Abstract

CLARK, THOMAS DANIEL. An Examination of Hybrid Vehicle Performance in Cold Weather and a Novel Method for Improving Such Performance. (Under the direction of Dr. Richard Gould).

Previous research has shown that hybrid vehicles experience diminished performance due to cold weather. While most studies have attributed this phenomenon to decreased battery capacity, this preliminary study suggests an alternative hypothesis. On the contrary, hybrid batteries lose heat slowly enough that any daily use will keep them warm enough to maintain their performance in all but the coldest of climates. In this research, a 20° Fahrenheit (-6.7° Celsius) ambient temperature led to a battery temperature that never fell below 59° F (15° C), despite aggressive attempts to accelerate cooling. Additionally, a method to use engine heat to warm hybrid batteries was tested and found to increase battery temperature. This increase in battery temperature failed to improve hybrid system performance but has not been tested in the extreme climates where battery temperatures can cause capacity and power losses. This research was performed on the Toyota Prius, the most studied and well-known hybrid in the automotive market.

An Examination of Hybrid Vehicle Performance in Cold Weather and a Novel Method for Improving Such Performance

by
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Biography

Thomas Daniel Clark was born October 1, 1996 in Chapel Hill, North Carolina. He was raised in Chapel Hill by Daniel Clark, an attorney, and Sandra Clark, a physician, both of whom instilled in him a passion for science and logic as he progressed through his education. From an early age, he was fascinated with engineering concepts, always seeking out explanations for the complex systems that make up our world. One of his favorite systems to study throughout his childhood was cars, as the concept of converting fuel into motion through millions of tiny explosions never ceased to amaze him. He graduated from Carrboro High School in 2014 with the goal of becoming an engineer.

At North Carolina State University, he continued his search for scientific knowledge by completing a bachelor's degree in mechanical engineering. While at North Carolina State, he had the opportunity to pursue several passions simultaneously. He learned about and promoted sustainability through his work with the NC State Stewards organization over five years. He received his first research experience with an undergraduate project designing part of an autonomous boat with Dr. Gregory Buckner in 2016. He learned the inner workings of jet engine mechanics from a 2017 co-op with General Electric Aviation in Evendale, Ohio. The next year, he elevated his passion for cars even further through a co-op with BMW in Spartanburg, South Carolina. After his graduation in 2019, he continued to pursue his passions by pursuing a master's degree in mechanical engineering. After discovering that hybrid vehicles lose such a substantial amount of fuel economy solely due to cold weather, he spent the next two years designing and implementing a possible solution as his thesis project.

Acknowledgements

Throughout the course of this project, I have received support from countless friends, family, and advisors. I would first like to thank my parents for their advice and their patience as I worked through the many stages of this project. Their unwavering support helped me immeasurably and allowed me to focus my efforts on coursework and project work throughout my undergraduate and graduate careers.

I would also like to thank my committee chair, Dr. Gould, for his help in the detailed design of the final product. He helped guide me towards the most robust heat transport system possible and set a timeline for important project milestones. I would also like to thank Dr. Buckner, Dr. Echekki, and Dr. Saveliev, for their heat transfer and thermodynamics expertise when I was first formulating the design. I would also like to thank NC State University for supplying funding for project materials and access to the dozens of academic papers I needed to research hybrid technology.

Next, I would like to thank my co-driver, Julia Rubin, for her help in conducting the trials on the day of the experiments. With her help, I was able to tune the cooling fan speed and check on the battery temperatures in real time.

Finally, I would like to extend my deepest gratitude towards the Nerkar family, who generously loaned the test vehicle. Without their support, the entire project would not have been possible. When they heard about my thesis idea, they immediately offered their personal vehicle to help me.

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Introduction

Hybrid vehicles are already a marvel of modern engineering. Even in their simplest form, they can completely eliminate the energy waste from engine idling by powering all accessory functions while a car is stopped. They also reclaim a high percentage of the energy that would normally be lost with braking, instead using that energy to charge the hybrid batteries and eventually supplement the power from the engine. Conventional hybrids like the Toyota Prius have erased the efficiency gap between highway and city driving, enabling city drivers to waste as little energy as possible from their fuel. In more advanced hybrids like Plug-in Hybrid Electric Vehicles (PHEVs), drivers can avoid using gasoline entirely for short trips. When PHEVs and fully electric vehicles (EVs or BEVs) use only electrical power to operate, they effectively improve their thermal efficiency four-fold according to the EPA's MPGe statistic. For example, the fully electric Tesla Model 3 achieves an unprecedented 141 MPGe[1] (combined city/highway), while the similarly sized, gas-powered Honda Civic makes only 35MPG[1]. The Model 3 boasts this incredible powertrain and drivetrain efficiency despite carrying significantly more weight and offering far more cargo capacity. Despite their advantages, however, EVs and PHEVs have yet to take over the global car market due to their higher up-front costs and the lack of charging infrastructure.

Because of these hurdles to EV adoption, conventional hybrids, with their small battery packs and independence from the electrical grid, will still be around for the foreseeable future. And while they cannot compete with PHEVs and EVs in efficiency, they generally boast lower purchase prices, longer ranges, and faster refueling. At current prices, an argument could be made that all gas-powered cars should be hybrids because they are so effective at reducing waste. However, all hybrids (and electric vehicles) suffer from diminished performance in cold weather, losing a key advantage over gas-powered cars. PHEVs and EVs can preheat their batteries while still attached to the grid, but standard hybrids are only able to warm up using their battery or engine power. Fortunately, hybrids also have a significant source of heat that is not currently used by any current models: engine exhaust heat.

Whenever a gasoline or diesel engine is running, more than half of the energy it pulls from the fuel is wasted as heat. Some is absorbed into the engine, transmission, and cooling system, some is used to heat the cabin, and the rest is lost to the surroundings as exhaust (waste) heat. This exhaust heat can even exceed the work produced by the engine, which peaks at 150hp for most economy cars in the United States. In realistic city and highway driving, a car operates far below that peak power, but it may generate enough heat to warm small to medium-sized battery packs. By using a simple heat transfer apparatus, a portion of that exhaust heat could accelerate battery warm-up and improve cold-weather performance in hybrids.

Background & Literature Review

A central question in the expected performance of this heat transfer system is the extent to which battery performance changes with temperature. Several studies specifically testing lithium-ion battery packs have found that extreme low temperatures can almost entirely deplete their capacities. According to testing by G. Nagasubramanian in a study for the Journal of Applied Electrochemistry, reducing lithium-ion battery temperature from 77° F to -40° F (25° C to -40° C) decreases energy density from 100Wh/L to 5Wh/L (95%) and power density from 800W/L to 10W/L (99%).[2] This trend is shown in Figure 1 below. However, a more common temperature drop, from 68° to 14° F (20° C to -10° C), generates a far more modest ~12% capacity loss. Below 0° F (-17.8° C), battery performance loss accelerates drastically, losing all capacity at -50° F (-46° C). Not all studies agree on the temperature at which battery performance begins to drop drastically, though. According to a study by Zhu et al., 32° F (0° C) is the drop-off point.[3] In Buchmann's *Batteries in a Portable World,* both lithium-ion and nickel-metal hydride batteries lose their viability at -4° F (-20° C).[4]

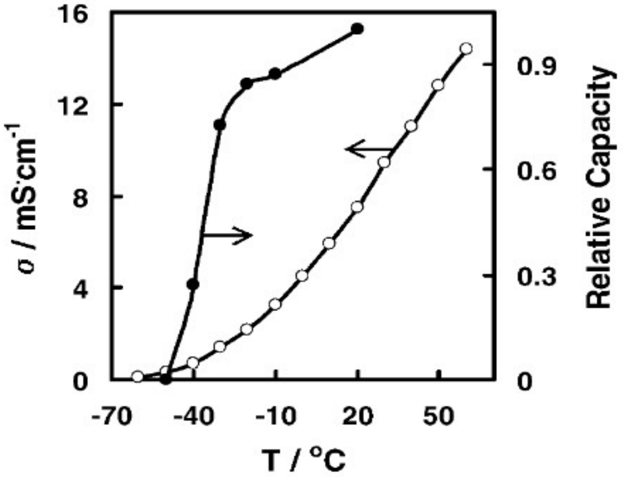

Figure 1. Relative Capacity and Energy Density of Lithium Batteries vs. Temperature.[5]

While a wide range of temperatures has been cited, there is scientific consensus that cold weather can sap over half of a battery's discharge and capacity performance in temperatures that are common in the contiguous United States. This is currently believed to be the primary reason why hybrid vehicles lose most of their practical benefits in the cold, especially in climates like the Northeast and upper Midwest United States, where temperatures regularly fall below freezing. As the theory states, since the batteries are unable to hold a charge as well as they do at standard temperature, the car relies entirely on the engine until the batteries warm up. Thus, for the first several minutes of operation, the vehicle would not be able to use its electric motors to move or recharge the battery, causing overall efficiency to drop to that of a gas-powered vehicle. In city driving, where hybrids enjoy an immense efficiency advantage, sufficiently cold batteries would completely remove that advantage. To make matters worse, the battery packs would then be adding unused weight to the vehicle, further reducing its range.

For a more practical assessment of battery performance in cold weather, the American Automobile Association (AAA) conducted a study of five new electric car models. Their research found that at 20° F (-6.7° C), the average driving range decreases by 41% percent[6] when compared to standard temperature. While this result may seem extreme compared to the figures cited above, the extra losses can be explained by the use of the cars' HVAC systems to heat the cabins. Without HVAC use, AAA measured a more modest range loss of 12%. The exact same performance losses are expected for the electric portion of drivetrains in hybrid vehicles, but with decreased losses associated with HVAC use because the car's engine heat contributes to cabin heating. An analysis of Environmental Protection Agency data by Oak Ridge National Laboratory cites a fuel economy loss of 31-34% for hybrid vehicles at 20° F (-6.7° C), compared to 12% for standard gas-powered vehicles.[7]

The primary reason why batteries lose so much of their effectiveness in low temperatures is the same reason why many other machines, devices, and systems perform worse in the cold. Low temperature represents a lowered energy state and less movement of molecules within a material. Interactions between molecules occur less frequently, and thus chemical reactions occur at a slower rate. In the case of electrons and positive ions moving across an electrolyte between two electrodes in a battery, colder temperatures slow down the electrical transport process. This reduces the current, voltage, and capacity of the batteries. The reduced current and voltage also handicap the batteries' maximum power, another major concern for a hybrid powertrain in cold weather.

Current scientific consensus blames this phenomenon for most of the 31-34% drop in fuel economy for conventional hybrids. If such a significant loss of performance can be mitigated or eliminated entirely, the effects could be monumental. With millions of hybrid vehicles on the road, many of which operate in cold climates, vast amounts of burned gasoline and their associated CO_2 and NO_x emissions could be avoided with a rather simple design change. Furthermore, improved winter performance could sway reluctant car buyers in cold climates to switch to a more efficient model.

Thermal Management in Current Hybrid Systems

In current conventional hybrid vehicles, there is no method for battery heating other than internal resistance. With this method, the current flowing through the batteries uses the inefficiency of the electrical system to produce heat rather than work. This process, also referred to as IR^2 or Ohm heating, is inherently inefficient, but it requires very little additional engineering to implement and is often considered suitable for most use cases. Since high temperature is the more common and potentially damaging condition, cooling is the primary focus of the typical hybrid thermal management system. The Prius, for example, uses the space between each battery cell and a blower fan to draw cabin air across the battery modules and cool them convectively. After flowing across the batteries, the air exits through a duct underneath the car. This system performs well for small battery packs and is still used by many current hybrid models.

Liquid cooling, by comparison, allows for significantly more heat transfer but adds weight and complexity to the hybrid system. In a vehicle that is already packed with large, expensive batteries, this additional equipment must provide a substantial performance benefit to be justified. In smaller battery packs, which require less cooling due to their smaller masses, the lower heat capacity of air does not limit system performance and thus does not present an issue. In PHEVs and BEVs, however, the battery sizes are several times larger than those of a conventional hybrid. In extreme cases, like the upcoming Hummer EV, the battery packs can reach up to 200kWh, a capacity that dwarfs the 1.3kWh battery of the Toyota Prius. Since it is infeasible to pull more than 150 times as much air from a cabin, liquid systems are, in some cases, the only viable option. The following equation shows the heat transfer equation for both liquid and air cooling:

$$Q = hA(T_{cell} - T_{fluid})$$

Where Q is the heat generated by the battery cell, h is the convective heat transfer coefficient, and A is the surface area. In a liquid-cooled system, the convection coefficient is dramatically higher than that of an air-cooled design. Since the contact area for both cooling systems is limited by cabin space, the coolant compound and temperature are the best factors to change in order to improve thermal performance. Therefore, changing the fluid from air to water or anti-freeze can substantially increase heat transfer. The same conclusion can be reached using a simple energy balance for the fluid. The heat value from the heat transfer equation is equivalent to the heat leaving the fluid in the equation below:

$$Q = \dot{m}c_p(T_{fluid,in} - T_{fluid,out})$$

Where $\dot{m}$ is the fluid mass flow rate and c_p is the specific heat of the fluid. Since controlling the inlet fluid temperature presents its own challenge, increasing the mass flow rate and specific heat of the fluid is the best method for increasing heat transfer. One experiment comparing a liquid coolant against air cooling found that the specific heat of the liquid coolant was three times as high as the specific heat of air for the same mass.[8] The liquid cooling system's performance is further improved by the fact that liquid coolants are hundreds of times denser than air, which increases the possible mass flow rate. While this also implies that the volumetric flow rate cannot practically match that of an air-cooled system because moving more mass also requires more energy, the same study found that a realistic liquid cooling system can still move three times as much mass as an air cooler with three times as much heat capacity. Thus, liquid cooling has nine times the cooling capacity of air cooling. This advantage in cooling performance is shown in the figure below comparing the required fluid inlet temperatures to achieve effective heat transfer.

While air cooling requires the fluid and batteries to have a sizeable temperature difference, liquid coolers can use a fluid nearly as warm as the batteries to provide the same performance.

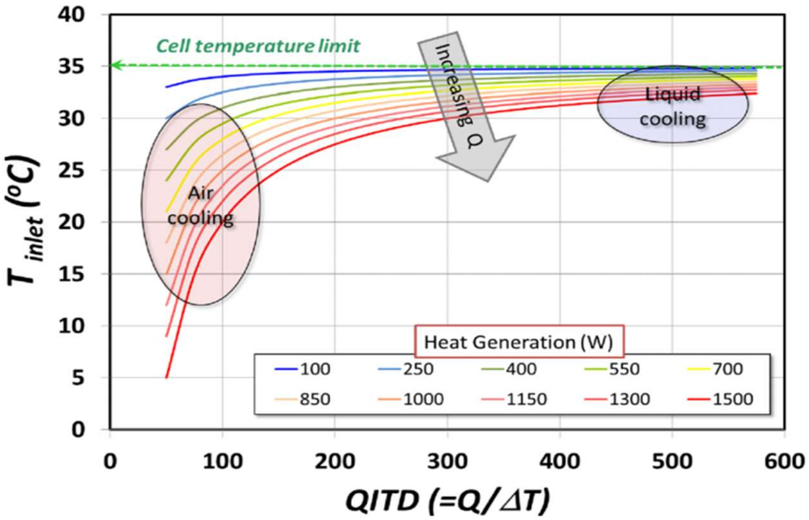

Figure 2. Liquid vs. air cooling performance with different fluid inlet temperatures.[8]

A large coolant reservoir kept at the ambient temperature can therefore provide more than enough heat transfer to maintain a desired battery temperature, just as it does with the radiator in an internal combustion engine. To achieve the same performance, an air-cooled system would need to have a chiller attached to its air inlet to drastically decrease the incoming air temperature. Since a chiller requires a large additional energy input, it is less practical for a system that values efficiency. While the liquid cooler needs a powered pump to cycle the coolant, its power draw is not comparable to an air conditioning unit. This simple reality of air- vs. liquid-driven heat transfer explains why most PHEV and BEV models phased out air cooling technology in favor of liquid cooling. However, neither liquid nor air cooling as described above can solve the problem of batteries that are too cold. The ambient air or coolant in such situations would cool the batteries even further, preventing them from reaching their ideal operating temperature. Rather than using ambient air or an additional coolant reservoir, if the engine coolant or exhaust heat is added to a hybrid’s thermal management system, the batteries will experience a temperature increase with no additional wasted heat. But while using the liquid coolant from the engine could provide the best possible heating performance, air cooling is expected to provide more than enough heat for this application.

Battery Technology over Time

The current standard for rechargeable battery technology is the lithium-ion cell. Lithium-ion technology has seen an astronomic rise in recent years due to its high energy density, low self-discharge property, nearly zero-memory effect, high open circuit voltage, and long lifespan.[9] After decades of development, they have become the most common battery type for small electronics, hybrid vehicles, full-electric vehicles, and even utility-scale energy storage.

Before lithium, lead-acid and nickel-metal hydride batteries dominated the automotive battery market. The first rechargeable battery was a lead-acid battery developed by Gaston Planté in 1859.[4] It used sulfuric acid as its electrolyte and lead as its plate material. As the battery discharged, the positive and negative plates would shed their hydrogen ions from their hydrogen sulfate on one electrode and form lead sulfate on the other, while the electrolyte was diluted by water formed in the chemical reaction. The transfer of these hydrogen ions and their corresponding free electrons formed the basis of the battery's electrical power, as the flowing of electrons generated a reversible electric current. Since the opposite reaction occurred when running an opposite current across the plates, it was then possible to recharge lead-acid batteries with an external power supply. Over time, lead-acid batteries became known for their ability to provide high currents, but their low energy density limited their possible use cases. These high starting currents, paired with excellent reliability, led to their widescale adoption in motor vehicles. Since 1912, vehicles have used an electric starter connected to a lead-acid battery to start the engine, and later vehicles would go on to use the batteries to run accessory functions.[4] For nearly a century, automotive battery use was limited to this basic functionality due to its low specific energy.

The next major step forward for automotive battery development was the nickel-metal hydride battery. While previous battery types, such as the nickel-cadmium cell, improved upon lead-acid's specific energy, nickel-metal hydride technology enabled them to move into large-scale energy storage. First developed in 1967, the battery was quickly able to achieve a specific energy of 50Wh/kg. These batteries also used the flow of electrons and positive ions between electrodes to generate an electric current, but rather than a liquid acid they incorporated a solid electrolyte such as potassium hydroxide. This allowed them to be significantly safer than their lead-acid counterparts because leaks did not involve extremely corrosive acids. Since they also drastically improved on the specific energy of lead-acid batteries, they were soon theorized to be suitable for mobile electronic devices and vehicles. In 1997, Toyota released the Prius, the first mass-market hybrid vehicle, with a nickel-metal hydride battery. By 2005, the real-world specific energy, including casing, of the Prius' NiMH batteries reached 31Wh/kg.[10] Since then, millions of hybrid vehicles (HEVs) with the NiMH battery chemistry have been sold worldwide. One example of the evolutionary difference between lead-acid and NiMH batteries was the General Motors EV1, the first mass-produced modern electric car. According to the EPA Guide from 1999, the lead-acid-powered EV1 had a range of 78 miles, while the NiMH-powered variant could travel 142 miles on a single charge.[11] With a nearly two-fold improvement in one generation of battery technology, it quickly became clear that NiMH batteries were the best way forward for automotive batteries over the next twenty years.

Although lithium-ion battery development began in the 1970s, they did not reach market viability until relatively recently due to their high production costs. These batteries were first theorized in 1973 when researchers used the flow of lithium ions in the electrolyte to form an electrical current. With carbon compounds replacing the electrodes of previous generations, the drastically changed chemistry of these new batteries allowed for massive performance improvements. With higher energy density, specific energy, and power density, they were primed to take over the energy storage market. A study by Landi et al.[12] combined data from Linden & Reddy's *Handbook of Batteries*[13] to produce the graphical comparison of the major rechargeable battery technologies. This graphic shows the progression in both volumetric energy density and specific energy density as batteries evolved from lead-acid to lithium-ion.

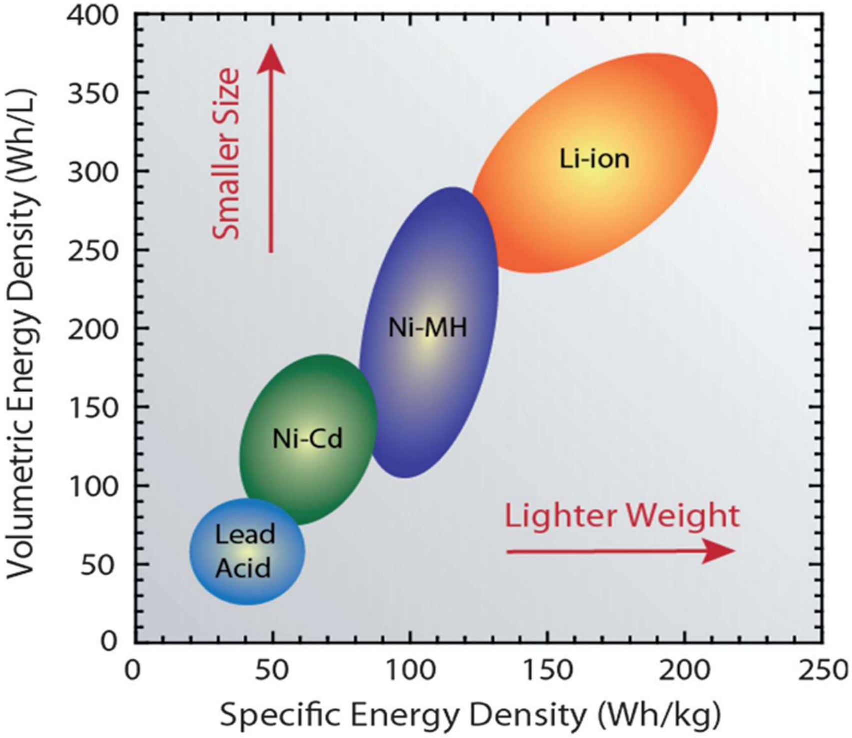

Figure 3. Comparison of battery technologies (2002).[12]

A detailed timeline of lithium battery development is shown in the figure below. First, they breached the market as small 1.5V batteries. Then they slowly replaced NiMH batteries in laptops and other small electronic devices. As prices continued to drop, they eventually became viable for large-scale storage and use in fully electric vehicles. The exceptional specific energy and sudden economic viability of lithium-ion cells finally enabled engineers and scientists to pack enough energy into a battery to make them competitive with internal combustion engines. According to a study by May et al., the specific energy of lithium-ion batteries has reached 150-180Wh/kg.[14] While a gallon of gasoline still holds a nearly ten-fold advantage over the best lithium-ion batteries in terms of energy density and specific energy, lithium-ion batteries make up for that gap by delivering power more efficiently. In modern electric vehicles, ranges have caught up to gas-powered cars by combining larger battery packs with excellent efficiency, with some models like the Tesla Model S Long-Range boasting over 400 miles of range.[1] However, current battery technology still faces significant roadblocks. Even the fastest charging infrastructures require over an hour to fully recharge an electric vehicle from empty, and the chemical composition of lithium batteries runs the risk of starting deadly, sustained fires if the batteries leak in an accident. These fires are especially dangerous because they involve extremely high temperatures and toxic fumes. Still, future generations of the technology are expected to alleviate these concerns. As the figure below posits, the future of lithium-ion batteries rests in solid-state or lithium-air batteries. Solid-state lithium batteries, which use a solid electrolyte rather than the aqueous compounds currently in production, are expected to provide boosts to energy density and charging speed while decreasing the risk of fires. Samsung's first solid state battery, for example, has achieved an energy density of 900Wh/L[15], while lithium batteries with liquid electrolytes top out around 670 Wh/L.[16] Both of these figures easily exceed the bounds of the previous graphic, suggesting that the theoretical chemical limits of lithium batteries are still being challenged with each breakthrough.

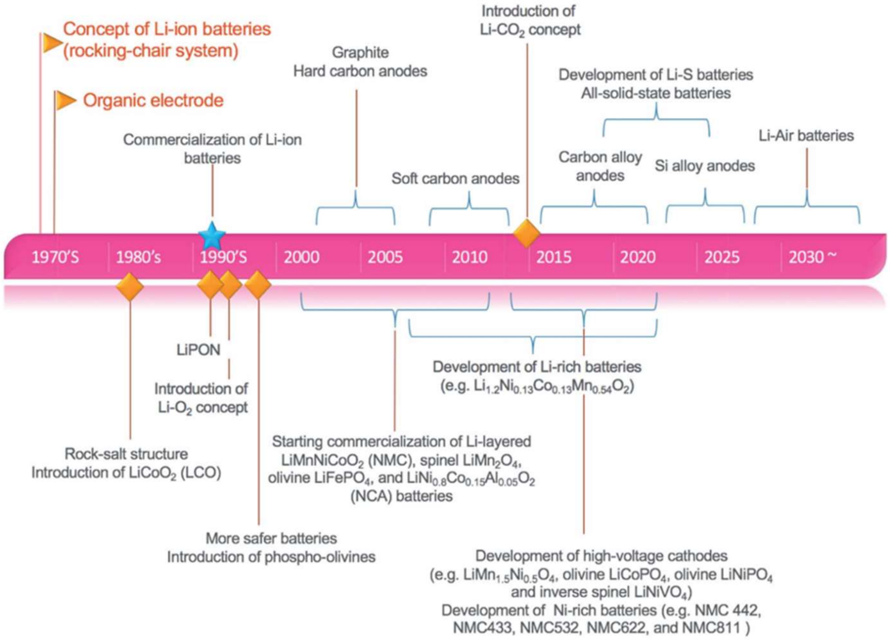

Figure 4. Lithium-ion battery development timeline.[9]

Despite the ongoing research and development in solid-state batteries, liquid electrolyte lithium batteries have already staked out a dominant position in the automotive battery market. They are the energy source of every plug-in electric vehicle on the market, replacing all but a few nickel-metal hydride batteries in some conventional hybrid models. According to the EPA, the difference between these two battery types even on the same platform are immense. The 2021 Toyota Camry is an excellent example of the two technologies in an apples-to-apples comparison. While the lithium-powered Camry Hybrid LE achieves 52 MPG in combined city-highway driving, the NiMH-powered Camry Hybrid XLE only manages 46 MPG[1]. Solely by upgrading the energy density and power delivery capabilities of the hybrid batteries, Toyota was able to claim a 13% improvement in fuel consumption. In a matter of years, it can be assumed that all vehicles with any form of electric propulsion will use some form of lithium battery technology. However, for the purposes of this research, since lithium and NiMH batteries have similar specific heats and performance characteristics at low temperatures, the outdated NiMH batteries in the 2005 Prius will still provide useful data.

Effects of Ambient Temperature on Motor Performance

In addition to their batteries, the traction motors found in hybrid vehicles are also known to experience performance losses due to changes in temperature. Since the motors use oil and magnets, both low and high temperatures can cause chemical processes to lose effectiveness or efficiency. The Prius uses a single permanent magnet synchronous motor rated for 67hp (50kW) at 1200rpm.[10] This motor, located next to the engine and attached to the Prius' eCVT transmission, provides power in addition to the power provided by the vehicle's engine. The Prius also has two generation motors that decelerate the vehicle when the brakes are applied and recharge the hybrid batteries. This parallel powertrain setup is used by most hybrids on the road, with the BMW i3 as the most notable exception. The motor components are shown in the illustration below from the Prius service manual:

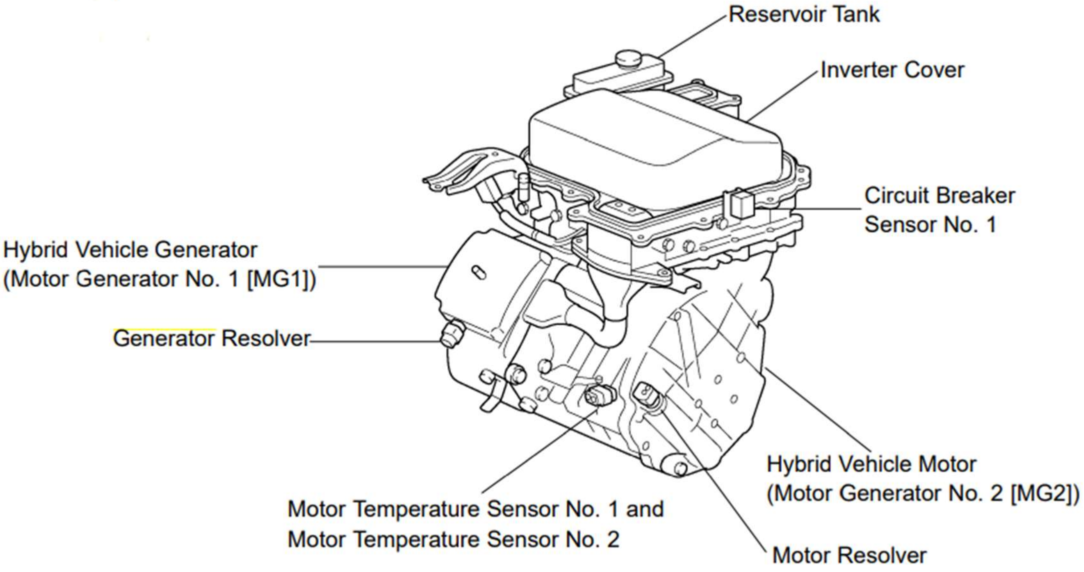

Figure 5. Toyota Prius motor configuration.[17]

One significant advantage of the permanent magnet synchronous motor over other types – namely induction motors – is its high efficiency. Induction motors, while cheaper and providing higher starting torques, produce unwanted eddy currents that waste energy and generate heat. In hot climates and high-performance situations, this waste heat can cause performance losses, which batteries also experience at high temperatures. These induction motors are common in the automotive industry, most notably on the Tesla Model 3. The synchronous motors on most other EVs and hybrids, on the other hand, avoid this potential loss in performance and thermal throttling.

A study by Oak Ridge National Laboratory examined how the Toyota Prius' traction motor performance changes at different power loads and temperatures.[18] As the motor's copper winding temperature increases from 124° F to 322° F (51° C to 161° C), the motor efficiency initially increases but eventually drops below its starting value. Peak efficiency occurs when the windings are between 149° F and 156° F (65° C and 69° C). This finding suggests that cold ambient temperatures, well below the normal operating temperature of the motor, may impact motor efficiency slightly. Since motors use oil for lubrication and cold oil experiences increased viscosity, the lubrication loses its effectiveness and hinders movement the same way it does in internal combustion engines. However, high temperatures are far more dangerous for motor performance. Motor overheating can cause the permanent magnets in the motor to approach their Curie temperature, which can permanently disable their magnetic field. The neodymium magnets found in the Toyota Prius have a Curie temperature of 593° F (312° C)[19], so their peak permissible temperature must be well below that point.

Another study conducted by Shumei et al. examined general motor performance in freezing ambient temperatures.[20] The research found that the current and voltage required to start an electric motor increase exponentially below 32° F (0° C), significantly increasing energy demand. They also found that maximum motor torque decreases dramatically as temperature decreases. Most importantly, efficiency decreases from a peak of 91% at 50° F (10° C) to 85% at -4° F (-20° C). This is due to the increased current demand at lower temperature as shown in the figure below. Since resistance is proportional to current, an increased current also increases resistance heating, a major source of inefficiency. In general, the motor operates around 90% efficiency at room temperature and 88% efficiency in cold (but not extremely cold) temperatures.

This 2% loss in efficiency can partially explain why hybrid and fully electric vehicles struggle to maintain their performance in cold weather. The decreased available torque also forces hybrid vehicles to become more reliant on engine power, further decreasing combined efficiency. Thus, reduced motor performance can be considered one of the major causes for the decrease in hybrid fuel economy in winter months.

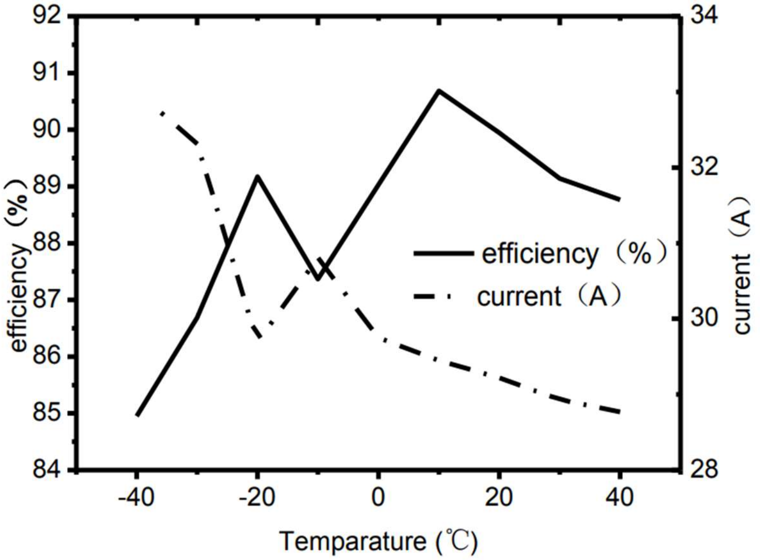

Figure 6. Electric motor efficiency vs. ambient temperature.[20]

Efficiency Losses due to Drag

In addition to engine and battery temperature affecting vehicle efficiency, additional drag due to denser air can also lead to losses. Since air density increases as temperature decreases, some of the performance losses in cold weather for both conventional and hybrid vehicles can be explained by this phenomenon. The formula for calculating drag is simple:

$$F_d = \frac{1}{2}\rho v^2 c_d A$$

Where ρ is the air density, v is the vehicle's velocity, c_d is the drag coefficient, and A is the cross-sectional area. Using the dimensions for the Toyota Prius[10], this formula simplifies to:

$$F_d = \frac{1}{2}\rho v^2 * .24 * 2.582m^2 = 0.20984 * \rho v^2$$

Since air density can be found using the Ideal Gas Law, the formula becomes:

$$F_d = 0.20984 * \frac{P}{R_{gas}T} v^2$$

Thus, assuming average atmospheric pressure, the drag force for varying vehicle velocities follows the relationship shown in the figure below:

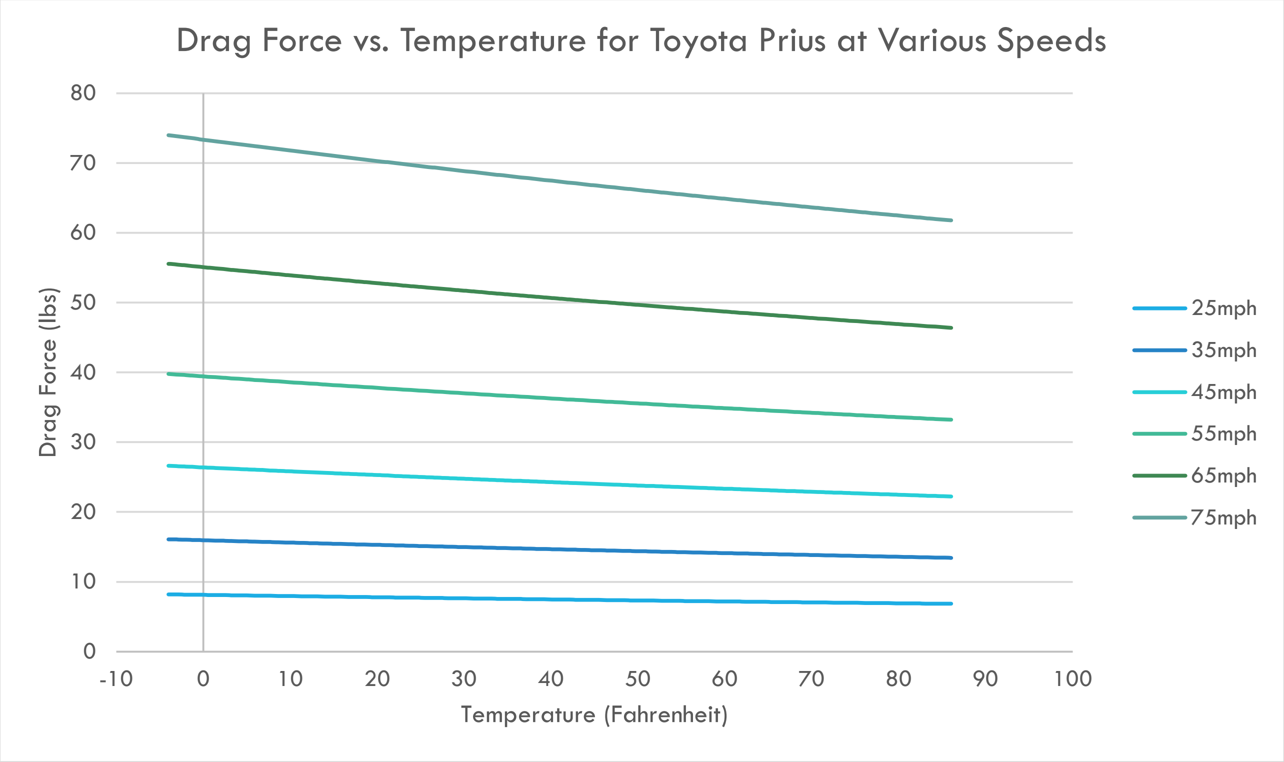

Figure 7. Drag force for Toyota Prius at multiple temperatures and speeds.

At low speeds, the drag force is largely independent of temperature, but at 55mph and above, there are noticeable losses in cold weather. For example, at 65mph, it takes 11.8% more force to overcome drag at 20° F (-6.7° C) than it does at 77° F (25° C). Thus, a significant portion of the loss in MPG for all vehicles in cold weather is due to denser air.

Energy Balance

A study by SAE found that in urban driving conditions, economy vehicles typically operate at 16-20% thermal efficiency for short trips with traffic and 40% without stops.[21] This study only collected data after the engine was warmed up, so real-world efficiencies in winter are expected to be about 10%, or 1.6-2 percentage points, lower. Thus, assuming accessory and cooling systems use one third of the remaining energy, the exhaust stream contains anywhere from 27 to

53% of the chemical energy of the fuel, depending on the trip conditions. For simplicity, an estimate of 33% of the energy produced by an engine at any given moment is assumed to be lost to the exhaust system.

To ensure optimal performance, the batteries in a hybrid system should be kept between 72° and 77° F (22° C and 25° C) according to most studies.[7,8] In order to heat up cold batteries, there must be significant heat transfer from the exhaust system to the battery compartment. For the example temperatures used in the EPA studies (20° F to 77° F), this is a temperature change of 57° F or 32° C. Depending on the size of the battery packs, achieving this result requires varying amounts of heat. Materials experience a temperature increase from energy addition based on their mass m and specific heat c_p, which in this circumstance can be assumed to be constant:

$$Q = mc_p(T_{final} - T_{initial})$$

Assuming a constant specific heat of 795 J/kg*K[22] for lithium ion batteries, the plug-in hybrid variant of the Toyota Prius would require:

$$\frac{785J}{kg * K} * 31.67K * 120.202kg = 2.988MJ$$

Assuming approximately 33% of combustion energy is lost through the exhaust system in a typical car, a vehicle operating at 33% efficiency generating 50hp will also emit 50hp of available heat, or 37.285kW. If 20% of that energy is added to the batteries, the battery pack will take 6.5 minutes to reach its ideal temperature under these conditions.

Standard hybrids with smaller battery packs would require significantly less warm-up energy. The standard Toyota Prius, which uses a smaller, Nickel-Metal Hydride battery pack weighing 42kg only requires:

$$\frac{787.5J}{kg * K} * 31.67K * 42kg = 1.047MJ$$

In this case, 20% of the exhaust heat could warm up the batteries in only two minutes. However, this analysis assumes that the car operates at a constant 50hp in city driving for those two minutes and that the exhaust pipe absorbs only a trivial amount of the available exhaust heat. In reality, the exhaust pipe would need to warm up before it allowed flow into the batteries. Assuming a weight of 20kg and a steel pipe, warming up the exhaust system would require:

$$\frac{420J}{kg * K} * 31.67K * 20kg = 0.266MJ$$

This energy figure represents over a quarter of the heat required for the batteries, so the exhaust pipe warm-up could extend the battery warm-up time by more than 25%.

Heat Transfer Analysis

The performance of any convective heat transfer system depends on the heat transfer area, convection heat transfer coefficient, and the temperature difference between the fluid and the heated surface.

$$Q = hA\left(T_{cell} - T_{fluid}\right)$$

The heat transfer coefficient for convection with air across a flat object can be approximated as:

$$h = 12.12 - 1.16v + 10v^{\frac{1}{2}}$$

This formula is based on empirical studies of turbulent air moving across a flat surface in a velocity range of 2-20 m/s.[23] The fluid in this research is a mixture of air and exhaust gas, but since the exact mixture at any given time varies, it can be roughly approximated as air. According to a study conducted by Zolot, Pesaran, and Mihalic, at full power the Toyota Prius battery cooling system can move 48.4 cubic feet of air per minute,[24] or 0.0228 cubic meters per second. Assuming a flat surface on each battery cell, the total contact area for the batteries, using dimensions from the same study, is:

$$A = 29 * 2 * 0.106m * 0.265m = 1.629m^2$$

The Toyota Prius has one long row of tightly packed battery modules as shown below.

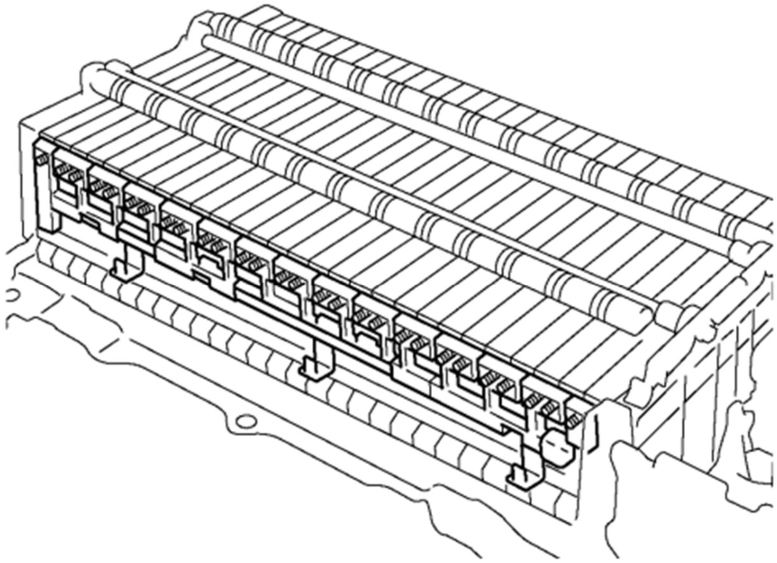

Figure 8. Toyota Prius battery pack configuration.[17]

With batteries spaced out at an average of approximately 1mm and 29 gaps surrounding 28 battery modules, the cross-section of the heat transfer area is:

$$A = 29 * 0.001m * .275m = 0.007975m^2$$

Thus, with the volumetric flow rate and the cross-sectional area of the fluid transport known, the fluid velocity in the battery passages of the Toyota Prius cooling system is:

$$v = \frac{\dot{V}}{A} = \frac{0.0228}{.007975} = 2.859m/s$$

The heat transfer coefficient of convection then becomes:

$$h = 12.12 - 1.16 * 2.859 + 10 * 2.859^{\frac{1}{2}} = 25.71 \frac{W}{m^2 * K}$$

With approximate values for the contact area and estimated heat transfer coefficient and exhaust gas estimated to be between 300 and 500 degrees Celsius hotter than the batteries:

$$Q = 25.71 \frac{W}{m^2 * K} * 1.629m^2 * (300K \mid 500K) = 12{,}550w - 20{,}950w$$

Assuming a sufficient supply of engine heat and the same heat requirements from the energy balance above, full battery warmup would take at most:

$$1.047 * 10^6 J * \frac{1s}{12{,}550J} = 83s$$

Based on this analysis, the Prius thermal management system is able to transfer more than enough warm air to the batteries to use up all available exhaust heat, even if the engine is already warm. In other words, the bottleneck for heating performance in the Toyota Prius is expected to be the availability of hot air rather than the rate of heat transfer to the batteries. Even at an average power level of 50hp, the batteries will easily accept as much heat as the exhaust system can provide. It is also worth noting that the battery modules are not actually flat and have small protrusions and bumps to increase their surface area, further improving heat transfer performance. This estimate also suggests that even with the engine producing highway-level power, the blower fan will not need to be run at full speed to provide adequate airflow.

Plug-in Hybrid Electric Vehicles

Many potential test vehicles were considered for this project. A wide range of vehicle specifications can affect the performance of a thermal management system, namely the size of the battery pack, the algorithm used by the vehicle's onboard computer, and the heat transfer capacity of the system. In theory, a PHEV could also be a candidate for exhaust diversion heating because they also employ a gas-powered engine, but in practice their applicability is questionable. Larger battery packs require proportionally more heat to warm up, and with a limited heat source like waste engine heat it is more sensible to test smaller packs. PHEVs also present an additional logistical challenge because they can function in full-electric mode for several miles before using the engine. Without the engine running, there is no source of heat for the batteries. They also have an option for battery and cabin pre-heating while tied to the grid, a feature that eliminates the need for engine heat. Thus, if a PHEV is operated as intended, the engine should not have to run unless the trip length exceeds the electric range. Since the conditions in which engine-aided battery heating are outside of the ideal use case for PHEVs, it makes little sense to design and implement such a system. Rather, a vehicle with a small battery in a conventional hybrid is an ideal candidate.

Conventional hybrids are also the more useful test case for exhaust diversion because they outnumber PHEVs in new vehicle sales by a factor of five, according to Bureau of Transportation statistics.[25] Vehicle sales data also suggest that while plug-in hybrids are popular, most consumers interested in plug-in vehicles prefer fully electric cars. Thus, PHEVs are a decidedly niche market compared to untethered hybrids and BEVs.

Methods

Design Choice

There are three simple methods of transferring heat from the exhaust pipe to the battery bay, each with advantages and limitations. The first method is to use a liquid coolant running through a heat exchanger. In this setup, an annular passage would be attached around the exhaust pipe, transferring the energy from the hot metal to a heat transfer fluid. The fluid would then be sent into the battery bay and spread along the outer surfaces of the battery modules. Alternatively, the engine coolant could be routed through the battery compartment to directly heat the batteries. This method would be the most effective at transferring heat but would require a total redesign of the vehicle's thermal management system. At the same time, it would add significant cost and complexity to the project, introduce leakage risks, and require additional power and pumps to function. Since the purpose of this research was to waste as little power as possible, adding more energy-draining components was not worth the increased performance, especially since the existing air-cooled system has already proven its effectiveness.

The second method is to use pure conduction. In this setup, a metal connector would run from the exhaust pipe to the battery bay. The connector would then branch off into a series of heatsinks, which would run across the outer surface of the battery cells. This is the least feasible solution because it requires a redesign of the vehicle's existing thermal management system and costly raw materials for optimal heat transfer.

The third method for transporting exhaust heat to the batteries is to cut into the exhaust pipe (downstream of the catalytic converter) and directly route the exhaust gases into the battery bay. This strategy has the advantage of requiring the fewest additional materials and takes advantage of the thermal management systems many hybrids already have in place. The Toyota Prius, for example, already has a cooling fan, passages between each pair of battery cells, and temperature sensors. The exhaust gases can be routed into the battery air intake stream and safely exit the battery exhaust, which flows back outside the cabin as shown below. The primary issue with this system is that unlike the other two, it requires modifications to the vehicle's exhaust system. This method also involves some of the exhaust bypassing the muffler, which would lead to increased cabin noise. Due to its simplicity and lack of required permanent vehicle modifications, the direct exhaust gas method was chosen for this research.

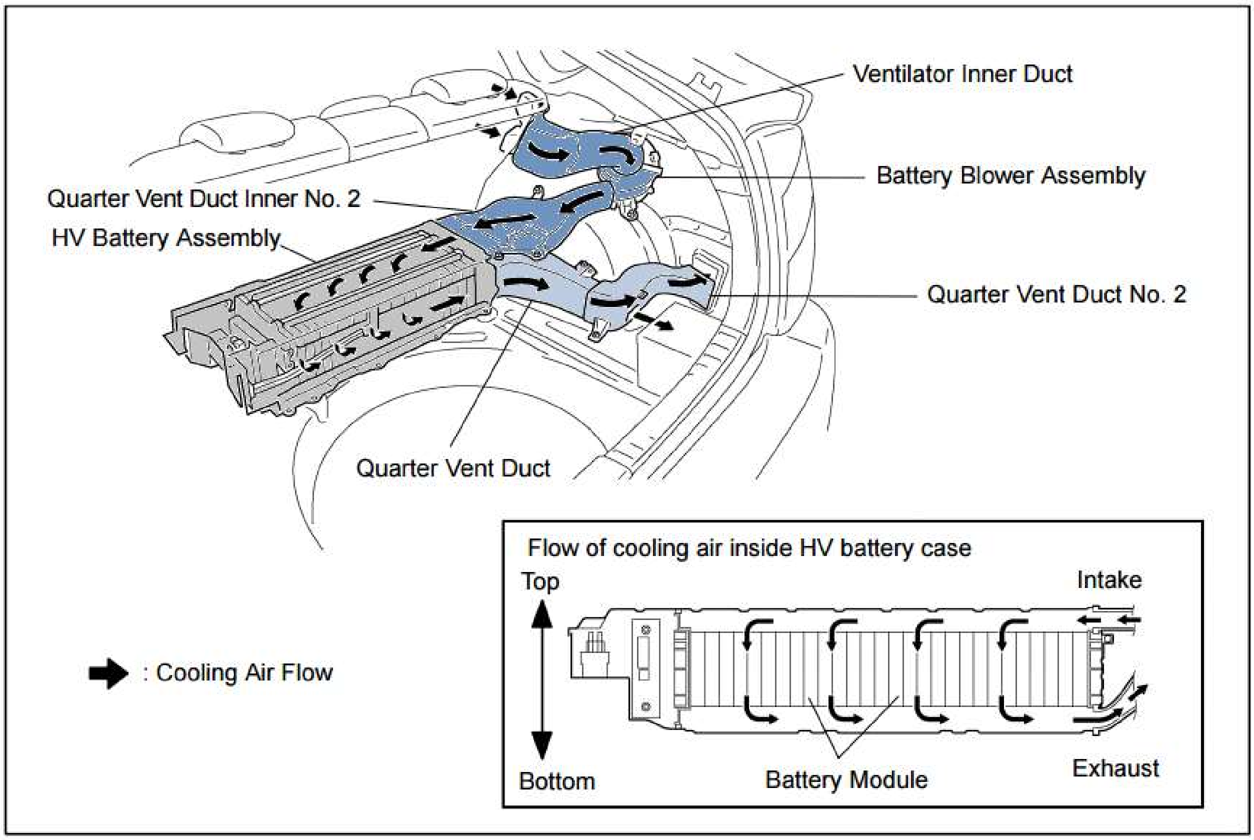

Figure 9. Toyota Prius Battery Thermal Management System.[17]

One concern for any system that uses a fluid inside the battery bay is chemical reactions with battery leakage. In some cases, the electrolyte from a battery can escape, creating a dangerous situation with or without toxic exhaust fumes to react with. Fortunately, the nickel-metal hydride batteries in most current hybrids are far safer than other variants. Since their electrolyte (potassium hydroxide) is a solid rather than a fluid, it is less likely to leak in a dangerous way. Furthermore, the only notable reaction with potassium hydroxide and exhaust gases is the formation of various salts. Thus, the first and third methods are low-risk if the fluid in question is air or exhaust gas. Lithium-ion batteries are more dangerous in cases of battery leakage, but their limitations will not be tested in this study.

Test Vehicle

After careful consideration, the Toyota Prius was chosen as the ideal test vehicle for this project. In addition to its status as the quintessential hybrid, the Prius has excellent existing documentation and has already been the subject of several research papers examining powertrain efficiency. With a combined EPA rating of 46 MPG[10] for the 2005 model year, it is still one of the most efficient vehicles on the road, such that weather-related efficiency losses would be more pronounced. Finally, the value of an older Prius is low enough that any unanticipated damage would not be a significant issue. After attempts to find a used Prius to purchase specifically for the project failed, a 2005 example with 130,000 miles was loaned to the university through a personal connection. In addition to being the perfect vehicle model for an exhaust diversion project, this specific example had recently had its hybrid batteries replaced, so there were very few miles on the battery pack compared to most other 2005 Priuses on the road. Additionally, the vehicle's engine and drivetrain were in excellent condition and the catalytic converter was brand new. Thus, the test vehicle was relatively representative of a new 2005 Prius even in December 2020. The vehicle's condition makes it more reasonable to compare experimental MPG results with EPA projections because a heavily degraded battery pack or motor would cause even steeper efficiency losses compared to a new vehicle.

Vehicle Modifications

The vehicle modifications for this project can be broken into two sections: the exhaust pipe reroute and the heat transport to the battery. To divert the exhaust stream, the vehicle was fitted with a cast iron wye joint between the catalytic converter and the muffler, where the straight, least-resistance path led to the batteries and the angled path led to the muffler. Cast iron was chosen for its excellent high-temperature performance, although steel adapters were required to allow the part to be welded to the exhaust. The wye joint also served as a reducer, bringing the pipe size from 1.5" NPT thread to a more standard 1". The wye joint-adapter setup is shown in the figure below.

Figure 10. Cast iron wye joint in place.

A lever-activated ball valve was later attached to the wye joint to allow either most or none of the exhaust gas to travel through the battery thermal management system. A commercial version of this design would use a rotary actuator valve that automatically shuts when the batteries reach an ideal temperature, but this research did not require that level of cost or complexity. The ball valve was simply opened or closed for each trial. After the ball valve was installed, a 3-foot steel pipe was attached to the ball valve to reach farther toward the rear of the car, where the battery bay is easily accessed. A flexible steel dryer hose was used to transport the exhaust from underneath the car to the batteries in the trunk. Inside the trunk, a hole was drilled into the thermal management inlet, which was then fed by the dryer hose. The dryer hose was wrapped in insulation to protect cabin plastics and reduce rattling. The piping design is shown in the figures below:

Figure 11. Vehicle modifications underneath vehicle.

Figure 12. Exhaust transport hose feeding into battery compartment.

These parts, along with a heat shield for the section inside the cabin, were the only hardware components required for this design. Additionally, the only permanent modifications to the car were the holes in the metal floor of the car's trunk and the plastic casing for the battery bay's thermal system inlet. Notably absent are any additional airflow fans or temperature sensing components. Both functions were accomplished with an OBDII tool that recorded telemetry from the car computer and forced the battery's cooling fan to push exhaust heat through the batteries. This OBDII tool also allowed the battery temperatures to be monitored in real time so that fan speed adjustments could be made accordingly. However, the software, which required Windows 7 to run, proved to be prone to crashing, causing ten minutes of data to be lost at the start of the trials. The bill of materials below shows the total cost and source of all parts used in the final design.

Table 1. Final design bill of materials.

Item	Qty	Description	Source	Price
Wye Joint	1	Low-pressure, high-temperature cast iron, NPT 1.5" to 1"	McMaster-Carr	45.66
Ball valve	1	Brass, lever-operated, NPT 1" thread	McMaster-Carr	26.01
Thread Adapter	2	Zinc-plated steel, NPT 1.5" thread	Lowe's	8.75
Extension Pipe	1	Steel, NPT 1" thread, 3' length	Lowe's	13.70
Bendable Hose	1	HoldRite Stainless Steel, NPT 1" thread, 2' length	Amazon	12.99
Diagnostic Tool	1	OBDII interface, USB cable included, Techstream V14 included	Amazon	27.99
Heat Shield/Insulation	1	YaeMarine aluminized fiberglass heat sleeve, hook and loop fastened, 35.43" x 6.5"	Amazon	12.99
			Total	148.09

Compared to other vehicle modifications and other methods for implementing exhaust heat transport, this exhaust diversion system was inexpensive despite using the best available parts. The only cost not included in this bill of materials is the $60.00 labor cost for the muffler shop to weld the wye joint onto the exhaust pipe. Since the diagnostic tool was only needed for testing, the true cost of the modifications was a modest $120.10, or $180.10 including labor. After trials were completed, the vehicle was restored to its stock configuration for the same $60.00 cost at the muffler shop.

Lessons from Prototyping Process

An earlier proposed design for the project involved a completely different method for monitoring the batteries and controlling airflow. Originally, the plan was to measure the battery temperature with three thermocouples. The thermocouples, attached to a microcontroller via a Type-K Arduino adapter, would log the temperature every tenth of a second to provide a glimpse of how the batteries responded to normal operation and thermal management over time. This system was tested and working well before the date of the trials but was not considered to be as reliable as the onboard, professionally calibrated temperature sensors already installed on the batteries.

Additionally, much thought was given to driving adequate airflow to the batteries. The original design called for a second blower fan to be added to the thermal management system to push hot air through the batteries on demand, rather than using the triggers coded into the vehicle. However, spatial constraints limited the airflow capability of any installed fan. The small opening in the battery casing would have only allowed for a 25mm fan, which would have to be powered externally. Since such a fan would require an extremely high speed to create the desired pressure differential, this solution was deemed impractical. Fortunately, the Prius' blower fan is more than capable of providing sufficient airflow. A previous study found that at full power, the Prius can move 48.4 cubic feet of air per minute with a pressure drop of 0.770 in.[24] H_2O. In theory and in practice, this allowed all of the hot air to be forced through the batteries and safely outside of the vehicle. This solution, however, created a new challenge.

Since hybrid vehicles already have methods for controlling battery temperature that are entirely focused on cooling, the thermal management algorithm will never trigger unless the vehicle is receiving high temperature sensory data from the batteries. Initially, the plan was to detach the temperature sensors used by the car and reattach them to the exhaust inlet hose, which would trick the car into triggering the fan. Since the thermocouples were originally expected to log battery temperatures, this method may have been viable. At the same time, the Prius' control software most likely has a failsafe in place that cuts off battery use once they reach a certain temperature to prevent damage. Since warmed up exhaust air is well above the temperature where batteries start to fail, the fan would run as intended but the powertrain computer would refuse to draw power from the batteries. With these concerns in mind, the best solution was to find a way to control the fan without removing the temperature sensors. The OBDII tool, using Toyota's Techstream software, allowed the thermal management fan to be controlled manually without disturbing the rest of the vehicle's algorithms. It also allowed more accurate temperature measurements to be taken and recorded.

Testing procedure

Producing replicable results in a fuel economy test is exceedingly difficult due to the wide range of external factors that cannot be controlled. Sudden changes in temperature, humidity, and air density can drastically alter fuel economy, so each test required nearly identical ambient conditions. Additionally, consecutive tests in a short time span are difficult to conduct because of the need to wait for the engine and batteries to cool to the ambient temperature. To simplify the process, the following requirements were set on the ambient conditions to be able to compare different trials: the starting and ending temperatures must be within two degrees Fahrenheit of other trials and the ambient temperature must be 20° F (-6.7° C) or below. Since humidity generally avoids dramatic swings in the middle of the night, it was assumed to not be a factor in this research.

To eliminate HVAC use as a confounding variable, each city trial was run without cabin heating on. This caused all excess exhaust heat to be directed toward battery heating, allowing the diversion system to move as much heat as possible. Eliminating HVAC use also prevented the car from running the engine just to heat the cabin, which significantly harms fuel economy. To maximize battery and engine cooling between runs, the vehicle was left outside with all doors open, and the hood and rear hatch raised. The first two trials consisted of city driving with and without diversion, while trials three and four tested highway driving. A final city run with diversion was conducted to verify the result since that scenario was by far the most consequential. The trial order is also detailed in the table below:

Table 2. Experimental trial order.

Trial Number	Location/Type	Diversion
1	City	Off
2	City	On
3	Highway	On
4	Highway	Off
5	City	On

Driving Route

To simulate a quick city trip, the car was driven in a simple circuit around Chapel Hill, North Carolina for thirty minutes per trial. However, the Techstream software defaults to a twenty-minute cycle time, so the data recorded for the city trials represents the first twenty minutes. Since the batteries were warmed up well before the twenty-minute mark, the truncation of the last ten minutes of each trial was not an issue. This drive involved several stops at traffic lights to charge the hybrid batteries and test the ability of the fully electric mode to take over at low speeds. To avoid traffic and ensure the coldest possible temperatures, the trials were run between midnight and 6:00 A.M. This time period was also ideal because of its lack of major temperature swings; on the day of the trials, the temperature over the six-hour span never changed by more than two degrees Fahrenheit. This route also allowed more than enough time for the engine and batteries to reach operating temperature, a process which the vehicle modifications sought to accelerate. The vehicle's fuel mass flow rate sensor was used to determine fuel efficiency for each trial. The exact route is shown in the figure below. Extra loops around the Franklin St. area were added as needed to reach exactly 30 minutes per trial. Speed limits for this route ranged between 25 and 45 miles per hour, with the majority of the distance traveled at 25 miles per hour. Trials one, two, and five used this route.

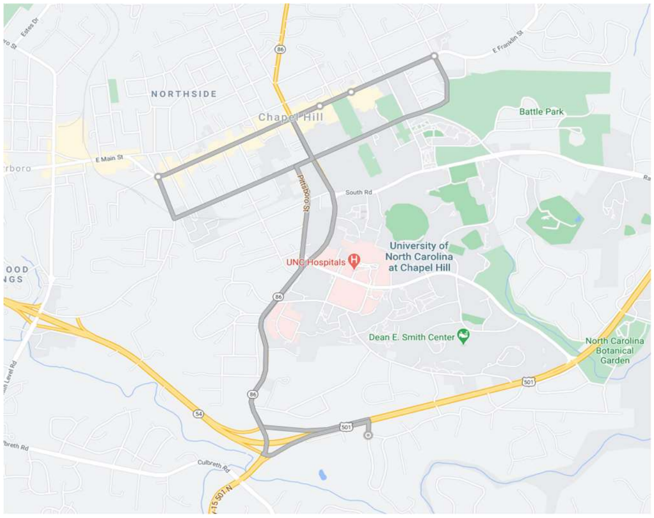

Figure 13. City driving route.[26]

To test performance on longer trips, the vehicle was driven ten miles on the interstate each way to the same start/end point. The vehicle was kept at a constant 65 miles per hour throughout both trials. This test sought to identify potential gains in performance in situations where the engine warms up quickly, but the batteries lag behind. If the batteries are exposed to low ambient temperatures, the outside air could potentially cool the batteries faster than they warm themselves up. However, since the batteries in the test vehicle are fully enclosed in the cabin – unlike those in most PHEVs or BEVs – this was not expected to have a major impact. The route used for the highway tests is shown in the figure below.

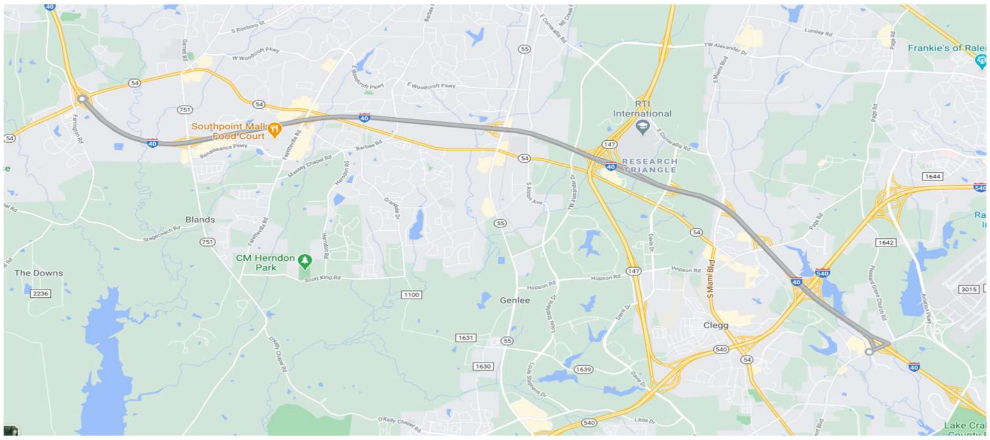

Figure 14. Highway driving route.[27]

Data Collection

All data for the trials was collected by Techstream, a Toyota-developed software package that can be used to monitor every sensor in the vehicle and send instructions to the onboard computers. This software and OBDII connection allowed each parameter of interest to be monitored in real time by a co-driver. The co-driver was also able to manipulate the thermal management system's fan to find the optimal speed for battery heating while still recording data. Unfortunately, the software is currently only compatible with Windows 7, an outdated operating system with performance limitations. Likewise, the computer used to log the data, a 2010 Lenovo Thinkpad, struggled to keep up with commands. Because of these issues, the program overloaded the system memory on the first trial and crashed Techstream, permanently erasing ten minutes of critical trial data. The rest of the trials avoided any issues by minimizing the amount of data logged by the software. Techstream consolidates the vehicle sensor data into different sections of the vehicle, and since "HV Battery" was the crucial area that needed to be monitored, it was ultimately the only system that had its data recorded. Ideally, the fuel mass flow rate also would have been tracked, but opening multiple modules at the same time frequently crashed the software and was deemed infeasible for the actual trials. Fortunately, engine coolant temperature was included in the "HV Battery" sensor list, so it was possible to monitor engine and battery temperature simultaneously. All graphs shown in the results were generated by Techstream because the program does not allow the raw data to be pulled into other software.

Results

City Driving: Battery Temperature

The Toyota Prius uses three battery temperature sensors in different sections of the battery pack, which will be referred to as Sensor 1, 2, and 3 in these results. Unfortunately, a hardware failure on the data monitoring laptop caused the data for the first ten minutes of Trial 1 to be lost. Thus, while Figures 16 and 17 below show the first twenty minutes of Trials 2 and 5, Figure 15 shows the final twenty minutes of Trial 1. However, the critical initial battery temperature was still known to be significantly higher than that of the surroundings. The temperature of all three battery sensors was recorded at 59° F (15° C) at the start of the trials, twelve hours after the vehicle's last use. The surroundings, meanwhile, were at a frigid 20° F (-6.7° C) throughout the trials. Note that throughout the results, Sensor 2 consistently shows a higher temperature than Sensors 1 and 3. This is believed to be due to a sensor calibration issue because the temperature trends are not affected by this different reading.

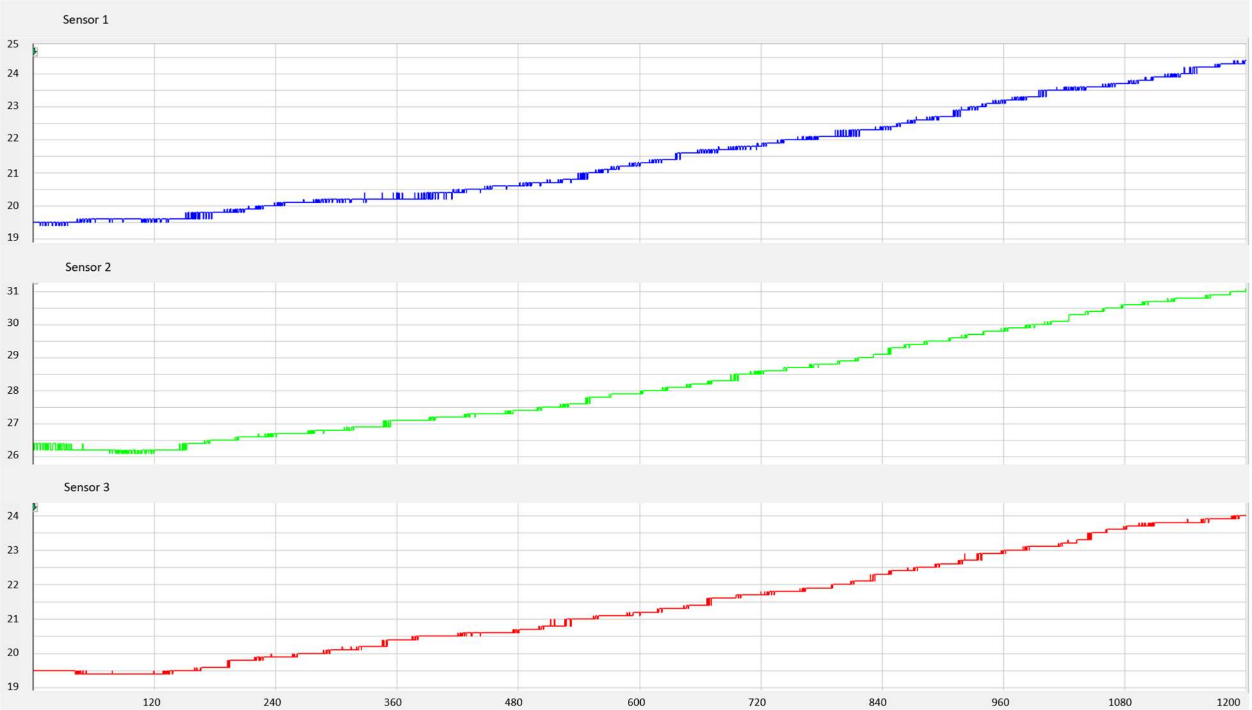

Figure 15. Battery temperatures (°C) over time (s) for first run without diversion (T1).

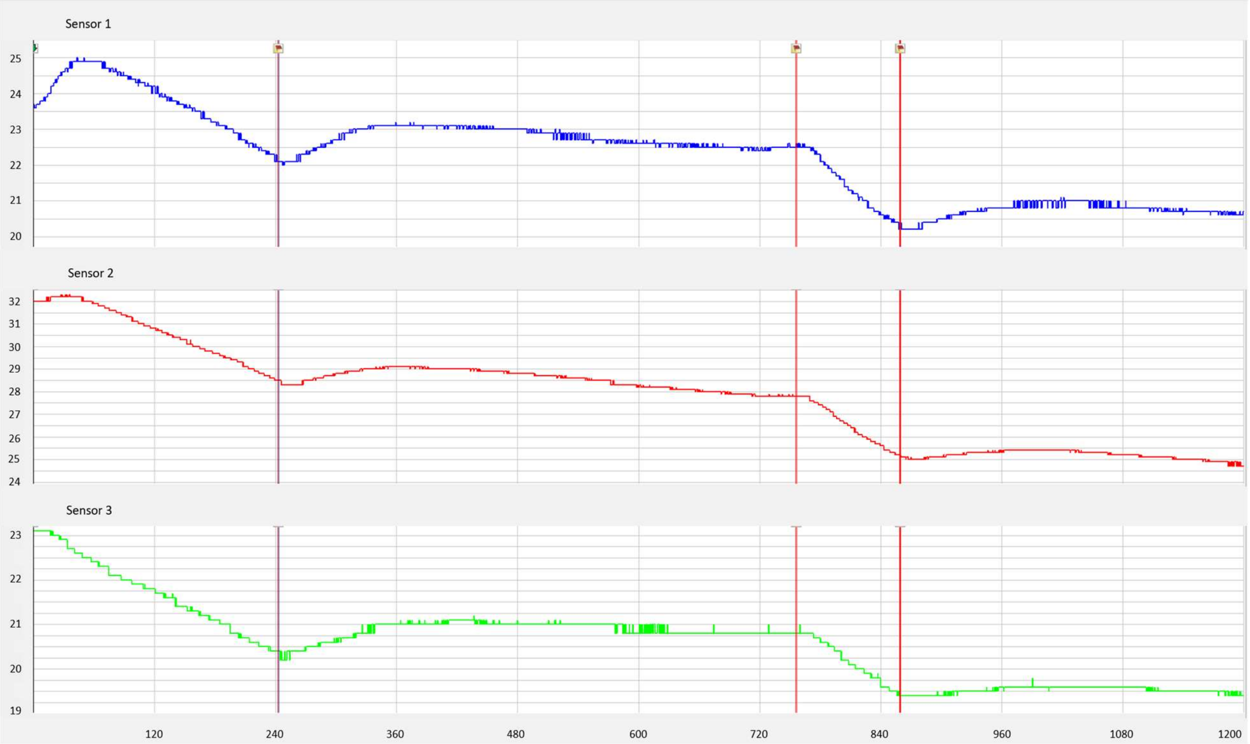

Figure 16. Battery temperatures (°C) over time (s) for first tun with diversion (T2).

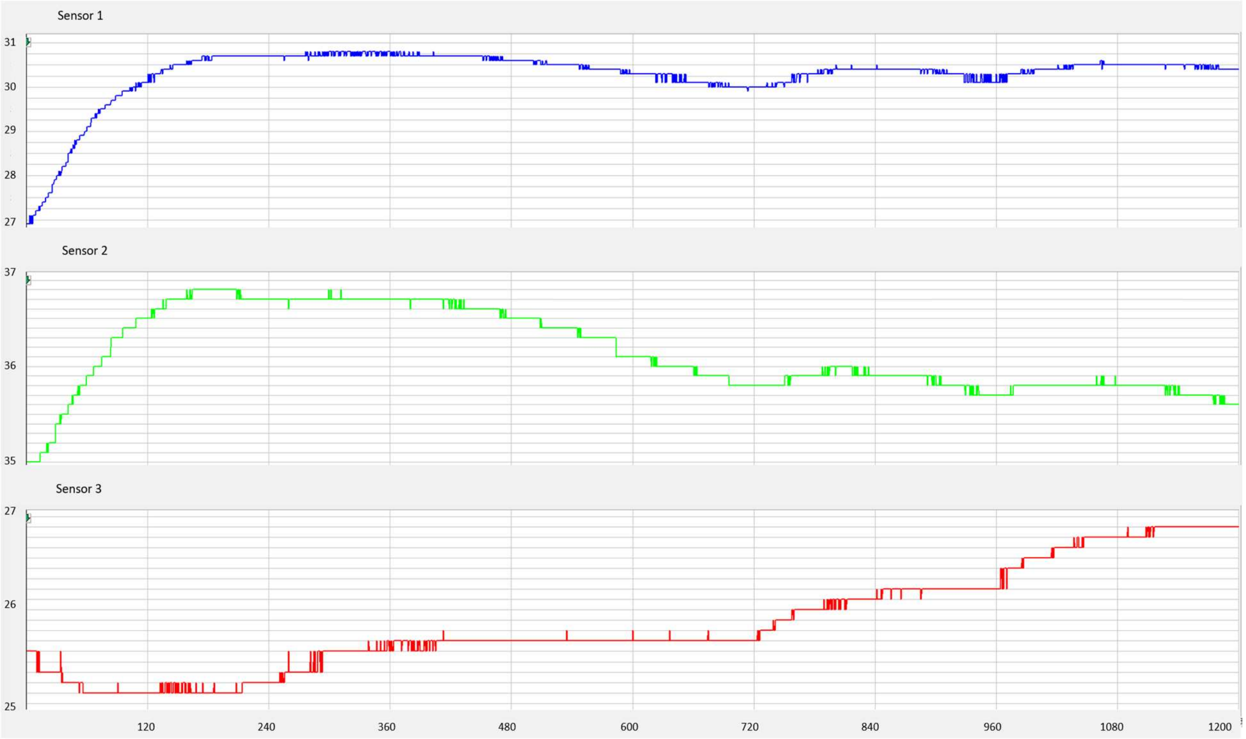

Figure 17. Battery temperatures (°C) over time (s) for second run with diversion (T5).

As Figure 15 demonstrates, the Prius is able to steadily increase its battery temperature through regular use. After a two-minute period where the temperatures were largely flat, Sensor 1 saw an average temperature increase of 0.50 $\frac{deg\ F}{min}$ (0.28 $\frac{deg\ C}{min}$), while Sensors 2 and 3 increased at 0.48 and 0.45 $\frac{deg\ F}{min}$ (0.27 and 0.25 $\frac{deg\ C}{min}$) respectively. Using the constant specific heats from the energy balance, this implies an energy input of:

$$\frac{787.5J}{kg * K} * 0.25\frac{K}{min} * \frac{1\ min}{60s} * 42kg = 138w$$

Therefore, the Prius' self-heating capability adds approximately 140 watts while operating in this temperature range. At no point in Trial 1 was any Prius battery temperature in a range where significant battery performance losses could be expected.

In Trial 2, the battery temperatures fluctuated wildly as the battery cooling fan speed was adjusted for optimal heating performance. In figure 16, the red vertical bars mark fan speed changes. At high speed, the fan drew in enough cold air from the cabin to *decrease* the battery temperature even as exhaust heat was added to the mix. When the fan speed was decreased, the battery temperature slowly increased before leveling off at an equilibrium temperature. The trend repeated itself on a second attempt, with high airflow leading to cooling and low airflow leading to slow heating. Thus, for Trial 5, the fan was set to the lowest speed. For the city runs with exhaust diversion on, the maximum heating rate of the batteries was 3.60 $\frac{deg\ F}{min}$ (2.00 $\frac{deg\ C}{min}$) for Sensor 1 for the first minute of Trial 5, suggesting that the system was able to effectively transfer some heat to the batteries. However, the heating was clearly uneven, with Sensor 2 experiencing slower heating and Sensor 3 cooling slightly over the same time period. The unevenness continued as the trial progressed, as Sensor 3 warmed up while Sensor 1 leveled off and Sensor 2 cooled.

City Driving: Fuel Efficiency

In city driving, the diversion system was not found to have a significant impact on fuel efficiency. While both trials with exhaust diversion did show higher MPG averages than the run without, the averages over smaller time blocks suggest that this was unrelated to the battery temperature. Figure 18 below shows the MPG data collected in each run.

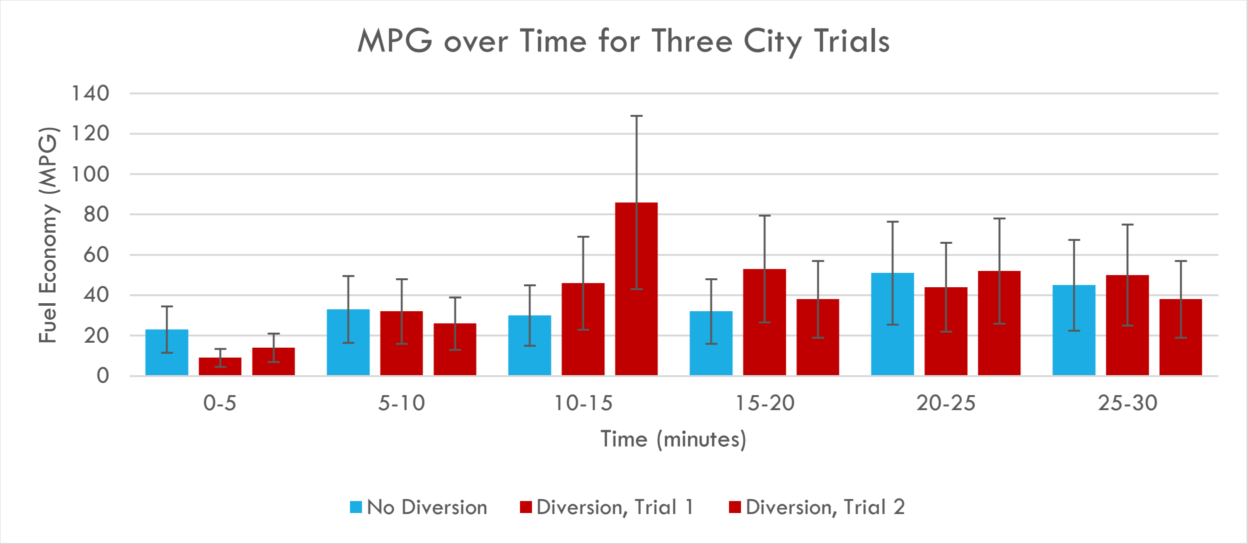

Figure 18. MPG in five-minute blocks for each Trial.

The error bars in the figure above indicate a 50% error in the results, which is meant to illustrate the extreme variability in MPG results. Even in the most controlled environments, the complexity of a hybrid powertrain introduces several variables that can cause uncertainty. These variables include battery charge level, engine efficiency, motor efficiency, and the Prius' complex powertrain control algorithms. In order to prove that exhaust diversion is effective, the first two time blocks, or first ten minutes, are critical. The faster increase in battery temperature should lead to higher battery efficiency, and therefore higher total efficiency. However, the Prius hybrid system managed the best MPG performance over the first ten minutes in Trial 1, even though the batteries started at their lowest temperature. The trials with diversion showed advantages in time blocks three and four, but performance for all three trials was nearly identical in the last ten minutes. Therefore, the results showed predictable real-world variability, but did not demonstrate a need for improved battery heating. The average fuel consumption for all three runs over the full thirty minutes is shown below.

Table 3. Fuel economy (MPG) averages for each city trial.

No Diversion	Diversion, Trial 1	Diversion, Trial 2
41.9	44.6	47.4

Highway Driving

As expected, the exhaust diversion system had no impact on the hybrid system efficiency in highway driving, even in 20° F (-6.7° C) weather. Despite the cold, the batteries maintained a nominal operating temperature throughout both trials. While there may be some potential for floor-mounted batteries in BEVs and PHEVs to lose heat through convective cooling underneath the car, the trunk-mounted batteries in conventional hybrids are relatively safe from such heat loss. In two otherwise equivalent highway trials (Trials 3 and 4), the vehicle averaged 35.1 MPG without diversion and 36.9 MPG with diversion, a small enough difference to be attributed to uncontrollable external factors and random variability. The following graphs show how the battery temperatures changed over time, the first with exhaust diversion on and the second with it switched off.

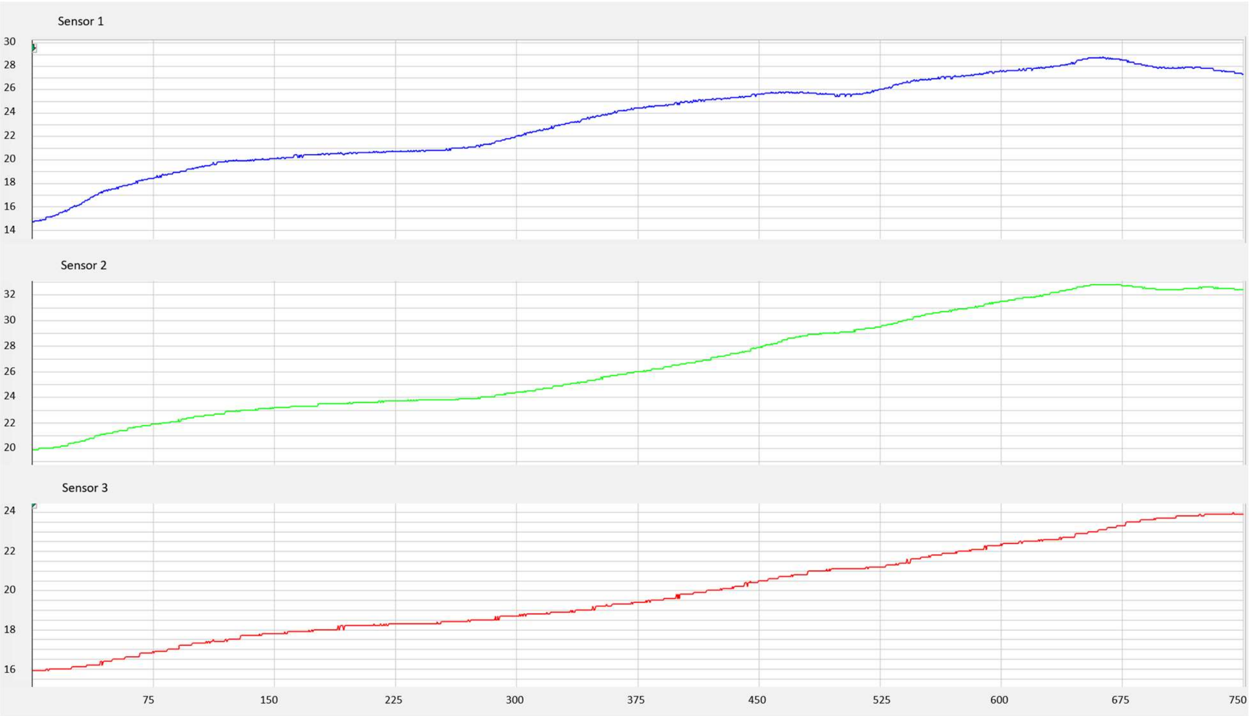

Figure 19. Battery temperatures (°C) over time (s) for highway run with diversion (T3).

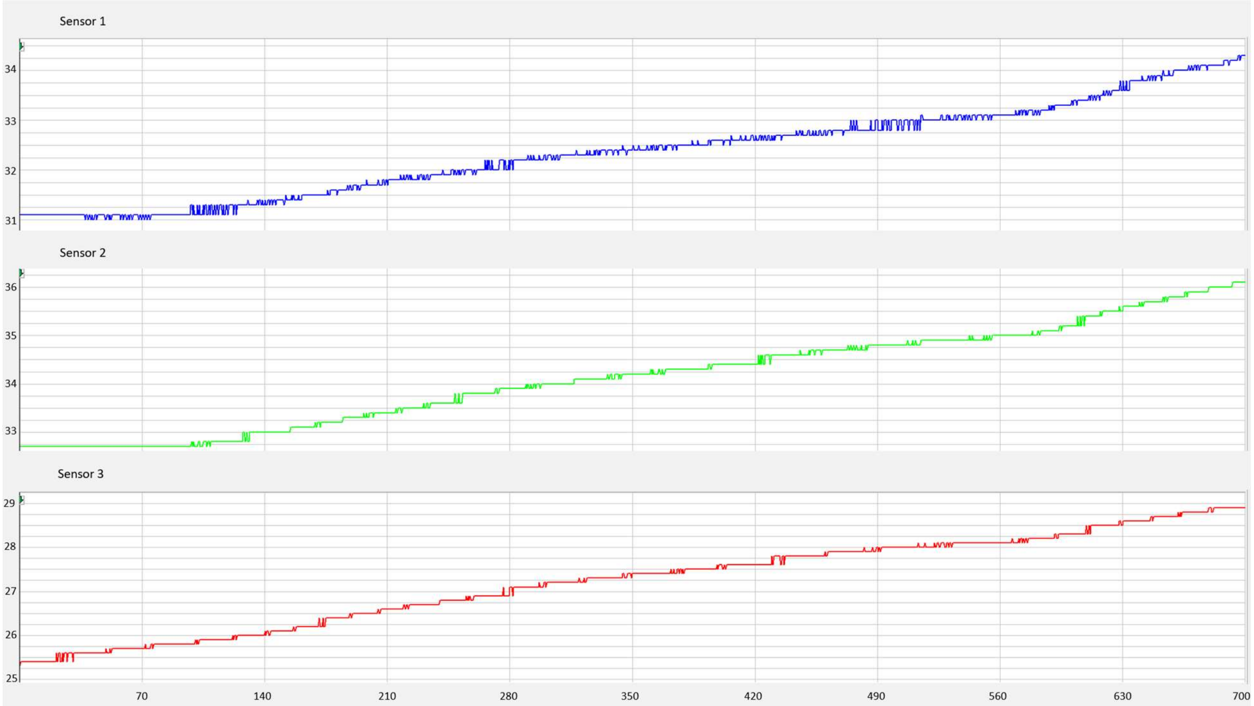

Figure 20. Battery temperatures (°C) over time (s) for highway run without diversion (T4).

Looking at the rates of battery temperature increase, exhaust diversion appeared to have a large impact on battery warming. Sensor 1 saw a 27° F (14° C) increase in temperature over about 650 seconds, or 2.32 $\frac{deg\ F}{min}$ (1.29 $\frac{deg\ C}{min}$), while Sensor 2 increased at 2.16 $\frac{deg\ F}{min}$ (1.20 $\frac{deg\ C}{min}$) and Sensor 3 increased at 1.09 $\frac{deg\ F}{min}$ (0.608 $\frac{deg\ C}{min}$). Without diversion, all three batteries heated up at a rate of, on average, 0.437 $\frac{deg\ F}{min}$ (0.243 $\frac{deg\ C}{min}$). This result clearly showed that exhaust diversion is capable of steadily increasing battery temperature, although the heat did not spread evenly between the batteries. Furthermore, the heating would have been significantly faster had the initial battery temperature been closer to the ambient temperature since convection is dependent on the temperature difference.

Using a least-squares quadratic fit for the temperature distribution between the three sensors and taking the area under the curve, the average temperature increase across the battery bay was found to be 2.02 $\frac{deg\ F}{min}$ (1.12 $\frac{deg\ C}{min}$), which implies a total heat generation of 600. w in the battery compartment. Assuming the same self-heating speed as the trial with no diversion, this suggests the exhaust added 462w of heat in highway driving. This figure is lower than the predicted amount in the exhaust energy balance, which can mostly be explained by the cold air being drawn in from the cabin and diluting the hot exhaust gases.

The highway test with exhaust diversion also triggered a warning code from the vehicle’s computer system. With the higher power levels required for highway driving, the system provided significantly more heat to the batteries, causing the Prius to warn that the inlet air temperature was too hot. This warning code did not suggest any damage to the batteries, as they were still well below a dangerous temperature. However, the fully warmed exhaust air in this trial melted some of the plastic around the diversion system’s inlet hose. Despite the fiberglass insulation that was wrapped around the hot air hose, the heat was substantial enough to cause the surrounding plastic to reach its melting point of 392° F (200° C). The molten plastic dripped and bonded to the metal below but did not spread outside of its immediate area. The damage caused by this one run, shown below, suggests that if this type of system were to be replicated in a production vehicle, it would need to replace the plastic inlet casing with metal.

Figure 21. Damage to thermal management system inlet

Battery Temperature Between Tests

Perhaps the most surprising result from the trials was just how slowly the batteries expelled heat while not in use. Despite being left completely open to the elements (trunk and doors open) with more than a 40° F (22° C) temperature difference from the outside air, the battery temperature decreased by a negligible amount between city trials. In most cases, the battery temperature at the beginning of one trial was identical to the temperature at the end of the previous trial. This finding suggests that it would have taken over a day of nonuse for conventional hybrid batteries to reach the ambient temperature. With closed vehicle doors trapping some of the heat, the cooling rate would slow to a crawl long before it reached a temperature where performance is compromised. This finding also implies that only extremely low temperatures (below 0° F or -18° C) would be capable of bringing the Prius' hybrid batteries to the point of losing their efficiency.

The one exception to this trend of extremely slow battery cooling occurred after the second highway trial, in which the battery temperatures peaked just above 97° F (36° C). While Sensors 2 and 3 saw a minimal temperature drop after Trial 4, Sensor 1 saw a 13° F (7° C) decrease. This result suggests that the vehicle's cooling system kicked in while the car was not running between trials. This was expected because the battery temperature reached a value well above the operating range. Since the same thermal management struggled to evenly heat the batteries, it follows that if battery cooling was also uneven it was due to the cooling system's efforts.

Engine Warmup

Since the warmup time of the engine corresponds exactly to the warmup time of the exhaust, the engine coolant temperature was a valuable statistic to track over each trial. Throughout the trials, the engine tended to take about four minutes to warm up in city driving. This involved no idling time except at traffic lights and stop signs. Typically, as shown in the figure below, the engine reached its ideal operating temperature of 176° F (80° C) after about 200 seconds of driving. The engine also retained heat well despite the frigid ambient temperature, starting the trials well over 104° F (40° C) despite the open hood allowing sub-freezing air into the engine bay. Therefore, the engine and exhaust system in the Prius and similarly sized hybrids can be expected to warm up significantly faster than the batteries, providing a source of hot air soon after startup. Despite the lack of need for battery heating in these trials, this result further reinforces the idea that using engine heat can be effective.

Figure 22. Engine coolant temperature (°C) vs. time (s) in Trial 5.

Discussion

Real Impact of Cold Weather on Fuel Economy

The major factors that were expected to affect fuel economy in cold weather in this experiment were drag, motor temperature, engine warm-up time, HVAC use, and battery temperature. HVAC use was removed from consideration, leaving drag, motor temperature, engine warm-up, and battery temperature. The data clearly demonstrated that battery temperature was not a detriment to performance for the ambient temperatures tested, so only drag, motor temperature, and engine warmup were left. Since the 2005 Prius was originally rated for 45 MPG on the highway and 48 MPG in the city (46 combined), the results from the experiments were mostly within expectations. The city trials yielded an average fuel economy of 44.6 MPG, 7.6% lower than the EPA rating. On the highway, the Prius averaged 36.0 MPG, missing the EPA rating by 20%. Since miles per gallon is inversely related to specific fuel consumption, the actual differences in fuel consumption (gallons per mile) on the highway and in city driving were 25% and 7.4%, respectively. Since the city trials involved minimal drag while cold air at 65 miles per hour increases the drag force by 11.8%, that larger performance loss for highway driving can be mostly attributed to drag. Fuel consumption and drag force are not necessarily correlated one-to-one, but an 11.8% increase in required energy should translate to a roughly 11.8% increase in fuel consumption. The rest of the fuel consumption gap can be attributed to degradation of the vehicle, motor and engine warmup in the city trials, and random variability.

Since these factors combined to not even approach the 31-34% loss of fuel economy that has been measured in countless other studies, the single largest source of inefficiency in hybrids in winter is most likely HVAC use. The city results recorded on the coldest day of the year were extremely similar to the MPG figures observed in nominal weather for the vehicle, a far cry from the nearly one-third loss that was expected. Although highway driving saw a substantial, measurable increase in fuel consumption due to drag, city MPG was essentially the same regardless of weather. With that known, the only remaining variable that could account for such a significant increase in fuel consumption was excess engine runtime with the goal of warming the cabin.

Effects of Exhaust Diversion on Performance

The results of this experiment lead to two key conclusions. First, conventional hybrids, contrary to popular belief, do not appear to experience significant performance losses due to battery temperature in typical cold weather (20° F or -6.7° C). Temperatures below 0° F (-18° C) may present some minor issues, but the Prius' ability to maintain a 40° F (22° C) temperature difference between its batteries and the outside air suggests that hybrids are able to maintain their excellent efficiency even in extremely cold conditions. However, this conclusion is at odds with previous research indicating that hybrids lose a larger percentage of their efficiency in cold weather compared to conventional gas-powered cars. Still, the two hypotheses, that cold weather does not strip hybrid batteries of their performance benefits and that cold weather hurts hybrid efficiency, are not mutually exclusive. Rather, this experiment demonstrated that HVAC use is the primary cause of performance loss in cold weather. While hybrid vehicle owners often notice that the engines in their hybrids run more often in cold weather than in warm weather, they seem to do this solely to heat the cabin. As observed in the experiment, with cabin heating turned off, the engine had no reason to run other than to provide power to the wheels. At each stop in each city trial, the engine shut off, regardless of the outside temperature or engine temperature. Thus, engines in hybrid vehicles run more often than necessary in cold weather just to provide warmth to the driver, causing a substantial system inefficiency. Furthermore, the inefficiencies caused by cabin heating would be expected to have a larger impact on hybrids than conventional vehicles because hybrids have a higher initial efficiency value. If both vehicle types lose the same percentage of their efficiency, hybrids will suffer more because they lose the same fraction of a larger value.

Second, the tested exhaust diversion system showed some potential to affect battery temperature, but not in a consistent enough manner to suggest widespread adoption in the industry. Even in the brief periods where the diversion caused accelerated battery heating, that heating was uneven across the battery bay and undermined by the frigid air drawn from the cabin. This mixed observable benefit came despite the system performing exactly as intended. The diversion system rerouted a large portion of the exhaust gases, required only a minimal amount of fan power for airflow, and warmed the batteries significantly faster than their self-warming capability. On the other hand, the encouraging performance of exhaust diversion came with some drawbacks. Since the exhaust stream through the batteries bypassed the muffler, it was exceedingly obvious when the system was working because it dramatically increased cabin noise. In the test vehicle, the additional piping also rattled against the entry point in the trunk and increased cabin vibration. Additionally, the diversion system melted the plastic around the hot air entry point during the highway trials even though the piping inside the trunk was well-insulated. Thus, while exhaust diversion can move significant amounts of heat to the batteries, the impact of that heating is inconsistent and ultimately unnecessary for most climates.

Applicability to PHEV and BEV Performance in Winter

The most surprising result in this experiment was the slow rate at which the hybrid batteries lost their heat. With so much attention given to battery temperature in electrified vehicles, it was assumed from the start that the batteries would be at or near the ambient temperature after a few hours of nonuse. Experimental data showed this assumption to be flawed, with hybrid batteries losing heat slowly enough that no significant performance loss could be expected through daily use. However, the same conclusion does not appear to be valid for plug-in vehicles. Since the battery packs in PHEVs and BEVs are significantly larger than those in conventional hybrids, they require more advanced thermal management systems for their batteries. These vastly different systems may explain why conventional hybrids are less prone to low battery temperatures. Since they generate significantly more heat, they are designed to shed heat in all circumstances rather than retain it. They also, more often than not, store their batteries on the underside of the vehicle rather than inside the cabin. This leaves them exposed to the colder outside air and even provides additional convective cooling while the vehicle is in motion. The result of this design strategy is that cooling performance is improved, but the batteries in PHEVs and BEVs reach much lower temperatures in cold weather than their conventional hybrid competitors. The results from the AAA study referenced previously suggest as much, but the results are even more concrete when considering standstill charging speeds. Since the act of driving introduces some amount of variability, the charging performance of plug-in vehicles provides an excellent demonstration of the slowed chemical reactions occurring in cold charging. A study conducted by the Idaho National Laboratory found that the charge rate is drastically slower at 32° F (0° C) than at 77° F (25° C).[28] In the figure below, an hour of charging provided approximately 30% less charge in the cold compared to the ideal charging temperature.

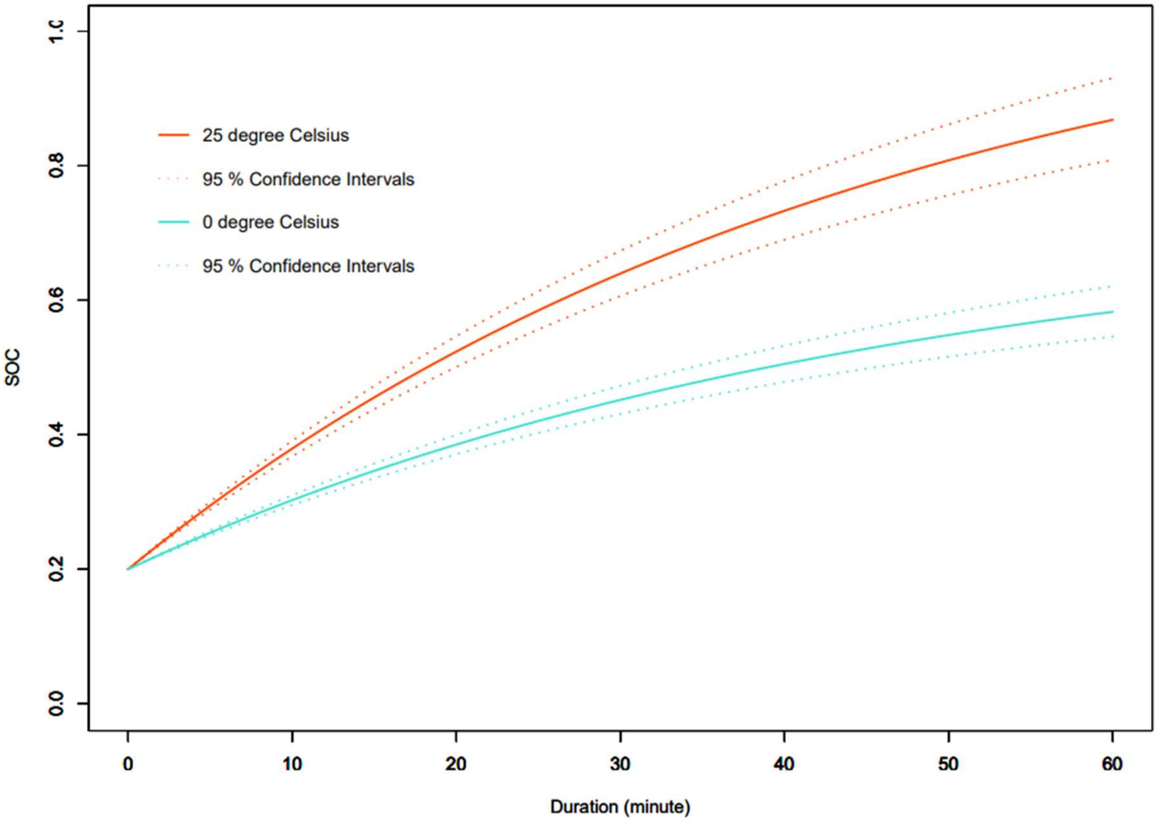

Figure 23. Charging speeds for Nissan LEAF at 25 and 0 degrees Celsius.[28]

Efficiency of Using Engine Heat Compared to a Space Heater

The Toyota Prius has a total interior area of 110 cubic feet according to the EPA. Using the Ideal Gas Law, this volume of air at atmospheric pressure and 20° F (-6.7° C) amounts to a mass of:

$$m = \frac{PV}{RT} = \frac{101kPa * 110ft^3 * \dfrac{0.0283168m^3}{1ft^3}}{0.287\dfrac{kJ}{kg * K} * 266.483K} = 4.135kg$$

Using the air tables in Çengel & Boles' <u>Engineering Thermodynamics</u>[29], air at 270 K and 300 K contains 192 kJ/kg and 214 kJ/kg respectively, assuming no boundary work. With a constant mass of air, the energy required to heat 4.135 kg of air to a comfortable cabin temperature is:

$$\Delta U = m * \Delta u = 4.135 * (214.07 - 192.6) = 88.78kJ$$

Since a space heater is 100% efficient at converting electricity into heat, this is the amount of energy required from the grid to heat up the air in a Prius cabin. However, this is a limited calculation because it does not account for the thermal mass of the interior components. Converting to more useful units, the vehicle can be warmed up with only 0.025 kWh. At average utility costs ($0.1054 per kWh[30]), this process would cost the average driver a third of a cent. This would not include the heating of vehicle surfaces, but most modern vehicles include electric heated seats, which can use battery power to efficiently warm up. Heating up the cabin air is the primary goal and the process that a space heater can most effectively complete to replace unnecessary engine operation.

In comparison, the Prius engine requires five minutes of idling to heat the cabin the same amount. Cars consume at least 0.19 gallons per hour while idling,[31] so a single warm-up on a single car requires 0.016 gallons of gas, or 4.8 cents at $3.00 per gallon. In theory, a space heater can be approximately 15 times less expensive than an engine at heating up a Prius cabin. Considering how often this process is necessary for every driver in temperate climates worldwide, the potential fuel savings could be enormous if all hybrid drivers adopted this tactic. If a million hybrid drivers used only electric heating for their cabins for 60 days a year, it could save 960,000 gallons of gasoline annually. Preheating cabins would not completely make up for the winter efficiency gap – the cabin will still lose heat to the surroundings while the vehicle is in use – but it could provide substantive energy savings.

Toyota Prius Hybrid Powertrain Algorithms

One focus of this experiment was to examine whether a hybrid could be made to rely more on the batteries and electric motor than it normally would. In theory, colder electrical components decrease available current and force the vehicle to be more reliant on engine power. In practice, however, it was revealed that the electrical components provided the same amount of power with or without additional heat added because they never dropped below a comfortable operating temperature. HVAC use can obfuscate the algorithms used by the vehicle because in many cases, the engine will run despite not providing any power. After a few minutes of driving, the vehicle is warmed up and stops relying on the engine as much. The original hypothesis was that the batteries needed to warm up before the car could use them effectively. With HVAC use removed as a variable, this research rejected that hypothesis. The algorithms Toyota and similar brands use to determine whether to run the engine or use EV mode are simple:

1. If the cabin HVAC is on and the cabin is below the set temperature, run the engine regardless of vehicle speed.
2. If the vehicle is not moving and the cabin is at the set temperature OR HVAC is switched off, run in EV mode.
3. For startup acceleration, run in EV mode up to 5 miles per hour to take advantage of the electric motor's instant torque and then turn the engine on to continue accelerating.
4. When the vehicle is coasting and the cabin is not demanding hot air, switch the engine off.

These instructions from the Prius' computers deviate slightly based on the battery charge level, but in general they are extremely consistent. By switching the engine off at all stops, the vehicle saves the fuel that would normally be used idling and prevents unwanted engine vibrations. The system uses as little fuel as possible by only operating the engine when it is needed for acceleration. These algorithms were not affected by the ambient temperature because the outside air did not drain enough heat from the batteries to become a factor.

Uneven Heating

In trial five, which saw the most compelling evidence of exhaust heat being capable of increasing battery temperature, only two of the temperature sensors measured this increase. The Toyota Prius uses three temperature sensors evenly spaced along the bottom of the battery pack, as shown in the Prius service manual:

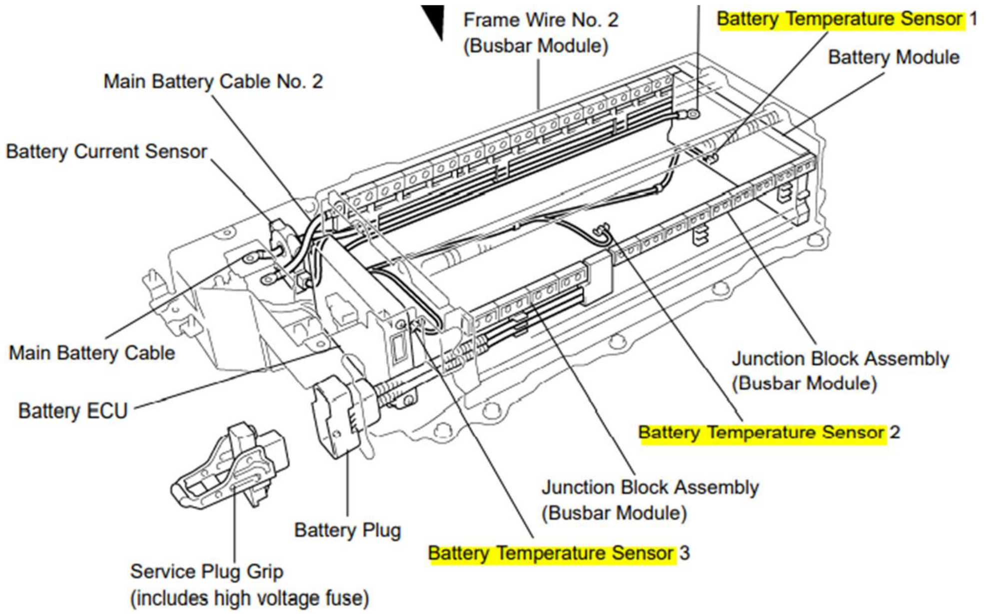

Figure 24. Prius battery temperature sensor locations.[17]

This schematic, paired with the uneven heating results, clearly demonstrate that the battery cells closest to the air inlet are most affected by the thermal management system. Almost all of the hot air provided by the exhaust system went to the first two thirds of the battery bay, while the batteries above the third sensor appeared to self-heat primarily through resistance heating. While Sensors 1 and 2 measured exponential temperature increases, Sensor 3 mirrored the linear heating for all three sensors in Trial 1. At least in the context of battery heating, this result exposes a potential design flaw for using hot air to control battery temperatures. If the fan speed is too low, only the batteries closest to the inlet are heated. If the fan speed is increased to drive more aggressive airflow and more effectively spread the heat, it also pulls in more cold air from the cabin and dilutes the hot air. This would not be as problematic if the ambient temperature and battery temperature were close, as was expected at the beginning of the experiment; the hot air and cool air would still combine to be significantly warmer than the batteries. However, since the batteries remained warm from previous use, the cabin air was cold enough to remove heat even when combined with exhaust air.

Trial and error adjustments between seven different fan speeds showed that the lowest fan speed was the only option that effectively heated any of the batteries in city driving, but the setting did not provide the desired uniform heating. Any future projects seeking to use hot air to warm batteries must also devise a more robust method for spreading the heat without drawing in cold air as well.

Experimental Limitations

This experiment had several limitations that prevented it from being a decisive case study on hybrid vehicle performance in cold weather. First, the experiment only included five trials when ideally there would have been several replications over several days. Unfortunately, the weather in late 2020 and early 2021 only delivered one day that was cold enough (20° F or -6.7° C) to severely impact battery performance. Furthermore, since the vehicle was borrowed, there was a limited amount of time with the vehicle to perform more tests. It also would have been helpful to conduct the same tests on the stock Prius at an ideal spring temperature, but that was not possible. Another major limitation is the fact that the results may not be applicable to other hybrid vehicles. In theory, most hybrids use nearly identical cooling systems and store the batteries in the same location, but other designs may not be as effective at retaining heat as the Prius. There may be other hybrids that have worse insulation around the batteries, allowing heat to escape too fast and causing the batteries to reach the ambient temperature faster.

Finally, the single largest limitation was the lack of a trial that left the batteries unused for 24 hours. Since the 12-hour cooldown was expected to be more than enough before the first trial, this limitation was completely unanticipated. A valuable additional piece of data for the experiment would have been to log the battery temperature every hour over a 24-hour period in extremely cold weather to measure how it changes over time. The experiment concluded that daily use in climates that only reach 20° F (-6.7° C) a few times a year is more than enough to keep batteries warm, but it did not test scenarios where the vehicle is used less frequently or in more extreme climates. However, this temperature-tracking exercise would have presented its own issue; since the Techstream software only connects when the car is fully powered on, the mere act of measuring the temperature is guaranteed to raise it slightly. It takes at least a minute of operation to start up the software and start logging data, so every time the temperature is measured the data becomes more skewed.

Additionally, there was one notable unmeasured parameter that would have aided the analysis of the results. First, it would have been helpful to have mass flow rate sensors on the exhaust diversion system and the exhaust to determine exactly how much of the exhaust stream was used on the batteries. At idle, the system clearly sent the majority of the exhaust through the diversion system, but it was not clear how the ratio changed while the vehicle was moving. However, flow rate sensors are expensive and usually calibrated for a specific fluid rather than exhaust gas, which has a constantly variable chemical composition. Therefore, obtaining usable data from flow rate sensors would have been excessively burdensome.

Conclusions and Recommended Future Work

The data provided in this preliminary study suggests that current conventional hybrids stand to gain little to no performance benefit from changes to their thermal management systems. In warm and hot weather, hybrid configurations provide massive efficiency benefits, and in cold weather cabin heating is likely the main factor preventing them from providing those same benefits. However, these findings suggest that other habitual changes could provide the efficiency gains hybrid owners seek in cold climates. Just as BEVs and PHEVs take advantage of their grid ties to preheat their cabins, conventional hybrids can maintain their efficiency by using electric space-heaters while their drivers prepare for their commutes. An inexpensive space heater tied to the home electrical grid can heat the cabin at a near-perfect efficiency, eliminating the need for the engine to run. In theory, the preheated cabin will allow the engine to shut off earlier and more frequently without sacrificing comfort. Since grid-provided electricity is more efficient than a gas engine, this strategy would be more environmentally friendly and less expensive for the drivers. A future study could determine the difference in fuel economy when hybrid vehicle cabins are preheated in a garage vs. left outside.

Another possible area for more research would be testing battery heating methods in different configurations and ambient conditions. For example, a study could test a similar exhaust diversion method in extreme climates (<0° F) to determine whether lower temperatures can throw off battery performance. A future study could also test the other heat transfer methods mentioned. A heat exchanger attached to the exhaust pipe or a system that runs engine coolant through the battery bay could provide better performance than an exhaust diversion system. Of course, these systems would need to be tested in different ambient conditions than those present in this research. Although unlikely based on the data provided, sub-zero ambient temperatures could cause substantial performance losses in the batteries.

A future study on the effects of low ambient temperatures on hybrid motor performance in the field would also be useful. In the literature review, it was found that electric motors in automotive applications tend to perform best when their temperatures are around 150° F (65° C). Motors, like engines, produce far more waste heat than batteries because of their high rates of mechanical motion and friction generation, such that they are able to warm themselves to that high temperature relatively quickly. A future experiment could study the rate at which hybrid motors heat themselves in cold weather versus ideal weather. Since motor temperature affects hybrid performance and efficiency, a practical assessment of thermal performance in cold weather would be revealing.

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