Thermal & Efficiency Analysis for a High-Speed Gearbox

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Thermal and Efficiency Analysis for a High-Speed Gearbox

Austin Owen, Noah Schultz, and Reid Larson

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Industry Mentor: CAViDS Executive Director John Bair

Industry Sponsor: WMU CAViDS

Group: 4-22-14

Submitted: April 19th, 2022
1: Abstract

The aim of this project was to design and build a test stand to validate a thermal model of a high-speed gearbox developed by Western Michigan University’s (WMU) Center for Advanced Vehicle Design and Simulation (CAViDS) consortium. At the completion of this project, the experimental results measured from tests will be compared to those from a Siemens Amesim model of the same gearbox. For these tests, an electric inverter/motor/gearbox package was connected to an intermediate transmission for the purpose of output speed matching to an electric dynamometer. This dynamometer applied a load to the motor/gearbox to replicate its designed running conditions. To develop the test stand, mounting plates and rotating connections for the motor and gearbox were custom designed, evaluated with finite element analysis (FEA), and fabricated; cooling systems were designed and constructed to maintain and monitor the temperature in each system component; and electric motor/inverter speed controls were procured and adapted for this specific application. To measure the system’s input power and thermal output, a combination of digital and analog tools were used. The data signals were connected to LabVIEW for data acquisition.
## 2: Acknowledgement

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3: Disclaimer

This project report was written by students at Western Michigan University to fulfill an engineering curriculum requirement. Western Michigan University makes no representation that the material contained in this report is error-free or complete in all respects. Persons or organizations who choose to use this material do so at their own risk.
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6: Introduction

Background

Western Michigan University’s Center for Advanced Vehicle Design and Simulation (CAViDS) is a research center which, through a partnership between students, faculty, and industry leaders, develops solutions that lead to technological advancements, while providing hands-on learning experiences for WMU students. The CAViDS center receives investments from the government, various foundations, and industry partners to research new technologies. The center has opportunities for multiple disciplinary engineering problems. The project at hand was advised by CAViDS Director Dr. Claudia Fajardo-Hansford and CAViDS Executive Director Mr. John Bair. Through the aid of faculty and industry mentors, the efficiency and cooling requirements of a high-speed gearbox for an electric vehicle (EV) were to be evaluated against a simulation software developed through a previous undergraduate research project at WMU.

For the purpose of the senior design project, this team was assigned the first phase of this thermal study, which focused on designing and setting up the test stand to be used for experimental validation of the thermal model.

Problems Posed and Need

The technical problem investigated in this project was the thermal characteristics of a high-speed gearbox, specifically designed for a medium-duty vehicle application. Electric motors are already becoming mainstream in the consumer vehicle market, with many cars and some sport utility vehicles (SUVs) utilizing one or more of these motors and gearboxes. However, as the technology progresses, and other segments may become electrified (i.e., the medium-duty
market), the need for more robust solutions will increase. To ensure these powertrains are
designed to withstand the increase in required load commonly affiliated with medium-duty
applications and to be provided with adequate cooling, experiments such as those defined in this
project are required. This not only helps further the technology in the industry, but also ensures
that it has the reliability expected for its users at minimum cost. It can also support the
development of more challenging applications such as the heavy-duty market. WMU’s CAViDS
research laboratory does not currently possess the physical environment to conduct these
validation tests. Therefore, this team of students designed and implemented a test system to
enable experimental validation.

**Objective of Work**

The objective of this project was to develop and implement a physical test system to
measure the thermal properties of a high-speed motor/gearbox unit. Upon the completion of the
validation testing, the experimental data can be compared to simulation results to verify the
accuracy of the *Siemens’ Amesim* model. Once validated, the model may be used to predict the
cooling requirements of the gearbox with minimum additional laboratory testing, which reduces
the overall project cost. The validation of thermal characteristics and efficiency of the test
gearbox will be completed through the use of thermocouples to record temperatures in multiple
places on the system, transducers to record the output speed and torque from the intermediate
transmission, and a dynamometer to apply a load to the input motor and test gearbox. Custom
fixtures will be designed and fabricated to mount the system on an existing test bedplate in the
CAViDS Hybrid Electric Applied Research (CHEAR) laboratory. Flexible couplers will be
specified to connect components, and Finite Element Analysis (FEA) was used to evaluate each
custom-designed component. Finally, the solid models developed for the FEAs were used to manufacture components necessary to complete the test stand.

Major engineering tasks were to design and fabricate pedestal mounts for the motor/gearbox, design cooling systems for both the gearbox and also the electric motor, inverter, and auxiliary transmission systems, and configure the supplied electric motor and inverter to operate with power supplied by a battery simulator in the CHEAR laboratory. One of the major challenges in this project was physical size limitations of the CHEAR laboratory test bedplate. The existing test bed was fabricated and machined to have a flat top mounting surface. This ensures that when components are attached to the bed, their axes of rotation remain parallel to the test bedplate. Fitting the supplied electric motor, test gearbox, intermediate transmission, torque transducer, and dynamometer onto the CHEAR Laboratory test bedplate while maintaining axial alignment of components in a constricted space was critical. It was necessary that each part’s centerline was concentric with the others to ensure smooth and safe operation of the system during testing and prevent excessive vibration and failure of components, especially at high rotational speeds. Provided more time and resources, the test bedplate should have been replaced with a much larger one to accommodate all components. This is proposed as a long-term project in section #16: Next Steps. The idea was also proposed to the CAViDS executive members. Another critical component to the project was identifying and choosing the intermediate transmission. It was necessary that this transmission matched the output speed and torque of the gearbox being studied to the input speed requirements of the dynamometer. Next, two separate cooling systems were designed to dissipate the heat generated during testing. The first cooling system was used to cool the gearbox connected to the output of the electric motor and measure the gearbox heat generated to validate the Siemens Amesim model. The second
cooling system transfers heat away from the electric motor, its inverter, and the auxiliary transmission used to match the torque-speed curve of the dynamometer. Finally, all the mounting fixtures, torque cell, and connecting shafts were designed, fabricated, and procured to connect and hold the transmissions and motor.

**Definition of Problem**

As EVs become more mainstream and extend into other segments of the motor vehicle industry, the drivetrain components will need to minimize and dissipate the heat generated by the significant gear reduction (i.e., higher speeds) and torque multiplication associated with them. The gearbox thermal simulation model previously developed at WMU needs to be validated experimentally, so that it can be used as a design tool to reduce future physical experimental testing of EV gearboxes. More research and development are needed to ensure that these systems will perform as designed, while maintaining the safety and reliability requirements.

**Scope and Limitation of Work**

This experiment focused on a single gearbox’s thermal characteristics. This gearbox used a supplied motor as an input and a medium duty transmission to match speed and torque output of the test gearbox to the dynamometer. This project will not investigate motors of different sizes, manufacturers, or specifications, and will not introduce modification and optimization of the components. This experimental setup will be further used for research and data collection of the motor and gearbox provided, and validation of the gearbox thermal model developed in *Amesim*.

**Specification and Requirements**

Requirements to consider this project successful include the following:
1. A test plan that defines the parameters and test conditions required to verify thermal data predicted in the previous project.

2. A test stand design that will produce the data specified by Deliverable 1.

3. A functional test stand that will produce the data specified by Deliverable 1.

4. Documentation of the test stand design and operation.
7: Goals and Objectives

Solution Ideas and Alternatives

The team was given the task of designing a test stand to produce data as specified at the outset, with the constraints of using as much existing hardware as possible and minimizing the total cost of the project with the time constraints of completing the work in one academic year.

Throughout the process of working on this project, the team developed multiple designs for the mounting hardware used to attach the test gearbox/motor system connecting to the existing laboratory dynamometer and torque transducer, designed multiple cooling systems, and developed an output shaft for the test gearbox.

In order to verify the Amesim model, the team used the high-speed test gearbox and electric motor/inverter in conjunction with an auxiliary transmission to align the torque curves of the gearbox to that of the CAViDS CHEAR laboratory dynamometer. Several transmissions were provided as an option to best match the two torque curves, and the team identified which intermediate transmission would best fit the application. As discussed in section #15: Results, since the preferred auxiliary transmission was unavailable, the team selected an acceptable alternative. This substitution provided an opportunity to conduct a study on the availability vs. performance.

A second area where multiple solutions and alternatives exist is the physical layout of the equipment in the CHEAR laboratory. An initial analysis found that all of the required test components could not fit on the existing length of the test stand bedplate. A study of trade-offs determined that extending the existing test stand was most effectively done by designing a
fixture for the motor/inverter/gearbox that overhung the end of the existing bedplate. This alternative component setup design saved $2,000 worth of material and machining costs.

**Methods (Theoretical, Experimental, and Combinations)**

There are three main components to this CAViDS project. The first is a computer simulation of the thermal performance of the gearbox. This portion of the project has been previously completed using the engineering modeling software package *Amesim*.

The next part of the project is to develop a test system to measure the actual thermal performance of the gearbox. This setup will enable conducting the desired tests in a controlled laboratory environment. The primary parameters that will be monitored to evaluate the thermal performance of the gearbox are input motor speed and torque, to define the input power to the gearbox, as well as oil inlet and outlet temperatures and flow rate to define the heat generated in the gearbox. Auxiliary parameters measured will be housing temperatures of the electric motor, the test gearbox, inverter, the intermediate transmission; inlet and outlet temperatures of the intermediate transmission, inverter, and electric motor, as well as temperature throughout the coolant side of each cooling system. To do this, a series of instruments will be used including thermocouples, flowmeters, torque sensors, and surface temperature thermocouples. Many of the sensors and motor controls will be connected to the laboratory computer through a data acquisition card. The data will be monitored and displayed through a LabVIEW interface.

The final stage of the project will be to verify the operation of the test stand and collect data to verify the simulated results.
**Project Plan/Schedule/Activities/Deliverables**

The general project plan is shown in the Gantt Chart displayed in the Appendices. This plan was followed and updated weekly to make sure the team maintained forward progress and completed all the project deliverables. The deliverables needed from this project are outlined in section #6: Specifications and Requirements of this report. Weekly meetings with the senior design team, the faculty mentor, and industrial mentor were set in place to monitor project status, discuss challenges and brainstorm on potential solutions to ensure the team completed the tasks.

**Benchmarking**

The main benchmark for the physical data collected is the *Amesim* computer model previously created. This gearbox could be compared to gearboxes of similar performance. In addition, the motor and inverter could be included in the thermal model. With additional resources and capital, this would be the next step in the development and testing of the powertrain; however, this is outside the scope of this project.

**Decision Matrix**

Within the group, decisions were made through a combination of teammate collaboration and recurring meetings with industry and faculty mentors. The purpose of these weekly meetings was to make sure that the decisions made fit the scope of the project, the budget allowed, and to determine what outside resources were needed to complete the task. When the senior design team was not in full agreement with one another, the industry and faculty mentors were called upon to help the team evaluate the problems and weigh in on challenging decisions. Frequent meetings and consultation from mentors ensure decisions were made in a timely fashion to keep on track with the schedule of the project. When one component of the project, which possessed multiple design choices, required in-depth analysis, the team opted to create a decision matrix.
based on parameters which were influential to guide the decision on which design would best fit the needs of this project. One example of this decision matrix was that of the gearbox output shaft design which can be found in section #10: Gearbox Design Considerations.
8: Facilities

Needs and Availabilities

This test system was developed in the WMU CAViDS CHEAR laboratory. The motor/inverter and test gearbox, dynamometer, test bed, battery simulator, transmission pedestal, torque cell, and laboratory computer were all obtained prior to the start of this senior design project. The components that were loaned to CAViDS from its industry partners, or from WMU, included the intermediate transmission, the correct oil for the intermediate transmission, some sensors, and materials for the cooling systems. Components which were purchased by CAViDS for this project can be found in section #18: Budget.

Figure 1. CAViDS CHEAR Lab Bedplate
Instrumentations and Equipment

The main equipment used in this project was the supplied electric motor and inverter, the test gearbox, the intermediate transmission, and a dynamometer. All these components were mounted to a flat steel bedplate. To collect the required data, assorted digital and analog measurement tools were used. These included, but were not limited to, thermocouples, speed and torque sensors, flowmeters, and surface probes. Most of the data will be collected electronically with computer interface (DAQ card) through National Instruments LabVIEW software. The basic LabVIEW interface was developed as part of this project and will be refined by the next student group.
9: Physical Bed Plate Setup

Test Bed

The steel bedplate in the CAViDS laboratory contains the major components to this project’s experimental setup. The bedplate holds the dynamometer, torque transducer, transmission, and motor/gearbox system. As shown in *Figure 2*, the motor, inverter, and gearbox are positioned off the end of the test bed with mounts and supports. The dynamometer, torque transducer, and transmission were all mounted with pedestals already found in the laboratory. The bedplate was made with large steel c-channel beams. The top mounting surface was then machined flat to ensure proper component alignment, and rubber isolators were placed on the bottom to support the bedplate and isolate any vibration. Additionally, the large concrete pad that the bedplate sits on was isolated from the rest of the foundation, to further reduce the effect of vibrations on the system.

*Figure 2. Test Facility Experimental Setup*
**Dynamometer Torque Speed Matching**

The first step in getting the system functional was matching the speeds and torques of the electric motor/gearbox and the dynamometer. Through analysis of documentation provided by the test gearbox manufacturer, the speed at the output of the gearbox was lower than the normal operating range of the dynamometer at 700 rpm and 3925 rpm respectively, and more critically the torque is higher than the dynamometer is capable of supporting at 3672 N-m and 763 N-m respectively. To decrease the torque and increase the speed, the intermediate transmission with its input and output reversed was utilized. The transmission selected delivers a lower ‘effective gearbox torque’ of 509 N-m at the dynamometer input at low rotational speeds, but still will overload the dynamometer at a speed of 4000 rpm (see Figure 3.) This is due to the reduced maximum supportable torque of the dynamometer as speed increases. This causes the test gearbox to be limited to a maximum speed of 5,994 rpm and applying the gear ratio of the test gearbox establishes the maximum speed the electric motor can be operated at, to ensure the dynamometer is not overloaded.

![Figure 3. Torque-Speed Characteristic of Dynamometer and Electric Motor](image-url)
**Gearbox Mounting Plate**

The motor/gearbox system was mounted cantilevered off the steel test bed with a custom mount supporting the motor and gearbox. This mount was designed as part of this project to support not only the weight of the motor and gearbox, but the large torque produced by the gear-reduction of the test gearbox as well. This mount also allows all the electrical connections for the parking brake assembly to be accessible, as well as the inlet and outlet oil flows from the gearbox to accommodate cooling and temperature monitoring of the gearbox oil. After several design revisions, a computer simulated Finite Element Analysis (FEA) was created to evaluate the design for operation of the gearbox without excessive stress or deflection in the mounting bracket.

To conduct the FEA, the bracket was set to the properties of A-36 steel. A section of the base was then marked off where the bedplate would interface with the bottom plate of the mount. This creates the support that fixes the plate to the test bed. Next, the motor and gearbox models were added in and mated to the gearbox mounting plate via the three mounting holes on the front of the gearbox. These connections are considered rigid, creating a force and reaction moment on the plate. Finally, all the attachment points were specified using bolt connections. These allowed the required ‘flex’ in the bolts to be modeled, as well as correct forces on the plate. A torque of 10,000 Nm was applied to the output shaft of the gearbox, along with a bearing load to support the structure, and the overall combined weight of the electric motor and gearbox of 180 pounds was applied. This torque was selected to incorporate a factor of safety of at least twice the 3672 N-m maximum torque produced from the gearbox to ensure the gearbox mounting plate would not be susceptible to yielding and unnecessary deflection. The gearbox mounting plate should
have a minimum deflection since this would introduce unwanted motion between the gearbox output and in the input of the intermediate transmission.

Results from the FEA simulation are shown in Figure 5. The bracket was found to support the required weight and torques necessary with an average stress of 85 MPa compared to the yield stress of the selected A36 steel which is 250 MPa [27]. Figure 5 does indicate stresses higher than 85 MPa, but this is due to the bolt attachment setup of the SolidWorks Finite Element Analysis (FEA). The team input a torque specification of the mounting bolts to connect the mounting plate to the test bed at 130 N-m, causing high peak stresses in the simulation. The team was therefore confident that the results of the FEA would translate into a reliable part once manufactured. This design was then sent to various fabrication shops and steel suppliers to receive quotes or pricing and fabrication costs. Ultimately, the team chose 4 Flutes Machining (Vicksburg, MI) [28] to produce the gearbox mounting plate based on lowest cost and production
lead time. Upon delivery of the gearbox mounting plate, the team worked with faculty specialist Mike Konkel to enlarge holes in the base plate of the plate due to imperfections in the laser cutting of the holes. *Figure 7* identifies the holes which needed rework due to a small defect in manufacturing to cause the holes to be undersize. *Figure 8* shows the fixture installed on the bedplate.

*Figure 5. FEA of Gearbox Mounting Bracket*

*Figure 6. Final Gearbox Mounting Plate Design*
Figure 7. Reworked Gearbox Mounting Plate Holes

Figure 8. Gearbox Mounting Plate Installed on Test Bed
**Intermediate Transmission Mount**

The intermediate transmission, an Eaton FS-6305B, was mounted with an existing mount from the CHEAR laboratory. As shown in *Figure 9*, it is comprised of a large, machined face to hold the bellhousing of the transmission, and a flat base plate with mounting holes for the t-slot connections. There are additional gussets placed on both sides to prevent the base from buckling under the load. The intermediate transmission provided to CAViDS for this project contained a bellhousing pattern which aligned with the SAE #2 pattern. This same pattern was on the existing mounting bracket shown in *Figure 9*. Reusing this mount saved several hundred dollars on the project budget since a new bracket did not have to be fabricated. The team also did not conduct stress testing on this mount since the bracket has previously been used in CAViDS projects and further evaluation of this bracket was deemed unnecessary.

*Figure 9. Intermediate Transmission Mount*
Dynamometer Mounting Structure

The dynamometer is mounted on a large tubular steel structure. There are machined flat plates on the bottom to affix it to the bed, and flat plate mounts on the top to attach the dynamometer to the structure. The dynamometer is mounted as far back on the test bed as possible to maximize the space for the rest of the components. No stress evaluation was conducted on this structure since it has previously been used in CAViDS projects.

![Dynamometer Frame](image)

Figure 10. Dynamometer Frame

Dynamometer to Torque Transducer Coupler

To connect each component shown in the overall system layout depicted in Figure 2, a series of hard mount adapters, flexible couplers, and drive shafts are used. The torque transducer was well supported by the dynamometer bearings, and its overhung weight was not considered a dynamic issue. Therefore, the team selected a hard axial mount piloted connection, which saved axial test bed space. This adapter was created using an existing mounting fixture for the dynamometer, and newly fabricated step-down reducer to the torque transducer shaft size. This allowed the system to be modular and help increase future utility. The coupler is mounted using
one piece of 3/8” key stock and two locking set screws to hold the torque transducer shaft in place inside the coupler. This design was also sent to 4 Flutes Machining for fabrication. *Figures 11 and 12* show the final design of the coupler and the coupler installed in the dynamometer fixture, respectively.

Through discussions with the faculty mentor, industrial mentor, and faculty specialist, the team decided that the torque transducer should not be rigidly mounted on its existing steel bracket. A rigid connection between the dynamometer/torque transducer and torque transducer/test bed would likely introduce noise into the torque and speed readings obtained by the torque transducer, since it is extremely difficult to get components perfectly concentric about their axis of rotation. To resolve this potential problem and allow small vertical motion of the torque transducer without inducing high loads, high-density foams blocks were placed between the bottom of the torque transducer and the bracket to attach it to the test bed. This allows a small amount of flex in the system, eliminating unwanted vibration. *Figure 13* identifies the installed torque transducer on its respective bracket.

![Figure 11. Dynamometer Coupler Design](image)
Figure 12. Dynamometer Coupler Installed on Dynamometer

Figure 13. Torque Transducer and Torque Transducer Mount

**Torque Transducer to Intermediate Transmission Coupler**

To connect the torque transducer and the intermediate transmission, a high torque flexible coupler was used. This coupler allows the connection between the torque transducer and
intermediate transmission to be up to 3.5mm out of axial misalignment without inducing high stress and vibration on the system. This coupler was already in the CAViDS CHEAR laboratory and was confirmed by the manufacturer, R+W America [1], to support the load that was required. Through additional communication with R+W America, the team identified this coupler is capable of transmitting a continuous torque of 1500 Nm and can support brief loads up to 150% of this continuous rated torque. One side uses a press-fit adapter that is tightened with bolts, and the transmission side has a splined hole that matches the transmission’s input. This side is tightened with a large bolt and is clamped around the shaft.

![Figure 14. Torque Transducer to Intermediate Transmission Coupler](image)

**Intermediate Transmission to Motor and Gearbox Coupler**

The connection between the intermediate transmission output shaft and the test gearbox output shaft involved investigation. The initial plan was to use a similar flexible coupler to the one previously mentioned; however, the lead time and price were prohibitive. Quotes received
from the coupler manufacturer indicated costs over $2,000 for a stock bore (unmachined) flexible coupler, which would then require machining and production of an adapter flange to interface with the gearbox output shaft and intermediate transmission input. Additionally, the flexible coupler would not arrive until June 2022, due to supply chain issues and global events. To resolve this problem, the choice was made to use a custom-made drive shaft. This alternative will still address the slight misalignment in the system to be and eliminate vibration and system flex. This driveshaft will be sourced by a local Kalamazoo company, Martin Spring and Driveline [2] to support local business and minimize lead times. This will also allow space savings on the bed plate, as the driveshaft utilizes a shorter companion flange on the transmission and a custom, shortened drive shaft length.

![Figure 15. Companion Flange to Driveshaft Yolk](image)

**Installation of Components and Alignment**

This project required the installation of multiple heavy components. Meticulous alignment of each component which was attached to the test bedplate for the final setup of the
test bed was crucial to avoid system vibration, dynamic loading, and excessive wear on component bearings. The team utilized the university’s faculty and resources to aid in the installation of the components in the system. Forklifts were used by the university personnel to operate them to install the heavier components in the system as well as help with the installation. The forklifts were able to hold the intermediate transmission stationary in the air while the team mounted it to its respective pedestal.
10: Gearbox Design Considerations

The team encountered numerous challenges while trying to fabricate a gearbox output shaft design that would fit the project needs. Lack of product availability for original equipment (OE) output shafts for the test gearbox evolved into both the differential and the output shaft being analyzed for the highest strength and least expensive design. With the aid of the team’s industrial mentor, the gearbox was disassembled to better understand the internal component layout. Using this hands-on experience, the team was able to make decisions on how to handle the designs for the differential and the output shaft of the gearbox.

**Differential**

Another major challenge for assembling the components in the test stand was developing a connection between the output shaft from the gearbox and input of the intermediate transmission. The gearbox uses an open differential to transmit power. With only one output being utilized in this project, no torque would be output to the dynamometer without locking the differential. *Figure 16* [3] illustrates an open differential and how the power would be transmitted based on the side with least resistance.
To address this problem the team identified two possible solutions:

1. Lock the spider gears inside the differential by welding them together

2. Create a new differential resembling a spool type differential which contains no spider gears, *Figure 17* [4]. With this option, all input power is transmitted equally through the outputs. Additionally, a custom designed straight output shaft would replace a splined output shaft which exactly matched the splines in the test gearbox differential.

The selected alternative was to lock the existing differential by welding the internal spider gears together, and to create a splined shaft that matched the current spline pattern.
Figure 17. Example Spool Differential

The basic design of the replacement hub was a mounting plate that supports the bolts connecting the ring-gear, and a series of concentric stepdown discs to hold the shape, force, and the bearing required. Cut in one end is a keyed hole allowing the shaft to slot in and transmit power to the rest of the system.

**Output Shaft**

The next challenge was sourcing a coupler that would fit within the space requirements of the test gearbox, transmit the maximum output torque of the test gearbox, and interface with the input of the intermediate transmission. The splines on the shaft are specific to the differential which originally came in this gearbox, so very few off the shelf components are available. After reaching out to the manufacturer of the test gearbox, shaft suppliers, and other contacts, the choice was made to create a custom output shaft and differential. This allowed the shaft to be made as short as possible, and custom flanges to be attached. The main design challenge
associated with this configuration is the large torque applied to the output shaft of the test
gearbox: 3672 N-m. As specified in section #9: Dynamometer Torque-Speed Matching, this
performance specification was based on the 7.22:1 gear reduction in the intermediate
transmission, and the maximum output torque of the gearbox being limited to 3672 N-m. Torque
production high than this will overload the dynamometer. This shaft was designed using a
combination of hand calculations and FEA simulations. A large radius fillet was added to the
shaft to help displace some of the torque along the length of the shaft.

The main design consideration was how to transfer the power from the differential hub to
the shaft. The two options explored were creating a splined shaft similar to OEM designs, or
designing a keyed shaft, using large key stock to transfer the power. The spline option would
have the best overall power-transfer and would cause the lowest point-stresses. This however is a
complex machining process and would make the project more expensive. The keyed shaft option
(see Figure 20 and 21,) would allow more design freedom to mesh with the custom designed
differential hub but increase the peak stresses on the keyways. The options were evaluated using
SolidWorks’ FEA software. The results from all were compared again industry leading tools as
well as hand calculations to determine the best option.

To complete the analysis, and make an overall decision, the team hosted a meeting with
Mr. Gerald Burke and Mr. Caleb Gurd from Eaton Corporation, one of the CAViDS’ industry
partners. During these meetings, the team presented their preliminary gearbox output shaft
designs, and brought questions regarding the high stresses being predicted by the team’s
SolidWorks FEAs. The main features in the output shaft design that needed to be addressed were
the method of power transfer (keyways versus splines)main shaft design, validating the
SolidWorks FEA’s prediction of shaft stresses over the yield stress limit of the selected material,
the stress limit, and how to incorporate the fatigue life cycle analysis into the shaft design when the test stand is expected to operate for extended periods of time. The team narrowed their options for a power transfer mechanism to two possibilities, a shaft which contained keyways, and a splined shaft. The team then subjected each shaft design to the maximum gearbox output torque of 3672 N-m due to the assumption that the gearbox differential will be locked to ensure all input power from the electric motor is transferred out of the gearbox. In regard to the keyed shaft design, the team explored 1, 3, and 4 key options and studied their impact on the reduction of stress in both the keyway slot and the main body of the output shaft. Analyzing the splined output shaft resulted in the team identifying the minor most diameter of the splines and calculating what shaft stresses would be expected. Additionally, the team utilized resources from Eaton Corporation to predict the output shaft stresses in the splined shaft design. Finally, to incorporate fatigue limits into the output shaft considerations, Mr. Gerald Burke of Eaton Corporation suggested that the new effective yield stress be taken as 50% of the selected material’s yield strength in situations where a lack of information is present in regard to the material properties.

The stress limit was based on the yield strength of the heat treated 4340 steel (Austenitized at 840C, Oil Quenched, Tempered at 400 F,) which has a yield strength of 1860 MPa [30], and the fatigue limit was assumed to be 50% of the yield strength, which corresponds to a new effective yield strength of 930 MPa, as the properties of this material were limited. After weighing the options for these parameters, as well as the cost of manufacturing, the team made the decision to advance with the splined output shaft design. This approach had a higher torque capacity before reaching the fatigue capacity of 2,270 N-m compared to 620 N-m for the keyed shaft. The splined shaft also has a lower cost estimate of about $1,500 vs $2,300 for the
keyed shaft which would also require a new gearbox differential to be manufactured. Finally, the splined output shaft had the lowest amount of gearbox modification required, as the current differential could be used, eliminating the need to manufacture a replacement one.

<table>
<thead>
<tr>
<th>Shaft Criteria</th>
<th>4-Keyed Shaft</th>
<th>Splined Shaft</th>
</tr>
</thead>
<tbody>
<tr>
<td>Torque Limit (N/m)</td>
<td>620</td>
<td>2,270</td>
</tr>
<tr>
<td>Cost Estimate ($)</td>
<td>2,300</td>
<td>1,500</td>
</tr>
<tr>
<td>Gearbox Modification Effort</td>
<td>Higher</td>
<td>Lower</td>
</tr>
</tbody>
</table>

*Figure 18. Output Shaft Decision Matrix*

---

![Shaft Design Comparison](image)

*Figure 19. Output Shaft Stress Comparison*
Figure 20. Output Shaft Design from Gearbox to Intermediate Transmission

Figure 21. Gearbox to Intermediate Transmission Output Shaft FEA
11: Cooling System

EV powertrain systems, similar to internal combustion engines, require liquid cooling systems to maintain proper operating temperatures of each component. For the purpose of the gearbox thermal study, the cooling of the test system is broken into three components:

1. The primary cooling system isolates heat generated in the test gearbox and is used to measure the heat generated for comparison to the Amesim model.
2. The secondary cooling system is concerned with the bulk to the cooling load generated.
3. The test cell cooling system is responsible for maintaining test cell ambient conditions.

To model the performance of the primary and secondary cooling systems, the team developed a spreadsheet-based (Excel) tool which predicts the output temperatures from inputs supplied by the user.

Primary Cooling System

The primary cooling system is responsible for the heat generation within the test gearbox. The team designed this cooling system separate from the secondary cooling system because the heat generation inside the gearbox is the main focal point of the modeling effort. Therefore, it is critical that this system be isolated for measurement.

In the primary cooling system, the fluid inside the test gearbox is pumped out of it and into a copper-brazed high efficiency heat exchanger (Kelvion GBS 200H-14 [16]). This heat exchanger has a heat capacity of 69,000 BTU/hr and also operates at a flowrate of 7 GPM. The gearbox oil enters this heat exchanger and transfers the heat into a liquid coolant mixture (a 50/50 mixture of ethylene glycol and water,) as shown in Figure 22. The team assumed that all heat contained in the gearbox oil is transmitted through the heat exchanger to the coolant.
mixture, as these lines will be thermally wrapped. Inlet and outlet temperatures of the test gearbox and heat exchanger were calculated according to Equations 22-25.

\[ Q_{oil} = m_{oil} * C_{p, oil} * (T_{oil, outlet} - T_{oil, inlet}) \]  

Equation 22

\[ T_{oil, outlet} = \frac{\dot{Q}_{oil}}{m_{oil} * C_{p, oil}} + T_{oil, inlet} \]  

Equation 23

\[ T_{oil, inlet} = T_{coolant, inlet \ HE} \]  

Equation 24

\[ C_{p, oil} = 1.67 \text{ kJ/kgK} \]  

[4]

Owen, Schultz, Larson
To complete the gearbox oil subsystem, an oil transfer pump (BLACKHORSE-RACING [17]) was used, as shown in Figure 23. This pump was capable of 16GPM, due to the 7GPM limit of the heat exchanger, a ball valve and 5GPM flowmeter (King Instrument Company [18]) were used to control the flow.

\[
\dot{Q}_{\text{oil}} = \dot{m}_{\text{coolant}} \cdot C_{p,\text{coolant}} \cdot (T_{\text{coolant, outlet HE}} - T_{\text{coolant, inlet HE}})
\]

Equation 25

\[
T_{\text{coolant, outlet HE}} = \frac{\dot{Q}_{\text{oil}}}{\dot{m}_{\text{coolant}} \cdot C_{p,\text{coolant}}} + T_{\text{coolant, inlet HE}}
\]

Equation 25a

Figure 23. Blackhorse Racing Oil Transfer Pump
Once the heat is transferred to the liquid coolant mixture, the coolant enters a copper radiator (Pro-Select), shown in Figure 25. This radiator also dissipates the heat from the test gearbox into the test cell air. Using the NTU method of analysis in the Excel tool developed, the outlet temperatures of the radiator and test cell air after passing through the radiator can be calculated. These equations model the exact same approach as the primary cooling system, as shown in Equations 6-17.
To complete the primary cooling system, the outlet of the Pro-Select radiator is connected to a water pump (*Dayton 2ZWP1 [19]*) to circulate the coolant mixture (the same 50/50 mix as in the primary cooling system) around the cooling system. The outlet of the *Dayton* pump is also connected to a variable control flow meter (*Liquatec PMF-1010 [20]*) to regulate flow of the coolant mixture. The set point for the liquid coolant is at 7 GPM due to the flow rate limit of the heat exchanger [16]. Again, the team neglected any heat loss through heat transfer of the rubber coolant hoses. The team is also assuming that the test cell temperature, which is also the inlet temperature of the air into the radiator is constant, depending on the set point of the Test Cell cooling system, and that the flowmeter and pumps do not contribute to heat generation. The
gearbox was also wrapped in R-38 insulation [15] to reduce the amount of heat transferred to the test cell air from the gearbox so that the measurement for the thermal validation would be more accurate.

Figure 26. Dayton Pump for Primary Cooling System
Secondary Cooling System

The secondary cooling system is designed and built to handle the heat generated in the test system. This cooling system absorbs heat generated in the intermediate transmission, the electric motor inverter, and the electric motor. For the intermediate transmission, the team relied on an industry accepted estimate that 2% of the transmitted peak power is converted to heat generation in the two-mesh intermediate transmission. This heat is transferred into the oil which lubricates the gears inside the transmission. To maintain a constant fluid temperature in the intermediate transmission, the secondary cooling system incorporates an oil transfer pump and a high efficiency heat exchanger to remove heat from the oil before cycling it back into the system.
intermediate transmission. The system is shown in Figure 28. As a simplifying assumption, the team neglected the heat transfer through the rubber hoses as the oil is cycled through its subsystem. The oil is pumped around this subsystem using an Apex [5] brand oil transfer pump capable of flowing 4.25 GPM (Figure 29). The heat exchanger used to transfer the heat out of the oil to a liquid ethylene glycol and water mixture was one which was already available in the CAViDS CHEAR laboratory (Bell & Gossett BP400-10 [6]) with a heat capacity of 60,000 BTU/hr at a flow rate of 6 GPM. Shown in Figure 30 is a photograph of the heat exchanger used. For the purpose of this project, the team also assumed that all heat generated inside the intermediate transmission is transmitted through the heat exchanger, since less than 20% of the heat exchanger’s capacity was being utilized. Using the estimated heat generation by the intermediate transmission, and applying heat transfer equations 1 through 3, inlet and outlet temperatures of the oil from the intermediate transmission were calculated.

\[
\dot{Q} = Heat_{generated} = 0.02 \times P_{in\ peak} \quad \text{Equation 1}
\]

\[
\dot{Q}_{oil} = m_{oil} \times C_{p\ oil} \times (T_{oil, outlet} - T_{oil, inlet}) \quad \text{Equation 2}
\]

\[
T_{oil, outlet} = \frac{\dot{Q}_{oil}}{m_{oil} \times C_{p\ oil}} + T_{oil, inlet} \quad \text{Equation 2a}
\]

\[
T_{oil, inlet} = T_{coolant, inlet\ HE} \quad \text{Equation 3}
\]

\[
C_{p\ oil} = 1.67 \text{ kJ/kgK} \quad [7]
\]

\[
C_{p\ coolant} = 3.626 \text{ kJ/kgK} \quad [8]
\]
Figure 28. Intermediate Transmission Oil Cooling System

Figure 29. Intermediate Oil Transfer Pump
On the cooling side of the heat exchanger a liquid ethylene glycol [9] and water mixture, at a ratio of 50/50, is used to absorb the heat from the intermediate transmission. The inlet and outlet temperatures of the heat exchanger were calculated according to *Equation 4*.

\[
\dot{Q}_{oil} = \dot{m}_{coolant} \cdot C_{p,coolant} \cdot (T_{coolant, outlet \ HE} - T_{coolant, inlet \ HE})
\]  

*Equation 4*

\[
T_{coolant, outlet \ HE} = \frac{\dot{Q}_{oil}}{\dot{m}_{coolant} \cdot C_{p,coolant}} + T_{coolant, inlet \ HE}
\]  

*Equation 4a*

As shown in cooling system schematic of *Figure 36* the coolant mixture is then routed through the supplied inverter and also electric motor. According to [10], the heat generated through the operation of the electric motor and electric motor inverter is approximately 200W for every 1 kW of power produced by the electric motor. The electric motor is capable of producing 135kW of peak power. According to [10], this falls inside the range of 100kW to 150kW of peak power, and the assumption of 200W/1kW of power produced. The inlet and outlet temperatures for the electric motor inverter and electric motor are calculated using *Equation 6*.
\[
\dot{Q}_{\text{motor \& inverter}} = P_{\text{motor}} \times \frac{200 \text{ W}}{1 \text{ kW}}
\]

\[
\dot{Q}_{\text{motor \& inverter}} = \dot{m}_{\text{coolant}} \times C_p \text{ coolant} \times (T_{\text{coolant, outlet EM}} - T_{\text{coolant, inlet EM}})
\]

\[
T_{\text{coolant, outlet EM}} = \frac{\dot{Q}_{\text{motor \& inverter}}}{\dot{m}_{\text{coolant}} \times C_p \text{ coolant}} + T_{\text{coolant, inlet EM}}
\]

\[
T_{\text{coolant, inlet EM}} = T_{\text{coolant, outlet HE}}
\]

\[
T_{\text{coolant, inlet RAD}} = T_{\text{coolant, outlet EM}}
\]

Finally, after absorbing all the calculated heat from the heat exchanger, the electric motor inverter, and the electric motor, the coolant mixture is fed into an aluminum radiator (Griffin 1-45202-X [11]) to dissipate the heat into the test cell air. The NTU method for the radiator analysis was incorporated into the (Excel) spreadsheet developed by the team, to calculate the outlet temperatures of the radiator and test cell air after passing through the radiator.
\[ C_{\text{coolant}} = c_{p,\text{coolant}} \cdot m_{\text{coolant}} \]  
\[ C_{\text{air}} = c_{p,\text{air}} \cdot m_{\text{air}} \]  
\[ C_{\text{min}} = C_{\text{coolant}} \]  
\[ C_{\text{max}} = C_{\text{air}} \]  
\[ C_r = \frac{C_{\text{min}}}{C_{\text{max}}} \]  
\[ m = \frac{2h}{\sqrt{kt}} \]  
\[ \eta_{\text{fin}} = \frac{\tanh (mL)}{mL} \]  
\[ A_{\text{fin}} = (\text{Rad width} \times \text{fin thickness}) \times (N \text{ rows}) \]  
\[ A = \eta_{\text{RSA}} \times (\text{Rad width} \times \text{Rad height}) \]  
\[ \eta_o = 1 - \left( \frac{A_{\text{fin}}}{A} \right) \times (1 - \eta_{\text{fin}}) \]  
\[ \frac{1}{UA} = \frac{1}{(\eta_o \times h \times A)_{\text{cold}}} + \frac{R_{f,\text{cold}}''}{(\eta_o \times A)_{\text{cold}}} + \frac{R_{f,\text{hot}}''}{(\eta_o \times A)_{\text{hot}}} + \frac{1}{(\eta_o \times h \times A)_{\text{hot}}} \]  
\[ NTU = \frac{UA}{C_{\text{min}}} \]  
\[ \varepsilon = 1 - \exp \left( -C_r^{-1} \{1 - \exp[-C_r \times NTU]\} \right) \]  
\[ q_{\text{max}} = C_{\text{min}} (T_{\text{coolant,in RAD}} - T_{\text{air,in}}) \]  
\[ q = \varepsilon \times q_{\text{max}} \]  
\[ q = C_{\text{min}} (T_{\text{coolant, in RAD}} - T_{\text{coolant, out RAD}}) \]  
\[ q = C_{\text{max}} (T_{\text{air, out}} - T_{\text{air, in}}) \]  

To complete the secondary cooling system, the outlet of the *Griffin* radiator is connected to a pump (*Little Giant* TE-6-MD-HC [12]) to cycle the coolant mixture around the cooling system.
system. The outlet of the *Little Giant* pump is also connected to a variable control flow meter (*Cole Parmer* [13]) to regulate flow of the coolant mixture. The set point for the liquid coolant is at 6 GPM due to the flow rate limit of the *Bell & Gossett* heat exchanger [6]. Heat losses through the rubber coolant hoses were neglected as a simplifying assumption. The test cell temperature, which is also the inlet air temperature into the radiator, was also assumed constant, depending on the set point of the Test Cell cooling system. Contribution of the flowmeter and pumps to heat generation were neglected. To limit unwanted heat transfer between the gearbox and electric motor the team created a gasket out of a Mica sheet [14] to minimize heat transfer from the housing of the electric motor to the housing of the test gearbox. The gearbox was also wrapped in R-38 insulation [15] to reduce the amount of heat transferred from it to the test cell air, to increase the accuracy of the gearbox thermal validation.

![Little Giant Pump for Secondary Cooling System](image)

*Figure 32. Little Giant Pump for Secondary Cooling System*
Table 3. Cole Parmer Flowmeter for Secondary Cooling System

<table>
<thead>
<tr>
<th>System Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Secondary Cooling System Load</td>
<td>18.95 kW</td>
</tr>
<tr>
<td>Inlet Temperature of Secondary Radiator Coolant</td>
<td>43.77°C</td>
</tr>
<tr>
<td>Outlet Temperature of Secondary Radiator Coolant</td>
<td>30.52°C</td>
</tr>
<tr>
<td>Inlet Temperature of Secondary Radiator Air</td>
<td>23°C</td>
</tr>
<tr>
<td>Outlet Temperature of Secondary Radiator Air</td>
<td>36.04°C</td>
</tr>
</tbody>
</table>

**Test Cell Ambient Air-Cooling System**

To ensure that the test cell remains at a consistent temperature, an *Emerson Liebert* 5-Ton (58,100 BTU/hr) air conditioning unit is connected to the test cell. The ducting system from a prior project was reassembled. This system passes duct work through a custom test cell door, which contains two large openings. The lower opening is for inlet air out of the test cell into the AC unit, and the upper opening is for outlet air back into the test cell from the AC unit. This allows ample air circulation in the room temperature control. The interface of the *Emerson Liebert* was set at a temperature of 65°F and a relative humidity control specified by WMU.
facilities management. For future work, if set points of the system are required, the proper process of notifying facilities management is required. For the purpose of this senior design project, the set points on the system were acceptable.

Figure 34. Room Temperature Control

Figure 35. Room Temperature Control
Heat Transfer

Figure 36. Secondary Cooling System Schematic

Figure 37. Primary Cooling System Schematic
12: System Power

Power Supply

To operate the test stand, the motor and inverter required an external power source output speed and torque to the system. To provide this power, the motor and inverter were connected to an ABC-150 battery simulator dual channel cycling system. This battery simulator is capable up to 420V DC at 265A and up to 125kW of power [21]. This exceeded the required power to operate the system. To connect to the inverter, the 2-phase power is run from the ABC-150 to the inverter. After being converted from DC to AC in the inverter, a 3-phase connection is run from the inverter to the motor to supply the necessary voltage.

Electric Motor Control

In normal industrial or production applications, the inverter for the electric motor would be controlled with the OEM vehicle’s ECU. In the absence of an OEM solution, an aftermarket
unit the ThunderstruckEV VCU [22] was used to control the speed in this test. This system takes the power from the battery and safely routes it through a pre-charge circuit to the inverter. It also takes inputs for an ignition switch, forward/neutral/reverse switch, and throttle and communicates them to the inverter. Additionally, this system re-programs the inverter to ensure that all the factory controls and coding are removed prior to operation. Refer to Figures 39 and 40.

The first issue that this system fixes is the battery charging. The motor and inverter that is used in the test laboratory requires an extra capacitor circuit to be added, known as the pre-charge circuit. This is because if direct power was applied to the inverter, the internal capacitors and components would have too much power and would be overloaded. The pre-charge circuit ensures that the power is transferred safely. The VCU also addresses the ignition, throttle/brake, and drive direction. Using inputs from a 12V ignition source, forward/neutral/reverse switch, and a basic throttle pedal, the computer is able to take these inputs and apply them to the motor. This allows control of the direction of the motor, as well as controlling the speed of the motor, which is important as it needs to be limited based on the torque-speed characteristic of the dynamometer.

The VCU can also be used to program the inverter. In its current state, the inverter is coded to run on the OEM system that the motor and inverter originally were installed in. This is problematic because these systems are not available to the public and are hard to obtain. Additionally, if a system like this was acquired it would be very difficult to control. The VCU allows the inverter to be custom coded. This means that the maximum speed, torque, acceleration curves, and more can be specified by the user. This is important for this application for two reasons. One, it allows the motor to be controlled and two, it lets the system be altered and
limited to the required torque and speed based on the torque-speed characteristic of the
dynamometer. This programming is done through *PuTTY* software [29]. A free and opensource
option for serial connection programming and control.

Figure 39. ThunderstruckEV VCU

Figure 40. ThunderstruckEV VCU
13: **Instrumentation**

**Temperature Measurement**

Monitoring fluid temperatures throughout the system is critical for quantifying the thermal and efficiency performance of the test gearbox. As part of this project the system was equipped with K-type and J-type thermocouples to monitor the temperatures at various points across the setup. The temperature ranges for these thermocouples can be found in *Figure 43* [25]. To accurately monitor fluid temperature, the procedure consisted of removing the protective PVC casing from the thermocouple wire and then the individual casing from each wire. The now exposed wires were twisted together and then placed in a PVC tee which then would be connected in-line with the hoses transporting the fluid which is desired to be monitored. *Figure 41* indicates the method of inserting thermocouple wire into a PVC connector to monitor coolant temperature. This method was used in both the primary and secondary cooling systems. To ensure a tight seal and prevent coolant leaks, the thermocouple wire was epoxied into the PVC connector using *J-B Weld Water Weld* [26]. Fluid temperature for the gearbox oil and intermediate transmission oil was done using J-type thermocouples, which contained a stainless-steel threaded bung, threaded into a PVC tee-connector. Finally, to monitor housing temperatures, K-type thermocouples were twisted together and then attached to the housings using ring terminal connectors and bolted to the housing, *Figure 44*. 
Figure 41. Thermocouples inserted into PVC Connector
Table: Thermocouple Temperature Ranges

<table>
<thead>
<tr>
<th>Calibration</th>
<th>Temp Range</th>
<th>Std. Limits of Error</th>
<th>Spec. Limits of Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>J</td>
<td>0°C to 750°C (32°F to 1338°F)</td>
<td>Greater of 2.2°C or 0.75%</td>
<td>Greater of 1.1°C or 0.4%</td>
</tr>
<tr>
<td>K</td>
<td>-200°C to 1250°C (-328°F to 2282°F)</td>
<td>Greater of 2.2°C or 0.75%</td>
<td>Greater of 1.1°C or 0.4%</td>
</tr>
<tr>
<td>E</td>
<td>-200°C to 900°C (-328°F to 1652°F)</td>
<td>Greater of 1.7°C or 0.5%</td>
<td>Greater of 1.0°C or 0.4%</td>
</tr>
<tr>
<td>T</td>
<td>-250°C to 350°C (-328°F to 662°F)</td>
<td>Greater of 1.0°C or 0.75%</td>
<td>Greater of 0.5°C or 0.4%</td>
</tr>
</tbody>
</table>

Figure 42. NI DAQ for Thermocouples

Figure 43. Thermocouple Temperature Ranges
The secondary cooling system contains 13 thermocouples to record the temperatures of the intermediate transmission, electric motor inverter, electric motor, heat exchanger, and primary cooling system radiator. There are thermocouples at the radiator inlet and outlet to record the temperatures that the coolant is flowing at when coming in and out of the radiator. The heat exchanger has thermocouples at the inlets and outlets at the oil and coolant side. The intermediate transmission thermocouples are connected at the oil inlet and outlet as well. The inverter contains a thermocouple at the inlet to measure the temperature of the coolant but does not need one at the outlet as it is close enough to the motor to get an accurate reading. To complete the thermocouple setup in the secondary cooling system, the electric motor temperature is monitored at the coolant inlet and outlet.
While the primary cooling system is less complex, it still has nine thermocouples to measure temperatures to verify the thermal model of the gearbox. The gearbox is equipped with thermocouples at the inlet and outlet to measure the temperatures there. There is also a thermocouple placed on the gearbox housing. The heat exchanger has four thermocouples, one at each inlet and outlet of the oil and coolant sides. The radiator is also equipped with thermocouples at the inlet and outlet. A thermocouple is also used to monitor the test cell temperature. The team also created a document to identify the channel in the DAQ chassis that is affiliated with each thermocouple.

**LabVIEW Interface**

Sensor data was routed to a laboratory PC through a data acquisition card. A data acquisition (DAQ) card (NI SCXI-1000), shown in *Figure 42* was used to relay the thermocouple connections back to the computer and *LabVIEW* program as shown in *Figures 45* and 46. The torque transducer is connected to the dynamometer control Inertia box, as well as the DAQ card to allow both the *LabVIEW* interface and the dynamometer control software to read the correct torque values. A *LabVIEW* interface was created to record all the temperatures, torques, and speeds.
Figure 45. LabVIEW VI Interface

Figure 46. LabVIEW VI Plotting Thermocouple Temperature
Fluid Flow Measurement

Each cooling system is outfitted with flowmeters to regulate the amount of fluid passing through the system as well as allowing users to set and record corresponding flow rates. This was especially important in the heat exchangers as they were limited to a maximum flow rate of 6 GPM in the secondary cooling system, and 7 GPM in the primary cooling system. A flowmeter was used in the secondary cooling system to regulate the flow of coolant, but one was not used on the oil side since the maximum flow rate of the Apex oil transfer pump was 4.25 GPM which is below the limit. The primary cooling system required two flowmeters, since both the coolant and oil pumps were capable of flowing more than 7 GPM.

Torque Transducer

The torque transducer, a S. Himmelstein and Co., was rated for 5000 lb-in, records the torque output at the output of the intermediate transmission. Using the known gear ratios of the intermediate transmission, 7.22:1, and test gearbox, the output torque of the test gearbox and electric motor can be calculated. The torque transducer will send signals back to the computer to be displayed along with the rest of the data. Working with Peter Thannhauser, the team was able to trace down the voltage signal outputted from the torque transducer where it communicates with the laboratory computer controlling the dynamometer. This voltage signal was then copied and connected to the NI DAQ chassis which housed the thermocouple measurements from the test stand. The team then incorporated this torque transducer voltage signal into the program written to record and monitor data from the test stand when operating. Finally, the team identified the scaling factor which converts the torque transducer voltage signal into a torque value and modified the program to save torque values alongside the temperature values.
Computers and Software

The data acquisition and other monitoring in this experiment was conducted using a laboratory computer. To connect the sensors to the computer, a National Instruments NI SCXI-1000 DAQ card was used. The raw data from these sensors was then processed within the LabVIEW program. To control the battery simulator, a similar system is used. Rather than a LabVIEW interface however, the ABC-150 uses its own control software. The computer will also be used to control the ThunderstruckEV VCU, allowing motor speed to be specified.

To reprogram the inverter, the PuTTY software was used. This is a powerful, opensource software that allows control and monitoring of the computer’s serial connection. Using various commands for the VCU, the inverter can be modified to adjust the maximum operating speed and torque of the motor, as well as modify parameters such as throttle response and regenerative braking. It is connected to the motor through the CANbus connection and is connected to the computer’s serial connection through a USB cable. From here, the commands are input into PuTTY, and are uploaded to the inverter. This software also allows the monitoring of certain motor parameters such as torque and speed. They are the theoretical values that the inverter is supplying power for, so the experimental motors speeds may differ slightly, but it is a tool for basic calibration and monitoring of the speeds.
14: System Operation

As mentioned in the section #6: Scope and Limitations of Work of this report, one of the project objectives is to develop the documentation of the test stand and its operation. Before operation of the stand for the purpose of validating the thermal model of the test gearbox, the dynamometer torque and speed range had to be matched to the output of the test gearbox utilizing the intermediate transmission.

Documentation of System Operation

In order to achieve an operational system and begin validating the thermal performance and efficiency of the test gearbox, the following documents are needed to make the system functional. These have all been complied into one master document.

- Thermal and Efficiency Analysis Testing Instructions
- Dynamometer Start-Up/Shutdown Procedure
- LabVIEW Thermal and Efficiency VI Instructions
- Primary and Secondary Cooling System Start-Up/Shutdown Procedure
- Test Cell Temperature Control Instructions
- Operation Manual for Thunderstruck EV VCU to control electric motor
- ABC-150 Start-Up/Shutdown Procedure

To aid in understanding the thermocouple connections, thermocouple type, and a systems level diagram of both the primary and secondary cooling systems, a document titled LabVIEW Connection Diagram was created. This document should also be referenced when working with the data collection.
**Preliminary System Testing**

The preliminary testing will help to determine if the system is aligned correctly, confirm that all components are functioning as intended, calibrate all the systems, and check the instrumentation layout and measurement systems. From here, the data can be collected from full data tests, and compared to the simulation file.
15: Results

The scope of this project was not as focused on experimental results as other senior design projects. However, there were results from the gearbox plate design, dynamometer coupler design, and the cooling system performance.

The gearbox plate design went through multiple design iterations to ensure the plate would support the gearbox as well as the motor. The gearbox plate design was originally conceived with two smaller rectangular plates no supporting gussets. The team discovered that with the limited space on the test bed, and that the upright plate of the mounting bracket could not be a rectangle without interfering with the output shaft of the gearbox, that the mounting plate needed to be longer to allow more space between the output of the gearbox and input of the intermediate transmission for a coupler. Additionally, the upright plate of the mounting plate needed chamfers in it to accommodate the gearbox output shaft, and a clearance hole was added to allow the parking brake controller on the gearbox to remain intact. The SolidWorks FEA was conducted with using a safety factor of at least 2.0 so that the plate would be more than strong enough to support the torque output from the test gearbox. After running simulations on each design iteration for the mounting plate the team developed a final design shown in Figure 5 of the report. The analysis indicated that the highest amount of displacement in the gearbox mounting plate was 0.640 mm at a point which is farthest from the base of the plate, and an average stress of about 83 MPa. The final design incorporated enough support to the gearbox and motor for proper mounting on the system.

The team was able to acquire more design experience with the dynamometer coupler that was designed. The dynamometer coupler was designed to interface with the existing flange face coupler on the dynamometer input shaft. This coupler made use of a single key stock to index the
coupler to the torque transducer shaft and also transmit the torque being supplied from the intermediate transmission to the dynamometer. The team selected this coupler to be rigid as the torque transducer does not experience significant axial displacement, and also has a flexible coupler connection to the intermediate transmission and isolation foam underneath the torque transducer. The outcome of this design was a properly fitting connection from the torque transducer to the dynamometer.

The cooling system needed to properly cool all the components on the test stand. The cooling is needed to both isolate the heat generation in the gearbox being evaluated, but to ensure that the components do not overheat while testing. The primary cooling system is used to cool and monitor the test gear box, and the secondary cooling system is sued to cool the intermediate transmission and electric motor/inverter. This will be done using an air to liquid heat transfer cooling loop, with radiators to help dissipate the heat. The cooling system calculations performed by the team offered quantitative results to accurately evaluate the cooling system designs. The primary cooling system used the ProSelect radiator, and the secondary cooling system utilized the Griffin 1-45202-X radiator. Since these radiators were readily available in the laboratory, one of the main goals of the calculations was to validate that they could dissipate the heat generated in the components. The maximum heat transfer that the Griffin 1-45202-X radiator could theoretically handle was found to be 29.7 kW and the actual heat which needed to be dissipated was found to be 18.95 kW. The temperatures at the outlets of the hot and cold sides of the secondary cooling system radiator were predicted to be 31°C and 36°C respectively. These values proved to show that the secondary cooling system met the requirements to cool the system. The ProSelect radiator in the primary cooling system was unable to be validated as the
maximum heat transfer, actual heat transfer, and the radiator outlet temperatures at the hot and cold side are part of the thermal analysis which needs to be conducted on the test gearbox.
16: Conclusions

The objectives of this project were:

1. Design and develop a test stand to analyze a high-speed gearbox.
2. Implement a test stand based on the proposed design.
3. Produce documentation of test stand operation for upcoming validation.

The first objective of the project was completed through 3D modeling in SolidWorks to design the layout of the bedplate as well as the different components in the system. The second objective was finalized by reaching out to different suppliers to purchase the components needed for the project. Local machine shops were also contacted to compare quotes for the custom components of the system. Finally, the team produced documentation of the system’s operation to ensure that the next team would be able to start working on the next phase of the project with ease.

The team initially identified that the space on the bedplate in the laboratory was going to be inadequate for the project. To address this issue, the team proposed different methods of extending the bedplate and their affiliated costs. The team concluded that it would be ideal to use the bedplate already in the laboratory and design a cantilever type mounting plate for the test gearbox and electric motor. The other two options were not selected because extending the bedplate would be too difficult in regard to maintaining a continuous flat plane for mounting components and making a new test bed would be cost prohibitive. The team designed different mounts and couplers to maximize the space on the current test bedplate and help increase the efficiency of the lab space given.
The team then ran into challenges connecting all the components together. The team researched different flexible and rigid couplers to connect the components on the test bed. In areas that had high torque outputs, flexible couplers were used to account for any movement within the system so that it would operate smoothly such as the connection between the test gearbox and intermediate transmission, as well as the intermediate transmission and torque transducer. The connection between the dynamometer and torque transducer was able to use a rigid coupler because of redundancies incorporated into mounting the torque transducer.

After getting all the components sourced, manufactured, and delivered, they could be mounted to the test bed. This included mounting the motor and gearbox and the intermediate transmission to their respective mounts, connecting each part with the coupler of choice, and assembling the cooling systems. This step also included setting up the instrumentation devices and wiring the motor control unit.

After implementing the test stand setup, the laboratory was ready to begin validation on the thermal model provided. To ensure smooth transfer to the following groups, the proper documentation for the startup procedure was created. This documentation outlined the startup procedures for each component in the lab and would make sure that the system could be analyzed in an easy and efficient manner.

Another challenge faced in this project was budgetary constraints. There was no set budget for this project, but the team was instructed to spend money as needed. The team was able to accomplish this by using components already found in the laboratory, receiving quotes from multiple manufacturers, and finding sources to donate equipment. The design decisions were made with both cost and feasibility in mind to choose the best and most cost-effective solution. If a part met the requirements of the application but was too high of a cost, the team
would look for a less-expensive solution, identify methods to produce them on their own, and contact laboratory sponsors for assistance. Examples included a pedestal already found in the laboratory to mount the intermediate transmission, two automotive-style radiators, and a heat exchanger that were used on different projects and validated for use in the cooling systems. The dynamometer and torque transducer were also passed down from other previous projects, saving money and wasted resources. When the custom parts were designed, the team made sure to receive multiple quotes from different sources to compare the costs and choose the lowest one with an appropriate delivery time. In addition to this, the team also worked internally at the university by contacting faculty in the machine shop to gain their insight and have their support on in-house machining if available. The team also reached out to the CAViDS consortium industry sponsors when additional technical support was needed. The team was able to get the intermediate transmission donated by one of the CAViDS consortium companies as well as the test gearbox, motor, and inverter.
17: Next Steps

The first step that is needed to get the system fully operational is to complete the design and manufacturing of the output shaft and differential for the test gearbox. Using the designs created during this study, and the input given from industry leaders, the most effective and safe option can be produced. Producing the output shaft of the test gearbox will also determine the choices available for the driveshaft to connect the gearbox and intermediate transmission. This component is contingent on the length of the output shaft, so establishing maximum length between the output of the test gearbox and the input of the intermediate transmission, a local driveshaft shop can manufacture the correct driveshaft.

Once the gearbox output shaft is installed the gearbox can be reassembled and installed back on the test stand. The test gearbox was taken apart to understand the inner workings of the gearbox and allow for a better final design of the output shaft. As part of the gearbox reassembly, all of the bolts that hold the two-halves of the gearbox housing together will need to be tightened down to the proper torque, as specified in the data sheet. The gearbox and motor will then be bolted together with a 0.04” thick Mica sheet acting as a gasket in between the motor and gearbox to prevent unwanted heat transfer and isolate the test gearbox. To complete the installation of the test gearbox, the R-38 insulation will also need to be wrapped around the test gearbox, without interfering with the output shaft or creating a fire hazard with the input power cables.

One additional improvement to this test stand which should be incorporated before conducting full-scale thermal testing on the gearbox is to modify the operation of the ThunderstruckEV VCU. Although the team worked to obtain the VCU and attempt to get the electric motor/inverter operational, from a long-term operating standpoint the throttle should be
controlled via computer software. Currently, the supplied throttle pedal from ThunderstruckEV is being used to control the speed of the electric motor. This pedal is located inside the test cell and requires constant human input to operate. Relocating the speed control outside the test cell not only protects individuals who wish to use the test stand, but also limits potential safety hazards. By also incorporating the electric motor speed control into the laboratory computer which performs the instrumentation measurements, more precise and automated control over the electric motor could be obtained. The team recommends that the test stand is not operated for any thermal testing until this is completed.

After all the installation of the system is complete the gearbox will be ready to be tested for its thermal performance and efficiency. The documentation provided by the team will be used to aid in operating the system in the proper way. Using the LabVIEW program set up by the team the next group will be able to record data at different speeds and torques supplied by the electric motor. The next group can then compare this experimental data to the model already developed in Amesim and either validate or provide metrics to quantify ant discrepancies between validation approaches.
18: Budget

Cost Estimates:

Many of the components required for the completion of this project were sourced from prior projects or loaned to CAViDS for the duration of the study. Equipment, instrumentation, and additional resources were funded through CAViDS. The cost of several components needed for the project cannot be disclosed, per the terms of the industry partner’s non-disclosure agreement. Provided below is the budget information which can be shared.

Actual Project Budget

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<td><strong>$4,456.54</strong></td>
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</tr>
</tbody>
</table>
19: References


20: Appendices

Figures, Drawings, Pictures, and Calculations:

![Figure 47. Project Gantt Chart](image-url)
21: Acronyms

WMU: Western Michigan University
CAViDS: Center for Advanced Vehicle Design and Simulation
EV: Electric Vehicle
ICE: Internal Combustion Engine
SUV: Sport Utility Vehicle
CHEAR: CAViDS Hybrid Electric Applied Research
FEA: Finite Element Analysis
OE: Original Equipment
DAQ card: Data Acquisition Card
SAE: Society of Automotive Engineers
NTU: Number of Transfer Units
BTU: British Thermal Units
GPM: Gallons per Minute
OEM: Original Equipment Manufacturer
ECU: Electronic Control Unit
VCU: Vehicle Control Unit
CANbus: Controller Area Network bus
ABET Program Evaluation Questionnaire

Mechanical and Aerospace Engineering Project (ME/AE 4800) Program Outcomes’ Indicators Assessment Worksheet

Mechanical and Aerospace Engineering Programs

Semester: Spring Project Group Number: 4-22-14

Project: Thermal & Efficiency Analysis for a High-Speed Gearbox

Student Team Members: Austin Owen, Noah Schultz, and Reid Larson

Faculty Team Members: Dr. Claudia Fajardo-Hansford, CAViDS Executive Director John Bair

Please respond to all of the following questionnaires as best you can.

Outcome (2)

An ability to apply engineering design to produce solutions that meet specified needs with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors.

Performance Indicators:

1. Generates a detailed statement of all the specified engineering needs for the design project.
2. Identifies and lists potential public health, safety and welfare concerns for consideration in the design process.
3. Identifies and lists global, cultural, social, environmental, and economic factors that are relevant to the development of the project product.
4. Produces solutions that satisfy the engineering needs, address the public concerns, and consider the effects of the relevant design factors.

(If you copy and paste from the report, mention Section number or page numbers. If any question or item is not relevant to your project, write N/A)
Performance Indicator 1
Describe the engineering needs for this project.

The technical problem investigated in this project was the thermal characteristics of a high-speed gearbox, specifically designed for a medium-duty vehicle application. Electric motors are already becoming mainstream in the consumer car market, with many cars and some sport utility vehicles (SUV's) utilizing one or more of these motors. However, as the technology progresses, and other segments will become electrified (i.e., the medium-duty market,) the need for more robust solutions will increase. To ensure these powertrains are designed to withstand the increase in required load commonly affiliated with medium-duty applications, experiments such as those defined in this project are required. This not only helps to further the technology in the industry, but also ensures that it is safe for mass consumption. It can also support the development of more intense applications such as the heavy-duty market.

(Section Problem Posed and Need)

List the project goals along with performance criteria.

1. A test plan that defines the parameters and test conditions required to verify thermal data predicted in the previous project.
2. A test stand design that will produce the data specified by Deliverable 1.
3. A functional test stand that will produce the data specified by Deliverable 1.
4. Preparing the test stand for other individuals to perform testing to correlate the physical laboratory data to the simulation model outputs.

(Section Specification and Requirements)

List the project constraints.

This experiment focused on a single gearbox’s thermal characteristics. This gearbox used a supplied input motor to drive it and a medium-duty transmission to match speed and torque output of the test gearbox to the dynamometer. This project will not investigate motors of different sizes, manufacturers, or specifications, and will not introduce modification and optimization of the components. This experimental setup will be further used for research and data collection of the motor and gearbox provided, and validation of the gearbox thermal model developed in Amesim.

(Section Scope and Limitation of Work)
List the methods/procedures that were implemented to ensure that the customer expectations were addressed.

To ensure that the customer’s (the WMU CAViDS lab) needs were satisfied, constant contact was kept with the lab leaders and program supervisors. Additionally, through the process weekly progress meetings were held to make sure that the program was going in the right direction. These weekly progress meetings were held with the faculty mentor, industry mentor, and other faculty/industry specialists as needed. At the conclusion of every weekly meeting a task list document was updated with meeting minute notes, comments about progress on a specific part of the project and assigned a progress metric (in percent) to quantify progress.

**Performance Indicator 2**
Describe potential public health, safety, and welfare concerns regarding this project and describe how they were addressed in the final design.

*Public Health:*

Due to this project being executed in the WMU CAViDS CHEAR laboratory, it is not accessible to the public. Access to this laboratory is restricted to swipe access and must be approved by the faculty mentor. The results of this physical laboratory testing could impact the public if changes to the test gearbox design are necessary. However, this falls outside the scope of the project this senior design team is concerned with.

*Public safety:*

This project is aimed at taking a commercially available gearbox and motor and testing it in the test system developed to validate a previously developed thermal computer model. This physical testing is done to ensure the thermal model results align with physical data collected. A strong correlation between data sets is needed to rely on the computer model software for the design of future EV gearboxes and make sure they can withstand the increased loads expected in the future. This process will help to create more robust and safe gearboxes for future vehicles and will make sure that the safety of the user is held paramount.

*Public welfare:*

N/A

**Performance Indicator 3**
List and explain all possible global, cultural, social, environmental, and economic factors relevant to the product of this project.
Global factors:

This gearbox and motor combination is often used by international companies, so it is important that it operates safely as it will reach a wide array of people, countries, and standards.

Cultural factors:

N/A

Social factors:

N/A

Environmental factors:

This system contained an electric motor, electric motor inverter, and test gearbox attached to the test system developed by this senior design team for the purpose of creating a system which is ready to validate the thermal performance of the test gearbox. This gearbox is designed for implementation into an EV. This technology will help reduce carbon emissions in the future and increase the health of the earth. Additionally, many parts were recycled from the lab’s industry partners or the lab itself, helping to reduce the overall environmental/waste impact of this project.

Economic factors:

Creating a safe and reliable physical test system will reduce costs for future thermal validation of EV gearboxes if a strong correlation between the physical test system and the thermal computer model can be identified. This will then allow gearbox manufacturers to reduce the amount of physical testing needed and rely more on computer simulations. This hopefully will then reduce the cost of purchase for consumers of EVs.

Performance Indicator 4
(To be addressed by the faculty adviser).
Outcome (5)

An ability to function effectively on a team whose members together provide leadership, create a collaborative and inclusive environment, establish goals, plan tasks, and meet objectives.

Performance Indicators:

1. Student’s ability to function effectively
2. Student provides task specific leadership.
3. Student creates a collaborative and inclusive environment.
4. Group establishes goals.
5. Group plans tasks

(If you copy and paste from the report, mention Section number or page numbers.)

Performance Indicator 1
(Project’s adviser will determine whether the listed tasks were completed).

Performance Indicators 2 & 5
List all tasks required to accomplish the goals of this project and name the group member responsible for the completion of each task.

<table>
<thead>
<tr>
<th>Task</th>
<th>Group Member(s)</th>
</tr>
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<tbody>
<tr>
<td>Design Steel Bed</td>
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<tr>
<td>Transmission Decision</td>
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<tr>
<td>Determine max torques and speeds</td>
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<tr>
<td>Purchase Parts</td>
<td>All</td>
</tr>
<tr>
<td>Design gearbox mount</td>
<td>Reid Larson</td>
</tr>
<tr>
<td>Design Torque Transducer to Dynamometer Coupler</td>
<td>Austin Owen and Reid Larson</td>
</tr>
<tr>
<td>Relocate Dynamometer Fixture</td>
<td>Austin Owen</td>
</tr>
<tr>
<td>Mount Transmission</td>
<td>Austin Owen</td>
</tr>
<tr>
<td>Align system with couplers</td>
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</tr>
<tr>
<td>Mount Motor/Gearbox</td>
<td>All</td>
</tr>
<tr>
<td>Primary Cooling System Design</td>
<td>Austin Owen</td>
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<tr>
<td>Primary Cooling System Calculations</td>
<td>Austin Owen</td>
</tr>
<tr>
<td>Secondary Cooling System Design</td>
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<td>Secondary Cooling System Calculations</td>
<td>Noah Schultz</td>
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<tr>
<td>Primary Cooling System Construction</td>
<td>Austin Owen and Noah Schultz</td>
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</table>
Validation of Existing Flexible Couplers  |  Austin Owen  
|--------------------------------------|-----------------|
| Motor and Speed Control of Electric Motor  |  Austin Owen and Reid Larson  
|--------------------------------------|-----------------|
| Electrical Wiring for Electric Motor and Inverter  |  Austin Owen and Noah Schultz  
|--------------------------------------|-----------------|
| Schematic of Instruments  |  Austin Owen and Noah Schultz  
|--------------------------------------|-----------------|
| Mount Measuring Devices  |  All  
|--------------------------------------|-----------------|
| Thermal Insulation of Test Gearbox  |  Austin Owen and Noah Schultz  
|--------------------------------------|-----------------|
| Initial System Testing  |  All  
|--------------------------------------|-----------------|
| Complete Setup of Equipment  |  All  
|--------------------------------------|-----------------|
| Testing/Data Analysis  |  All  
|--------------------------------------|-----------------|
| Completion of Project  |  All  
|--------------------------------------|-----------------|
| Presentation  |  All  

Every student must answer the following question (add Student 3 & 4 if needed):

Student 1 name: Austin Owen

For project tasks in which I was not the leader, I provided the following inputs towards their completion:

For the tasks which I did not lead, I provided support by reviewing calculations, reviewing FEA's, and offering alternatives when the current solution was not feasible. This consisted of helping find additional faculty/industrial mentors to help evaluate our engineering processes.

Student 2 name: Noah Schultz

For project tasks in which I was not the leader, I provided the following inputs towards their completion:

For the tasks in which I was not the leader, I provided support by researching other alternative solutions, completed subsections of the topic at hand, and verifying other’s ideas or work. A lot of the project tasks were big enough to need a group effort, so it was easy to constantly check each other’s work. Also, most of the time the group did not proceed with the first idea for many tasks, so it was important for everyone to provide different solutions to the problem.

Student 3 name: Reid Larson

For project tasks in which I was not the leader, I provided the following inputs towards their completion:
For many of the task, I helped give support in the calculations, or aided in general competition of the topics. This varied from checking calculations, helping acquire parts, mounting components, testing design, and more. On many of the projects, it was a group effort and I provided additional input to help progress the project.

**Performance Indicator 3**
For project tasks in which you were the leader, describe the input other group members provided towards the successful completion of these tasks.

Student 1:

In the tasks which I was the leader, the other group members were always willing to contribute, review my work, and offer alternative suggestions. This helped to reduce the amount of rework that had to be done on this project and ensure a high level of quality and fidelity in our work.

Student 2:

In the tasks in which I was the leader, the other group members were always willing to review my work, offer a set of fresh eyes on the issue, and offer changes to the solutions I presented before submission to our advisor or manufacturers. This helped out a ton as I have not had much experience in a field like this which prevented the team from having to redo work.

Student 3:

The other group members helped in many of the programs that I was leader on. They helped create additional designs for the gearbox or couplers, helped to verify numbers and run simulations, help mount components and test fit parts, as well as double checking everything before submission to faculty or manufacturers.

**Performance Indicator 4**
List all goals this project had to satisfy to be considered successfully completed.

1. A test plan that defines the parameters and test conditions required to verify thermal data predicted in the previous project.
2. A test stand design that will produce the data specified by Deliverable 1.
3. A functional test stand that will produce the data specified by Deliverable 1.
4. Preparing the test stand for other individuals to perform testing to correlate the physical laboratory data to the simulation model outputs.

**Performance Indicator 6**
(To be addressed by the faculty adviser)
Outcome (7)

An ability to acquire and apply new knowledge as needed, using appropriate learning strategies.

Performance Indicators:

1. Student’s ability to find information relevant to problem solution without guidance.
2. Student’s ability to identify the additional knowledge needed to complete project.
3. Student’s ability to acquire and apply the additional knowledge needed to complete project.

Performance Indicator 1

Describe what information you found in order to successfully complete the tasks you were assigned in the project.

Student 1:

In order to validate the flexible coupler torque capacity, I used [1] to compare dimensions of existing couplers in the lab to the product data sheet to identify the couple torque capacity. [6] was how I verified the heat capacity of the heat exchanger also already available in the lab. [7]-[11] were used to find information on the specific heat capacity of coolant and oil, approximate the heat generated in the operation of an electric motor, and identify the radiator already existing in the lab. All other existing lab equipment, such as the pumps, flowmeters, ABC-150 battery simulator, and thermocouples needed product validation of their individual specifications and were referenced in the Sources section of this report.

Student 2:

There was information that needed to be found from the start of the project. In order to pick the right material and size for a gasket in between the motor and gearbox, so I found the Mica sheet on a manufacturer website that met the requirements. The cooling calculations needed certain constants and values, so I used a previous heat transfer textbook from a previous class as well as google to find material properties. I also used sources on the internet to determine information for the thermocouples used for the project. Other lab equipment that the team didn’t know the specs for was obtained from the manufactures website often displayed on a spec sheet.

Student 3:

The first information that I used was torque and speed data for the motor and dyno. I then used resources and data about the intermediate transmission to help determine what to select. To design the gearbox mount, I used drawings provided to us to create correct mounting points, as
well as lab measurements to get the correct dimensions. Using online websites and guides, I was able to find the correct controller for the motor and inverter, as well as determine the spline data necessary for the output shaft. Finally, we were able to use documentation in the lab to get the dyno and other components running.

What sources did you use to find this information?

Student 1:

To find the necessary information, I began by using Google to look for the manufacturer’s website for a given product. I then would search their website for product data sheets on the particular item. If only distributors were available, this was deemed second best for obtaining the necessary information. Finally using forums, or other websites was deemed a last resort. All information which was found online has been cited in this report in the Sources section.

Student 2:

To find this information, I began on google to look up certain parts with a specific number to find a spec sheet that would match. Often times some of the specific values I was looking for was not directly displayed on the manufacturer’s website, so I would either reach out over the phone to obtain information or email the company. Sometimes the information was not on the manufacturer’s website so I would look for a distributor for the part specs I was looking for. Finally, if none of those options were available other professionals within the university were contacted by the team.

Student 3:

**Performance Indicator 2**

Describe what additional knowledge/skills you needed to acquire or improve in order to successfully complete the tasks you were assigned in the project.

Student 1:

Some of the major areas where I needed to acquire or improve my knowledge/skills to complete my tasks was with understanding and simulating FEAs on the designs our team created for the gearbox mounting plate, gearbox output shaft, and gearbox differential. Additionally, I required expanded knowledge when designing and evaluating the performance of the primary and secondary cooling systems. Finally, when working with the setup for the test cell.
instrumentation, I needed to improve my knowledge with *using National Instruments LabVIEW*. For many of these areas, I was able to work with faculty at WMU or other professionals to gain more experience.

Student 2:

Some knowledge/skills I needed to acquire or improve on were my knowledge of heat transfer for the cooling system calculations. Another part of my knowledge I needed to expand on was my instrumentation skills, because I have only had basic courses of instrumentation. It was helpful to have other professionals and faculty through WMU that were knowledgeable in some of these areas.

Student 3:

The main knowledge that I had to obtain was the certain material properties for the materials we used to create certain parts, as well as guidance on how to better conduct the FEA simulations on the parts. I also needed to learn some basic electronic circuit creation, as well as computer programming.

**Performance Indicator 3**

Describe what approach/process you followed in order to acquire or improve the additional knowledge/skills you needed.

Student 1:

The approach I used to acquire/improve the knowledge/skills I needed was to formulate the problem I was facing into a manner that another person unfamiliar with the project would understand, identify a person who may be able to offer assistance, create a list of questions I wanted to ask the individual, ask numerous questions and take notes based on the responses I received, identify a different individual if the previous person was not the correct one to ask. Finally, I would take the responses received and reevaluate if I now possessed enough knowledge/skill to continue or continue to ask for assistance.

Student 2:

The most helpful approach for myself to improve these skills were to work with another team member or a faculty member that had the knowledge or skill I needed. Often, I would come up with the questions I had or information I was unsure about and discuss potential solutions with people that were more knowledgeable on the topic. When there wasn’t an available person with this knowledge, I would turn to online sources to try to figure out what the best way to go about a problem is. After consulting these sources, I would take another look at the problem and reassess it, and from there I would see if I needed more help.
Student 3:

The knowledge that I acquired throughout this project came from various places. Some of help came from internet research and documentation, but a large amount came from interactions with company sources, contacts, and outside people. Simply reaching out in a call or email I was able to get a lot of the knowledge that I needed, or resources to help me get what I needed.