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TEMPERATURE EFFECTS ON ELECTRIC AND HYBRID VEHICLE EFFICIENCY

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ABSTRACT

Electrified vehicle technologies are increasingly being adopted across the U.S. vehicle fleet. In 2019, AAA's Electric Vehicle Range [1] research determined that ambient temperature, particularly when coupled with HVAC operation, has a significant impact on battery electric vehicle (BEV) driving range and equivalent fuel economy. AAA testing conducted in 2019 found that, relative to a 75°F baseline, operation at 20°F with the HVAC system enabled resulted in average reductions of 41% in combined driving range and 39% in combined MPGe for battery electric vehicles (BEVs). At 95°F with HVAC operation, BEVs exhibited average reductions of 17% in both combined driving range and MPGe. While these results demonstrate that BEVs experience measurable efficiency and range degradation under temperature extremes, limited comparative data are available to assess whether hybrid electric vehicles (HEVs) exhibit similar efficiency losses under equivalent hot and cold operating conditions.

This research evaluates the powertrain efficiency of select BEVs and HEVs tested at ambient temperatures of 20°F, 75°F, and 95°F using an AVL emissions test cell chassis dynamometer. BEV test vehicles include the Chevrolet Equinox EV, Ford Mustang Mach-E, and Tesla Model Y. HEV test vehicles include the Toyota Prius, Honda CR-V Hybrid, and Hyundai Tucson Hybrid. The objective of this study is to quantify temperature-related efficiency changes and assess whether hybrid powertrains mitigate efficiency losses more effectively compared to fully electric vehicles under hot and cold environmental conditions.

The results indicate that hot and cold ambient temperatures—most notably cold conditions—substantially increase energy demand due to reduced battery discharge efficiency and elevated thermal management and cabin conditioning loads. The findings underscore the importance of incorporating seasonal and HVAC-related energy impacts into range planning and performance assessments, as real-world operating range can deviate significantly from EPA-rated values under non-ideal environmental conditions.

The results of this study are intended to provide consumers, policymakers, and automotive stakeholders with objective data regarding electrified vehicle performance in cold and hot weather operation. The cost comparison between operating a BEV and an HEV provides a quantitative basis for informing consumers about which powertrain configuration may be most appropriate for their specific usage patterns and operating conditions.

FOREWORD

AAA Automotive Engineering conducts independent research to evaluate vehicle technologies and operating conditions that affect consumer safety, cost of ownership, and real-world vehicle performance. As vehicle electrification expands, understanding how environmental factors influence efficiency is increasingly important for consumers considering alternative powertrains.

AAA Automotive Engineering designed this research to ensure repeatability, transparency, and comparability across vehicle technologies. All testing was conducted under controlled laboratory conditions using standardized procedures and instrumentation.

RESEARCH QUESTIONS AND KEY FINDINGS:

1. Do hybrid electric vehicles exhibit efficiency degradation comparable to battery electric vehicles when subjected to standardized low-temperature (20°F) and high-temperature (95°F) operating conditions relative to baseline temperatures?

- **Cold-weather operation (20°F) resulted in the most significant efficiency losses across all powertrains.**
    - BEVs showed a **35.6% reduction in MPGe** and a **39.0% reduction in calculated range** relative to 75°F baseline conditions.
    - HEVs exhibited a **22.8% reduction in fuel economy (MPG)** under the same cold-temperature conditions.
- **High-temperature operation (95°F) produced moderate but measurable efficiency degradation.**
    - BEVs experienced a **10.4% reduction in MPGe** and an **8.5% reduction in range** compared to baseline.
    - HEVs showed a **12.0% reduction in MPG** at elevated temperatures.

2. What are the "fuel" costs of battery electric vehicles and hybrids across cold, hot, and baseline temperatures when real-world range and HVAC use are considered?[1]

- **Cold-weather operation (20°F) substantially increased BEV and HEV operating costs.**
    - BEV cost increased by **$32.11 per 1,000 mi** at residential electricity rates and **$76.93 per 1,000 mi** at commercial charging rates.
    - HEV operating cost increased by **$28.44 per 1,000 mi**, reflecting higher fuel consumption from the engine and from cabin warm-up and auxiliary loads.
- **Hot-weather operation (95°F) cost impacts were comparatively small.**
    - BEV operating costs increased by $**6.78 per 1,000 mi** (residential) and **$16.25 per 1,000 mi** (commercial).
    - HEV operating costs increased by **$13.02 per 1,000 mi**.
- **Cold-weather operation (20°F) resulted in the most significant cost difference when comparing powertrains.**
    - BEV cost **less** to operate by **$36.19 per 1,000 mi** at residential electricity rates and cost **more** to operate by **$86.26 per 1,000 mi** at commercial rates when compared to their HEV counterparts.
- **High-temperature operation (95°F) produced moderate but measurable cost differences when comparing powertrains.**
    - BEV cost **less** to operate by **$46.11 per 1,000 mi** at residential electricity rates and cost **more** to operate by **$41.00 per 1,000 mi** at commercial rates when compared to their HEV counterparts

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[1] Retail fuel price: $3.978 per gallon; commercial EV charging: $0.418 per kWh; residential EV charging: $0.1745 per kWh; fuel and electric prices as of 27-Mar-2026

GLOSSARY

Ambient Temperature: The controlled environmental temperature within the test cell during vehicle operation. Ambient temperature directly influences battery performance, HVAC load, and overall vehicle efficiency.

Battery Electric Vehicle (BEV): A vehicle powered exclusively by an onboard rechargeable battery pack and one or more electric traction motors. BEVs do not use an internal combustion engine and rely solely on electrical energy for propulsion.

Chassis Dynamometer (Chassis Dyno): A laboratory instrument that simulates road-load conditions by applying controlled resistance to a vehicle's wheels and used to measure energy consumption, emissions (for HEV), and driving-range performance under repeatable conditions.

Cycle Energy Consumption: The total electrical or fuel energy consumed by a vehicle over a standardized drive cycle, typically expressed in kWh/100 miles or gallons-equivalent per 100 miles.

Drive Cycle: A prescribed speed-versus-time trace used to simulate real-world driving behavior in a controlled test environment. Examples include UDDS, HWFET, US06, and custom cycles developed for AAA research.

Driving Range: The maximum distance a vehicle can travel on a fully charged battery (BEV) or a combination of battery and fuel (HEV) under specified operating conditions.

Electric Traction Motor: The primary propulsion device in BEVs and HEVs that converts electrical energy into mechanical torque at the wheels.

Energy Efficiency: A measure of how effectively a vehicle converts stored energy (battery or fuel) into usable propulsion. For BEVs, typically expressed as miles per kWh; for HEVs, miles per gallon (MPG) or MPGe.

Environmental Control System (ECS): The test-cell system used to regulate temperature, humidity, and airflow to ensure consistent and repeatable test conditions.

Heating, Ventilation, and Air Conditioning (HVAC) Load: The electrical or mechanical power required to operate the vehicle's climate-control system; HVAC load significantly affects BEV driving range, especially at extreme temperatures.

Hybrid Electric Vehicle (HEV): A vehicle that combines an internal combustion engine with an electric motor and battery system. HEVs cannot be externally charged and rely on regenerative braking and the internal combustion engine to maintain battery state of charge.

Internal Combustion Engine: A conventional gasoline or diesel engine used in HEVs to provide propulsion and recharge the onboard battery.

Kilowatt (kW): A unit of power representing the rate of energy transfer; used to quantify motor output, charging power, and HVAC system demand.

Kilowatt-Hour (kWh): A unit of energy representing one kilowatt of power sustained for one hour. The primary metric for BEV battery capacity and energy consumption.

Range Degradation: The reduction in driving range due to environmental conditions, HVAC usage, battery aging, or increased load.

Regenerative Braking: A system that recovers kinetic energy during deceleration and converts it into electrical energy stored in the battery.

Road-Load Coefficients (A, B, C): Parameters used to model aerodynamic drag, rolling resistance, and mechanical losses. These coefficients are programmed into the chassis dyno to replicate real-world driving forces.

State of Charge: The percentage of usable energy remaining in the vehicle's battery relative to its total capacity.

Test Cell: A controlled laboratory environment equipped with an AVL emissions measurement system, chassis dynamometer, and environmental controls used to evaluate vehicle performance, energy consumption, and emissions.

Thermal Management System: The vehicle subsystem responsible for regulating battery, motor, and power electronics temperatures to maintain performance and longevity.

Cradle-to-Grave (C2G) Analysis: A full life-cycle assessment (LCA) framework that quantifies environmental impacts from raw material extraction ("cradle") through manufacturing, vehicle use, and end-of-life processing ("grave").

CONTENTS

I. INTRODUCTION

Electrified vehicle powertrains encompass a range of architectures intended to improve energy efficiency and reduce emissions. Among these, Battery Electric Vehicles (BEVs) and Hybrid Electric Vehicles (HEVs) represent two distinct technological approaches.

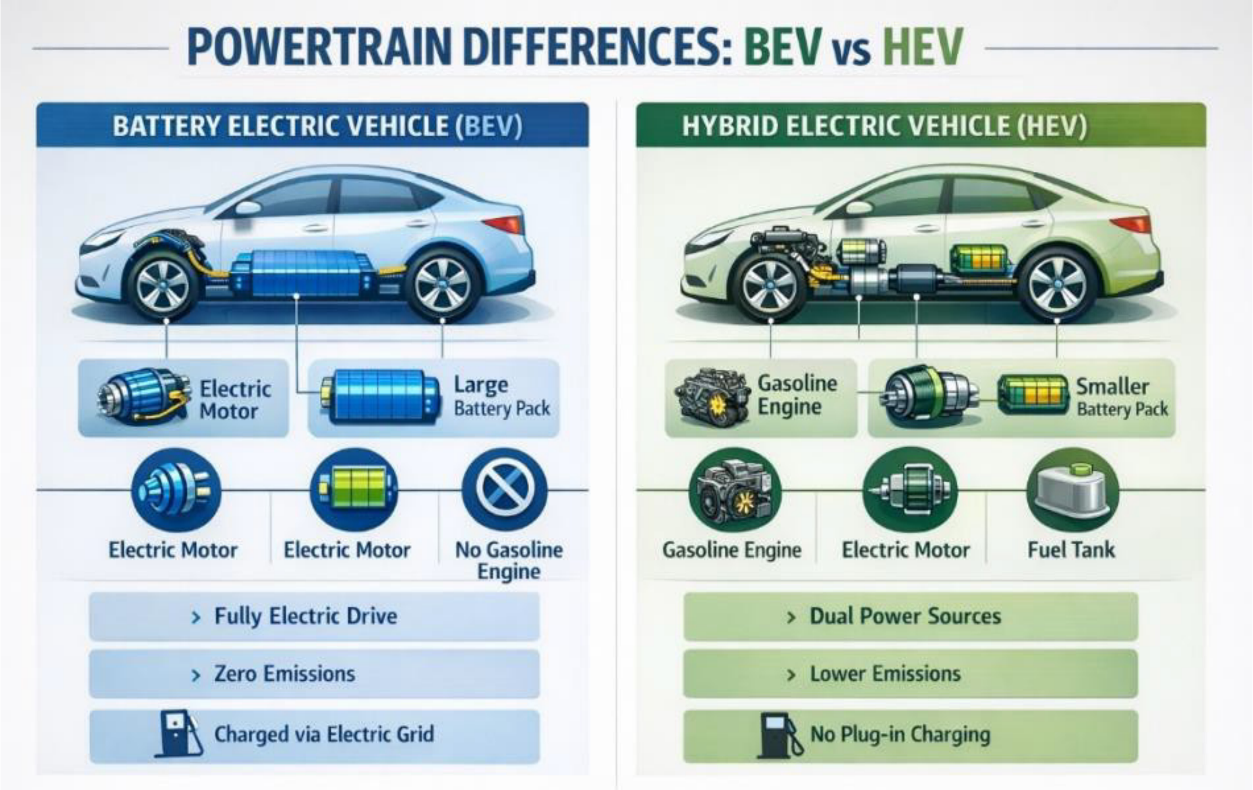


Figure 1: Powertrain Comparison BEV vs HEV Image **Source: AAA Inc (created with AI)**

BEVs utilize electric motors powered exclusively by onboard high-voltage battery systems for propulsion. All vehicle functions, including propulsion, cabin heating, and cooling, are supplied by electrical energy stored in the battery. As a result, BEV efficiency is closely linked to battery performance, power electronics efficiency, and thermal management systems, all of which are sensitive to ambient temperature.

HEVs combine an internal combustion engine with one or more electric motors and a relatively small battery pack. These vehicles are designed to optimize efficiency by blending engine and electric propulsion depending on operating conditions. Unlike BEVs, HEVs can utilize waste heat from the engine for cabin heating and rely on liquid fuel for the majority of stored energy. However, HEVs still depend on electrical components whose performance may vary with temperature.

Understanding how these different powertrain architectures respond to ambient temperature extremes is essential for evaluating their real-world efficiency and operational characteristics.

II. WHAT POWERTRAIN IS BETTER FOR THE PLANET?

HEVs have traditionally been viewed as environmentally favorable due to their higher efficiency relative to conventional internal combustion engine vehicles. However, the rapid expansion of BEVs has renewed debate regarding which powertrain offers the greatest overall environmental benefit. Although BEVs eliminate tailpipe emissions during operation, their large traction batteries require energy-intensive manufacturing processes and significant extraction of lithium and other critical materials.

Researchers at Argonne National Laboratory conducted a comprehensive cradle-to-grave life-cycle assessment of current and emerging on-road vehicle technologies [2]. The comparison of HEVs and BEVs reveals a fundamental tradeoff between vehicle-cycle emissions—stemming from raw material extraction, component manufacturing (particularly traction batteries), and end-of-life processes—and fuel-cycle/use-phase emissions associated with energy production and in-use operation. HEVs reduce fuel consumption relative to conventional internal combustion engine vehicles and therefore achieve lower operational carbon dioxide equivalent (CO_2e) emissions, but they retain combustion-related tailpipe emissions and upstream petroleum fuel-cycle impacts. BEVs generally incur higher manufacturing emissions due to battery production but shift operational energy demand from liquid fuels to electricity, enabling substantially lower use-phase emissions, especially as grid carbon intensity continues to decline.

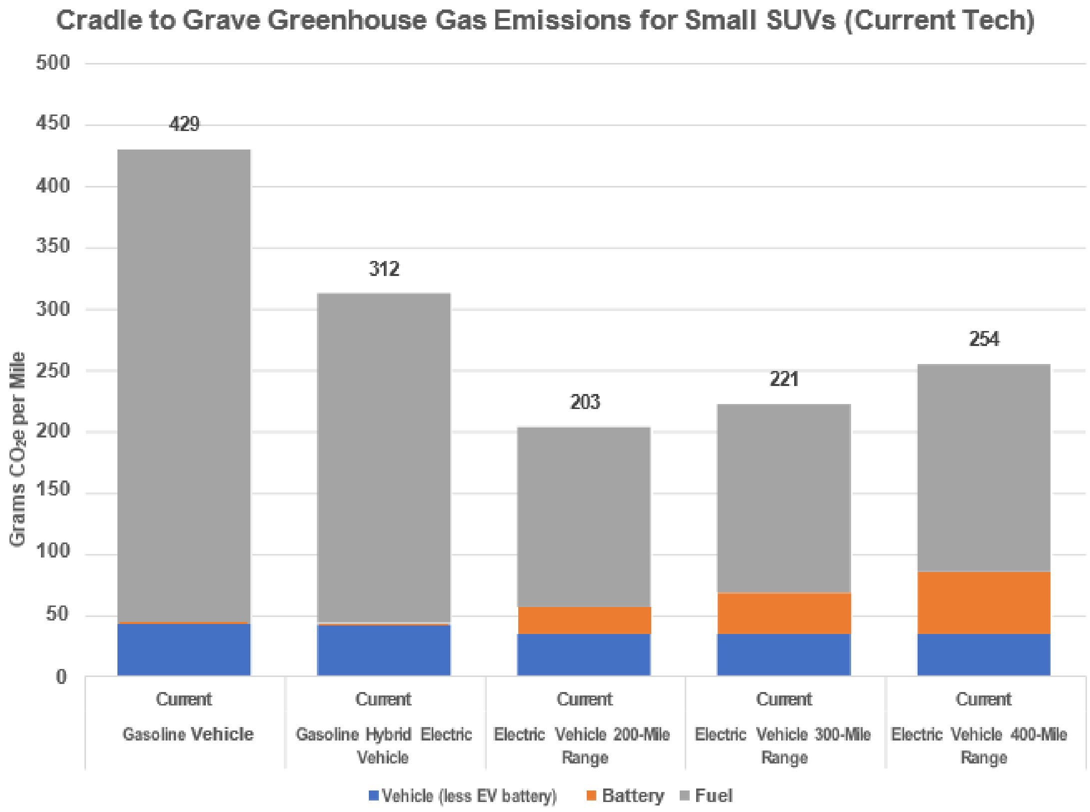


Figure 2: Cradle-to-Grave Analysis for Hybrid and Electric Vehicles **Data Source: Argonne National Laboratory / Image AAA Inc.**

Quantitatively, BEVs demonstrate lower total life-cycle greenhouse gas GHG emissions than comparable HEVs under both current and projected future technology scenarios. For a current-technology midsize sedan, the HEV case is approximately 312 g CO_2e/mi, while BEVs range from 203 to 254 g CO_2e/mi depending on battery range (200 to 400 miles) [2].

As operational emissions decline—particularly for BEVs—the relative contribution of vehicle production becomes more significant, with manufacturing impacts representing on the order of tens of grams of CO_2e per mile for midsize vehicles. Consequently, the HEV-versus-BEV comparison is best interpreted as a full-system evaluation, in which BEVs trade higher upfront manufacturing emissions for significantly lower lifetime operational emissions. Under lower-carbon electricity scenarios and future grid decarbonization pathways, BEVs exhibit a clear and growing cradle-to-grave emissions advantage over HEVs, provided consistent assumptions are applied for vehicle class, performance equivalency, electricity mix, and technology timeframe.

The results indicate a clear overall carbon footprint advantage under baseline conditions; however, the reduction in BEV range and efficiency at low temperatures—and the additional energy required for cabin heating—can increase overall energy consumption. When these seasonal effects are considered, the total carbon impact of a BEV may move closer to that of an HEV, particularly in regions with prolonged cold weather or limited access to efficient charging.

III. BACKGROUND

Ambient temperature influences vehicle efficiency through its impact on propulsion systems, energy storage, and accessory loads. These effects are particularly pronounced in electrified vehicles due to the thermal sensitivity of batteries and power electronics and the lack of heat energy generated from an internal combustion engine for the cabin HVAC system.

In BEVs, cold temperatures reduce battery chemical activity and increase internal resistance, resulting in reduced usable energy and higher energy consumption. Additional energy is often required to warm the battery and cabin via the HVAC system, further decreasing efficiency. High ambient temperatures can also reduce efficiency due to increased cooling demands and thermal protection strategies that limit power output.

HEVs are affected by ambient temperature through a combination of engine warm-up behavior, battery performance, and accessory loads. Cold temperatures can increase engine run time due to providing heat for the HVAC in addition to engine warm-up time and reduce battery efficiency, while hot temperatures increase requirements to run the engine for the HVAC system and the cooling requirements for both the engine and electrical components. However, the presence of an internal combustion engine allows HEVs to leverage engine waste heat for cabin heating, potentially reducing efficiency losses relative to BEVs in cold conditions.

Despite these known mechanisms, limited data exists directly comparing BEV and HEV efficiency under identical environmental and test conditions. This study addresses that gap by evaluating both powertrain types using consistent test methods and controlled ambient temperatures.

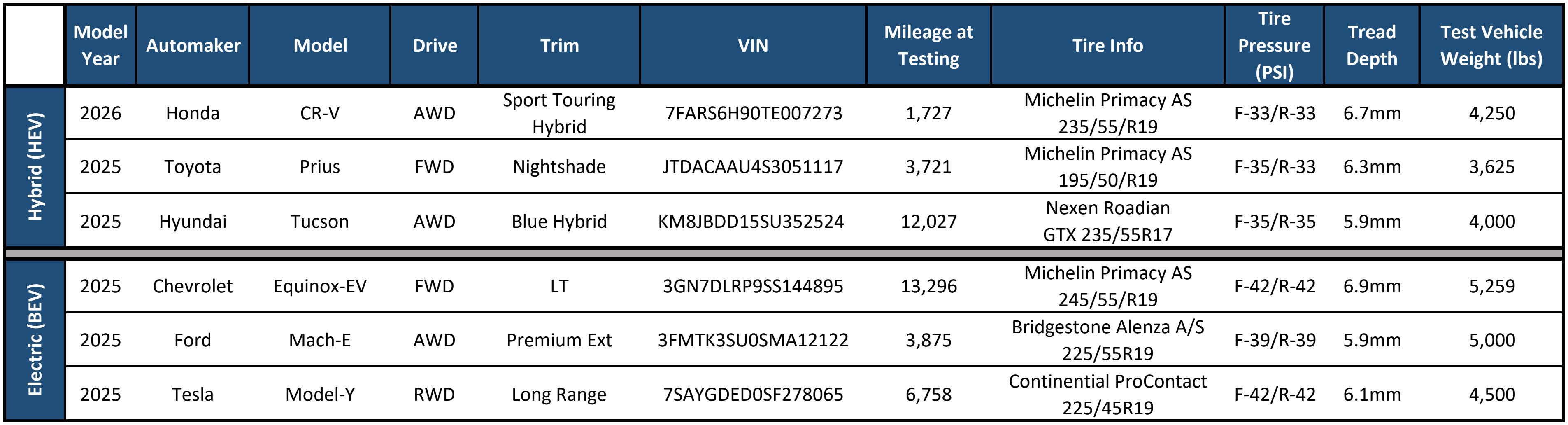
IV. VEHICLE SELECTION & PREPARATION

This study evaluates the performance of BEVs and HEVs within a controlled test-cell environment to determine whether HEVs exhibit efficiency losses comparable to those observed in BEVs under extreme temperature conditions. Test vehicles were selected using market-level sales data and segment popularity criteria, and all units were procured either through commercial rental fleets or manufacturer press-fleet programs

A. Test Vehicle Selection Process

- The vehicle selection process was structured to create a balanced and unbiased test fleet for comparing BEV and HEV efficiency in an emissions-grade test cell. Sales data from *Automotive News* [3] was used to identify the highest-volume models in each category, ensuring the study reflected vehicles commonly purchased by U.S. consumers.
- To avoid manufacturer-specific bias, **BEVs and HEVs were not selected from the same manufacturer**, and only one vehicle per manufacturer was included in the fleet. Six vehicles were chosen based on sales volume and availability through rental or press fleets, with alternate models identified if a top-selling option was unavailable.
- All selected vehicles were required to be 2025 model year or newer, of similar size, and compliant with SAE J1634 (BEV) and SAE J1711 (HEV) testing procedures. BEVs were selected strictly by sales volume and manufacturer representation.
- This approach ensured a diverse, current, and technically appropriate set of vehicles for evaluating BEV and HEV efficiency under controlled temperature conditions.

B. Test Vehicles



	Model Year	Automaker	Model	Drive	Trim	VIN	Mileage at Testing	Tire Info	Tire Pressure (PSI)	Tread Depth	Test Vehicle Weight (lbs)
Hybrid (HEV)	2026	Honda	CR-V	AWD	Sport Touring Hybrid	7FARS6H90TE007273	1,727	Michelin Primacy AS 235/55/R19	F-33/R-33	6.7mm	4,250
	2025	Toyota	Prius	FWD	Nightshade	JTDACAAU4S3051117	3,721	Michelin Primacy AS 195/50/R19	F-35/R-33	6.3mm	3,625
	2025	Hyundai	Tucson	AWD	Blue Hybrid	KM8JBDD15SU352524	12,027	Nexen Roadian GTX 235/55R17	F-35/R-35	5.9mm	4,000
Electric (BEV)	2025	Chevrolet	Equinox-EV	FWD	LT	3GN7DLRP9SS144895	13,296	Michelin Primacy AS 245/55/R19	F-42/R-42	6.9mm	5,259
	2025	Ford	Mach-E	AWD	Premium Ext	3FMTK3SU0SMA12122	3,875	Bridgestone Alenza A/S 225/55R19	F-39/R-39	5.9mm	5,000
	2025	Tesla	Model-Y	RWD	Long Range	7SAYGDED0SF278065	6,758	Continential ProContact 225/45R19	F-42/R-42	6.1mm	4,500

Figure 3: Test Vehicle Detailed Information at Time of Testing. **Image Source: AAA Inc.**

The research team made significant efforts to procure early model test vehicles from the same model year. However, due to limitations of vehicle sourcing, a combination of 2025 and 2026 test vehicles had to be utilized. Discussions with the automaker confirmed that both the 2025 and 2026 Honda CR-V hybrid utilized identical powertrain technology.

1) 2026 Honda CR-V Hybrid AWD: The 2026 Honda CR-V Hybrid AWD is equipped with a two-motor hybrid-electric powertrain paired with an electronically controlled all-wheel-drive system. Propulsion is provided by a naturally aspirated 2.0-liter Atkinson-cycle inline-four gasoline engine operating in conjunction with two electric motor-generators and a lithium-ion battery pack. Electrical energy is recovered through regenerative braking during deceleration. The AWD system utilizes a mechanically driven rear differential with electronic control to provide rear-axle torque when traction or stability demands are detected. The powertrain control system manages engine operation, electric motor output, and torque distribution to optimize overall system efficiency across the tested drive cycles and ambient conditions.

Figure 4: 2026 Honda CRV-Hybrid AWD. **Image Source: AAA Inc.**

2) 2025 Toyota Prius Hybrid FWD Nightshade: The 2025 Toyota Prius FWD Nightshade is powered by a fifth-generation series-parallel hybrid-electric powertrain driving the front axle. The system combines a naturally aspirated 2.0-liter Atkinson-cycle inline-four gasoline engine with two electric motor-generators integrated within an electronically controlled continuously variable transmission (e-CVT) and a lithium-ion battery pack. Electrical energy is recovered through regenerative braking during deceleration. The powertrain control system continuously blends engine and electric motor operation to support electric-only, engine-only, or combined hybrid operation as required. Control strategies are optimized to maximize system efficiency across the tested drive cycles and ambient operating conditions.

Figure 5: 2025 Toyota Prius Nightshade FWD. Image Source: AAA Inc.

3) 2025 Hyundai Tucson Blue Hybrid AWD: The 2025 Hyundai Tucson Blue Hybrid AWD is equipped with a parallel hybrid-electric powertrain paired with an electronically controlled all-wheel-drive system. Propulsion is provided by a turbocharged 1.6-liter gasoline direct-injection inline-four engine combined with an electric traction motor integrated into a six-speed automatic transmission and a lithium-ion polymer battery. Electrical energy is recovered through regenerative braking during deceleration. The AWD system distributes drive torque between the front and rear axles based on traction demand and operating conditions. The powertrain control system coordinates engine operation, motor assist, transmission shifting, and torque distribution to optimize overall system efficiency across the tested drive cycles and ambient conditions.

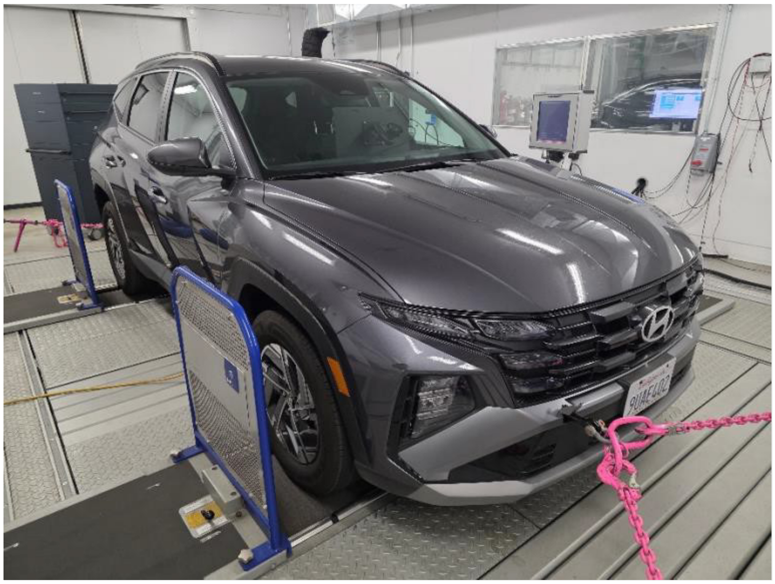


Figure 6: 2025 Hyundai Tucson Blue Hybrid AWD. **Image Source: AAA Inc.**

4) 2025 Chevrolet Equinox EV FWD: The 2025 Chevrolet Equinox EV FWD is powered by a single-motor, front-wheel-drive battery electric powertrain. Propulsion is provided by a permanent-magnet electric traction motor driving the front axle through a single-speed reduction gear, with electrical energy supplied by an underfloor lithium-ion battery pack. Energy recovery is achieved through regenerative braking during deceleration. An active liquid-based thermal management system regulates battery, motor, and power electronics temperatures to support performance and durability. Thermal conditioning loads, including battery heating or cooling, influence overall energy consumption, particularly during low- and high-ambient temperature operation. The powertrain control system manages motor torque delivery, regenerative braking, and thermal operation to optimize efficiency across the tested drive cycles.

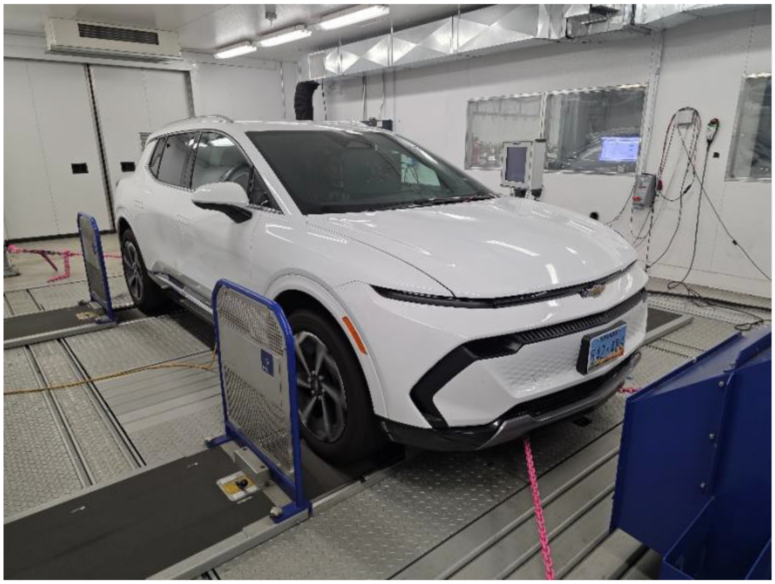


Figure 7: 2025 Chevrolet Equinox-EV FWD. **Image Source: AAA Inc.**

5) 2025 Ford Mustang Mach-E AWD: The 2025 Ford Mustang Mach-E AWD is powered by a dual-motor, all-wheel-drive battery electric powertrain. Front and rear permanent-magnet electric traction motors provide propulsion through single-speed reduction gearsets, with electrical energy supplied by an underfloor lithium-ion battery pack. Energy recovery is achieved through regenerative braking during deceleration. An active liquid-based thermal management system regulates battery, motor, and power electronics temperatures to support performance and durability. Thermal conditioning loads, including battery heating or cooling, influence overall energy consumption, particularly during low- and high-ambient temperature operation. For the 2025 model year Ford Mach-E, Ford implemented a patented vapor-injection heat-pump architecture coupled with revised thermal control algorithms. The system is designed to mitigate efficiency and range losses associated with elevated HVAC and battery thermal demands at temperature extremes. The powertrain control system coordinates torque distribution, regenerative braking, and thermal operation to optimize efficiency across the tested drive cycles.

Figure 8: 2025 Ford Mustang Mach-E AWD. **Image Source: AAA Inc.**

6) 2025 Tesla Model Y RWD: The 2025 Tesla Model Y RWD is powered by a single-motor, rear-wheel-drive battery electric powertrain. Propulsion is provided by a rear-mounted electric traction motor driving the rear axle through a single-speed reduction gear, with electrical energy supplied by an underfloor lithium-ion battery pack. Energy recovery is achieved through regenerative braking during deceleration. An active liquid-based thermal management system regulates battery, motor, and power electronics temperatures to support performance and durability. Thermal conditioning loads, including battery heating or cooling, influence overall energy consumption, particularly during low- and high-ambient temperature operation. Powertrain control strategies manage motor torque delivery, regenerative braking, and thermal operation to optimize efficiency across the tested drive cycles.

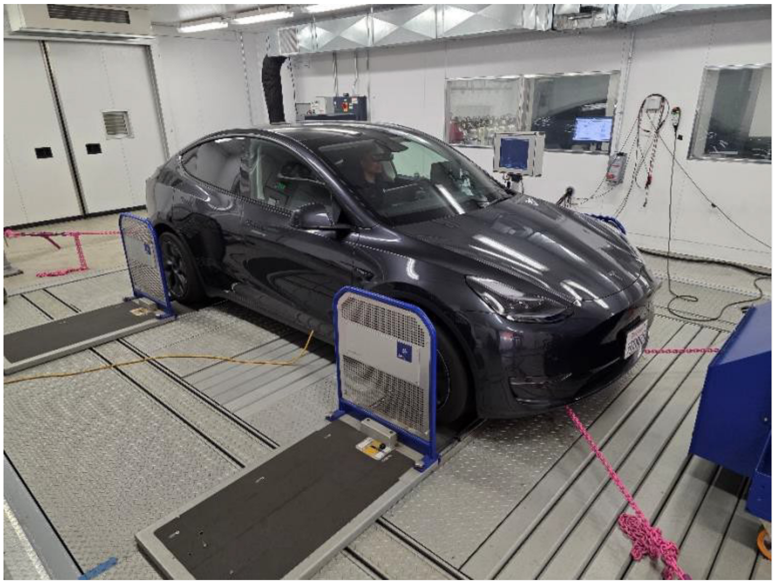


Figure 9: 2025 Tesla Model Y Long Range RWD. Image Source: AAA Inc.

C. Pre-Testing Inspection Criteria

The following inspections were completed prior to chassis-dyno testing to ensure all vehicles met consistent mechanical and operational standards appropriate for an engineering evaluation:

- Vehicles were required to have between 3,000[2] and 20,000 miles at the start of testing, with initial mileage selected to ensure they remained within this range through the full test program.
- All four tires were verified to be matching, of the correct OEM-specified size, and free of damage or irregular wear.
- Tires were confirmed to be properly broken in, with adequate tread depth and overall condition suitable for controlled testing.
- Minimum tread depth was verified to be at least 50% of the original specification, or 6/32 inch when the manufacturer’s value was not provided.
- Tire pressures were set to the OEM-recommended cold inflation pressure using a calibrated gauge.

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[2] The 2026 Honda CRV-Hybrid had 1,727mi at the start of testing, however this vehicle was previously tested on an emissions dynamometer and had been broken in according to testing criteria.

- For HEVs, the fuel system was drained and refilled with EPA-certified test fuel, ensuring at least 30% fuel capacity. A single batch of test fuel was used across all applicable vehicles.
- BEVs were conditioned and charged in accordance with the relevant SAE test procedures prior to each test sequence.
- Cabin air temperature was set to 72°F (auto) for all test scenarios to maintain consistent HVAC load.
- A full vehicle health check was performed to confirm that no warning indicators were illuminated and that no mechanical or electrical faults were present.

V. TEST EQUIPMENT AND RESOURCES

A. AVL 4-Wheel Emissions Test Cell / Dynamometer

The Automobile Club of Southern California's Automotive Research Center (ARC) conducts vehicle testing using an AVL four-wheel chassis dynamometer capable of accommodating front-, rear-, and all-wheel-drive configurations. The system includes a 150 kW front unit and a 220 kW rear unit, both equipped with 48-inch diameter rolls, and is designed to reproduce vehicle tractive forces under controlled laboratory conditions. The dynamometer is installed within a temperature- and humidity-controlled environmental chamber operating between 20° and 95°F. All BEV and HEV evaluations in this study were performed on this dynamometer in accordance with SAE J1634 and SAE J1711 procedures.

High-voltage electrical measurements were integrated into the test cell through the AVL software architecture. iGEM2 served as the real-time measurement and control interface, acquiring DC bus voltage and current from external instrumentation. When a Hioki power analyzer was used, it measured high-voltage parameters via precision voltage taps and current probes and transmitted the data over Ethernet to iGEM2 for conditioning, scaling, and synchronization with chassis dynamometer signals from VECON. The processed channels were then accessed by AVL PUMA 2 for cycle control, efficiency analysis, and data logging. In this configuration, the Hioki analyzer provides high-accuracy electrical measurements, iGEM2 manages acquisition and synchronization, and PUMA 2 integrates the combined dataset to support fully automated EV testing.

1) Road Load / Coast Down Coefficient: EPA road load coefficients represent the forces acting on a vehicle during real-world driving and are used to replicate those forces accurately during chassis dynamometer testing. Derived from coast down testing conducted on a test track, the coefficients (commonly expressed as A, B, and C terms) quantify rolling resistance (A), speed-proportional losses such as drivetrain and bearing drag (B), and aerodynamic drag (C). These coefficients define the tractive effort required to propel the vehicle as a function of speed and are submitted by manufacturers to the EPA for certification testing.

For this research program evaluating BEV and HEV performance, published EPA coast down (road load) coefficients were used to configure the chassis dynamometer for each test vehicle. The coefficients were applied in accordance with SAE procedures to match the dynamometer load settings to the certified road load values at the specified test weight. This approach ensured that laboratory energy consumption, fuel economy, and range measurements were representative of real-world driving resistance and remained comparable to EPA-certified values across both BEV and HEV platforms.

2) Data and Calculations: Equations described in SAE J1634 (BEV) [4] and SAE J1711 (HEV) [5] are used to calculate city, highway, and combined driving range and equivalent fuel economy based on the data collected during dynamometer testing.

3) EPA Drive Cycles for Electrified Vehicle Testing: EPA drive cycles provide standardized laboratory conditions for evaluating energy consumption, fuel economy, and range in electrified vehicles. Three primary procedures—Urban Dynamometer Driving Schedule (UDDS), Highway Fuel Economy Test (HWFET), and Multi-Cycle Testing (MCT)—capture distinct operating regimes and collectively support comprehensive performance assessment for BEVs and HEVs.

- **UDDS:** Represents low-speed, stop-and-go operation typical of urban driving. BEVs benefit from frequent regenerative braking and low aerodynamic load, while HEVs leverage electric-motor assist, engine stop-start, and regenerative recovery to achieve high urban-cycle efficiency.
- **HWFET:** Characterizes steady-state, higher-speed operation typical of highway driving. BEVs experience increased aerodynamic drag and limited regenerative opportunities, while HEVs rely more heavily on the internal combustion engine, resulting in lower fuel economy relative to UDDS.
- **Multi-Cycle Testing (MCT):** Sequential execution of multiple EPA cycles (UDDS and HWFET) to evaluate cumulative energy use. MCT enables full-range depletion testing for BEVs by testing the vehicle through hundreds of miles worth of simulated drive cycles.

Figure 10: Honda CR-V Hybrid with EPA drive cycle tracing monitor **Image Source: AAA Inc.**

Figure 11: AVL Chassis Dynamometer with Toyota Prius (HEV). **Image Source: AAA Inc.**

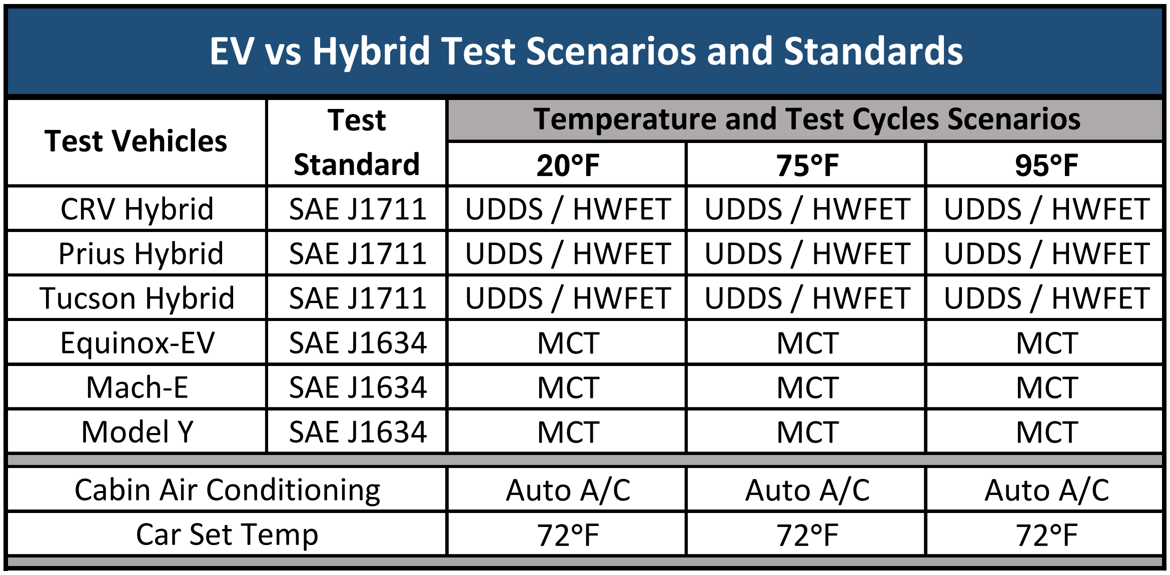
VI. INQUIRY #1: DO HYBRID ELECTRIC VEHICLES EXHIBIT EFFICIENCY DEGRADATION COMPARABLE TO BATTERY ELECTRIC VEHICLES WHEN SUBJECTED TO STANDARDIZED LOW-TEMPERATURE (20°F) AND HIGH-TEMPERATURE (95°F) OPERATING CONDITIONS RELATIVE TO BASELINE TEMPERATURES?

A. Objective

Examine the influence of ambient temperature on the fuel efficiency and range of BEVs and HEVs using a temperature-controlled test cell and four-wheel emissions dynamometer.

B. Methodology

- Dynamometer drive cycles will be performed according to SAE J1634 (BEV) and SAE J1711 (HEV) at an ambient temperature of 20°F, 75°F, and 95°F. Refer to the test matrix shown below for drive cycles, temperature, and vehicle HVAC settings.
- Road load coefficients were sourced from EPA published resources based on vehicle details and powertrain configuration.
- AAA utilized a modified version of the SAE test standards shown below to better reflect how motorists would use their vehicles in the real world. The modified version enabled the use of cabin air conditioning set to 72°F as well as testing at temperature extremes of 20°F and 95°F.



EV vs Hybrid Test Scenarios and Standards

Test Vehicles	Test Standard	Temperature and Test Cycles Scenarios		
		20°F	75°F	95°F
CRV Hybrid	SAE J1711	UDDS / HWFET	UDDS / HWFET	UDDS / HWFET
Prius Hybrid	SAE J1711	UDDS / HWFET	UDDS / HWFET	UDDS / HWFET
Tucson Hybrid	SAE J1711	UDDS / HWFET	UDDS / HWFET	UDDS / HWFET
Equinox-EV	SAE J1634	MCT	MCT	MCT
Mach-E	SAE J1634	MCT	MCT	MCT
Model Y	SAE J1634	MCT	MCT	MCT
Cabin Air Conditioning		Auto A/C	Auto A/C	Auto A/C
Car Set Temp		72°F	72°F	72°F

Figure 12: SAE test standards and vehicle matrix **Image Source: AAA Inc.**

C. Vehicle Efficiency Results

Test vehicles were evaluated at baseline temperature of 75°F to document overall vehicle fuel efficiency and range estimates prior to testing at temperature extremes of 20°F and 95°F.

Disclaimer: The purpose of this report is to evaluate vehicle efficiency and range changes relative to baseline laboratory testing. The results presented here reflect modified test procedures designed to assess vehicle performance at temperature extremes.

Because the procedures utilized in this project differ from those specified in EPA certification protocols, the values reported should not be compared to EPA-published fuel-economy or range data.

	Test Cycle	Test Temp	MPGe	Percent Change	Calculated Range (mi)	Range Reduction (mi)	Range Percent Change
Tesla Model Y	UDDS	20°F	54.5	-53.8%	136.1	172.30	-55.9%
		75°F	118.0	-	308.4	-	-
		95°F	81.8	-30.7%	215.0	93.37	-30.3%
	HWFET	20°F	73.7	-32.3%	184.0	100.54	-35.3%
		75°F	108.9	-	284.6	-	-
		95°F	97.8	-10.2%	257.1	27.49	-9.7%
	Comb	20°F	61.7	-45.7%	157.7	140.01	-47.0%
		75°F	113.7	-	297.7	-	-
		95°F	88.3	-22.3%	233.9	63.72	-21.4%

Figure 13: Tesla Model Y drive efficiency by temperature **Image Source: AAA Inc.**

1) Tesla Model Y (BEV, RWD): At the **75°F baseline**, the Model Y achieved **113.7 MPGe combined** with a **calculated range of 297.7 mi**, representing the vehicle's highest overall efficiency condition in this test set. Cycle-level behavior shows the expected trend of higher UDDS efficiency than HWFET at baseline due to lower average road load and greater opportunities for regenerative braking during UDDS.

a) ***Cold (20°F):*** Combined efficiency decreased to **61.7 MPGe** (**−45.7% vs 75°F**) and calculated range decreased to **157.7 mi** (**−47.0%**). Both UDDS and HWFET degraded substantially, with the largest fractional losses typically occurring on UDDS where stop-and-go operation amplifies auxiliary load fraction and where regenerative braking may be reduced during initial low battery temperature operation. The observed losses are consistent with BEV cold-temperature mechanisms: increased battery internal resistance, energy consumed by battery heating and cabin heating, and potential limitations on regenerative braking acceptance early in the test.

b) ***Hot (95°F):*** Combined efficiency decreased to **88.3 MPGe** (**−22.3%**) with range decreasing to **233.9 mi** (**−21.4%**). The hot penalty is driven predominantly by **air-conditioning load** and additional **battery/power electronics thermal management** demand. Compared with 20°F, the magnitude of degradation is lower, indicating that the vehicle's largest temperature sensitivity is associated with cold-soak thermal conditioning and heating loads.

c) ***Key observation:*** The Model Y exhibited a strong baseline efficiency at 75°F, compared to the other BEVs, but exhibited a pronounced reduction in both efficiency and range at temperature extremes, particularly at 20°F.

	Test Cycle	Test Temp	MPGe	Percent Change	Calculated Range (mi)	Range Reduction (mi)	Range Percent Change
Chevy Equinox EV	UDDS	20°F	60.7	-49.2%	165.3	183.1	-52.6%
		75°F	119.5	-	348.4	-	-
		95°F	114.0	-4.7%	340.5	7.9	-2.3%
	HWFET	20°F	70.5	-28.5%	191.8	95.4	-33.2%
		75°F	98.5	-	287.2	-	-
		95°F	96.7	-1.9%	288.8	-1.6	0.6%
	Comb	20°F	64.7	-40.6%	177.2	143.6	-44.8%
		75°F	109.1	-	320.8	-	-
		95°F	105.5	-3.3%	317.2	3.6	-1.1%

Figure 14: Chevy Equinox EV drive efficiency by temperature Image Source: AAA Inc.

2) Chevy Equinox EV (BEV, FWD): At **75°F**, the Equinox EV delivered **109.1 MPGe combined** and **320.8 mi calculated range**, indicating robust baseline efficiency and the highest baseline range among the BEVs evaluated.

a) ***Cold (20°F):*** Combined efficiency decreased to **64.7 MPGe** (**−40.6%**) and calculated range decreased to **177.2 mi** (**−44.8%**). Cycle-level results show a larger relative reduction on **UDDS** than **HWFET**, which is typical when the auxiliary loads (battery conditioning and cabin heat) represent a larger fraction of total energy during lower-speed operation. The magnitude of range reduction indicates that cold-weather thermal loads and battery electrochemical inefficiency materially increased energy consumption during the test.

b) ***Hot (95°F):*** Combined efficiency was **105.5 MPGe** (**−3.3%**) with calculated range **317.2 mi** (**−1.1%**). This represents a comparatively small hot penalty relative to the other BEVs. The result suggests that, under the tested duty cycle and control strategy, incremental **A/C and thermal management loads** remained modest versus baseline.

c) ***Key observation:*** The Equinox EV showed the expected BEV cold sensitivity, but it demonstrated the smallest degradation at 95°F within the BEV group.

	Test Cycle	Test Temp	MPGe	Percent Change	Calculated Range (mi)	Range Reduction (mi)	Range Percent Change
Ford Mach-E	UDDS	20°F	73.6	-24.5%	206.8	84.8	-29.1%
		75°F	97.4	-	291.6	-	-
		95°F	90.9	-6.7%	279.4	12.2	-4.2%
	HWFET	20°F	79.8	-15.4%	224.2	57.9	-20.5%
		75°F	94.2	-	282.1	-	-
		95°F	90.3	-4.2%	277.7	4.4	-1.6%
	Comb	20°F	76.2	-20.6%	214.6	72.7	-25.3%
		75°F	96.0	-	287.3	-	-
		95°F	90.6	-5.6%	278.7	8.7	-3.0%

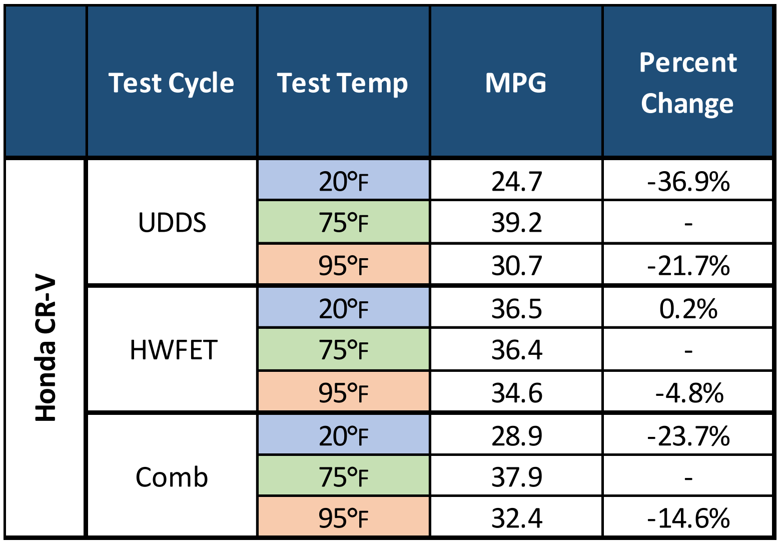
Figure 15: Ford Mach-E drive efficiency by temperature **Image Source: AAA Inc.**

3) Ford Mach-E (BEV, AWD): At **75°F**, the Mach-E achieved **96.0 MPGe combined** and **287.3 mi calculated range**. The AWD configuration introduces additional drivetrain parasitic losses relative to FWD/RWD variants, particularly noticeable during transient acceleration segments and at higher speeds.

a) ***Cold (20°F):*** Combined efficiency decreased to **76.2 MPGe** (**−20.6%**) and range decreased to **214.6 mi** (**−25.3%**). The cold penalty is significant but smaller in percent terms than the other BEVs in this dataset. For the 2025 model year Ford Mach-E, Ford implemented a patented vapor-injection heat-pump architecture coupled with revised thermal control algorithms. The system is designed to mitigate efficiency and range losses associated with elevated HVAC and battery thermal demands at temperature extremes. Cycle-level reductions remain consistent with BEV cold-temperature behavior (battery heating/cabin heating, higher internal resistance, reduced regenerative acceptance early in the test). AWD driveline losses can also be incrementally higher at cold temperatures due to increased lubricant viscosity and component friction until warm-up.

b) ***Hot (95°F):*** Combined efficiency decreased to **90.6 MPGe** (**−5.6%**) and range decreased to **278.7 mi** (**−3.0%**). The hot penalty is consistent with additional HVAC and thermal management loads but remains moderate overall.

c) ***Key observation:*** The Mach-E displayed measurable but comparatively restrained temperature sensitivity relative to the other BEVs, with the largest impact at 20°F.



	Test Cycle	Test Temp	MPG	Percent Change
Honda CR-V	UDDS	20°F	24.7	-36.9%
		75°F	39.2	-
		95°F	30.7	-21.7%
	HWFET	20°F	36.5	0.2%
		75°F	36.4	-
		95°F	34.6	-4.8%
	Comb	20°F	28.9	-23.7%
		75°F	37.9	-
		95°F	32.4	-14.6%

Figure 16: Honda CR-V (HEV) drive efficiency by temperature **Image Source: AAA Inc.**

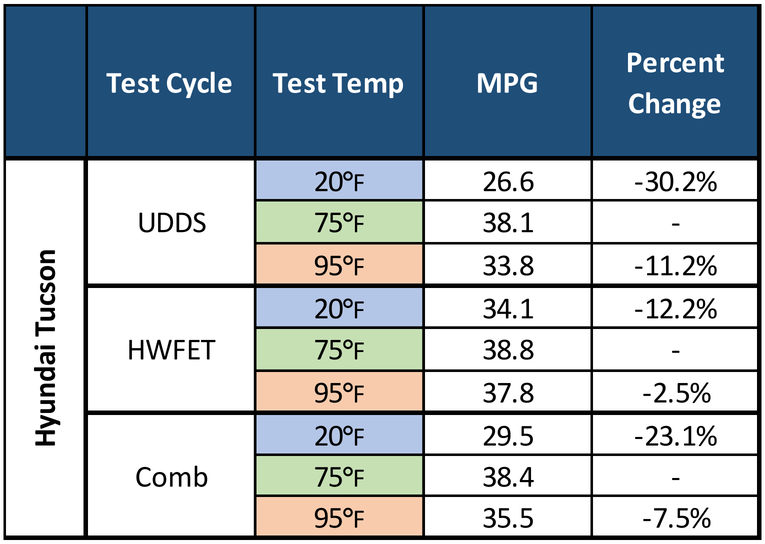
4) Honda CR-V (HEV, AWD): At **75°F**, the CR-V hybrid achieved **37.9 MPG combined**. At baseline temperature, the hybrid system can maintain favorable engine operating regions and leverage electric assist and regenerative braking to reduce fuel consumption relative to a conventional powertrain.

a) ***Cold (20°F):*** Combined fuel economy decreased to **28.9 MPG** (**−23.7% vs 75°F**). The reduction is primarily attributable to **engine warm-up requirements** (higher friction, enrichment, and less favorable combustion efficiency until full operating temperature is reached) and increased engine runtime to provide **cabin heating**. At 20°F, hybrid battery power capability and charge acceptance can also be reduced, limiting electric assist and regenerative energy recovery during early operation.

Cycle note: The HWFET change at 20°F was minimal and slightly positive relative to 75°F, which is best interpreted as **within test variability** rather than a true cold-weather efficiency improvement; the combined metric still shows a clear cold penalty.

b) ***Hot (95°F):*** Combined fuel economy decreased to **32.4 MPG** (**−14.6%**). The hot-temperature penalty is driven primarily by **air-conditioning compressor load**, increased cooling system operation, and control actions that keep engine and power electronics within thermal limits—reducing opportunities for engine-off operation and shifting operating points away from peak efficiency.

c) ***Key observation:*** Temperature sensitivity is present but is primarily tied to internal combustion engine warm-up and HVAC loads rather than battery conditioning energy as in BEVs.



	Test Cycle	Test Temp	MPG	Percent Change
Hyundai Tucson	UDDS	20°F	26.6	-30.2%
		75°F	38.1	-
		95°F	33.8	-11.2%
	HWFET	20°F	34.1	-12.2%
		75°F	38.8	-
		95°F	37.8	-2.5%
	Comb	20°F	29.5	-23.1%
		75°F	38.4	-
		95°F	35.5	-7.5%

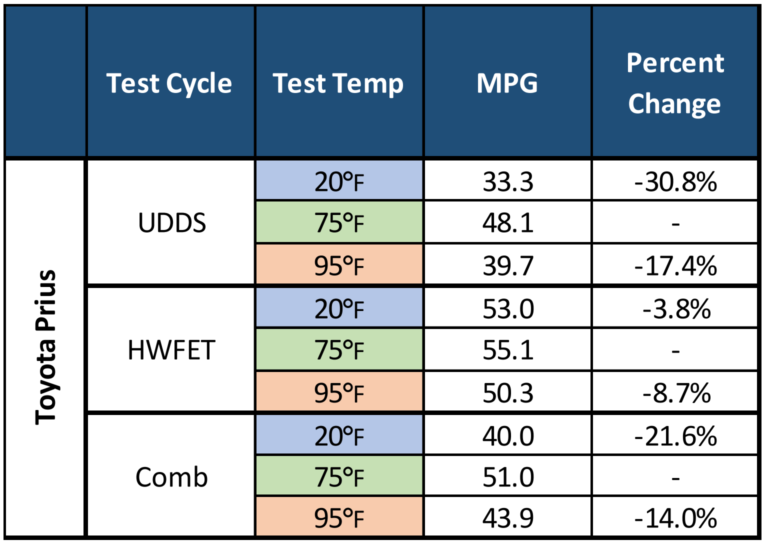
Figure 17: Hyundai Tucson (HEV) drive efficiency by temperature **Image Source: AAA Inc.**

5) Hyundai Tucson Hybrid (HEV, AWD): At **75°F**, the Tucson Hybrid achieved **38.4 MPG combined**, similar baseline efficiency to the CR-V hybrid.

a) ***Cold (20°F):*** Combined fuel economy decreased to **29.5 MPG** (**−23.1%**). The trend reflects typical HEV cold impacts: increased fuel use during warm-up, greater engine-on time to meet cabin heat demand, and reduced battery assist/regeneration capability at low battery temperatures.

b) ***Hot (95°F):*** Combined fuel economy decreased to **35.5 MPG** (**−7.5%**). The hot penalty is smaller than the CR-V and Prius in this dataset and is consistent with incremental A/C and cooling system loads without an extended warm-up penalty.

c) ***Key observation:*** The Tucson Hybrid demonstrated a cold temperature degradation comparable to the CR-V but a relatively smaller degradation at 95°F.



	Test Cycle	Test Temp	MPG	Percent Change
Toyota Prius	UDDS	20°F	33.3	-30.8%
		75°F	48.1	-
		95°F	39.7	-17.4%
	HWFET	20°F	53.0	-3.8%
		75°F	55.1	-
		95°F	50.3	-8.7%
	Comb	20°F	40.0	-21.6%
		75°F	51.0	-
		95°F	43.9	-14.0%

Figure 18: Toyota Prius (HEV) drive efficiency by temperature **Image Source: AAA Inc.**

6) Toyota Prius (HEV, FWD): At **75°F**, the Prius produced the highest HEV baseline performance at **51.0 MPG combined**, consistent with a highly optimized hybrid architecture with strong control strategies for engine loading, electric assist, and regenerative braking.

a) ***Cold (20°F):*** Combined fuel economy decreased to **40.0 MPG** (**−21.6%**). Losses are primarily associated with engine warm-up fuel consumption, increased engine operation to provide cabin heat, and reduced battery power/regen acceptance at low temperatures. While the Prius is optimized to minimize warm-up impacts, the cold condition still imposes a meaningful penalty relative to baseline.

b) ***Hot (95°F):*** Combined fuel economy decreased to **43.9 MPG** (**−14.0%**). The hot penalty is driven mainly by A/C load and elevated thermal management demand, which reduces the ability to maintain the most efficient engine operating points and can reduce engine-off operation.

c) ***Key observation:*** The Prius maintained the highest efficiency across all temperatures among the HEVs, but still exhibited measurable degradation at both 20°F and 95°F versus baseline.

D. Overall BEV vs HEV Performance Summary

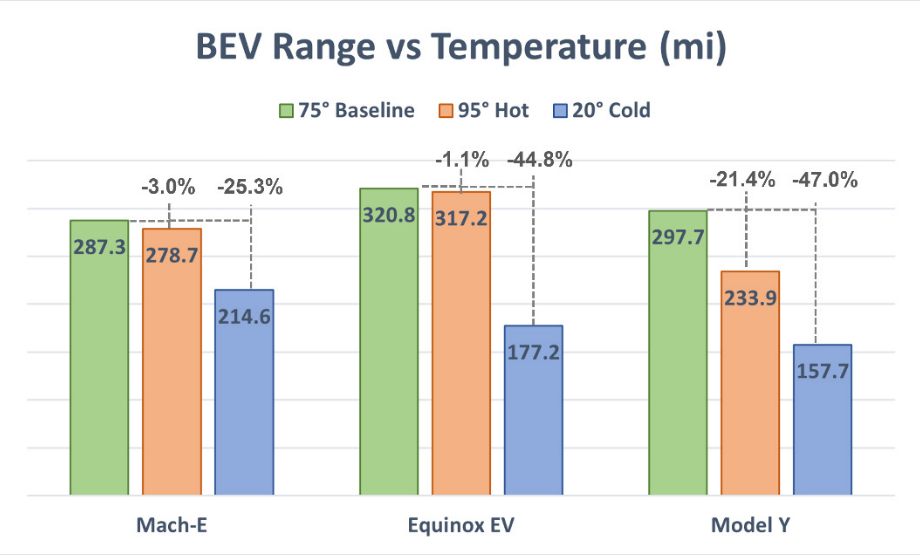
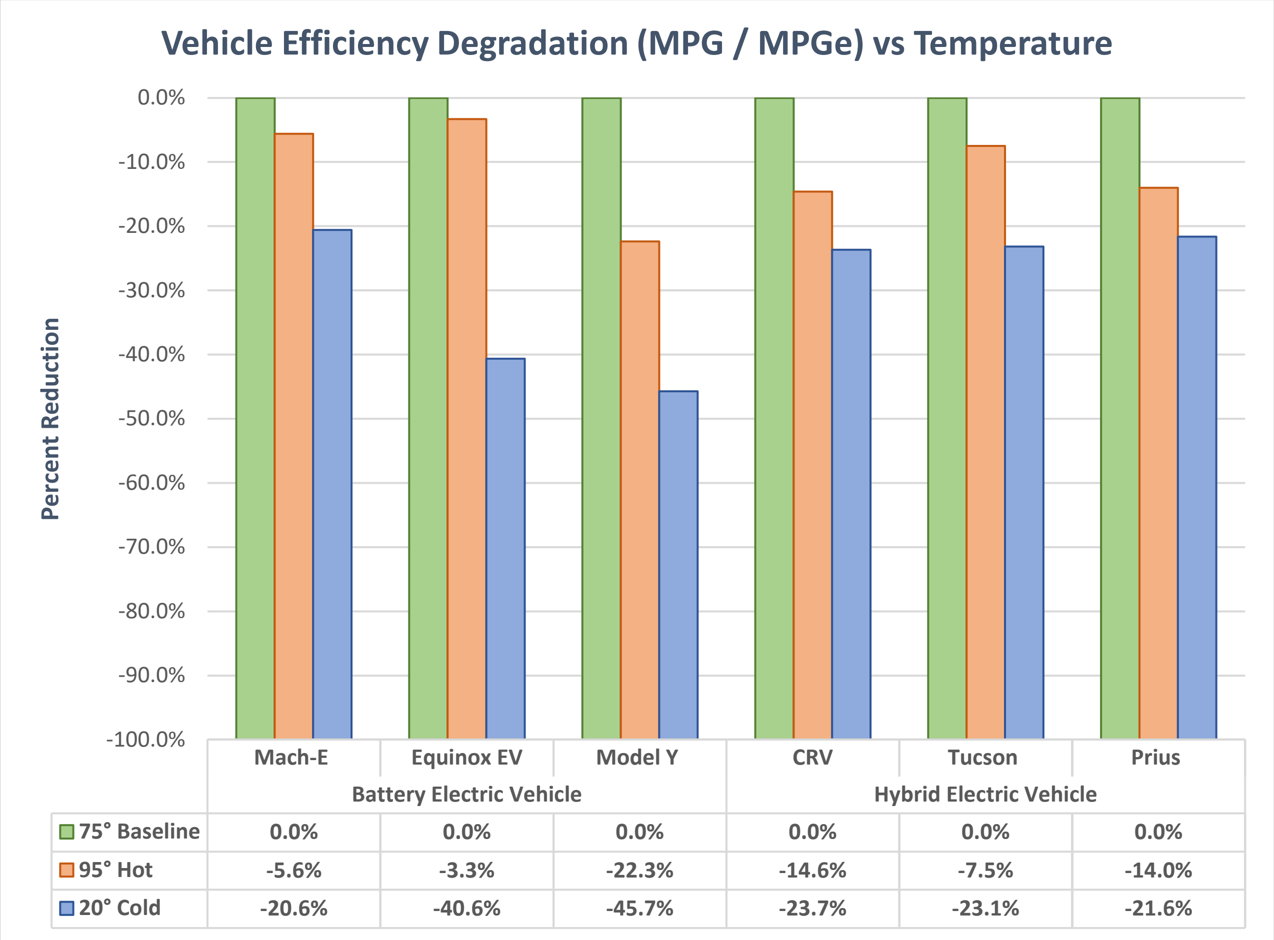


Figure 19: BEV Range Loss by Temperature **Image Source: AAA Inc.**

BEVs were evaluated using an MCT protocol in which the traction battery was fully depleted to determine effective driving range at baseline, hot, and cold ambient temperatures. HEVs were not tested to zero range due to fundamental differences in their test protocols and energy replenishment strategies. As a result, range-based comparisons are limited to BEVs and are not directly comparable to HEV results.

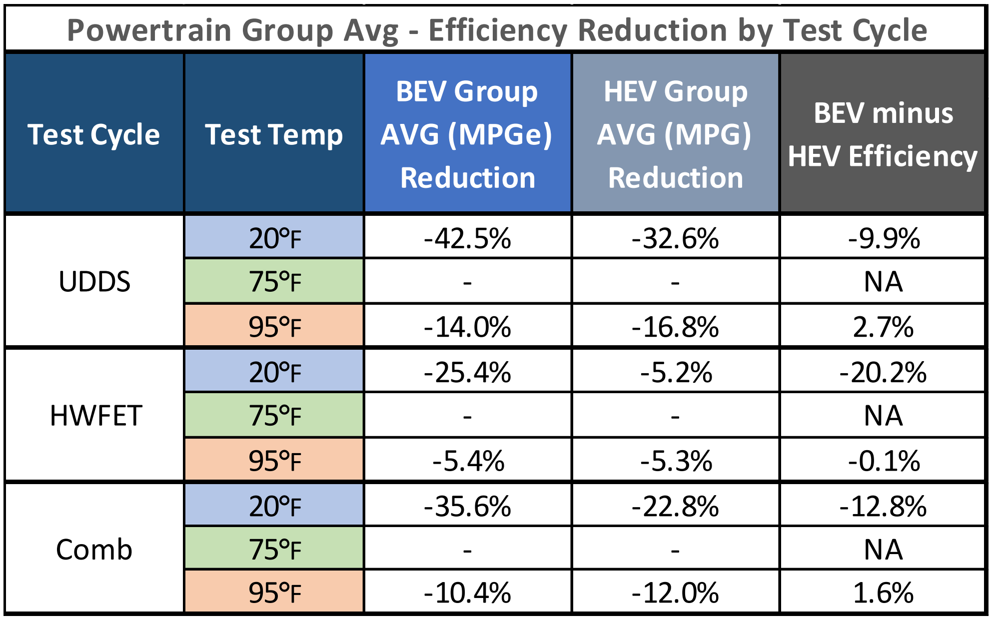
When evaluated relative to the 75°F baseline condition, a clear distinction emerged between BEV and HEV performance behavior. BEVs achieved substantially higher peak efficiency under nominal laboratory conditions but experienced large efficiency reductions during cold operation. At 20°F, propulsion energy demand associated with battery conditioning and cabin heating represented a dominant share of total energy consumption, particularly in urban driving (UDDS). These loads translated directly into significant range losses. High-temperature operation produced measurable but smaller penalties, indicating that cold-weather auxiliary demand is the primary limiting factor for BEV efficiency. The results from the efficiency degradation due to temperature are shown within the graph below.



	Mach-E	Equinox EV	Model Y	CRV	Tucson	Prius
	Battery Electric Vehicle			Hybrid Electric Vehicle		
🟩 75° Baseline	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
🟧 95° Hot	-5.6%	-3.3%	-22.3%	-14.6%	-7.5%	-14.0%
🟦 20° Cold	-20.6%	-40.6%	-45.7%	-23.7%	-23.1%	-21.6%

Figure 20: BEV vs HEV Efficiency at Temperature **Image Source: AAA Inc.**

Vehicle model efficiency results were averaged by powertrain category to compare BEVs and HEVs and to assess which powertrain type exhibited the smallest efficiency degradation under hot and cold conditions relative to baseline testing.



Powertrain Group Avg - Efficiency Reduction by Test Cycle

Test Cycle	Test Temp	BEV Group AVG (MPGe) Reduction	HEV Group AVG (MPG) Reduction	BEV minus HEV Efficiency
UDDS	20°F	-42.5%	-32.6%	-9.9%
	75°F	-	-	NA
	95°F	-14.0%	-16.8%	2.7%
HWFET	20°F	-25.4%	-5.2%	-20.2%
	75°F	-	-	NA
	95°F	-5.4%	-5.3%	-0.1%
Comb	20°F	-35.6%	-22.8%	-12.8%
	75°F	-	-	NA
	95°F	-10.4%	-12.0%	1.6%

Figure 21:BEV vs HEV Range and Economy Reduction by Cycle / Temperature Image Source: AAA Inc.

HEVs, while delivering lower peak efficiency at baseline, maintained tighter performance bands across temperature extremes. Cold-weather efficiency losses were moderate rather than severe, and high-temperature impacts were minimal. Because hybrids can shift propulsion energy toward internal combustion operation when battery performance declines, they experience reduced sensitivity to ambient conditions.

These findings highlight a fundamental tradeoff: BEVs maximize efficiency near nominal environmental conditions but are strongly influenced by cold-weather thermal demand, whereas HEV architecture prioritize operational stability and demonstrate greater cross-environment robustness.

E. Overall BEV vs HEV Performance Comparison (20°F / 95°F vs 75°F Baseline)

1) Baseline behavior at 75°F (reference condition)

a) BEVs: Highest absolute efficiency at baseline (combined values ranged from approximately **96 to 114 MPGe** in this dataset) with high calculated range.

b) HEVs: Lower baseline efficiency on an absolute energy basis than BEVs, but stable combined MPG values (here **~38 to 51 MPG**) with no range constraint comparable to BEVs.

2) Cold temperature sensitivity (20°F vs 75°F):

a) BEVs (combined average): Approximately **−35.6% MPGe** and **−39.0% calculated range**.

- Cold penalties are driven by **battery electrochemical inefficiency, battery heating, cabin heating**, and **reduced regenerative braking acceptance** at low battery temperature.
- The dataset shows large range reductions for BEVs in cold conditions (e.g., ~25% to ~47% depending on model).

b) HEVs (combined average): Approximately **−22.8% MPG**.

  - Cold penalties are dominated by **engine warm-up**, increased engine run time to supply **cabin heat**, and reduced effectiveness of electric assist/regeneration early in the cycle.

c) Interpretation: BEVs generally exhibit a larger cold-weather penalty because heating energy must be supplied electrically and because battery efficiency and power capability degrade at low temperature. HEVs also lose efficiency, but waste heat from the engine provides cabin heat and reduces the need for high auxiliary electrical loads.

3) Hot temperature sensitivity (95°F vs 75°F):

a) BEVs (combined average): Approximately **−10.4% MPGe** and **−8.5% calculated range**.

- Hot-temperature penalties primarily reflect **A/C compressor load** and **battery/power electronics cooling**.
- Magnitude is vehicle-dependent; in this dataset, one BEV showed minimal hot penalty while another showed a substantial reduction.

b) HEVs (combined average): Approximately **−12.0% MPG**.

- Hot-temperature penalties are largely due to **A/C load** increasing net engine work and reducing engine-off operation opportunities.

c) Interpretation: At 95°F, both powertrains experience HVAC-driven efficiency degradation. In regulated cycle testing, the magnitude depends on vehicle HVAC capacity, thermal management strategy, and control calibration.

F. Summary Conclusion

Across chassis dyno testing at 20°F, 75°F, and 95°F, BEVs demonstrated superior baseline efficiency at 75°F but showed greater sensitivity to cold ambient conditions, with substantial reductions in both MPGe and calculated range. HEVs showed smaller cold-weather penalties relative to BEVs, with losses primarily linked to engine warm-up and HVAC loads rather than battery conditioning energy. At 95°F, both BEVs and HEVs incurred efficiency penalties driven by cabin cooling and thermal management, with magnitude varying by vehicle architecture and control strategy.

VII. INQUIRY #2: WHAT ARE THE “FUEL” COSTS OF BEVs AND HEVs ACROSS COLD, HOT, AND BASELINE TEMPERATURES WHEN REAL-WORLD RANGE AND HVAC USE ARE CONSIDERED?

The ***AAA Your Driving Costs*** [6] calculator provides a standardized framework for estimating annual operating energy cost across all major light-duty powertrains, including internal-combustion engine vehicles, HEVs, plug-in hybrid electric vehicles, and BEVs. The tool incorporates region-specific gasoline and electricity prices along with representative annual mileage to generate geographically relevant operating-cost estimates. By applying localized energy-price and fuel data, the calculator enables consistent cross-powertrain comparisons that reflect real-world operating conditions rather than national averages.

The ***AAA Your Driving Costs*** calculator relies on manufacturer-reported fuel-economy values and does not account for efficiency degradation as a function of ambient temperature. In this study, the research team quantified the potential cost impacts of operating BEVs and HEVs under temperature extremes and compared these results to baseline test conditions to illustrate the potential real-world operating costs associated with extreme-temperature driving.

In this report, publicly available data sources were used to determine national average fuel and electricity prices. All fuel and electricity pricing values were updated as of March 27, 2026, to ensure consistency across the analysis.

The following fuel prices and electricity rates were used within this analysis:

- **Retail Fuel Price:** $3.978 per gallon (Source: AAA Fuel Prices [7])
- **Commercial EV Charging:** $0.418 per kWh (Source: AAA EV Charging Prices [8])
- **Residential EV Charging:** $0.1745 per kWh (Source: U.S. EIA data [9])

Hybrid Electric Vehicle Fuel Cost Calculation:

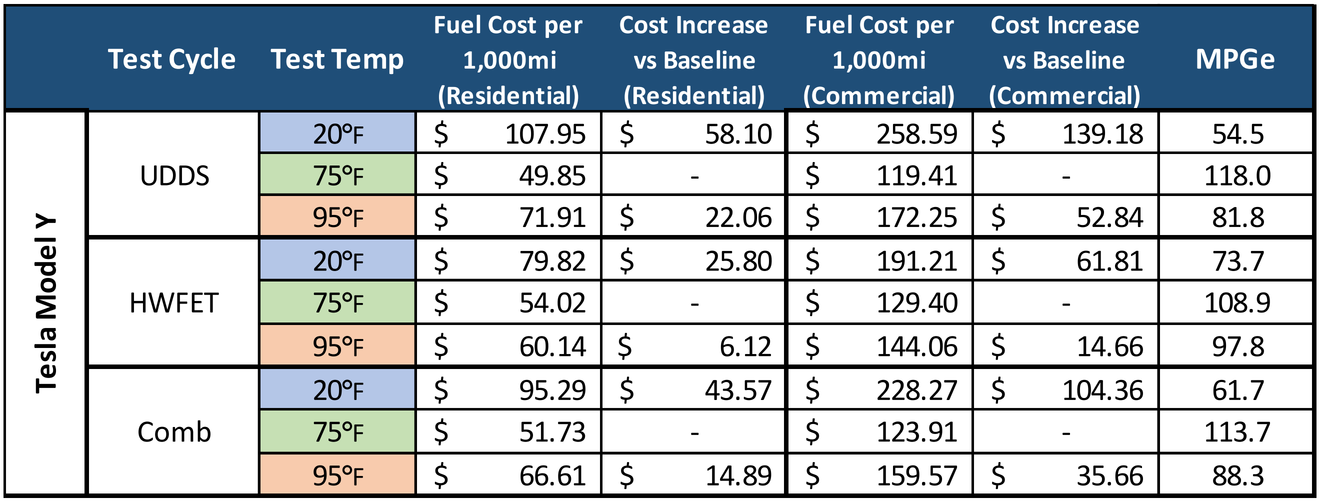
$$Fuel\ Cost\ per\ 1{,}000 mile\ [\$] = \frac{Price[\frac{\$}{gal}]}{MPG\ [\frac{mi}{gal}]} \times\ 1{,}000\ [mi]$$

Battery Electric Vehicle Fuel Cost Calculation:

$$Fuel\ Cost\ per\ 1{,}000 mile\ [\$] = 33.7\ \left[\frac{kWh}{gal}\right] \times \left[\frac{Price\left[\frac{\$}{kWh}\right]}{MPGe\left[\frac{mi}{gal}\right]}\right] \times 1{,}000\ [mi]$$

A. Vehicle Model Cost-to-Drive Performance Summary

Cost Impact per 1,000 Miles – 20°F and 95°F Relative to 75°F Baseline: Testing conducted on an EPA-certified chassis dynamometer at 20°F, 75°F (baseline), and 95°F shows measurable increases in the cost to drive 1,000 miles for all vehicles evaluated. The magnitude of this change varies by powertrain architecture and, for BEVs, by charging cost structure (residential versus commercial). Although annual fuel-cost calculators commonly use 10,000–15,000 miles, presenting results on a 1,000-mile basis more clearly illustrates the seasonal cost impacts associated with limited periods of extreme hot or cold ambient temperatures.

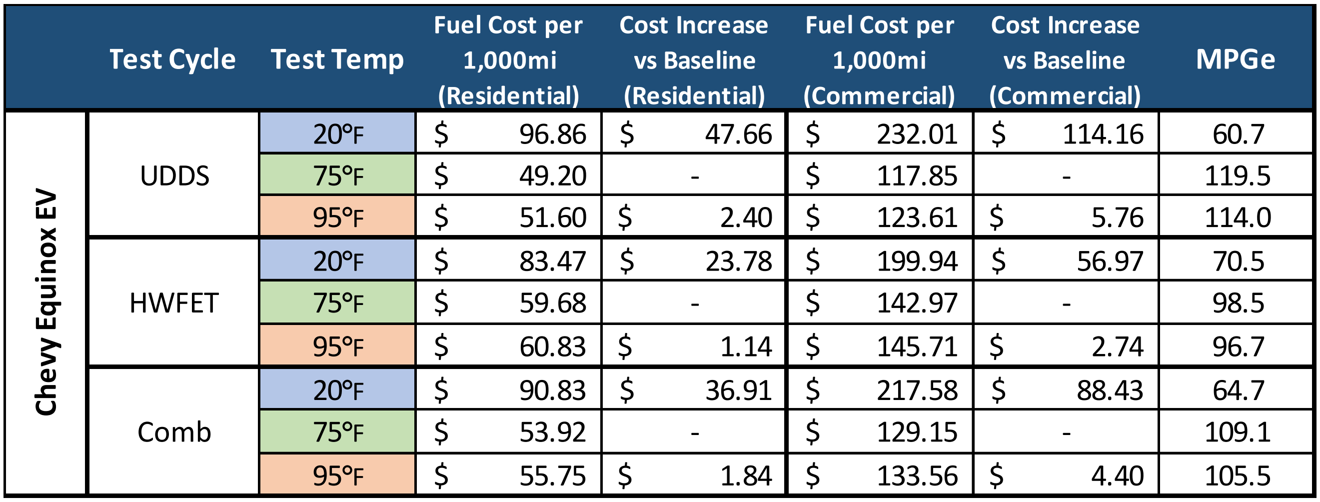


	Test Cycle	Test Temp	Fuel Cost per 1,000mi (Residential)	Cost Increase vs Baseline (Residential)	Fuel Cost per 1,000mi (Commercial)	Cost Increase vs Baseline (Commercial)	MPGe
Tesla Model Y	UDDS	20°F	$ 107.95	$ 58.10	$ 258.59	$ 139.18	54.5
		75°F	$ 49.85	-	$ 119.41	-	118.0
		95°F	$ 71.91	$ 22.06	$ 172.25	$ 52.84	81.8
	HWFET	20°F	$ 79.82	$ 25.80	$ 191.21	$ 61.81	73.7
		75°F	$ 54.02	-	$ 129.40	-	108.9
		95°F	$ 60.14	$ 6.12	$ 144.06	$ 14.66	97.8
	Comb	20°F	$ 95.29	$ 43.57	$ 228.27	$ 104.36	61.7
		75°F	$ 51.73	-	$ 123.91	-	113.7
		95°F	$ 66.61	$ 14.89	$ 159.57	$ 35.66	88.3

Electrical Rate: Residential $0.1745/kWh and Commercial $0.4180/kWh

Figure 22: Tesla Model Y Cost to Drive 1,000mi **Image Source: AAA Inc.**

At baseline (75°F), the Tesla Model Y delivered low cost-to-drive, but it was highly sensitive to cold. At 20°F, cost increased by **$43.57/1,000 mi on residential** charging (from $51.73 to $95.29) and by **$104.36/1,000 mi on commercial charging** (from $123.91 to $228.27). At 95°F, the increase was smaller but still measurable: **$14.89/1,000 mi residential** ($51.73 to $66.61) and **$35.66/1,000 mi commercial** ($123.91 to $159.57). In practical terms, the Tesla Model Y's operating cost is strongly driven by cold-weather energy demand, and the charging price structure significantly magnifies that penalty.



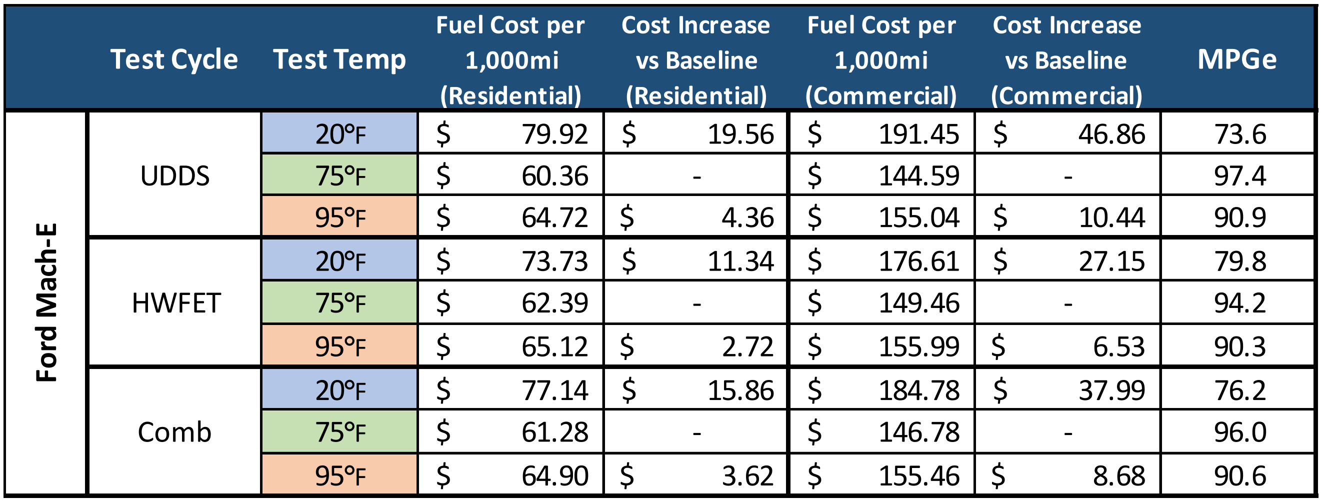
	Test Cycle	Test Temp	Fuel Cost per 1,000mi (Residential)	Cost Increase vs Baseline (Residential)	Fuel Cost per 1,000mi (Commercial)	Cost Increase vs Baseline (Commercial)	MPGe
Chevy Equinox EV	UDDS	20°F	$ 96.86	$ 47.66	$ 232.01	$ 114.16	60.7
		75°F	$ 49.20	-	$ 117.85	-	119.5
		95°F	$ 51.60	$ 2.40	$ 123.61	$ 5.76	114.0
	HWFET	20°F	$ 83.47	$ 23.78	$ 199.94	$ 56.97	70.5
		75°F	$ 59.68	-	$ 142.97	-	98.5
		95°F	$ 60.83	$ 1.14	$ 145.71	$ 2.74	96.7
	Comb	20°F	$ 90.83	$ 36.91	$ 217.58	$ 88.43	64.7
		75°F	$ 53.92	-	$ 129.15	-	109.1
		95°F	$ 55.75	$ 1.84	$ 133.56	$ 4.40	105.5

Electrical Rate: Residential $0.1745/kWh and Commercial $0.4180/kWh

Figure 23: Chevy Equinox-EV Cost to Drive 1,000mi **Image Source: AAA Inc.**

The Chevy Equinox EV followed the same basic pattern—cold dominates price increase, hot temperatures have a minor impact—but with an even clearer split between temperature extremes. At 20°F, cost increased **by $36.91/1,000 mi residential** (from $53.92 to $90.83) and **$88.43/1,000 mi commercial** (from $129.15 to $217.58). At 95°F, the change was essentially a rounding error compared to the cold shift**:**

$1.84/1,000 mi residential ($53.92 to $55.75) and **$4.40/1,000 mi commercial** ($129.15 to $133.56). This suggests the Equinox EV's high-ambient HVAC load produced only a small incremental cost change relative to baseline, while low-ambient thermal demand was the primary driver.

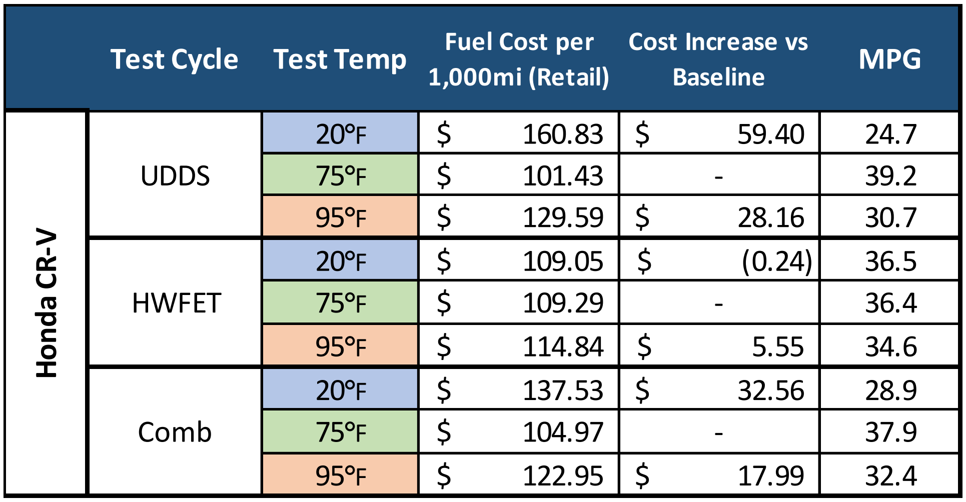


	Test Cycle	Test Temp	Fuel Cost per 1,000mi (Residential)	Cost Increase vs Baseline (Residential)	Fuel Cost per 1,000mi (Commercial)	Cost Increase vs Baseline (Commercial)	MPGe
Ford Mach-E	UDDS	20°F	$ 79.92	$ 19.56	$ 191.45	$ 46.86	73.6
		75°F	$ 60.36	-	$ 144.59	-	97.4
		95°F	$ 64.72	$ 4.36	$ 155.04	$ 10.44	90.9
	HWFET	20°F	$ 73.73	$ 11.34	$ 176.61	$ 27.15	79.8
		75°F	$ 62.39	-	$ 149.46	-	94.2
		95°F	$ 65.12	$ 2.72	$ 155.99	$ 6.53	90.3
	Comb	20°F	$ 77.14	$ 15.86	$ 184.78	$ 37.99	76.2
		75°F	$ 61.28	-	$ 146.78	-	96.0
		95°F	$ 64.90	$ 3.62	$ 155.46	$ 8.68	90.6

Electrical Rate: Residential $0.1745/kWh and Commercial $0.4180/kWh

Figure 24: Ford Mach-E Cost to Drive 1,000mi **Image Source: AAA Inc.**

The Ford Mach-E was the most stable BEV in this set. At 20°F, cost increased by **$15.86/1,000 mi residential** (from $61.28 to $77.14) and **$37.99/1,000 mi commercial** (from $146.78 to $184.78). At 95°F, the increase was modest: **$3.62/1,000 mi residential** ($61.28 to $64.90) and **$8.68/1,000 mi commercial** ($146.78 to $155.46). Relative to the other BEVs, the Mach-E shows lower cold-cost escalation, which improves operating-cost stability across ambient conditions.

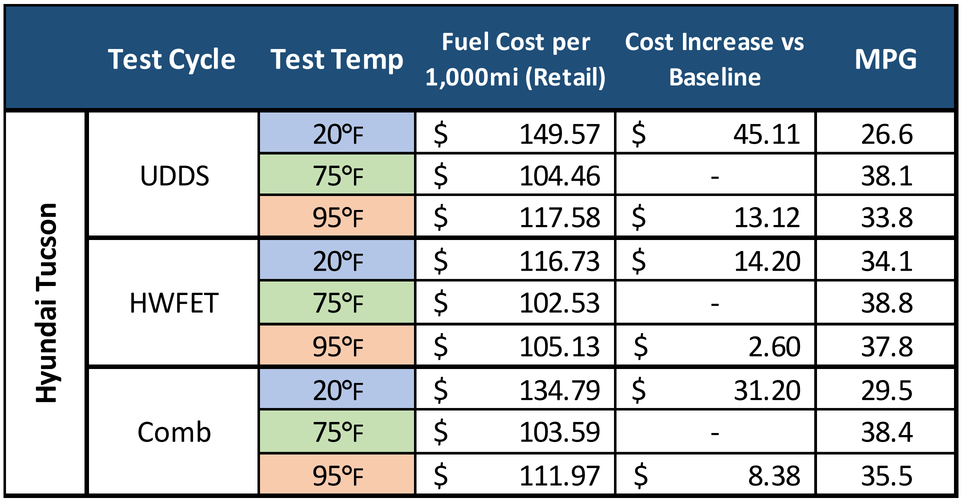


	Test Cycle	Test Temp	Fuel Cost per 1,000mi (Retail)	Cost Increase vs Baseline	MPG
Honda CR-V	UDDS	20°F	$ 160.83	$ 59.40	24.7
		75°F	$ 101.43	-	39.2
		95°F	$ 129.59	$ 28.16	30.7
	HWFET	20°F	$ 109.05	$ (0.24)	36.5
		75°F	$ 109.29	-	36.4
		95°F	$ 114.84	$ 5.55	34.6
	Comb	20°F	$ 137.53	$ 32.56	28.9
		75°F	$ 104.97	-	37.9
		95°F	$ 122.95	$ 17.99	32.4

Fuel Price: $3.978/gallon

Figure 25: Honda CR-V Cost to Drive 1,000mi **Image Source: AAA Inc.**

For the Honda CR-V Hybrid, cost increases were present at both extremes, with cold still the larger driver. At 20°F, cost increased by **$32.56/1,000 mi** (from $104.97 to $137.53). At 95°F, cost increased by **$17.99/1,000 mi** (from $104.97 to $122.95). Compared with BEVs, the Honda CR-V's cost sensitivity is less dependent on "energy price structure" and more directly tied to fuel economy degradation under warm-up and HVAC load.

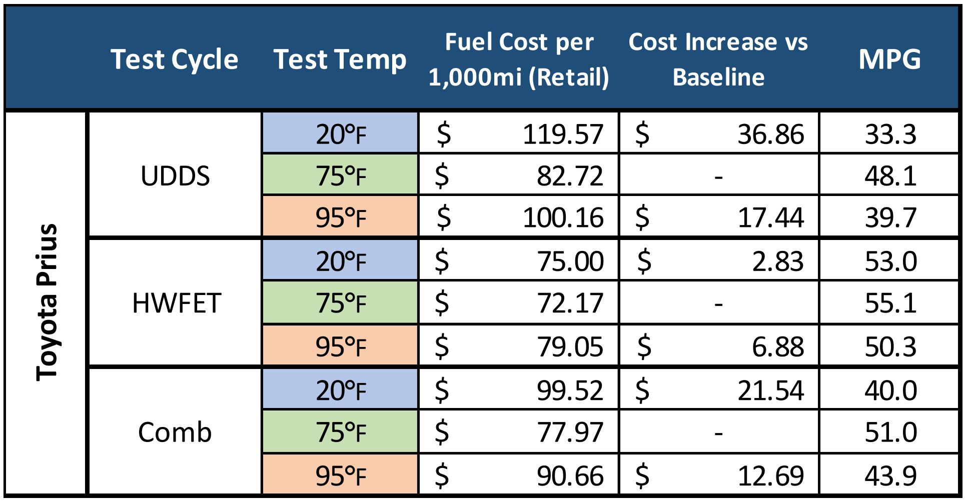


	Test Cycle	Test Temp	Fuel Cost per 1,000mi (Retail)	Cost Increase vs Baseline	MPG
Hyundai Tucson	UDDS	20°F	$ 149.57	$ 45.11	26.6
		75°F	$ 104.46	-	38.1
		95°F	$ 117.58	$ 13.12	33.8
	HWFET	20°F	$ 116.73	$ 14.20	34.1
		75°F	$ 102.53	-	38.8
		95°F	$ 105.13	$ 2.60	37.8
	Comb	20°F	$ 134.79	$ 31.20	29.5
		75°F	$ 103.59	-	38.4
		95°F	$ 111.97	$ 8.38	35.5

Fuel Price: $3.978/gallon

Figure 26: Hyundai Tucson Cost to Drive 1,000mi **Image Source: AAA Inc.**

The Hyundai Tucson Hybrid showed a cold penalty similar to the Honda CR-V, but a smaller hot penalty. At 20°F, cost increased by **$31.20/1,000 mi** (from $103.59 to $134.79). At 95°F, cost increased by **$8.38/1,000 mi** ($103.59 to $111.97). Overall, the Tucson behaves like a typical HEV: noticeable cold sensitivity, but less escalation than BEVs (especially versus BEVs on commercial charging).

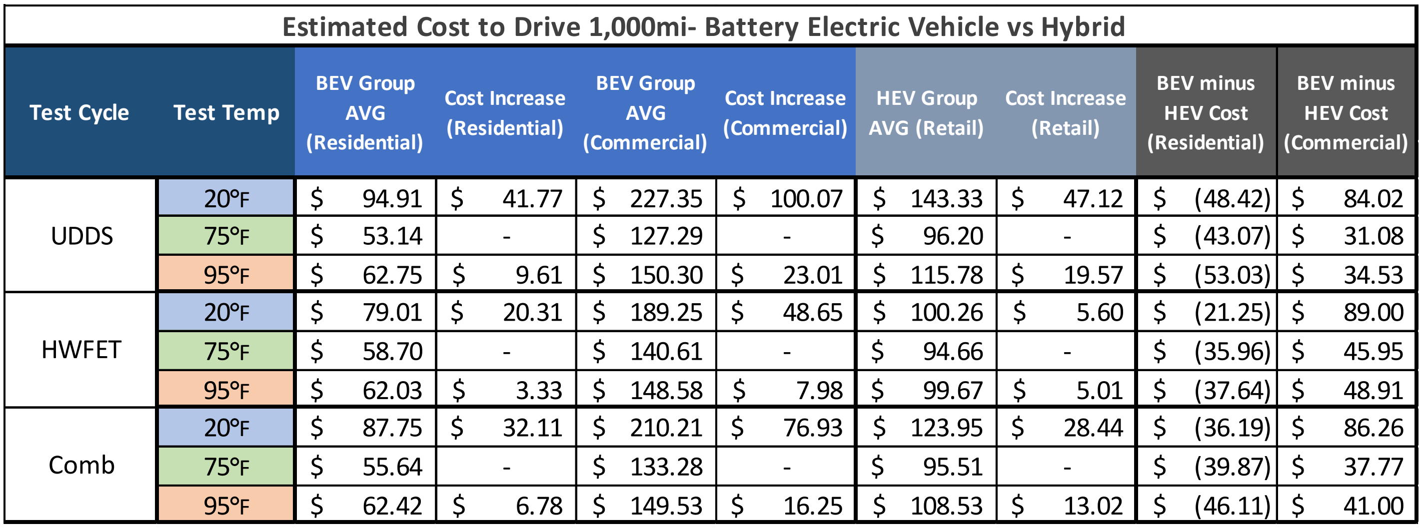


	Test Cycle	Test Temp	Fuel Cost per 1,000mi (Retail)	Cost Increase vs Baseline	MPG
Toyota Prius	UDDS	20°F	$ 119.57	$ 36.86	33.3
		75°F	$ 82.72	-	48.1
		95°F	$ 100.16	$ 17.44	39.7
	HWFET	20°F	$ 75.00	$ 2.83	53.0
		75°F	$ 72.17	-	55.1
		95°F	$ 79.05	$ 6.88	50.3
	Comb	20°F	$ 99.52	$ 21.54	40.0
		75°F	$ 77.97	-	51.0
		95°F	$ 90.66	$ 12.69	43.9

Fuel Price: $3.978/gallon

Figure 27: Toyota Prius Cost to Drive 1,000mi **Image Source: AAA Inc.**

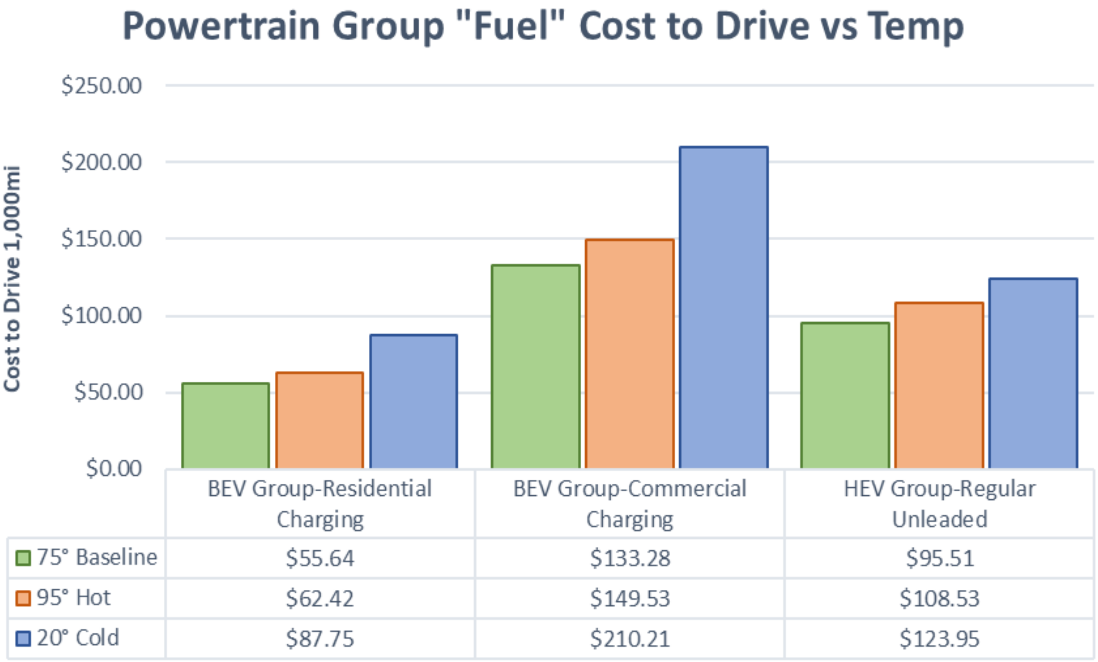
The Toyota Prius delivered the lowest cost sensitivity among the HEVs in this dataset. At 20°F, cost increased by **$21.54/1,000 mi** (from $77.97 to $99.52). At 95°F, cost increased by **$12.69/1,000 mi** (from $77.97 to $90.66). The Toyota Prius' strong baseline efficiency helps limit the absolute cost increase even when temperature-driven losses are present.



Estimated Cost to Drive 1,000mi- Battery Electric Vehicle vs Hybrid

Test Cycle	Test Temp	BEV Group AVG (Residential)	Cost Increase (Residential)	BEV Group AVG (Commercial)	Cost Increase (Commercial)	HEV Group AVG (Retail)	Cost Increase (Retail)	BEV minus HEV Cost (Residential)	BEV minus HEV Cost (Commercial)
UDDS	20°F	$ 94.91	$ 41.77	$ 227.35	$ 100.07	$ 143.33	$ 47.12	$ (48.42)	$ 84.02
	75°F	$ 53.14	-	$ 127.29	-	$ 96.20	-	$ (43.07)	$ 31.08
	95°F	$ 62.75	$ 9.61	$ 150.30	$ 23.01	$ 115.78	$ 19.57	$ (53.03)	$ 34.53
HWFET	20°F	$ 79.01	$ 20.31	$ 189.25	$ 48.65	$ 100.26	$ 5.60	$ (21.25)	$ 89.00
	75°F	$ 58.70	-	$ 140.61	-	$ 94.66	-	$ (35.96)	$ 45.95
	95°F	$ 62.03	$ 3.33	$ 148.58	$ 7.98	$ 99.67	$ 5.01	$ (37.64)	$ 48.91
Comb	20°F	$ 87.75	$ 32.11	$ 210.21	$ 76.93	$ 123.95	$ 28.44	$ (36.19)	$ 86.26
	75°F	$ 55.64	-	$ 133.28	-	$ 95.51	-	$ (39.87)	$ 37.77
	95°F	$ 62.42	$ 6.78	$ 149.53	$ 16.25	$ 108.53	$ 13.02	$ (46.11)	$ 41.00

Figure 28: BEV vs HEV average cost by powertrain to drive 1,000 miles **Image Source: AAA Inc.**



	BEV Group-Residential Charging	BEV Group-Commercial Charging	HEV Group-Regular Unleaded
🟩 75° Baseline	$55.64	$133.28	$95.51
🟧 95° Hot	$62.42	$149.53	$108.53
🟦 20° Cold	$87.75	$210.21	$123.95

Figure 29: BEV vs HEV average cost by powertrain to drive 1,000 miles **Image Source: AAA Inc.**

B. Overall powertrain cost summary: BEV vs HEV

When evaluating the vehicles by powertrain type, the results tell a consistent story:

- Cold operation (20°F) drives the largest cost increases for every vehicle, but BEVs show the largest cold sensitivity relative to their 75°F baseline, especially when costs are calculated using commercial charging.
- When comparing powertrains (BEV vs. HEV) at 20°F using residential charging, BEVs were $36.19 cheaper than HEVs per 1,000mi; however, when using commercial charging, BEVs were considerably more expensive with a $86.26 increase in cost for the same miles driven.
- On a fleet-average basis, BEVs increased by about $32.11/1,000 mi (to $87.75 from $55.64) at 20°F on residential charging, but that rose to roughly $76.93/1,000 mi (to $210.21 from $133.28) when the same cold-weather energy demand is priced at commercial charging rates.
- HEVs increased by about $28.44/1,000 mi (to $123.95 from $95.51), at 20°F versus baseline reflecting higher fuel consumption due to warm-up penalties and auxiliary loads.
- At 95°F, both architectures showed smaller impacts: BEVs averaged about $6.78/1,000 mi (to $62.42 from $55.64) (residential) and $16.25/1,000 mi (to $149.53 from $133.28) (commercial), while HEVs averaged about $13.02/1,000 mi (to $108.53 from $95.51).

From an engineering perspective, the key takeaway is that BEVs maintain low operating cost in baseline conditions, but their cost stability across ambient extremes is strongly influenced by thermal loads and charging assumptions. HEVs show more moderate variability across temperature extremes, with cost shifts driven primarily by fuel economy degradation rather than energy-price tier effects.

VIII. DRIVING COST DISCUSSION

A. Vehicle model cost-to-drive summary (per 1,000 miles)

Across the fleet, both cold (20°F) and hot (95°F) testing increased cost to drive 1,000 miles relative to the 75°F baseline, but the pattern differs by powertrain. For the BEVs, the cold condition clearly drives the largest cost increase, and the effect is amplified when costs are calculated using commercial charging rates. The Tesla Model Y showed the strongest cold sensitivity, with a large step-up in cost per 1,000 miles at 20°F versus baseline under both residential and commercial charging. The Chevrolet Equinox EV followed a similar trend—substantial cold increase but relatively little change at 95°F—indicating that hot-weather efficiency losses were comparatively minor for this vehicle. The Ford Mustang Mach-E was the most stable BEV in the group, showing the smallest cold-driven cost increase and only a modest hot-weather increase relative to baseline.

For the HEVs, the cost penalty was present at both temperature extremes but generally less variable than the BEVs in cold conditions. The Honda CR-V Hybrid and Hyundai Tucson Hybrid showed similar cold-weather increases versus baseline, consistent with additional warm-up fuel demand and accessory loads, while the Toyota Prius had the lowest cold penalty in the HEV set, reflecting its higher baseline efficiency. At 95°F, HEV cost increases were measurable but typically smaller than the 20°F condition, aligning with HVAC-driven load increases rather than major powertrain efficiency shifts.

B. Overall powertrain comparison (BEV vs HEV)

When viewed at the powertrain level, the results show a consistent takeaway: cold ambient operation is the dominant driver of cost-to-drive increases, and BEVs are more sensitive to cold operation than HEVs when compared to their 75°F baseline. For BEVs, the cold penalty is driven by added electrical demand for battery thermal conditioning and cabin heating, and the cost impact scales directly with the assumed charging rate—meaning the same efficiency loss translates into a much larger cost per 1,000-mile increase under commercial charging than under residential charging. In contrast, HEVs show a more moderate cold penalty and a relatively balanced response across cold and hot extremes, since the vehicle can rely on waste heat from combustion for cabin heating but still incurs additional fuel consumption during warm-up and under high accessory loads.

Overall, the dataset supports that BEVs maintain low operating cost at baseline conditions, but their cost stability across temperature extremes is strongly tied to thermal load management and charging price assumptions, while HEV variability is primarily governed by fuel economy degradation under warm-up and HVAC load conditions.

IX. KEY FINDINGS

1. Do hybrid electric vehicles exhibit efficiency degradation comparable to battery electric vehicles when subjected to standardized low-temperature (20°F) and high-temperature (95°F) operating conditions relative to baseline temperatures?

- **Cold-weather operation (20°F) resulted in the most significant efficiency losses across all powertrains.**
  - BEVs showed a **35.6% reduction in MPGe** and a **39.0% reduction in calculated range** relative to 75°F baseline conditions.
  - HEVs exhibited a **22.8% reduction in fuel economy (MPG)** under the same cold-temperature conditions.
- **High-temperature operation (95°F) produced moderate but measurable efficiency degradation.**
  - BEVs experienced a **10.4% reduction in MPGe** and an **8.5% reduction in range** compared to baseline.
  - HEVs showed a **12.0% reduction in MPG** at elevated temperatures.

2. What are the "fuel" costs of battery electric vehicles and hybrids across cold, hot, and baseline temperatures when real-world range and HVAC use are considered?[3]

- **Cold-weather operation (20°F) substantially increased BEV and HEV operating costs.**
  - BEV cost increased by **$32.11 per 1,000 mi** at residential electricity rates and **$76.93 per 1,000 mi** at commercial charging rates.
  - HEV operating cost increased by **$28.44 per 1,000 mi**, reflecting higher fuel consumption from the engine and from cabin warm-up and auxiliary loads.
- **Hot-weather operation (95°F) cost impacts were comparatively small.**
  - BEV operating costs increased by $**6.78 per 1,000 mi** (residential) and **$16.25 per 1,000 mi** (commercial).
  - HEV operating costs increased by **$13.02 per 1,000 mi**.
- **Cold-weather operation (20°F) resulted in the most significant cost difference when comparing powertrains.**
  - BEV cost **less** to operate by **$36.19 per 1,000 mi** at residential electricity rates and cost **more** to operate by **$86.26 per 1,000 mi** at commercial rates when compared to their HEV counterparts.
- **High-temperature operation (95°F) produced moderate but measurable cost differences when comparing powertrains.**
  - BEV cost **less** to operate by **$46.11 per 1,000 mi** at residential electricity rates and cost **more** to operate by **$41.00 per 1,000 mi** at commercial rates when compared to their HEV counterparts

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[3] Retail fuel price: $3.978 per gallon; commercial EV charging: $0.418 per kWh; residential EV charging: $0.1745 per kWh; fuel and electric prices as of 27-Mar-2026

X. RECOMMENDATIONS

Seasonal temperature changes have a noticeable effect on how efficiently BEVs and HEVs operate, how far they can travel on a charge or tank, and how much they cost to drive. Cold weather has the biggest impact especially for BEVs, while hot weather still affects performance but to a lesser degree. The recommendations below translate these findings into practical guidance for motorists choosing a new vehicle or looking to get the most out of the one they already own.

A. Understanding How Climate Shapes Vehicle Choice

Cold conditions place extra demand on both BEVs and HEVs, but BEVs feel the impact more strongly because batteries are less efficient at low temperatures and cabin heating draws heavily from the battery. Drivers who regularly face long winters should expect shorter driving range, more frequent charging, and higher seasonal energy use. HEVs tend to maintain more consistent performance in winter, which may appeal to motorists who prioritize predictable cold-weather operation. When shopping for a new vehicle, motorists should consider regional weather and potential economy reductions when choosing between a BEV and an HEV.

B. Technology Impact on Efficiency

Continued innovation across the automotive industry has driven meaningful improvements in vehicle efficiency under challenging real-world conditions. Technologies such as Ford’s vapor-injection heat pump system exemplify how advanced, integrated thermal management can reduce efficiency losses in both hot and cold environments. By more effectively capturing, transferring, and reusing thermal energy, these systems lessen reliance on energy-intensive heating and cooling strategies, helping preserve efficiency, range, and overall energy consumption. These advancements underscore the industry’s commitment to pushing vehicle systems forward to deliver more consistent and efficient performance across a wide range of operating temperatures.

C. Accounting for Seasonal Operating Costs

Energy use rises in cold weather for all powertrains, but the cost increase is most noticeable for BEVs particularly for drivers who rely on commercial charging, where electricity prices are higher. HEVs also see higher winter fuel consumption due to engine warm-up and cabin heating. Motorists comparing long-term ownership costs should consider how often they drive in cold conditions and what type of charging or fueling they will rely on.

D. Managing Efficiency in Hot Weather

High temperatures also affect efficiency, though the impact is smaller than in winter. Air-conditioning loads increase energy use for both BEVs and HEVs, but the overall effect on range and cost is modest. Drivers in hot climates should still expect some reduction in efficiency during peak summer heat, but not to the same extent seen in cold weather.

E. Strategies to Improve Real-World Efficiency

Motorists can reduce temperature-related losses with a few practical habits:

- Precondition the cabin while the vehicle is plugged in to reduce the load once driving begins.
- Use targeted comfort features, such as seat or steering-wheel heaters rather than heating or cooling the entire cabin.
- Keep tires properly inflated, especially in winter when pressure naturally drops.
- Avoid sustained high-speed driving in extreme temperatures, which increases both aerodynamic and thermal loads.
- For BEVs, plan charging sessions to minimize unnecessary fast-charging in cold weather, which can be much costlier than home or Level-2 charging.

F. Evaluating Charging Access and Energy Pricing

Because BEV operating costs depend heavily on electricity pricing, charging access is an important consideration. Home charging helps keep winter costs manageable, while frequent use of commercial charging can lead to larger seasonal cost swings. Prospective BEV buyers should think about where they will charge most often and how local electricity rates vary.

G. Using AAA Tools for Better Decision-Making

The ***AAA Your Driving Costs*** calculator can help motorists estimate the real-world cost of owning and operating a BEV or HEV by incorporating local climate, driving habits, and energy prices. Given the temperature-related changes observed in this study, these tools provide a clearer picture of how each powertrain will perform financially over the course of a year.

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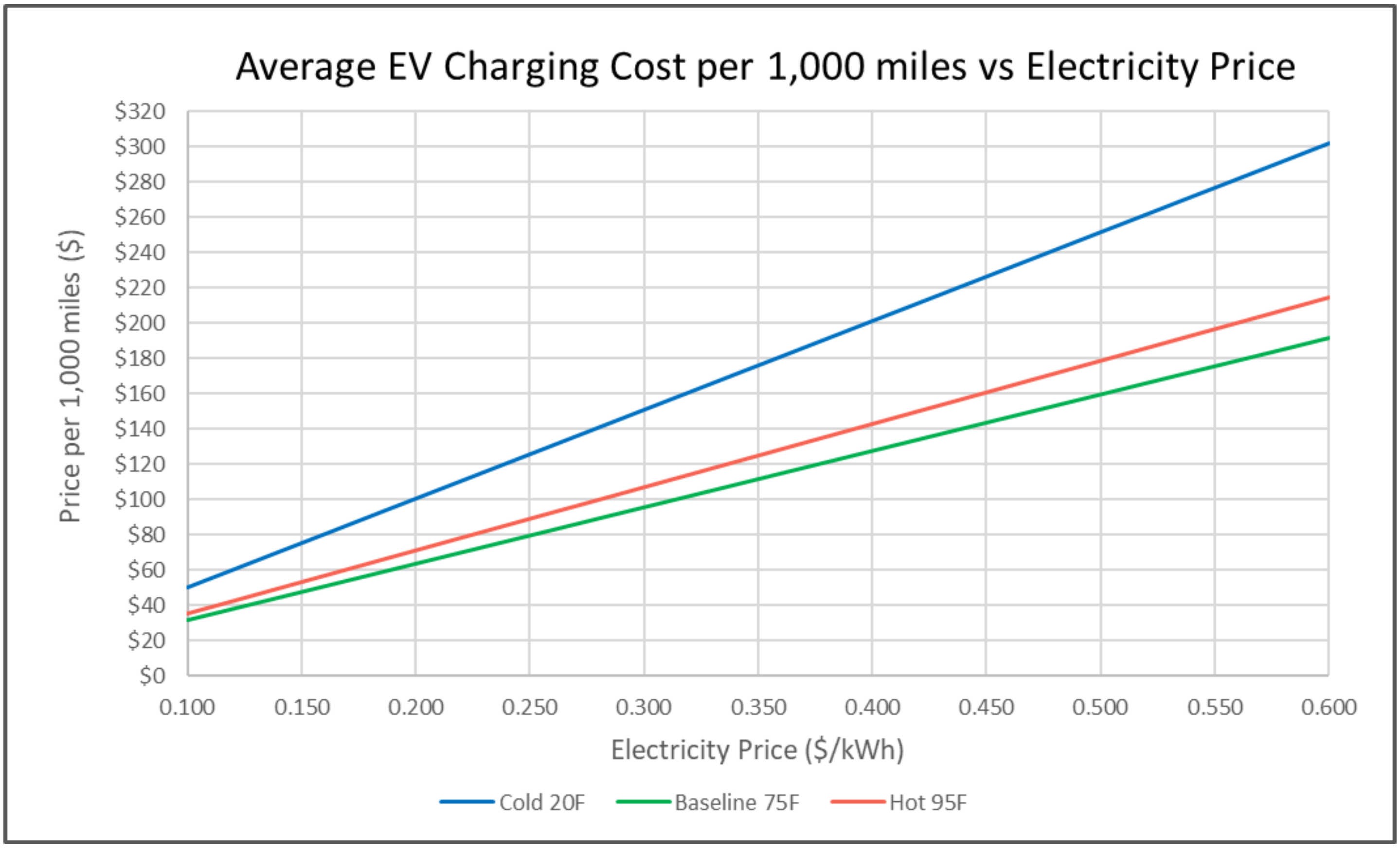
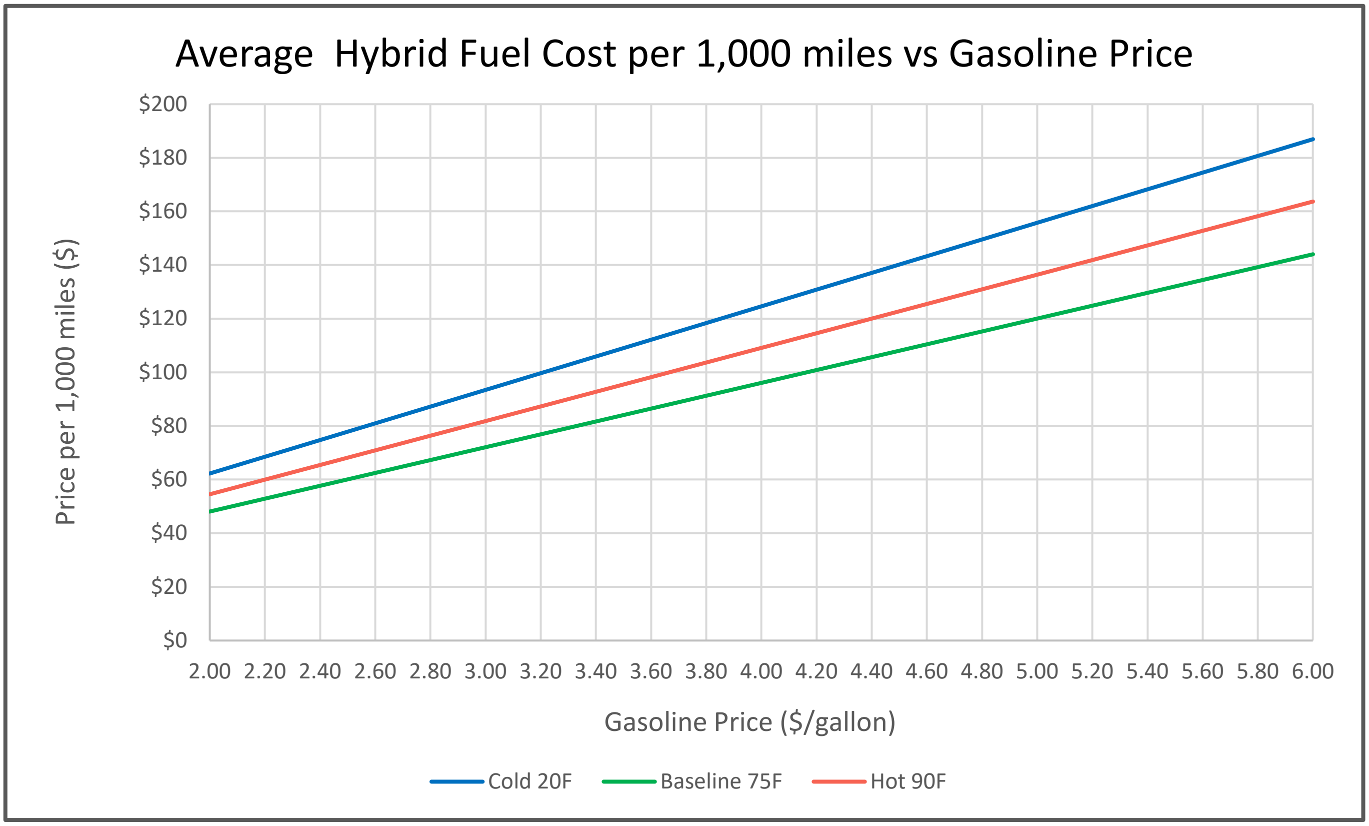
XII.APPROVALS

		Date	**Signature**
Group Manager, Automotive Research Center, ACE	Megan McKernan		
Project Lead—AAA Inc.	Josh VanWynsberghe		
Director of Research—AAA Inc.	Greg Brannon		

XIII.APPENDIX- GRAPHS FOR ALTERNATE FUEL PRICE MODEL

- Powertrain efficiency test data from AAA's 2026 research project evaluating battery electric vehicle (BEV) and hybrid electric vehicle (HEV) efficiency at hot and cold temperatures was used to model energy and fuel costs across multiple electricity and fuel price assumptions, providing insight into how ambient operating conditions affect vehicle cost to drive.




Average Hybrid Fuel Cost per 1,000 miles vs Gasoline Price
Price per 1,000 miles ($)
$200
$180
$160
$140
$120
$100
$80
$60
$40
$20
$0
2.00
2.20
2.40
2.60
2.80
3.00
3.20
3.40
3.60
3.80
4.00
4.20
4.40
4.60
4.80
5.00
5.20
5.40
5.60
5.80
6.00
Gasoline Price ($/gallon)
Cold 20F
Baseline 75F
Hot 90F