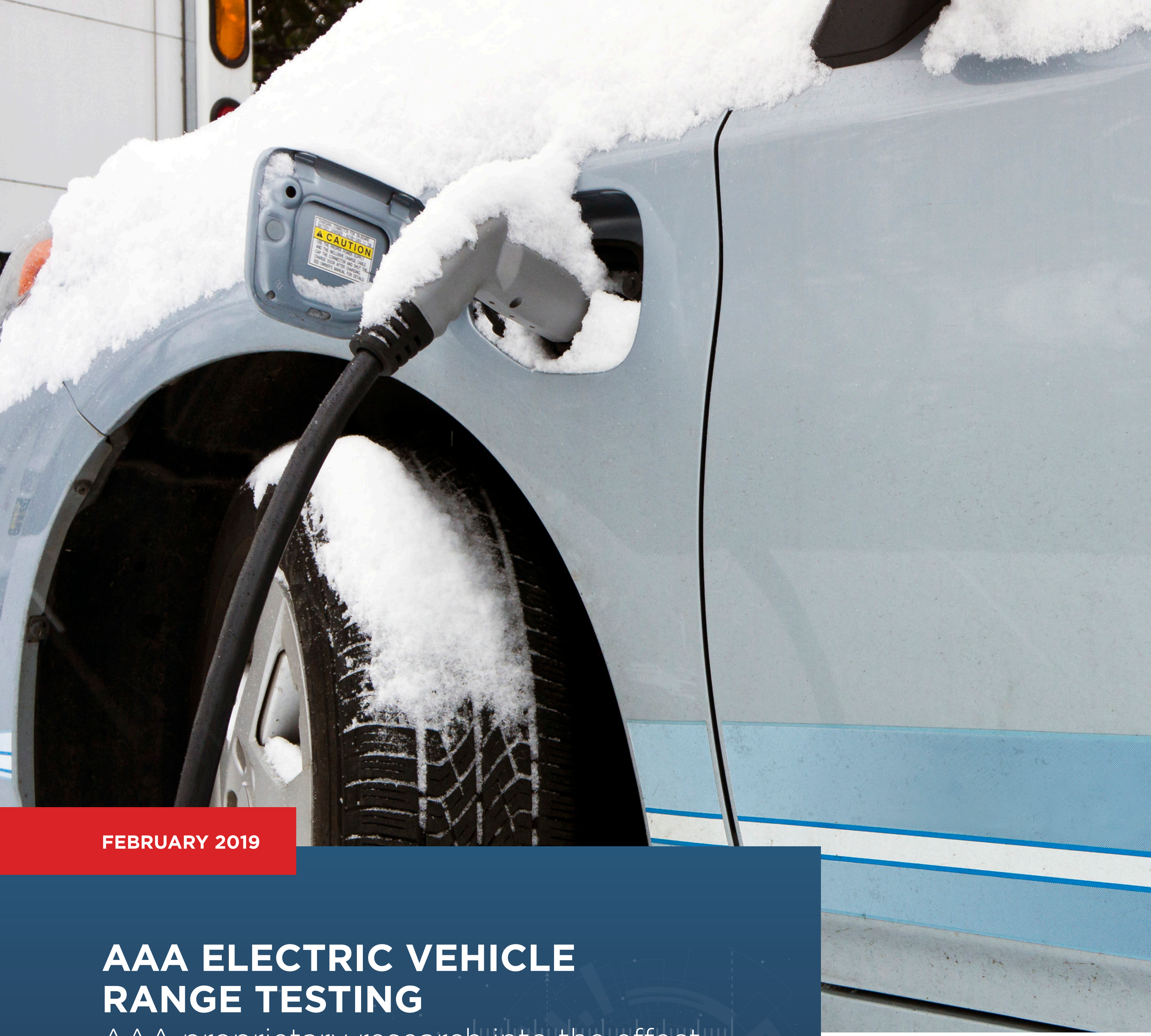

FEBRUARY 2019

AAA ELECTRIC VEHICLE RANGE TESTING

AAA proprietary research into the effect of ambient temperature and HVAC use on driving range and MPGe

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Abstract

AAA conducted primary research to understand the effects of ambient temperature on the range and equivalent fuel economy of five (5) battery electric vehicles (BEVs) sold throughout the United States. Testing was performed according to guidelines established in SAE International[1] standard J1634, Battery Electric Vehicle Energy Consumption and Range Test Procedure. Evaluated ambient temperatures included 20°F, 75°F and 95°F.

For hot and cold temperatures, the effect of various HVAC systems on battery range and equivalent fuel economy was evaluated. Additionally, the cost of driving 1000 miles in various environments with and without the HVAC system engaged was quantified.

Research Questions:

1. How do driving range estimates of the tested BEVs vary with respect to ambient temperature?
    a. Evaluated at 20°F
    b. Evaluated at 75°F
    c. Evaluated at 95°F
2. What effect does heating, ventilation, and air conditioning (HVAC) have on the driving range of the tested BEVs?
    a. Evaluated at 20°F
    b. Evaluated at 95°F
3. Based on real-world driving range estimations, what is the monetary cost of driving in various environments with and without the HVAC system engaged?

Key Findings:

1. In isolation, hot and cold ambient temperatures resulted in modest reductions of driving range and equivalent fuel economy. Driving range and equivalent fuel economy reductions slightly differ due to the temperature dependency of both the recharge allocation factor (RAF) and battery discharge capacity.
    a. On average, an ambient temperature of 20°F resulted in a 12 percent decrease of combined driving range and an 8 percent decrease of combined equivalent fuel economy (when compared to testing conducted at 75°F).
    b. On average, an ambient temperature of 95°F resulted in a 4 percent decrease of combined driving range and a 5 percent decrease of combined equivalent fuel economy (when compared to testing conducted at 75°F).
2. HVAC use results in significant reductions of driving range and equivalent fuel economy.
    a. On average, HVAC use at 20°F resulted in a 41 percent decrease of combined driving range and a 39 percent decrease of combined equivalent fuel economy (when compared to testing conducted at 75°F).

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[1] Society of Automotive Engineers

    b. On average, an ambient temperature of 95°F resulted in a 17 percent decrease of both combined driving range and combined equivalent fuel economy (when compared to testing conducted at 75°F).

3. Depending on ambient temperature, HVAC use results in a significant monetary cost increase.

Contents

1 Introduction

While the commercial use of battery-powered cars can be traced as far back as 1897, when New York City had electric taxis, the modern era of electric cars arguably began in 2008 with the introduction of the Tesla Roadster. Today, more than a dozen electric vehicle models are available from a variety of manufacturers, with more on the way.

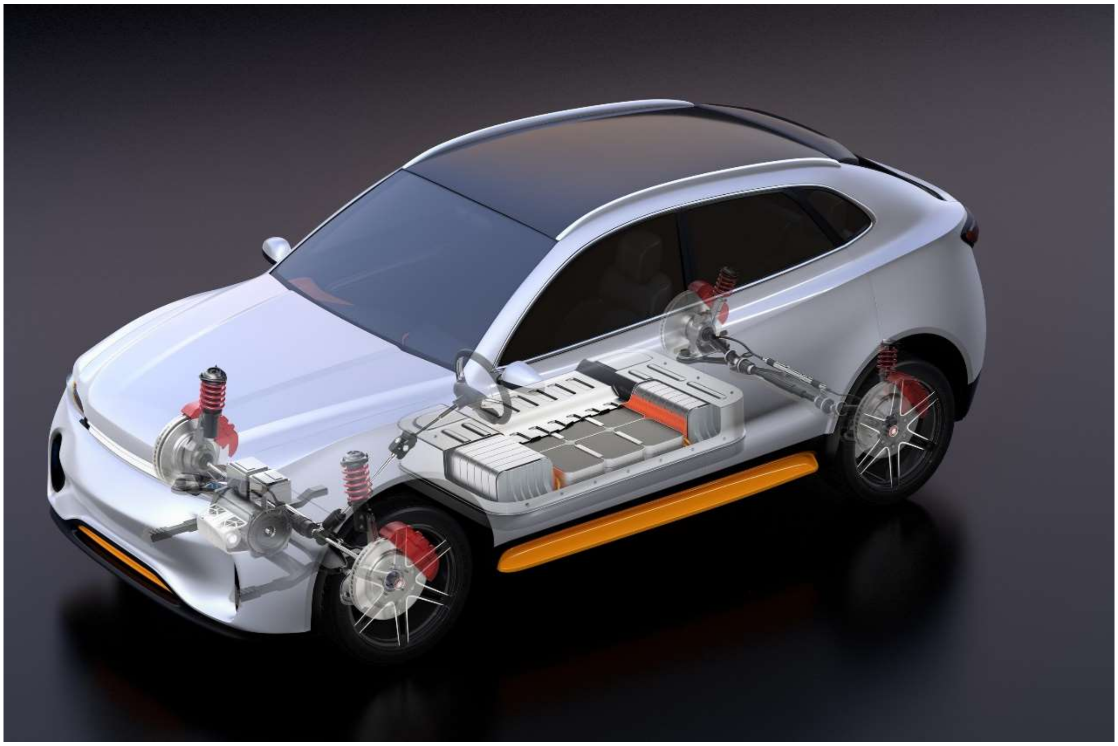


Figure 1: Visual representation of typical EV architecture Image Source: AAA

Electric vehicles (EVs) are energy efficient, environmentally friendly and reduce dependence on imported oil because they use domestically produced energy. In addition, automobiles propelled by electric motors generally offer smooth operation, good standing-start acceleration, and require less maintenance than vehicles with internal combustion engines (ICEs). However, three areas where electric vehicles currently suffer in comparison to their ICE counterparts are driving range, recharging infrastructure, and recharging (refueling) time. Fortunately, EVs are constantly improving in terms of battery capacity, safety, recharge time and public charging infrastructure.

To provide information on real-world driving range and operational costs, AAA evaluated five (5) commonly available BEVs available for sale throughout the United States. For each vehicle, the driving range and equivalent fuel economy at three different temperatures was measured; for hot and cold conditions, the driving range and equivalent fuel economy with and without HVAC use was compared.

2 Background

Most motorists today are familiar with hybrid automobiles that achieve improved fuel efficiency by using an electric motor to help the ICE propel the car. The motor receives power from a modestly sized battery that is automatically recharged during vehicle operation using a generator driven by the car's ICE.

In contrast, the vehicles evaluated in this research employ larger batteries that can be charged by plugging the car into an external electrical outlet or charging unit. Energy stored in the battery is then used to power an electric motor that can propel the car for a number of miles without the use of an ICE.

2.1 Battery Technology

Most discussions of electric vehicle batteries focus on the battery that propels the car down the road. However, modern EVs normally have *two* battery systems, a "starter" battery and a "traction" battery, both of which play important roles in vehicle operation.

The starter battery in an EV is a 12-volt, lead-acid unit similar to that in a conventional car, although it is generally smaller in both size and capacity. The starter battery powers the car's keyless entry and security systems, maintains various electronic "memories", and provides the energy needed to "wake up" the EV's computer control systems when the ignition is turned on. The starter battery also powers a large relay that connects the traction battery with the vehicle powertrain to enable electric operation.

At the heart of every EV is a high-voltage traction battery pack that powers the electric motor that propels the car down the road. The traction battery also charges the starter battery and, depending on the vehicle, powers some or all of the vehicle electrical system, including high-load accessories such as the air conditioning, headlamps and heater.

Unlike the starter battery, the EV traction battery is a lithium-ion design that has much greater energy density, albeit at a significantly higher cost. Automakers warranty their EV traction batteries for at least 8 years or 100,000 miles, but after that period, battery replacement is expected to cost from $2,500 to over $10,000, depending on the vehicle.

Every traction battery pack is made up of dozens of smaller individual cells whose configuration varies with the automaker and battery supplier. Some are cylindrical like common household "C" or "D" cells, while others are flat and rectangular – similar in shape to a small notebook computer. The individual cells are typically combined into assemblies that are then installed in a special housing and connected using series and/or parallel circuits to supply the high power (up to 500 volts) necessary for efficient EV operation.

The nominal rating of an EV battery pack, such as 24 kilowatt hour (kWh), represents the amount of energy available for vehicle use. The total battery capacity is actually somewhat greater, but for maximum life, a lithium-ion battery pack should not be deeply discharged or charged to its total design capacity. Modern EVs take these restrictions into account and typically limit the battery's state of charge to between 20 and 90 percent of its total capacity under most operating conditions. When discussing EV battery states of charge, common expressions such as “empty” or “fully charged” refer only to the portion of a battery’s capacity that is available for normal use, not its entire energy potential.

2.2 Battery Chemistry

In order to facilitate the development and uptake of EVs, traction batteries with high specific energy, high current capability, long cycling life and low production costs are essential. To meet these requirements, Li-ion batteries are currently utilized within EVs. This chemistry has an energy density of about 150 Wh/kg, which currently exceeds any competing chemistries by at least a factor of 2.5 [1]. The voltage of a Li-ion cell will slightly vary with respect to specific design architecture but is usually on the order of 4 V. Li-ion batteries utilized for EVs typically contain a graphite anode, a lithium cobalt oxide cathode and a liquid carbonate electrolyte with a dissolved lithium salt such as lithium hexaflorophosphate [2]. Nickel and manganese are other cathode materials commonly incorporated by battery designers.

During discharge, lithium ions move from the anode to the cathode in a reversible intercalation process that is accompanied by movement of electrons from the anode to the cathode via an external circuit. During charging, lithium ions at the cathode diffuse back to the anode along with the movement of electrons from cathode to anode via external circuit.

Current Li-ion batteries contain numerous shortcomings that must be addressed to enable the eventual transition away from ICE vehicles. These barriers include stability, cycle life, cost and operational temperature range [2]. To solve these challenges, breakthroughs in anode and cathode materials as well as electrolyte compositions (such as solid-state materials) are required.

Many avenues of research pertaining to traction batteries are underway. The following descriptions of selected research topics are intended to provide a general overview of the state of the field. As these research initiatives are currently in preliminary stages, it is uncertain if tangible results will eventually lead to feasible deployment within production vehicles.

One of the most promising areas of research involves the utilization of ionic liquids (ILs) as a Li-ion battery electrolyte [3]. An ionic liquid is a molten salt at low to moderate temperatures. These highly concentrated electrolytes are typically composed of large organic cations and anions with a high degree of delocalized charge. The main benefit of ionic liquid electrolytes relates to their non-flammability and thermal stability up to temperatures of 300-400 °C. Numerous publications describe experimental and theoretical studies pertaining to ILs and their possible application within advanced Li-ion batteries and other theoretical battery chemistries.

The long-term development of traction batteries will involve battery chemistries besides Li-ion [4]. Li-air chemistry is one possible alternative to conventional Li-ion designs. Li-air batteries utilize atmospheric oxygen as the oxidizing agent; as a result, they can be significantly lighter than Li-ion designs. Additionally, the theoretical specific energy of a Li-air battery is comparable to gasoline (~46.4 MJ/kg). Significant obstacles towards the commercialization of Li-air batteries include the insolubility of discharge products within the pores of electrodes causing premature termination of energy transfer and the inherent incompatibility of lithium and water vapor within the environment. Lithium-sulfur is another promising battery chemistry for future traction batteries due to its high theoretical specific energy of roughly 13.4 MJ/kg. Like Li-air chemistry, there are significant hurdles that continue to impede development including corrosion of the lithium anode by dissolved polysulphides produced during cell discharge and low conductivity of the sulfur-based cathode.

Significant investments by governments, academia and industry to support research and development programs have led to many promising developments within battery chemistries previously described. Collaboration will be essential for the development of next generation traction batteries that will ultimately enable the widespread adoption of EVs.

2.3 EV Driving Range

The driving range of any EV is determined by two factors, the capacity of its fully-charged battery pack and the efficiency of its electric powertrain. With most EVs, one kWh of electrical energy from the battery pack will provide between two to four miles of driving range. The EPA publishes range estimates for all EVs, but real world results can, and do, vary based on several factors:

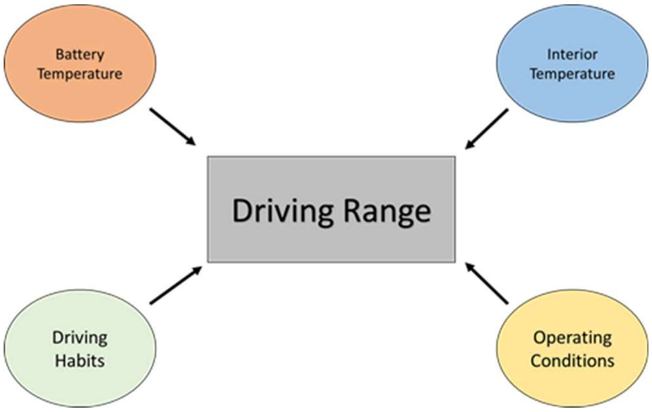


Figure 2: Contributing factors to EV driving range Image Source: AAA

- Battery temperature – for most efficient operation, an EV's battery pack likes to be kept within a certain temperature range. Depending on the vehicle, operating conditions and ambient air temperature, some of the available power may be required to heat or cool the battery when the car is not plugged into the grid.
- Interior temperature – people prefer to keep the interior of their vehicles within a comfortable temperature range as well. With an EV, this may mean using electric air conditioning or heating systems that can draw significant amounts of battery power – with an accompanying reduction in driving range. To reduce battery loads, the interiors of many EVs can be "pre-conditioned" using grid power for heating or cooling before the car is placed in service.
- Driving habits – in any car, gasoline or electric, the faster and more aggressively it's driven, the quicker the vehicle's energy supply will become depleted. With EVs, moderate acceleration and braking will provide maximum operating range.
- Operating conditions – EVs typically get better "mileage" in stop-and-go city driving, where frequent regenerative braking helps recharge the battery, than they do in sustained freeway

operation. Naturally, the load on the vehicle also influences its range. For example, an EV will have a much shorter range climbing a mountain than it would coasting down the other side.

EVs operating on battery power use no gasoline, so to help quantify the efficiency of electric vehicles the U.S. Environmental Protection Agency (EPA) created a Miles Per Gallon Equivalent (MPGe) rating system. MPGe is similar to normal mpg, but instead of representing the number of miles a vehicle can travel per gallon of gasoline, MPGe represents how many miles an EV can travel using the same amount of energy as that contained in a gallon of gasoline. Currently, the EPA assumes that one gallon of gasoline contains 33,705 Watt hours for fuel economy labeling purposes. Within this work, the terms "MPGe" and "equivalent fuel economy" are used interchangeably and refer to the same measurement.

2.4 EV Charging

EV charging is the equivalent of filling the fuel tank on a gasoline-powered car and, from a driver's perspective, the process is not all that different. However, instead of a fuel hose with a nozzle that fits into a fuel filler opening, EV charging employs a power cable with a special connector that plugs into a matching socket on the vehicle. Similarly, just as a gasoline pump shuts off automatically when the tank is full, EV charging equipment ends the charging process when the battery reaches its maximum rated storage capacity.

The hardware used to charge EVs is collectively referred to as Electric Vehicle Supply Equipment (EVSE). This includes the charging station, cables, cable connectors and vehicle sockets. All modern EVs can be charged using alternating current (AC) electricity and some can be charged with direct current (DC) electricity as well. For brevity, only AC charging will be discussed in this work.

The majority of EVs today are routinely charged using AC from a wall socket (120V or 240V) at home. However, since batteries can only store direct-current (DC) electricity, household AC must be converted to DC before it can be used to charge an EV. The component that does this conversion is called an on-board charger.

2.4.1 AC Level 1 Charging

AC Level 1 charging is the simplest, but slowest, method of charging an EV. Using a standard 120-volt outlet and a dedicated charging cable that comes with the car, AC Level 1 charging can provide the battery with 1.4 kW (15-amp circuit) of power per hour – the rough equivalent of three to five miles of driving range per hour (some level 1 chargers can provide 1.9 kW on a 20-amp circuit). AC Level 1 charging rates are limited by the amount of electrical power available at the wall outlet, not the capacity of the EV's on-board charger.

For a typical commuter who travels 40 miles a day, AC Level 1 charging can fully restore the battery overnight in 8-13 hours, depending on the current rating of the outlet being used. However, higher levels of battery discharge require proportionately longer charging times, and EV owners who drive more than 40 miles per day, or need to operate their vehicle over a time span of more than 12 hours each day, may find AC Level 1 charging is impractical given their driving habits.

2.4.2 AC Level 2 Charging

AC Level 2 charging provides more rapid EV charging, but calls for a dedicated 240-volt circuit similar to that of an electric clothes dryer, electric stove/oven or arc welder. It also requires a special charging station in one's garage, carport or driveway at a cost of $200 to $1,500 plus installation. By doubling available voltage and increasing current flow to as much as 80 amps (dependent on the vehicle), AC Level 2 charging can deliver up to 19.2 kW of power per hour to an EV battery. However, this maximum charge rate is rarely achieved in the real world because the AC-to-DC conversion ability of the EV's on-board charger becomes a limiting factor.

The installation cost will vary depending on the configuration of the home, its electrical circuitry, local code requirements and the type of equipment installed. A licensed electrical contractor should be consulted for an estimate. Installation expenses may be offset by a federal tax credit equal to 50 percent of the cost, with a $2,000 maximum per charger installed. Certain states also provide tax benefits, and some utility companies offer rebates and incentives on EV charging units.

2.5 EV Charging Costs

Just as gasoline prices vary with location, station, season, fuel grade and other factors, the price of electricity also spans a broad range. General information on electricity costs can be obtained by visiting the U.S. Energy Information Administration web site and searching for "State Electricity Profiles." But, any consumer considering the purchase of an EV should first contact their local utility company and determine how at-home charging will impact their monthly bill.

In many areas, utilities offer lower rates and encourage EV charging at night when demands on the power grid are lower and excess generating capability is available. Nighttime EV charging also helps minimize the need for utilities to purchase power from other areas if peak demand exceeds local generating capacity during the day.

Regardless of the rate plan available, it is important to understand how it works. Many plans charge a flat price per kWh, although the rate will often vary with season or time of day. Some plans employ *declining* rate blocks – the more electricity you use, the cheaper it gets. Under this type of plan, extra electricity used for EV charging gets billed at lower rates. However, other plans employ *inclining* rate blocks – the more electricity you use the costlier it gets. Under this type of plan, additional energy consumed for EV charging becomes more expensive.

Where special rate plans are available for EV charging, it is common for the utility company to require proof of EV ownership. In addition, some special rate programs may require a separate meter to measure the electricity used for EV charging.

2.5.1 Cost Calculation

Electricity is a very affordable way to power a car, and generally costs quite a bit less than gasoline or diesel fuel on a Miles Per Gallon Equivalent (MPGe) basis. Total charging costs will vary with the price of fuel, the amount paid for electricity and the efficiency of the EV as measured in miles per kWh. Efficiency is affected by differences in vehicle design, driving conditions and driver habits.

Here is a sample calculation of the energy costs to drive 1,000 miles per month in an EV versus a gasoline-powered conventional car. It is important to note that the following calculations only account for the base electrical rate; additional taxes and surcharges will vary depending on the municipality and region. These numbers are based on an EV that can travel 3 miles per kWh, on typical base electrical rates and on gasoline prices as of mid-2018:

- If electricity is 12.5¢ per kWh (not including taxes/surcharges) and the EV gets 3 miles per kWh…
    - 1,000 miles ÷ 3 miles/kWh = 333.33 kWh x 0.125 = $41.66 monthly energy cost
- If gasoline is $2.947 per gallon and the conventional ICE vehicle gets 26 miles per gallon…
    - 1,000 miles ÷ 26 mpg = 38.46 gallons x 2.947 = $113.35 monthly energy cost
- The numbers in this example add up to a 63 percent reduction in energy costs and an annual energy cost savings of $860.28.

It is important to keep in mind that energy costs (regardless of type) are only one component of the overall cost to own and operate a vehicle. EVs usually have higher initial purchase prices than comparable ICE vehicles. Even with lower energy costs and reduced maintenance requirements, it can take years to recover the difference.

3 Vehicle Selection Methodology

To be eligible for testing, prospective EVs had to be available for sale throughout the United States and have a minimum EPA estimated driving range of 100 miles. Tested EVs featured either resistive or heat-pump cabin heating systems; both types were included within test vehicles to analyze differences in efficiency with respect to cabin heating type. Additionally, one (1) vehicle per manufacturer was tested to prevent overrepresentation of a single brand.

Once eligible EVs were identified, AAA researchers utilized sales data to select the following five (5) vehicles for testing:

- 2018 BMW i3s
- 2018 Chevrolet Bolt
- 2018 Nissan Leaf
- 2017 Tesla Model S 75D
- 2017 Volkswagen e-Golf

All vehicles were procured and inspected to determine suitability for dynamometer testing according to the following criteria originating from SAE J1634 [5]:

i. Check that the odometer reading is between 1,000 and 6,200 miles
ii. Verify that the battery ampere-hour capacity is within acceptable limits before and after testing

In addition, it was verified that no warning lights were illuminated at any point before or during testing.

4 Test Equipment and Resources

The Automobile Club of Southern California performed all laboratory testing at the Automotive Research Center (ARC) located in Los Angeles, California.

4.1 Data Logging Equipment

4.1.1 Ampere-Hour Meter

A Hioki power analyzer (model number PW3390) was used to measure current leaving and entering the traction battery pack at a sampling frequency of 20 Hertz (Hz). The power analyzer was also utilized to measure AC recharge energy (kWh) for each vehicle at all tested ambient temperatures.

4.1.2 OBD-II Scan Tool

Both laptop-based and phone app-based OBD-II scan tools were used to capture traction battery voltage from vehicle network data as specified by SAE J1634 Part 4.6.b. AutoEnginuity, a Windows program, was used for the VW, the Chevy, and the BMW. Leaf-Spy Pro and ScanMyTesla, both Android apps, were used for the Nissan and Tesla, respectively.

4.2 Dynamometer

ARC utilizes a pair of AVL 48-inch diameter electric chassis dynamometers in order to test front-, rear- and all-wheel drive vehicles. The front dynamometer is rated for 150 kW while the rear dynamometer is rated for 220 kW. The dynamometer is used to simulate the same tractive forces that a vehicle encounters when it is driven in naturalistic environments.

The dynamometer is located inside of a temperature and humidity-controlled environmental chamber. The operating range of the chamber is between 20-95°F. All testing was performed on this chassis dynamometer as specified by SAE J1634.

5 Inquiry #1: How do energy consumption and driving range estimates vary with respect to ambient temperature?

5.1 Methodology

Energy consumption, driving range and equivalent fuel economy estimates were calculated at 20°F, 75°F and 95°F to determine the effect of ambient temperature on energy consumption and driving range. All equipment, vehicles and drivers were provided by ARC.

5.1.1 Dynamometer Drive Sequence

Driving range and MPGe estimates published on the Monroney sticker of all new EVs are typically calculated with respect to an ambient temperature ranging between 20 to 30 °C (68 to 86 °F). The standard test procedure utilized by the EPA is derived from SAE J1634 and currently consists of four (4) Urban Dynamometer Driving Schedule (UDDS) cycles and two (2) Highway Fuel Economy Driving Schedule (HWFET) cycles in a specified sequence including mid-test and end-of-test constant speed cycles (CSCs). The CSCs serve as a rapid “depletion phase”; these phases are usually run at 65 mph for a duration dependent on the vehicle’s battery capacity.

Utilizing equations defined in SAE J1634, energy consumption $(\frac{W*h}{mi})$, driving range (mi) and MPGe are calculated for city, highway and aggressive driving. The EPA currently applies a correction factor to calculated values to more accurately reflect figures consumers can expect in the real world. For most

EVs, the city/highway fuel economy and range values are multiplied by 0.7 and the city/highway energy consumption values are divided by 0.7 to derive the Monroney sticker estimates [6]. In this work, provided US06 values have been multiplied or divided by 0.7 for consistency. As such, reported US06 values represent a lower bound of performance that could be reasonably expected in naturalistic environments.

While these estimations provide objective figures that may be used for vehicle comparisons, the EPA emphasizes that “actual mileage may vary” depending on a range of factors including ambient temperature, driving behavior, vehicle maintenance, etc.

To conduct range testing representative of naturalistic driving environments, a custom drive sequence was constructed with a combination of EPA dynamometer drive schedules as specified in Appendix B of SAE J1634. The UDDS was performed first, immediately followed by the HWFET and a ten (10) minute soak period. After the soaking period, the UDDS and US06 Driving Schedule (or Supplemental FTP) were performed in succession. Immediately following the US06, a mid-test CSC at 65 mph was driven. The distance of the CSC was specific to each vehicle and was selected such that the end-of-test CSC was about 20 percent of the distance driven throughout the entirety of the test procedure. After the mid-test CSC, the UDDS-HWFET-soak-UDDS-US06 test sequence was repeated and an end-of-test CSC at 65 mph was driven until the vehicle was unable to maintain steady-state speed. The constructed drive sequence was utilized for all test vehicles and ambient temperatures.

5.2 Test Procedure and Results

Test vehicles were evaluated at three (3) temperatures because traction battery packs must operate under a wide range of ambient temperatures. At low temperatures, Li-ion battery packs are less efficient due to increased heat generation. As temperature decreases, diffusion, conductivity and reaction rates decrease; this leads to increased voltage perturbation and heat generation [7]. Additional heat generation represents a waste of useful energy; at the macro level, this is manifested as reduced driving range and equivalent fuel economy. Additionally, depending on the ambient temperature and the specific architecture of the battery thermal management system, energy may be expended to heat the traction battery via resistive heating.

At elevated temperatures, liquid or passive air-cooling is utilized to keep the traction battery at an acceptable temperature. This can also result in reduced driving range because liquid cooling requires energy that could otherwise be used to propel the vehicle. Aggressive driving will result in higher rates of heat generation, consequently increasing traction battery cooling demands.

Prior to instrumented dynamometer testing, target road-load coefficients were obtained from manufacturer-supplied EPA certification documentation for each vehicle. Road loads were matched to the dynamometer by using the target road-load coefficients and the test weight of the vehicle according to SAE J2264 [8]. This procedure was performed for each vehicle at each tested ambient temperature.

After dynamometer set coefficients were obtained for each ambient test temperature, the vehicle was preconditioned by driving through a series of standard emissions test cycles (US06, HWFET, UDDS, 65 mph CSC) until the battery was fully depleted. Immediately following the preconditioning drive, the vehicle was placed on charge and soaked between the allowed 12-36 hours (15-17 hours typically) in the test cell at the test temperature. The vehicle was on charge for the entirety of the soak period; charging took place in the dynamometer cell such that no vehicle movement was required at the conclusion of soaking.

For each vehicle, instrumented dynamometer tests were performed under the following conditions:

1) Ambient temperature of 75°F and climate control switched off
2) Ambient temperature of 95°F and climate control switched off
3) Ambient temperature of 95°F and climate control switched on
4) Ambient temperature of 20°F and climate control switched off
5) Ambient temperature of 20°F and climate control switched on

The following procedure was used for each instrumented dynamometer test:

Testing was initiated within one hour of the vehicle being removed from charge. The test driver was provided a screen that displayed the targeted vehicle speed trace; vehicle speed was not allowed to deviate more than ± 4 mph from the prescribed speed trace at any point during the test.

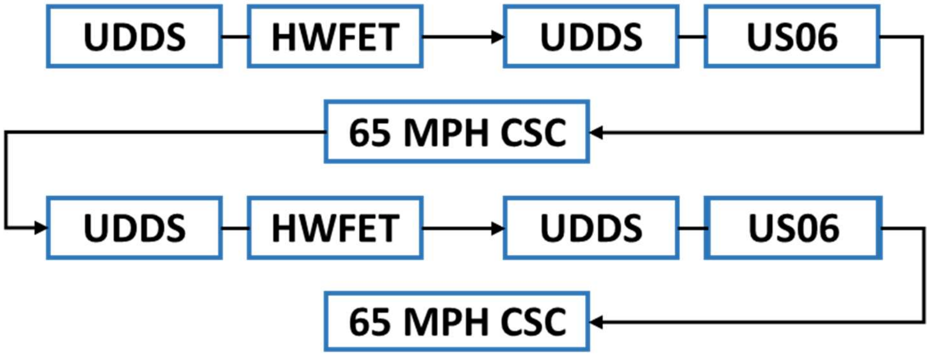


Figure 3: Sequence of drive cycles for instrumented dynamometer testing Image Source: AAA

A 15-second key-on pause occurred between UDDS/HWFET, UDDS/US06 and US06/CSC drive phases. A 10-minute key-off soak occurred between HWFET/UDDS phases. The end-of-test CSC was terminated once the vehicle speed fell below the 65 mph target speed by the 4 mph tolerance specified in SAE J1634 (i.e., 61 mph) and the vehicle was brought to a stop. Within three (3) hours of test completion, the vehicle was placed on charge within the dynamometer cell at the previously tested ambient temperature. The Hioki power analyzer was configured to measure voltage and current entering the charging equipment for each recharge event. To calculate AC recharge energy, the equipment utilized a measuring frequency of 1 Hz for a minimum of 12 hours as specified in SAE J1634.

Each test vehicle was allowed to fully charge at the tested temperature before moving on to the next test temperature. Once a vehicle finished charging and it was time to change test temperatures, the vehicle was soaked for a minimum of 4 hours after the test cell stabilized at the new test temperature before carrying out a new road-load derivation and running preconditioning cycles until the battery was depleted.

For all dynamometer tests, the power analyzer captured all current entering and leaving the traction battery pack at a rate of 20 Hz. Traction battery voltage was obtained from vehicle network data with a sampling frequency dependent on Controller Area Network (CAN) traffic and architecture. In order to synchronize current and voltage data, cubic spline interpolation was performed on the captured voltage dataset to provide interpolated data with a frequency of 20 Hz. Voltage interpolation was time synchronized and multiplied with current data to calculate traction battery wattage output/input.

For each dynamometer test, the calculated wattage was numerically integrated with respect to time to calculate *total* DC discharge watt-hours and DC discharge watt-hours for each drive phase. These values were utilized to calculate phase scaling factors and DC energy consumption (kWh/mi) per drive phase. Utilizing equations specified in SAE J1634, DC energy consumption (kWh/mi) and driving range (mi) were calculated for each drive schedule in addition to combined city/highway values.

To calculate MPGe for each drive schedule, the total AC recharge energy was measured. The AC energy consumption can be calculated for each drive schedule because this value is effectively proportional to that drive schedule's DC discharge energy [5]. The total AC recharge energy was divided by the total DC discharge energy to derive the dimensionless recharge allocation factor (RAF). The total DC discharge energy per drive schedule was multiplied by the RAF to determine the AC discharge energy for each drive schedule. This value was utilized to determine MPGe.

In most cases, the driving range and equivalent fuel economy will exhibit differing percent reductions relative to 75°F. This is due to the temperature dependency of both the RAF and the maximum discharge capacity of the traction battery. Specifically, the RAF will only influence the MPGe calculation whereas the maximum discharge capacity will only influence the driving range calculation as shown by Equations 1 & 2, respectively:

$$\mathrm{RAF} \times \frac{1}{\mathrm{Avg\ DC\ Energy\ Consumption}_{\mathrm{Drive\ Cycle}} \frac{\mathrm{kWh}}{\mathrm{mi}}} \times 33.705\,\frac{\mathrm{kWh}}{\mathrm{gal}} = \mathrm{MPGe}\,\frac{\mathrm{mi}}{\mathrm{gal}} \tag{1}$$

$$\frac{\mathrm{Total\ DC\ Discharge\ Energy\ kWh}}{\mathrm{Avg\ DC\ Energy\ Consumption}_{\mathrm{Drive\ Cycle}} \frac{\mathrm{kWh}}{\mathrm{mi}}} = \mathrm{Driving\ Range}_{\mathrm{Drive\ Cycle}}\ \mathrm{mi} \tag{2}$$

The temperature dependency of the RAF and traction battery discharge capacity will vary between vehicles.

The values calculated for the UDDS test are representative of city driving whereas values calculated for HWFET and US06 drive schedules are representative of highway and aggressive driving, respectively. Total DC energy consumption, driving range and MPGe values reported herein have been adjusted via the EPA correction factor previously discussed in Section 5.1.1.

For each vehicle, detailed test data are provided in the Appendix.

5.2.1 2018 BMW i3s

The traction battery has a rated energy capacity of 33.8 kWh and a gravimetric energy density of 132 Wh/kg.

5.2.1.1 Owner's Manual Information

The owner's manual contains the following information and directions regarding operation in hot/cold environments:

- Page 68 – "Energy Recovery: Charge energy cannot be recovered in the following situations:
    - When temperature of the high-voltage battery is very low or very high. In winter, it might be possible that the energy recovery is temporarily unavailable after startup."
- Page 69 – "In exceptional cases, it is possible that the high-voltage battery heats up sharply when the vehicle is stationary. E.g. with extreme external temperatures and direct solar radiation. With an overheated high-voltage battery, drive readiness cannot be switched on."
- Page 83 – "The range can be abruptly reduced or increased based on the following factors:
    - Climate and terrain conditions
    - Driving style"
- Page 164 – "At high temperatures, initially the high-voltage battery is cooled. The charging process can be started with a delay."

5.2.1.2 Ambient Temperature Testing

All values provided in this section were obtained with the HVAC system off throughout testing.

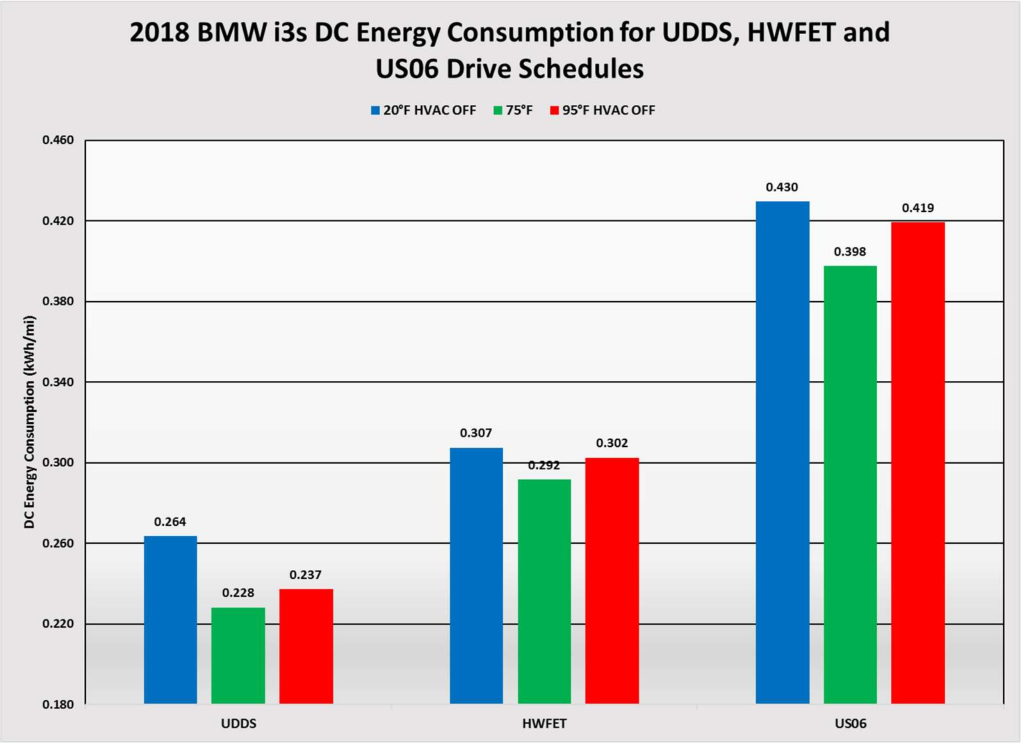


Figure 4: DC energy consumption with respect to ambient temperature Image Source: AAA

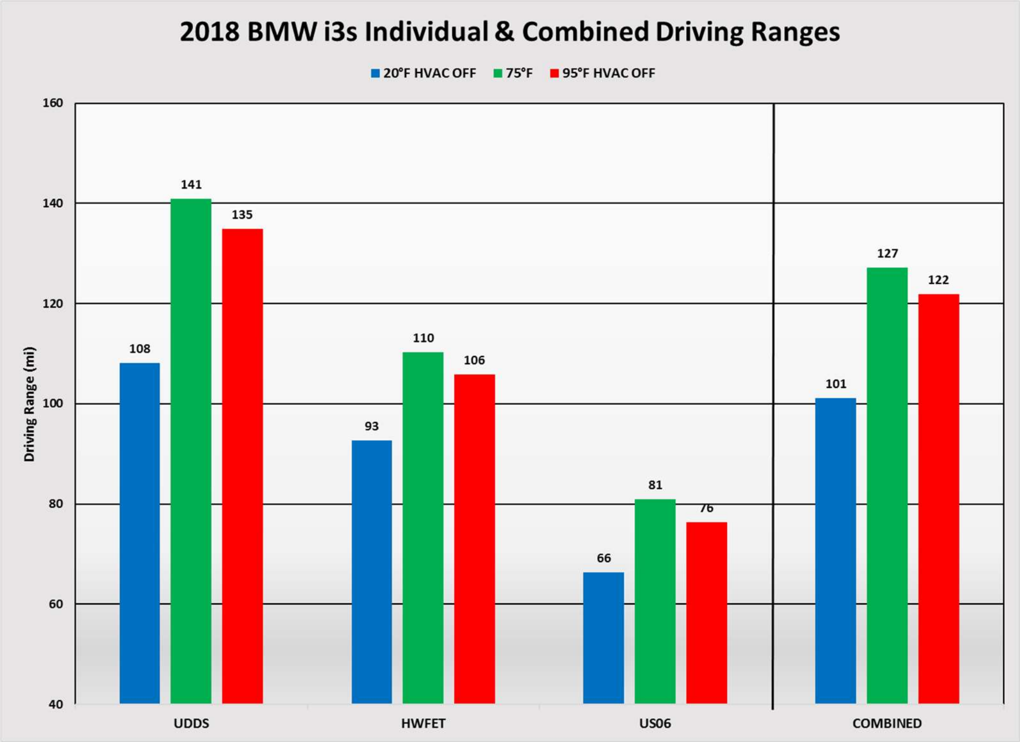


Figure 5: Driving range with respect to ambient temperature Image Source: AAA

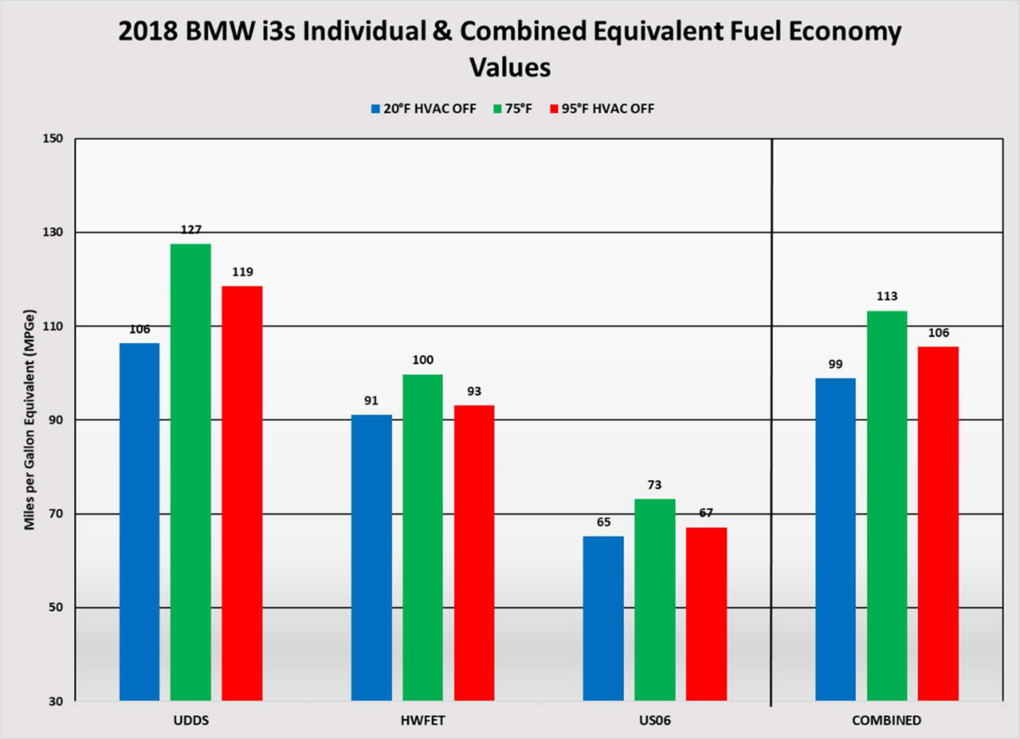


Figure 6: MPGe with respect to ambient temperature Image Source: AAA

The total DC discharge energy was reduced at an ambient temperature of 20°F; this will consequently result in a reduction of driving range. The RAF was also increased at 20°F and 95°F; this will result in a reduction of equivalent fuel economy. Compared to 75°F, the combined driving range and equivalent fuel economy at 20°F decreased by 26 miles and 14 MPGe, respectively. This equates to a 20 percent decrease in combined driving range and a 13 percent decrease in combined equivalent fuel economy relative to 75°F.

At 95°F, the combined equivalent fuel economy decreased by 7 MPGe; this equates to a 7 percent decrease relative to 75°F.

5.2.2 2018 Chevrolet Bolt

The traction battery has a rated energy capacity of 60 kWh and a gravimetric energy density of 140 Wh/kg.

5.2.2.1 Owner's Manual Information

The owner's manual contains the following information and directions regarding operation in hot/cold environments:

- Page 30 – "In colder temperatures, while these efficiency tips will help, the electric vehicle driving range may be lower due to higher energy usage."
- Page 30 – "Keep the vehicle plugged in, even when fully charged, to keep the battery temperature ready for the next drive. This is important when outside temperatures are extremely hot or cold."
- Page 123 – "Regenerative power may be limited when the high voltage battery is near full charge or cold. The regen battery icon will appear gray when limited."
- Page 207 – "Parking the vehicle in extreme cold for several days without the charge cord connected may cause the vehicle not to start. The vehicle will need to be plugged in to allow the high voltage battery to be warmed sufficiently."
- Page 264 – "Propulsion power may be reduced in extremely cold temperatures, or if the high voltage battery is too cold. BATTERY TOO COLD, PLUG IN TO WARM will display."

5.2.2.2 Ambient Temperature Testing

All values provided in this section were obtained with the HVAC system off throughout testing.

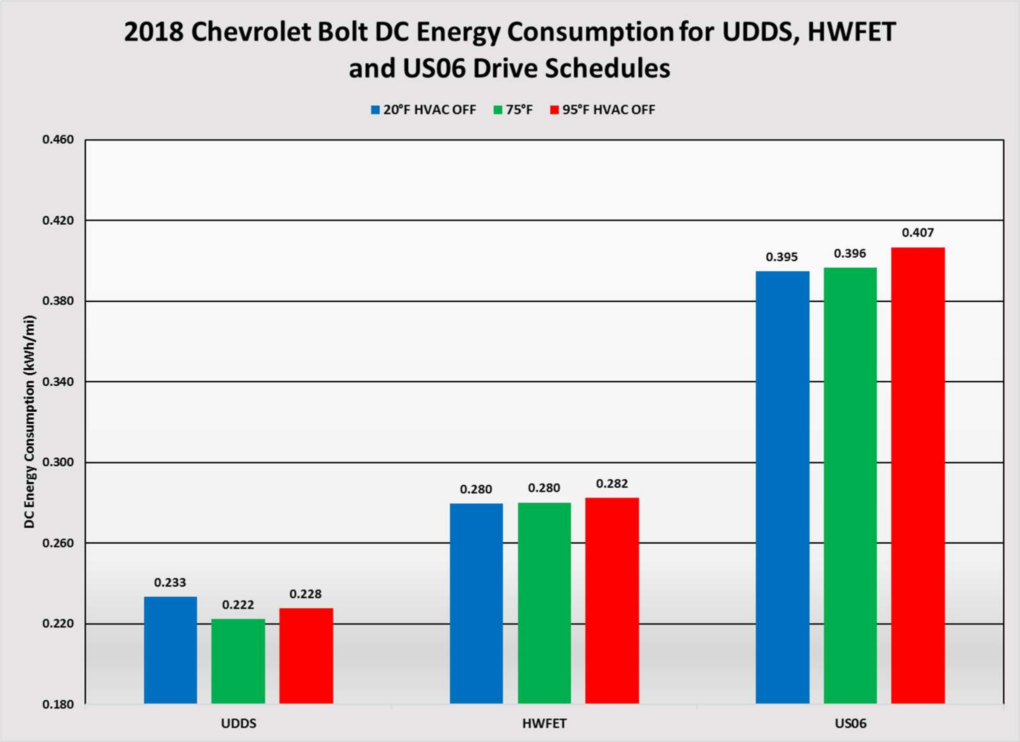


Figure 7: DC energy consumption with respect to ambient temperature Image Source: AAA

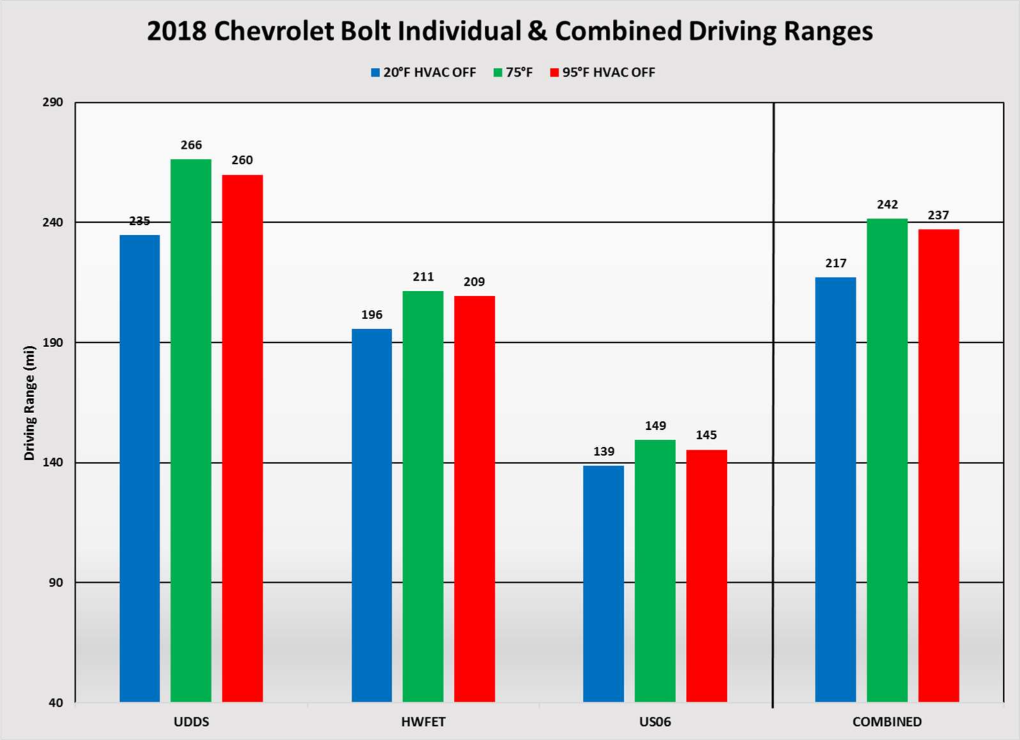


Figure 8: Driving range with respect to ambient temperature Image Source: AAA

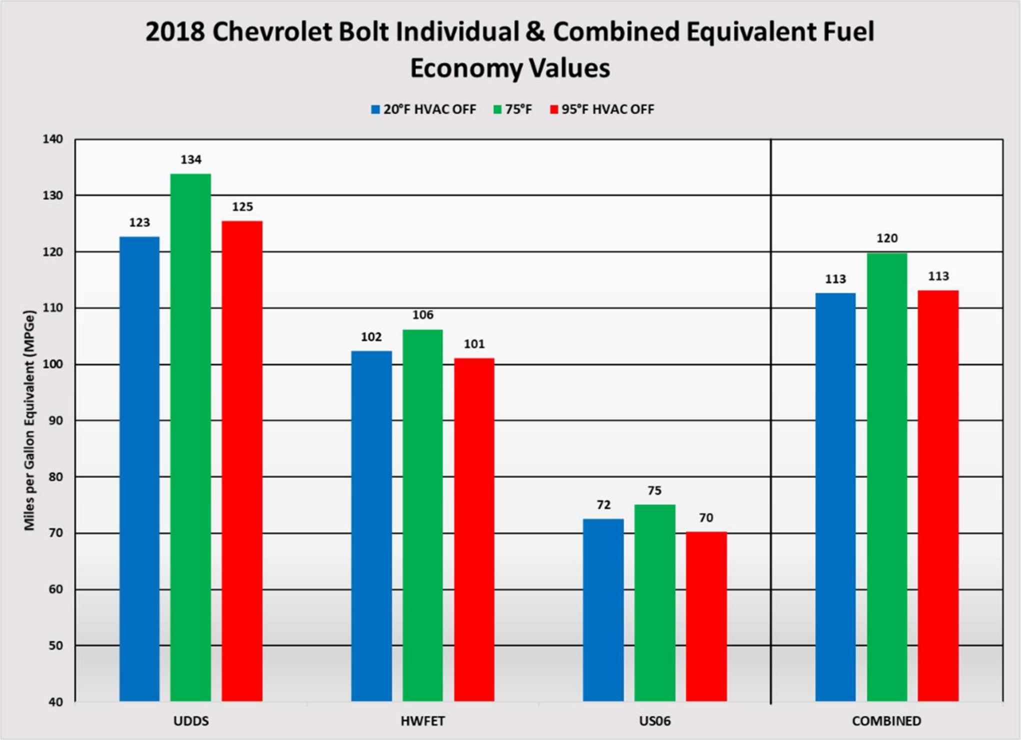


Figure 9: MPGe with respect to ambient temperature Image Source: AAA

The total DC discharge energy was reduced at an ambient temperature of 20°F; this will consequently result in a reduction of driving range. The RAF was also increased at 20°F and 95°F; this will result in a reduction of equivalent fuel economy. Compared to 75°F, the combined driving range and equivalent fuel economy at 20°F decreased by 25 miles and 7 MPGe, respectively. This equates to a 10 percent decrease in combined driving range and a 6 percent decrease in combined equivalent fuel economy relative to 75°F.

At 95°F, the combined equivalent fuel economy decreased by 7 MPGe; this equates to a 6 percent decrease relative to 75°F.

5.2.3 2018 Nissan Leaf

The traction battery has a rated energy capacity of 40 kWh and a gravimetric energy density of 132 Wh/kg.

5.2.3.1 Owner's Manual Information

The owner's manual contains the following information and directions regarding operation in hot/cold environments:

- Page 23 (EV-2): "To prevent damage to the Li-ion battery: Do not expose the vehicle to extreme ambient temperatures for extended periods. Do not store the vehicle in temperatures below −13°F (−25°C) for more than seven days."

- Page 24 (EV-3): “NOTE: If the outside temperature is −13°F (−25°C) or less, the Li-ion battery may freeze and it cannot be charged or provide power to run the vehicle. Move the vehicle to a warm location.”
- Page 26 (EV-5): “CAUTION: The Li-ion battery warmer does not operate if the available Li-ion battery charge is less than approximately 15% and the charger is not connected to the vehicle. To help prevent the Li-ion battery from freezing, do not leave the vehicle in an environment if temperatures may go below -1°F (-17°C) unless the vehicle is connected to a charger.”
- Page 26 (EV-5): “The Li-ion battery warmer helps to prevent the Li-ion battery from freezing and helps to prevent significant reductions in the Li-ion battery output when the temperature is cold. The Li-ion battery warmer automatically turns on when the Li-ion battery temperature is approximately -1°F (-17°C) or colder. The Li-ion battery warmer automatically turns off when the Li-ion battery temperature is approximately 14°F (-10°C) or higher.”
- Page 27 (EV-6): “Vehicle driving range is reduced if the Li-ion battery warmer operates (Li-ion battery temperature approximately -1°F (-17°C) or colder) while driving the vehicle. You may need to charge the Li-ion battery sooner than in warmer temperatures.”
- Page 40 (EV-19):
    - “Vehicle range may be substantially reduced in extremely cold conditions (for example, -4°F (-20°C)).
    - Using the climate control system to heat the cabin when the outside temperature is below 32°F (0°C) uses more electricity and affects vehicle range more than when using the heater when the temperature is above 32°F (0°C).
    - When it is cold, use the steering wheel heater in substitution for the heater/air conditioner. The steering wheel heater consumes less power than the heater/air conditioner.”
- Page 41 (EV-20): “The Li-ion battery's ability to hold a charge can be affected by how you drive the vehicle, store the vehicle, how you charge the Li-ion battery and Li-ion battery temperature during vehicle operation and charging.”
- Page 480 (5-141): “Vehicle range may be substantially reduced in extremely cold conditions (for example under -4°F (-20°C)).”

5.2.3.2 Ambient Temperature Testing

All values provided in this section were obtained with the HVAC system off throughout testing.

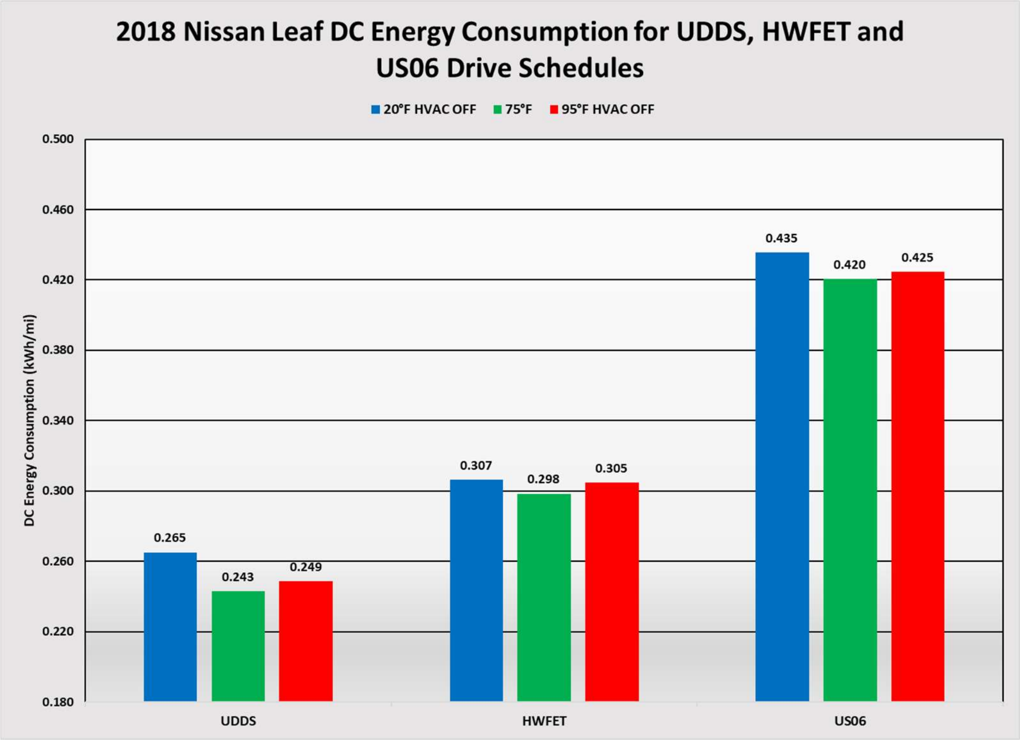


Figure 10: DC energy consumption with respect to ambient temperature Image Source: AAA

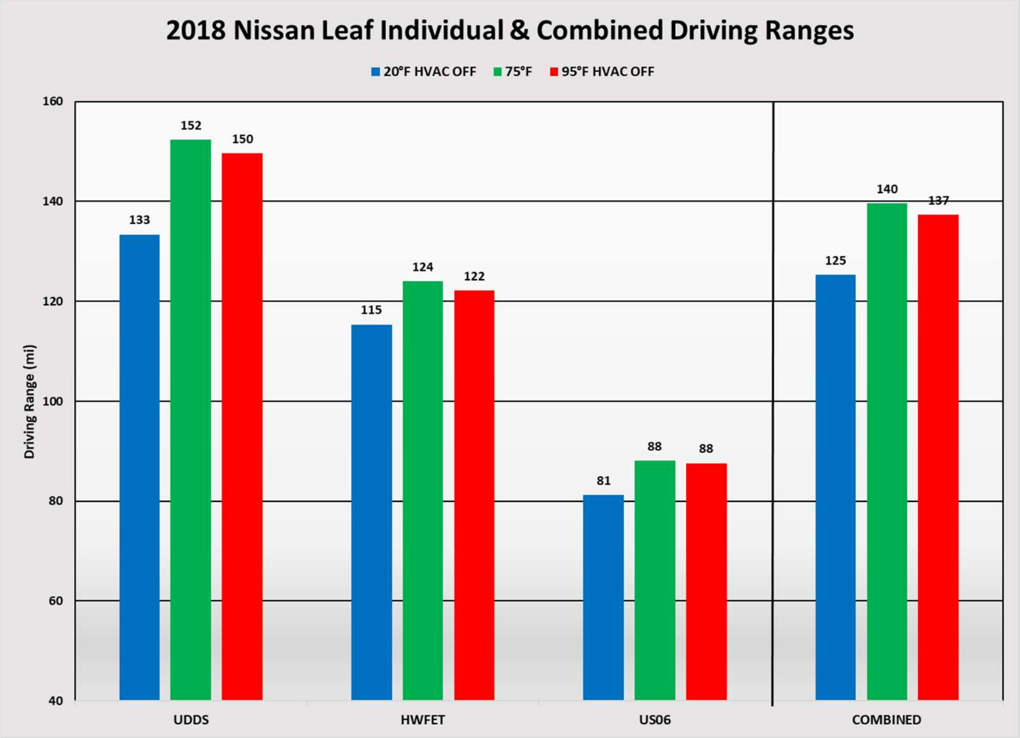


Figure 11: Driving range with respect to ambient temperature Image Source: AAA

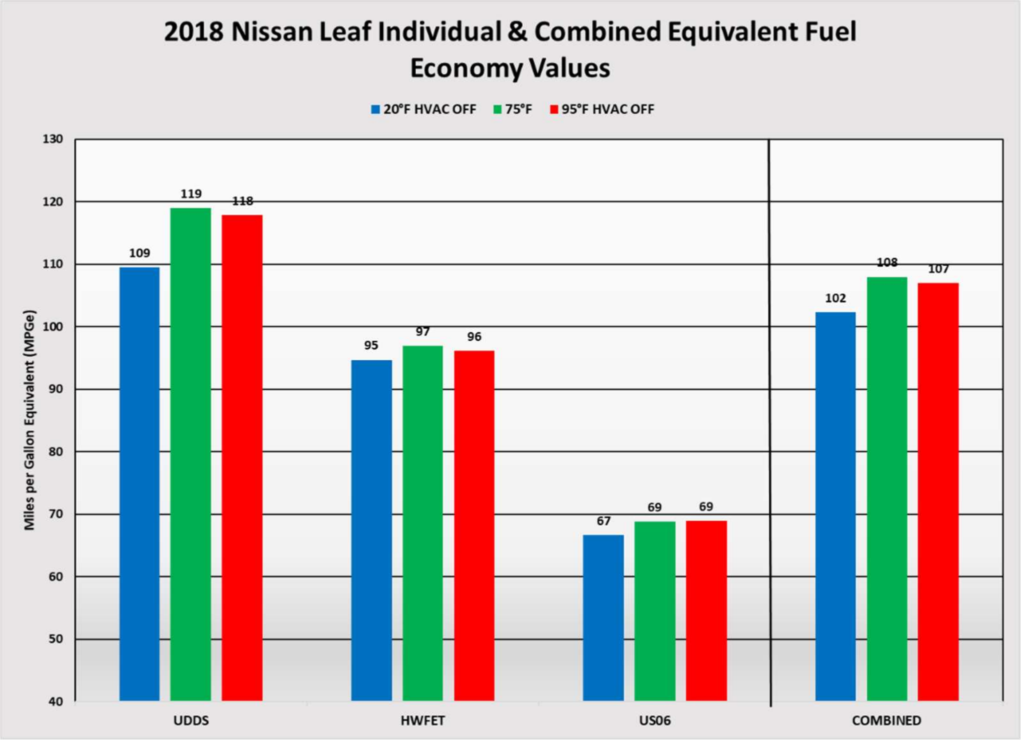


Figure 12: MPGe with respect to ambient temperature Image Source: AAA

The total DC discharge energy was reduced at an ambient temperature of 20°F; this will consequently result in a reduction of driving range. Compared to 75°F, the combined driving range and equivalent fuel economy at 20°F decreased by 15 miles and 6 MPGe, respectively. This equates to a 10 percent decrease in combined driving range and a 5 percent decrease in equivalent fuel economy relative to 75°F.

At 95°F, the combined driving range and equivalent fuel economy decreased by 3 miles and 1 MPGe, respectively. This equates to a 2 percent decrease in combined driving range and a 1 percent decrease in equivalent fuel economy relative to 75°F. These differences are largely insignificant; driving range and equivalent fuel economy are not affected by warm temperatures in isolation.

5.2.4 2017 Tesla Model S 75D

The traction battery has a rated energy capacity of 75 kWh and a gravimetric energy density of 170 Wh/kg.

5.2.4.1 Owner's Manual Information

The owner's manual contains the following information and directions regarding operation in hot/cold environments:

- Page 62: "…Energy consumption depends on environmental conditions (such as cold weather and hilly roads). To get the maximum mileage from a charge: … Limit the use of resources such as heating, signature lighting, and air conditioning. Using seat heaters to keep warm is more efficient than heating the cabin. To automatically limit the amount of power that the climate control system uses to maintain the temperature of the battery and the cabin area, touch Controls > Driving > Range Mode > ON."

- Page 62: "The power meter on the instrument panel and the Energy app (described next) provide feedback on energy usage. With this feedback, you will soon become familiar with how driving habits and environmental conditions impact how much energy Model S is using."
- Page 130: "Temperature Limits: For better long-term performance, avoid exposing Model S to ambient temperatures above 140° F (60° C) or below -22° F (-30° C) for more than 24 hours at a time."

5.2.4.2 Ambient Temperature Testing

All values provided in this section were obtained with the HVAC system off throughout testing.

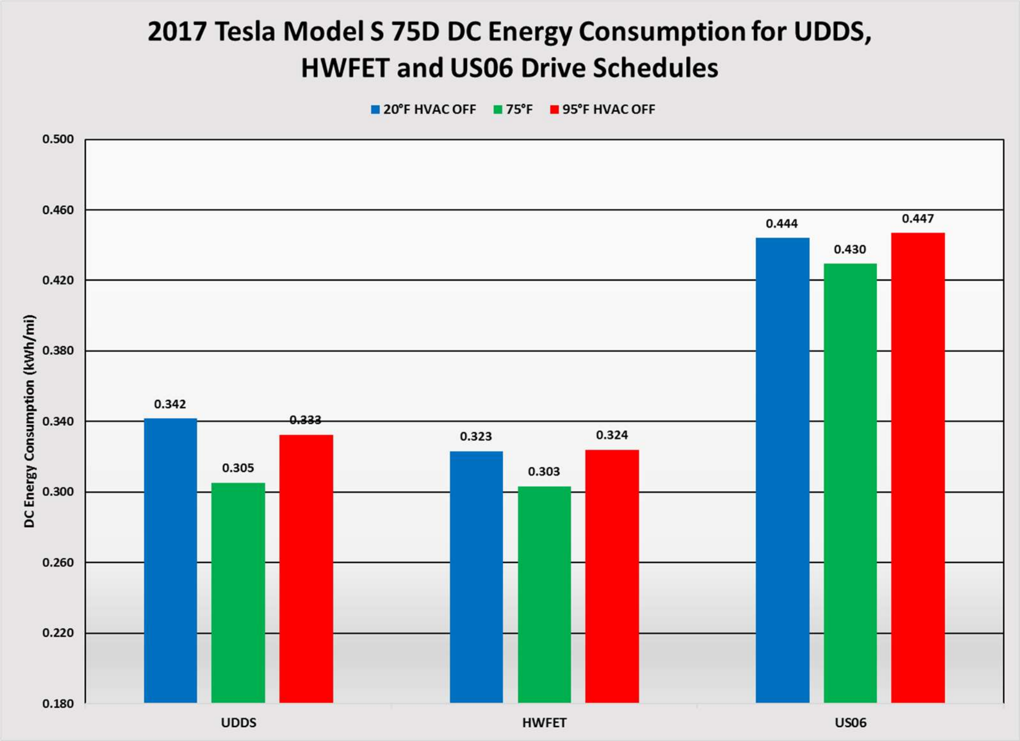


Figure 13: DC energy consumption with respect to ambient temperature Image Source: AAA

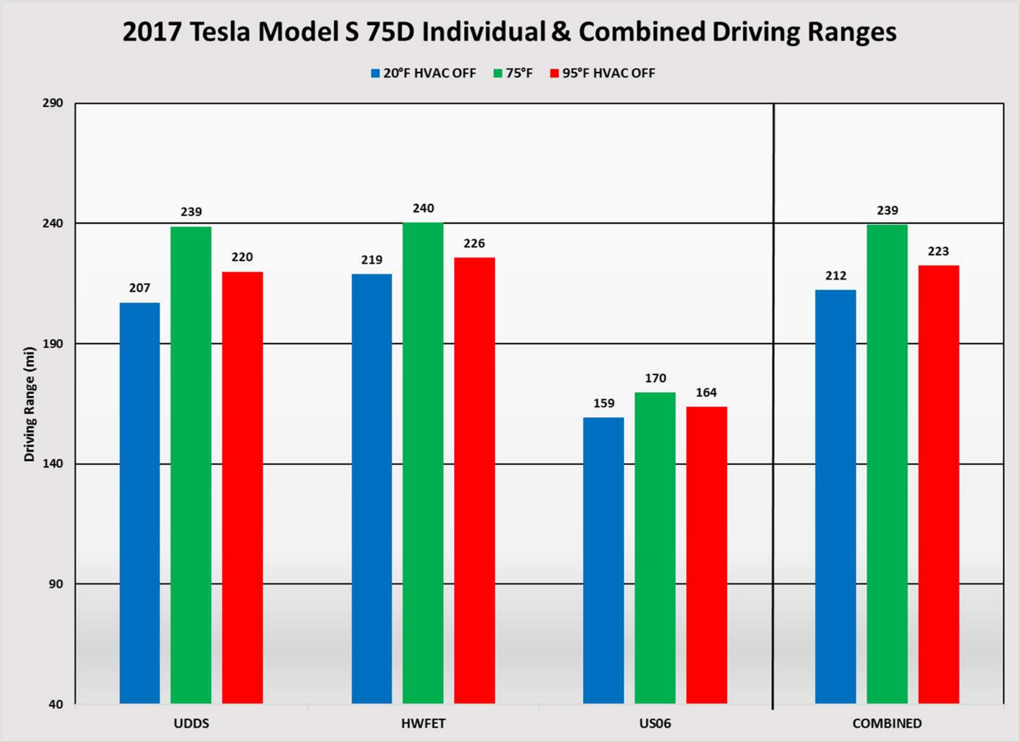


Figure 14: Driving range with respect to ambient temperature Image Source: AAA

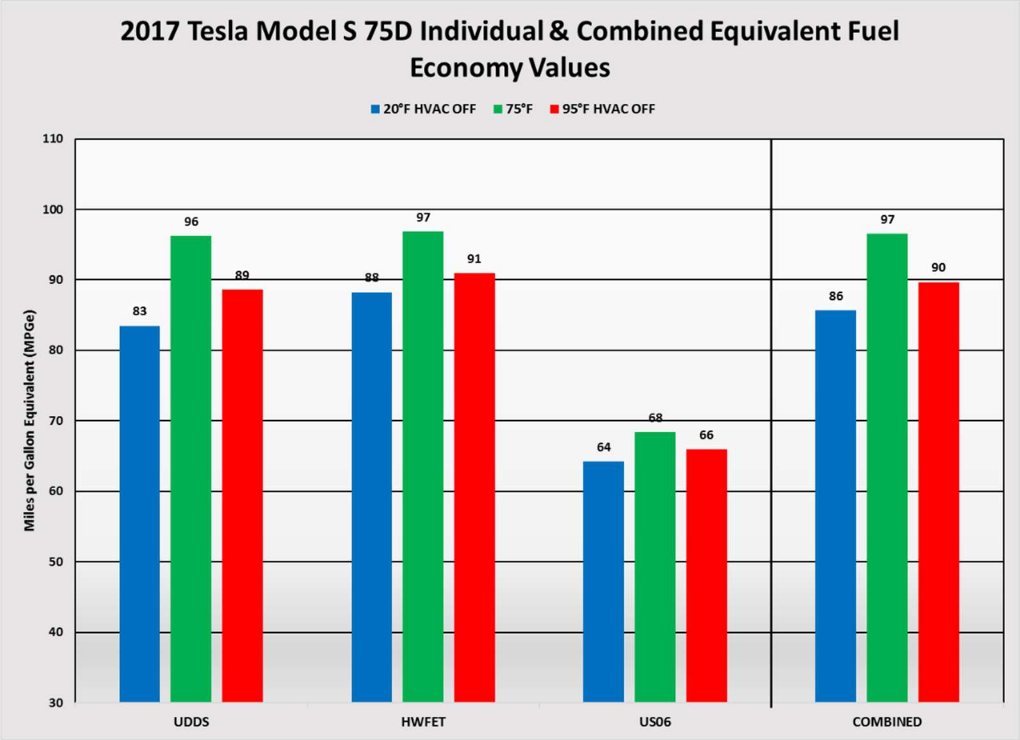


Figure 15: MPGe with respect to ambient temperature Image Source: AAA

The total DC discharge energy was reduced at an ambient temperature of 20°F; this will consequently result in a reduction of driving range. The RAF was also increased at 20°F; this will result in a reduction of equivalent fuel economy. Compared to 75°F, the combined driving range and equivalent fuel economy at 20°F decreased by 27 miles and 11 MPGe, respectively. This equates to an 11 percent decrease in both combined driving range and equivalent fuel economy relative to 75°F.

At 95°F, the combined driving range and equivalent fuel economy decreased by 16 miles and 7 MPGe, respectively. This equates to a 7 percent decrease in both combined driving range and equivalent fuel economy relative to 75°F.

5.2.5 2017 Volkswagen e-Golf

The traction battery has a rated energy capacity of 35.8 kWh and a gravimetric energy density of 104 Wh/kg.

5.2.5.1 Owner's Manual Information

The owner's manual contains the following information and directions regarding operation in hot/cold environments:

- Page 212 – "At very low outside temperatures when the high-voltage battery is consequently very cold, electrical driving and the vehicle range may be limited."
- Page 215 – "The limited power availability can be dependent on driving style, like rapid acceleration. The power availability is also generally limited under the following conditions:
    - Very cold or very hot high-voltage battery temperatures"
- Page 249 – "Should the vehicle be parked for longer than 2 days at temperatures of below -13°F, the high voltage battery could freeze and not be able to provide energy to the electric motor. Temperatures colder than -13°F can cause the battery to freeze even faster. The battery will start working again, once it warms up. Should you have to park your vehicle at very low temperatures for longer than 1 day, make sure that the high-voltage battery does not freeze by parking the vehicle in a garage that is heated or protected from the outside temperature."
- Page 249 – "The high-voltage battery can be damaged and the capacity can be decreased when the vehicle is parked for longer than 24 hours when the ambient temperature is higher than 118°F. Always make sure that the high-voltage battery is not exposed to temperatures above 118°F for a long time."
- Page 249 – **"NOTICE – Always make sure that the high-voltage battery is not exposed to extremely low and high temperatures as well as to water especially for a longer time. Failure to protect and care for the high voltage battery can lead to serious damage and/or a decrease of the capacity void coverage under the New Vehicle Limited Warranty."**
- Page 315 – **"NOTICE – If the vehicle is left standing in the cold for a long time, protect the vehicle battery from freezing. A battery will be permanently damaged by freezing."**

5.2.5.2 Ambient Temperature Testing

All values provided in this section were obtained with the HVAC system off throughout testing.

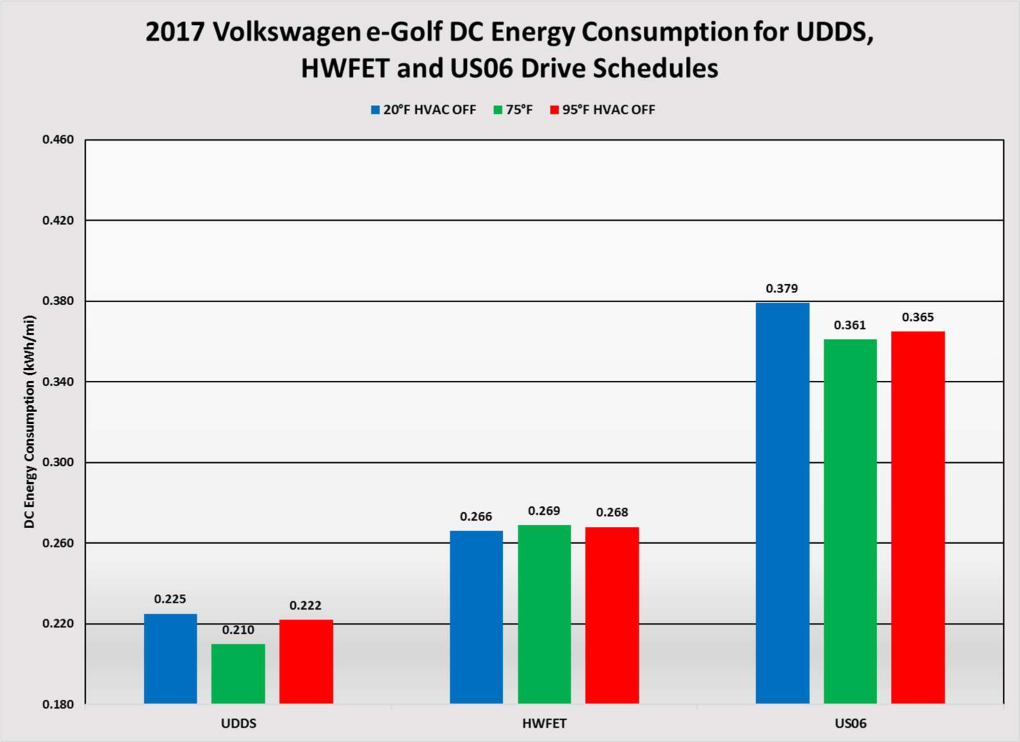


Figure 16: DC energy consumption with respect to ambient temperature Image Source: AAA

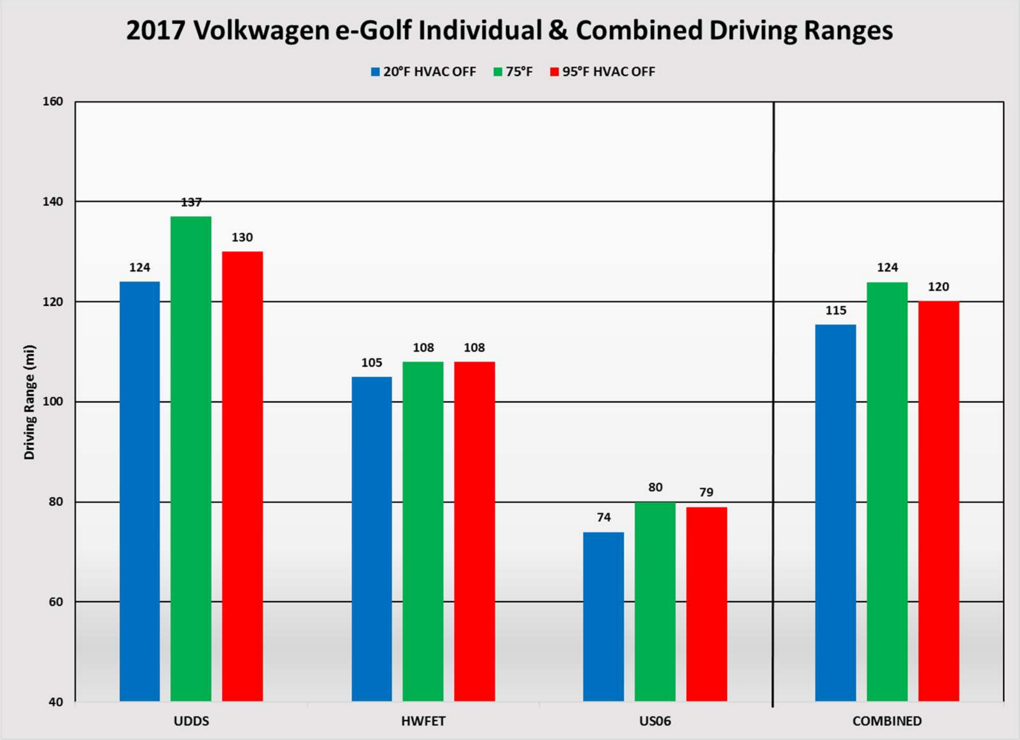


Figure 17: Driving range with respect to ambient temperature Image Source: AAA

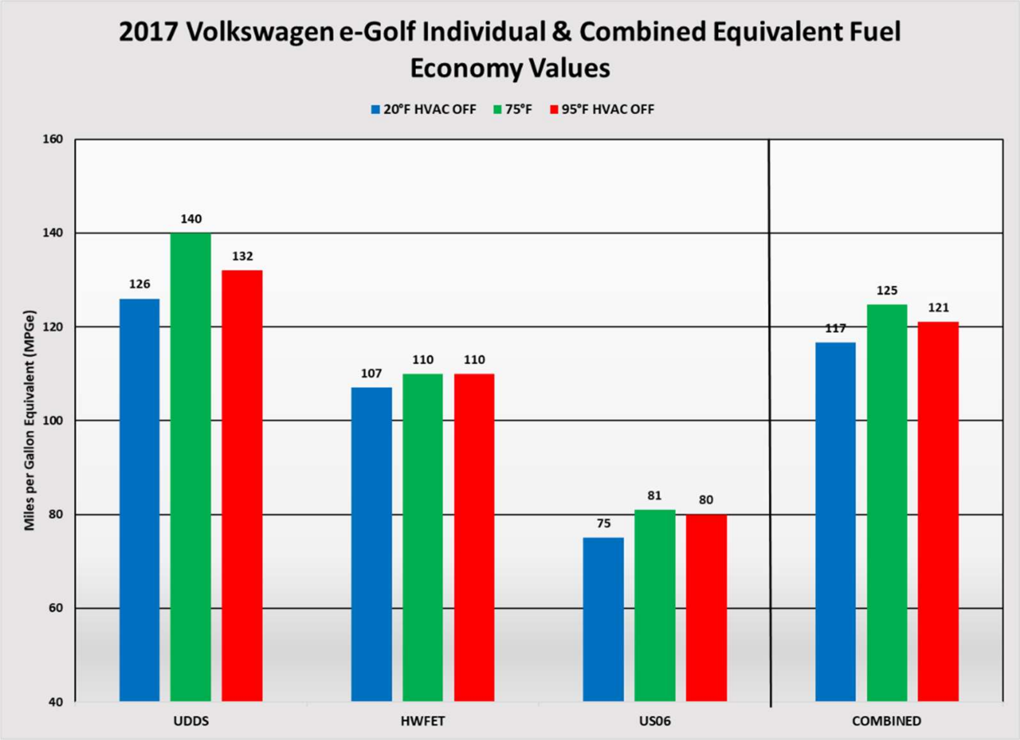


Figure 18: MPGe with respect to ambient temperature Image Source: AAA

The total DC discharge energy was reduced at an ambient temperature of 20°F; this will consequently result in a reduction of driving range. The RAF was also increased at 20°F; this will result in a reduction of equivalent fuel economy. Compared to 75°F, the combined driving range and equivalent fuel economy at 20°F decreased by 9 miles and 8 MPGe, respectively. This equates to a 7 percent decrease in combined driving range and a 6 percent decrease in equivalent fuel economy relative to 75°F.

At 95°F, the combined driving range and equivalent fuel economy decreased by 4 miles and 4 MPGe, respectively. This equates to a 3 percent decrease in both combined driving range and combined equivalent fuel economy relative to 75°F. These differences are largely insignificant; driving range and equivalent fuel economy are not affected by warm temperatures in isolation.

5.3 Summary of Test Results

When tested at 20°F, each test vehicle reduced the maximum discharge capacity of the traction battery to prevent damage. This affected the driving range of all drive cycles to varying degrees. For all test vehicles, it was observed that the UDDS drive cycle (representative of urban driving environments) was most affected by ambient temperature in terms of driving range and equivalent fuel economy (MPGe). Specifically, UDDS drive cycles performed at 20°F exhibited larger reductions of driving range and MPGe than corresponding drive cycles conducted at 95°F.

As a result, combined driving range and combined MPGe values exhibited larger reductions at 20°F. Combined values are derived from the UDDS and HWFET values according to Equations 3 & 4:

$$Driving\ Range_{Combined} = 0.55 Driving\ Range_{UDDS} + 0.45 Driving\ Range_{HWFET} \quad (3)$$

$$MPGe_{Combined} = \frac{1}{\frac{0.55}{MPGe_{UDDS}} + \frac{0.45}{MPGe_{HWFET}}} \tag{4}$$

Figures 19-20 illustrate the percent change of combined driving range and combined MPGe values relative to testing conducted at an ambient temperature of 75°F.

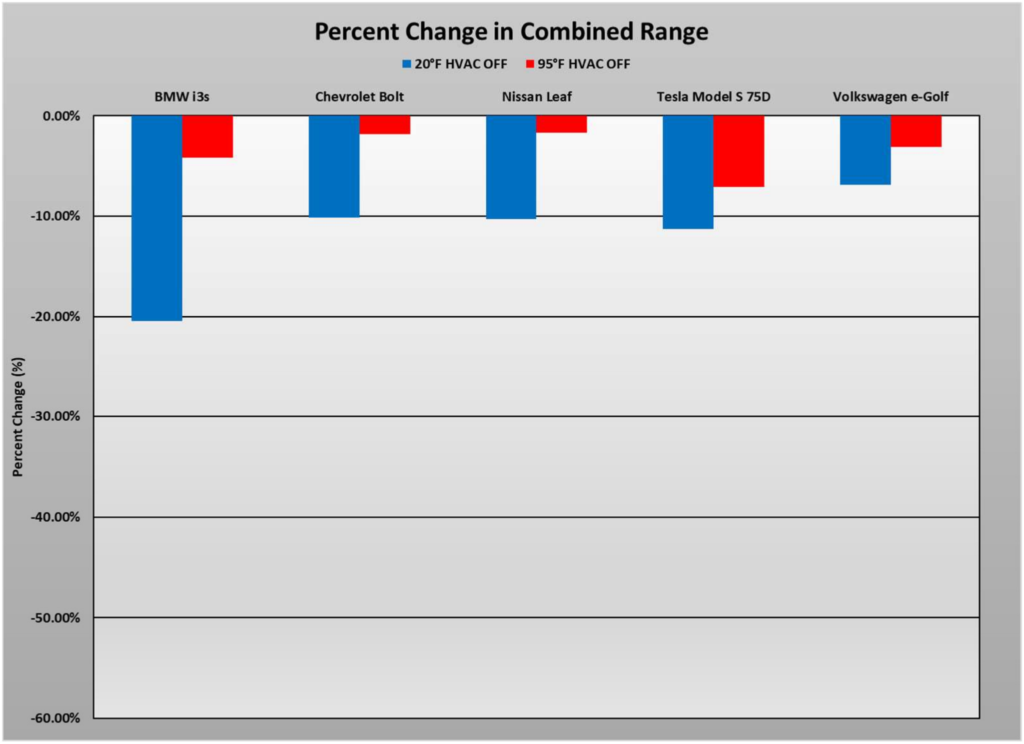


Figure 19: Percent change in combined driving range relative to testing conducted at 75°F Image Source: AAA

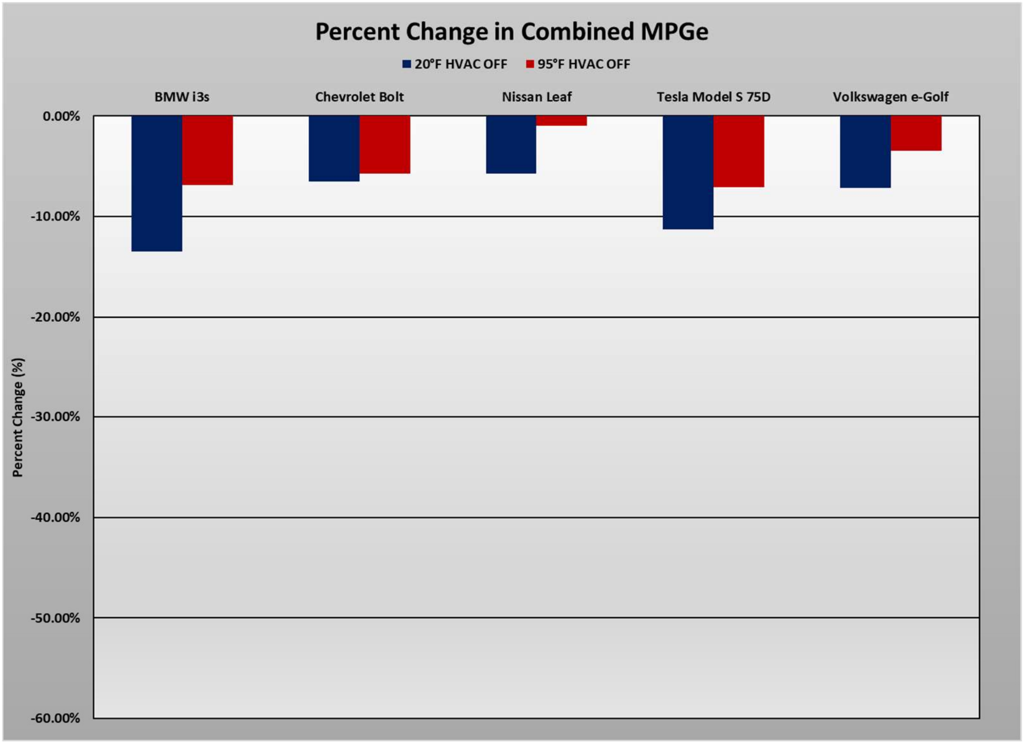


Figure 20: Percent change in combined MPGe relative to testing conducted at 75°F Image Source: AAA

At 20°F, combined driving range and combined MPGe figures were reduced by an average of 12 percent and 8 percent, respectively (w/respect to testing at 75°F). At 95°F, combined driving range and combined MPGe figures were reduced by an average of 4 percent and 5 percent, respectively (w/respect to testing at 75°F).

In isolation, hot and cold ambient temperatures did not cause dramatic reductions of driving range and equivalent fuel economy. However, it was observed that ambient temperature influences both parameters to some degree regardless of driving behavior and HVAC use. Motorists that utilize electric vehicles should be mindful of ambient temperatures in their area and plan to compensate for decreased driving range during periods of extreme hot or cold weather.

HWFET (representative of highway driving) and US06 (representative of aggressive driving) drive cycles also exhibited reductions in terms of driving range and equivalent fuel economy at 20°F and 95°F. However, the HWFET drive cycle was modestly affected relative to UDDS and US06 drive cycles; this was especially true at 95°F. This finding suggests that highway driving is not significantly influenced by ambient temperature alone.

6 Inquiry #2: What effect do heating, ventilation, and air conditioning (HVAC) systems have on the driving range of tested EVs?

6.1 Objective

Quantify the impact of the vehicle's HVAC system on driving range and MPGe. Additionally, determine if various HVAC system types have differing impacts on driving range and MPGe.

6.2 Methodology

To warm the passenger cabin, resistive heating or heat pumps are utilized. Of the five (5) test vehicles, the Chevrolet Bolt, Tesla Model S and Volkswagen e-Golf feature resistive heating for cabin heating whereas the BMW i3s BEV and Nissan Leaf feature a heat pump system for cabin heating with auxiliary resistive heating for extremely low temperatures.

It is hypothesized that EVs primarily relying on heat pumps for cabin heating will lose significantly less driving range and equivalent fuel economy than EVs that exclusively employ resistive heating. Heat pumps within EVs are based on the vapor compression cycle. Heat energy is transferred in the opposite direction of spontaneous heat transfer via the movement of a refrigerant through an evaporator, compressor, condenser and expansion valve. These heat pumps are energy efficient because only a small fraction of electricity is required to run the air compressor in comparison to the overall amount of transferred thermal energy. In contrast, resistive heating systems route current flow through a high resistance conductor to produce heat. The amount of heat produced is determined by the Joule-Lenz law, which states that produced thermal energy is proportional to the square of the current multiplied by the conductor's resistance. This requires a significant amount of energy from the traction battery; typically 2-4 kW depending on the vehicle.

Dynamometer testing was performed at ambient temperatures of 20°F and 95°F with the vehicle's HVAC system engaged. Test methodology previously described in Section 5.2 was utilized to evaluate the impact of HVAC use on driving range and MPGe. For each vehicle and ambient temperature, the HVAC system was placed in "Auto" mode with a temperature set point of 72°F. If possible, "recirculation" mode was selected (some vehicles will disable auto mode if any climate control button is depressed). If the fan speed was user selectable in auto mode, the maximum blower speed was selected. The results contained herein include reference values measured at 75°F with no HVAC.

For each vehicle, detailed test data are provided in the Appendix.

6.3 Test Results

6.3.1 2018 BMW i3s

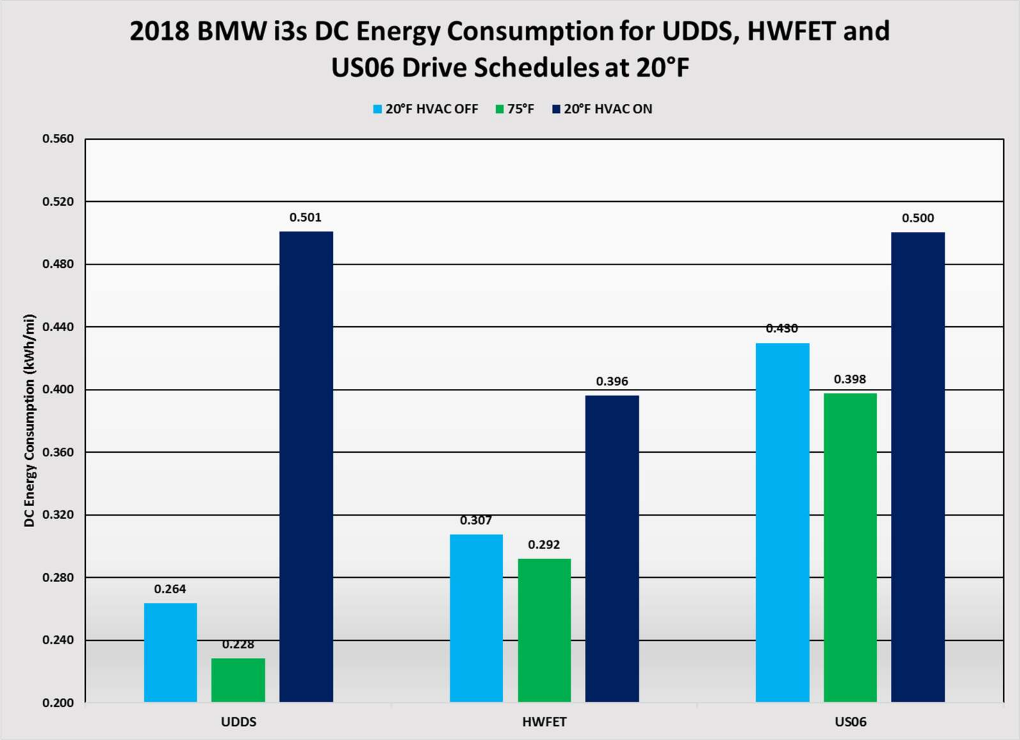


Figure 21: DC energy consumption at 20°F Image Source: AAA

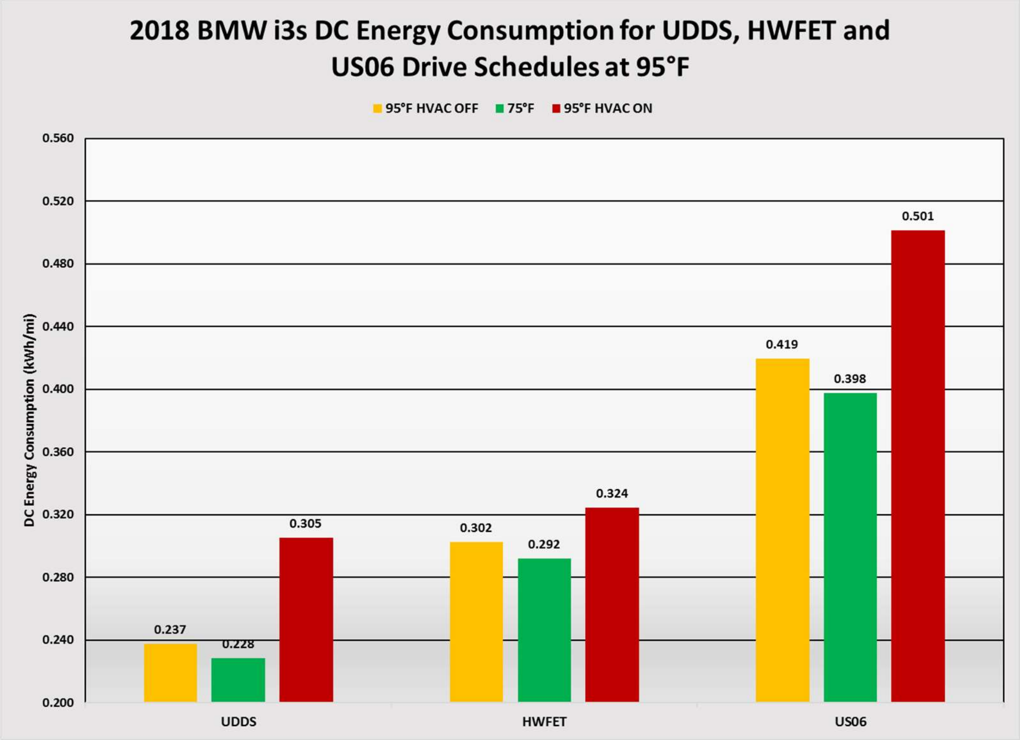


Figure 22: DC energy consumption at 95°F Image Source: AAA

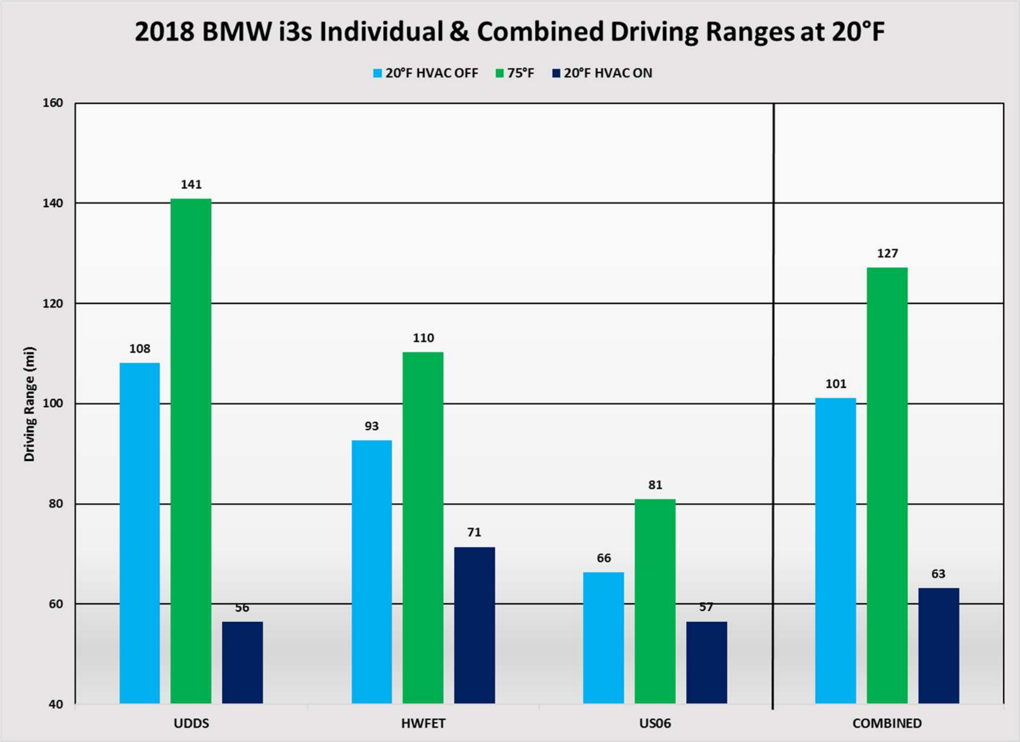


Figure 23: Driving range at 20°F Image Source: AAA

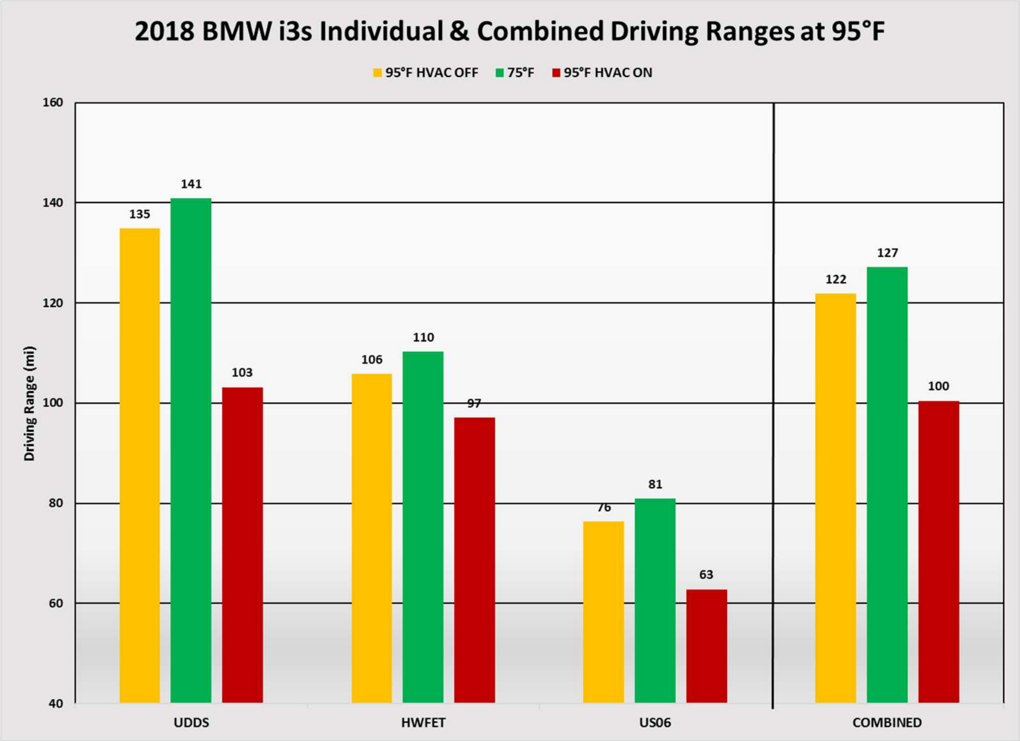


Figure 24: Driving range at 95°F Image Source: AAA

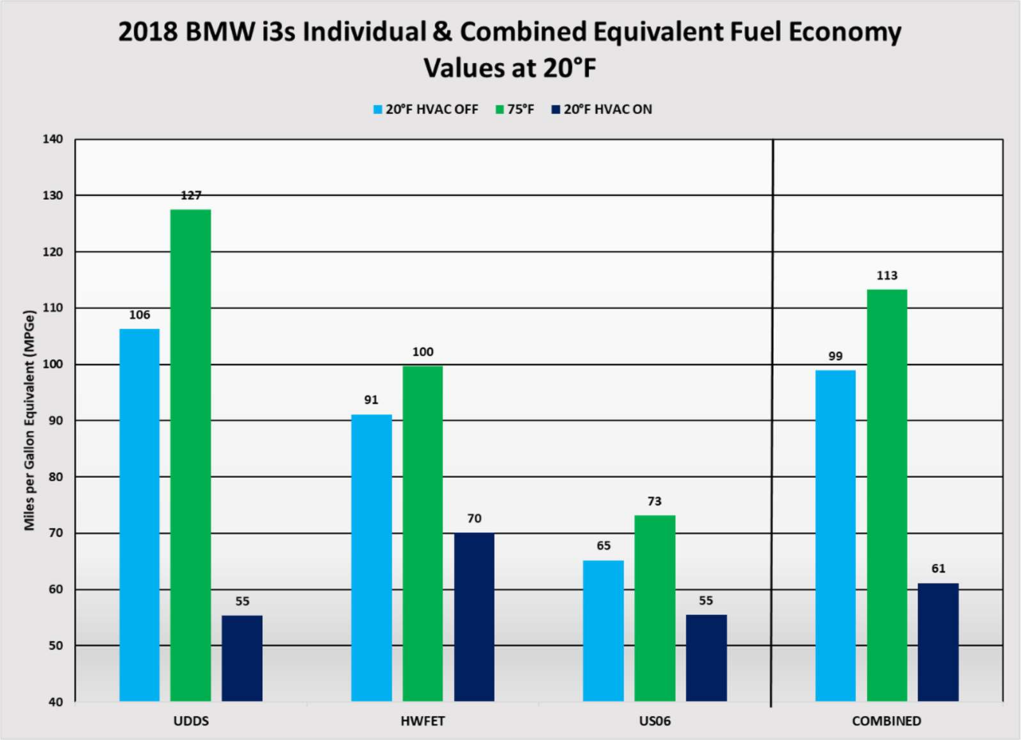


Figure 25: Equivalent fuel economy at 20°F Image Source: AAA

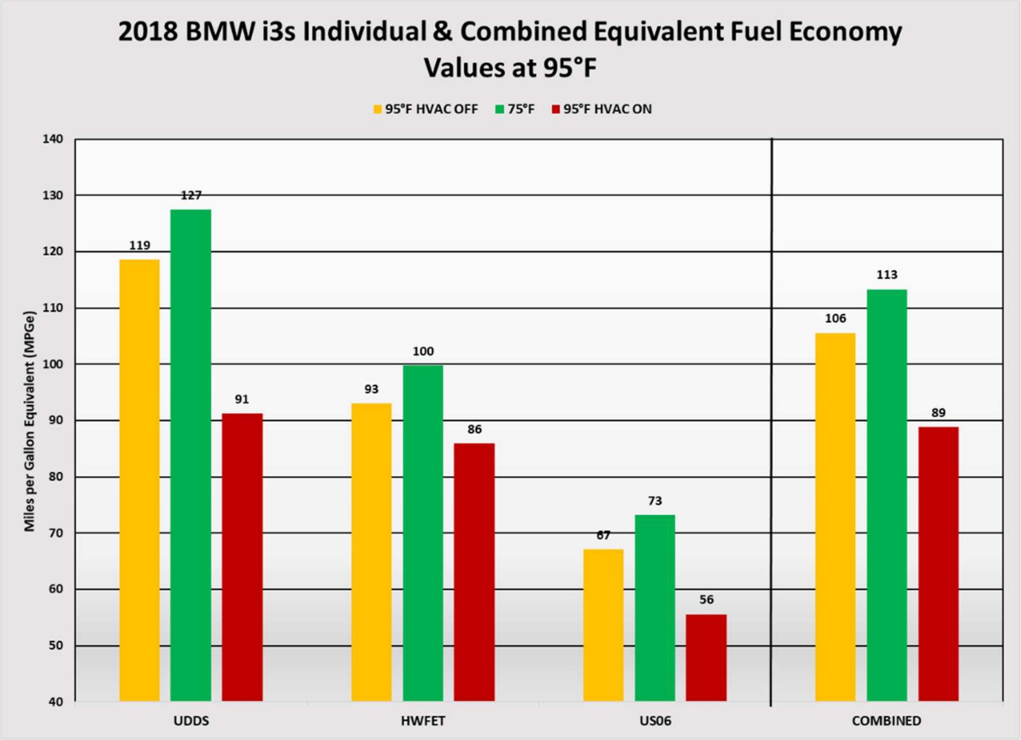


Figure 26: Equivalent fuel economy at 95°F Image Source: AAA

With the HVAC engaged, the driving range and equivalent fuel economy were significantly reduced for all drive types (city, highway, aggressive) at 20°F. Compared to 75°F with HVAC off, the combined driving range and combined MPGe were reduced by 50 percent and 46 percent, respectively.

At 95°F with the HVAC engaged, the driving range and equivalent fuel economy were reduced for all drive types. However, reductions were less severe than corresponding reductions exhibited at 20°F. Compared to 75°F, the combined driving range and equivalent fuel economy were reduced by 21 percent and 22 percent, respectively.

6.3.2 2018 Chevrolet Bolt

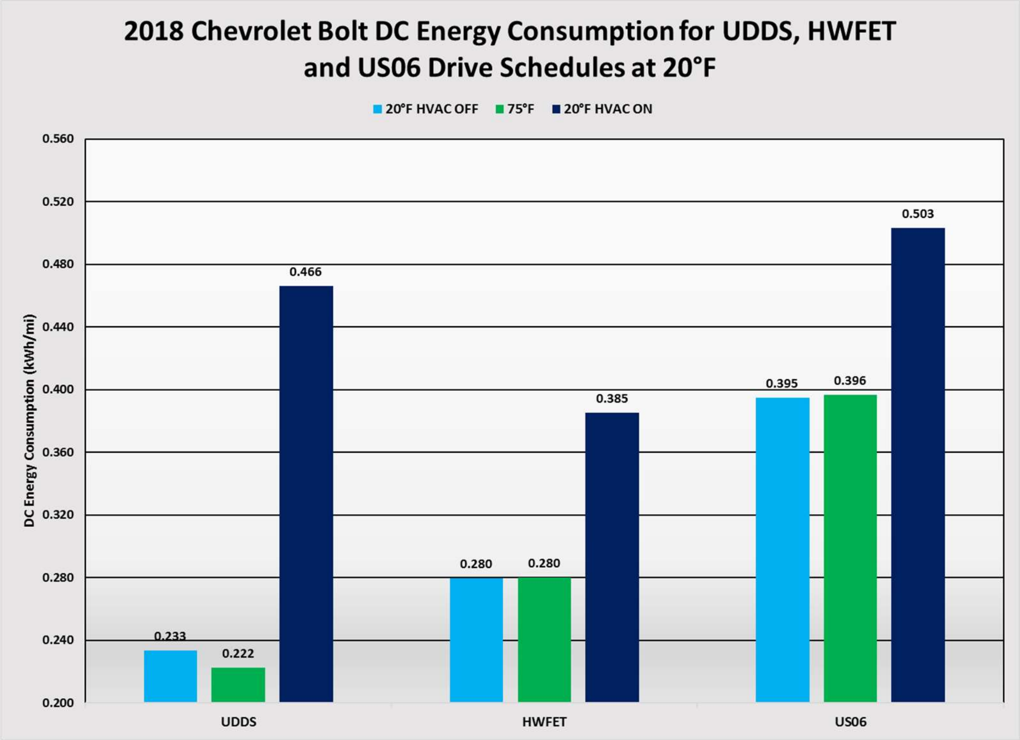


Figure 27: DC energy consumption at 20°F Image Source: AAA

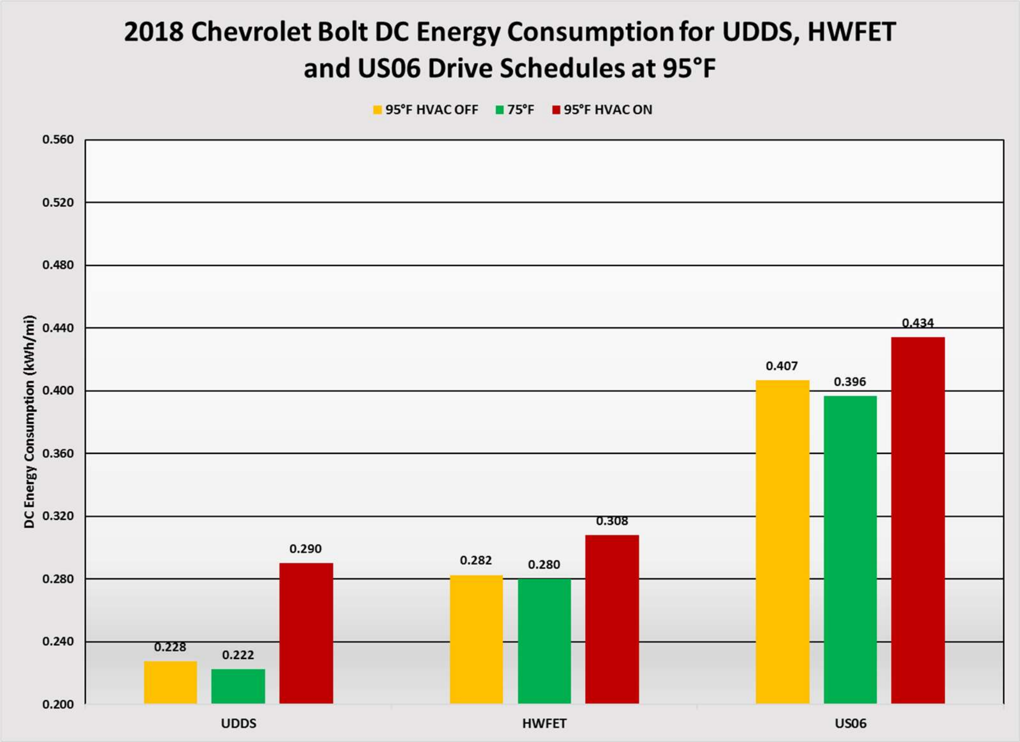


Figure 28: DC energy consumption at 95°F Image Source: AAA

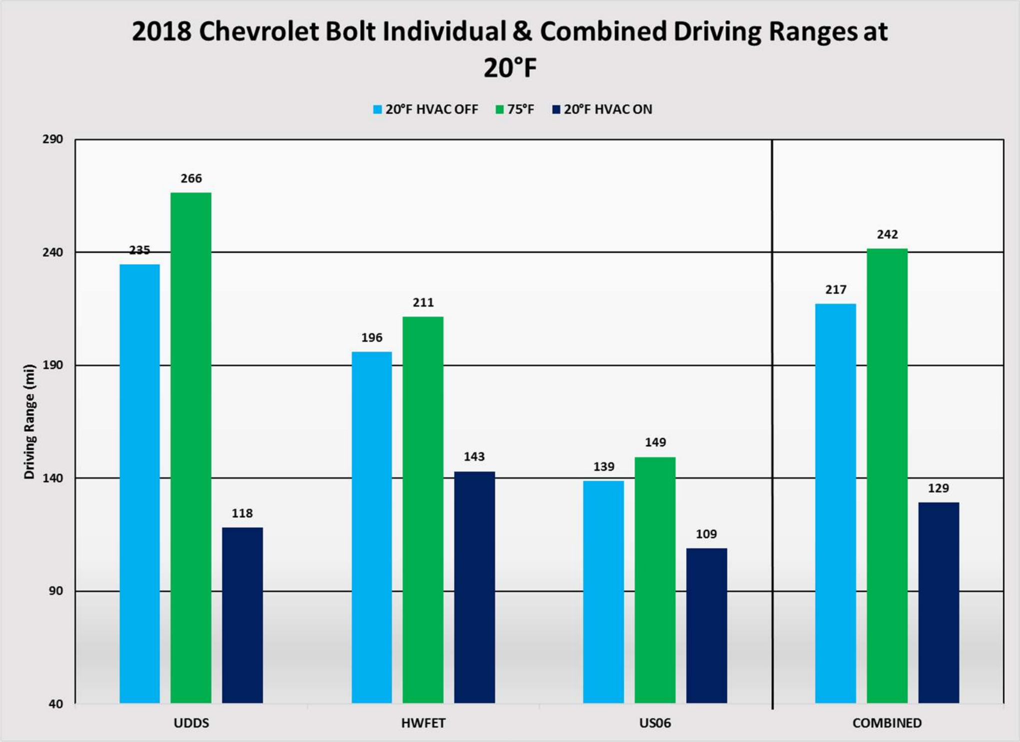


Figure 29: Driving range at 20°F Image Source: AAA

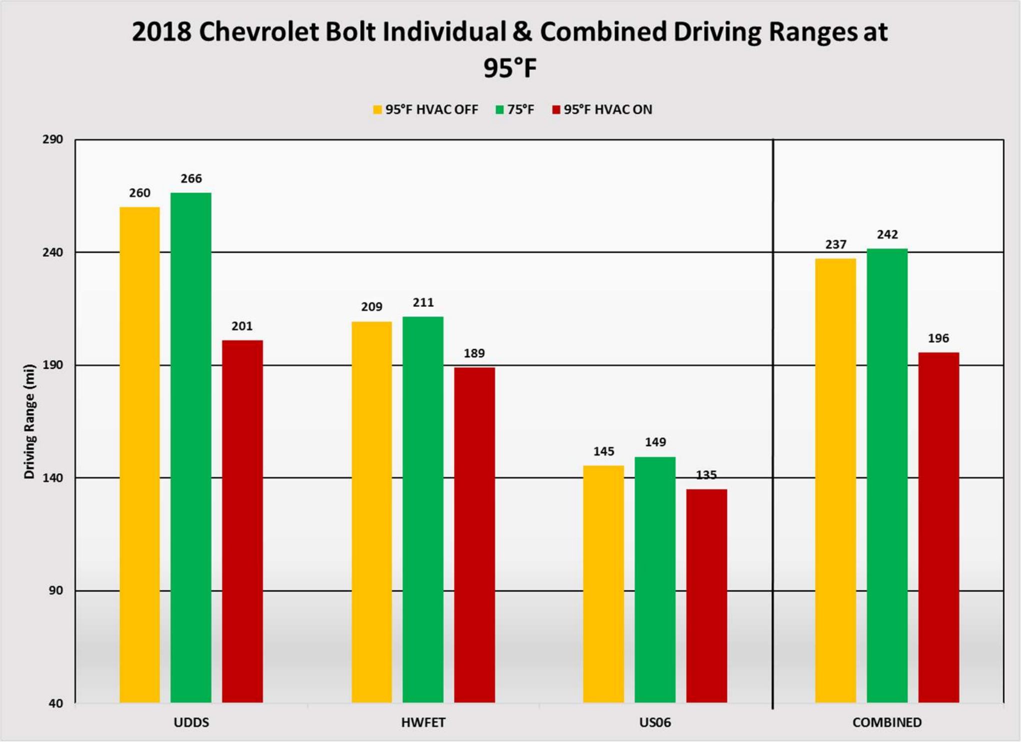


Figure 30: Driving range at 95°F Image Source: AAA

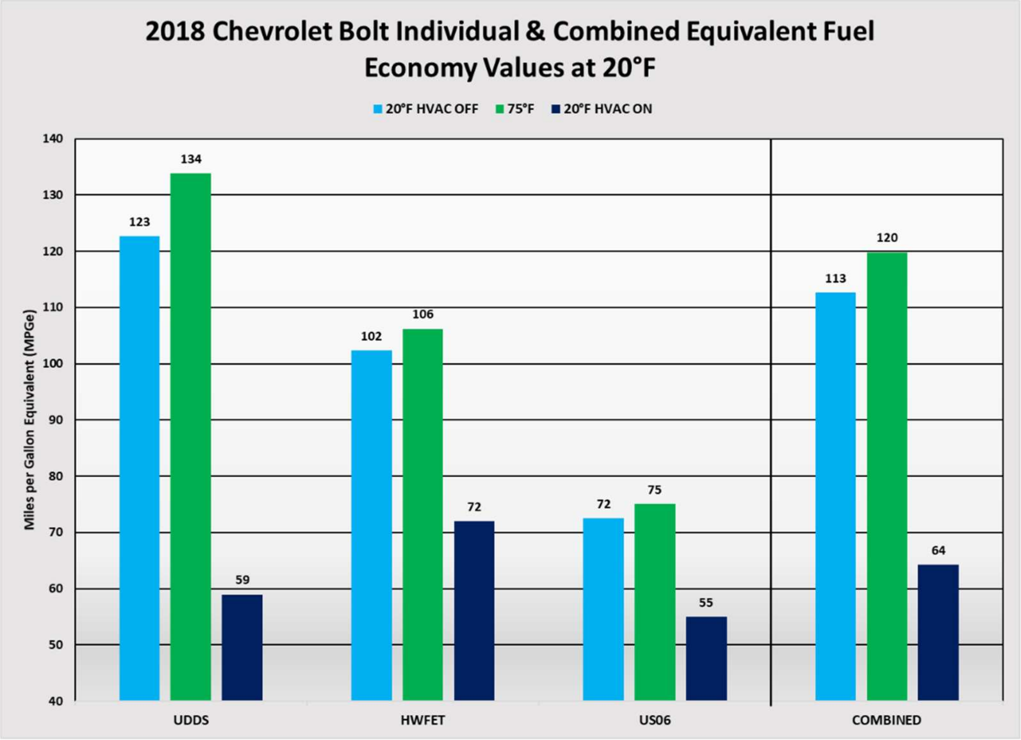


Figure 31: Equivalent fuel economy at 20°F Image Source: AAA

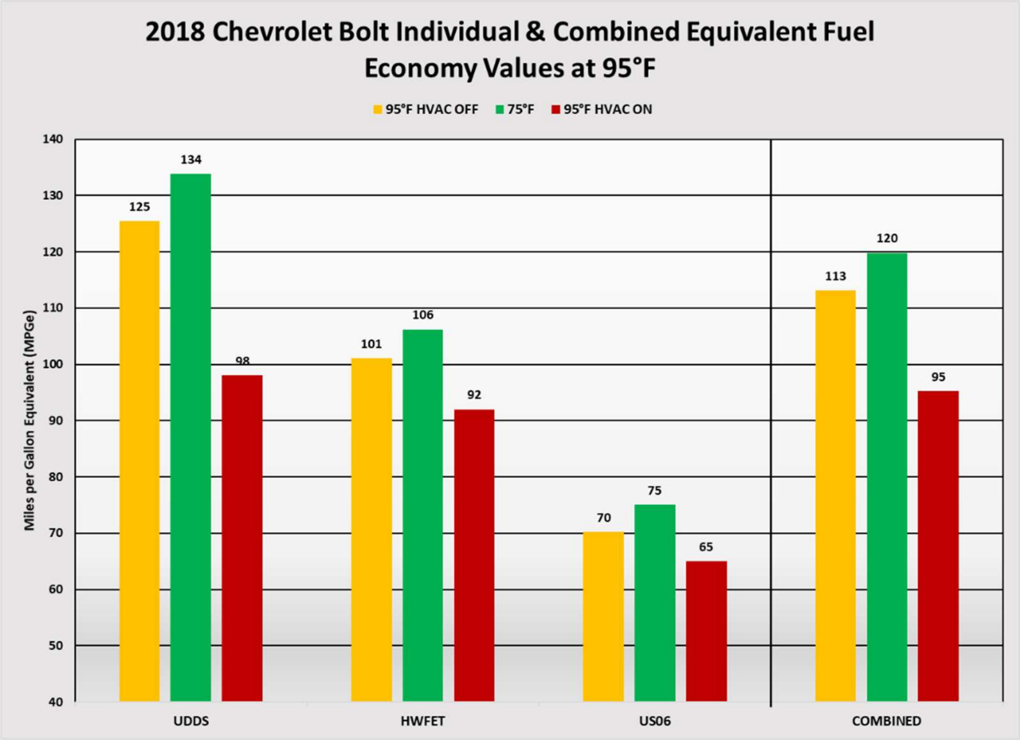


Figure 32: Equivalent fuel economy at 95°F Image Source: AAA

With the HVAC engaged, the driving range and equivalent fuel economy were significantly reduced for all drive types (city, highway, aggressive) at 20°F. Compared to 75°F with HVAC off, the combined driving range and combined MPGe were reduced by 47 percent and 46 percent, respectively.

At 95°F with the HVAC engaged, the driving range and equivalent fuel economy were reduced for all drive types. However, reductions were less severe than corresponding reductions exhibited at 20°F. Compared to 75°F, the combined driving range and equivalent fuel economy were reduced by 19 percent and 21 percent, respectively.

6.3.3 2018 Nissan Leaf

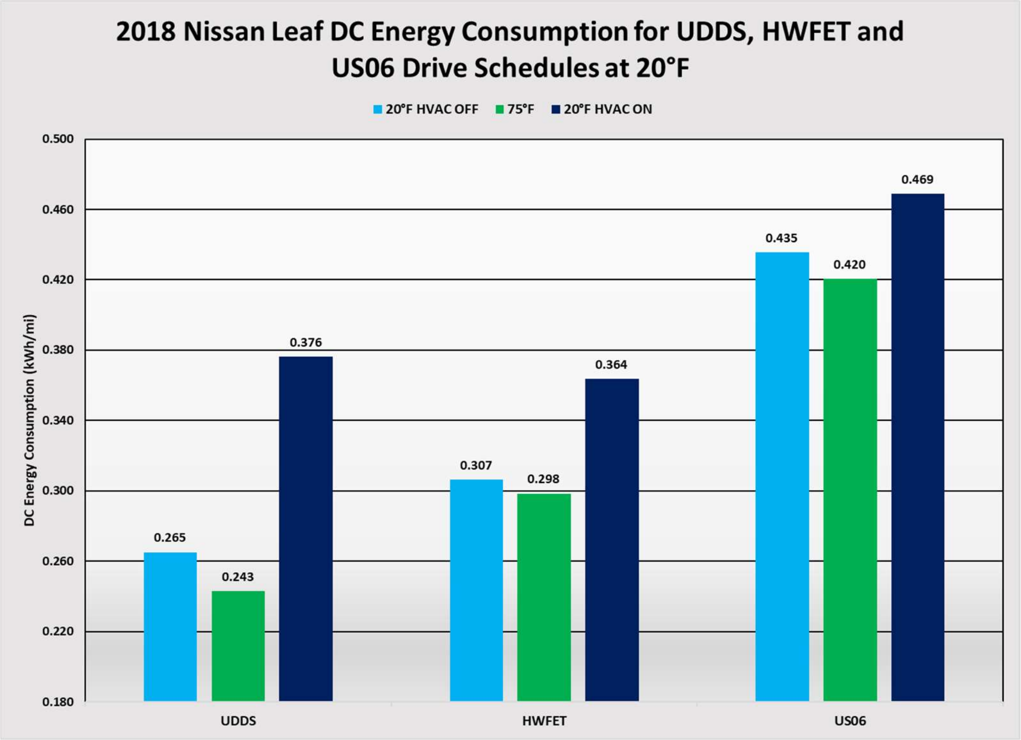


Figure 33: DC energy consumption at 20°F Image Source: AAA

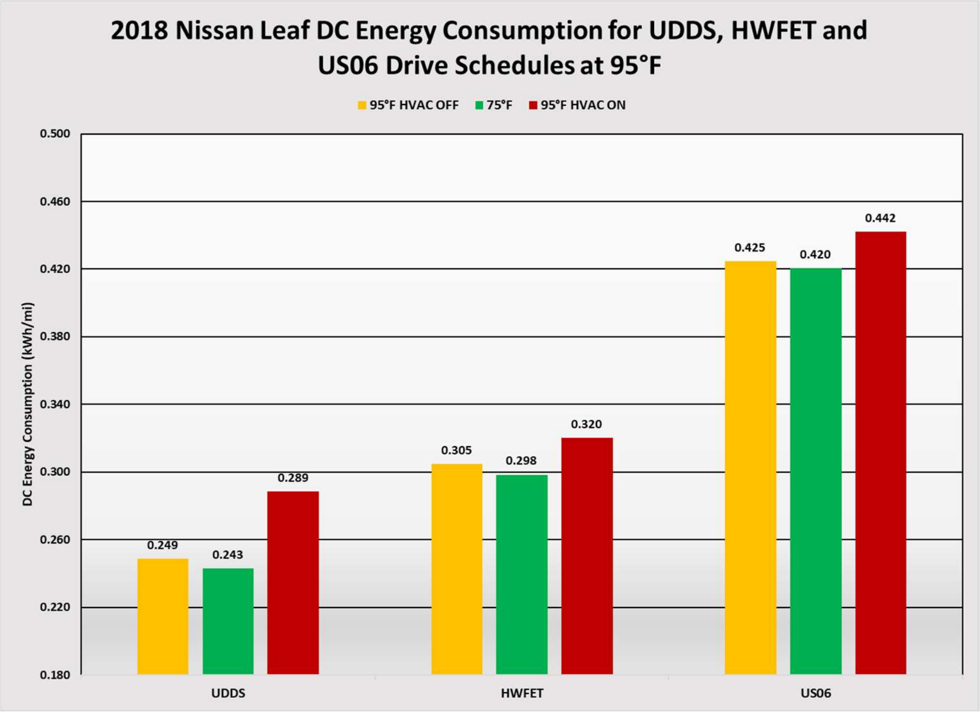


Figure 34: DC energy consumption at 95°F Image Source: AAA

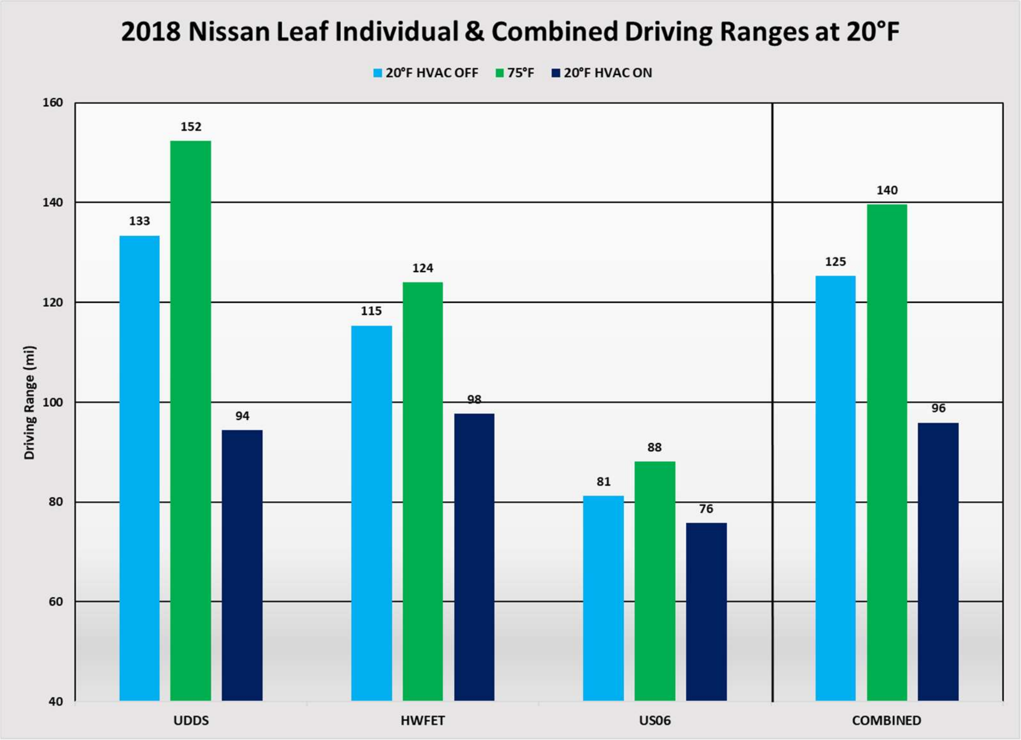


Figure 35: Driving range at 20°F Image Source: AAA

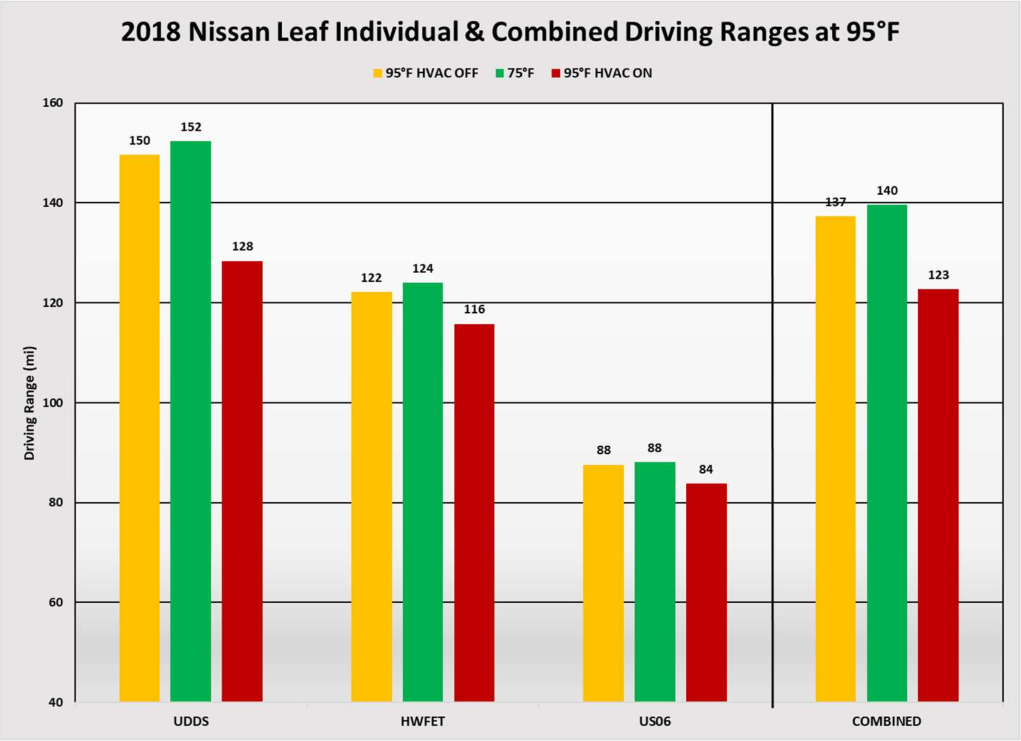


Figure 36: Driving range at 95°F Image Source: AAA

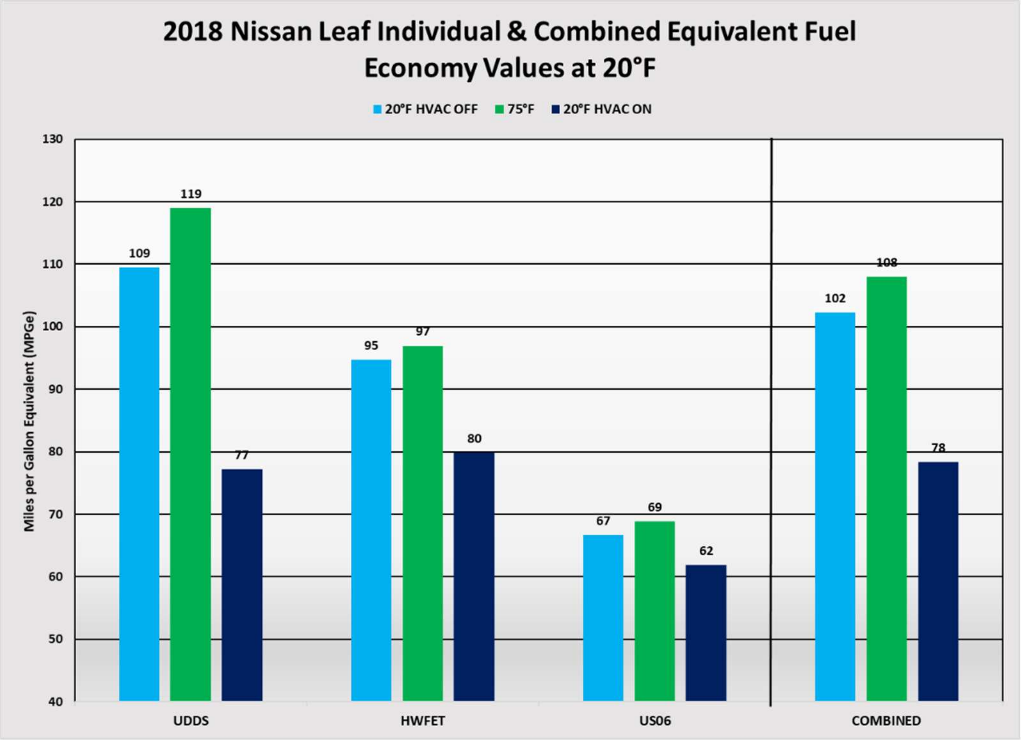


Figure 37: Equivalent fuel economy at 20°F Image Source: AAA

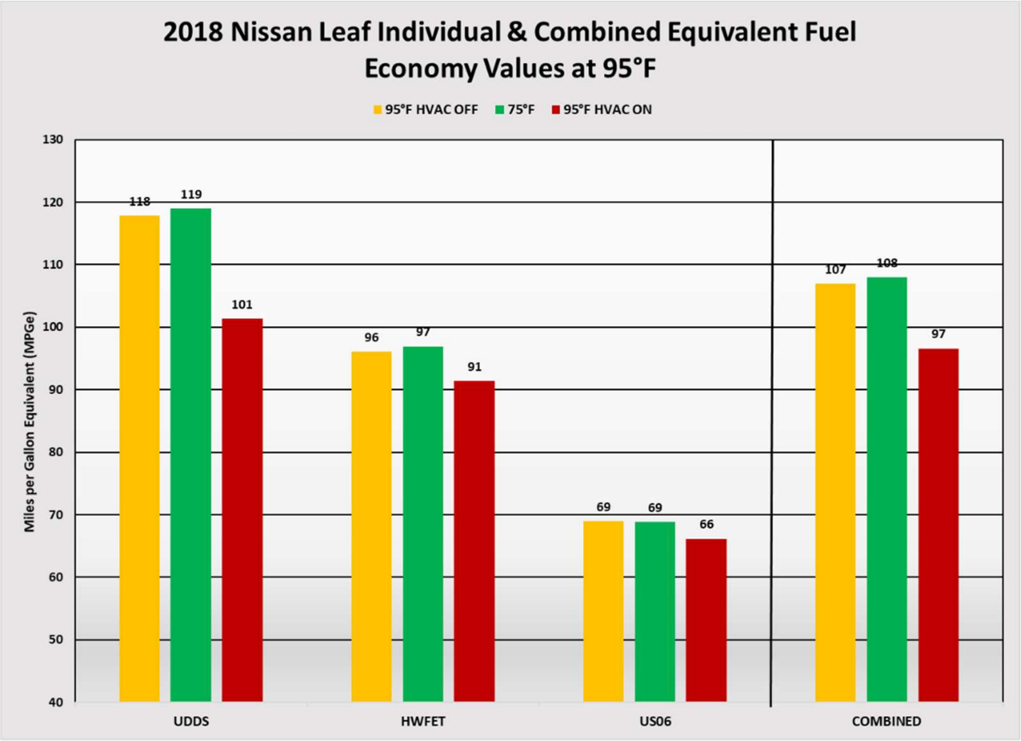


Figure 38: Equivalent fuel economy at 95°F Image Source: AAA

With the HVAC engaged, the driving range and equivalent fuel economy were significantly reduced for all drive types (city, highway, aggressive) at 20°F. Compared to 75°F without HVAC, the combined driving range and combined MPGe were reduced by 31 percent and 27 percent, respectively.

At 95°F with the HVAC engaged, the driving range and equivalent fuel economy were reduced for all drive types. However, reductions were less severe than corresponding reductions exhibited at 20°F. Compared to 75°F, the combined driving range and combined MPGe were reduced by 12 percent and 11 percent, respectively.

6.3.4 2017 Tesla Model S 75D

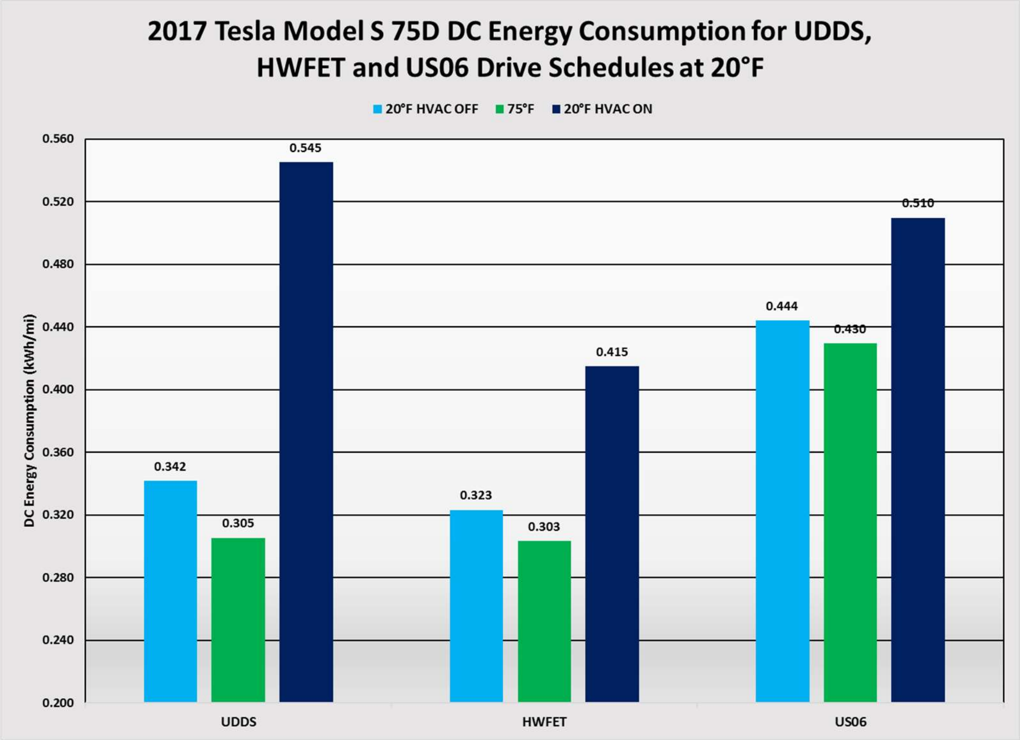


Figure 39: DC energy consumption at 20°F Image Source: AAA

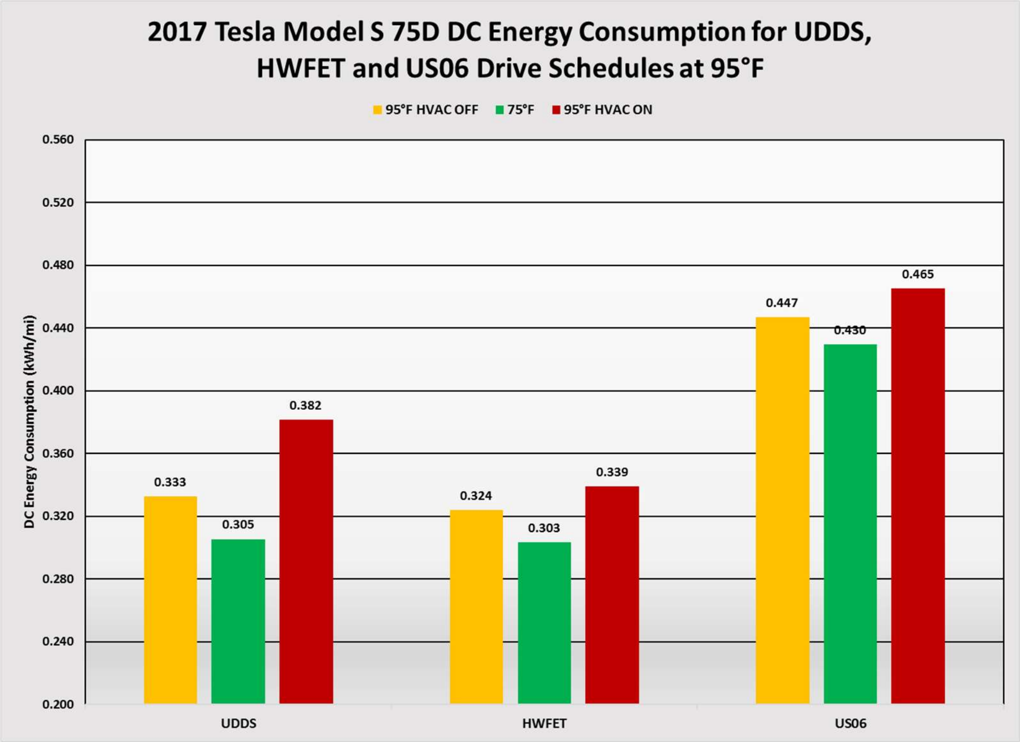


Figure 40: DC energy consumption at 95°F Image Source: AAA

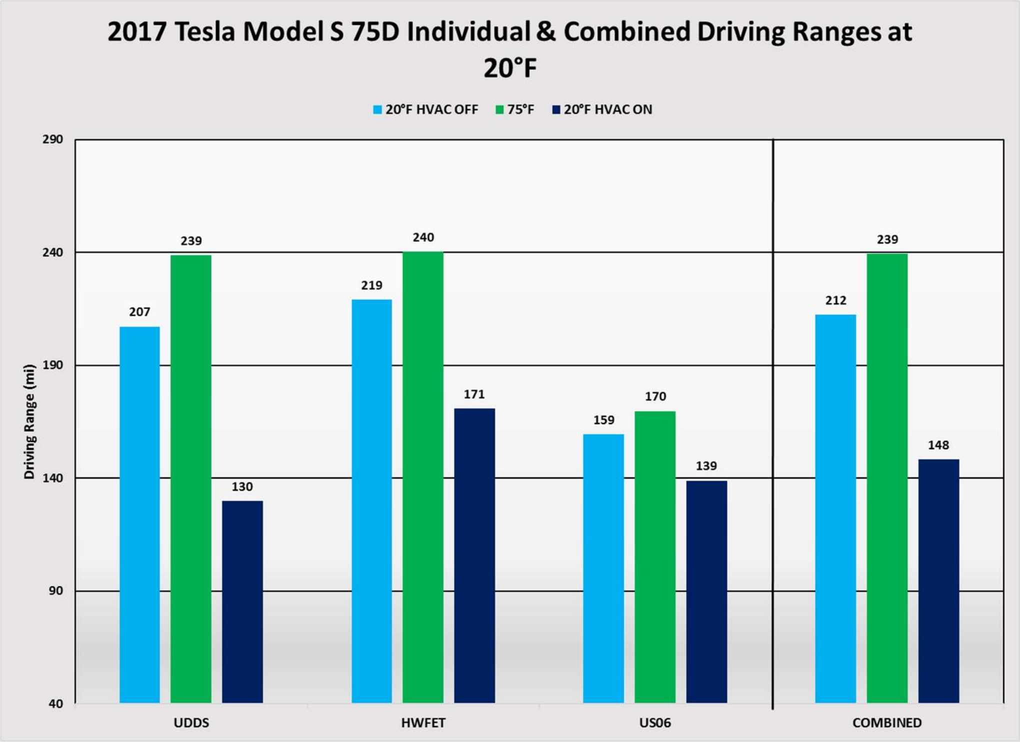


Figure 41: Driving range at 20°F Image Source: AAA

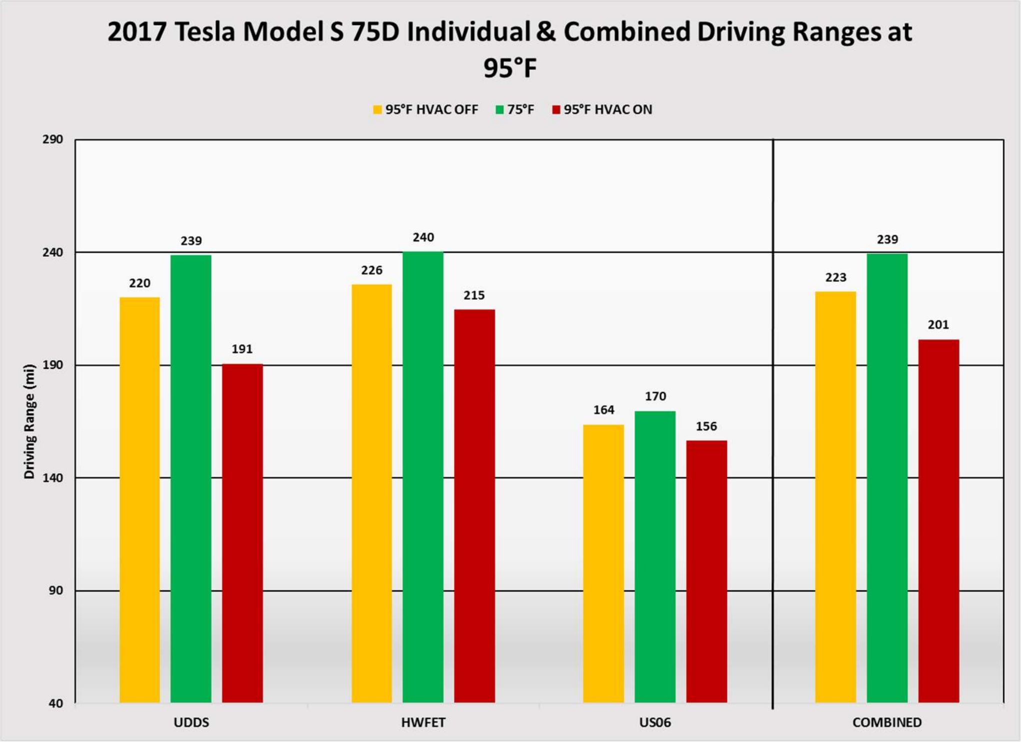


Figure 42: Driving range at 95°F Image Source: AAA

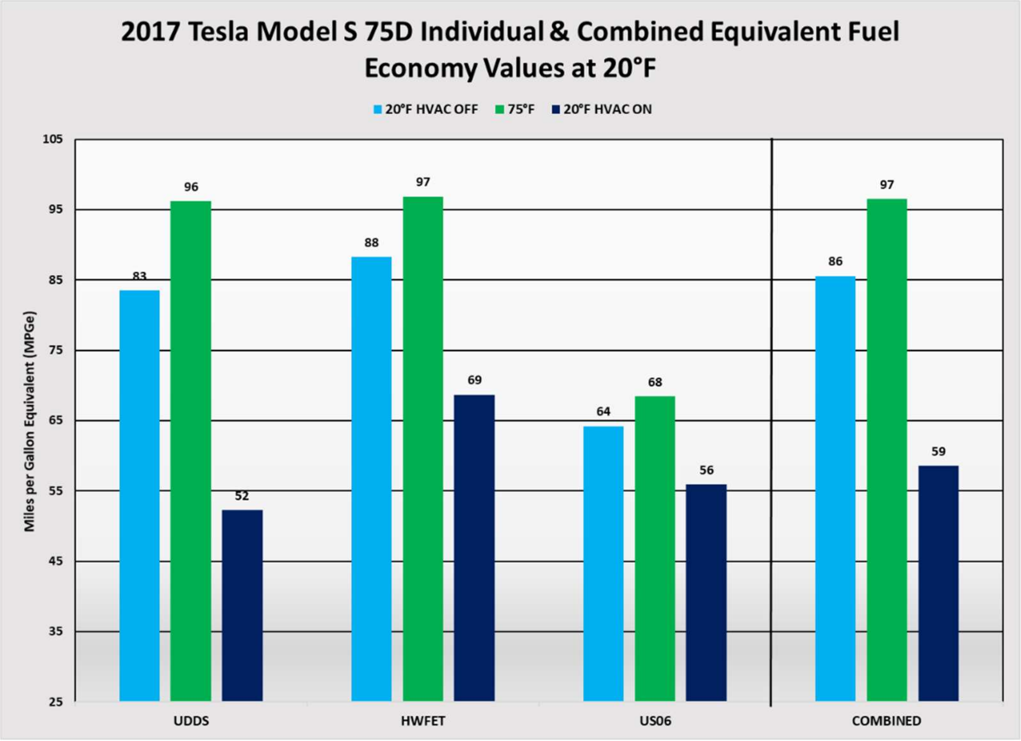


Figure 43: Equivalent fuel economy at 20°F Image Source: AAA

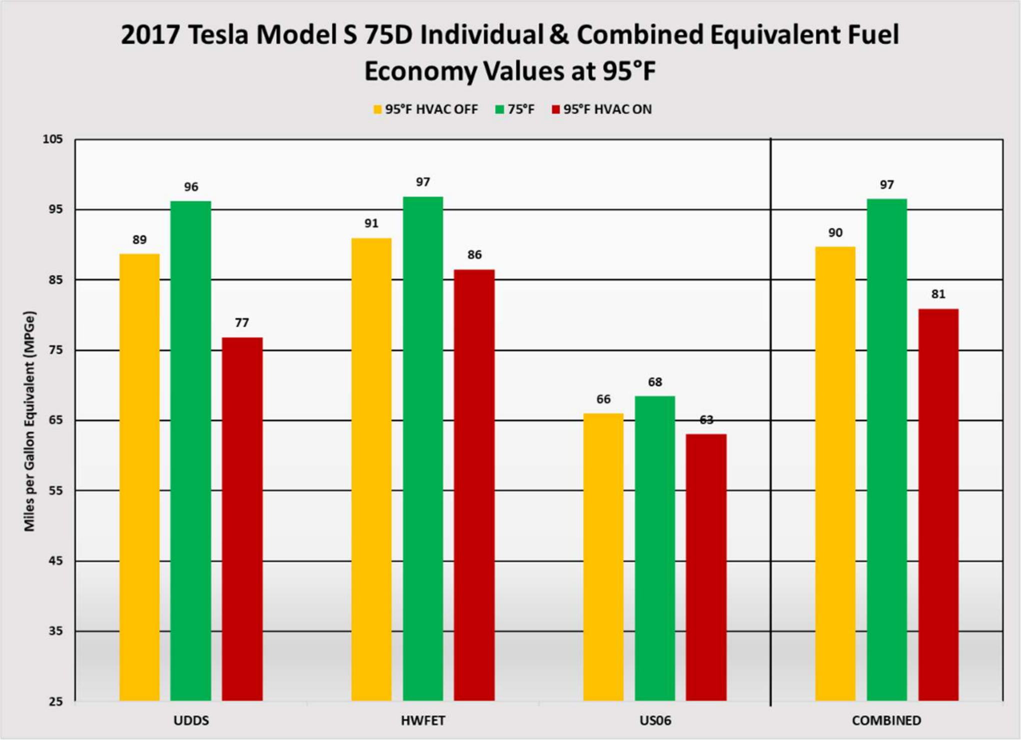


Figure 44: Equivalent fuel economy at 95°F Image Source: AAA

With the HVAC engaged, the driving range and equivalent fuel economy were significantly reduced for all drive types (city, highway, aggressive) at 20°F. Compared to 75°F without HVAC, the combined driving range and combined MPGe were reduced by 38 percent and 39 percent, respectively.

At 95°F with the HVAC engaged, the driving range and equivalent fuel economy were reduced for all drive types. However, reductions were less severe than corresponding reductions exhibited at 20°F. Compared to 75°F, both parameters were reduced by 16 percent.

6.3.5 2017 Volkswagen e-Golf

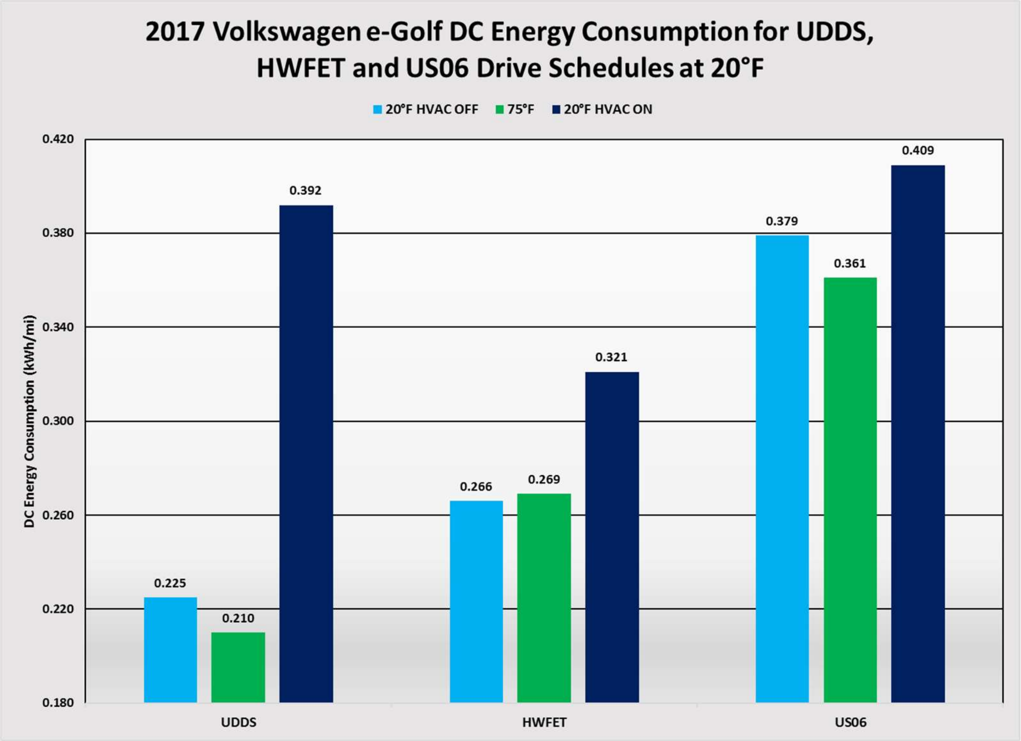


Figure 45: DC energy consumption at 20°F Image Source: AAA

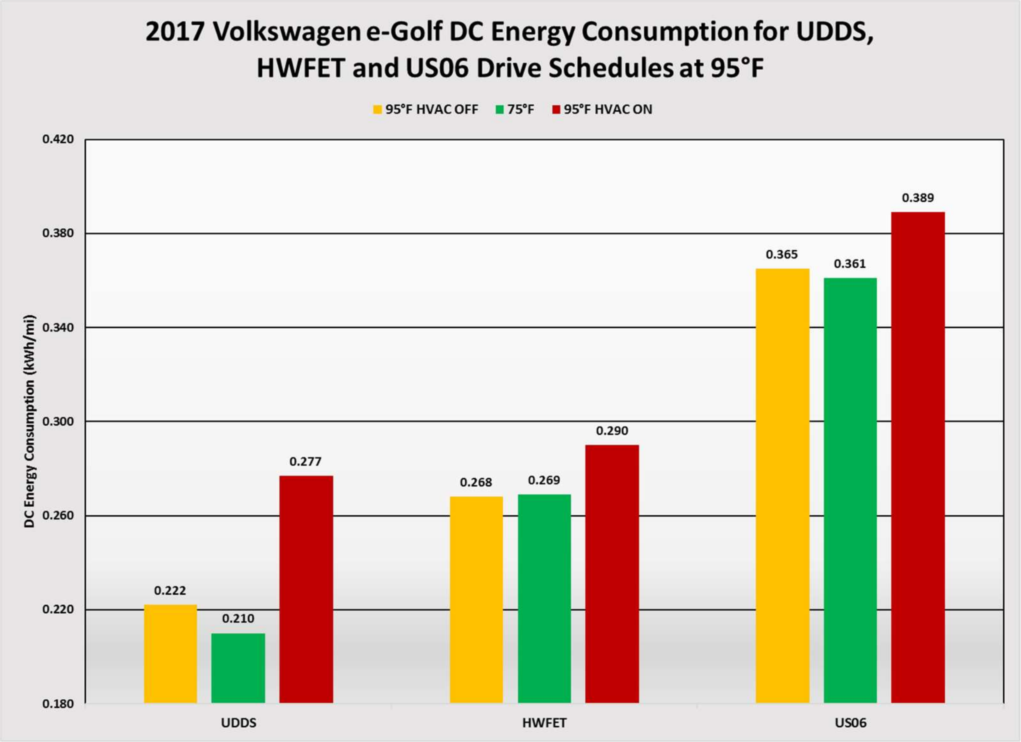


Figure 46: DC energy consumption at 95°F Image Source: AAA

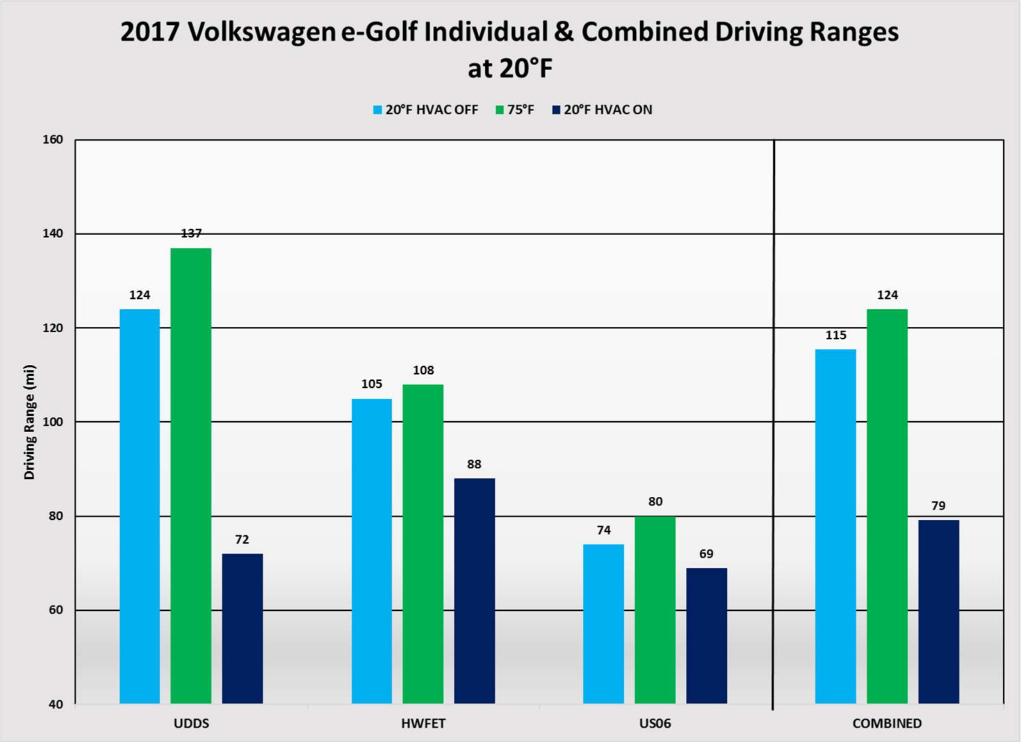


Figure 47: Driving range at 20°F Image Source: AAA

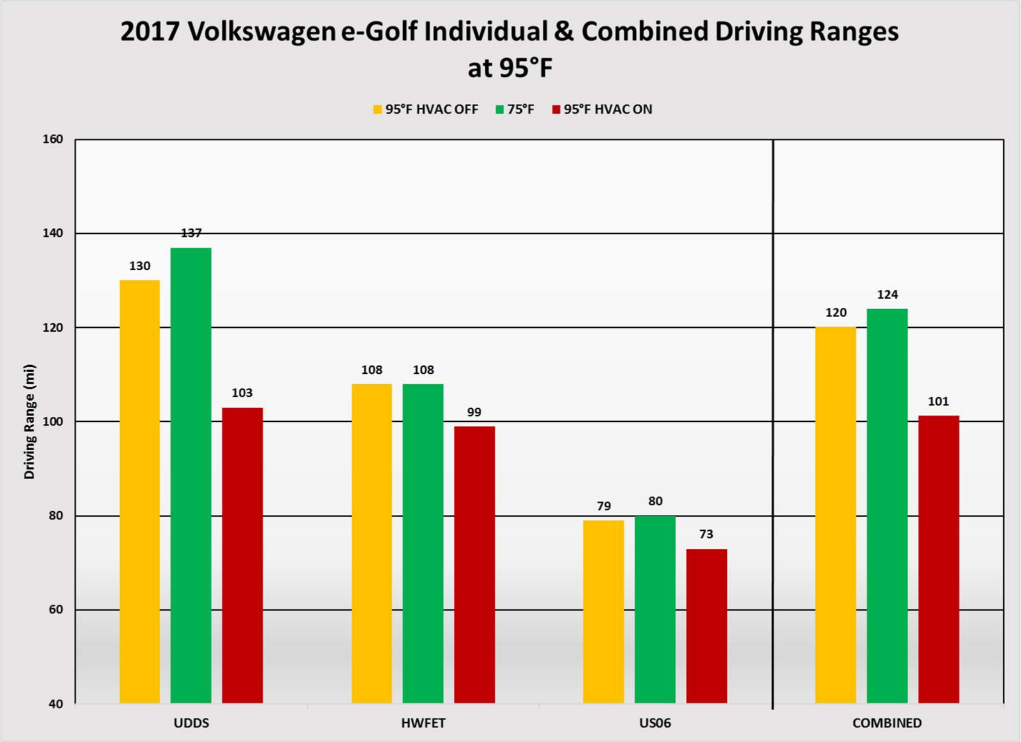


Figure 48: Driving range at 95°F Image Source: AAA

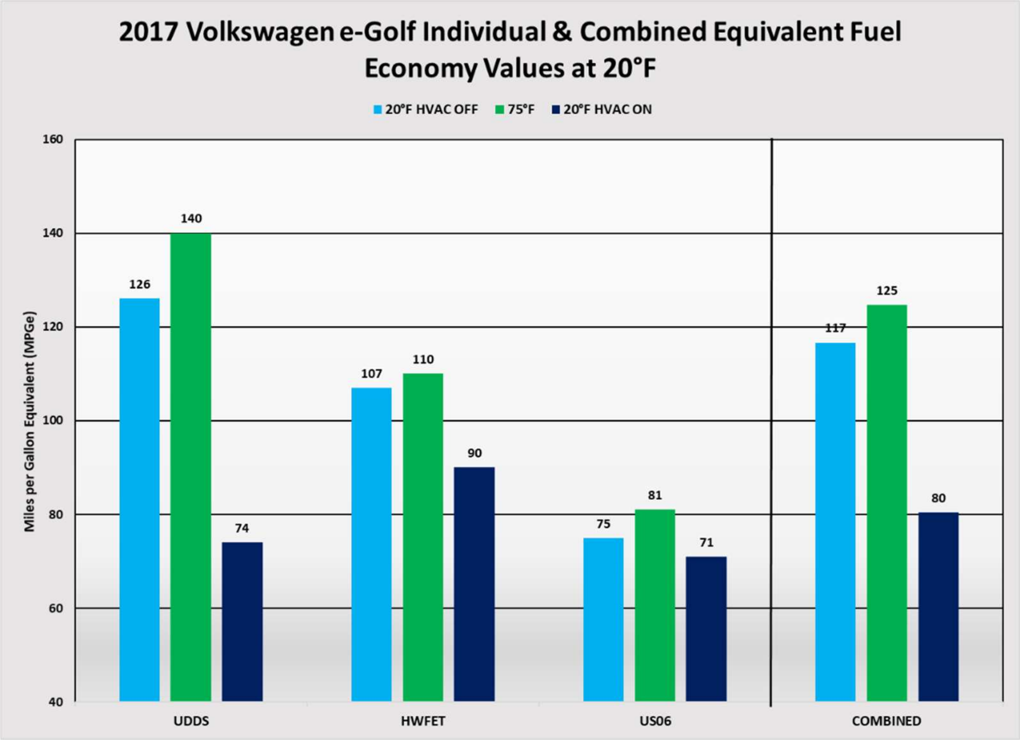


Figure 49: Equivalent fuel economy at 20°F Image Source: AAA

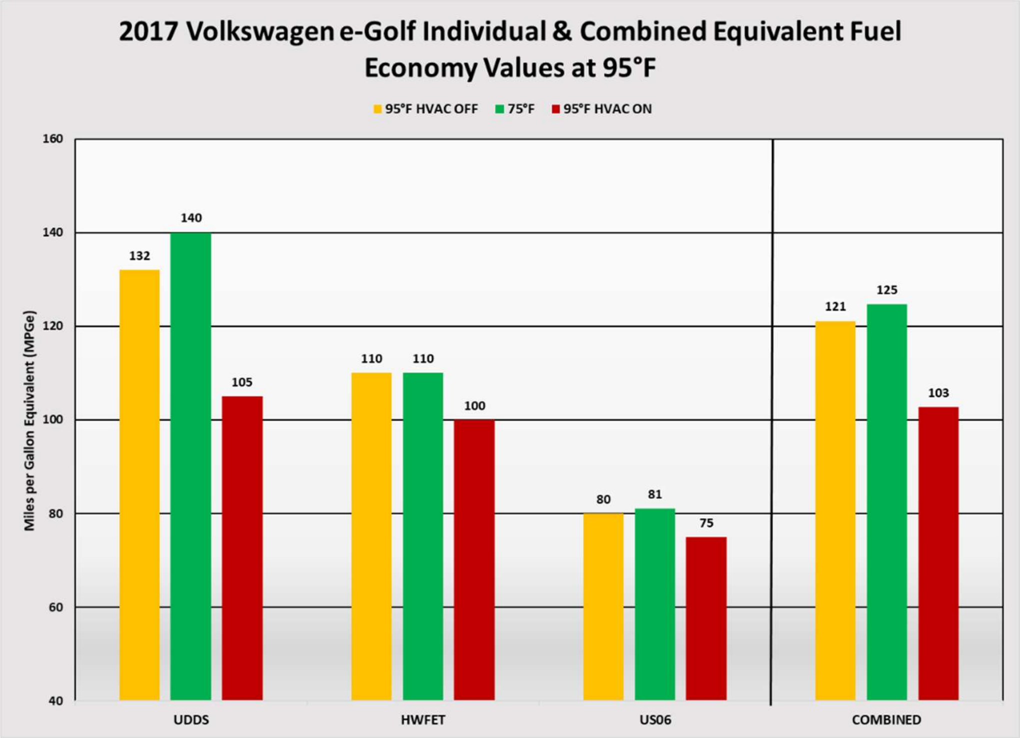


Figure 50: Equivalent fuel economy at 95°F Image Source: AAA

With the HVAC engaged, the driving range and equivalent fuel economy were significantly reduced for all drive types (city, highway, aggressive) at 20°F. Compared to 75°F without HVAC, the combined driving range and combined MPGe were both reduced by 36 percent.

At 95°F with the HVAC engaged, the driving range and equivalent fuel economy were reduced for all drive types. However, reductions were less severe than corresponding reductions exhibited at 20°F. Compared to 75°F, the combined driving range and combined MPGe were both reduced by 18 percent.

6.4 Summary of Test Results

For tests conducted at 20°F and 95°F, HVAC use resulted in significant reductions in driving range and equivalent fuel economy. For all test vehicles, it was observed that the UDDS drive cycle was most affected in terms of increased energy consumption, reduced driving range and reduced MPGe. This consequently resulted in reductions of combined driving range and combined MPGe values as previously discussed in Section 5.3.

Compared to 75°F, HVAC use at 20°F resulted in an average reduction of combined driving range and combined MPGe by 41 percent and 39 percent, respectively. HVAC use at 95°F resulted in an average reduction of both combined driving range and combined MPGe by 17 percent.

Figures 51-52 illustrate the percent change of combined driving range and combined MPGe values relative to testing conducted at an ambient temperature of 75°F.

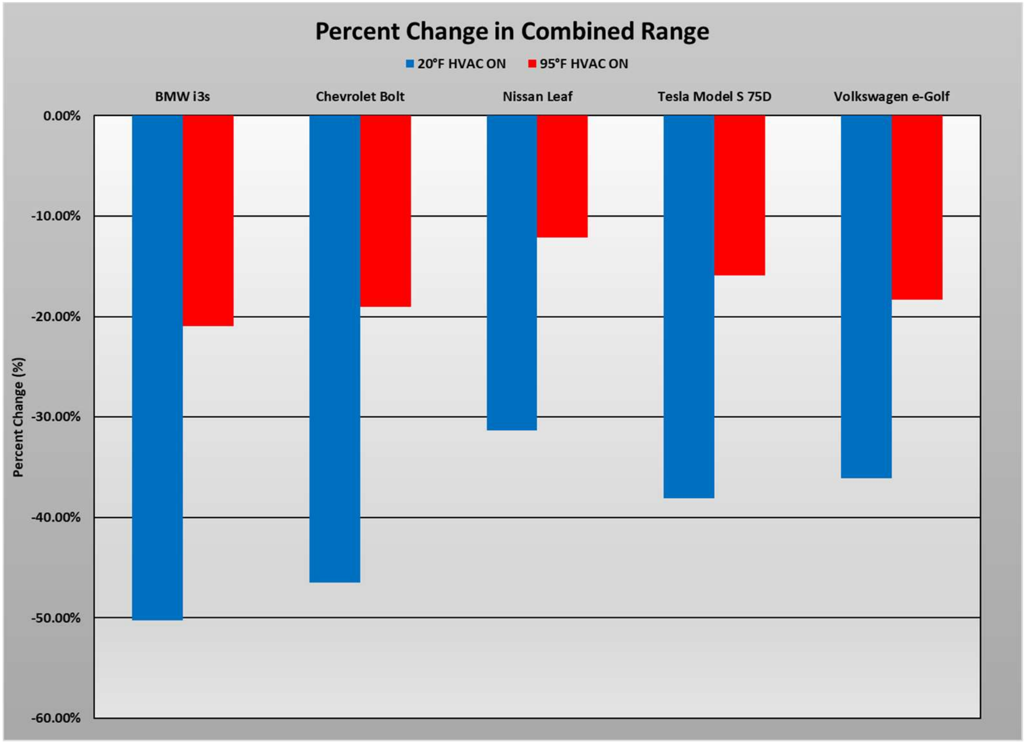


Figure 51: Percent change in combined driving range relative to testing conducted at 75°F Image Source: AAA

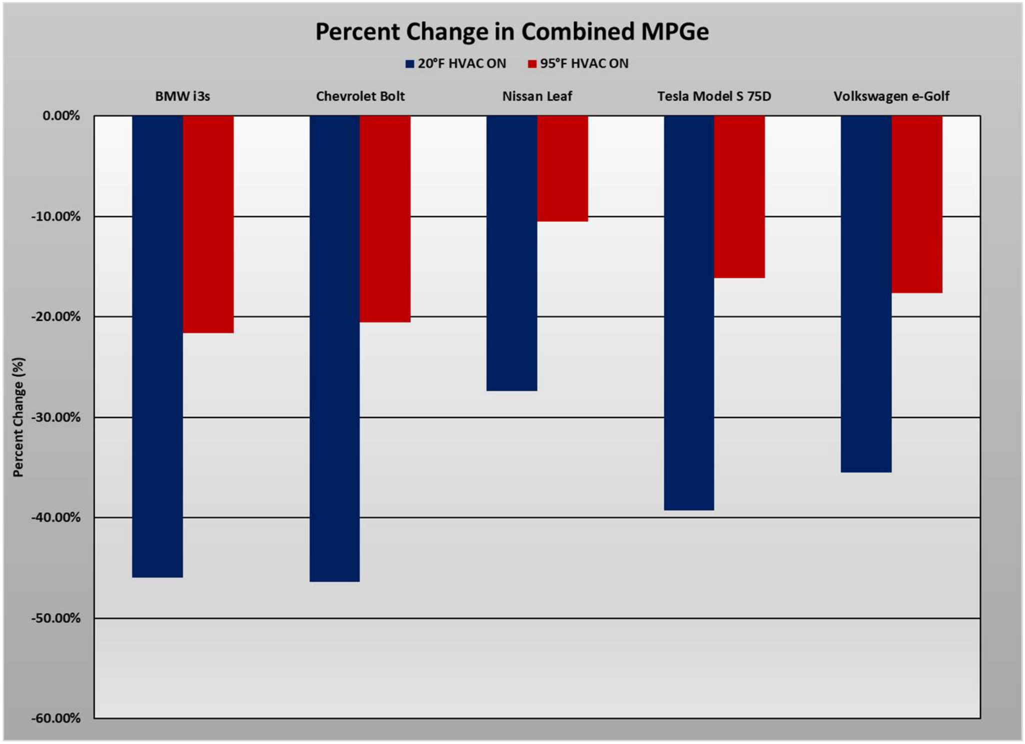


Figure 52: Percent change in combined MPGe relative to testing conducted at 75°F Image Source: AAA

With the HVAC engaged, HWFET and US06 drive cycles also exhibited reductions in terms of driving range and equivalent fuel economy at 20°F and 95°F. For all test vehicles, reductions were more severe at 20°F.

Hot or cold ambient temperatures in combination with HVAC use resulted in significant reductions of driving range and equivalent fuel economy for all test vehicles. It was noted that the cabin heating mechanism did not significantly affect vehicle performance in terms of energy consumption, driving range and equivalent fuel economy. Heat pumps are largely ineffective within extremely cold environments. At 20°F, auxiliary resistive heating was likely utilized to maintain cabin temperature.

Motorists who own electric vehicles should be mindful that regardless of driving behavior, hot and cold ambient temperatures combined with HVAC use results in significant reductions of driving range and equivalent fuel economy. Minimizing HVAC use regardless of ambient temperature can mitigate these impacts.

7 Inquiry #3: Based on real-world driving range estimations, what is the cost of driving in various environments with and without the HVAC system engaged?

7.1 Objective

For urban, highway, combined city/highway and aggressive driving behavior, quantify the cost of driving in hot and cold environments with and without the HVAC system engaged. Additionally, the cost of driving at 75°F will be quantified.

7.2 Methodology

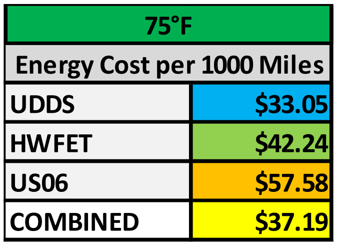
For each vehicle, the miles traveled per kilowatt-hour was calculated for each drive cycle at all tested ambient temperatures according to Equation 5:

$$\frac{Mi}{kWh_{Drive\ Cycle}} = \frac{1}{RAF*DC\ Discharge\ Energy_{Drive\ Cycle}} * 0.7 \qquad (5)$$

Raw values were multiplied by 0.7 to reflect real-world figures obtained during naturalistic driving. The energy costs provided in Section 7.3 assume 1000 miles driven per month and an average national base electricity cost of 12.5 cents per kilowatt-hour. As discussed in Section 2.5.1, the base electricity rate utilized herein does not account for additional taxes and surcharges that are dependent on municipality and region.

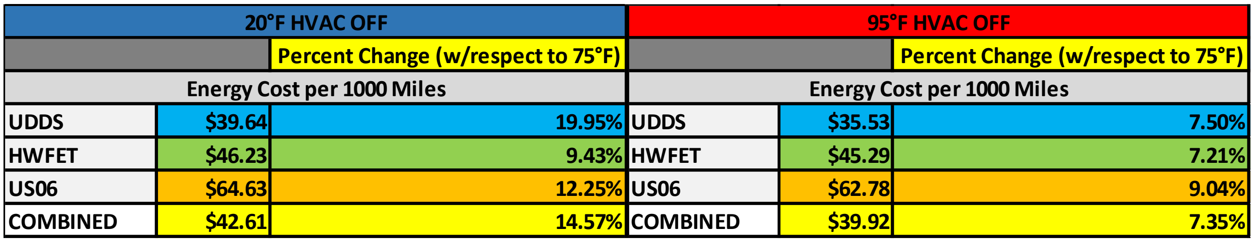
7.3 Results

7.3.1 2018 BMW i3s



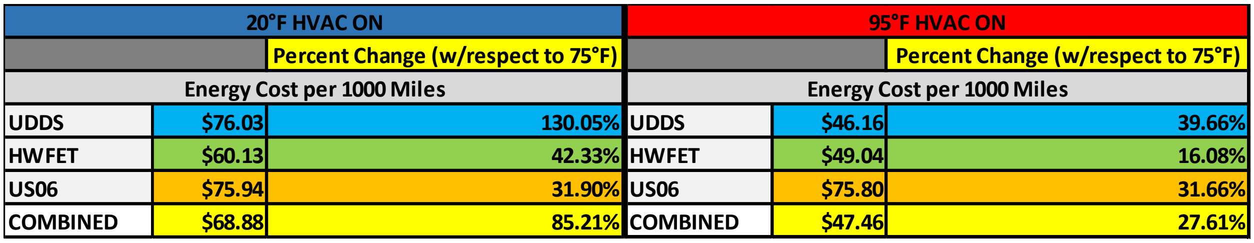
75°F	
Energy Cost per 1000 Miles	
UDDS	$33.05
HWFET	$42.24
US06	$57.58
COMBINED	$37.19

Figure 53: Energy cost to drive 1000 miles at 75°F for city, highway, aggressive and combined driving Image Source: AAA



20°F HVAC OFF			95°F HVAC OFF		
		Percent Change (w/respect to 75°F)			Percent Change (w/respect to 75°F)
Energy Cost per 1000 Miles			Energy Cost per 1000 Miles		
UDDS	$39.64	19.95%	UDDS	$35.53	7.50%
HWFET	$46.23	9.43%	HWFET	$45.29	7.21%
US06	$64.63	12.25%	US06	$62.78	9.04%
COMBINED	$42.61	14.57%	COMBINED	$39.92	7.35%

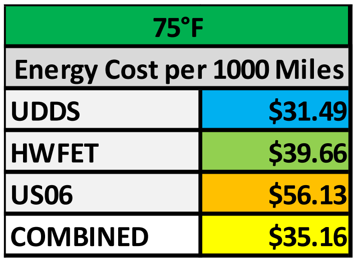
Figure 54: Energy cost to drive 1000 miles without HVAC for city, highway, aggressive and combined driving Image Source: AAA



20°F HVAC ON			95°F HVAC ON		
		Percent Change (w/respect to 75°F)			Percent Change (w/respect to 75°F)
Energy Cost per 1000 Miles			Energy Cost per 1000 Miles		
UDDS	$76.03	130.05%	UDDS	$46.16	39.66%
HWFET	$60.13	42.33%	HWFET	$49.04	16.08%
US06	$75.94	31.90%	US06	$75.80	31.66%
COMBINED	$68.88	85.21%	COMBINED	$47.46	27.61%

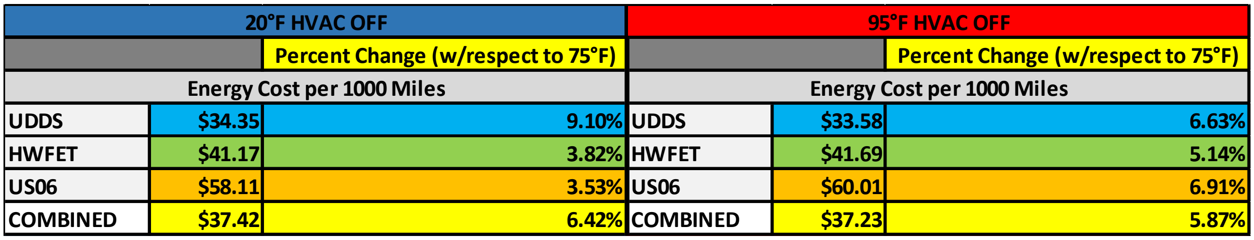
Figure 55: Energy cost to drive 1000 miles with HVAC for city, highway, aggressive and combined driving Image Source: AAA

7.3.2 2018 Chevrolet Bolt



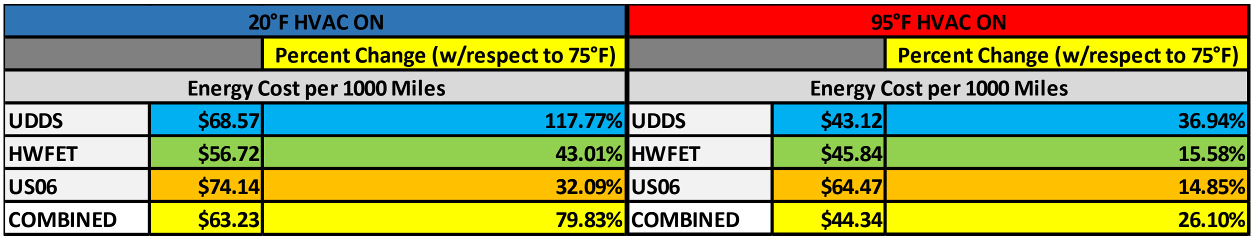
75°F	
Energy Cost per 1000 Miles	
UDDS	$31.49
HWFET	$39.66
US06	$56.13
COMBINED	$35.16

Figure 56: Energy cost to drive 1000 miles at 75°F for city, highway, aggressive and combined driving Image Source: AAA



20°F HVAC OFF			95°F HVAC OFF		
		Percent Change (w/respect to 75°F)			Percent Change (w/respect to 75°F)
Energy Cost per 1000 Miles			Energy Cost per 1000 Miles		
UDDS	$34.35	9.10%	UDDS	$33.58	6.63%
HWFET	$41.17	3.82%	HWFET	$41.69	5.14%
US06	$58.11	3.53%	US06	$60.01	6.91%
COMBINED	$37.42	6.42%	COMBINED	$37.23	5.87%

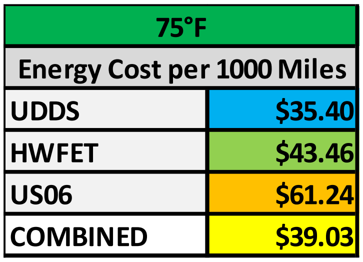
Figure 57: Energy cost to drive 1000 miles without HVAC for city, highway, aggressive and combined driving Image Source: AAA



20°F HVAC ON			95°F HVAC ON		
		Percent Change (w/respect to 75°F)			Percent Change (w/respect to 75°F)
Energy Cost per 1000 Miles			Energy Cost per 1000 Miles		
UDDS	$68.57	117.77%	UDDS	$43.12	36.94%
HWFET	$56.72	43.01%	HWFET	$45.84	15.58%
US06	$74.14	32.09%	US06	$64.47	14.85%
COMBINED	$63.23	79.83%	COMBINED	$44.34	26.10%

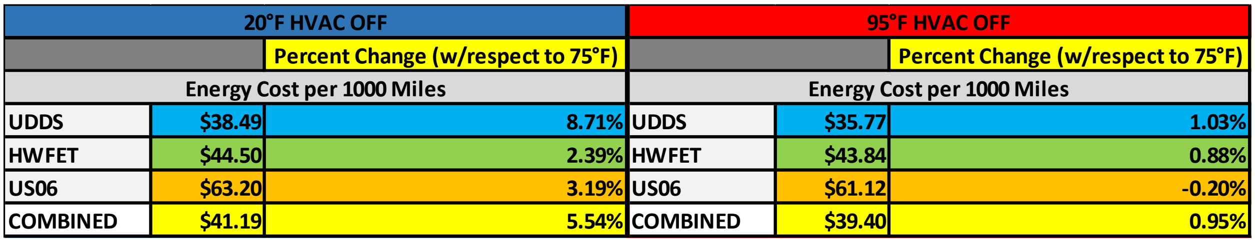
Figure 58: Energy cost to drive 1000 miles with HVAC for city, highway, aggressive and combined driving Image Source: AAA

7.3.3 2018 Nissan Leaf



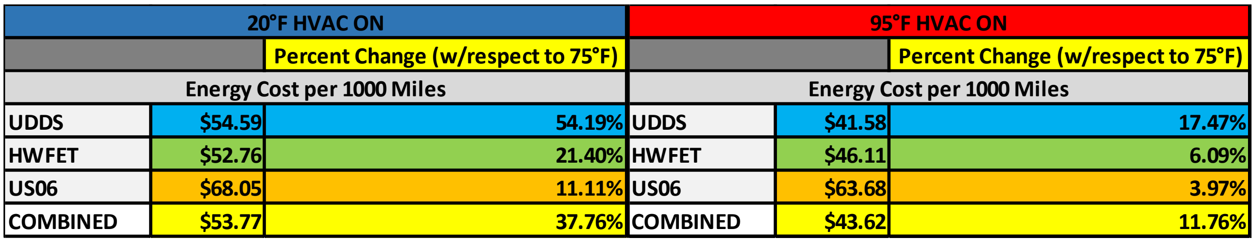
75°F	
Energy Cost per 1000 Miles	
UDDS	$35.40
HWFET	$43.46
US06	$61.24
COMBINED	$39.03

Figure 59: Energy cost to drive 1000 miles at 75°F for city, highway, aggressive and combined driving Image Source: AAA



20°F HVAC OFF			95°F HVAC OFF		
		Percent Change (w/respect to 75°F)			Percent Change (w/respect to 75°F)
Energy Cost per 1000 Miles			Energy Cost per 1000 Miles		
UDDS	$38.49	8.71%	UDDS	$35.77	1.03%
HWFET	$44.50	2.39%	HWFET	$43.84	0.88%
US06	$63.20	3.19%	US06	$61.12	-0.20%
COMBINED	$41.19	5.54%	COMBINED	$39.40	0.95%

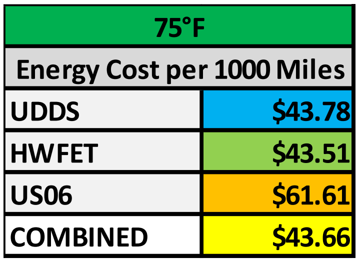
Figure 60: Energy cost to drive 1000 miles without HVAC for city, highway, aggressive and combined driving Image Source: AAA



20°F HVAC ON			95°F HVAC ON		
		Percent Change (w/respect to 75°F)			Percent Change (w/respect to 75°F)
Energy Cost per 1000 Miles			Energy Cost per 1000 Miles		
UDDS	$54.59	54.19%	UDDS	$41.58	17.47%
HWFET	$52.76	21.40%	HWFET	$46.11	6.09%
US06	$68.05	11.11%	US06	$63.68	3.97%
COMBINED	$53.77	37.76%	COMBINED	$43.62	11.76%

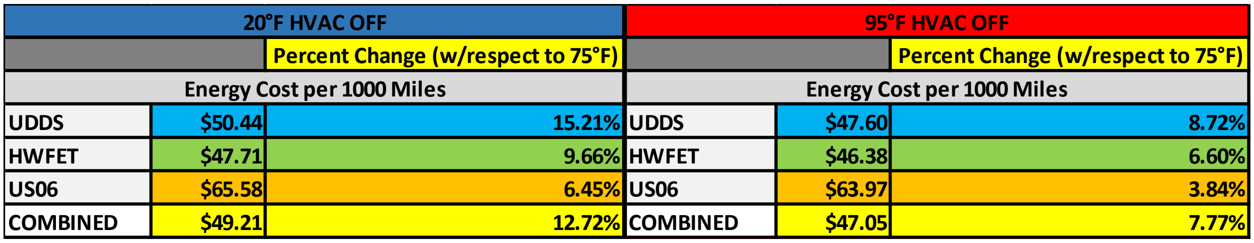
Figure 61: Energy cost to drive 1000 miles with HVAC for city, highway, aggressive and combined driving Image Source: AAA

7.3.4 2017 Tesla Model S 75D



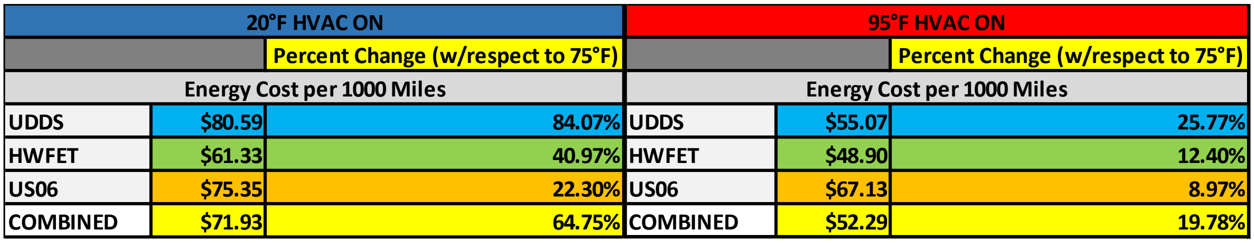
75°F	
Energy Cost per 1000 Miles	
UDDS	$43.78
HWFET	$43.51
US06	$61.61
COMBINED	$43.66

Figure 62: Energy cost to drive 1000 miles at 75°F for city, highway, aggressive and combined driving Image Source: AAA



20°F HVAC OFF			95°F HVAC OFF		
		Percent Change (w/respect to 75°F)			Percent Change (w/respect to 75°F)
Energy Cost per 1000 Miles			Energy Cost per 1000 Miles		
UDDS	$50.44	15.21%	UDDS	$47.60	8.72%
HWFET	$47.71	9.66%	HWFET	$46.38	6.60%
US06	$65.58	6.45%	US06	$63.97	3.84%
COMBINED	$49.21	12.72%	COMBINED	$47.05	7.77%

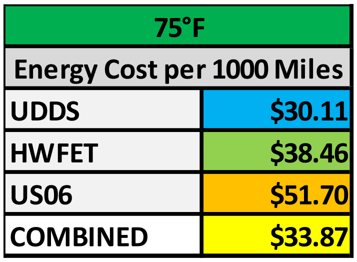
Figure 63: Energy cost to drive 1000 miles without HVAC for city, highway, aggressive and combined driving Image Source: AAA



20°F HVAC ON			95°F HVAC ON		
		Percent Change (w/respect to 75°F)			Percent Change (w/respect to 75°F)
Energy Cost per 1000 Miles			Energy Cost per 1000 Miles		
UDDS	$80.59	84.07%	UDDS	$55.07	25.77%
HWFET	$61.33	40.97%	HWFET	$48.90	12.40%
US06	$75.35	22.30%	US06	$67.13	8.97%
COMBINED	$71.93	64.75%	COMBINED	$52.29	19.78%

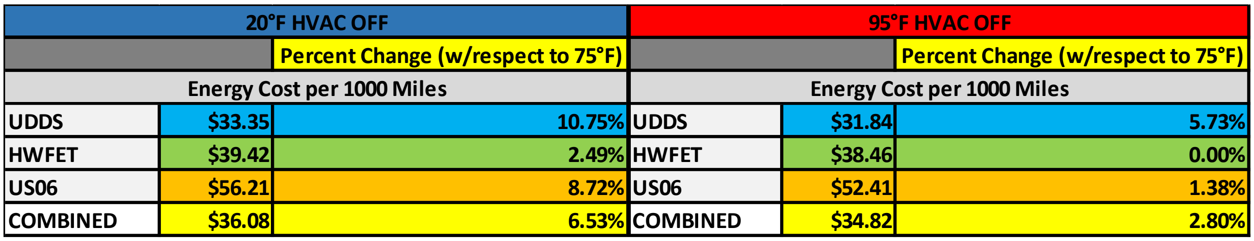
Figure 64: Energy cost to drive 1000 miles with HVAC for city, highway, aggressive and combined driving Image Source: AAA

7.3.5 2017 Volkswagen e-Golf



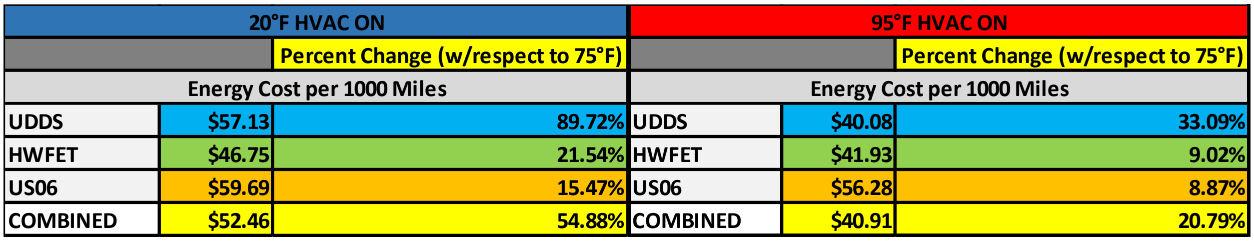
75°F	
Energy Cost per 1000 Miles	
UDDS	$30.11
HWFET	$38.46
US06	$51.70
COMBINED	$33.87

Figure 65: Energy cost to drive 1000 miles at 75°F for city, highway, aggressive and combined driving Image Source: AAA



20°F HVAC OFF			95°F HVAC OFF		
		Percent Change (w/respect to 75°F)			Percent Change (w/respect to 75°F)
Energy Cost per 1000 Miles			Energy Cost per 1000 Miles		
UDDS	$33.35	10.75%	UDDS	$31.84	5.73%
HWFET	$39.42	2.49%	HWFET	$38.46	0.00%
US06	$56.21	8.72%	US06	$52.41	1.38%
COMBINED	$36.08	6.53%	COMBINED	$34.82	2.80%

Figure 66: Energy cost to drive 1000 miles without HVAC for city, highway, aggressive and combined driving Image Source: AAA



20°F HVAC ON			95°F HVAC ON		
		Percent Change (w/respect to 75°F)			Percent Change (w/respect to 75°F)
Energy Cost per 1000 Miles			Energy Cost per 1000 Miles		
UDDS	$57.13	89.72%	UDDS	$40.08	33.09%
HWFET	$46.75	21.54%	HWFET	$41.93	9.02%
US06	$59.69	15.47%	US06	$56.28	8.87%
COMBINED	$52.46	54.88%	COMBINED	$40.91	20.79%

Figure 67: Energy cost to drive 1000 miles with HVAC for city, highway, aggressive and combined driving Image Source: AAA

7.4 Summary of Results

In cold temperatures, HVAC use comes with a significant cost penalty. In terms of combined urban/highway driving, HVAC use at 20°F resulted in an average cost increase of 65 percent when compared to the cost of combined urban/highway driving at 75°F. On average, this equals an extra $24.27 for every 1000 miles.

HVAC use during hot temperatures resulted in a modest cost increase. At 95°F, the corresponding cost increase was 21 percent or an extra $7.94 for every 1000 miles.

Without HVAC use, combined urban/highway driving at 20°F resulted in an average cost increase of 9 percent or an extra $3.52 for every 1000 miles when compared to the cost of combined urban/highway driving at 75°F. At 95°F, the corresponding cost increase was 5 percent or an extra $1.90 for every 1000 miles.

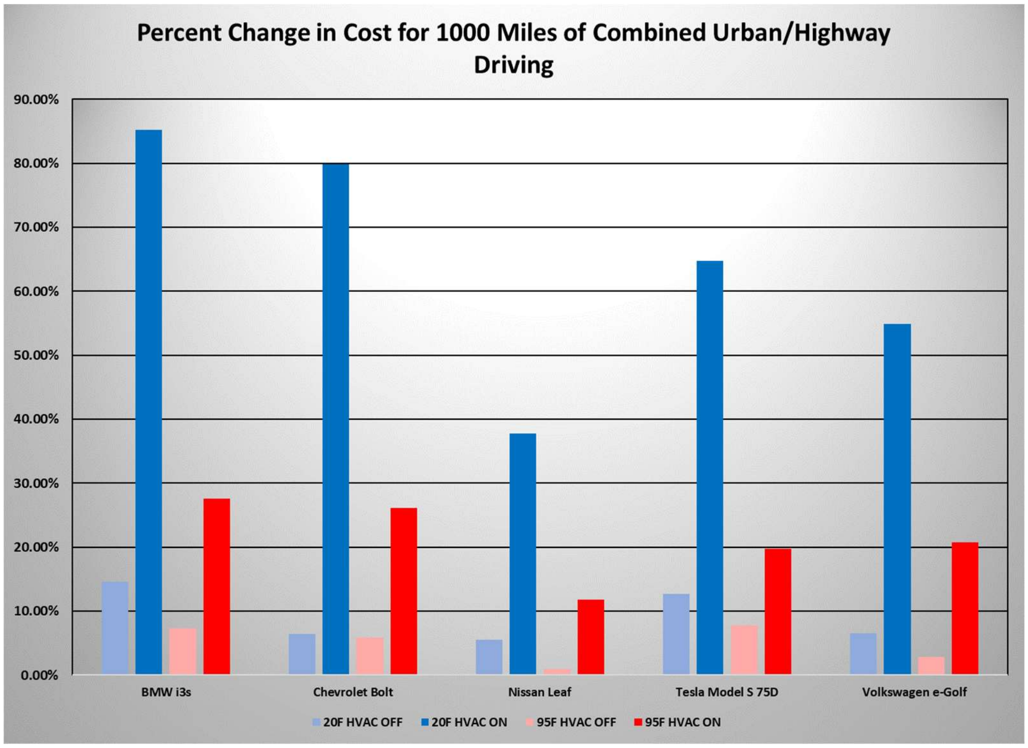


Figure 68: Percent change in cost for 1000 miles of combined urban/highway driving relative to 75°F Image Source: AAA

8 Key Findings

1. In isolation, hot and cold ambient temperatures resulted in modest reductions of driving range and equivalent fuel economy. Driving range and equivalent fuel economy reductions slightly differ due to the temperature dependency of both the recharge allocation factor (RAF) and battery discharge capacity.

    a. On average, an ambient temperature of 20°F resulted in a 12 percent decrease of combined driving range and an 8 percent decrease of combined equivalent fuel economy (when compared to testing conducted at 75°F).
    b. On average, an ambient temperature of 95°F resulted in a 4 percent decrease of combined driving range and a 5 percent decrease of combined equivalent fuel economy (when compared to testing conducted at 75°F).
2. HVAC use results in significant reductions of driving range and equivalent fuel economy.
    a. On average, HVAC use at 20°F resulted in a 41 percent decrease of combined driving range and a 39 percent decrease of combined equivalent fuel economy (when compared to testing conducted at 75°F).
    b. On average, an ambient temperature of 95°F resulted in a 17 percent decrease of both combined driving range and combined equivalent fuel economy (when compared to testing conducted at 75°F).
3. Depending on ambient temperature, HVAC use results in a significant monetary cost increase.

9 Summary Recommendations

1. Owners of EVs should be aware of environmental conditions in their area and plan for reduced driving range during periods of hot or cold temperatures.
2. If possible, limit HVAC use to minimize impacts on driving range and equivalent fuel economy.
3. EV owners should understand that HVAC use during periods of cold weather may result in significantly increased energy costs.

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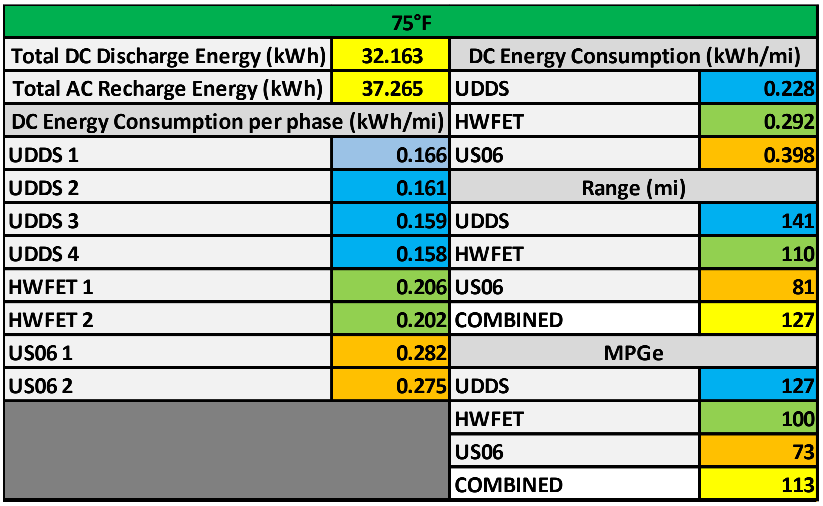
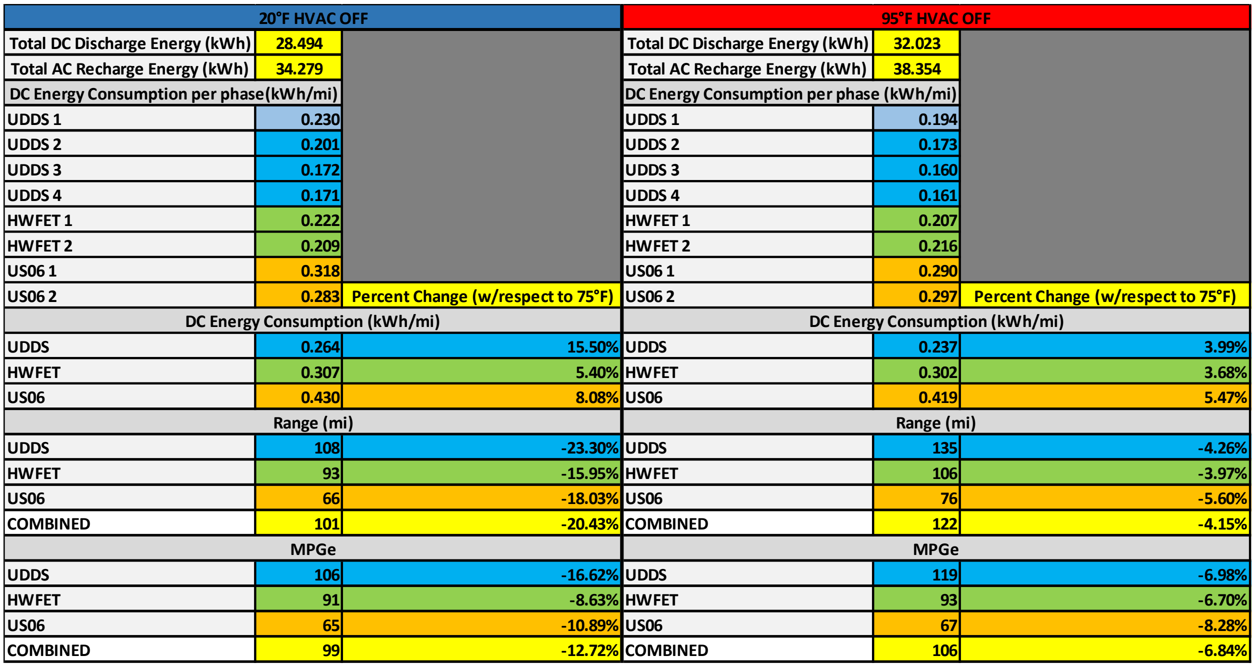
11 Appendix

11.1 2018 BMW i3s



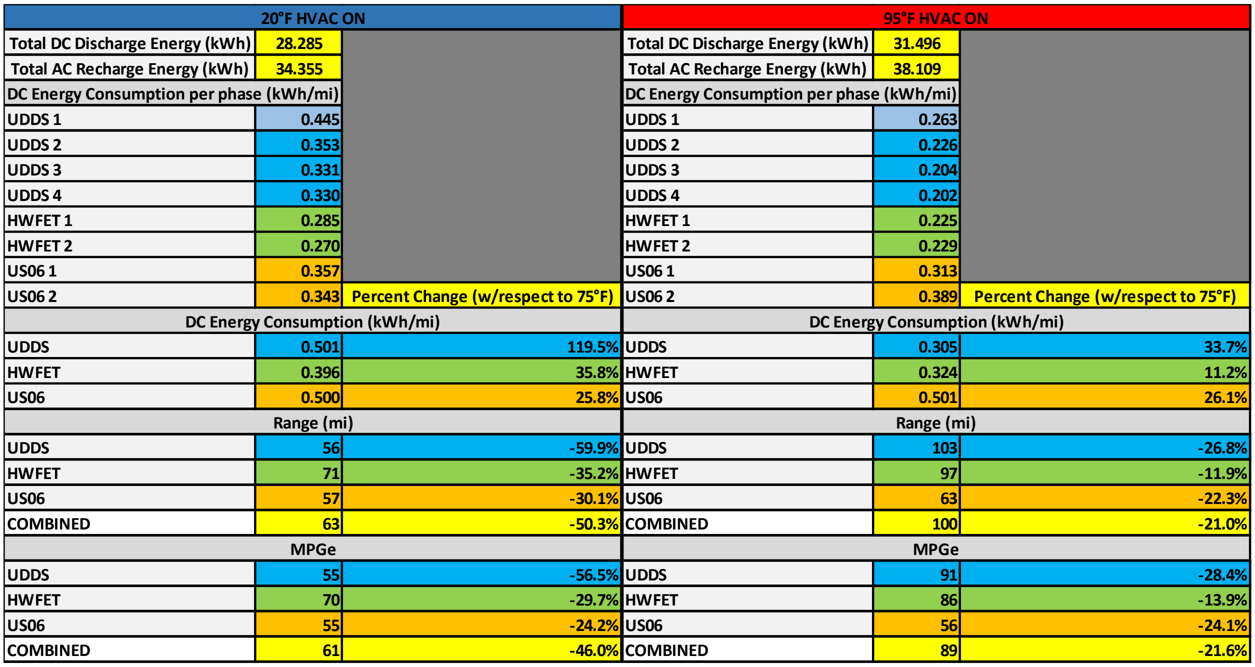
75°F			
Total DC Discharge Energy (kWh)	32.163	DC Energy Consumption (kWh/mi)	
Total AC Recharge Energy (kWh)	37.265	UDDS	0.228
DC Energy Consumption per phase (kWh/mi)		HWFET	0.292
UDDS 1	0.166	US06	0.398
UDDS 2	0.161	Range (mi)	
UDDS 3	0.159	UDDS	141
UDDS 4	0.158	HWFET	110
HWFET 1	0.206	US06	81
HWFET 2	0.202	COMBINED	127
US06 1	0.282	MPGe	
US06 2	0.275	UDDS	127
		HWFET	100
		US06	73
		COMBINED	113

Figure 69: 2018 BMW i3s raw DC energy consumption, corrected total DC energy consumption, driving range and MPGe at 75°F Image Source: AAA



20°F HVAC OFF			95°F HVAC OFF		
Total DC Discharge Energy (kWh)	28.494		Total DC Discharge Energy (kWh)	32.023	
Total AC Recharge Energy (kWh)	34.279		Total AC Recharge Energy (kWh)	38.354	
DC Energy Consumption per phase(kWh/mi)			DC Energy Consumption per phase (kWh/mi)		
UDDS 1	0.230		UDDS 1	0.194	
UDDS 2	0.201		UDDS 2	0.173	
UDDS 3	0.172		UDDS 3	0.160	
UDDS 4	0.171		UDDS 4	0.161	
HWFET 1	0.222		HWFET 1	0.207	
HWFET 2	0.209		HWFET 2	0.216	
US06 1	0.318		US06 1	0.290	
US06 2	0.283	Percent Change (w/respect to 75°F)	US06 2	0.297	Percent Change (w/respect to 75°F)
DC Energy Consumption (kWh/mi)			DC Energy Consumption (kWh/mi)		
UDDS	0.264	15.50%	UDDS	0.237	3.99%
HWFET	0.307	5.40%	HWFET	0.302	3.68%
US06	0.430	8.08%	US06	0.419	5.47%
Range (mi)			Range (mi)		
UDDS	108	-23.30%	UDDS	135	-4.26%
HWFET	93	-15.95%	HWFET	106	-3.97%
US06	66	-18.03%	US06	76	-5.60%
COMBINED	101	-20.43%	COMBINED	122	-4.15%
MPGe			MPGe		
UDDS	106	-16.62%	UDDS	119	-6.98%
HWFET	91	-8.63%	HWFET	93	-6.70%
US06	65	-10.89%	US06	67	-8.28%
COMBINED	99	-12.72%	COMBINED	106	-6.84%

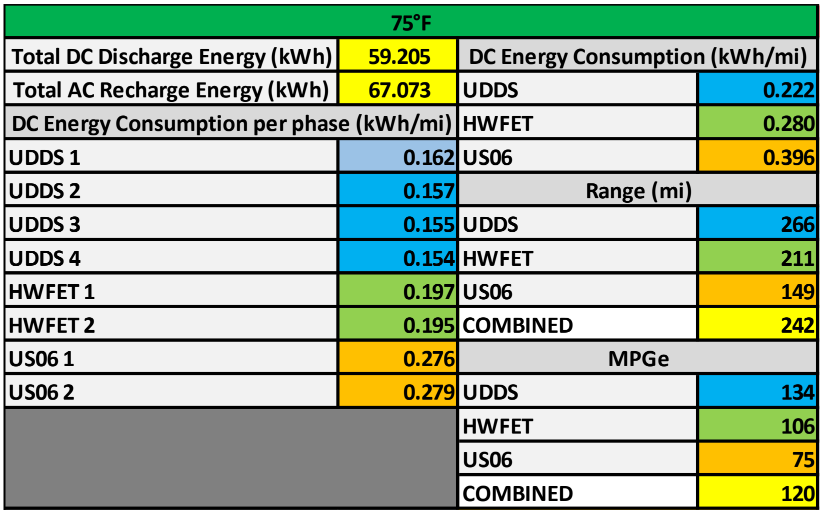
Figure 70: 2018 BMW i3s raw DC energy consumption, corrected total DC energy consumption, driving range and MPGe without HVAC Image Source: AAA



20°F HVAC ON			95°F HVAC ON		
Total DC Discharge Energy (kWh)	28.285		Total DC Discharge Energy (kWh)	31.496	
Total AC Recharge Energy (kWh)	34.355		Total AC Recharge Energy (kWh)	38.109	
DC Energy Consumption per phase (kWh/mi)			DC Energy Consumption per phase (kWh/mi)		
UDDS 1	0.445		UDDS 1	0.263	
UDDS 2	0.353		UDDS 2	0.226	
UDDS 3	0.331		UDDS 3	0.204	
UDDS 4	0.330		UDDS 4	0.202	
HWFET 1	0.285		HWFET 1	0.225	
HWFET 2	0.270		HWFET 2	0.229	
US06 1	0.357		US06 1	0.313	
US06 2	0.343	Percent Change (w/respect to 75°F)	US06 2	0.389	Percent Change (w/respect to 75°F)
DC Energy Consumption (kWh/mi)			DC Energy Consumption (kWh/mi)		
UDDS	0.501	119.5%	UDDS	0.305	33.7%
HWFET	0.396	35.8%	HWFET	0.324	11.2%
US06	0.500	25.8%	US06	0.501	26.1%
Range (mi)			Range (mi)		
UDDS	56	-59.9%	UDDS	103	-26.8%
HWFET	71	-35.2%	HWFET	97	-11.9%
US06	57	-30.1%	US06	63	-22.3%
COMBINED	63	-50.3%	COMBINED	100	-21.0%
MPGe			MPGe		
UDDS	55	-56.5%	UDDS	91	-28.4%
HWFET	70	-29.7%	HWFET	86	-13.9%
US06	55	-24.2%	US06	56	-24.1%
COMBINED	61	-46.0%	COMBINED	89	-21.6%

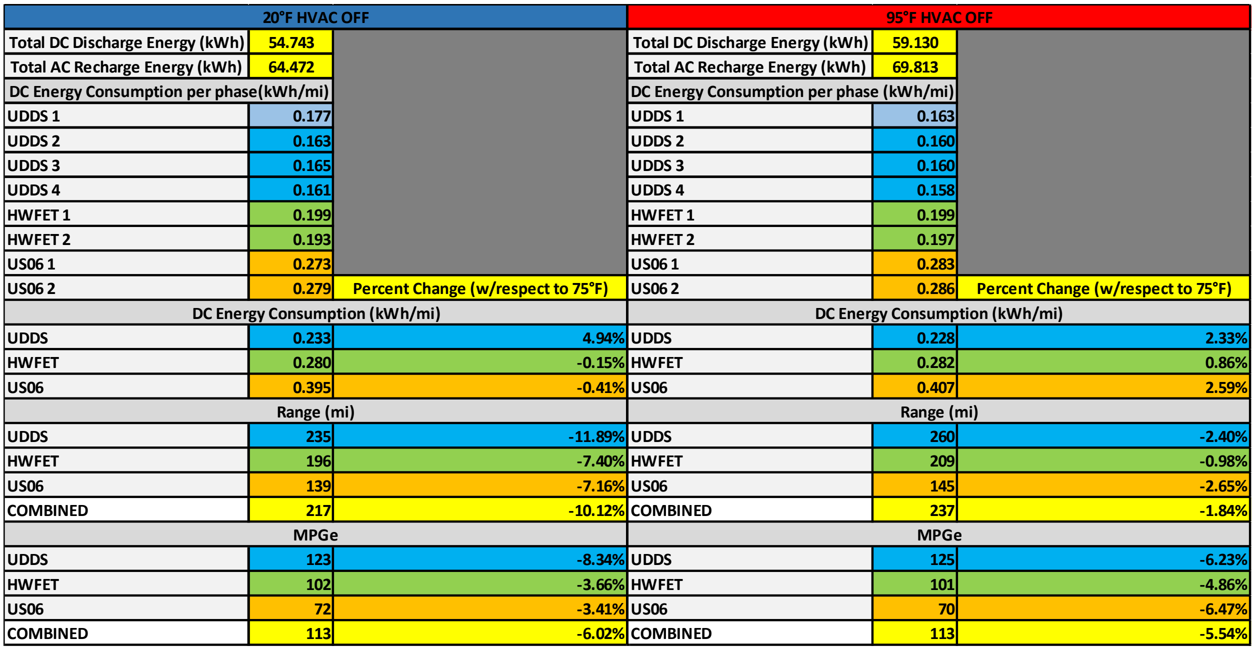
Figure 71: 2018 BMW i3s raw DC energy consumption, corrected total DC energy consumption, driving range and MPGe with HVAC engaged Image Source: AAA

11.2 2018 Chevrolet Bolt



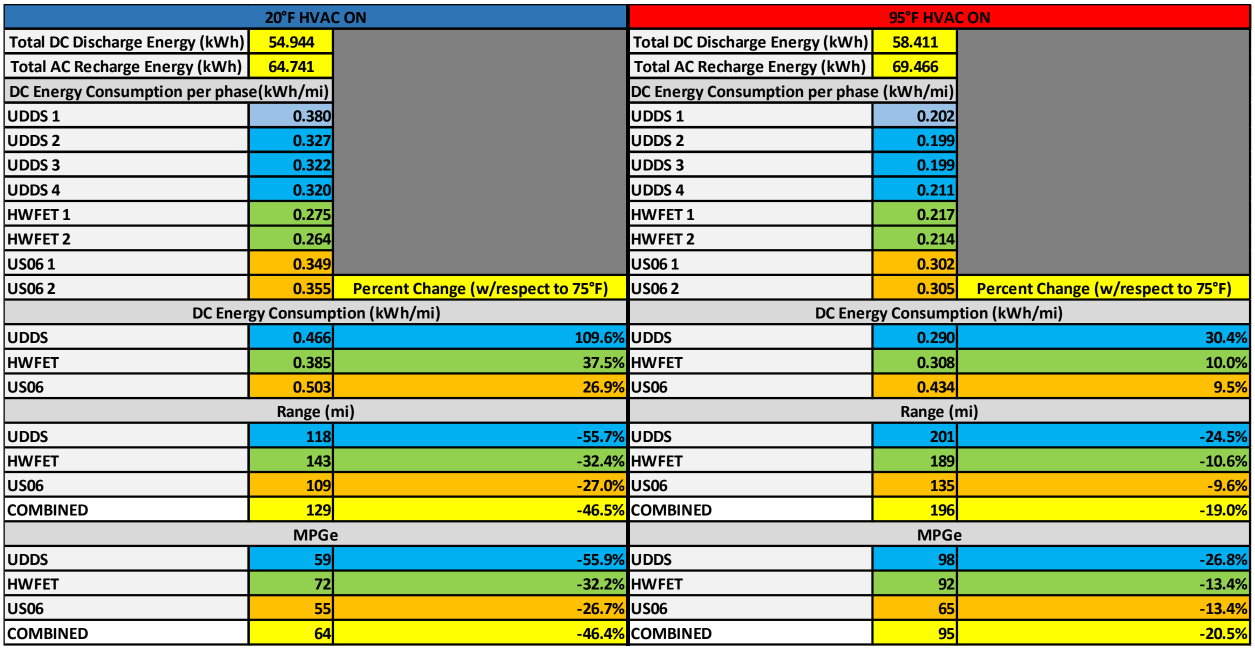
75°F			
Total DC Discharge Energy (kWh)	59.205	DC Energy Consumption (kWh/mi)	
Total AC Recharge Energy (kWh)	67.073	UDDS	0.222
DC Energy Consumption per phase (kWh/mi)		HWFET	0.280
UDDS 1	0.162	US06	0.396
UDDS 2	0.157	Range (mi)	
UDDS 3	0.155	UDDS	266
UDDS 4	0.154	HWFET	211
HWFET 1	0.197	US06	149
HWFET 2	0.195	COMBINED	242
US06 1	0.276	MPGe	
US06 2	0.279	UDDS	134
		HWFET	106
		US06	75
		COMBINED	120

Figure 72: 2018 Chevrolet Bolt raw DC energy consumption, corrected total DC energy consumption, driving range and MPGe at 75°F Image Source: AAA



20°F HVAC OFF			95°F HVAC OFF		
Total DC Discharge Energy (kWh)	54.743		Total DC Discharge Energy (kWh)	59.130	
Total AC Recharge Energy (kWh)	64.472		Total AC Recharge Energy (kWh)	69.813	
DC Energy Consumption per phase(kWh/mi)			DC Energy Consumption per phase (kWh/mi)		
UDDS 1	0.177		UDDS 1	0.163	
UDDS 2	0.163		UDDS 2	0.160	
UDDS 3	0.165		UDDS 3	0.160	
UDDS 4	0.161		UDDS 4	0.158	
HWFET 1	0.199		HWFET 1	0.199	
HWFET 2	0.193		HWFET 2	0.197	
US06 1	0.273		US06 1	0.283	
US06 2	0.279	Percent Change (w/respect to 75°F)	US06 2	0.286	Percent Change (w/respect to 75°F)
DC Energy Consumption (kWh/mi)			DC Energy Consumption (kWh/mi)		
UDDS	0.233	4.94%	UDDS	0.228	2.33%
HWFET	0.280	-0.15%	HWFET	0.282	0.86%
US06	0.395	-0.41%	US06	0.407	2.59%
Range (mi)			Range (mi)		
UDDS	235	-11.89%	UDDS	260	-2.40%
HWFET	196	-7.40%	HWFET	209	-0.98%
US06	139	-7.16%	US06	145	-2.65%
COMBINED	217	-10.12%	COMBINED	237	-1.84%
MPGe			MPGe		
UDDS	123	-8.34%	UDDS	125	-6.23%
HWFET	102	-3.66%	HWFET	101	-4.86%
US06	72	-3.41%	US06	70	-6.47%
COMBINED	113	-6.02%	COMBINED	113	-5.54%

Figure 73: 2018 Chevrolet Bolt raw DC energy consumption, corrected total DC energy consumption, driving range and MPGe without HVAC Image Source: AAA

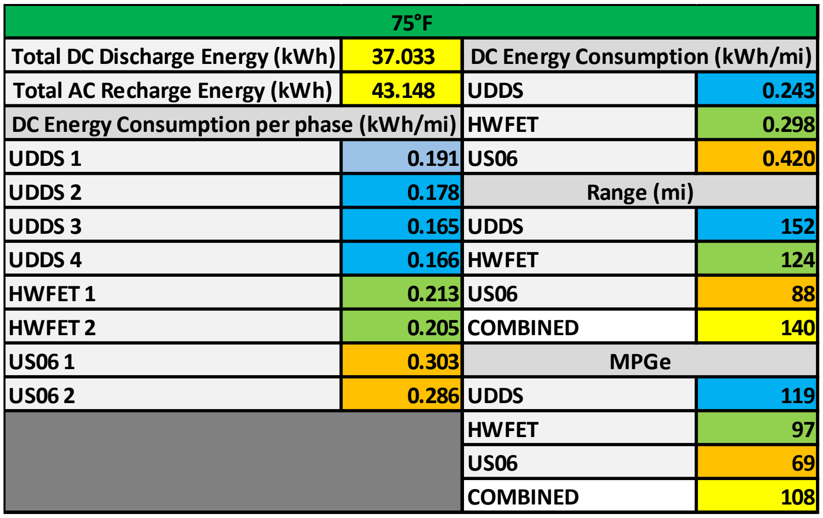


20°F HVAC ON		
Total DC Discharge Energy (kWh)	54.944	
Total AC Recharge Energy (kWh)	64.741	
DC Energy Consumption per phase(kWh/mi)		
UDDS 1	0.380	
UDDS 2	0.327	
UDDS 3	0.322	
UDDS 4	0.320	
HWFET 1	0.275	
HWFET 2	0.264	
US06 1	0.349	
US06 2	0.355	Percent Change (w/respect to 75°F)
DC Energy Consumption (kWh/mi)		
UDDS	0.466	109.6%
HWFET	0.385	37.5%
US06	0.503	26.9%
Range (mi)		
UDDS	118	-55.7%
HWFET	143	-32.4%
US06	109	-27.0%
COMBINED	129	-46.5%
MPGe		
UDDS	59	-55.9%
HWFET	72	-32.2%
US06	55	-26.7%
COMBINED	64	-46.4%

95°F HVAC ON		
Total DC Discharge Energy (kWh)	58.411	
Total AC Recharge Energy (kWh)	69.466	
DC Energy Consumption per phase (kWh/mi)		
UDDS 1	0.202	
UDDS 2	0.199	
UDDS 3	0.199	
UDDS 4	0.211	
HWFET 1	0.217	
HWFET 2	0.214	
US06 1	0.302	
US06 2	0.305	Percent Change (w/respect to 75°F)
DC Energy Consumption (kWh/mi)		
UDDS	0.290	30.4%
HWFET	0.308	10.0%
US06	0.434	9.5%
Range (mi)		
UDDS	201	-24.5%
HWFET	189	-10.6%
US06	135	-9.6%
COMBINED	196	-19.0%
MPGe		
UDDS	98	-26.8%
HWFET	92	-13.4%
US06	65	-13.4%
COMBINED	95	-20.5%

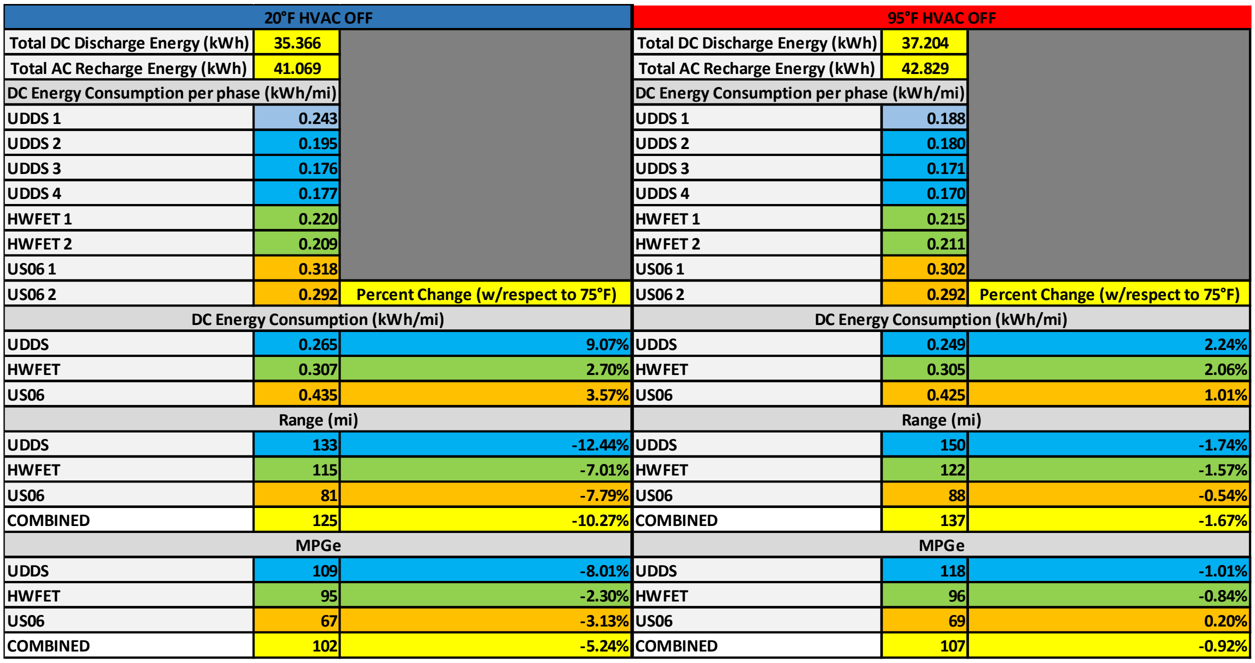
Figure 74: 2018 Chevrolet Bolt raw DC energy consumption, corrected total DC energy consumption, driving range and MPGe with HVAC engaged Image Source: AAA

11.3 2018 Nissan Leaf



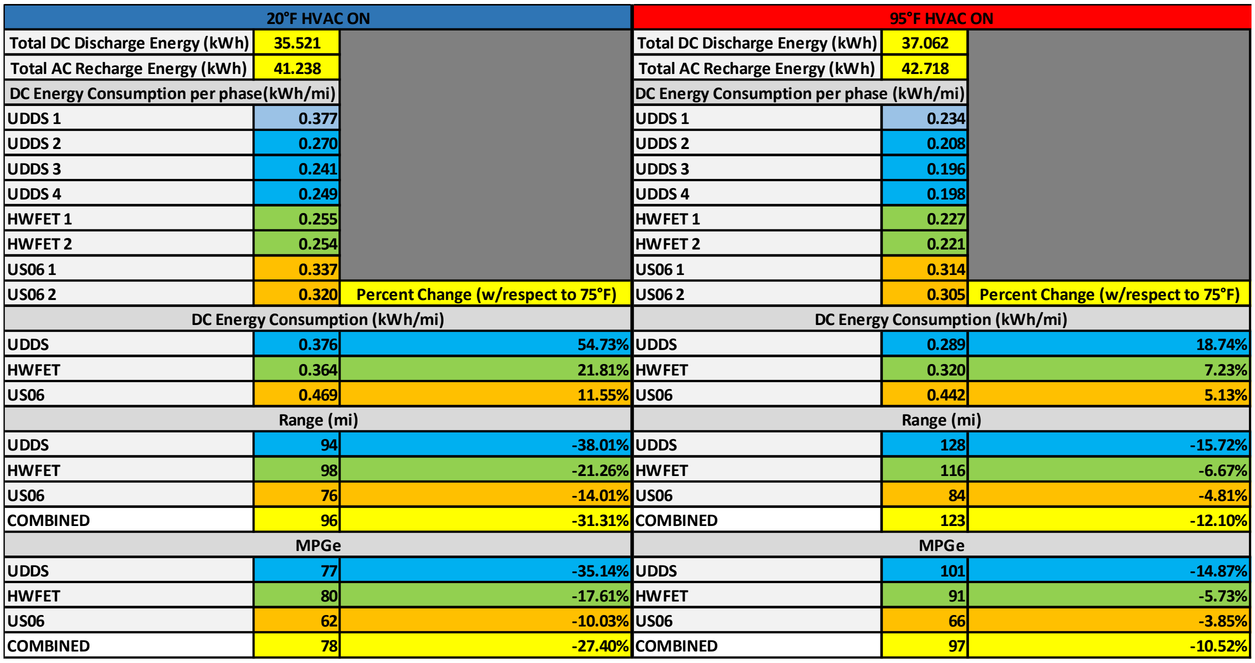
75°F			
Total DC Discharge Energy (kWh)	37.033	DC Energy Consumption (kWh/mi)	
Total AC Recharge Energy (kWh)	43.148	UDDS	0.243
DC Energy Consumption per phase (kWh/mi)		HWFET	0.298
UDDS 1	0.191	US06	0.420
UDDS 2	0.178	Range (mi)	
UDDS 3	0.165	UDDS	152
UDDS 4	0.166	HWFET	124
HWFET 1	0.213	US06	88
HWFET 2	0.205	COMBINED	140
US06 1	0.303	MPGe	
US06 2	0.286	UDDS	119
		HWFET	97
		US06	69
		COMBINED	108

Figure 75: 2018 Nissan Leaf raw DC energy consumption, corrected total DC energy consumption, driving range and MPGe at 75°F Image Source: AAA



20°F HVAC OFF			95°F HVAC OFF		
Total DC Discharge Energy (kWh)	35.366		Total DC Discharge Energy (kWh)	37.204	
Total AC Recharge Energy (kWh)	41.069		Total AC Recharge Energy (kWh)	42.829	
DC Energy Consumption per phase (kWh/mi)			DC Energy Consumption per phase (kWh/mi)		
UDDS 1	0.243		UDDS 1	0.188	
UDDS 2	0.195		UDDS 2	0.180	
UDDS 3	0.176		UDDS 3	0.171	
UDDS 4	0.177		UDDS 4	0.170	
HWFET 1	0.220		HWFET 1	0.215	
HWFET 2	0.209		HWFET 2	0.211	
US06 1	0.318		US06 1	0.302	
US06 2	0.292	Percent Change (w/respect to 75°F)	US06 2	0.292	Percent Change (w/respect to 75°F)
DC Energy Consumption (kWh/mi)			DC Energy Consumption (kWh/mi)		
UDDS	0.265	9.07%	UDDS	0.249	2.24%
HWFET	0.307	2.70%	HWFET	0.305	2.06%
US06	0.435	3.57%	US06	0.425	1.01%
Range (mi)			Range (mi)		
UDDS	133	-12.44%	UDDS	150	-1.74%
HWFET	115	-7.01%	HWFET	122	-1.57%
US06	81	-7.79%	US06	88	-0.54%
COMBINED	125	-10.27%	COMBINED	137	-1.67%
MPGe			MPGe		
UDDS	109	-8.01%	UDDS	118	-1.01%
HWFET	95	-2.30%	HWFET	96	-0.84%
US06	67	-3.13%	US06	69	0.20%
COMBINED	102	-5.24%	COMBINED	107	-0.92%

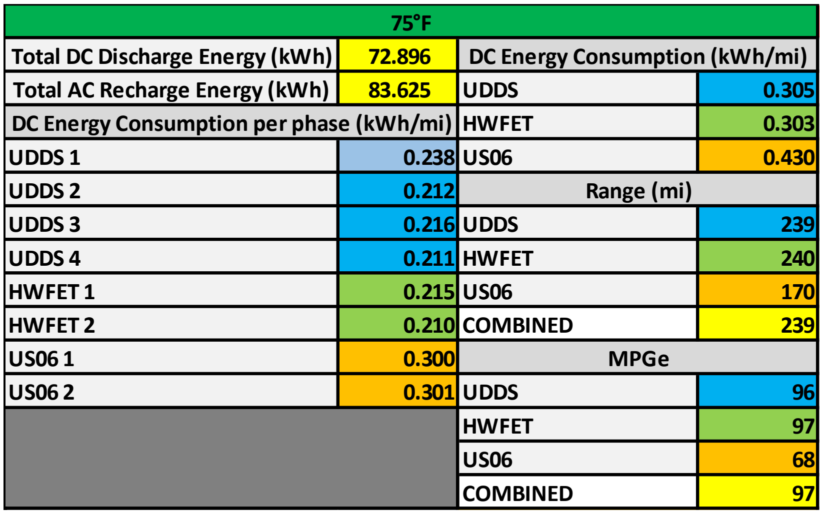
Figure 76: 2018 Nissan Leaf raw DC energy consumption, corrected total DC energy consumption, driving range and MPGe without HVAC Image Source: AAA



20°F HVAC ON			95°F HVAC ON		
Total DC Discharge Energy (kWh)	35.521		Total DC Discharge Energy (kWh)	37.062	
Total AC Recharge Energy (kWh)	41.238		Total AC Recharge Energy (kWh)	42.718	
DC Energy Consumption per phase(kWh/mi)			DC Energy Consumption per phase (kWh/mi)		
UDDS 1	0.377		UDDS 1	0.234	
UDDS 2	0.270		UDDS 2	0.208	
UDDS 3	0.241		UDDS 3	0.196	
UDDS 4	0.249		UDDS 4	0.198	
HWFET 1	0.255		HWFET 1	0.227	
HWFET 2	0.254		HWFET 2	0.221	
US06 1	0.337		US06 1	0.314	
US06 2	0.320	Percent Change (w/respect to 75°F)	US06 2	0.305	Percent Change (w/respect to 75°F)
DC Energy Consumption (kWh/mi)			DC Energy Consumption (kWh/mi)		
UDDS	0.376	54.73%	UDDS	0.289	18.74%
HWFET	0.364	21.81%	HWFET	0.320	7.23%
US06	0.469	11.55%	US06	0.442	5.13%
Range (mi)			Range (mi)		
UDDS	94	-38.01%	UDDS	128	-15.72%
HWFET	98	-21.26%	HWFET	116	-6.67%
US06	76	-14.01%	US06	84	-4.81%
COMBINED	96	-31.31%	COMBINED	123	-12.10%
MPGe			MPGe		
UDDS	77	-35.14%	UDDS	101	-14.87%
HWFET	80	-17.61%	HWFET	91	-5.73%
US06	62	-10.03%	US06	66	-3.85%
COMBINED	78	-27.40%	COMBINED	97	-10.52%

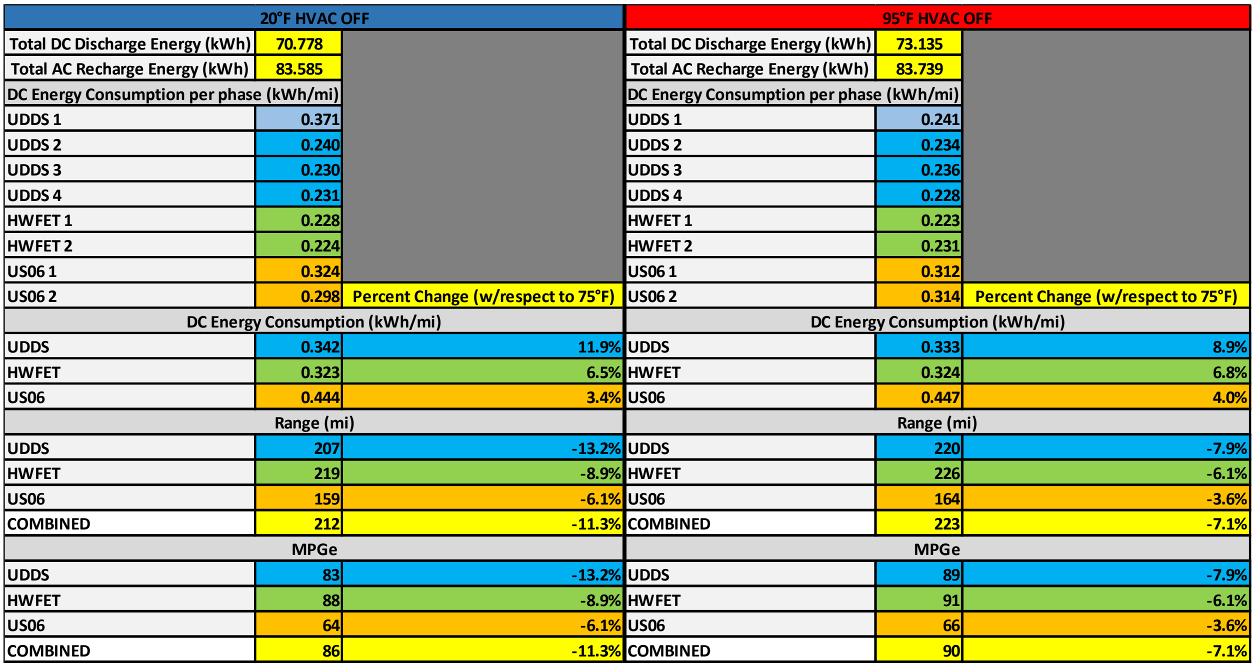
Figure 77: 2018 Nissan Leaf raw DC energy consumption, corrected total DC energy consumption, driving range and MPGe with HVAC engaged Image Source: AAA

11.4 2017 Tesla Model S 75D



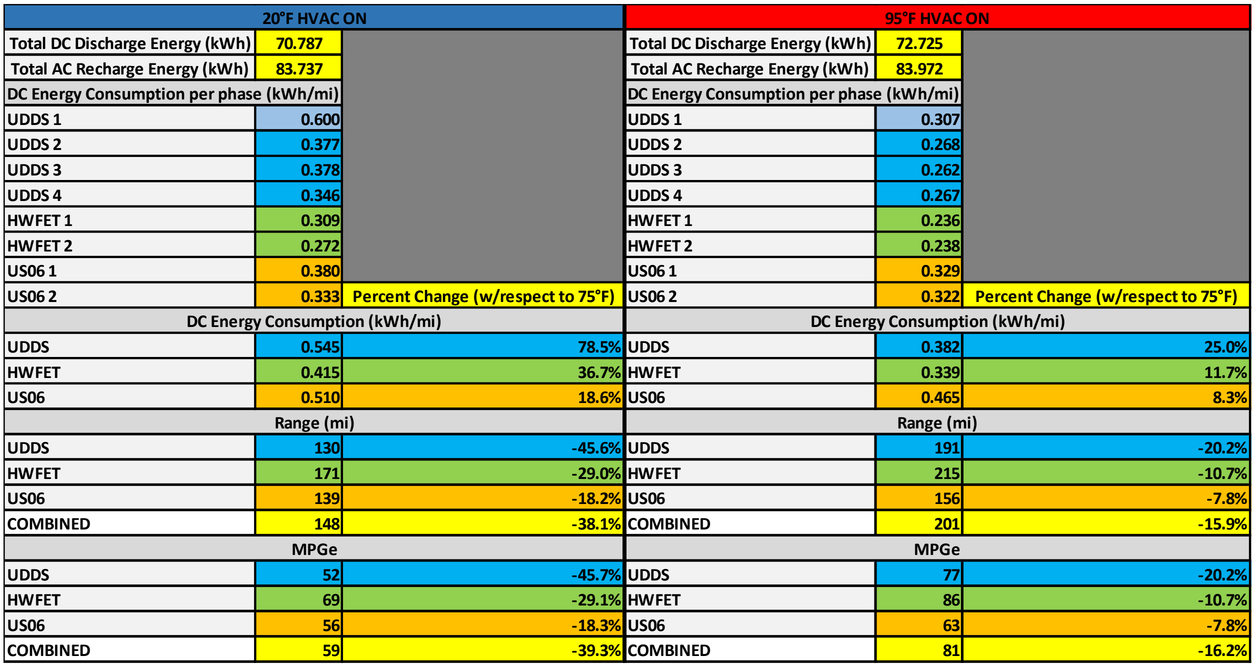
75°F			
Total DC Discharge Energy (kWh)	72.896	DC Energy Consumption (kWh/mi)	
Total AC Recharge Energy (kWh)	83.625	UDDS	0.305
DC Energy Consumption per phase (kWh/mi)		HWFET	0.303
UDDS 1	0.238	US06	0.430
UDDS 2	0.212	Range (mi)	
UDDS 3	0.216	UDDS	239
UDDS 4	0.211	HWFET	240
HWFET 1	0.215	US06	170
HWFET 2	0.210	COMBINED	239
US06 1	0.300	MPGe	
US06 2	0.301	UDDS	96
		HWFET	97
		US06	68
		COMBINED	97

Figure 78: 2017 Tesla Model S 75D raw DC energy consumption, corrected total DC energy consumption, driving range and MPGe at 75°F Image Source: AAA



20°F HVAC OFF			95°F HVAC OFF		
Total DC Discharge Energy (kWh)	70.778		Total DC Discharge Energy (kWh)	73.135	
Total AC Recharge Energy (kWh)	83.585		Total AC Recharge Energy (kWh)	83.739	
DC Energy Consumption per phase (kWh/mi)			DC Energy Consumption per phase (kWh/mi)		
UDDS 1	0.371		UDDS 1	0.241	
UDDS 2	0.240		UDDS 2	0.234	
UDDS 3	0.230		UDDS 3	0.236	
UDDS 4	0.231		UDDS 4	0.228	
HWFET 1	0.228		HWFET 1	0.223	
HWFET 2	0.224		HWFET 2	0.231	
US06 1	0.324		US06 1	0.312	
US06 2	0.298	Percent Change (w/respect to 75°F)	US06 2	0.314	Percent Change (w/respect to 75°F)
DC Energy Consumption (kWh/mi)			DC Energy Consumption (kWh/mi)		
UDDS	0.342	11.9%	UDDS	0.333	8.9%
HWFET	0.323	6.5%	HWFET	0.324	6.8%
US06	0.444	3.4%	US06	0.447	4.0%
Range (mi)			Range (mi)		
UDDS	207	-13.2%	UDDS	220	-7.9%
HWFET	219	-8.9%	HWFET	226	-6.1%
US06	159	-6.1%	US06	164	-3.6%
COMBINED	212	-11.3%	COMBINED	223	-7.1%
MPGe			MPGe		
UDDS	83	-13.2%	UDDS	89	-7.9%
HWFET	88	-8.9%	HWFET	91	-6.1%
US06	64	-6.1%	US06	66	-3.6%
COMBINED	86	-11.3%	COMBINED	90	-7.1%

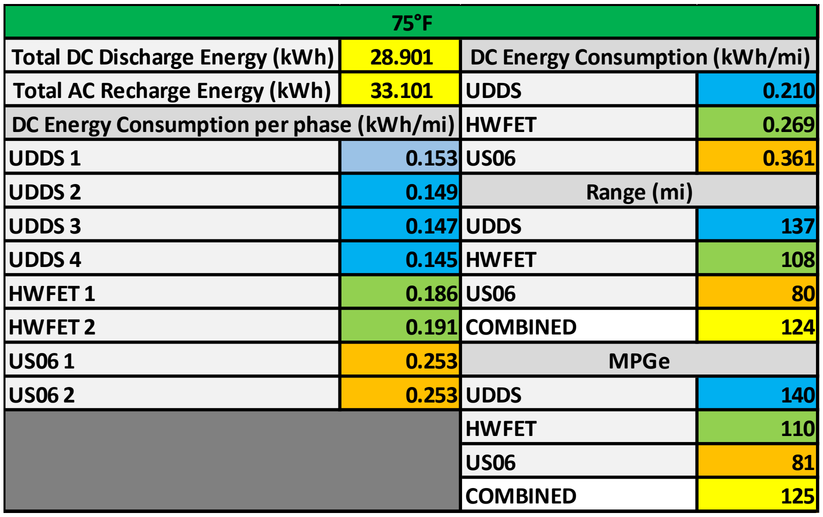
Figure 79: 2017 Tesla Model S 75D raw DC energy consumption, corrected total DC energy consumption, driving range and MPGe without HVAC Image Source: AAA



20°F HVAC ON			95°F HVAC ON		
Total DC Discharge Energy (kWh)	70.787		Total DC Discharge Energy (kWh)	72.725	
Total AC Recharge Energy (kWh)	83.737		Total AC Recharge Energy (kWh)	83.972	
DC Energy Consumption per phase (kWh/mi)			DC Energy Consumption per phase (kWh/mi)		
UDDS 1	0.600		UDDS 1	0.307	
UDDS 2	0.377		UDDS 2	0.268	
UDDS 3	0.378		UDDS 3	0.262	
UDDS 4	0.346		UDDS 4	0.267	
HWFET 1	0.309		HWFET 1	0.236	
HWFET 2	0.272		HWFET 2	0.238	
US06 1	0.380		US06 1	0.329	
US06 2	0.333	Percent Change (w/respect to 75°F)	US06 2	0.322	Percent Change (w/respect to 75°F)
DC Energy Consumption (kWh/mi)			DC Energy Consumption (kWh/mi)		
UDDS	0.545	78.5%	UDDS	0.382	25.0%
HWFET	0.415	36.7%	HWFET	0.339	11.7%
US06	0.510	18.6%	US06	0.465	8.3%
Range (mi)			Range (mi)		
UDDS	130	-45.6%	UDDS	191	-20.2%
HWFET	171	-29.0%	HWFET	215	-10.7%
US06	139	-18.2%	US06	156	-7.8%
COMBINED	148	-38.1%	COMBINED	201	-15.9%
MPGe			MPGe		
UDDS	52	-45.7%	UDDS	77	-20.2%
HWFET	69	-29.1%	HWFET	86	-10.7%
US06	56	-18.3%	US06	63	-7.8%
COMBINED	59	-39.3%	COMBINED	81	-16.2%

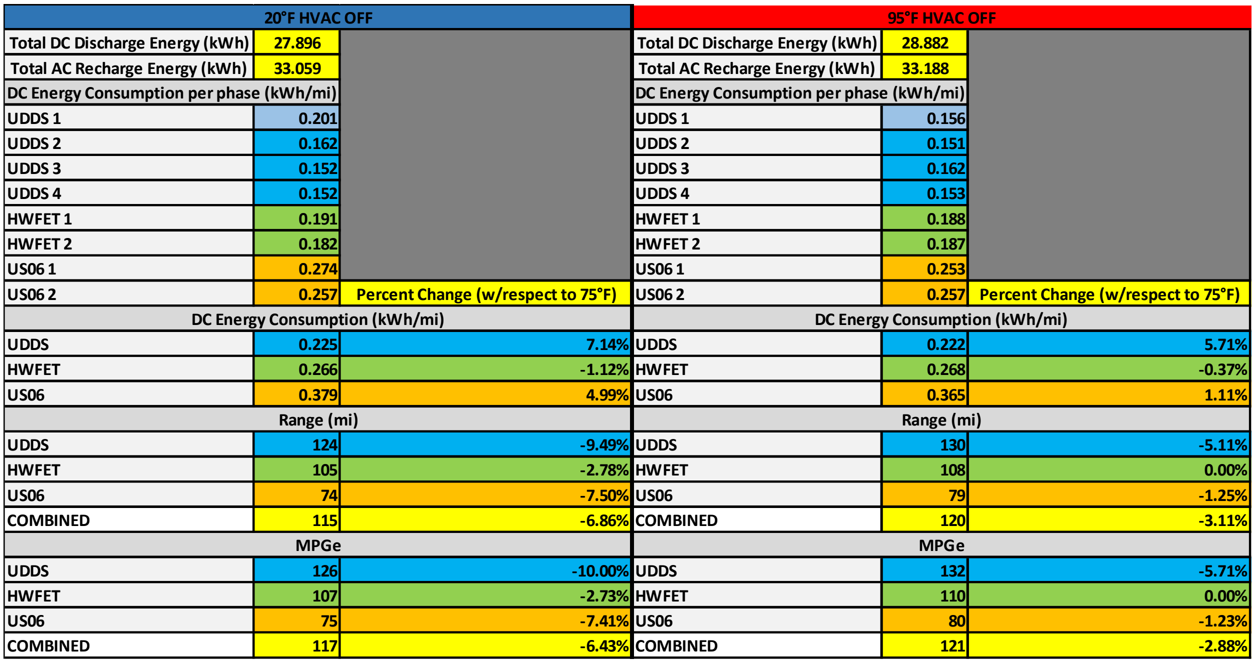
Figure 80: 2017 Tesla Model S 75D raw DC energy consumption, corrected total DC energy consumption, driving range and MPGe with HVAC engaged Image Source: AAA

11.5 2017 Volkswagen e-Golf



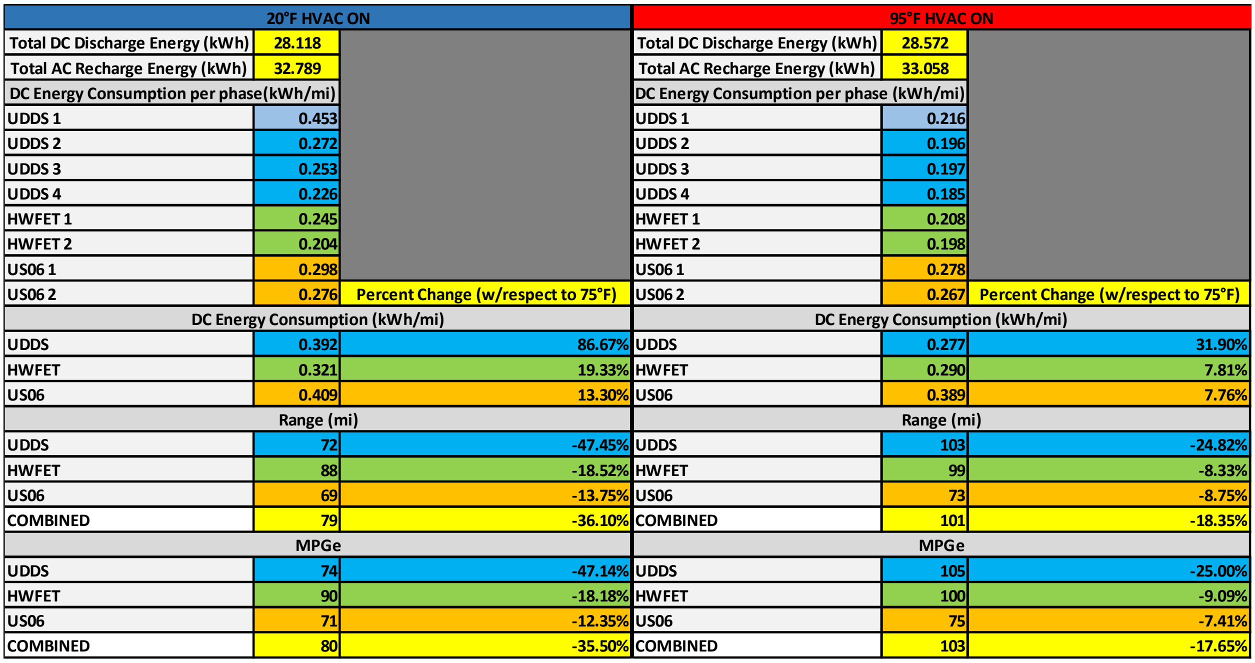
75°F			
Total DC Discharge Energy (kWh)	28.901	DC Energy Consumption (kWh/mi)	
Total AC Recharge Energy (kWh)	33.101	UDDS	0.210
DC Energy Consumption per phase (kWh/mi)		HWFET	0.269
UDDS 1	0.153	US06	0.361
UDDS 2	0.149	Range (mi)	
UDDS 3	0.147	UDDS	137
UDDS 4	0.145	HWFET	108
HWFET 1	0.186	US06	80
HWFET 2	0.191	COMBINED	124
US06 1	0.253	MPGe	
US06 2	0.253	UDDS	140
		HWFET	110
		US06	81
		COMBINED	125

Figure 81: 2017 Volkswagen e-Golf raw DC energy consumption, corrected total DC energy consumption, driving range and MPGe at 75°F Image Source: AAA



20°F HVAC OFF			95°F HVAC OFF		
Total DC Discharge Energy (kWh)	27.896		Total DC Discharge Energy (kWh)	28.882	
Total AC Recharge Energy (kWh)	33.059		Total AC Recharge Energy (kWh)	33.188	
DC Energy Consumption per phase (kWh/mi)			DC Energy Consumption per phase (kWh/mi)		
UDDS 1	0.201		UDDS 1	0.156	
UDDS 2	0.162		UDDS 2	0.151	
UDDS 3	0.152		UDDS 3	0.162	
UDDS 4	0.152		UDDS 4	0.153	
HWFET 1	0.191		HWFET 1	0.188	
HWFET 2	0.182		HWFET 2	0.187	
US06 1	0.274		US06 1	0.253	
US06 2	0.257	Percent Change (w/respect to 75°F)	US06 2	0.257	Percent Change (w/respect to 75°F)
DC Energy Consumption (kWh/mi)			DC Energy Consumption (kWh/mi)		
UDDS	0.225	7.14%	UDDS	0.222	5.71%
HWFET	0.266	-1.12%	HWFET	0.268	-0.37%
US06	0.379	4.99%	US06	0.365	1.11%
Range (mi)			Range (mi)		
UDDS	124	-9.49%	UDDS	130	-5.11%
HWFET	105	-2.78%	HWFET	108	0.00%
US06	74	-7.50%	US06	79	-1.25%
COMBINED	115	-6.86%	COMBINED	120	-3.11%
MPGe			MPGe		
UDDS	126	-10.00%	UDDS	132	-5.71%
HWFET	107	-2.73%	HWFET	110	0.00%
US06	75	-7.41%	US06	80	-1.23%
COMBINED	117	-6.43%	COMBINED	121	-2.88%

Figure 82: 2017 Volkswagen e-Golf raw DC energy consumption, corrected total DC energy consumption, driving range and MPGe without HVAC Image Source: AAA



20°F HVAC ON			95°F HVAC ON		
Total DC Discharge Energy (kWh)	28.118		Total DC Discharge Energy (kWh)	28.572	
Total AC Recharge Energy (kWh)	32.789		Total AC Recharge Energy (kWh)	33.058	
DC Energy Consumption per phase(kWh/mi)			DC Energy Consumption per phase (kWh/mi)		
UDDS 1	0.453		UDDS 1	0.216	
UDDS 2	0.272		UDDS 2	0.196	
UDDS 3	0.253		UDDS 3	0.197	
UDDS 4	0.226		UDDS 4	0.185	
HWFET 1	0.245		HWFET 1	0.208	
HWFET 2	0.204		HWFET 2	0.198	
US06 1	0.298		US06 1	0.278	
US06 2	0.276	Percent Change (w/respect to 75°F)	US06 2	0.267	Percent Change (w/respect to 75°F)
DC Energy Consumption (kWh/mi)			DC Energy Consumption (kWh/mi)		
UDDS	0.392	86.67%	UDDS	0.277	31.90%
HWFET	0.321	19.33%	HWFET	0.290	7.81%
US06	0.409	13.30%	US06	0.389	7.76%
Range (mi)			Range (mi)		
UDDS	72	-47.45%	UDDS	103	-24.82%
HWFET	88	-18.52%	HWFET	99	-8.33%
US06	69	-13.75%	US06	73	-8.75%
COMBINED	79	-36.10%	COMBINED	101	-18.35%
MPGe			MPGe		
UDDS	74	-47.14%	UDDS	105	-25.00%
HWFET	90	-18.18%	HWFET	100	-9.09%
US06	71	-12.35%	US06	75	-7.41%
COMBINED	80	-35.50%	COMBINED	103	-17.65%

Figure 83: 2017 Volkswagen e-Golf raw DC energy consumption, corrected total DC energy consumption, driving range and MPGe with HVAC engaged Image Source: AAA