MAE 4291: Supervised Senior Design Experience, Fall 2023

DESIGN OF AN EDDY-CURRENT ELECTRIC MOTOR DYNAMOMETER

For use by the Cornell Electric Vehicles Project Team

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19 December 2023

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Executive Summary

The executive summary is intended to satisfy the requirements outlined by the Senior Design Form. Following this section is a more in-depth technical report with figures showing the design itself. In particular, the rest of the report is crucial towards understanding the details of the design.

1. What are the desired function(s) of your design?

The goal of this project is to design a dynamometer in order to characterize the efficiency of the motor used by my project team, Cornell Electric Vehicles. Beyond this, this dynamometer is intended to double as a motor testing-benchtop for our Drivetrain and Electrical teams, based on past experiences trying and failing to test the motor with incremental loads before installation in the car. While dynamometers currently exist in many forms, they are generally very expensive and meant for applications much larger than both the size of our vehicle and the general loads under which it operates. For this reason, this senior design project is aimed to create a testing system which is affordable and more relevant for CEV's current vehicle (dubbed "The Chicken Coupe").

2. What constraints related to the main function(s) must your design satisfy?

It is important for this design to be easily manufacturable. The goal is to do the majority- if not all of- the manufacturing in-house through the Emerson Machine Shop and the RPL. Even with off the shelf components and estimated labor costs, the goal is for my dynamometer to be significantly cheaper than what is currently on the market (their high prices can be explained by the fact that they generally test much larger, more intense systems). Beyond this, the design should be adaptable, for use with multiple motors in the future. Ideally, it fits on a table/benchtop.

Overall, though, the main function of the design is to output torque as a function of (angular) velocity, which can be used to track power generated by the motor over time and at different loads. Ultimately, this data will be used to figure out the efficiency of the motor as a function of power output.

3. What are the performance objectives of your design? (Give quantitative metrics as much as possible).

The dynamometer is intended to be able to apply a maximum of 15-20 Nm worth of torque. This number was chosen based on the Chicken Coupe, which takes roughly 12 Nm of torque to overcome rolling resistance and begin driving. A larger margin was chosen in order to hopefully test a wider range of systems and motors in the future. Given that this iteration of the design was modeled after our current motor, the design must be able to support its weight (3.26 kg) at a minimum. Ideally, the design supports a weight of at least 7kg for a factor of safety greater than 2. It should also be able to withstand the motor's worst case bending moment, stall torque at the shaft.

As the final design involves electromagnets, temperature must be closely monitored so as not to melt the components at hand (in particular, the aluminum rotor, which would melt at approximately 660°C (or roughly 933°K). Temperatures should fall far below these critical points.

4. What alternative design concepts were considered?

There are several styles of dynamometers used to test electric motors. Three different designs were considered for this project: the friction brake dynamometer, the DC motor dynamometer, the eddy current dynamometer.

The friction brake dynamometer, as the name suggests, relies purely on friction in order to provide a braking torque onto a spinning rotor. This is usually done with wooden blocks or some similar material. The DC motor dynamometer couples the motor to be tested with a secondary, more powerful motor which backdrives the testing motor. Lastly, the eddy current dynamometer uses electromagnetic eddy currents to induce a braking force on a spinning rotor, and that load gets measured. All three dynamometers have similar methods of torque measurement; the primary difference just comes in the source of braking torque to oppose the output torque of the motor.

Of these three, the DC motor dynamometer was ruled out early on due to its high costs. Between the friction brake dynamometer and the eddy current dynamometer, the two designs had different RPM ranges to produce usable data. The friction brake dynamometer was useful at high RPM, while the eddy current dynamometer was useful in the low to mid RPM range, under which the Chicken Coupe falls.

5. What analyses were used to select among these alternative design concepts?

Rough sketches of both the friction brake and the eddy current dynamometer were made. Initially, the friction brake dynamometer was more appealing due to its ease of manufacturing; however, a former member of CEV attempted this design without success. For both a unique design challenge and a more reliable design overall, the eddy current dynamometer was then favored.

However, logic and evidence must ultimately be the main supporter of such a large design decision, so a decision matrix was created to compare the advantages and disadvantages of each design. The eddy current dynamometer, of the three designs, was the most reliable at low and mid range RPMS, making it the most applicable for CEV's load cases. The Chicken Coupe travels at a max of 10 m/s, which is less than 1000 RPM at the motor shaft, nearly half of what car motors tend to output (and which is thus what market dynamometers tend to test). Since the friction brake dynamometer makes it difficult to precisely apply a specific load, the eddy current dynamometer was ultimately chosen for its precision while also being of a reasonable cost.

6. What industry or society standards were used to inform or evaluate your design?

Industry standards have pushed me to look into ASME and other standards which may apply to my design. Based on past jobs and internships, I have become well versed in ASME Y14.5 and while my drawings do not use GD&T due to the known precision of the materials and machine shop available to me, it has nonetheless helped me in making good engineering drawings. ASME/ANSI B29 was also used to define the sprocket geometry, both in the Chicken Coupe and for this dynamometer setup.

Societal standards have pushed me to consider adding dedicated safety features for future work, such as a chain guard and a dedicated E-Stop in case of emergency. Beyond that, societal standards have let me to consider how best to minimize waste, particularly in the manufacturing process. That is, how to make weight reductions while also keeping in mind how much material will be cut away and wasted, to try and minimize this and help with environmental impact.

7. Which concepts or skills learned in your coursework were applied to the design? Projects are expected to make substantial use of MAE and related ENGRD classes. Please provide a list with each entry providing the department and number of the course, plus a brief description of the particular concept or skill used.

Almost every course I have taken in my time at Cornell has in some way influenced this project by teaching me fundamental engineering practices which are now being applied.

PHYS 2213 (Electricity and Magnetism) gave me all of the tools needed to relate eddy currents to a quantifiable braking torque, upon which this entire design relies. Concepts such as Ampere's and Maxwell's laws allowed me to do the calculations necessary to make progress with my design.

MAE 2020 (Statics) taught me the fundamentals of models and structural analysis using free body diagrams, force balances, and more which were all applied here from the beginning.

MAE 2250 (Mechanical Synthesis) taught me about mechanical design considerations down to which fasteners to use and when, while also improving my ability to design for manufacturing.

MAE 3260 (System Dynamics) and MAE 4780 (Feedback Controls) are what inspired me to try and characterize our team's motor. A future goal of mine is to use this dynamometer as a way of testing feedback loops alongside our electrical team, for more efficient control of the motor overall.

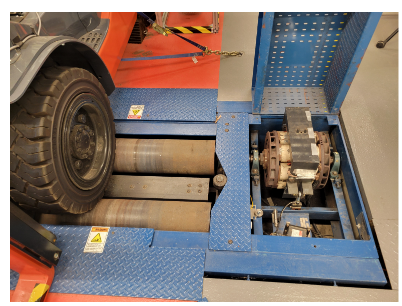
Lastly, MAE 4272 (Fluid and Heat Transfer Laboratory) taught me about experimental design, and even gave me experience with both torque brakes and an eddy-current dynamometer, albeit on a much larger scale given that it was designed for a forklift. Seeing the forklift dynamometer design, although it was quite late into my own design process, helped me in validating my methodology and looking for ways to improve. Experiments in the wind tunnel also informed my load cell selection, as I was able to experience firsthand the drawbacks of using a load cell rated for a much higher load than what it would be tested with, and how that can make data more difficult to process. As a result of this, I was willing to spend more money on a load cell more closely rated for what torque range this dynamometer would output.

8. Evaluate your design, relative to its function(s) and constraints. How well did your design meet each of the performance objectives? How well does your design compare to other, existing solutions to the problem?

The final design has 5 main components, as well as the electrical hardware needed: the rotor/stator subassembly, the load cell subassembly, the motor mount subassembly, and the structural components.

My design was able to reduce the cost of a commercial eddy current dynamometer significantly, as they can often run for several thousand dollars a piece without including the cost of the motor to be tested or any additional adapter supplies or power sources. Likewise, it fits within a 2ft by 3ft area, meeting the requirement of being small enough to fit on a table and serve as a benchtop testing setup. Almost all parts can be manufactured by hand in Emerson or the RPL, which was also a large goal of the project; some parts such as the sprockets will need water-jetting, but this is also easily accessible at Cornell and affordable through LASSP. Design for manufacturability played a large role in simplifying the design in order to make this feat possible.

Some examples of market dynamometers are shown below. Many of them are either too physically large, too expensive, or meant for load cases so much higher than the Chicken Coupe that running them with 15-20 Nm of torque would likely produce incomplete data. At $1134.01, my dynamometer design is much cheaper than what is offered commercially, and it will almost entirely be manufactured in-house.

	
AW Electric Motor Dynamometer, quoted for several thousand dollars [Source]	*Forklift Dynamometer, MAE 4272*

Ultimately, the design is predicted to be able to output a maximum of 15 Nm of braking torque, which is still larger than the roughly 12 Nm of torque that the Chicken Coupe requires. Given that the team is unexpected to ever design for torques larger than this range, the goal of adaptability is also met. The system is also designed to allow for any ratio of sprockets (so long as neither is so large that their radii interfere), which can allow for different gear ratios to be tested by the team and even potentially a full transmission in the future.

9. What impact do you see your design, if implemented, having upon public health, safety, and human welfare, as well as upon current global, cultural, social, environmental, and economic concerns?

If implemented, the goal of this design is to make a more accessible motor characterization setup for educators, students, and hobbyists who may not need or be able to afford larger setups such as what is shown above. High torque motors are also used outside of the automotive industry, such as the healthcare industry through wheelchair motors. It is crucial to test something such as a wheelchair motor thoroughly, and make them durable and highly efficient; an adaptable dynamometer such as this one could be used to accomplish such tests, ideally. A main goal of this project was accessibility, adaptability, and affordability in order to positively impact society.

10. What format did your design take? For example, is it a complete set of CAD drawings, a working prototype, a full finished product, a system configuration, a process map, or something else?

The final format of this project is a full CAD assembly of the design, alongside a manufacturing plan and Bill of Materials (BOM).

11. Describe each student's role in the design project if it was a group project.

This was not a group project.

Introduction

The purpose of this project is to develop a robust motor testing setup, used to evaluate general performance under load as well as overall efficiency. This is for use by the Cornell Electric Vehicles Project Team. While projects with a similar goal have been attempted in the past, only one was manufactured and it did not succeed. The proposal to be outlined in this project is for an entirely different methodology and dynamometer design.

To define the context of the overall system, initial calculations (to be reviewed in the Design Requirements section were based off of our team's most recent vehicle (dubbed "The Chicken Coupe") and its 24V brushless DC motor. The system's drivetrain works from the inside out, transmitting power from the motor and amplifying its torque via a chain and sprocket system, before being transmitted outward through a differential and to each wheel, as described in Figure 1 below:

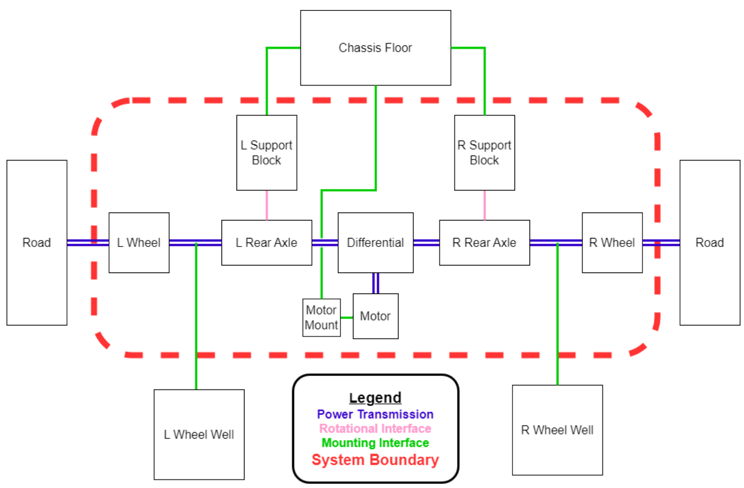


Figure 1: Propulsion Diagram

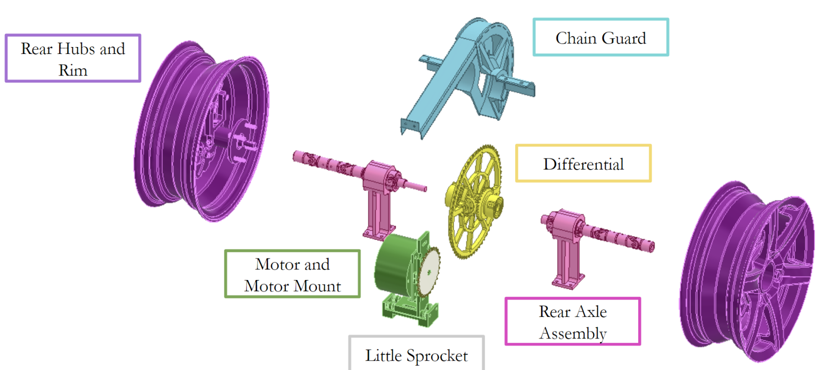


Figure 2: Exploded view of current powertrain design

Design Requirements

The dynamometer must be able to output, read, and control a range of torque up to approximately 12-20 Newton-meters (based off of vehicle dynamics, described in Appendix A3).

Aside from the basic dynamometer function of relating torque to power, the goal of this project is to create a dynamometer which doubles as a benchtop setup for the team's drivetrain subsystem. To do this, the design should be capable of mounting various motors, multiple gear ratios, as well as be able to apply loads incrementally. A more long term requirement of the system is to develop a user-friendly GUI meant to easily visualize the data.

This particular iteration of the dynamometer is meant to be modeled after the Koford 129H42A/A20 motor, which is in use in the current car. The motor has the following specifications:

Weight	3.26 kg
Supply Voltage	24V
Max Continuous Current*	20A
Max Power Output*	480W
Max RPM	1040
Stall Torque	7.96 Nm
Mechanical Time Constant	1.2 ms

Table 1: Motor specifications

*requirement set by Electrical subteam, not motor manufacturer

This means the system, and in particular any bearings used, must be able to support at minimum the weight of the motor with a factor of safety included. The motor mount should be able to withstand the worst-case in which the motor reaches its stall torque and a large bending moment is created. It is also important to design for safety throughout the system. As will be outlined below, several different dynamometer designs involve braking methods which may cause large losses of heat. As many components within the system will be made of aluminum, it is important to provide heat sinks to avoid overheating, which can be dangerous. Aluminum in particular has a melting temperature of 660°C (993°K), and plastic parts can have much smaller melting points. It is important to design a system which never exceeds a temperature of a few hundred degrees Celsius, and have temperature monitoring technology.

Before continuing, it is also important to acknowledge that there are also commercially available solutions. However, many of these solutions run for a minimum of a thousand dollars, and/or are meant for much larger magnitudes of loads and RPMs. This dynamometer is meant to combat these cost concerns, while also being tailor-made for CEV's goals.

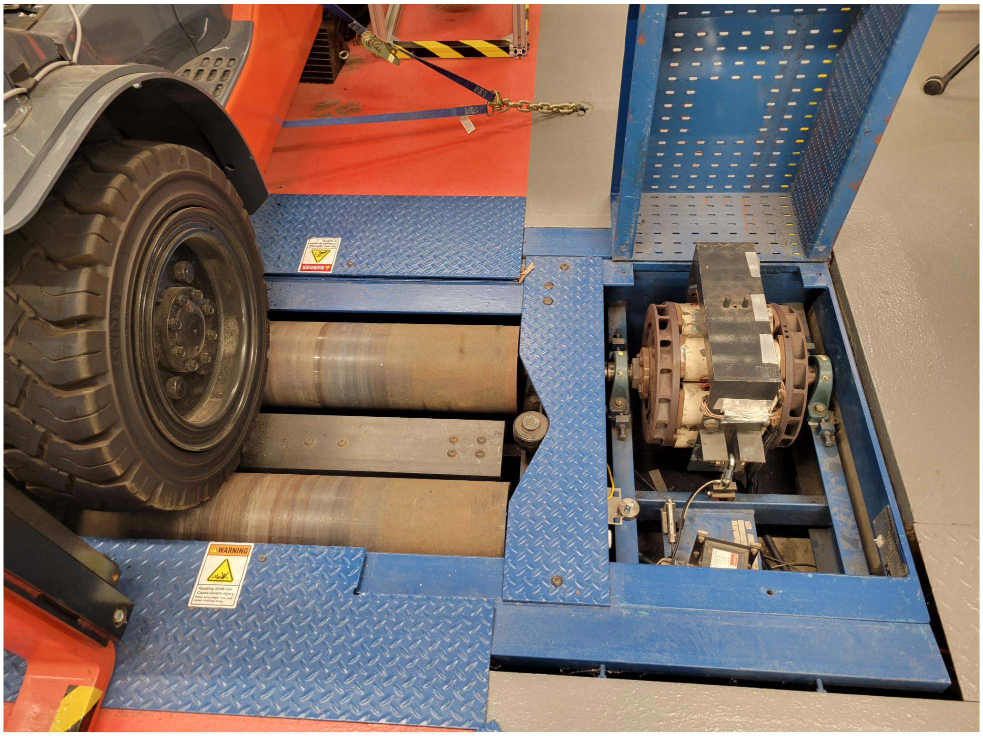


Figure 3: Example of an eddy current dynamometer, as used by MAE 4272 in the Forklift lab. A forklift is not only significantly larger and heavier than the Chicken Coupe, but undergoes very different load cases.

Alternate Designs Considered

There are three primary types of electric motor dynamometers used by industry today:

Prony/Friction Brake Dynamometer
This design relies on two blocks pressing against a rotor, and measuring the resultant traction force to determine power, based on the relation P=F*v. Velocity is controlled directly via the motor, while force is dependent on how tight the brake blocks are relative to the rotor, often referred to as a 'flywheel.' Force is generally measured via load cell using some known length of lever arm. A typical prony brake setup is diagrammed below:

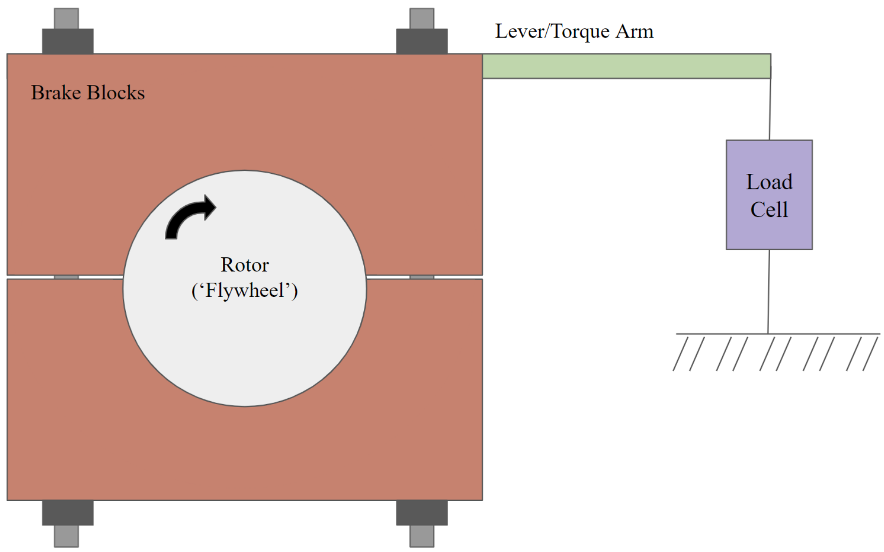


Figure 4: Basic principles of the prony brake dynamometer design.

Prony brake dynamometers are some of the most simple to manufacture, and thus are cost effective. However, because force applied is purely controlled by physical tightening of the blocks, these dynamometers can be unreliable at low RPM and experience heavy vibration.

DC Motor Dynamometer
The DC motor dynamometer was arguably the simplest alternative design considered. It consists of coupling the motor to be tested with a second DC motor with known characteristics. The secondary motor acts as a brake, where RPM is proportional to braking torque. Torque is measured in the same way, with a load cell and a known lever arm. While this method is the simplest to design, it is also quite expensive as it requires a powerful secondary braking motor.

It, like the friction brake dynamometer, is also intended for high RPM, which the Cornell Electric Vehicles team does not necessarily consider relevant.

Eddy Current Dynamometer
The final decided upon method is the Eddy Current dynamometer. Working principles of the dynamometer will be discussed further in the Design Overview section of the report, though to summarize, this style of dynamometer relies on generating electromagnetic back currents to create a variable braking force used to stop a rotor. Torque is, again, measured via a load cell and known lever arm. Braking torque itself is varied through voltage supplied to the electromagnets.

Based on research into all 3 methods, a decision matrix was made:

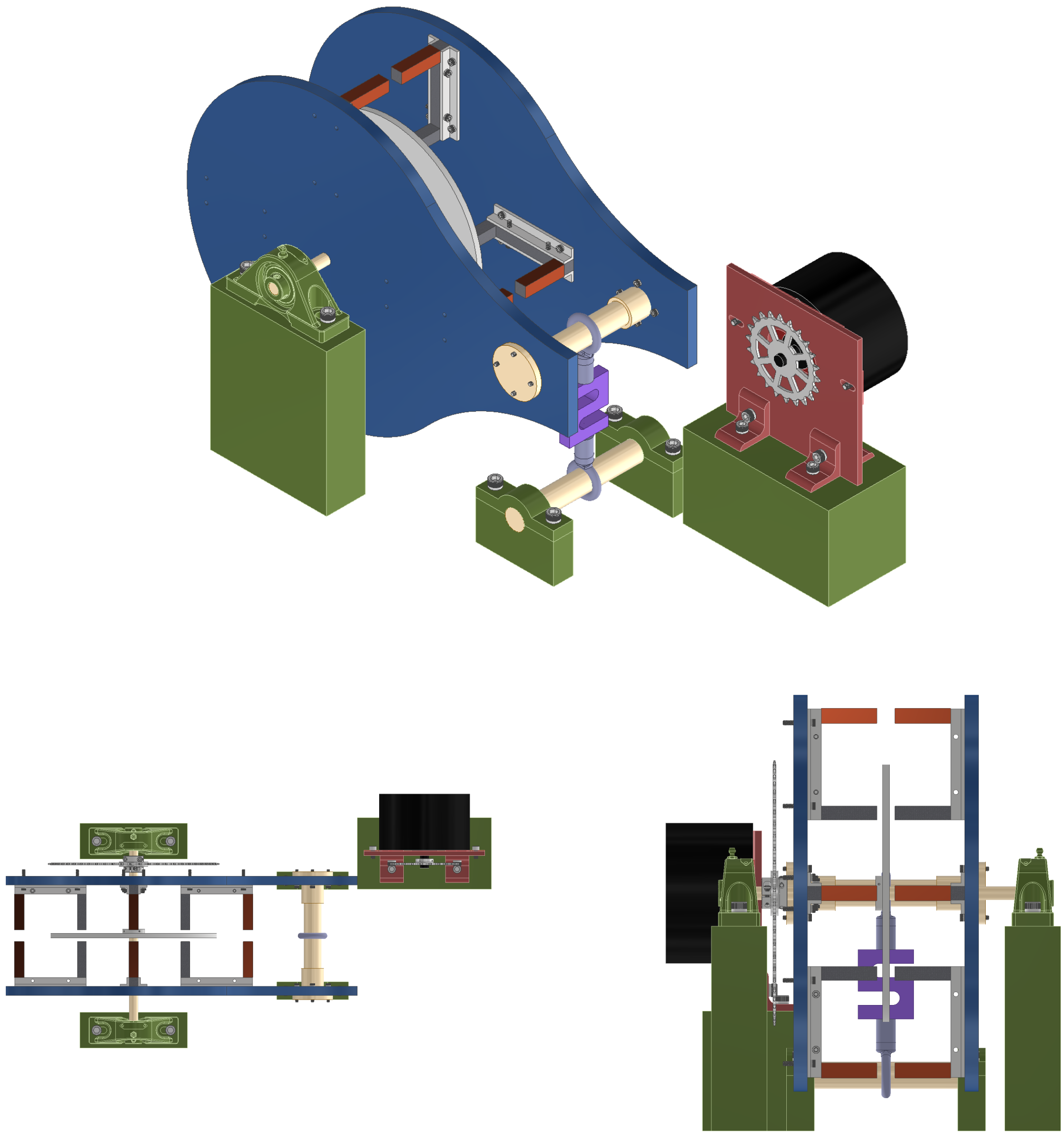
	Pros	**Cons**
Friction Brake	- Ease of assembly - Affordable	- Unreliable at low RPM
DC Motor	- Ease of assembly, only need to control the motors themselves	- Would be very expensive to buy a motor - Unreliable at low RPM
Eddy Currents	- Reliable for a larger range of RPM - Easy to modify into a full benchtop	- Can be expensive due to electromagnet materials

Table 2: Decision Matrix comparing dynamometer designs

Ultimately, the eddy current dynamometer design was selected because while this design can be more complex due to the electromagnets, it is generally considered the most reliable for low RPMS and more reliable in varying loads, since it does not rely on physical principles as the prony brake design does. Beyond this, this method was in part selected due to the unique design challenges it posed and strong application of concepts learned throughout college.

Design Overview

The final design can be seen below:



Figures 5-7: Isometric (top), Top-Down (left) and Back (right) views of the design

The design will be reviewed in several categories: the electromagnetic/eddy current principles, rotor and stator design, torque measurement methods, general structural design, and finally electrical design. The first five of these can be seen in Figure 8, an “exploded view” of the design.

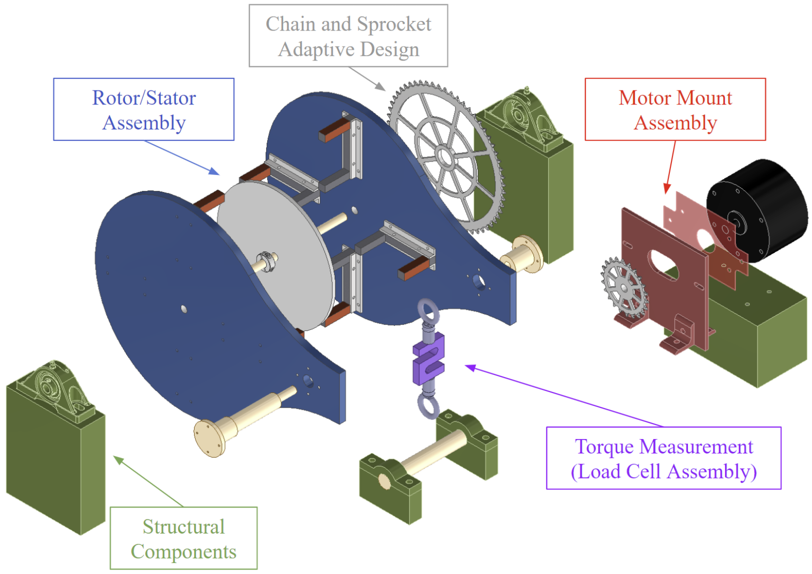


Figure 8: Exploded View. Electrical components and chain not shown; fasteners excluded.

Eddy Current Working Principles

Eddy currents are closed loop currents which circulate within conductor materials in response to changing magnetic fields. The direction of the induced current will oppose that of the change in flux which caused it, which is the primary characteristic of this phenomenon which will be utilized by the dynamometer.

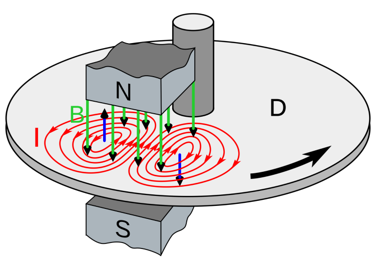


Figure 9 :Eddy Current Model, showing the currents (red), magnetic field (green), and poles. [Source]

The key components of an eddy current dynamometer are the stator and the rotor. The rotor, made of a conductive material, constantly rotates at a speed dependent on the RPM output of the motor shaft (and, in the case of this specific design, the gear ratio). The rotor rotates in between two stators, which contain cast-iron core electromagnets in order to recreate the eddy current effect shown in Figure 9.

The amount of braking torque generated by the eddy current is highly dependent on the design of the rotor and stator, due to the fact that power dissipated by the rotor-stator setup is directly proportional to braking torque, which can be used to trace back overall motor efficiency. This braking force can be derived as follows:

Each magnet within the stator can be modeled as shown in Figure 10. Key characteristics include *N*, the number of coils per magnet; *r*, the radius of the magnet core; *d*, the thickness of the rotor; and *l,* the total air gap between each magnet (where air gap on each side would be (*l*/2)-(*d*/2) assuming everything is perfectly centered).

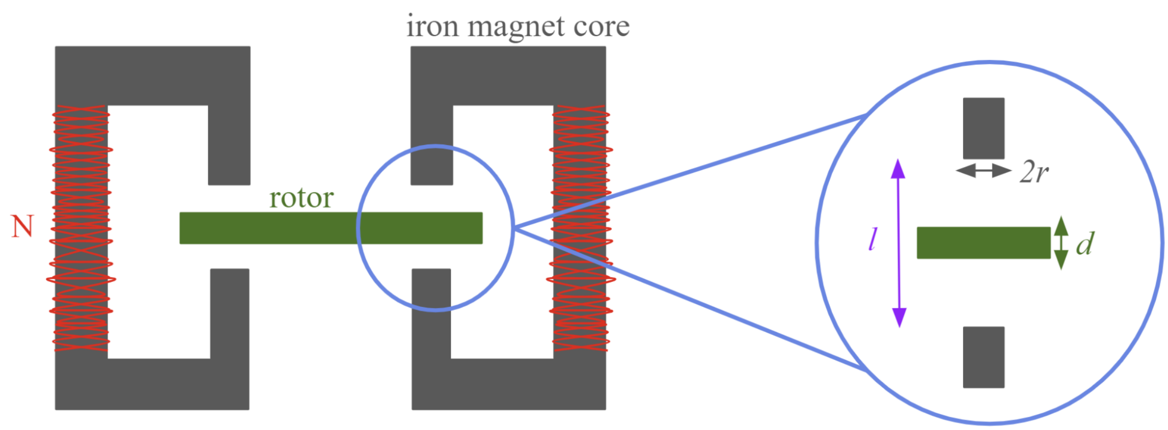


Figure 10: Stator/Rotor magnet model used in derivations

Starting from Ampere's Law (1), and magnetic flux density (2), the flux per coil in the dynamometer's stator can be derived:

$$\oint Hdl = NI \quad (1)$$

$$\Phi = BA = \frac{\mu NIA}{l} \quad (2)$$

Then, define magnetic force $F_{mag} = NI$ and reluctance $R = l/\mu A$. (3-4)

From equations 3-4, flux per coil Φ_c can be defined as

$$\Phi_c = \frac{F_{mag} - F_{eddy}}{R_c + R_{air} + R_{rotor}} \quad (5)$$

Coil reluctance is assumed to be negligible here, leaving (where μ_0 is the relative permeability of air) .

$$R_{total} = R_{air} + R_{rotor} = \frac{l-d}{\mu_0 A_{magnet}} + \frac{d}{\mu_{rotor}\mu_0 A_{rotor}}. \quad (6)$$

Then, calculating the resultant force of the eddy currents,

$$F_{eddy} = Jrd \tag{7}$$

Where the current density J can be written as $J = \sigma a(\overline{\omega} x \overline{B}) = \sigma a(\omega x \frac{\Phi_c}{A})$ from (2).

a is defined as the distance from the center of the rotor to the magnet center, which here I will assume to be equal to the rotor radius or one half the diameter, *D/2* . From this,

$$F_{eddy} = NI - \Phi_c R_{total} \tag{8}$$

Combining equations (5), (6), and (8) results in

$$\Phi_c = \frac{NIA_{rotor}}{R_{tot}A_{rotor} + \sigma(D/2)dr\omega} \tag{9}$$

Power dissipated is the actual desired quantity from which braking force, and thus motor torque, can be derived. Here, the volume of the rotor is just assumed to be that of a perfect cylinder.

$$P_{diss} = \rho J^2 V_{disc} = \rho(\sigma \frac{D}{2} \omega B) A_{rotor} d \tag{10}$$

$A_{rotor} = \frac{\pi}{4} D^2$, so

$$P_{diss} = \rho\sigma\omega B\pi(D/2)^3 d \tag{11}$$

And, from (11),

$T = \frac{P_{diss} x}{\omega}$, where x is a known lever arm distance (12)

This conclusion in equations (11) and (12) means that rotor radius and thickness are the most important parameters to optimize.

Rotor and Stator Design, Optimization

Stator Design

Several options were considered for the stator design, using various placements of the electromagnets relative to the rotor. Ultimately, a C-shaped magnet design was chosen, with the rotor being in between the two opposing stator magnets with a set air-gap. Each magnet is mounted to the stator with aluminum brackets and ¼-20” threaded fasteners with a Nylock nut at the other end for increased security.

The walls of the stator itself serve two purposes: mounting the four electromagnets, which are each 90 degrees apart from one another, as well as mounting the load cell. It is important for torque measurements that the load cell is a known distance away from the rotor, where torque is being applied. For this application, 10 inches was selected. The goal of the wall was for it to be light, but strong due to the weight of the magnets mounted on it. Ultimately, the goal is to 3D print the stator walls out of Onyx, a carbon-fiber filled nylon composite material. Aside from this, the entire rotor-stator subassembly will be supported by large load-bearing mounted ball bearings, which will ease some of the load off of the stator walls itself.

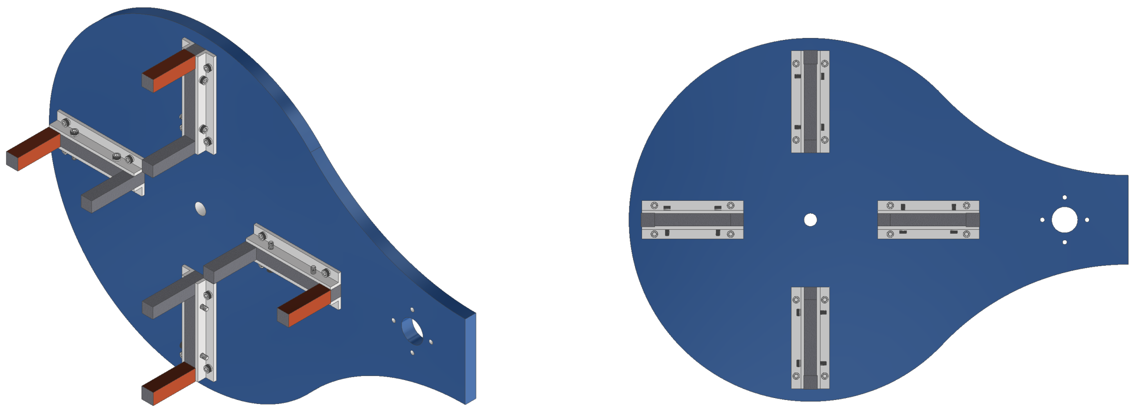


Figure 11-12: Stator and Magnet Designs, Isometric (Left) and Head-On (Right) Views

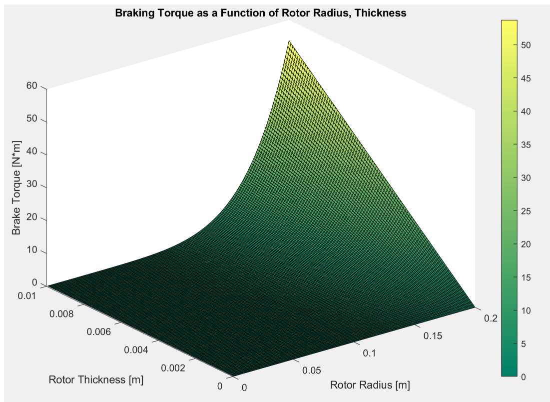
Rotor Thickness and Radius

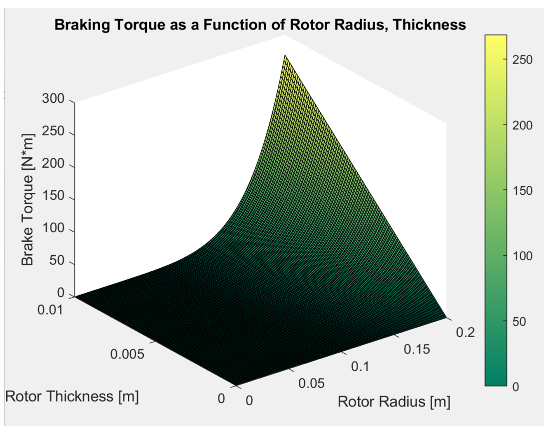
Based on equations (11) and (12) above a Matlab Script was written to determine an optimal rotor radius and thickness to maximize braking torque output while minimizing mass and other characteristics. Normally mass reduction would occur by making certain non-structural cutouts on the rotor, for example a design with spokes. However, because power is directly proportional to the rotor surface area, these mass reductions were ultimately not used in order to maximize usable surface area.

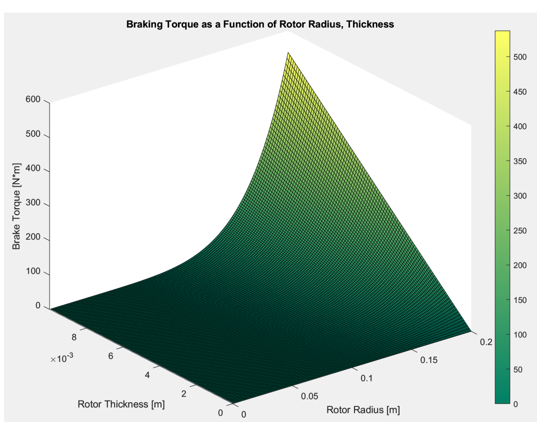
Certain assumptions were made for this optimization. Namely,

- Air gap, *l*, was set such that there would be 5mm between the rotor and the magnet on each side
- Angular velocity was calculated based on a set steady state linear velocity of 10 m/s, based on the fastest velocity of the team's current vehicle
- The dynamometer was set to have 4 electromagnets total, to have symmetry but also be cost efficient
- The rotor material was decided to be Aluminum, specifically AL6061-T6. Copper was also considered, but aluminum was ultimately chosen because it is significantly lighter but has comparable conductivity.

From the above assumptions, as well as equations (11) and (12) in the previous section, braking torque was plotted as a function of rotor radius and thickness. 6 total cases were tested, for 3 different values of N (the number of coils per electromagnet) and two different magnet core diameters, 0.5 inches and 1 inch. The results are shown in Figures X-Y below. The full script can be found in Appendix A2.

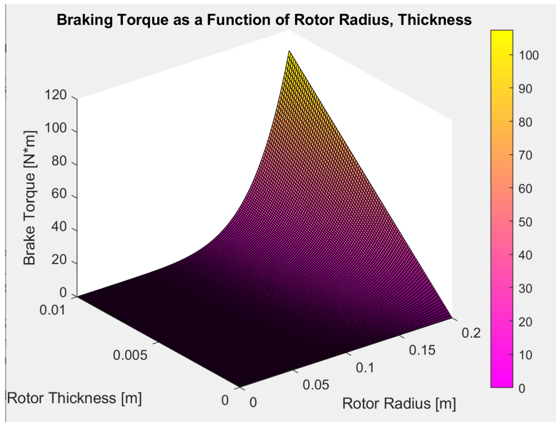
<table>
<tr><th colspan="2">$\phi_{magnet} = 2.0\ inches$</th></tr>
<tr><td></td><td>N = 100 coils per magnet
R = 6.85 in
d = .25 in

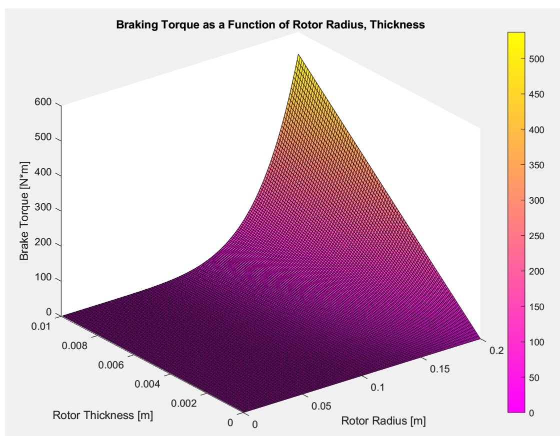
For ~15 Nm torque</td></tr>
<tr><td></td><td>N = 500 coils per magnet
R = 5.2 in
d = .25 in

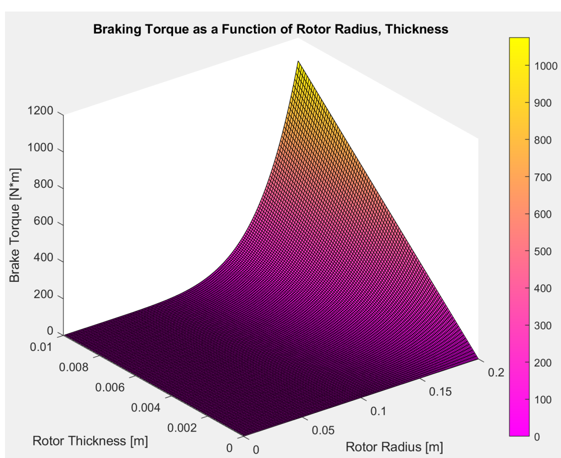
For ~15 Nm torque</td></tr>
<tr><td></td><td>N = 1000 coils per magnet
R = 4.72 in
d = .25 in

For ~15 Nm torque</td></tr>
</table>

Figure 13-15: Maximum Braking Torque as a function of rotor thickness and radius, for a magnet core diameter of 2 inches.

<table>
<tr><th colspan="2">$\phi_{magnet} = 1.0\ inches$</th></tr>
<tr><td>
</td><td>N = 100 coils per magnet
R = 6.3
d = .25 in

~for roughly 15 Nm torque</td></tr>
<tr><td>
</td><td>N = 500 coils per magnet
R = 4.64
d = .25 in

~for roughly 15 Nm torque</td></tr>
<tr><td>
</td><td>N = 1000 coils per magnet
R = 4.45
d = .25 in

~for roughly 15 Nm torque</td></tr>
</table>

Figure 16-18: Maximum Braking Torque as a function of rotor thickness and radius, for a magnet core diameter of 1 inch.

In all cases, for the range of torque output less than roughly 20 Nm, rotor thickness had little effect on overall torque produced (at higher torques, it had an exponential effect, however these operating torques are magnitudes higher than this application will ever need). For this reason, a baseline thickness of .25 inches was decided, primarily due to its ease of purchase and manufacturability. The case of a smaller magnet diameter of 1.0 inches was then chosen, based on the fact that it essentially doubled torque output in all three cases. Lastly, the N=500 coils per magnet was chosen for an overall rotor diameter of 4.64 inches was the decided upon design. The smaller radius case with N=1000 coils was not chosen because the magnet size would have had to increase by a significant amount in order to have 1000 coils, increasing cost and overall size of the design. The additional roughly .2 inches in radius added by making N=500 was more beneficial for manufacturing.

Torque Measurements

Torque measurements will be taken by applying the principle T=F*d to a force reading taken from a load cell at a known distance from the rotor-stator subassembly. In particular, the CALT DYLY 10 kg S-Beam Load Cell is to be used (see BOM for more information). A low-load capable load cell was chosen despite being slightly more expensive than commonly found load cells in order to try and minimize the uncertainty which tends to come from measuring small loads with high-rated load cells. 10 kg is much closer to the raw braking force expected to be output by the dynamometer, and should produce more accurate measurements overall.

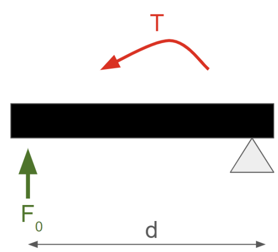


Figure 19: Free Body Diagram of Load Cell when rotor is spinning.

The load cell itself will be mounted to the stator assembly as well as the baseplate with eyebolts and a custom designed mounting rod, as is overviewed in the Structural Components section.

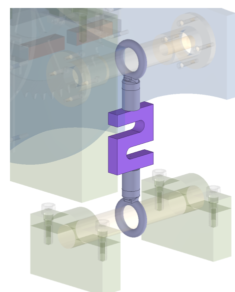


Figure 20: Load Cell Assembly

Adaptive Design

Motor Mount

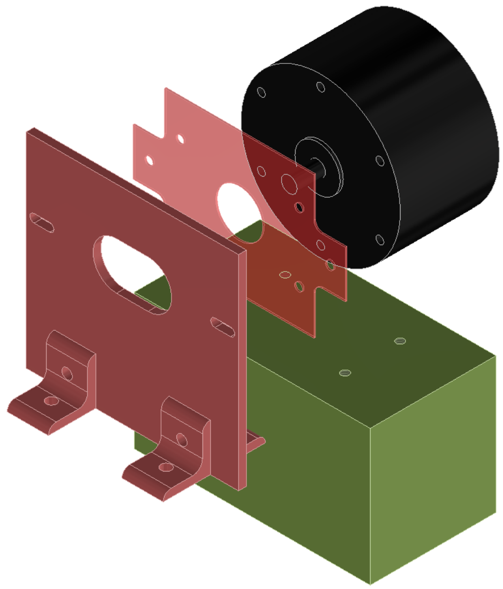


Figure 21: Exploded view of motor mount design (fasteners excluded)

The motor mount, aside from serving as structural support for the motor, is also intended to allow for chain tightening. The two slots on the motor mounting block (opaque red block) allow for translation in the plane parallel to that of the sprockets. 0.5 inches worth of movement is allowed, in order to increase tension from the chain until satisfied.

Secondly, the mount is made to be adaptable to other (similarly sized) motors. The motor itself interfaces with a Stainless Steel flat plate (translucent red piece). This serves two benefits: firstly, the motor itself has greater surface area contact with the rest of the mount, which aids its overall strength. Secondly, new flat plates can easily be manufactured via water jetting in order to service other motors (without modifying the rest of the mount).

Chain and Sprocket

The chain and sprocket design was adapted from the existing Chicken Coupe drivetrain. The tooth design itself follows the ANSI B29 Standard, shown below in Figure 17. The key parameter is pitch, which was chosen based on common bike chains.

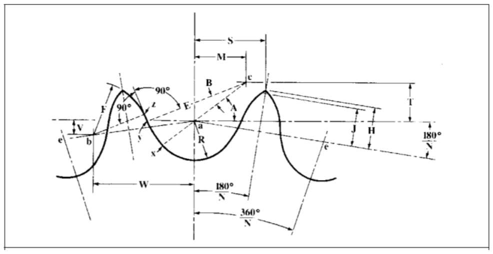


Figure 22: Standard for Sprocket Design [Source]

The two main goals of the sprocket design were to make the sprockets have minimal mass but good clamping strength onto the shaft. Mass cutouts were based on the existing Chicken Coupe Differential Sprocket design, upon which I conducted static structural analysis on in January of 2023 and concluded it to be plenty strong. Similar mass cutouts were made on the small sprocket.

Clamping to the shaft will be done with two cone point set screws, placed 90 degrees apart from one another in order to end up with maximum force overall. The cone point set screws were selected due to their reliability during high vibration scenarios. For the larger sprocket, because there is already a bearing inside, shaft collars will be used to hold it in its location in order to avoid asymmetry (for ease of manufacturing). A tradeoff of this is that the shaft collars must be tightened very carefully, since misalignment of the sprockets can lead to the chain snapping off. However, the load bearings, to be discussed in the Structural Components section, will hopefully absorb some of the vibration rather than the shaft collars.

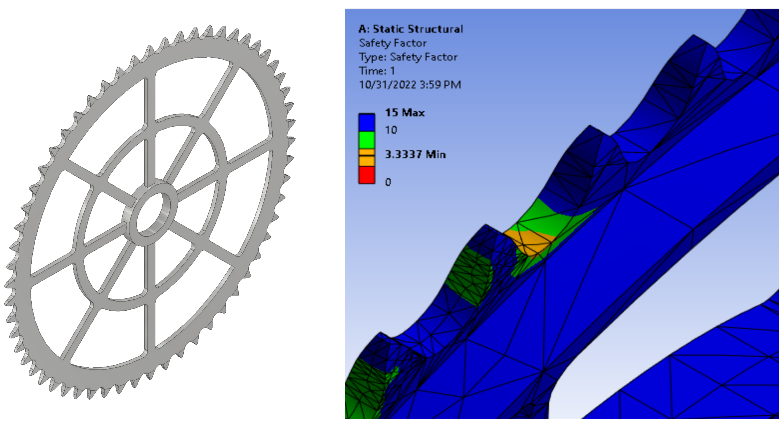


Figure 23: Sprocket Design (left) and analysis done on a similar design in early 2023

Master Model [CAD Strategy]

A key part of the design process involved making the CAD as adaptable as possible. This was especially important because the rotor design was parameterized, but the entire stator design (namely the size and spacing of the electromagnets) was dependent on the radius of the rotor.

In order to achieve this level of adaptability, a “Master Model” was used. This took the form of a part file (.ipt) in Autodesk Inventor with several named parameters, axes, and planes from which all rotor and stator parts, as well as the assembly constraints, were designed.

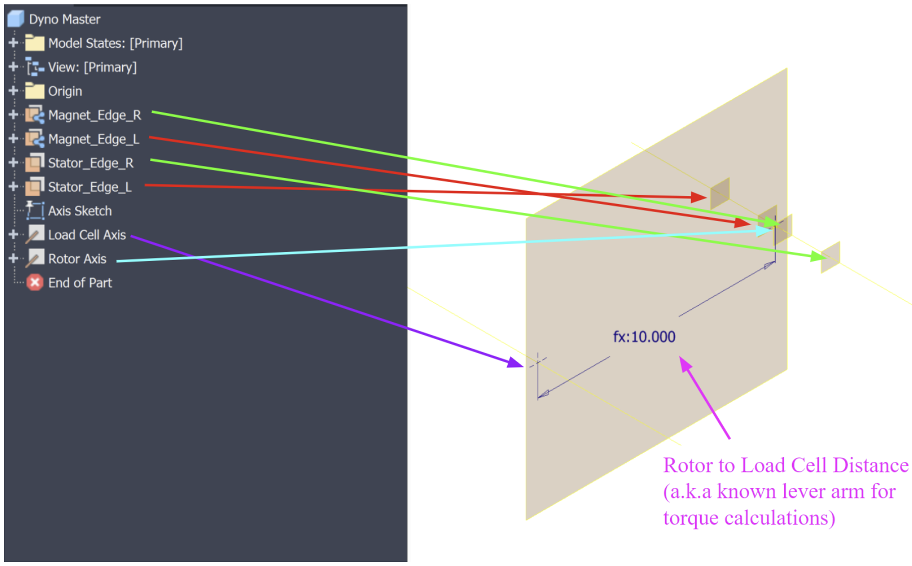


Figure 24: Planes and Axes within the Master Model. These were based off of parameters in Figure 25 below, and used to constrain the overall assembly seen in Figure 4

.

	Parameter Name	Consumed by	Unit/Type	Equation	Nominal Value	Tolerance	Model Value
	Model Parameters						
1	d3	Magnet_Ed...	in	(air_gap / 2 ul + rotor_t / 2 ul)	0.325000	<Default>	0.325000
1	d4	Magnet_Ed...	in	-(air_gap / 2 ul + rotor_t / 2 ul)	-0.325000	<Default>	-0.325000
1	d5	Stator_Edge...	in	magnet_core_length	2.000000	<Default	2.000000
1	d6	Stator_Edge...	in	-magnet_core_length	-2.000000	<Default	-2.000000
1	d7	Axis Sketch	in	load_cell_dist	10.000000	<Default	10.000000
	User Parameters						
2	rotor_rad		in	4.64 in	4.640000		4.640000
2	rotor_t	d4, d3	in	0.25 in	0.250000		0.250000
2	air_gap	d4, d3	in	0.4 in	0.400000		0.400000
2	num_magnets		ul	4 ul	4.000000		4.000000
2	num_coils	coil_length	ul	100 ul	100.000000		100.000000
2	coil_length	magnet_cor...	in	num_coils * 0.02 in	2.000000		2.000000
2	magnet_core_length	d6, d5	in	coil_length / 2 ul + 1 in	2.000000		2.000000
2	stator_wall_t		in	0.25 in	0.250000		0.250000
2	load_cell_dist	d7	in	10.0 in	10.000000		10.000000

Figure 25: List of user model parameters (“1”) and user defined parameters (“2”), the latter of which defines the former. These parameters were imported into all designs.

Initial versions of this design did not include this form of master modeling. Then, the rotor-stator design changed, however adapting each part of the assembly proved so inefficient that it was actually faster to take the time to create a master model in order to prevent this in the future. Now, changing any of the user-parameters shown in Figure 25 will update the entire assembly accordingly.

Structural Components

It is important for the system as a whole to be able to support high loads and remain stable in high-vibration conditions, due to the nature of stress-testing a high-torque motor. The entire rotor/stator assembly is supported on either side by mounted ball bearings from McMaster Carr which can support up to 2600 lbs of dynamic load and 1400 lbs of static load. Though these bearings are expensive, it is important for the stator in particular to be stable.

Other components, such as the load cell, are supported by custom made mounting blocks in order to avoid more extra cost. The load cell in particular has custom designed aluminum shafts which attach to the stator walls. These shafts (pale yellow pieces, in Figure 26) run through eye bolts which thread into the off-the-shelf load cell.

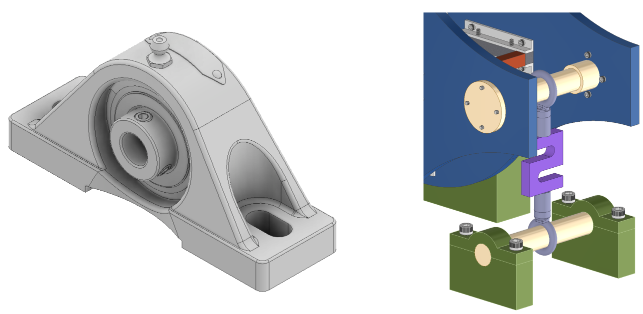


Figure 26: McMaster 7728T51 Mounted Ball Bearing (Left) compared with custom mounting design for the load cell (right).

To reduce vibration, the entire dynamometer will be mounted on an aluminum plate which is then rigidly mounted to a frame made of 80-20 bars. These bars will have simple rubber bumpers to serve as dampers which can absorb the extra vibration and make the system more rigid for better torque measurement data.

Electrical Components

Sensor Selection Proposal

Aside from the load cell, not all exact sensors have been selected. However, it would be beneficial to include a tachometer in the design in order to verify the rotation speed at the rotor, or even at the motor shaft; this will help in identifying sources of energy loss within the system. This energy loss research can then be used to improve the design of the dynamometer itself, or also verify motor (in)efficiency.

The sensors themselves can be powered and controlled by an Arduino board. A rough diagram of power flow in the system is shown in Figure 22.

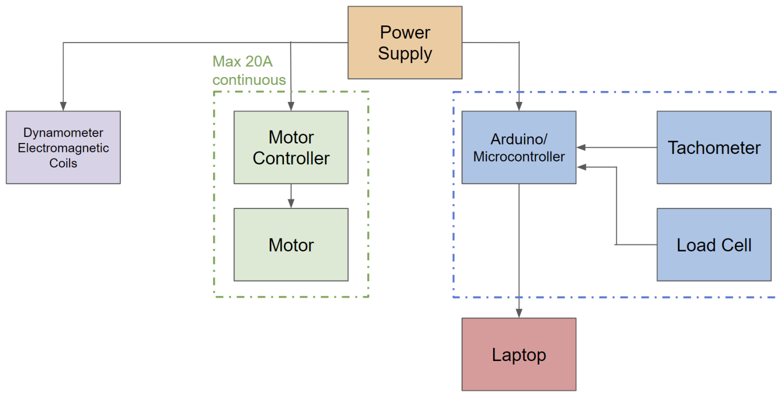


Figure 27: Power Flow Diagram

Several thermistors for monitoring temperature will also be installed around the system. Most importantly, they will be placed within the rotor-stator assembly itself, both towards the outer perimeter and along the rotor shaft (so long as there is no risk of tangled wires, given that this is a moving system).

Manufacturing Plan

Another goal of this design was for it to have as many components manufactured in-house as possible, through the Emerson machine shop as well as the RPL. This section will introduce a brief outline of how certain parts will be machined or manufactured, and the Bill of Materials (BOM) will show associated costs as well.

<table>
<tr><th>Part</th><th>Subassembly</th><th>Manufacturing Method</th><th>Notes</th></tr>
<tr><td>Stator Mounting Block x2</td><td>Rotor/Stator</td><td>Mill</td><td rowspan="2">AL 6061. Simple facing off of the top and bottom surfaces followed by drilling and tapping holes.</td></tr>
<tr><td>Motor Mounting Baseplate</td><td>Motor Mount</td><td>Mill</td></tr>
<tr><td>Motor Mounting Block</td><td>Motor Mount</td><td>Mill</td><td>AL 6061. Facing off, then just drilling holes and slots</td></tr>
<tr><td>Motor Mount Flat Plate</td><td>Motor Mount</td><td>Waterjet</td><td>Stainless Steel. Can be done at LASSP</td></tr>
<tr><td>Rotor Shaft</td><td>Rotor/Stator</td><td>Lathe</td><td rowspan="2">Both are just cylinders, can be done quickly and easily on a Lathe</td></tr>
<tr><td>Load Cell Shaft</td><td>Load Cell</td><td>Lathe</td></tr>
<tr><td>Load Cell Mounting Shaft and Cap</td><td>Load Cell</td><td>(Trak) Lathe, Mill</td><td>AL 6061. Slightly more complex Lathe part. May benefit from being done on a Trak Lathe, but is not ultimately necessary. Mill needed for adding the mounting holes after.</td></tr>
<tr><td>Magnet Bracket x16</td><td>Rotor/Stator</td><td>Mill</td><td>AL 6061. Small and simple L-bracket parts. Will have to be wary of the clamping force of the vice and make sure it does not deform the part itself, however this is overall unlikely</td></tr>
<tr><td>Magnet x8</td><td>Rotor/Stator</td><td>Mill</td><td>Cast Iron. May be difficult to machine, but I have seen and supervised people doing it in Emerson before.</td></tr>
<tr><td>Large Sprocket</td><td>Sprocket</td><td>Waterjet, Lathe</td><td>Basic shape and mass cutouts can</td></tr>
</table>

		or CNC mill	be done with water jetting, however it will need to match the thickness of the extrusions for the ball bearing. Part must be put on a lathe or CNC mill after to clear the extra thickness and do the taper post-processing.
Small Sprocket	Sprocket	Waterjet, CNC Milling	Basic shape and mass cutouts can be done with water jetting, however it will need to match the thickness of the extrusions for the ball bearing. Part must be put on a lathe or CNC mill after to clear the extra thickness and do the taper post-processing. Milling is also needed for the set-screw holes.
Rotor	Rotor/Stator	Waterjet, CNC Milling	Same process as the small sprocket, but much shorter as there is no taper and no extra mass cutouts.

Table 3: Manufacturing Plan

Future Work

While this design is mostly complete, there is still much which can be done to fine tune it. Before beginning the prototype stage, I would like to design some safety features, especially a chain guard, to shield both the stator assembly and nearby humans from a chain potentially snapping at high speeds. Because this is a high speed, high torque testing setup, it may also be beneficial to wire in an E-Stop (Emergency Stop) button as a form of a last-resort.

Once this addition to the design is complete, I would like to perform modal analysis on the assembly in ANSYS to check where the first few system resonance frequencies are expected to be. Depending on the results of these simulations, I can make the decision as to whether additional anti-vibration and damping components are needed in the system, aside from simple rubber feet. Other static structural analysis may also be beneficial, in particular on the motor mount since the motor itself is heavy and somewhat cantilevered.

I would also like to do research into other sensors to include such as a tachometer, and work on developing a Matlab GUI for testing. Regarding the latter, I consider it important to have an easy to navigate GUI that the team can use for years to come, regardless of whether I or any other current students involved in the motor design process are available.

From there, I would like to develop a prototype of the model, ideally early in 2024, before going to fully manufacture it. In particular I would like to prototype the magnet design in full (from cast iron mold to the actual coil winding) several times before assembling a final design, to characterize their polarization and other properties.

Once the above is complete, the full design can be manufactured and testing can commence, going from no load, to a minimal load representing the weight of the tires only, to a full load representing the entire load of the vehicle, which will simulate rolling resistance. Eventually, I would like to work with our Electrical subteam to develop and test various feedback control loops via the Motor Controller board.

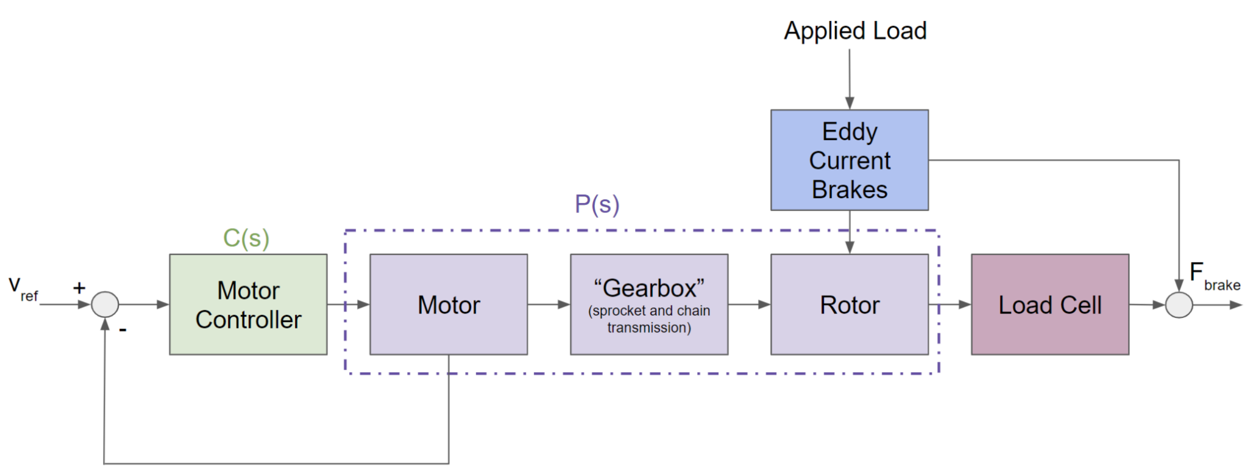


Figure 28: Possible block diagram/feedback loop of the system

Discussion and Learnings

Upon taking on this project, I realized it was a much larger scope than I originally anticipated. I had to spend quite some time relearning basic electricity and magnetism concepts from 2214, while also doing research as to how to connect them to more complex topics like deriving torque from Eddy Currents. This is the aspect of the project which ended up taking much longer than I expected. I wish that I had foreseen this earlier, and spent less time scoping alternative designs to allow these calculations to be done earlier. I had more experience with design challenges than this pre-design calculation work, going in. I feel much better off now to handle such issues in the future with a mix of research and applied knowledge from classes.

It was also difficult to decide when and when not to spend extra money on components that would be stronger or would ease manufacturing. As a student on a Project Team with a strict budget, I am used to sacrificing design quality for cost. I tried to minimize that in this design, and justify costs at both ends of the extreme (as in, very cheap and very expensive), however at the end of the day even small costs from components like fasteners add up very quickly.

At $1134.01, or around $900 if pre-owned materials are excluded, this project is still quite costly. I would like to do further work into changing designs to be cheaper, likely by minimizing metal stock to be purchased. I may replace some of the current aluminum mounting blocks with wood or a similar cost-effective alternative if possible. Finite element analysis would help to determine if this is possible. Making these material changes may also help reduce the waste that tends to be produced while machining.

Ultimately, I feel satisfied by what was accomplished over the span of a single semester with this project. The design is solid mechanically, however I wish I had spent more time developing early stage electrical and software components; this, alongside manufacturing, will have to be something I continue moving forward and perhaps get help with from teammates.

Appendix

A1. Bill of Materials (BOM)

The most up to date BOM is shown below:

1	Category	Part	Product Link	Vendor	Qty	Total Price	Status		Total	
2	Sensors	10kg Load Cell	https://www.ama	Amazon	1	48	To Buy		$1,134.01	
3	Fasteners, etc	5/16-18" fully threaded fasteners, 1 inch	https://www.mcm	McMaster	1 pack	14.37	Alread…			
4	Fasteners, etc	8-32 fully threaded fasteners, 1 inch	https://www.mcm	McMaster	1 pack	10.38	Alread…		**Estimated Labor Costs**	
5	Fasteners, etc	1/4-20 fully threaded fasteners, 7/8 inch	https://www.mcm	McMaster	1 pack	13.74	Alread…		$210.00	LASSP ($70/hr of water jetting)
6	Fasteners, etc	3/8" fully threaded fasteners, 1 inch		McMaster	1 pack	11.28	Alread…			
7	Fasteners, etc	Mounted ball bearing, 1/2" shaft	https://www.mcm	McMaster	2	259.56	To Buy		**Total, Excluding Pre Owned Items**	
8	Fasteners, etc	1/2" ID Shaft Collar	https://www.mcm	McMaster	2	12.44	To Buy		$905.66	
9	Fasteners, etc	1/2" ID ball bearing	https://www.mcm	McMaster	1	7.11	To Buy			
10	Fasteners, etc	Steel Eyebolt	https://www.mcm	McMaster	2	12.14	To Buy			
11	Fasteners, etc	4-40 cone point set screw	https://www.mcm	McMaster	1 pack	9	To Buy			
12	Fasteners, etc	Corner Mounting Bracket	https://www.mcm	McMaster	4	26.08	To Buy			
13	Stock	AL 6061, Stator and Motor Mounting Block Stock	https://www.midv	MidWest Steels	6"x12"x2" plate	117.65	Alread…			
14	Stock	AL 6061, Motor Mount Stock	https://www.midv	MidWest Steels	7"x7"x.25" plate	31.26	Alread…			
15	Stock	AL 6061, Load Cell Shaft Stock	https://www.midv	MidWest Steels	2.25 diamx6" length rod	37.36	To Buy			
16	Stock	AL 6061, Rotor and Load Cell Shaft Stock	https://www.midv	MidWest Steels	0.5" diam x 15" length rod	9.19	To Buy			
17	Stock	AL 6061, Magnet Bracket Stock	https://www.midv	MidWest Steels	Qty 6 of 0.5"x0.5"x12" plate	74.58	To Buy			
18	Stock	Magnet Cast Iron Stock	https://www.mcm	McMaster	2.5"x6"x12" plate	118.44	To Buy			
19	Stock	AL 6061, Rotor, Big Sprocket Stock	https://www.midv	MidWest Steels	Qty 2 of 10"x10"x.5" plate	81.76	To Buy			
20	Stock	AL 6061, Small Sprocket Stock	https://www.midv	MidWest Steels	4"x4"x0.5" plate	19.85	Alread…			
21	Stock	304 Steel, Motor Flat Plate Stock	https://www.midv	MidWest Steels	5"x18" sheet	9.82	Alread…			

A2. MATLAB Code for Rotor Design

```
%Nila Narayan, nn257
%Senior Design Calculations

clear all
close all

%fixed properties
p = 2.7e3; %kg/m^3, density of aluminum
sigma = (2.868e-8)^-1; %1/ohm*m, specific conductivity of aluminum)
r = .0254/2; %m, "radius" of magnet core which is currently a 1inx1in square but
will model as a circle
n = 100; %number of turns in coil  --> NOT REALLY SURE OF THIS RN
N = 4; %number of magnets
I = 20; %A, applied current --> NOT REALLY SURE OF THIS RN
mu_air = 1; %relative permeability of vacuum
mu_al = 1.00002; %relative permeability of aluminum

%properties dependent on rotor thickness and radius
[R, d] = meshgrid(0:.001:0.2, 0:0.0001:0.01);
l = d + 0.01; %5mm air gap on either side of rotor
A = pi .* R.^2; %area of rotor disc
rel_air = (l-d) ./ (mu_air * pi * r^2);
rel_disc = d ./ (mu_al * mu_air .* A);
rel_tot = rel_air + rel_disc; %reluctance of disc + air gap
w = 10 ./ R; %angular velocity, based on v_max of car being 10 m/s

%flux per coil
coil_flux = (n * I .* A) ./ ((rel_tot .* A) + (sigma * r .* w .* R .* d));
```

```
%total magnetic flux for N magnets
B = N .* coil_flux; %total mag flux, Tesla

%dissipated power
P = p * sigma * pi .* B .* R.^3 .* d;

%power -> torque
T = P .* (d ./ w);

figure
surface(R, d, T)
colormap(spring)
colorbar()
view(3)
xlabel('Rotor Radius [m]')
ylabel('Rotor Thickness [m]')
zlabel('Brake Torque [N*m]')
title('Braking Torque as a Function of Rotor Radius, Thickness');
```

A3. Referenced Motor Torque Calculations

The referenced 12 Nm of torque needed to overcome rolling resistance for the Chicken Coupe is based on calculations done by myself and my peers on the Drivetrain subteam in Fall 2022. These calculations use F=ma and power relations in order to determine torque required at the shaft and the wheels themselves.

A summary of these results is shown below:

Steady State Power Requirements

Case	Total Race Time (min) [NO STOPS]	Time/Lap (min)	Linear Speed (m/s)	Angular Speed (rad/s)	Wheel RPM	Shaft RPM	Power loss due to Rolling Resistance (W)	Power Loss Due to Air Resistance (W)	Power Loss due to Bearings (W)	Power Req (Best Case) (W)	Power Req (Worst Case) (W)
1	35	8.75	7.661904762	25.32861078	241.8704165	519.5734872	50.73521786	72.69738448	3.18	137.6223938	270.9682026
2	30	7.5	8.938888889	29.55004591	282.1821525	606.1690684	59.1910875	115.4407541	3.18	193.2737408	380.5415434
3	28	7	9.577380952	31.66076348	302.3380206	649.466859	63.41902232	141.9870791	3.18	226.7240232	446.4026481

Track Info

Max Race Time	**35 mins**
# Laps	4
Track Dist (miles)	10
Track Dist (m)	16090
max allowable speed	**10 m/s**
max allowable startup time	**20 seconds**

Power Reqs - Acceleration from Steady State to 10 m/s

VERY MUCH A BALLPARK, assumes constant acceleration

Steady State Velocity (m/s)	Time to Accelerate (s)	Rate of Acceleration (m/s^2)	Power Requirement (W)
6	5	0.8	576
	10	0.4	288
	20	0.2	144
7	5	0.6	324
	10	0.3	162
	20	0.15	81
8	5	0.4	144
	10	0.2	72
	20	0.1	36

Power Reqs to Start Car

Time to Accelerate (s)	Rolling Resistance Force (N)	Acceleration Force (N)	Drag Force (N)	Wheel Torque (Nm)	Motor Torque (Nm)	Best Case Power at Motor (W)	Worst Case Power at Motor (W)
10	26.487	88.29	0.04040625	34.73226539	16.16846837	29.04863164	57.19458355
15	26.487	58.86	0.04040625	25.82969039	12.02416622	21.60288576	42.53446668
20	26.487	44.145	0.04040625	21.37840289	9.952015139	17.88001283	35.20440825
Final velocity:	**0.5**	**m/s**	**<-Changeable parameter!**				

***assumes acceleration to be constant, looking into ways to remedy this but it should be okay for a ballpark**

Working Backward, time to accelerate to x m/s based on Motor Power Output

Power (W):	480				**<-changeable**
V_final (m/s):	0.1	->	w_shaft (rad/s):	0.3305785124	**<-change v**
	best case	*worst case*			
Motor Torque (N	1335.84	678.46152			
Wheel Torque (N	2869.582222	1457.435858			
F_accel (N)	9459.694816	4791.442372			
t (s)	0.01866656414	0.03685320334			
t (min)	0.000311109402	0.00061422005			
a = dv/dt (m/s^2	5.357172282	2.713468327			
dist traveled	0.000933328206	0.001842660167			
% race complete	0.00000580067	0.000011452207			

Car Info + Other Constants

Mass w/ Driver (kg)	180
Gravity (m/s^2)	9.81
Coeff Rolling Resistance	0.015
Mass of Tire (kg)	13.2
Mass of Rim (kg)	6
Rim OD (m)	0.414
Tire OD (m)	0.605
I_tire	0.4360302
Density of Air (kg/m^3)	1.293
Drag Coefficient	0.25
Sprocket Teeth Ratio	**2.148148148**
Sprocket Radius Ratio	**2.389874739**
Worst Case Drivetrain Efficiency	**0.46726**
Best Case Drivetrain Efficiency	**0.92**

A4. CAD Files

The CAD files and full assembly will be attached via a zipped folder, or emailed.

A5. References/Research Materials

Brin, Wesley, "Design and Fabrication of an Eddy Current Brake Dynamometer for Efficiency Determination of Electric Wheelchair Motors," 2013.

https://corescholar.libraries.wright.edu/cgi/viewcontent.cgi?article=1892&context=etd_al

Nunes, Alexandre et. Al, "Designing an Eddy Current Brake for Engine Testing,"

https://knepublishing.com/index.php/KnE-Engineering/article/view/7094/12772

A6. Original Proposal

I will be doing this project for CEV (Cornell Electric Vehicles, not on the dropdown list above). The goal of the project is to design a motor dynamometer used to characterize power output and torque vs RPM of our team's brushless DC motor, thus telling us the motor efficiency. I will need to model the car's mass as a rotational load; I would like for this dynamometer to double as an easy-to-use progressive load testing benchtop setup for our Drivetrain and Electrical teams to use, in order to more effectively test the motor before putting it in the car. I suspect this may pose a design challenge, given the fact that a dynamometer often relies on a single rotational load but the real life inertia of the tires may be more difficult to accurately model due to the distance of the loads from the motor; we also have a differential on our real car. While this is not needed for the basic dyno setup, it could be something interesting to include. Overall, being able to isolate the system will help our team acquire better data in order to improve our efficiency- something we have been struggling with in regard to the motor, despite it being a major source of efficiency. Given that our team has minimal budget to invest in a stock motor or chassis dyno, the goal is to have the most efficient in-house testing method possible. This will require both mechanical design and controls design.