bus data and evaluates the effects of change in ambient temperature on the efficiency and range for those buses. The report does not recommend that transit agencies adopt any particular zero emission technology for any given climate. Rather, it seeks to provide transit agencies with planning insights as they contemplate strategies for replacing their own existing fleets with zero emission buses.

The Study Team collected data from eight transit agencies, four that deployed hydrogen fuel cell and four that deployed battery electric buses. The agencies were located in variable climate conditions, ranging from hot (southern California) to cold (northern Minnesota), and included one from Europe. Of the four battery electric bus transit systems, two used "en route" recharging systems.

The results of the analysis showed that for temperature drops from 50-60° to 22-32° Fahrenheit, battery electric buses lost around 32.1% efficiency, while fuel cell electric buses dropped 28.6%. For those planning fleet replacement, however, the rate of fuel consumption is only one consideration. The cost of acquiring vehicles and building refueling/recharging infrastructure may be more important than the cost of fuel. Accordingly, a transit agency that expects to swap out its diesel for zero emission buses on a 1 for 1 basis will need to consider vehicle range for the zero emission buses.

For this reason, the Study Team also looked at the effects of weather on bus range. While the "en route" recharging data could be analyzed for efficiency, it could not readily be compared to other EV buses for effects on range, so the transit agencies using these buses were removed from the range analysis.

The loss in range going from 50-60°F to 22-32°F was greater for battery electric buses (37.8% decrease) than for fuel cell electric buses (23.1% decrease). Since battery electric buses typically have a smaller range than fuel cell electric buses even under optimal conditions, this may be an important consideration for transit agencies located in cold weather climates that are seeking 1 for 1 bus replacements.

The following table shows the effects of temperature change on zero emission bus (ZEB) range for the six transit agencies evaluated. Four used fuel cell electric buses while two used battery

electric buses. One transit agency, Sunline, is located in Southern California, and did not experience average daily outdoor temperatures that were near or below freezing.

Estimated Mean Range in Miles per ZEB at Selected Ambient Temperatures

ZEB Type	Agency	Ambient Temperature (F)							
		10°	*20°*	*Freezing*	*40°*	*50°*	*60°*	*70°*	*80°*
Fuel Cell Electric Bus (FCEB)	BC Transit (Victoria, BC)	N/A	162	185	204	230	258	246	240
	Ruter (Oslo, Norway)	96	107	125	139	164	162	159	156
	SARTA (Canton, OH)	194	207	224	237	253	270	247	227
	SunLine (Thousand Palms, CA)	N/A	N/A	N/A	293	294	294	277	258
	***Average range for FCEBs*[1]**	**166**	**171**	**180**	**201**	**233**	**253**	**250**	**246**
Battery Electric Bus (BEB)	DDOT (Washington, DC)	60	69	90	106	131	162	165	145
	Duluth Transit (Duluth, MN)	123	132	143	151	163	167	165	N/A
	***Average range for BEBs*[2]**	**111**	**117**	**119**	**122**	**142**	**164**	**165**	**145**

The report establishes that fuel economy of electric drive buses may vary significantly with temperature. The effects of temperature change on range may be particularly important in planning fleet development, especially for transit agencies located in cold weather climates. Agencies in cold weather climates may have to acquire additional buses or infrastructure to maintain full service during cold weather conditions. This will be especially so for those agencies thinking about replacing their diesel fleet with battery electric buses.

[1] Weighted by miles traveled for temperatures 3° above and below those appearing in each column heading for *Ambient Temperature (F)*.
[2] *Id.*

1. Introduction

A. Background.

Technology improvement in battery electric and fuel cell electric vehicles, together with an increasingly urgent need to reduce greenhouse gas emissions, have created considerable interest in acquiring zero-emission buses among transit agencies around the United States. Investments into either battery electric or fuel cell electric bus fleets require long-term commitment to one strategy or the other, so transit agencies have been cautious in selecting one form of electric bus over another.

No one wants to invest heavily into one technology only to see other technologies rapidly develop better performance and cost attributes. Yet climate change is upon us, and transit agencies are being strongly encouraged, and sometimes required, to transition to electric drive fleets. In 2018, the state of California implemented a mandate for all transit agencies to convert their buses to zero-emission vehicles by 2040.

There are a number of considerations that impact a transit agency's strategy in selecting a bus technology. This report will not go into all these considerations, nor does it purport to recommend one form of technology over another. Rather, it seeks to identify and isolate data that may inform some of the considerations transit agencies may have relating to performance in variable weather conditions, especially extreme cold.

The purpose of the report is to investigate how zero-emission bus performance has responded to changes in ambient temperature. The report relies on selected data that was made available to the Research Team, as set forth below. Due to the limited data and ever-evolving nature of these technologies, it is not possible to draw conclusions as to which technologies are most appropriate for which climates. For instance, the technologies used by the transit agencies that released their data have many differences besides being either fuel cell or battery dominant. Moreover, reporting methodologies vary enough that data cannot be easily aggregated. 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.

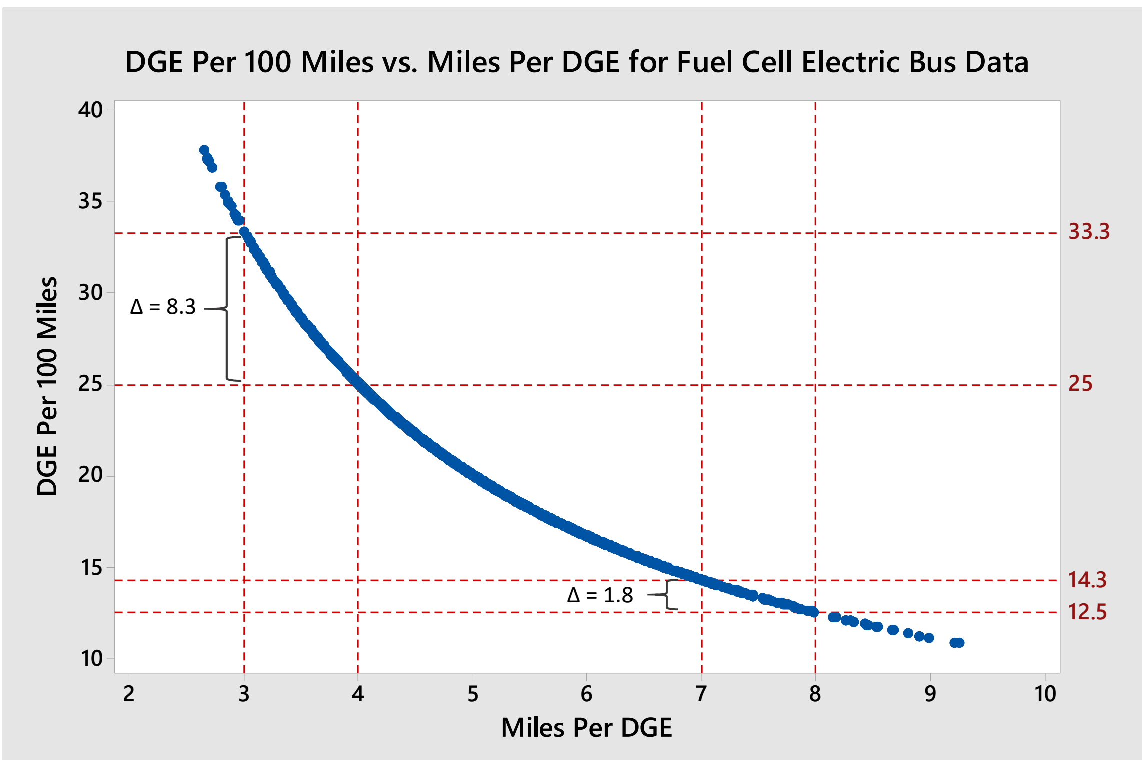
B. Industry Terms and Definitions.

Vehicle efficiency performance is understood by the general public in terms of "miles per gallon" of gasoline, which is how it is reported for vehicles sold commercially by new car or truck dealers. If the vehicle uses an alternative fuel, efficiency is commonly presented in terms of gasoline equivalency.[3] In the transit industry, however, fuel efficiency for buses is more commonly set forth as gallons of diesel equivalency (dge) per 100 miles. The reason for this is that transit

[3] U.S. Department of Energy fuel conversion factors as included in the Energy Policy Act were used in this study to convert all fuel measurement units into diesel gallon equivalents. *See* https://epact.energy.gov/fuel-conversion-factors

agencies think of fuel efficiency in terms of fuel acquisition. Using miles per gallon to measure efficiency can be misleading, especially for larger vehicles such as buses and trucks that drive a high number of miles with generally lower miles-per-diesel-gallon-equivalent (mpdge) efficiency. As can be seen in Figure 1 below, the impact of a 1 mpdge improvement on total fuel consumption varies depending on a vehicle's initial fuel economy. This effect is larger for vehicles with lower levels of mpdge efficiency, such as transit buses. For instance, a 1 mpdge decrease in efficiency for a bus with a fuel economy of 8 mpdge means 1.8 more diesel gallons purchased per 100 miles, but the same decrease for a vehicle getting 4 mpg would require an additional purchase of 8.3 gallons of diesel. Measuring fuel efficiency in dge/100 miles offers more value to transit agencies in understanding the impact from efficiency improvements. This is also consistent with most academic and industry literature.[4] We have followed this dge/100 miles reporting strategy, though we include both measures in some instances.

Figure 1. Impact of Change in Efficiency on DGE/100 Miles vs. Miles/DGE



[4] https://science.sciencemag.org/content/320/5883/1593

We have not attempted in his paper to quantify the costs of fuel based upon changes in weather conditions. Transit agencies deploy strategies for risk management that include projections for the costs of fuel acquisition.[5]

C. Prior Research

No propulsion technology, given current vehicle body and chassis designs, can prevent completely the reduction in fuel efficiency associated with outside temperature extremes. Both aerodynamic drag and the drag between tires and the road are appreciably higher at sub-freezing temperatures compared to ideal conditions (e.g. 75 degrees F).[6] The power requirements to overcome these drag forces will therefore be higher in colder temperatures regardless of whether a vehicle is "fueled" by electricity, hydrogen, or conventional gasoline and diesel. Likewise, all buses endure some loss in range ensuring that cabins are comfortable for riders during extreme weather, regardless of their fuel source.

What remains an open question is to what extent the magnitude of this decrease in fuel efficiency, and thus range, is different across the spectrum of vehicle propulsion technologies, especially for transit agencies that deploy zero-emissions platforms. Research undertaken by Argonne National Laboratory suggests that, on average, some fuel cell electric bus fleets operating in especially cold temperatures have experienced increased fuel consumption of around 0.21 diesel-gallons-equivalent per 100 miles for every 1° F drop in ambient temperature below 65° F.[7] The same research indicates that other fuel cell bus fleets operating in warmer temperature have seen an increase in fuel consumption of approximately 0.06 to 0.13 diesel-gallons-equivalent per 100 miles for every 1° F increase in ambient temperature above 65° F.

The Study Team was unable to identify previous studies examining the issue of diminishing fuel efficiency for battery-electric bus fleets operating in near- or sub-freezing temperatures. However, the results of the National Renewable Energy Laboratory's (NREL) initial Zero-Emissions Bus Evaluations on behalf of the Federal Transit Administration suggest that battery electric bus fleets operating in warmer temperature have seen fuel efficiency variation ranging from effectively zero to an increase of roughly 0.15 diesel-gallons-equivalent per 100 miles for every 1° F increase in ambient temperature above 65° F.[8] NREL's planned bus evaluations for transit agencies in Duluth, MN and Philadelphia, PA will shed important light on the performance of BEB fleets operating in cold weather climates. In addition, an upcoming Zero Emission Bus Study commissioned by AC Transit in Oakland, CA will provide performance

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[5] Risk management for transit agencies also encompasses minimizing exposure to liabilities in the form of damage to people and property. *See* http://onlinepubs.trb.org/onlinepubs/tcrp/tsyn13.pdf. We did not, in this study, attempt to quantify the dollar amount associated with operating zero-emissions buses in appreciably hotter and colder temperatures. Given that the essence of risk is uncertainty, measurements of which are often based on standard deviation statistics, our focus in this paper with regard to risk was to quantify the variability of performance indicators such as fuel economy and vehicle range. Placing a value on the losses associated with this uncertainty will be an area of future work. *See:* http://viking.som.yale.edu/will/hedge/Risk_BobJaeger.pdf).

[6] https://www.scientificamerican.com/article/why-is-the-fuel-economy-o/

[7] *See* Fig. 2a in Lee, D. Y., Elgowainy, A., & Vijayagopal, R. (2019). Well-to-wheel environmental implications of fuel economy targets for hydrogen fuel cell electric buses in the United States. *Energy policy*, *128*, 565-583. *See supra fn.* 1.

[8] *See* Zero-Emission Bus Evaluation Results for County Connection in San Francisco, CA, and King County Metro in Seattle, WA. https://www.nrel.gov/hydrogen/fuel-cell-bus-evaluation.html

comparison of BEBs and FCEBs made by the same manufacturer that operate under the same route conditions.[9] It is unlikely, however, that the AC Transit study will provide much insight into performance in extreme cold or heat, given the climate in Oakland.

2. Methodology.

A. Data Sources and Collection

The data used in this study constitute a convenience sample. The authors leveraged existing professional relationships and cold-called/emailed transit authorities over a 3-month period to obtain records of daily fueling and miles traveled per vehicle. Potential battery electric bus (BEB) agencies were identified using the Center for Transportation and the Environment's (CTE) active database of current projects. Potential fuel cell electric bus (FCEB) agencies included those tracked by the National Renewable Energy Laboratory (NREL),[10] as well as European agencies that participated in the Clean Hydrogen in Europe (CHIC) project.[11] Table 1 includes the transit agencies that were not only willing to share their fuel economy performance data with the study team, but also those with a system of daily information collection in place that allowed them to do so.

Because this study focuses on the impact of temperature on vehicle fuel economy, it was imperative to include daily-level data in the analysis. This significantly limited the number of transit agencies available to participate in the study, especially with respect to operators of battery electric buses. FCEB daily data can be easier to track: the fueling records for FCEBs often consist of daily hydrogen dispensed to an individual vehicle. Combining that information with daily block assignments makes it relatively straightforward to calculate the fuel consumption of an individual hydrogen fuel cell bus.

Fueling records for BEB fleets, on the other hand, are often comprised of utility bills which aggregate all energy dispensed to all of a transit agency's battery electric buses over the entire billing period, which is usually one month in duration. Some transit agencies have also put their vehicle chargers on the same electric meter as their facility, and, without additional data tracking, it is nearly impossible to differentiate between energy dispensed to vehicles and energy consumed by the facility.

In order for BEB operator data to be useful for this study, the operator needed to have a data collection system that recorded daily energy consumption on a per vehicle basis. This is becoming more common in the industry as operators recognize the variable nature of electric bus fuel economy, but it is not yet ubiquitous, and limited the data set available for this study.

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[9] *See* AC Transit. (2019). *ACT ZEBs*. http://www.actransit.org/environment/environment-zebs/
[10] For example, *see* https://www.nrel.gov/docs/fy19osti/72208.pdf
[11] For more information on CHIC, visit https://www.fuelcellbuses.eu/projects/chic

Inconsistencies between data collection systems are one of the many reasons it can be challenging to draw general conclusions from any individual operator's experience. Other factors that influence vehicle performance include block characteristics (topography, average and maximum speeds, stops per mile), weather conditions (temperature, snowfall, ice), and driver behavior.

The agencies that participated in this study (set forth in Table 1 below) operate in a variety of weather conditions.

Table 1. Participating Transit Agencies

Transit Agency	ZEB Type	Location	Data Collection Period
SARTA[12]	FCEB	Canton, OH	NOV 2017 – JUL 2019
Ruter	FCEB	Oslo, Norway	APR 2013 – AUG 2015
BC Transit	FCEB	Victoria, BC	FEB 2010 – JAN. 2013
SunLine	FCEB	Thousand Palms, CA	JUL 2017 – JUL 2019
DDOT[13]	BEB	Washington, DC	MAR 2018 – JUN 2019
DTA[14]	BEB	Duluth, MN	NOV 2018 – JUN 2019
Seneca[15]	BEB	Seneca, SC	SEPT 2014 – JUL 2018
WRTA[16]	BEB	Worcester, MA	SEPT 2013 – AUG 2017

The data sets acquired from the agencies set forth in Table 1 were deemed by the Study Team to be of adequate size for reliable certain statistical evaluation, such as regression analysis. The data were drawn from four agencies deploying BEBs and four agencies deploying FCEBs. Figures 2 and 3 show dge/100 miles fuel efficiency plotted against ambient temperature for the data that were collected from the FCEB and BEB agencies, respectively. For those who are more used to the miles per gallon approach used by commercial vehicle retailers, Figures 4 and 5 plot this same data for fuel efficiency in terms of mpdge. Plots use degrees Fahrenheit, since this is the temperature scale most commonly in use in the United States.

The fit lines in red were generated using locally weighted scatterplot smoothing (LOWESS). This technique for summarizing the data depicts the local relationship between fuel economy and

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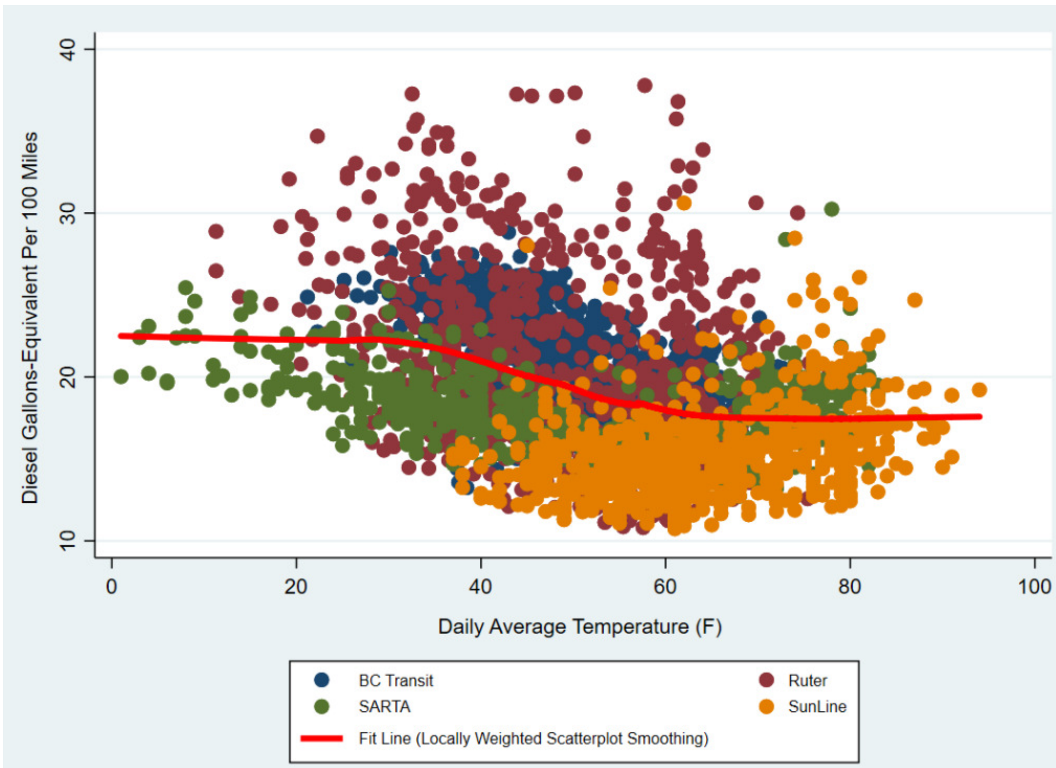
[12] Stark Area Regional Transit Authority, Canton, Ohio.
[13] District Department of Transportation, Washington, DC
[14] Duluth Transit Authority, Duluth, MN
[15] "The City of Seneca, SC owns these BEBs and outsources operations to CATbus (i.e. Clemson Area Transit).
[16] Worcester Regional Transit Authority, Worcester, MA.

temperature at temperature subintervals, or what can be characterized as data "neighborhoods."[17] This method is comparable to a moving average. Unlike more formal linear regression models, LOWESS makes no assumptions about the form of the relationship between *x* and *y* variables, allowing the form to be discovered using the data itself.[18]

Figure 2. Diesel Gallons-Equivalent Per 100 Miles Fuel Economy for FCEBs



[17] *See* https://www.itl.nist.gov/div898/handbook/pmd/section1/pmd144.htm
[18] https://www.ime.unicamp.br/~dias/loess.pdf

Figure 3. Diesel Gallons-Equivalent Per 100 Miles Fuel Economy for BEBs

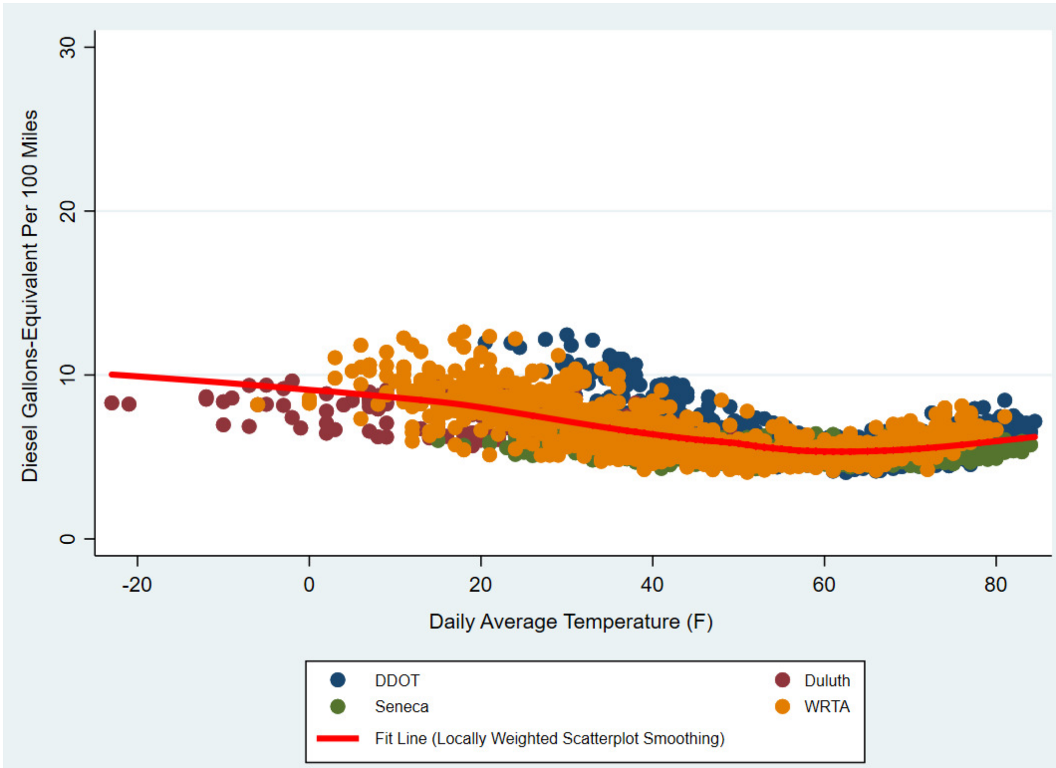


Figure 4. Miles Per Diesel Gallon-Equivalent Fuel Economy for FCEBs

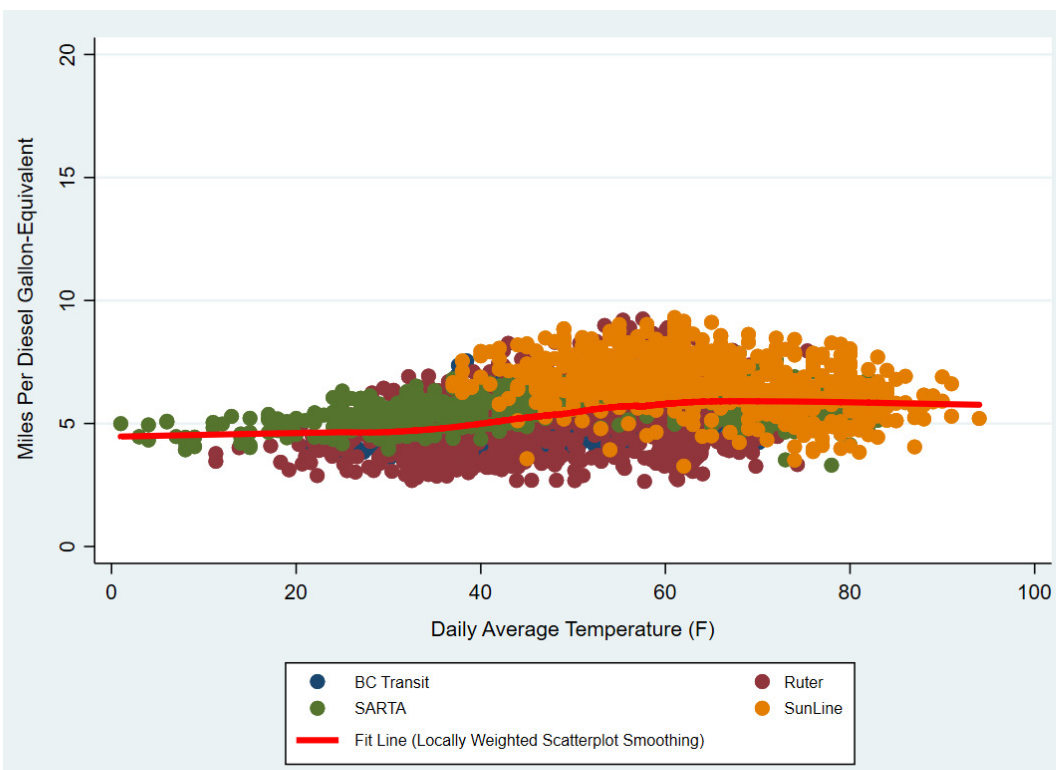
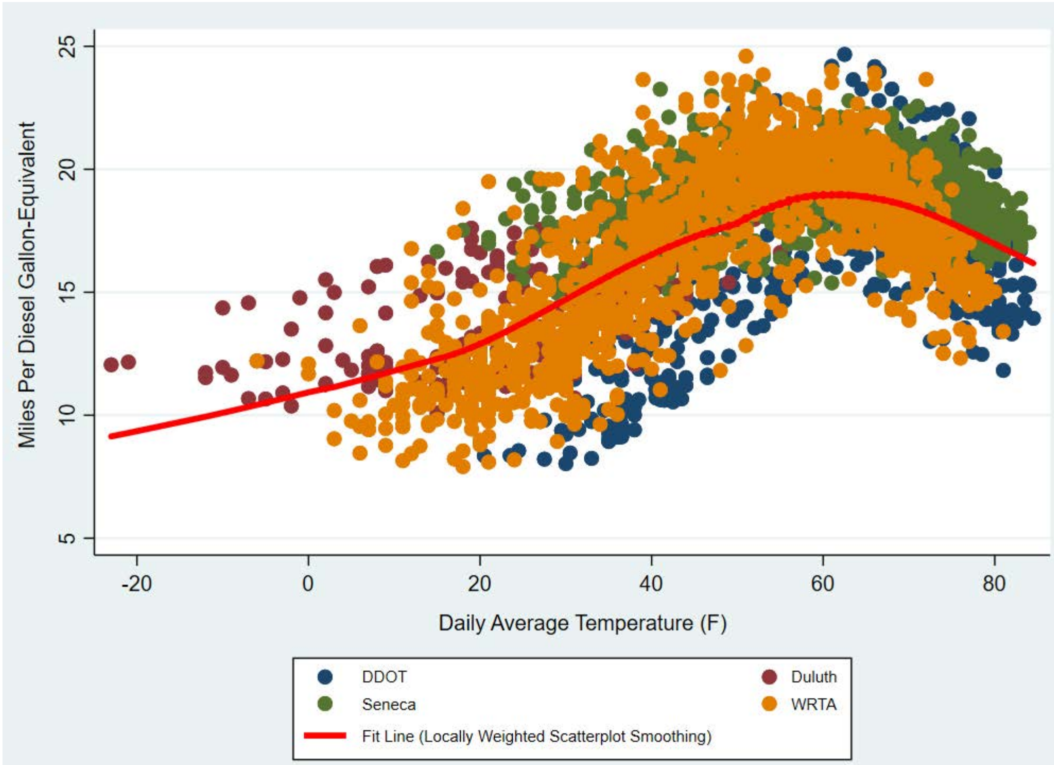


Figure 5. Miles Per Diesel Gallon-Equivalent Fuel Economy for BEBs



Figures 2 through 5 above illustrate how measuring fuel economy using the more common miles per gallon strategy can obscure a complete understanding of efficiency improvements. Using the LOWESS fit line as a guide, average miles per gallon fuel efficiency data for BEBs indicate a considerable loss in efficiency when temperatures drop from 65°F (18.8 mpdge) to 32°F (14.8 mpdge). The FCEB data indicate a loss from 6.0 to 4.7 mpdge for the same temperature drop. Both show a reduction of approximately 21%. However, using the dge/100 miles approach, we can see that the loss in efficiency for BEBs leads to a smaller increase in fuel consumption than it would for FCEBs. Over this same temperature drop, there is an average increase of 1.4 dge/100 miles (from 5.4 dge/100 miles to 6.8) for the BEBs, but 4.9 dge/100 miles (from 17.1 dge/100 miles to 22.0) for the FCEBs. This is because larger incremental change in terms of mpdge can actually result in smaller incremental change in terms of dge/100 miles, depending on the difference in initial fuel economy between two vehicle types.

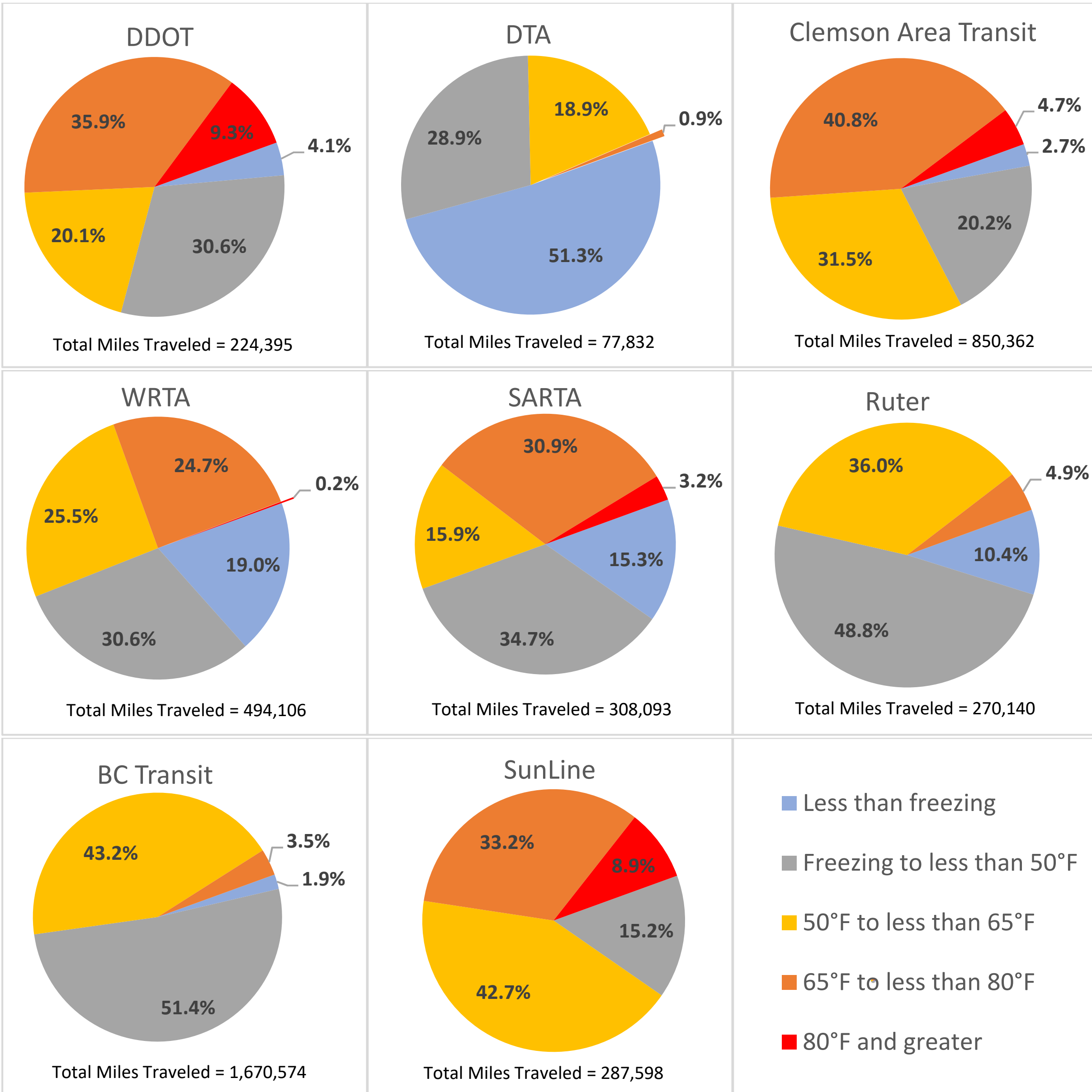
It is important, however, to remember that for those managing fleets, the cost of fuel may be small compared to the cost of acquiring vehicles and building refueling/recharging infrastructure. If a bus requires frequent refueling or recharging, fuel savings may not matter as much. A transit agency may have to purchase additional buses to meet its route demands if the efficiency reduction during extreme weather is high. For this reason, the Study also looks at the effects of temperature on vehicle range for BEBs and FECBs.

B. Temperature Data Collection

Daily average ambient temperature data used in our analyses were gathered from the websites of authoritative government scientific agencies. These included the U.S. National Oceanic Atmospheric Administration, Canada's Department of the Environment, and the Norwegian Meteorological Institute (converted to degrees Fahrenheit). See Appendix A for a detailed depiction of the frequency distribution of daily average outdoor temperature for the included transit agencies during the period of time for which data were collected.

The following series of pie charts summarizes the percentage of vehicle miles traveled by ambient temperature for each agency whose data we collected. Miles traveled for each agency's fleet of zero emissions buses were grouped according to the average temperature on the day a vehicle was in service. These temperature range groupings include: below 32°F (color coded light blue), 32°F to less than 50°F (gray), 50°F to less than 65°F (gold), 65°F to less than 80°F (orange), and 80°F and greater (red).

Figure 6. Proportion of Miles Traveled by Ambient Temperature

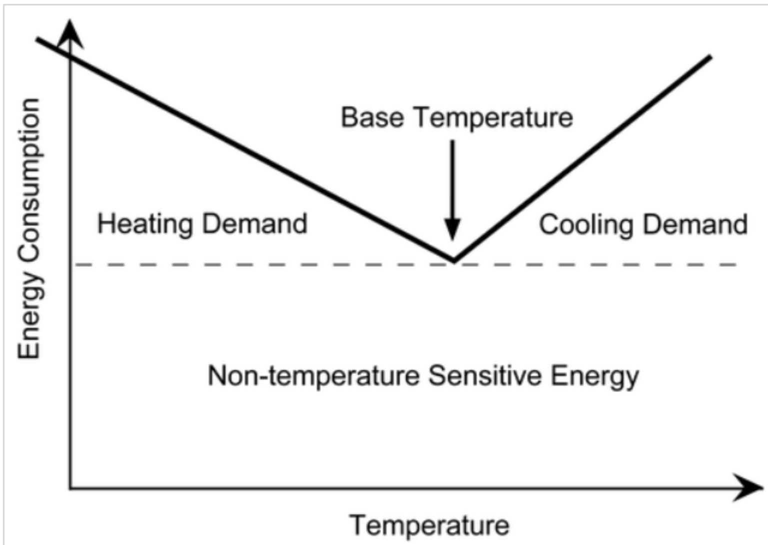


In addition to collecting daily data on fuel economy, distance traveled per vehicle, and ambient temperature, a final piece of information that had to be determined before proceeding with our analyses was the base temperature for each agency whose data we obtained. The base temperature is the outside temperature at which no heating or cooling is necessary to maintain comfort conditions.[19] Figure 7 illustrates the theoretical relationship between temperature and energy use for heating and cooling. Base temperatures used to study climate effects vary from

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

region to region.[20] We extended to heavy duty vehicles the guidelines developed by the American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE) for selecting base temperatures to analyze building energy consumption. The base temperature was determined by specifying a best-fit piecewise linear regression model, which is described further in the Research Methods and Analysis section below.[21]

Figure 7. Theoretical Relationship Between Ambient Temperature and Energy Consumption



Source: Lee, Baek, and Cho[22]

C. Research Methods and Analysis

The Study Team used statistical methods to evaluate the effects of outdoor temperature on the efficiency of FCEBs and BEBs that reported data for the study. The goal was to develop a model, using the existing data, to roughly predict temperature effects. The study team also evaluated the variability of fuel economy for the underlying data. Areas examined were (i) the coefficient of variation for the fuel economy data, (ii) the strength of the relationship between fuel economy and ambient temperature, and (iii) the strength of the relationship between vehicle range and ambient temperature. The research method is described below.

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[20] *See* Azevedo, J. A., Chapman, L., & Muller, C. L. (2015). "Critique and suggested modifications of the degree days methodology to enable long-term electricity consumption assessments: a case study in Birmingham, UK." *Meteorological Applications*, *22*(4), 789-796. *See, also,* Lee, K., Baek, H. J., & Cho, C. (2014). "The estimation of base temperature for heating and cooling degree-days for South Korea." *Journal of applied meteorology and climatology*, *53*(2), 300-309.

[21] For ASHRAE guidelines on identifying base temperatures, *see* *https://oaktrust.library.tamu.edu/handle/1969.1/153708*

[22] https://journals.ametsoc.org/doi/full/10.1175/JAMC-D-13-0220.1

i. Comparing the Dispersion of Fuel Economy Data

The coefficient of variation (COV) is a measure of risk or relative standard deviation, where in general

$$COV = \frac{standard\ deviation}{mean}$$

This metric is commonly used to compare the data dispersion between distinct series of data. Unlike the standard deviation that must always be considered in the context of the mean of the data, the coefficient of variation provides a relatively simple and quick tool to compare different data series. Stated in percentage terms, a higher value for this measurement suggests a higher degree of data variability. Greater variability means that transit agencies may face greater uncertainty in planning for fuel purchases or bus acquisition, especially when operating in more extreme conditions.

ii. Fuel Economy by Ambient Temperature

The ASHRAE guidelines and the theoretical relationship illustrated in Figure 7 above indicate that a piecewise regression model is appropriate for modeling fuel economy as a function of ambient temperature. This approach allows for different slopes for the regression line above and below the base temperature, thus allowing for potentially divergent changes in fuel economy to be captured in response to hotter versus colder temperatures.

Additionally, the Study Team sought to estimate the relative change (i.e. in percentage terms) of fuel economy in response to degree Fahrenheit temperature variation for FCEBs and BEBs. One common way to convert changes in variables into percentage changes is to convert the variable of interest -- in this case fuel economy -- by taking its natural logarithm. With this in mind, the basic piecewise regression used to estimate the relationship between ambient temperature and fuel economy was:

$$ln(fuel\ economy) = \beta_0 + \beta_1 t + \beta_2 x_1 + \beta_3 (x_1 - base\ temperature) x_2 + \varepsilon$$

where t represents a time trend, x_1 is daily ambient temperature, x_2 is an indicator variable for when daily ambient temperature exceeded the base temperature for a given region, and the beta coefficients (i.e. the βs) describe the percent change in fuel economy associated with a 1-unit change in their corresponding variables, holding all other variables constant. The error term ε describes the effects on percent change in fuel economy of all factors other than ambient temperature. *Fuel economy* specified here was in units of diesel-gallons-equivalent per 100 miles. The chosen *base temperature* was the one yielding the best fitting model.[23] For daily ambient temperatures above the base temperature, the results of this log-linear specification can be interpreted as the $100 \times (\beta_2 + \beta_3)\%$ change in *fuel economy* associated with a one-unit change in daily ambient temperature. For daily ambient temperatures below the base temperature, the results of this log-linear specification can be interpreted as the $100 \times (\beta_2)\%$ change in *fuel economy* associated with a one-unit change in daily ambient temperature.

iii. Range by Ambient Temperature

This above statistical model was also applied to estimated vehicle range data for the responding agencies. Due to the high cost of buses, many transit agencies are keenly interested in the range of zero emission buses, one reason being that they want to be able to replace conventional diesel vehicles on a 1:1 basis. Low gallons per mile numbers may not be as important if the range is such that multiple buses are required to cover the routes. The effects that weather changes may have on range may be highly relevant to transit planning. The following assumptions were made in estimating vehicle range:

- Usable hydrogen for calculating vehicle range for fuel cell buses is based on 95% tank capacity.[24]
- Usable energy for calculating vehicle range for battery electric buses is based on 80% nameplate battery capacity.[25]
- Vehicle range is the quotient of usable energy and vehicle efficiency, where

$$Range = Usable\ energy\ (in\ kg\ or\ kWh) \div Vehicle\ efficiency\ \left(in\ \frac{kg}{mile}\ or\ \frac{kWh}{mile}\right)$$ [26]

Table 2 below includes the estimated usable capacity for the zero emission bus models of the responding agencies given the above assumptions.

[23] "Best fitting" models were those that minimized the Bayes Information Criterion (BIC).
[24] *See* NREL's *Fuel Cell Buses in U.S. Transit Fleets: Current Status 2018.* https://www.nrel.gov/docs/fy19osti/72208.pdf
[25] *See* https://www.proterra.com/understanding-range-clarity-behind-the-calculations/
[26] *Id.*

Table 2. Estimated Capacity for Bus Models Used in Study

Agency	Bus Make and Model	Tank/Nameplate Capacity	Usable Capacity
DDOT	Proterra Catalyst E2, 40-foot[27]	440 kWh	352 kWh
Duluth	Proterra Catalyst E2, 40-foot	440 kWh	352 kWh
Seneca	Proterra EcoRide BE35[28]	88 kWh	70.4 kWh
WRTA	Proterra EcoRide BE35	88 kWh	70.4 kWh
SARTA	ElDorado Axess FC	50 kg	47.5 kg
BC Transit	New Flyer H40LFR	56 kg	53.2 kg
Ruter	Van Hool A330 FC	35 kg	33.25
SunLine[29]	ElDorado Axess FC and New Flyer Xcelsior (XHE40)	50 kg and 37.5kg	47.5 kg and 35.6 kg

3. Results and Analysis

The following are the results of the analyses undertaken. The coefficient of variation (COV) for fuel economy was calculated directly from the data for BEBs and FCEBs, both above and below a given agency's base temperature. Table 3 suggests that fuel economy for BEBs was *less* variable than FCEBs above base temperatures (median COV of 10.7% for BEBs compared to median COV of 17.6% for FCEBs), but *more* variable below base temperatures (median COV of 21.2% for BEBs compared to median COV of 16.7% for FCEBs). As a point of comparison, the COV of dge/100 miles fuel economy for Class 8 heavy duty diesel trucks is around 11.6% under national default temperature conditions according to fleet data collected by the U.S. Environmental Protection Agency as part of its SmartWay Truck Carrier Partner Program.[30] Fuel economy COVs for transit vehicles could potentially be higher given regional variation in HVAC demands for maintaining a comfortable cabin. As explained in Appendix B, the number of observations per agency—both above and below its corresponding base temperature—was deemed sufficiently large for stable COV measurement.

[27] Agencies deploying BEBs with the larger 440 kWh battery have been able to operate with depot charging only, forgoing the need for on-route charging. *See* https://www.transit.dot.gov/sites/fta.dot.gov/files/docs/FTA%20CTE%20Low-No%20ZEB%20Presentation_FINAL.pdf. *See also* https://cte.tv/case_studies/duluth-transit-authority/

[28] Agencies deploying BEBs with the smaller 88 kWh battery have operated with two on-route chargers to go along with depot charging. *See* https://www.nap.edu/catalog/25061/battery-electric-buses-state-of-the-practice. *See also* http://www.umasstransportationcenter.org/Document.asp?DocID=495

[29] Sunline has two different models for its fleet of FCEBs. However, the data were merged for this study, since this difference did not appear to materially impact change in range due to change in temperature.

[30] *See* p. 44 of https://www.epa.gov/sites/production/files/2019-01/documents/420b19003.pdf. Note that Class 8 Trucks do not have the same issues with cabin climate control and opening of doors that transit has.

Table 3. Coefficient of Variation for Fuel Economy for Buses

Coefficient of Variation for Fuel Economy where:	Transit Agency									
	BEBs					FCEBs				
	DDOT	Duluth	Seneca	WRTA	Median	SARTA	Ruter	BC Transit	SunLine	Median
Ambient temp. is less than/equal to base temp.	35.2%	16.5%	7.7%	25.9%	21.2%	12.5%	33.2%	15.1%	18.3%	16.7%
Ambient temp. is greater than base temp.	24.6%	5.6%	6.2%	15.1%	10.7%	13.4%	30.6%	10.4%	21.7%	17.6%

Research done at MIT on targeted Corporate Average Fuel Economy (CAFE) standards suggests that when comparing the fuel economy COV of two vehicle groups, a difference of 4-7% represents a significant increase in uncertainty for the vehicle group with the higher value for this metric.[31] Table 3 indicates a higher degree of fuel economy uncertainty for the FCEBs during higher temperatures (difference in median COV of 4.5%) and a higher degree of fuel economy uncertainty for the BEBs during colder temperatures (difference in median COV of 6.9%). Given that vehicle range is a function of fuel economy, the planning implications of these findings are that it seems more difficult to know with certainty the number of miles a FCEB will be able to run during higher temperatures and the number of miles a BEB will be able to run during lower temperatures.

Tables 4 and 5 below set forth the effects on efficiency, based upon mpdge/100 miles, due to changes in temperature**.** The regression model specified in the Methodology section was fit to the data using the method of ordinary least squares (OLS). The rightward columns highlighted in red and blue show the results of this analysis.[32] For higher temperatures (i.e. above the base temperature) the red column describes the percent change in fuel consumption associated with a 1° F increase in ambient temperature. For lower temperatures (i.e. at or below the base temperature) the blue column describes the percent change in fuel consumption associated with a 1° F decrease in ambient temperature.

[31] *See* http://web.mit.edu/sloan-auto-lab/research/beforeh2/files/CAFE_2012.pdf

[32] Heteroskedasticity- and autocorrelation-consistent (HAC) standard errors were used in fitting the model to the data. Subsequent residual analysis indicated neither departures from normality nor the violation of stationarity. On average, the model explained approximately 50% of the variability in fuel economy and range as indicated by adjusted R-squared statistics.

While not seen here, the results of applying the model to data for vehicle range mirror the findings for fuel economy, with the percent change being a decrease rather than an increase.[33] For example, during higher temperatures a 1° F increase in ambient temperature for SARTA's fuel cell buses was associated with a 0.90% increase in fuel consumption and a 0.90% *decrease* in range.

Table 4. Association of Fuel Efficiency and Temperature Change for FCEBs

Transit Agency	Daily Average Temp. Range (F)	Base Temp. (F)	Miles Traveled Above Base Temp.	Miles Traveled at or Below Base Temp.	Above the base temp., a 1° F increase in ambient temperature was associated with the following change in dge-per-100-miles fuel consumption:	At or below the base temp., a 1° F decrease in ambient temperature was associated with the following change in dge-per-100-miles fuel consumption:
SARTA	1.0 – 83.0	59.8	118,941	189,152	*0.90% increase	*0.57% increase
Ruter	11.3 – 77.7	52.8	96,054	174,086	*0.14% increase	*1.28% increase
BC Transit	21.2 – 75.4	59.5	308,747	1,361,827	*0.29% increase	*1.16% increase
SunLine	37.0 – 93.4	61.3	138,682	148,916	*0.70% increase	Insufficient number of days below Base Temp.
SARTA Diesel Fleet	1.0 – 83.0	59.8	660,827	328,844	*0.68% increase	*0.17% increase

*Statistically significant at the 5% level.

[33] Any difference in the magnitudes of estimated percent change in fuel efficiency and range was at the 0.01% decimal place.

Table 5. Effects on Fuel Efficiency and Temperature Change for BEBs

Transit Agency	Daily Average Temp. Range (F)	Base Temp. (F)	Miles Traveled Above Base Temp.	Miles Traveled at or Below Base Temp.	Above the base temp., a 1° F increase in ambient temperature was associated with the following change in dge-per-100-miles fuel consumption:	At or below the base temp., a 1° F decrease in ambient temperature was associated with the following change in dge-per-100-miles fuel consumption:
DDOT	13.5 – 86.5	64.3	102,902	121,494	*1.15% increase	*2.10% increase
DTA	-23.0 – 68.0	54.0	12,083	65,748	Insufficient number of days above Base Temp.	0.81% increase
Seneca	15.0 – 84.0	65.0	364,369	485,994	*0.71% increase	*0.33% increase
WRTA	0.0 – 81.0	56.7	188,850	305,256	*1.46% increase	*1.51% increase

*Statistically significant at the 5% level.

As seen in tables 4 and 5, no agencies operating FCEBs saw fuel consumption increase more than 1% per 1-degree increase in temperature during warmer periods while two agencies operating BEBs saw a greater than 1% increase in fuel consumption during warmer days. For periods with colder temperatures, two BEB fleets and two FCEB fleets realized fuel consumption increases greater than 1% per 1-degree drop in temperature, with one of the BEB fleet's increase in consumption per degree decrease exceeding 2%. Given the relationship between fuel economy and vehicle range, the largest relative declines in average range during days of both higher and lower temperatures were among the BEBs.

An important question to raise, given the results in tables 4 and 5, is *how does this compare to conventional diesel buses?* Previous studies have indicated that seasonal differences in fuel economy may be less pronounced for diesel buses compared to alternative fuel buses. For example, a 2013 evaluation of diesel and hybrid-electric buses operated on the campus of Iowa State University found that while miles-per-gallon fuel efficiency was around 11% higher on average in spring versus both summer and winter for hybrid buses, diesel bus mpg was around 6% higher in spring compared to the other two seasons.[34] Data for SARTA—the only agency for

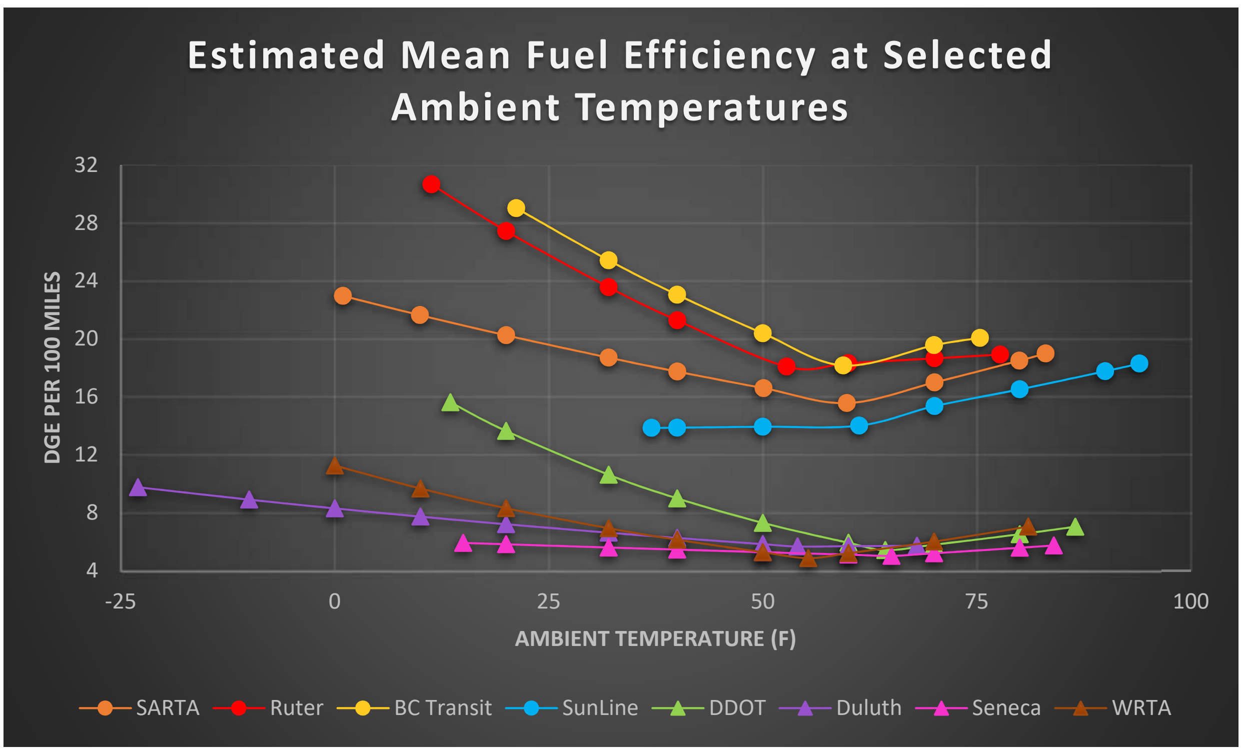
[34] Hallmark, S. L., Wang, B., Qiu, Y., & Sperry, R. (2013). Evaluation of in-use fuel economy for hybrid and regular transit buses. *Journal of Transportation Technologies*, *3*(01), 52.

which information on fuel economy for diesel vehicles was also obtained by the Study Team—suggest that fuel economy sensitivity to temperature change may indeed be higher for ZEBs than diesel buses. Applying the statistical model specified in the Methodology section to SARTA's diesel bus data resulted in an estimated relative increase in mean dge/100 miles fuel consumption of (a) 0.17% for every 1° Fahrenheit drop in ambient temperature below the region's base temperature, compared to 0.57% for the agency's FCEBs, and (b) 0.68% for every 1° Fahrenheit increase in ambient temperature above the region's base temperature, compared to 0.90% for the agency's FCEBs.

A. Association of Fuel Efficiency Decline to Change in Temperature

The following plots illustrate estimated mean fuel economy at various ambient temperatures that were derived by plugging these temperature values into the statistical model.

Figure 8. Fuel Efficiency Versus Temperature for Selected Transit Agencies



When grouped together by ZEB type, the increase in average dge/100 miles fuel consumption (i.e. a decline in fuel economy) going from a temperature interval of 50-60°F to 22-32°F was slightly greater for BEBs (32.1% increase) than for FCEBs (28.6% increase) when weighting by miles traveled below base temperature for the respective agencies, a difference of 3.5%.[35] Going

[35]Data for SunLine were not included for this comparison because no daily average temperatures were below freezing.

from a temperature interval of 50-60°F to 70-80°F, the increase in average dge/100 miles fuel consumption was minimally greater for FCEBs (6.6% increase) than for BEBs (6.4% increase), when weighting by miles traveled above base temperatures, a difference of 0.2%.

In addition to the point estimate of mean fuel efficiency seen in Figure 8, Appendix C illustrates fuel economy uncertainty for the transit agencies whose data was obtained by the Study Team. The plots show the range of all future fuel economy values that we would expect to fall within 1 and 2 standard deviations of the mean for days having a particular ambient temperature based on the variability in the underlying data. These value ranges correspond with prediction intervals that quantify the uncertainty (i.e. the expected spread) in fuel economy for new, individual observations.[36]

It is important to recognize that each of these buses has various configurations that may significantly impact fuel economy, especially as temperatures change. Some features, such as the bus body materials and other insulation strategies, can impact how efficiently a bus passenger cabin is kept warm or cool. Exploring these was beyond the scope of this analysis.

However, there are a few considerations worth noting. For instance, the Duluth Transit Authority (DTA) has a fuel-fired heater on its battery electric buses, which significantly reduces the electrical heating load in cold weather, and improves efficiency. The energy provided through this system was not included in this analysis, but this could explain why Duluth has a lower DGE per 100 miles at temperatures below freezing than other battery electric transit agencies do. This data also includes all days of operation in Duluth, but there have been modifications to its buses to reduce the heating load since deployment. The bulk of the data has the same heating control strategy, but some of the early data points may have had lower fuel economies than later data.

Additionally, in snowy or icy conditions, the DTA buses may experience a reduction in the energy captured during regenerative braking. If its BEBs detect slippery conditions, regenerative braking will be turned off until the bus comes to a complete stop. This can result in significantly reduced fuel economy in those conditions compared to a day with dry roads at the same temperature. These data points have been subsumed within the analysis, and cannot be separated out.

The only other data set that had information on energy captured during regenerative braking was the data provided by DDOT. There were no identified days with significant snow or ice that had a measurable impact on regenerative braking. However, there was a shift in the ratio of energy captured through regenerative braking to energy consumed by the vehicle powertrain midway through the data collection period. It is not clear what caused this shift. However, it did not appear to impact the fuel economy of the vehicles.

[36] For the distinction between predictions intervals and confidence intervals, *see* https://www.itl.nist.gov/div898/handbook/pmd/section1/pmd132.htm

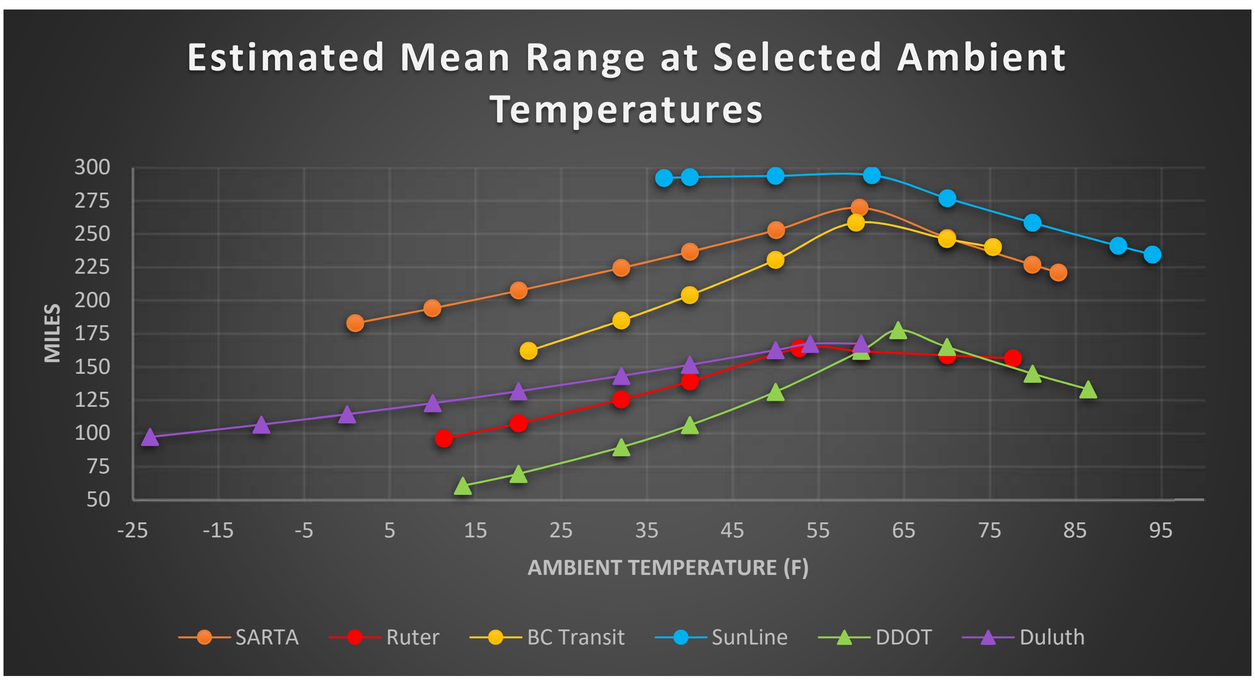
With respect to the hydrogen fuel cell electric buses, to our knowledge, none of these vehicle configurations captures the heat rejected from the fuel cell during operation. Future FCEBs may be able to use this heat to warm the passenger cabin, reducing electrical loads at extremely cold temperatures.

B. Association of Range Decline to Change in Temperature

Point and interval estimates of vehicle range at various ambient temperatures can be constructed by plugging in temperatures-of-interest into the statistical model. Ultimately, the relationship between range and temperature change may be the most important consideration for transit agencies in planning their zero-emission fleet technology. This is because extreme temperatures may affect bus range enough that it might require adding buses to the routes to ensure coverage. Figure 9 below looks at the association of range decline to change in temperature.

The Seneca and WRTA buses were removed from this analysis. The Seneca and WRTA buses have small batteries capable of high-powered charging. They are charged quickly on-route and would theoretically be capable of staying in service indefinitely. Their ranges will also be affected by temperature change, but they cannot be readily compared to the Duluth and DDOT buses, which are designed to complete their service on a single charge at the transit agency's facility. The Duluth and DDOT buses can also more readily be compared to the FCEBs.

Figure 9. Range Versus Temperature for Selected Transit Agencies



When grouped together by ZEB type, the decrease in average range going from a temperature interval of 50-60°F to 22-32°F was greater for BEBs (37.8% decrease) than for FCEBs (23.1%

decrease) when weighting by miles traveled below base temperature for the respective agencies, a difference of 14.7%.[37] A group comparison of changes in average range for increasing temperatures would have only included a single BEB fleet and was therefore not performed.

4. Conclusions and Future Work

This analysis shows that the fuel economy of electric drive buses may vary significantly with temperature. In planning zero emission fleet development strategy, it is important for transit agencies to understand how their zero-emission bus's performance may change with temperature. The effects of temperature change on range may be particularly important in planning fleet development, especially for transit agencies located in cold weather climates.

Range may be materially affected by extreme cold or heat. Agencies may have to acquire additional buses or infrastructure to maintain full service during cold weather conditions. This appears to be most relevant for battery electric buses, which tend to have a shorter range than fuel cell electric buses even in optimal weather conditions.

This study did not attempt to identify or establish causes for loss in efficiency, but rather only to note the association between the efficiency (or range) and the change in temperature. The most readily identifiable reason for loss of efficiency or range is from maintaining comfort in the bus cabins. However, there may be other reasons for efficiency loss relating to the nature of the battery or fuel cell system.

There are limitations to this study due to the nature of data set collected. Some data varied considerably, depending upon the transit agency and the equipment they used. As a result, transit agencies are cautioned to not simply assume that the models contained herein will accurately predict their own bus performance. The models are meant as a guide to understanding the association between extreme weather and performance.

Finally, more uniformly recorded data will need to be collected and studied to more fully understand the association of temperature change with performance. Refueling and recharging data should be recorded daily. As more zero emission buses are deployed, it will be easier to use statistical methods to analyze larger populations of data.

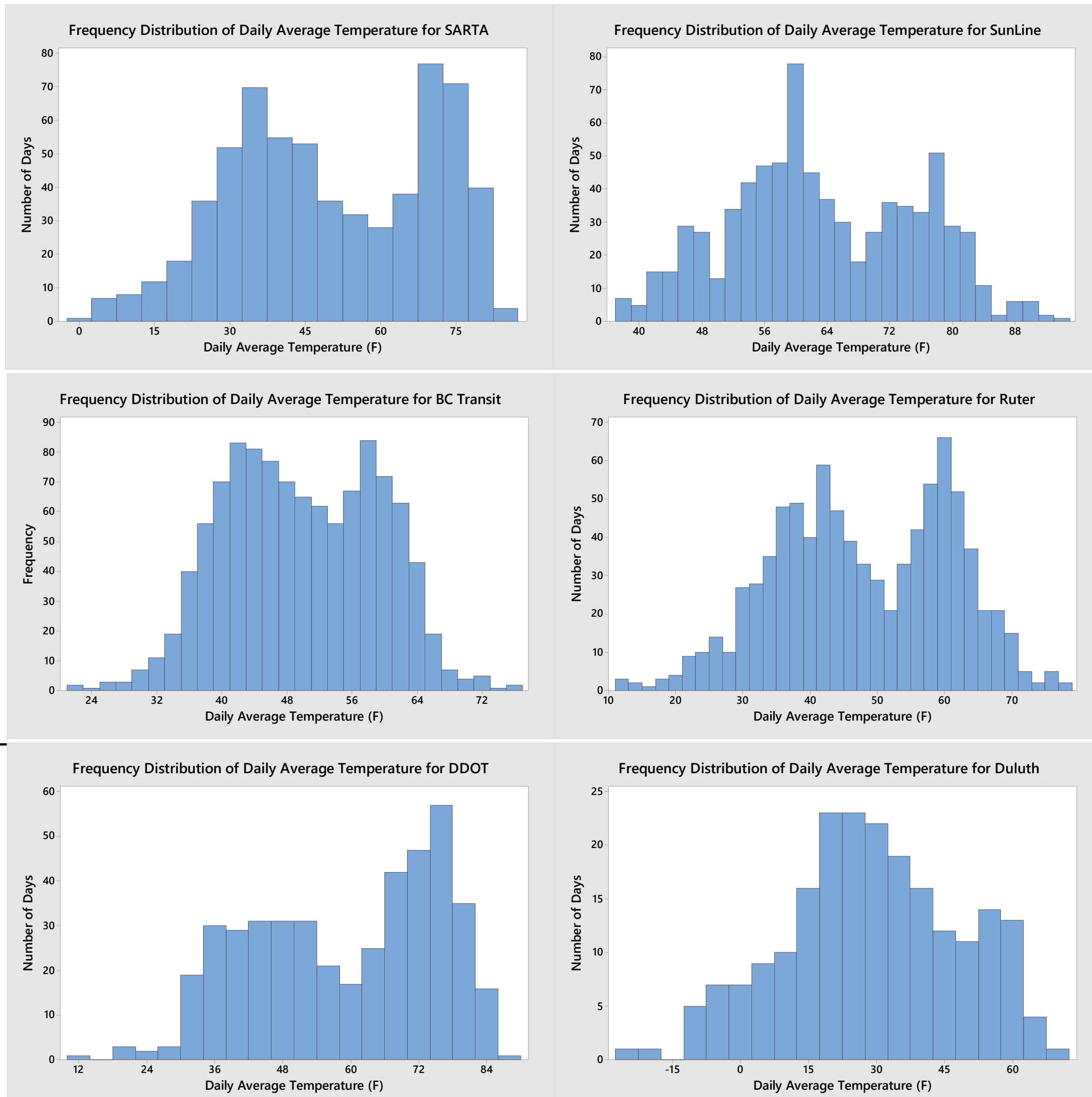
An area of future study will be to determine the financial consequences of the declines in fuel efficiency and vehicle range associated with temperature variability that were explored in this Study. It is not clear whether transit agencies are more sensitive to the operational costs incurred from worsening fuel economy or the capital expenditures resulting from vehicles with inadequate range. A proper life cycle cost analysis should be performed to better understand how the total cost of ZEB deployment is impacted by environmental risk factors. This would

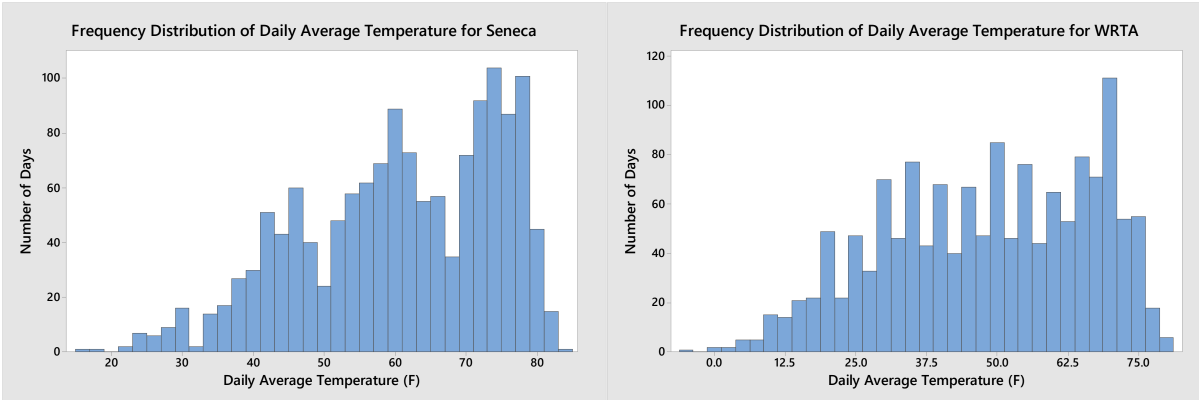
[37] Data for Seneca and WRTA were not included for this comparison given their limited range by design.

include identifying an appropriate planning horizon, which can be difficult to pinpoint in an industry where the state-of-the-art is evolving as rapidly as it is for zero emission transit vehicles.

Appendix A.

Figure 10. Frequency Distribution of Daily Mean Outdoor Temperature for Data Collection Period





Appendix B.

While the number of observations to calculate the coefficient of variation was not constant across agencies, there would seem to be enough data to reliably estimate this measure of uncertainty. For example, figures 11 and 12 below show the coefficient of variation for fuel economy plotted against the number of observations included in iteratively increasing random samples of *above/below base temperature* data subsets for SARTA. In both cases, the coefficient of variation for fuel economy appears to stabilize before reaching the sample size limit. The fuel economy coefficients of variation for all other agencies exhibited similar stabilizing behavior, suggesting that the varying sample sizes were nonetheless sufficiently large.

Figure 11. COV vs. Sample Size for Below-Base Temperatures

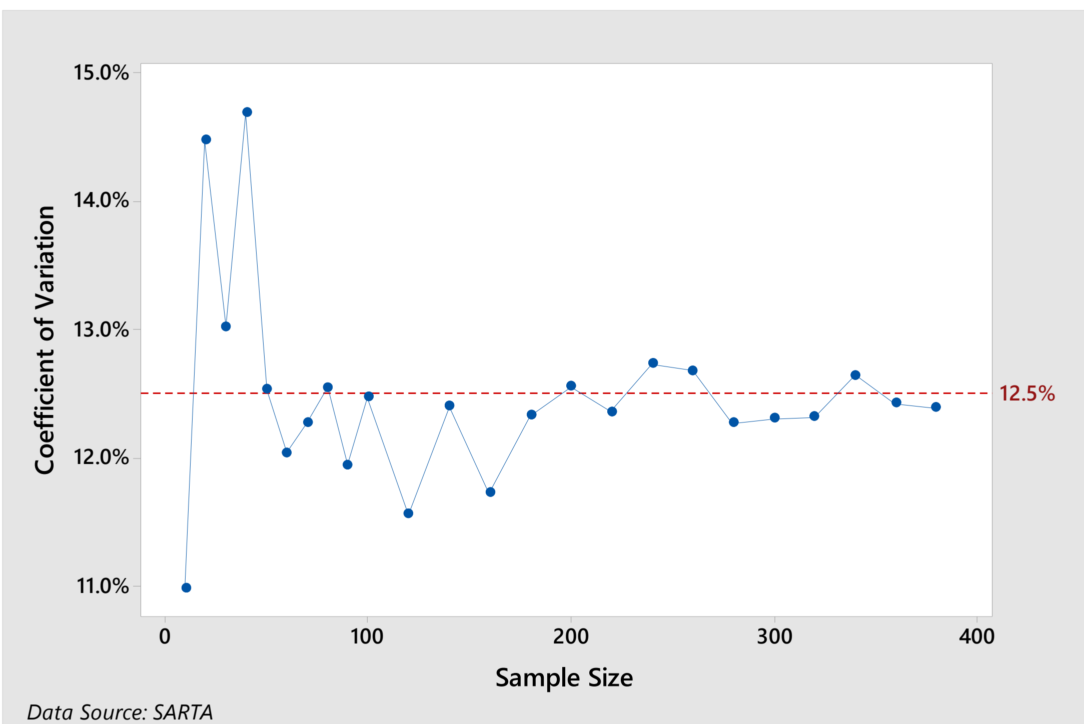
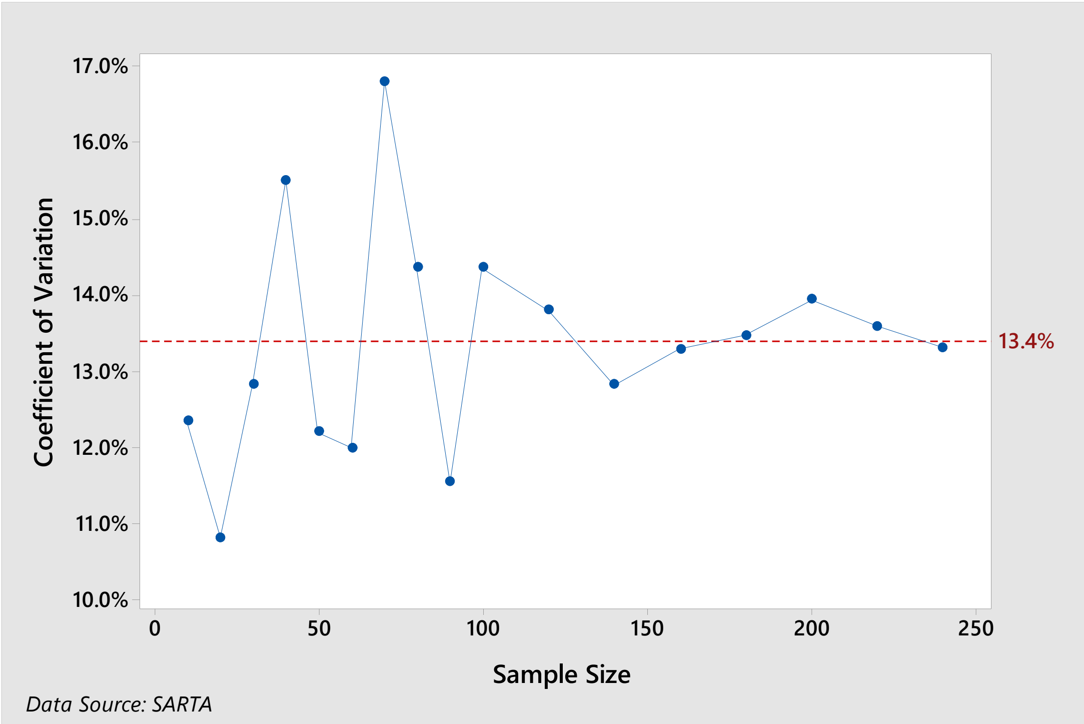
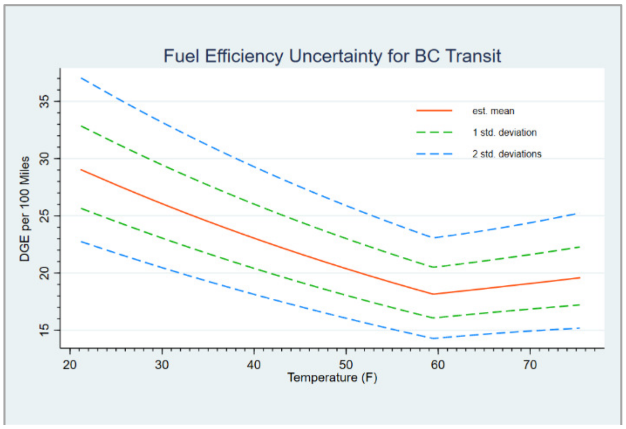
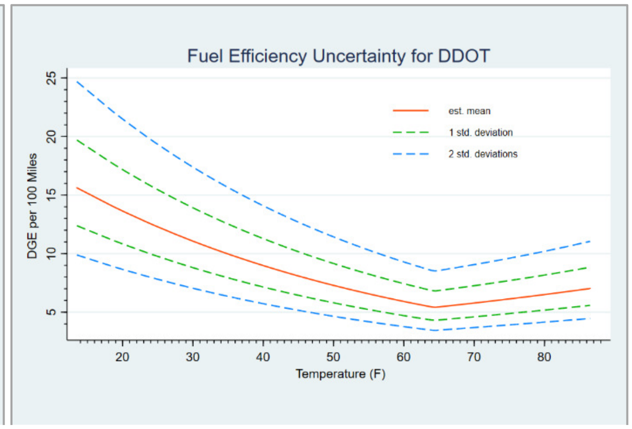


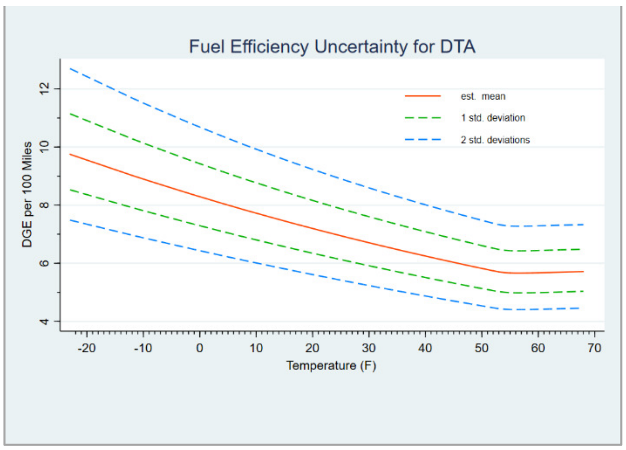
Figure 12. COV vs. Sample Size for Above-Base Temperatures

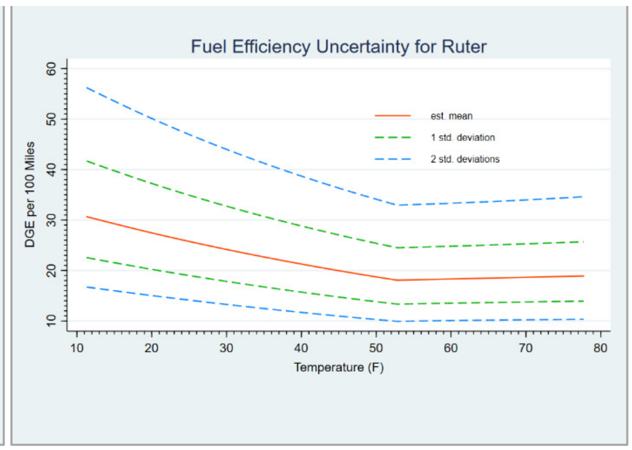


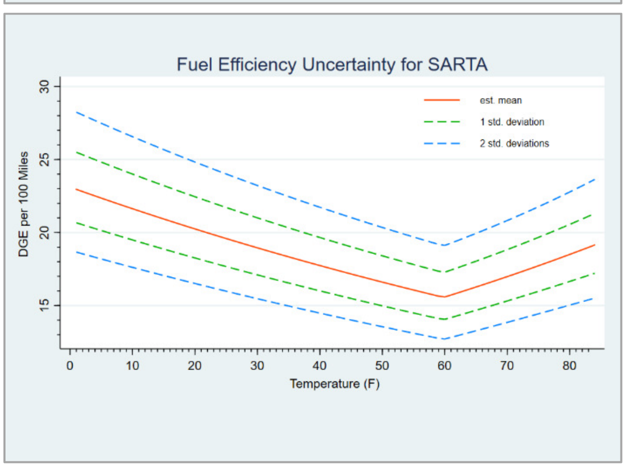
Appendix C.

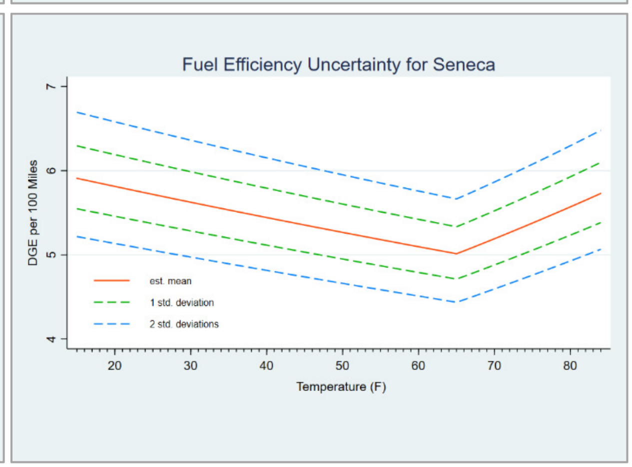

Fuel Efficiency Uncertainty for BC Transit
est. mean
1 std. deviation
2 std. deviations
DGE per 100 Miles
15 20 25 30 35
20 30 40 50 60 70
Temperature (F)

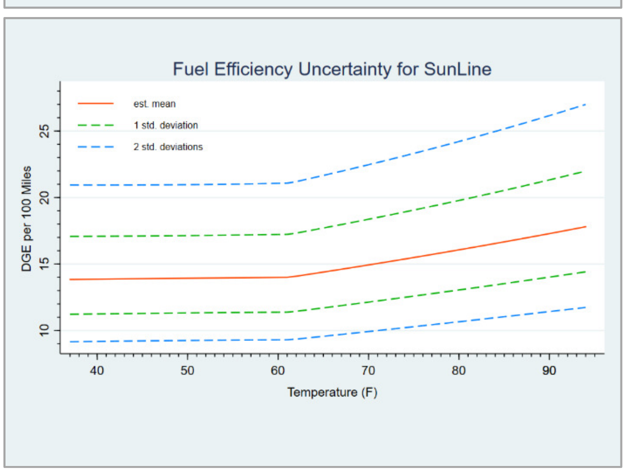

Fuel Efficiency Uncertainty for DDOT
est. mean
1 std. deviation
2 std. deviations
DGE per 100 Miles
5 10 15 20 25
20 30 40 50 60 70 80
Temperature (F)

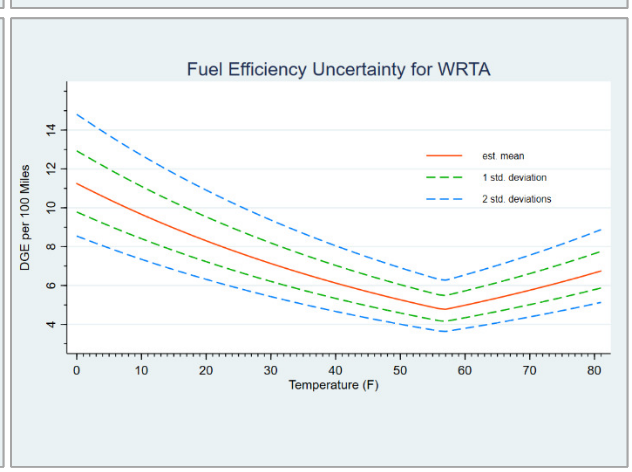

Fuel Efficiency Uncertainty for DTA
est. mean
1 std. deviation
2 std. deviations
DGE per 100 Miles
4 6 8 10 12
-20 -10 0 10 20 30 40 50 60 70
Temperature (F)


Fuel Efficiency Uncertainty for Ruter
est. mean
1 std. deviation
2 std. deviations
DGE per 100 Miles
10 20 30 40 50 60
10 20 30 40 50 60 70 80
Temperature (F)


Fuel Efficiency Uncertainty for SARTA
est. mean
1 std. deviation
2 std. deviations
DGE per 100 Miles
15 20 25 30
0 10 20 30 40 50 60 70 80
Temperature (F)


Fuel Efficiency Uncertainty for Seneca
est. mean
1 std. deviation
2 std. deviations
DGE per 100 Miles
4 5 6 7
20 30 40 50 60 70 80
Temperature (F)


Fuel Efficiency Uncertainty for SunLine
est. mean
1 std. deviation
2 std. deviations
DGE per 100 Miles
10 15 20 25
40 50 60 70 80 90
Temperature (F)


Fuel Efficiency Uncertainty for WRTA
est. mean
1 std. deviation
2 std. deviations
DGE per 100 Miles
4 6 8 10 12 14
0 10 20 30 40 50 60 70 80
Temperature (F)