To: Dr. Robert Severinghaus
From: The eBaja Team
Date: April 29, 2022
Subject: Final Project Presentation

Project Overview:
The following report outlines testing results from the eBaja capstone team. The team is tasked with implementing an electrical system and motor to drive the SAE Baja buggy. This system includes an 80V battery comprising 10 Nissan Leaf battery packs which are monitored by Battery Management System (BMS). From the battery, a motor controller is powered, which has an ignition switch, a “transmission” switch, and a throttle lever to control the direction and speed of the motor. From the main power line to the motor controller, a step-down converter is used to power the auxiliary system comprising the various lights on the buggy. For references on system design or diagrams, please refer to the appendices section of this report.

Executive Summary:
To determine the abilities of the battery and system, testing must be done on all the various components of the electric. In the following report, four tests have been outlined, two matrix tests, one step-by-step test, and a systems integration test. The two matrix tests took the team upwards of 10 hours to complete as we were conducting multiple longevity tests which required the battery to be recharged after each test. The step-by-step test took the team about an hour due to the immediate success and low power draw from the battery. The eBaja team was unable to complete the systems integration test due to a setback with the vehicle frame and the ME team. This will be further explained in the report; These tests were generally successful and gave the team insight into how the system behaves, however, the second matrix test designed to uphold the battery’s continuous C rating failed.

Introduction to System:

The eBaja team wanted to provide our client, Dr. Venkata Yaramasu, with an electric powered Baja vehicle capable of competing in an off-road competition while maintaining all industry-wide safety standards. Dr. Venkata Yaramasu is a professor at Northern Arizona University and specializes in electric drive technologies and power electronics. Currently, Dr. Yaramasu is involved with the Salt River Project to analyze the impact of zero net energy homes in Arizona and the development of charging stations for electric vehicles. He teaches various subjects here at NAU such as wind turbine technologies and electric vehicles.

This year, our capstone design team has been tasked with continuing the work started in 2019 to finish the construction of an electric off-road racing prototype buggy. This buggy will eventually be used in future SAE Baja Competitions, but for this project the team simply needs a working prototype to prove the concept. By the end of the project, the eBaja team plans to have the buggy withstand rough terrain while maintaining safety standards.

The design of the electric buggy consists of a 78V battery that is the main power source for the vehicle. This battery pack is a sealed pack of 10 Generation 2 Nissan Leaf battery packs each rated for a charge of 7.8V, which is balanced by a Lithium Battery Management System (BMS). This system monitors each cell of the pack and balances voltages so cells don't get overcharged or undercharged during operation. This pack powers not only the motor controller, but the Auxiliary System as well, which is composed of the headlights, taillights, and turn signals. However, since all of the auxiliary devices are 12V, a DC-DC Step Down Converter is used to step the 78V down to 12V. Continuing with the controller, it takes the 78V and converts it to AC to power the Permanent Magnet Synchronous Motor (PMSM). The speed of the motor is controlled by a throttle lever and the rotation direction is controlled by a "transmission" switch, which has modes for forward, neutral, and reverse. As for sensors, there is a state-of-charge sensor that will tell the driver the voltage of the battery and the current leaving the battery during operation. There is also a display that lets the driver know the rpms of the motor at any given time. This comprises the electrical system of the eBaja buggy and will be installed when the vehicle is ready for mounting. This document explains the tests used to verify the behaviors of our electrical system and the success and failures of each one.

System Architecture:

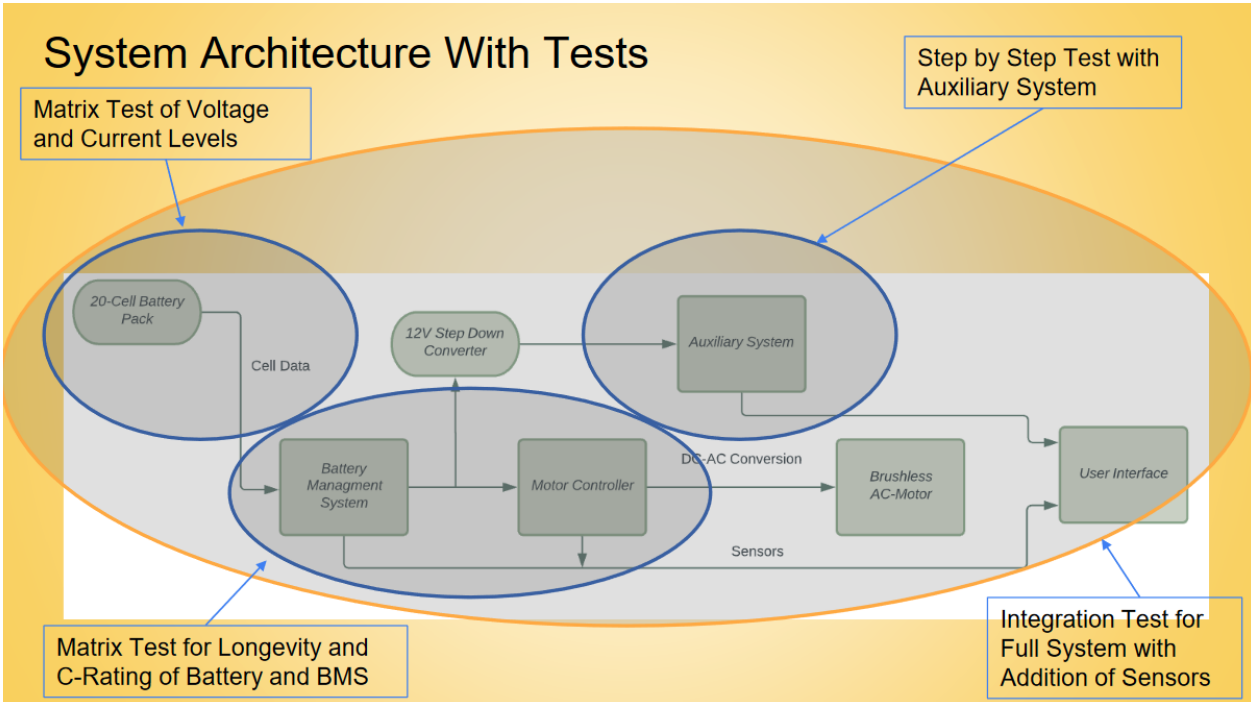


Figure 1: System Architecture and Areas Tested

The above image describes the overall architecture of the eBaja project and the following tests the team conducted. At the first stage of our system, there is a 20-cell battery pack that is the main power supply for our vehicle. The team tested the voltage and current levels under a fixed load to verify the vehicles operability. Cell data then gets sent to the battery management system (BMS) where the user can visualize how each cell is performing. The BMS then communicates with the motor controller before converting DC to AC to power the Permanent Magnet Synchronous Motor (PMSM). The team utilized a 12V step down converter to power our auxiliary system which contained multiple switches in the user interface. The team implemented multiple sensors to monitor the batteries state of charge, voltage, current, and rpms.

Requirements:

Type of Tes	Status	Req #	Requirement
		1	**Battery**
UTM		1.1	The battery will power the buggy system for at least 20 minutes at 50% throttle
UTS		1.2	A second identical battery will be constructed for ease of battery switching during the competition
UTS		1.3	Both batteries will have plug attachments to the system for quick plugging and unplugging from the vehicle.
Inspect		1.4	Battery management system for cell safety and voltage regulation.
UTM		1.5	Batteries current will not exceed 130A per battery specifications
UTM		1.6	Load test to verify batteries current state
UTM		1.7	Battery will be rated to run at 65A for 1 hour
		2	**System**
		2.1	Auxiliary
UTS		2.1.1	Tail lights will be present for safety
UTS		2.1.2	Headlights will be present
UTS		2.1.3	Turn signals will be present
Inspect		2.1.4	Auxiliary lights will be supplied by 12V via DC-DC step converter
UTS		2.1.5	High/Low beam lights will be present
		2.2	**Kill switches**
Integration		2.2.1	Switch inside the cabin for the driver to reach in case of emergency.
Integration		2.2.2.	Identical switch outside the cabin for bystanders in case of driver incapacitation.
UTM		2.2.3	Both switches will be rated for 80V
		3	**Safety**
Integration		3.2	Battery terminals and conductive components will be insulated.
Integration		3.3	Electronic mounts and straps to ensure components are stable during a crash
Integration		3.3.1	Components will have no disconnections when experiencing rough terrain
Inspect		3.4	Safe placement of electrical components behind the chassis
Inspect		3.5	Motor controller will contain a heat sink (thermal fins) for temperature control
Integration		3.6	Buggy will have a horn for alerting bystanders and other objects/vehicles
		4	**Performance**
Integration		4.1	The buggy will complete one loop in the parking lot
Inspect		4.2	The buggy will produce less noise than a gas engine.
			Sensors
Integration		5	Speedometer in MPH
Integration		5.1	Must be accurate within +/- 3 MPH
Integration		5.1.1	Battery State of Charge Indicator
Inspect		5.2	Must be accurate within +/- 0.1 V

Figure 2: Project Requirements Tested

Important Requirements:

1.1 - The Battery will power the buggy system for at least 20 minutes at 50% throttle.

If the battery is not able to power the buggy for the prescribed duration and strength it will not be a good power source for the competition. If the battery dies in less than 20 minutes this makes competing difficult as the buggy may lose power in the middle of the race or frequent pit stops may be required to replace the battery with a spare.

1.6 - Load Test to verify batteries' current state.

Load Test is needed to determine the battery's strength and its limits, which the vehicle must not attempt to exceed. Attempting to exceed the battery's limits would cause damage and compromise the project.

2.14 - Auxiliary lights will be supplied by 12V via DC-DC Step converter.

The Auxiliary lights are necessary for safe night driving. Dr. Yaramasu wishes for the buggy to be street legal. This requires headlights, taillights, and turn signals to be properly supplied and functional in order to be able to drive the buggy at any time of the day. The wiring diagram schematic can be found in Appendix A.

2.2.1 - Switch inside the cabin for the driver to reach in case of emergency.

The kill switch is necessary for safety. If something goes wrong with the ignition switch the motor controller is unable to be switched off, there must be a way for the driver to cut power from the battery. Without this requirement being met, the buggy could be very unsafe to operate if something were to go wrong.

4.1 - The buggy will complete one loop in the parking lot.

The ultimate litmus test of project success - if the vehicle is unable to move then it does not work. This requirement is most important to the client because it is imperative the team shows a functional vehicle.

Types of Tests:

Matrix Test:

Matrix Tests are testing specific modules of the system or process with the same type of input and only differ in the value. In order to extrapolate data, this type of test is used to test all possible input values. The team utilized this test in the longevity and max current/voltage levels of our battery under a fixed load.

Step by Step Test:

A Step by Step test is a checklist that lists the instructions for the test and gathering results. These tests change the specific inputs to view system behavior and compare against expected results. The team utilized this type of test for the Auxiliary system which operates on a flowchart model.

Integration Test:

The Integration Test examines how multiple subsystems work with one another and tests system operability. The team planned to utilize this test during the off-road integration where the team will monitor system functionality and the stability of components. Unfortunately, due to time constraints on the mechanical team's end of the project, the buggy is currently not ready for parts mounting. The systems integration test was to be done on the buggy to test requirements 2.2.1 and 4.1. We were unable to meet these requirements due to the fact the team could not conduct this test.

Inspection Test:

Inspection Test is a pass-or-fail test for testing components and if they meet the client/safety standards. This type of test can be completed by simple observation of the components or vehicle. The team utilized this test only for Longevity testing because there is only one input required.

Major Tests:

Load Test for Current Levels: Unit Test Matrix

The first load test was done to determine the behavior of the battery through different throttle positions. Using the setup shown in Appendix B, the electric motor was used to rotate the shaft of a generator that acted as a simulated load for the system. The output of the generator was attached to a series of power resistors to dissipate the energy created, and a multimeter was attached to the series of resistors to monitor the output voltage of the generator. This output voltage was used as a reference point to determine approximate throttle positions for the motor controller, 100V representing a small throttle displacement and 500V representing the full displacement of the throttle lever. The test started with displacing the throttle lever until the multimeter read 100V across the output of the generator. The throttle was kept in this position for 2 minutes of run time and the current was then recorded. When the 2 minutes were over, the throttle was released and the system shut off to let the battery rest for 5 minutes. Then the process was repeated, but the throttle lever was displaced until the multimeter read 200V. This was done for every 100V until 500V was reached and ran for 2 minutes. At the end of the test, a record of 128 Amps were coming out of the battery during the 500V leg of the test as seen in Figure 3.

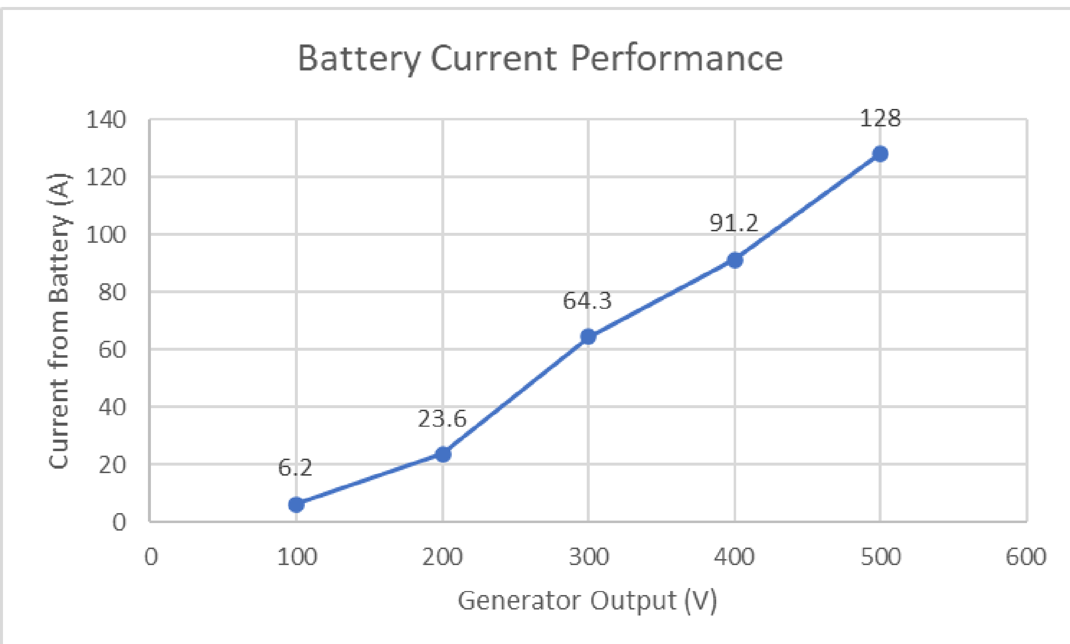


Figure 3: Current Test Results

Longevity Test: Unit Test Matrix

The longevity test was conducted to determine how long the battery life could last. This was an inspection test recommended by Dr. Yaramasu in which the system was run continuously to stress test the battery. Using the system-generator setup as seen in Appendix B, the motor was powered to provide torque to the generator which acted as a simulated load exactly how it acted in the load test previously. Using the generator's output as a reference point, the system would be run for 10 minutes starting at 400V on the generator's output. After the 10 minutes elapsed, the throttle would be released slightly until the output of the generator was reduced to 300V. This would be repeated with a reduction on the output by 100V until a final output of 100V was reached and held for 10 minutes. The test was planned to have been completed after 40 minutes as shown in Figure 4 .

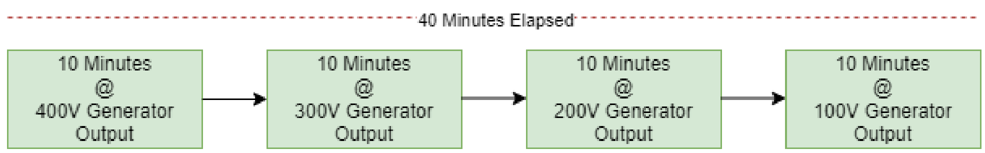


Figure 4: Longevity Test Process

During the test, the system was able to sustain 10 minutes at near full throttle. The starting voltage of the battery was 80.3V, but dropped rapidly to 65.4V by the end of the 10 minutes. This was a near 15V reduction in the battery and during the test the current coming out of it sat above 90 Amps consistently. When the throttle was released to lower the output voltage of the generator to 300V, the voltage of the battery jumped back up to 69.5V and slowly reduced to 62V. At about 6 minutes in, a certain beeping sound could be heard from the BMS on the battery and 1 minute later at 17 minutes and 36 seconds into the test, the entire system shut off. This test behavior is illustrated in Figure 5.

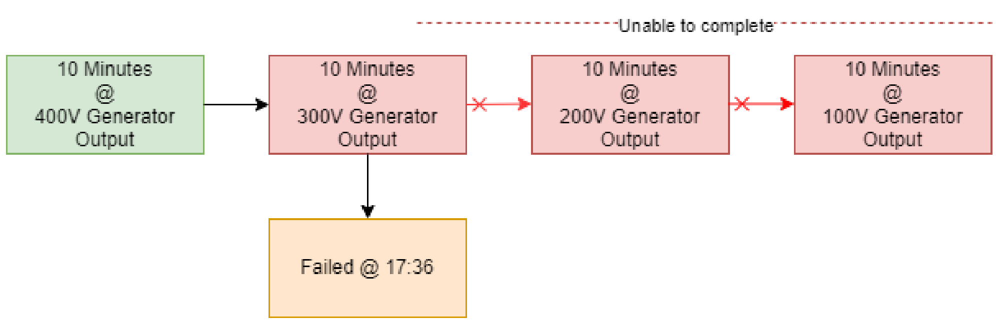


Figure 5: Longevity Test Results

Auxiliary Test: Unit Test Step by Step:

The Auxiliary Test is a step-by-step test that lists the instructions for the tests and explains what results are expected and acceptable. For the auxiliary system test, each state of the circuit and each input combination must be tested to ensure continuity of service. The process of this test is illustrated in a flowchart represented by Figure 6.

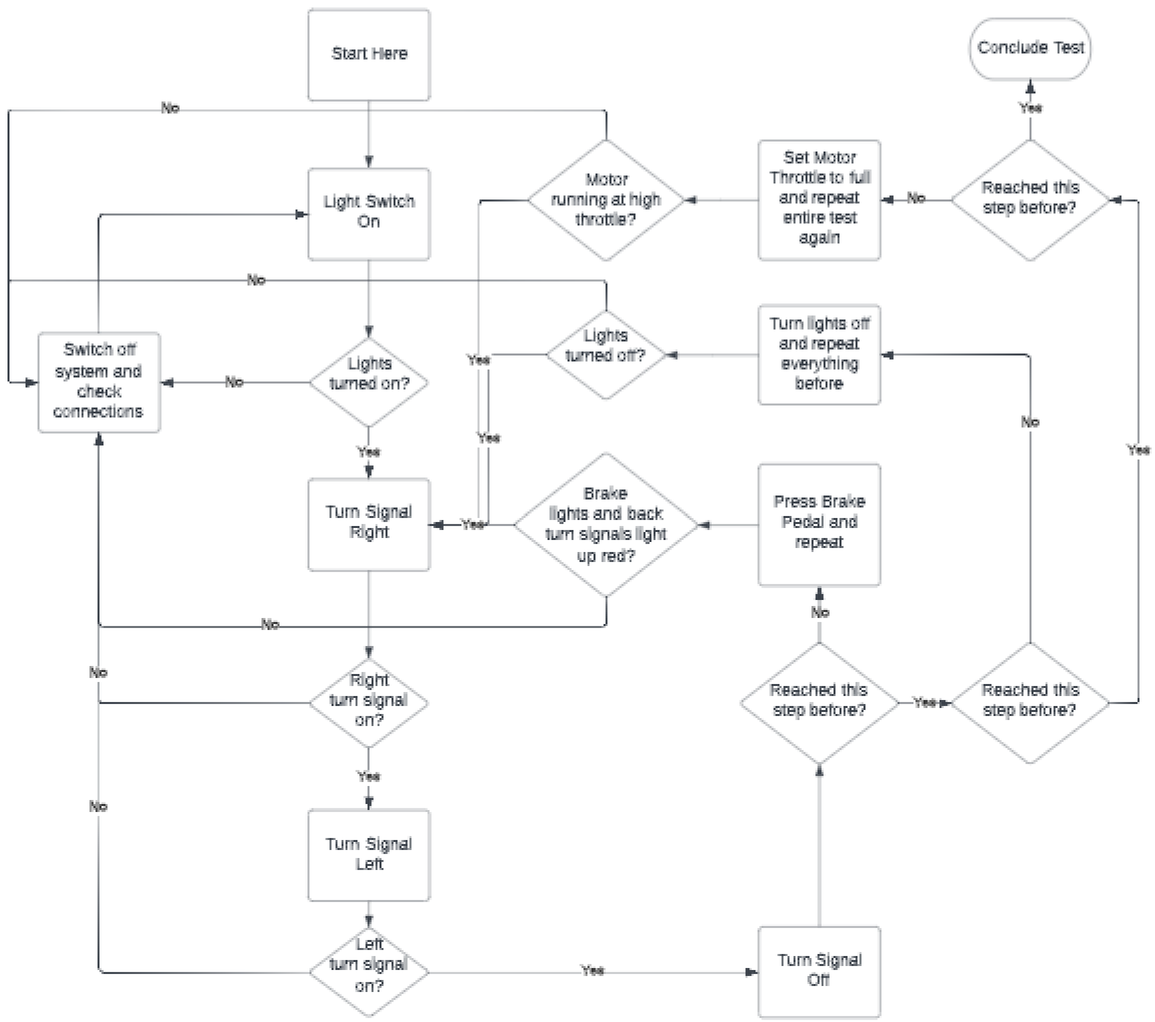


Figure 6: Auxiliary System Step-by-Step Test

Analysis of Results:

Load Test for Current/Voltage Levels Results: The results from this test were collected from a third run of the test. The system on the first attempt of the test instantly dropped 20V from 80V to 60V. This was happening on low throttle displacements, so the team assumed this problem had to do with the battery's connections rather than something to do with the controller. After readjusting the connections, the BMS was reading 80V again, so the team attempted the test again. However, in the second attempt the motor controller was throwing an overcharge voltage error. It was suspected that the regenerative braking was pushing the battery voltage too high and thus the controller shut itself off. However, the team could not determine the actual source of this issue and it resolved itself on the third attempt. As for the final results of the test, it was surprising seeing the amps reach so high. The battery is rated at a max continuous amperage of 130 A, and to see it reach 128 at full throttle is concerning. Despite the above than expected amperage of the battery, this test did satisfy requirement 1.6 and gave the team insight into the behavior of the battery under a load.

Longevity Test Results: The Longevity Test results were disappointing to the project. The team expected the battery to at least supply the system for 20 minutes, however the fact that the battery dropped so low in voltage in under 20 minutes shows that this battery either may be aged so much it cannot sustain the system long enough to be appropriate for an eventual competition application, or the motor controller demands too much energy from the battery. Unfortunately, this means that requirement 1.1 has not been met as of now.

Auxiliary Test Results: The Auxiliary Test results were perfect; all states of the circuit were tried and successful. The lights were unaffected by the throttle or by each other's state. This was as we expected, as the lights do not draw a significant amount of power from the battery. By successful completion of this test, we are able to fulfill requirement 2.1.4, which is that auxiliary lights will be supplied by 12V via DC-DC Step converter. The Auxiliary System wiring diagram can be found on Appendix A.

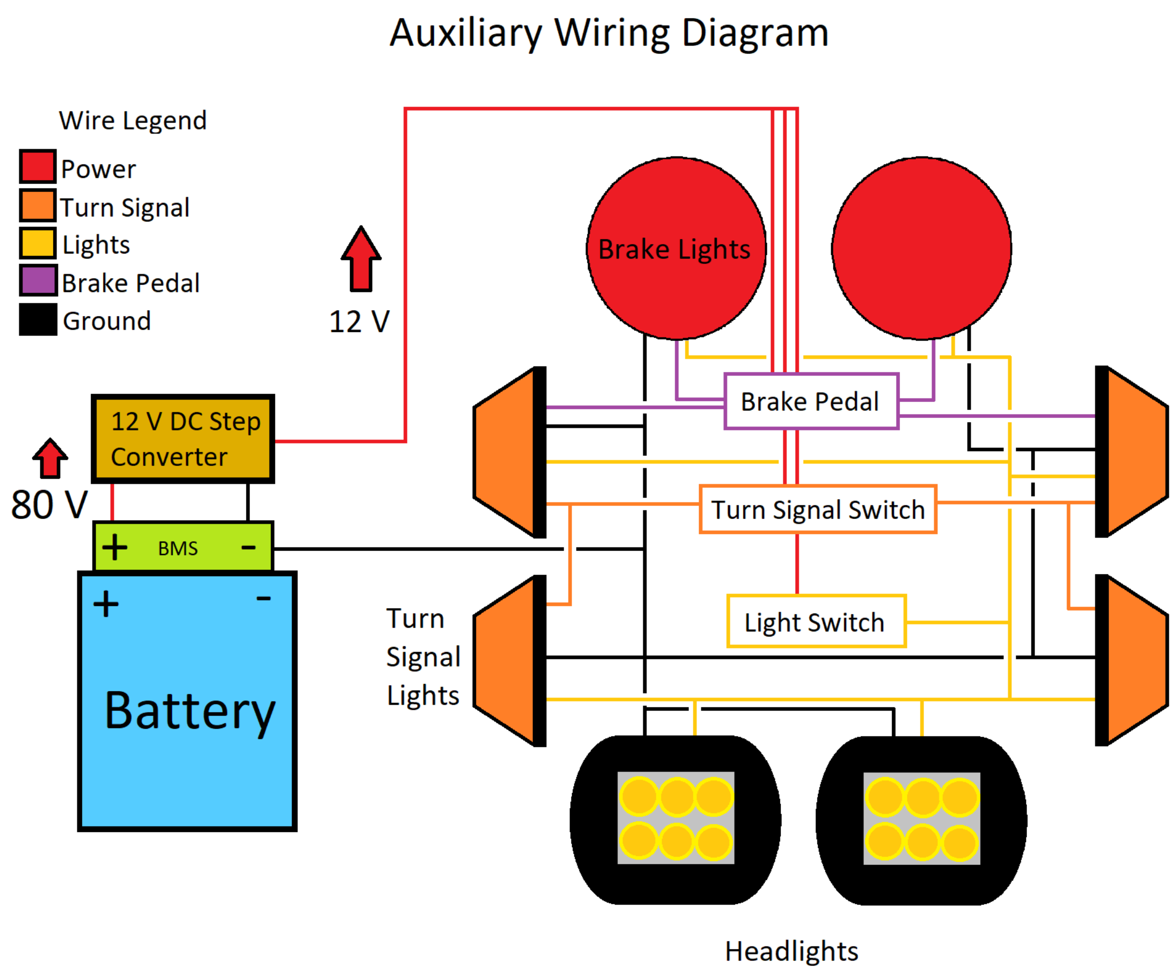
Lessons Learned:

Through the failures and the successes of testing our systems, building and assembling apparatuses, and regressions after modifications and changes, many lessons were revealed along the way. These lessons were learned shortly after problems emerged during testing different systems and identifying solutions. Some of the problems during testing included arbitrary motor controller failures such as overvoltage and undervoltage error messages. The BMS installed on the battery unit has trouble balancing cells during large discharges and continuously causes problems while charging and discharging. The battery unit has problems with large discharging with large voltage drops where the battery could go from 85% to 0% apparent state of charge.

Another test revealed that the battery's declared 1C rating of 65Ah is not accurate. The battery has clear degradation being around 12 years old. Additionally, the motor test caused significant centrifugal force that ended with dislodging the coupler. The generator load test had problems with stability while running and the coupler was moving with continuous rotations. This was resolved by adding extra L-brackets to the wooden structure holding the motor in place. Different Alan wrenches were used to secure the coupler tightly to the shafts of the motor and generator which prevented coupler movement during rotations.Problems with the Curtis motor controller were resolved by reconnecting all the battery management system wires to the terminals of all the cells/modules. Crimping new lugs onto multiple wires coming from the BMS made new and secure contacts to terminals. This eliminated the arbitrary motor controller error codes that would shut off the system while using.

An important lesson learned from this project was the usage of a previous battery management system integrated into the battery. This BMS is not programmable or traceable to a meaningful sheet of information. Outside of the degradation the battery received over time, the BMS has trouble charging and discharging the battery and keeping cells equalized. This should have been removed and replaced from the start with a more robust and competent management system that would allow programming and cell balancing without issues. A great adjustment made came from noticing the batteries maximum discharge limit of 130A during the 500V generator output test. The controller is designed to pull around 150A continuously which is well above this threshold for the battery. To resolve this issue identified through testing, the throttle will be mechanically restricted to have a 50% free range of motion. This prevents the current from exceeding 100A continuous.

Appendix A: Auxiliary Wiring Diagram - The Auxiliary Wiring Diagram illustrates how power is supplied to the auxiliary lights from the battery, using the BMS and the 12V DC Converter. The power is controlled by three inputs from the driver of the vehicle to the lights system and operates as a regular vehicle's.



Appendix B: Load Test Setup - Appendix B is an image of the load testing platform constructed by the eBaja team. It couples the electric motor to a generator in order to simulate a load on the motor. This is necessary as operating the motor without this load provides little insight into how the battery would operate on the buggy itself. Since the generator produces energy, that energy needs to be safely dissipated across the green power resistors in series.