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Cold Impacts on Vehicle Electrical Systems

Developing a Baseline for Cold Testing Military Vehicles

Alexander R. Stott, Caitlin A. Callaghan, Douglas A. Punt,
and Tyler J. Elliott

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Abstract

Low temperatures can significantly affect vehicle operation. While many of the effects, like increased fluid viscosity and decreased battery capacity, are well documented, the impacts on the electrical system as a whole are not. The objective of this study was to investigate the impacts of temperature on the electrical systems of select military vehicles and to develop a baseline for future testing. A High Mobility Multipurpose Wheeled Vehicle (HMMWV), a Heavy Expanded Mobility Tactical Truck (HEMTT), and a four-person diesel Polaris MRZR D4 were subjected to 15°C, 0°C, and −15°C temperatures while the loads on the battery and alternator were monitored. The HMMWV and MRZR were able to start on the first try for all tests. They both showed a slight increase in vehicle load current draw from the alternator as temperatures decreased. Future testing with more iterations and at lower temperatures will help identify clearer trends and improve testing procedures. As the Army becomes more reliant on electronic systems, it is becoming increasingly important that we understand how various climates will impact them.

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Preface

This study was conducted for the US Army Corps of Engineers under PE 0603734A, Project T15, "Energy and Technology Research in Cold and Arctic Regions." The technical monitor was Mr. Jared Oren, US Army Engineer Research and Development Center, Cold Regions Research and Engineering Laboratory (ERDC-CRREL).

The work was performed by the Engineering Resources Branch of the Research and Engineering Division, ERDC-CRREL. At the time of publication, Dr. Melisa Nallar was branch chief, Dr. John Weatherly was acting division chief, and Mr. David B. Ringelberg was the technical director for Cold Regions Science and Engineering. The acting deputy director of ERDC-CRREL was Dr. Ivan P. Beckman, and the director was Dr. Joseph L. Corriveau.

COL Christian Patterson was commander of ERDC, and Dr. David W. Pittman was the director.

1 Introduction

Half of the earth's land mass is considered *cold* with a quarter of it in the *severely* cold category and the other quarter considered *moderately* cold (Department of the Army 2017a; Diemand and Lever 2004). Operating in such conditions is difficult and can lead to dangerous situations when equipment fails. Vehicles struggle to function in the cold because most are not designed for the extreme weather found in cold regions (e.g., above the arctic circle). Therefore, this study examines how low temperatures impact vehicle electronic systems and seeks to develop a baseline for future investigations.

1.1 Background

Cold is the enemy of a functioning vehicle and many of its systems. The electrical system is not immune to the effects of low temperature. Batteries, for example, rely on chemical reactions to produce energy; and, at low temperatures, these reactions slow down and reduce battery capacity (Battery University 2019). Vehicles rely on batteries to start, so it is important that those batteries can provide the energy required to turn a vehicle's engine over. It is also at low temperatures that the effects of parasitic loads can be more severe. Because the capacity of a battery is less at lower temperatures, anything that draws a current while the vehicle is off can result in a dead battery much more quickly. In addition to parasitic loads, other factors can impact the ability of a vehicle to turn on and function at an optimal level.

When vehicles must operate at consistently below-freezing temperatures, changes to both the vehicle and how it is operated are necessary to allow them to function more efficiently. This is because vehicles were designed to start and operate optimally in a moderate climate. At lower temperatures, fuels, oils, and lubricants become more viscous, generating more resistance within vehicle components (Diemand 1992). Parts move less freely while oils and fuel are not be able to flow as quickly, which can result in difficulty starting an engine or wear and damage to parts if there is too much friction. To counteract this, technical manuals describe what oils and lubricants to use at lower temperatures. Installing different fluids that are rated for lower temperatures reduces resistance, which can improve vehicle performance in the cold (Departments of the Army, the Air Force, and Marine Corps 1996).

The military relies on diesel and JP-8 to fuel their vehicles. A diesel engine is a compression ignition system. This means that ignition is dependent on the air in the compression chamber reaching a hot enough temperature to ignite the working fluid. At low temperatures, a cold engine, cold fuel, and cold air intake can prevent the diesel fuel from igniting. Diesel engines typically incorporate components like glow plugs to aid with the combustion at low temperatures by increasing the air temperature within the combustion chamber to help ignite the working fluid. Glow plugs work but can be a big drain on the battery since they are essentially a large resistor that converts electricity into heat (Diemand 1991).

There are currently limited options to combat the cold at very low temperatures below −18°C. A vehicle can be stored inside in a warm space, kits such as engine-block and oil-pan heaters can help increase the temperatures of fluids and components, large heaters can heat up a cold vehicle, or the vehicle can be turned on periodically to maintain engine heat to help the vehicle start. All these options involve a significant amount of energy and time to be effective (Diemand 1991). Developing methods and technologies that can reduce the amount of energy a vehicle and its payload consumes for reliability is crucial for the Army. Understanding the relationship between the battery, alternator, and the vehicle load at various temperatures will allow for the design and development of more-resilient vehicle electrical system that can start in the extreme cold.

1.2 Problem statement

The cold regions are a harsh and deadly environment. “When employed in a cold region, a force actually faces two enemies—the tactical enemy and the geographic environment that aggressively attacks and destroys equipment and Soldiers” (Department of the Army 2017a). It is important that the Army is able to function reliably in these regions.

The military’s use of electrified systems has increased significantly in the past decade and will expand even further in coming years. It is the Army’s objective to “increase situational awareness, to lighten the Soldier’s physical and cognitive workloads, and to facilitate movement and maneuver among others with robotic and autonomous systems” (Department of the

Army 2017b). With technologies such as remotely operated vehicles, powered weapons, and vehicles with a wide range of capabilities, more electrical power is needed in the field to help facilitate missions. As a result, to ensure functionality and reliability in cold environments, it is important to understand how low temperatures will affect power systems.

1.3 Objective

The purpose of this study was to investigate the impacts of temperature on the electrical systems of select military vehicles and to develop a baseline for future testing. This will aid in Army readiness and resiliency by providing information to military decision makers about the current state of military vehicles and how they operate in the cold. This will lead to opportunities to improve the Army fleet and bolster our projection of force.

1.4 Impact to the Army

Regaining Arctic Dominance: The U.S. Army in the Arctic (Department of the Army 2021) is a strategic document developed by the Chief of Staff for the Army and recognizes the importance of cold performance for the Army. As it explains, “The Army will implement integrated solutions that emphasize readiness for operation in extreme cold and mountainous environments and bolsters the resiliency of our people and our installations” (Department of the Army 2021).

The ability of vehicles to start, transport, and power components at a moment’s notice is critical for the military. Increased activity in the Arctic by foreign adversaries has made readiness and reliability in the cold a priority (Department of the Army 2021; Office of Inspector General 2020). Cold weather has a significant impact on the functionality of equipment, and it is important that all equipment is designed or prepared to function in extreme cold conditions (Diemand 1992). Understanding how the electrical systems of currently used military vehicles behave in cold environments increases the awareness of our current capabilities. By innovating and mitigating any potential challenges that arise, we can create more resilient vehicle systems and develop new vehicles with improved capability in the cold.

Climate change is altering the conditions around the globe and more significantly in the arctic. Warming north of the Arctic Circle is occurring twice as fast as in the rest of the world and opening up new opportunities for resources. While warming is relative and the conditions are still very harsh in this region, activity is increasing and will require more of a military presence in the area. The US has multiple military bases within Alaska and above the Arctic Circle. As the presence of foreign entities in the Arctic increases, it is important that our military is able to respond in the event of a crisis. Ensuring that current military vehicles are capable of performing reliably in extreme cold is of the utmost importance (Department of the Army 2021).

1.5 Approach

This report provides the technical details for the instrumentation and testing of three military vehicles to assess the electrical systems and their functionality at a range of temperatures. Testing took place within the Materials Evaluation Facility (MEF) at the Cold Regions Research and Engineering Laboratory (CRREL) in Hanover, New Hampshire. Installation and testing took place between 31 August 2020 and 22 September 2020. The data provided in the report includes alternator rotations per minute and the voltage and current readings from the alternator and battery of each test vehicle at 15°C, 0°C, and –15°C. *

The report has six main sections. Following the section 1 introduction, Section 2 gives more detail about the electrical systems of vehicles. Section 3 describes the installation and testing methods, and section 4 provides the results and analysis. Section 5 describes the lessons learned, and section 6 provides the study's conclusions.

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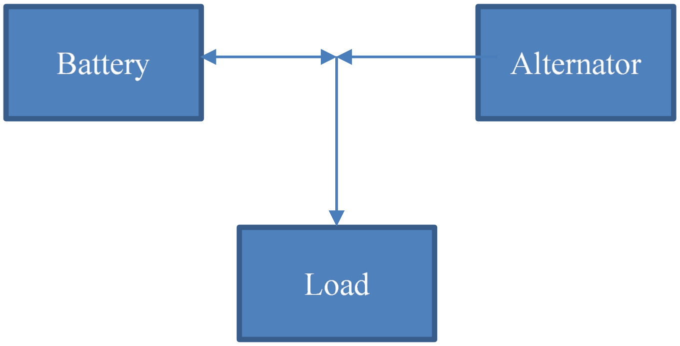
* For a full list of the spelled-out forms of the units of measure used in this document and their conversions, please refer to *US Government Publishing Office Style Manual*, 31st ed. (Washington, DC: US Government Publishing Office, 2016), 248–52 and 345–47, https://www.govinfo.gov/content/pkg/GPO-STYLEMANUAL-2016/pdf/GPO-STYLEMANUAL-2016.pdf.

2 Vehicle Electrical Systems: Challenges in Cold Climates

The cold affects vehicles in many ways, and there are many studies and investigations into how the cold impacts the various components. Diemand (1992) examined the various ways to increase the temperature of vehicles to improve performance in the cold. The Cold Regions Test Center's performance evaluations of various military vehicles examined how well a vehicle could start, how well the heaters worked, and a vehicle's mobility in the snow (US Army Cold Regions Test Center 2015). However, it was difficult to find other studies that investigated military vehicles and how, specifically, operating at different temperatures affected the electrical systems.

A basic vehicle electrical system is composed generally of a battery, a starter, an alternator, and the vehicle load. The first three components are critical to the functionality of a vehicle. If any one of these components fails, the vehicle will stop running. The vehicle load comprises all other parts of the vehicle that require power to function. Figure 1 provides a simple schematic illustrating how these components interact with one another.

Figure 1. Simplistic illustration of a vehicle electrical system



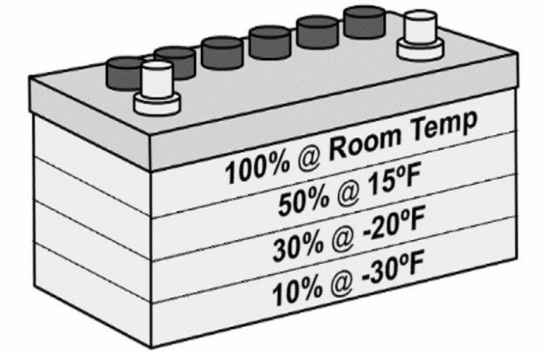
2.1 Batteries

To start a vehicle, it is necessary to have enough stored power to activate the starter. The only source of starting power is the vehicle battery. When the ignition is turned to the run position, a circuit is completed that allows current to flow from the battery to the starter. The amount of power needed depends on the size of the vehicle and on the internal resistance of the system. Generally, larger vehicles need more power.

The batteries used in this study are all lead-acid batteries. The four-person diesel Polaris MRZR D4 uses absorbed glass mat (AGM) batteries while the High Mobility Multipurpose Wheeled Vehicle (HMMWV) and Heavy Expanded Mobility Tactical Truck (HEMTT) used flooded or "wet-cell" batteries. The flooded lead-acid batteries use lead plates and a liquid sulfuric acid electrolyte to generate a chemical reaction to produce energy. For AGM batteries, fiber glass within the battery is impregnated with the sulfuric acid, which keeps the electrolyte in place, making it spill proof. The reduced internal resistance of AGM batteries increases the output voltage, decreases charge time, and reduces heat losses (Battery University 2019).

As temperatures get colder, batteries lose power due to the reduced chemical reactivity at lower temperatures. At –10°C, a lead-acid battery's capacity reduce to 50% of its full capacity at room temperature 20°C–25°C (Department of the Army 2017a). Figure 2 shows roughly the change in capacity for a flooded battery at various temperatures.

Figure 2. Flooded lead-acid battery power availability at varying temperatures. (Image reproduced from Department of the Army 2017a, Figure 3.1. Public domain.)



The importance of the battery in the vehicle is to provide the initial energy needed to start the engine. This in turn activates the alternator, which is the main power source of the vehicle while it is operating. A decreased capacity of a battery impacts its ability to provide enough energy to turn over the engine. In addition, the amount of energy required to start a vehicle typically increases in low temperatures. This could be caused by increased viscosities of lubricants and fuels at these temperatures, reduced compression as piston ring gaps deform out of spec from thermal contraction, and other issues.

2.2 Starter

The starter is what physically starts the motor. An engine runs on a feedback loop that is self-sustaining once it is running. It relies on the inertia from each cycle to initiate the next. Because an engine is not moving when off, the feedback loop is broken, and the engine cannot start without external energy. The starter provides that energy by turning the engine flywheel with a small pinion for a short period of time and then disengages once the engine starts (Muir, n.d.).

The starter needs a heavy electric current, which is drawn from the battery (Muir, n.d.). Typical manuals will instruct that a starter be engaged for a short period of time that is vehicle dependent. Holding the ignition longer, or running the starter continuously, will drain the vehicle battery faster and could heat up the starter, causing damage to it (Departments of the Army, the Air Force, and Marine Corps 1996). In addition, as temperatures decline, the resistance within a vehicle increases. Increased resistance requires more power to generate movement. This means that a starter will draw more power in colder climates to start the vehicle, increasing the likelihood of draining a battery more quickly. By monitoring the battery current, this study should be able to identify that increase in the power draw as temperatures get colder.

2.3 Alternator (and charging system)

The alternator charges the batteries and supplies power for the majority of the equipment on a vehicle while the vehicle is running. A pully connected to the crankshaft of the engine holds a belt that runs to the alternator. As the engine runs, the crankshaft turns a magnet in the alternator within a stationary coil of wire, generating electrical current. For the current to be usable by the electronics on the vehicle, a rectifier converts the alternating current (AC) to direct current (DC). A voltage regulator is attached to the alternator to ensure that the battery sees a nominal output of 14 V for 12 V systems. For 24 V systems, the nominal output is 28 V (Denton 2004). The biggest threat low temperatures impose on the alternator is how they change parts of the alternator system (e.g., the rubber belt; Hunting 2017). As temperatures decrease, the belt can stiffen, resulting in an increased chance of slipping (Lampe 2018). Slipping is when there is not proper contact between the rubber belt and the pully of the alternator or the crankshaft. This improper contact results in a less-than-ideal translation of motion from the engine to the alternator, which leads to power loss. It can also lead to a dangerous situation where the belt releases from the pullies completely and renders the vehicle inoperable until a new belt is installed.

Monitoring the alternator is critical when examining the electrical system of a vehicle because it is the main component that converts the mechanical energy of the engine to electricity that runs the electrical components of the vehicle. Knowing how cold affects it and monitoring the electrical draw from the alternator by other components can reveal problems further down in the system.

2.4 Vehicle electrical load

As stated earlier, the electrical load consists of all the other components of the vehicle that draw power from the alternator and battery to function. For your typical commercial vehicle, this includes the critical systems like the engine control unit, headlights, dash display, and antilock braking system (ABS) systems in addition to more basic components, such as the radio and external outlets (Denton 2004). Technology has come a long way since the 1960s when the alternator as we know it was introduced into vehicles. Some vehicles are now able to drive autonomously and include features such as Bluetooth, radar, and cameras, along with other safety and luxury systems run by the internal computer of the vehicle (Hunting 2017). Military vehicles, while not necessarily including most of the luxury accessories of a normal car, are no different and often require more power to run tactical equipment like night vision, radios, and other auxiliary equipment.

All of these components run off the alternator directly while you drive, but there are some that are able to run off the battery when the vehicle is off. Systems that are connected directly to the battery can sometimes become parasitic loads. A parasitic load is a component that draws power from a system unnecessarily, even when the vehicle is off. An example of this could be a faulty battery that continuously charges from the remaining batteries. Another example would be a light that is left on. This is why a battery can drain if a car’s headlights are left on. The impact of a parasitic load could be magnified in low temperatures because a battery’s capacity is already lowered due to the cold. It increases the likelihood of a drained battery if the vehicle is left to sit for any period of time.

As the number of power-drawing components in a vehicle increases, engineers must consider such aspects as power consumption, overall vehicle weight, space, and necessity. An alternator must be designed to output enough power to charge the battery after vehicle ignition, provide power to necessary vehicle components, and then be able to handle any auxiliary components attached to the vehicle (e.g., external batteries, computer systems, etc.).

3 Methodology

3.1 Vehicles tested

The vehicles tested include the following (Figure 3):

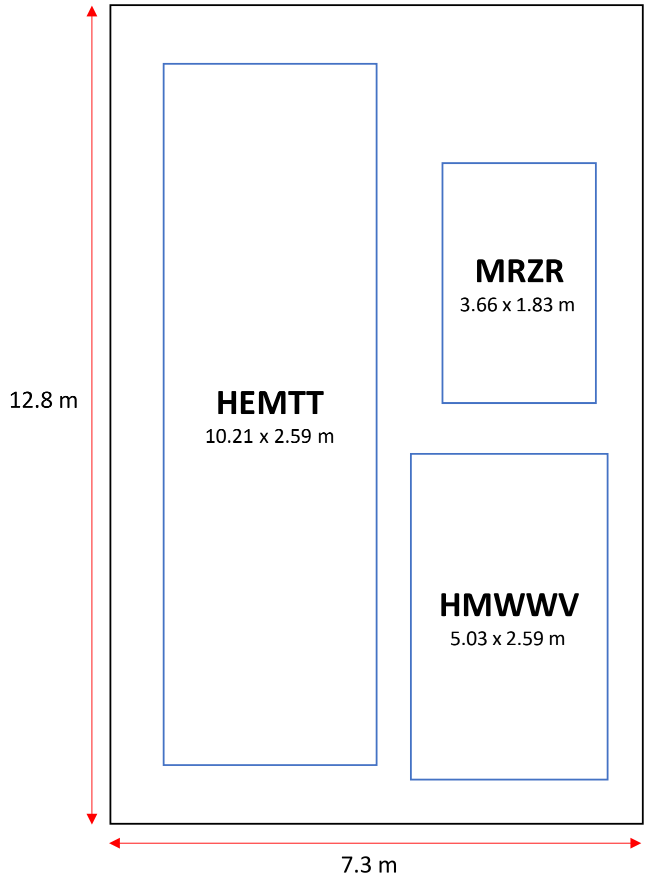
- M-1097-R1 High Mobility Multipurpose Wheeled Vehicle (HMMWV)
- M-977 Cargo Heavy Expanded Mobility Tactical Truck (HMETT)
- 2018 four-person diesel Polaris MRZR D4

Figure 3. Test Vehicles: (*a*) High Mobility Multipurpose Wheeled Vehicle (HMMWV); (*b*) Heavy Expanded Mobility Tactical Truck (HEMTT); (*c*) Polaris MRZR D4.

3.2 Testing location

We conducted testing in the MEF at CRREL. The facility space is roughly 12.8 m by 7.3 m with a 3.5 m wide bay door. It has the capability of reaching and maintaining temperatures down to minus 20°C. All three vehicles were placed in the MEF at the same time to conduct testing on all vehicles simultaneously, thereby increasing testing efficiency. Figure 4 shows the layout for the MEF. Additionally, the cover image of this report shows the vehicles positioned in MEF right before instrumentation began.

Figure 4. Vehicle layout in the MEF.



3.3 Safety precautions

To conduct the tests safely, we implemented measures to reduce the risk of serious injury. To maintain low temperatures, we conducted testing in an enclosed space. However, operating vehicles in an enclosed space poses a health risk since dangerous exhaust fumes generated while the engine is running could build up over time. To mitigate this issue, we created an exhaust system to pull the fumes directly from the tailpipe of the running vehicle to outside the building. This consisted of silicone tubing that ran through the wall of the building to a fan located outside to prevent damage to the fan from low temperatures (Figure 5).

Figure 5. Exhaust fan located outside of the MEF within a wooden housing to protect against rain. A Silicone hose runs into the MEF to the test vehicle.

A metal cone attached to the tailpipe of the running vehicle to capture as much of the exhaust as possible (Figure 6). In addition to the exhaust system, we installed a carbon monoxide detector to monitor the air quality in the space. If carbon monoxide levels got too high, and alarm would sound, and the team would turn on the external exhaust fan to help cycle cleaner air into the building.

Figure 6. Exhaust hose connected to the tailpipe of the MRZR test vehicle.

To ensure that everyone was safe during instrumentation and during battery removals, the first step was always to disconnect the negative terminal of the battery to prevent electrocution. We used foam padding to insulate the metal edges surrounding the batteries to prevent arcing when removing the batteries.

Because work occurred in a space with below-freezing temperatures, proper cold gear, such as gloves, hats, and jackets, were necessary while inside the MEF. Boots with good grips were also required to prevent falls. As an additional precautionary measure, any person going into the cold room needed to carry a walkie-talkie and use the buddy system.

3.4 Sensors and data acquisition

Table 1 lists the type and number of sensors used on all vehicles. Replicating the sensors eliminated the need to move sensors between vehicles before each test, reducing time between vehicle tests.

Table 1. Sensor list for all vehicles.

Sensor Type	Measurement	Specifications
Thermocouple 1	Battery temperature	Type T
Thermocouple 2	Alternator temperature	Type T
Thermocouple 3	Engine block temperature	Type T
Thermocouple 4	Exhaust temperature	Type T
Thermocouple 5	Air temperature near vehicle	Type T
Current transducer 1	Battery current	LEM LA 55-P and LA 125-P/SP4
Current transducer 2	Alternator current	LEM LA 55-P and LA 125-P/SP4
Voltage 1	Battery voltage	Wire to custom voltage divider
Voltage 2	Alternator voltage	Wire to custom voltage divider
Tachometer	Alternator revolutions per minute	Reflective optical sensor (BPR-301)

Type T thermocouples with Quick Tip Connectors monitored the temperature at multiple points around each vehicle during testing and cold-soaking periods. Each vehicle had five temperature sensors that measured battery, alternator, engine, exhaust, and air temperatures. Measuring temperatures at different points ensured that the vehicle was completely cold soaked and created consistency among each test.

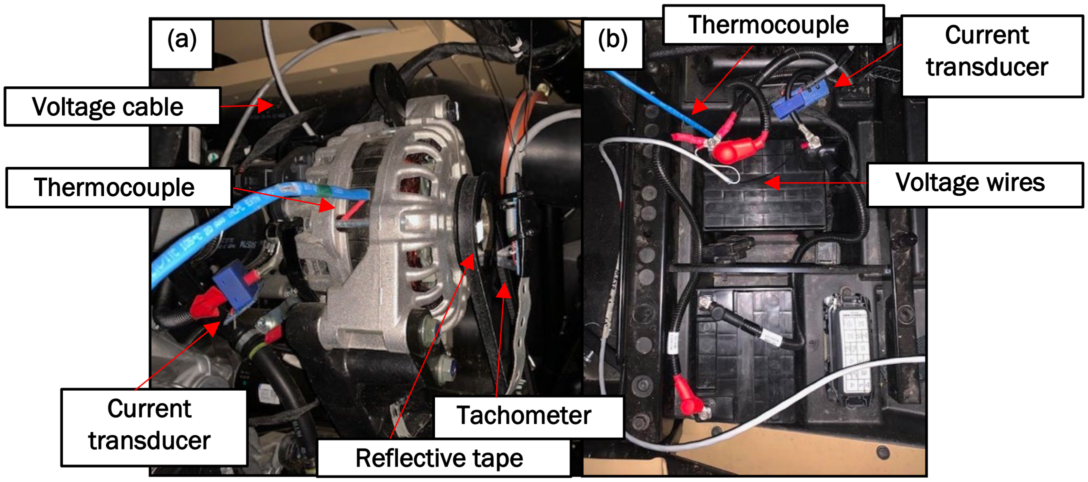
We measured total battery voltage using wires connected to the positive and negative terminals of the battery circuit. The HEMTT and HMMWV use a 24 V system, which uses two 12 V batteries in series. To measure this, the positive wire was connected to the positive terminal of the first battery and the negative wire was connected to the negative terminal of the second battery, measuring the voltage across the two batteries. The MRZR runs off a 12 V system and uses two 12 V batteries in a parallel configuration; we monitored only one battery since the voltage across both batteries is the same (Figure 7*b*). Alternator voltage was also measured by connecting to the positive and negative terminals of the alternator.

Current transducers monitored battery and alternator current. We placed them around the negative cables that were connected to the battery and alternator of each vehicle. Figure 7 shows this for both the alternator and battery for the MRZR. The purpose of monitoring both voltage and current was to observe the flow of power through the system at different points in time. Because the battery is used mainly to start the vehicle, it is important to capture the power draw needed to get the vehicle running and then be able to see how much power goes into the battery as the alternator charges it. Monitoring the alternators shows how much power the whole vehicle draws and not just the battery.

To accurately monitor the rotation of the alternator, we positioned a tachometer to look at the main alternator shaft to capture the rate of rotation of the alternator. A piece of reflective tape was placed on the rotating pully to capture each single rotation. Figure 7*a* shows this setup for the MRZR. The reason for monitoring the rotation of the alternator was to observe how the engine’s performance at lower temperatures affected the rotation of the alternator.

To collect the measurements obtained by the sensors, a National Instrument data acquisition system recorded the data at a 50 Hz frequency for the duration of the test. Each vehicle’s sensor array was designed so that the connectors to the acquisition system could be swapped out between tests for quick turnover. We designed the collection program, developed in LabView, so that the system worked the same for all three vehicles, limiting errors when switching between test vehicles. For the battery and alternator voltage value readings, because the maximum input voltage of the module is ±10 V, we constructed a voltage divider board to reduce the input voltage signals to within the range of the module.

Figure 7. Sensors installed on the Polaris MRZR: (*a*) placement on the alternator and (*b*) placement on batteries.



3.5 Testing procedure

Vehicles were placed into the MEF and instrumented with the sensor described in section 3.4. Testing was developed using guidance from Test Operating Procedures (TOP) 02-4-002A (US Army Cold Regions Test Center 2015) and 2-2-650 (Combat and Automotive Systems Division 2008) where applicable. C1 basic low temperatures were used and are defined by Department of Defense (2014) as the temperature range between −32°C and 0°C.

Prior to each test, we installed fully charged batteries in the vehicles. The vehicles sat for 12 hours minimum at the testing temperature to cold soak. Cold soaking ensured that all components of the vehicle were at testing temperature to mimic sitting outside for a long period of time. When all temperatures were within 2°C of the test temperature, we attached an exhaust vent to the exhaust pipe of the test vehicle. While one person monitored the data acquisition system, another sat in the driver's seat of the vehicle to turn the engine over. A third person at the exhaust fan was ready to turn it on once the engine turned over and was running so as not to impact the vehicle start process. The concern was that the suction of the fan would alter the airflow in the system.

Once the data acquisition system was on, we began attempts to start the vehicle. If the engine successfully engaged, we let the vehicle run for 15–30 minutes, depending on how quickly the engine reached a working temperature. If the engine did not engage, we made a maximum of three additional attempts as directed by the TOP.

Upon test completion, we shut off the vehicle and stopped the data acquisition. We used two sets of batteries for each vehicle to ensure that daily testing could occur. While one set of batteries was installed in a vehicle to cold soak for the next test, the other charged at room temperature. After a test was complete, we swapped the used batteries for the charged set. The newly installed batteries then cold soaked overnight with the rest of the vehicle. We repeated this process for all vehicles.

4 Results and Analysis

Table 2 shows the number of iterations conducted at each temperature for each vehicle.

Table 2. Test attempts for each vehicle at each temperature.

Test Vehicle	Number of Attempts at Each Temperature		
	15°C	0°C	−15°C
HMMWV	4	4	4
MRZR	4	2*	2*
HEMTT	3	5	5

* Four tests were conducted, but only two of the tests had reliable data.

4.1 HMMWV results

The HMMWV was able to start on the first attempt every time at all three temperatures. Voltage and current levels for the battery changed slightly between temperatures for this vehicle but not to the point where the vehicle was underpowered. Table 3 shows the average battery measurements with the standard deviation for each temperature.

Table 3. HMMWV battery results summary with the standard deviation in parentheses.

Temperature (°C)	Average Battery Voltage (V)			Average Battery Current (A)	
	Before Start	After 10 Minutes	Voltage Drop (Starter)	Current Draw (Starter)	After 10 Minutes
15	26.3 (0.7)	31.6 (0.6)	9.9 (1.9)	−186.5 (2.0)	3.7 (0.8)
0	25.5 (0.4)	30.1 (0.6)	9.9 (1.5)	−195.8 (9.2)	1.6 (0.2)
−15	25.3 (0.2)	29.5 (0.2)	8.0 (0.5)	−204.1 (5.7)	1.0 (0.2)

The average battery voltage while the HMMWV was running was 31.6 V, 30.1 V, and 29.5 V for 15°C, 0°C, and −15°C, respectively. The drop in voltage could indicate that the low temperatures decreased the capacity of the battery. The current going into the battery decreased as temperatures fell with values of 3.7 A, 1.6 A, and 1.1 A. As discussed in sections 1 and 2, the battery uses chemical reactions to release electricity. If cold reduces a battery's capacity, this will also limit a battery's ability to charge. The reduction in current to the battery could be a result of the low temperatures, which means that it is important to keep the battery warm to maintain charge capacity.

During ignition, the starter drew a significant amount of current from the battery over a very short period of time. The maximum current from the battery increased as the temperatures decreased, with current flowing out of the battery at 186.5 A, 195.8 A, and 204.1 A. Increased internal resistance might explain this. As the temperatures got lower, a larger current was needed to get the engine to turn over. Interestingly, the voltage drop of the battery during this time was less at the lowest test temperature at 8 V than the nearly 10 V drop at both 15°C and 0°C.

Table 4 shows the alternator results. The voltage and current for the alternator followed similar patterns as the battery since it is part of the same electrical system. As the temperature decreased, the voltage and current output also decreased. However, subtracting the draw of the battery from the alternator current shows that the rest of the vehicle load increases as the temperature decreases. While no optional components were turned on during testing, the trend indicates that as temperatures decrease, the current draw by the basic system increases by half an amp, from 3.1 A to 3.6 A, between 15°C and −15°C. While this increase is not that significant when compared to the relatively large amount of current the alternator is able to provide to the system, if the electrical system was maxed out with other equipment turned on, the small change in current draw among multiple components could impact the overall ability of the system to run effectively.

Table 4. HMMWV alternator results summary with the standard deviation in parentheses.

Temperature (°C)	Voltage (V)	Current (A)	Alternator—Battery Current (A)
15	31.8 (0.6)	6.8 (0.8)	3.1
0	30.3 (0.6)	4.9 (0.2)	3.3
−15	29.6 (0.2)	4.6 (0.2)	3.6

4.2 MRZR results

Like the HMMWV, the MRZR was also able to start on the first attempt every time at all three temperatures. The current going into the battery after 10 minutes decreased as temperatures fell, shown in Table 5. The values of the current were 3.05 A, 0.85 A, and 0.32 A at 15°C, 0°C, and −15°C, respectively. This follows the same pattern as the HMMWV battery, that as the temperatures drop, the capacity of the battery is less, and it will not charge as quickly as in higher temperatures. Unlike the HMMWV, the current draw by the starter did not show a trend. However, the voltage drop increased as temperatures decreased. This could be a result of a couple things. The low temperatures are resulting in more power being drawn from the battery. The difference between the average initial charge capacity at the start of each test for the different temperatures could also have affected the difference in the voltage drop. As testing progressed, our charging methods improved to better ensure the batteries were fully charged before testing. A low-amp smart charger was not available during testing, which is required for the MRZR batteries. We used a simple low-amp charger but were concerned that the batteries would be overcharged if left unattended, resulting in damage to the batteries.

Table 5. MRZR battery results summary with the standard deviation in parentheses.

	Average Battery Voltage (V)			Average Battery Current (A)	
Temperature (°C)	Before Start	After 10 Minutes	Voltage Drop (Starter)	Current Draw (Starter)	After 10 Minutes
15	10.5 (0.1)	12.8 (0.06)	4.8 (0.5)	−108.6 (9.1)	3.1 (0.7)
0	11.0 (0.1)	13.4 (0.04)	5.0 (0.3)	−105.7 (6.9)	0.8 (0.2)
−15	11.5 (0.04)	13.9 (0.01)	6.0 (0.1)	−110.6 (0.1)	0.3 (0.05)

Like the HMMWV, the MRZR alternator voltage and current followed similar trends when compared to the battery in all categories (Table 6). The voltage increased and the current decreased as the temperatures lowered. Also, similar to the HMMWV, when the battery load was removed from the total draw from the alternator, the load of the other components that were necessary to run the vehicle trended upward as temperature decreased, though the difference was very small. Between 15°C and −15°C, the current changed by only 0.3 A. Like the HMMWV, this increase is not that significant when compared to the relatively large amount of current the alternator is able to provide to the system. However, if the electrical system was maxed out with other equipment turned on, the small change in current draw among multiple components could impact the overall ability of the system to run effectively.

Table 6. MRZR alternator results summary with the standard deviation in parentheses.

Temperature (°C)	Voltage (V)	Current (A)	Alternator—Battery Current (A)
15	12.9 (0.05)	8.0 (0.7)	4.9
0	13.5 (0.04)	5.8 (0.2)	5.0
−15	13.9 (0.02)	5.5 (0.04)	5.2

4.3 HEMTT results

The HEMTT was not able to turn over consistently at or below freezing temperatures. The first two attempts to start the HEMTT at 0°C were successful, but all tests after that were not. At −15°C, there was no success in starting the HEMTT, so we could not conduct further analyses. We identified after testing that the starter was significantly damaged. Additionally, despite the team’s being assured before testing that all fluids were correct, the vehicle had either incorrect or very old oil, forcing the vehicle to work harder than normal to start. As a result, we did not conduct further analysis for the HEMTT.

5 Lessons Learned and Next Steps

The purpose of this study was to develop for select vehicles used by the military a baseline for better awareness of what happens to vehicle electrical systems as the temperature decreases. It is important that vehicles used by the military are able to operate reliably in all conditions. As indicated in TOP 02-4-002A (US Army Cold Regions Test Center 2015), it is a requirement that all vehicles should reliably turn over at temperatures as low as −32°C. That the HMMWV and MRZR were able to start and continue to function down to −15°C with minimal change to the electrical load was a positive result.

The tested HEMTT was not able to meet the unassisted start requirement at the lower temperatures tested. Unfortunately, we cannot determine if low temperatures were the cause of the HEMTT’s poor performance or if it was a result of a preexisting mechanical issue. Required maintenance a few months after testing revealed that the starter needed to be completely rebuilt. The maintenance found that the internal working parts of the starter, mainly the teeth of the pinion, were so damaged they could not turn over the engine well and would cause the batteries to drain while trying. This would help explain why the vehicle did not start in temperatures at or below freezing. A damaged starter pinion would have trouble engaging with the engine and result in a reduced ability to turn over the engine.

Before testing began, the operators of the machine indicated that the oil in the HEMTT was good and followed technical-manual guidance. The routine maintenance conducted after testing found that the oil in the HEMTT at the time of testing was too thick for the vehicle and did not follow the technical-manual guidance. This would create greater resistance at lower temperatures. Combined with the faulty starter, it is understandable that the vehicle did not start. It is most likely that the data for the HEMTT is not reliable and that the baseline for this vehicle would need to be reevaluated now that the HEMTT has been refurbished and the fluids swapped for 10W-40 oil, which has a cold cranking temperature of −25°C and a low pumping temperature of −30°C (SAE International 2021).

Because of unexpected delays in the project schedule and challenges with scheduling vehicle service, we tested the vehicles based on the rating of their existing fluids.* After looking at the specifications of the oils that were in the HMMWV and MRZR at the time of testing, all were rated to at least −20°C. It is possible that if we used oils rated for lower temperatures, the HEMTT's and HMMWV's ability to start could have improved. The MRZR uses lighter oil and is already rated to start at even lower temperatures.

Future testing should address the following:

1. Run more-complete vehicle diagnostics and vehicle service before testing.
2. Improve engine and exhaust temperature reading locations and increase the number of thermocouples to include oil pan temperature.
3. Use two data acquisition systems:
   a. One that runs at a higher rate to capture the vehicle-starting process in higher detail
   b. Another that runs at a slower rate for the remainder of the test to reduce the amount of unnecessary data collected
4. For consistent results, use the proper charger for each type of battery, and use a battery tester before each test to ensure that the batteries are fully charged before testing.
5. Develop better brackets to hold the tachometers to limit damage to the sensors. On two occasions, vibrations moved the sensor against the rotating parts, resulting in broken sensors.
6. Activate onboard equipment to see how turning on different electrical loads (e.g., headlights, heaters, and auxiliary system) impacts the power draw from the alternator at different temperatures.

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* The schedule for this project was delayed for several months due to the COVID-19 pandemic, which limited access both to the vehicles and to vehicle services.

6 Conclusion

Low temperatures affect vehicle performance in many ways. It increases mechanical resistivity, decreases battery performance, and makes starting diesel engines more difficult. This study attempted to examine the electrical system of multiple military vehicles and to determine how low temperatures affected some of the components and their interaction with the electrical system as a whole. By monitoring the alternator and batteries of the HMMWV and MRZR, we were able to identify a slight increase in the current draw by the vehicle load on the alternator. Other observations included a greater current draw on the battery by the starter as temperatures decreased, which points to the increase in internal resistivity at lower temperatures for both vehicles.

While the increased load for both vehicles was very small, it is important to verify that the electrical system will function as needed in cold environments. As more systems that need power are added and activated on vehicles, it is important for the Army to understand the impact the cold will have on the electrical load and to design vehicles that are resilient and reliable at all temperatures.

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Acronyms and Abbreviations

ABS	Antilock Braking System
AC	Alternating Current
AGM	Absorbed Glass Mat
CRREL	Cold Regions Research and Engineering Laboratory
DC	Direct Current
ERDC	US Army Engineer Research and Development Center
HMETT	Heavy Expanded Mobility Tactical Truck
HMMWV	High Mobility Multipurpose Wheeled Vehicle
MEF	Material Evaluation Facility
TOP	Test Operating Procedures

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14. ABSTRACT

Low temperatures can significantly affect vehicle operation. While many of the effects, like increased fluid viscosity and decreased battery capacity, are well documented, the impacts on the electrical system as a whole are not. The objective of this study was to investigate the impacts of temperature on the electrical systems of select military vehicles and to develop a baseline for future testing. A High Mobility Multipurpose Wheeled Vehicle (HMMWV), a Heavy Expanded Mobility Tactical Truck (HEMTT), and a four-person diesel Polaris MRZR D4 were subjected to 15°C, 0°C, and −15°C temperatures while the loads on the battery and alternator were monitored. The HMMWV and MRZR were able to start on the first try for all tests. They both showed a slight increase in vehicle load current draw from the alternator as temperatures decreased. Future testing with more iterations and at lower temperatures will help identify clearer trends and improve testing procedures. As the Army becomes more reliant on electronic systems, it is becoming increasingly important that we understand how various climates will impact them.

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