COLLEGE OF ENGINEERING
MECHANICAL ENGINEERING
UNIVERSITY OF MICHIGAN

Michigan Baja Racing Multifunction Dynamometer

Final Report

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1 Abstract

The goal of this project is to develop a multifunction dynamometer (dyno) to collect data on various components for an off-road vehicle currently under development by the Michigan Baja Racing team. This dyno must be able to support multiple systems at a time and on their own, namely the engine, continuously variable transmission (CVT), gearbox, and brakes. The team wishes to gather RPM, torque, and temperature data for each of these systems to more accurately drive the design and tuning of these components. Stakeholder analysis and interviews lead to the development of an extensive list of requirements and specifications for the design of this product. The scope of this report encompasses the context of the design problem, a high level overview of the design process employed to solve this problem, the research and derivation of requirements and specifications, benchmarking analysis, and a timeline illustrating project milestones, tasks, and status [1].

2 Introduction, Background, and Information Sources

2.1 The Competition

The Society of Automotive Engineers (SAE) organizes a Collegiate Design Series (CDS), which gives college students around the world the opportunity to design, build, and test solutions for a variety of vehicle engineering competitions. The Baja SAE event is one such competition. In Baja SAE, engineering students are tasked with designing and building a single-seat, four wheel drive, all-terrain sporting vehicle that is to be a prototype for a reliable, maintainable, ergonomic, and economic production vehicle that serves a recreational user market. The students must function as a team to design, engineer, build, test, promote, and compete with a vehicle within the limits of the rules [2]. This vehicle competes on non-standard off-road courses developed by the competition organizers unique to every contest. These courses are made for several distinct events to test the performance of the vehicle's suspension, acceleration, torque, durability, and maneuverability. These events are scored to sum to 1000 points; the team who accumulates the most points wins the competition [1].

2.2 The Team

Michigan Baja Racing (MBR) is a student team at the University of Michigan - Ann Arbor that competes to win the Baja SAE competition. MBR is a small group of dedicated undergraduate students who enjoy designing, building, and racing an off-road vehicle every year. The team is structured according to a team constitution document which sets out roles and responsibilities for a captain and administrative members. These administrative members are responsible for choosing the subsystem leads for each of the vehicle subsystems. Subsystem leads are then responsible for designing, testing, and in some cases manufacturing their subsystems. The team strives to manufacture as much of the vehicle at their facility as possible, with some select parts or operations being outsourced to specialty manufacturers. The team has access to a range of CNC and manual machine tools and metal fabrication tools, but lacks some which may become relevant to this project such as a wire EDM, a CNC mill with more than 4 axes, and any precision grinding tooling. The primary goal of the team is to win the overall competition, which drives vehicle level requirements that help push the car towards the best competition performance possible. MBR has won the world championship, known as the Mike Schmidt Memorial Iron Team Award, in seven of the past nine competition seasons [1].

2.3 Project Description

Section 2.3.1 gives an overview of the whole drivetrain power system. Section 2.3.2 will give an overview of MBR's engine and how the ability to measure the torque could yield a higher performance. Section 2.3.3 describes the continuous variable transmission subsystem. Sections 2.3.4 and 2.3.5 give an overview of the gearbox and brakes subsystems, respectively. If the reader is familiar with these subsystems, they may skip to Section 2.3.6 which gives the problem statement in a concise format.

2.3.1 Drivetrain Power Overview. The drivetrain of a vehicle is the set of systems that transfer power from the engine down through the wheels, allowing the vehicle to move. In the Michigan Baja Racing vehicle, a typical 2 wheel drive (2WD) drivetrain includes a mechanical continuously variable transmission (CVT), a fixed-ratio rear gearbox, and the rear driveshafts. A 4 wheel drive (4WD) drivetrain includes all of these components, plus a transfer case to split power towards the front of the car, a propshaft to carry power to the front, a front differential or gearbox to split power between the front wheels, and front driveshafts to carry power to the front wheels. In this project we will focus on the engine, CVT, and gearbox components. A computer aided design (CAD) model of the drivetrain for MBR 32 can be seen in Figure 2.3.1.

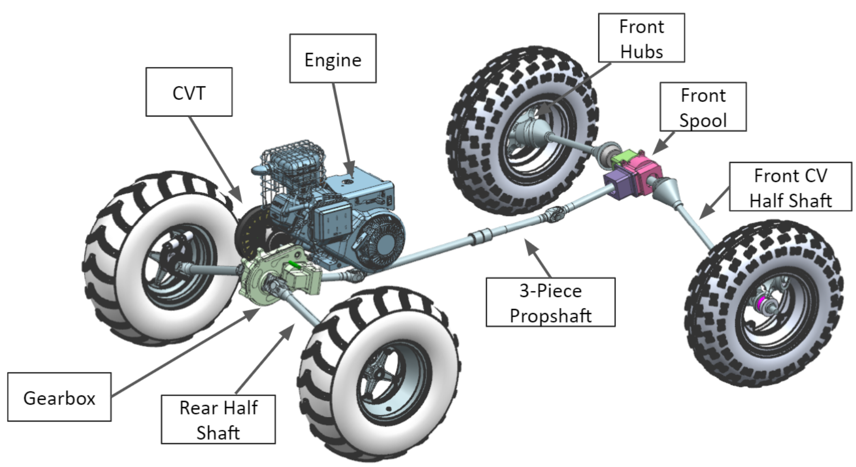

Figure 2.3.1. MBR 32 drivetrain CAD. Our area of concern for this project is the CVT, Engine, and Gearbox seen on the left side of the image.

The CVT, Engine, and Gearbox are all shown in figure 2.3.1 above. Our other area of concern for this project is on the brakes system, which is not part of the drivetrain but rather provides a stopping force for this system [1].

2.3.2 Engine Overview. SAE dictates that each Baja Racing Team must use a Kohler Command Pro CH440 engine to power their cars. This engine is shown in Figure 2.3.2. below [3].

Figure 2.3.2. A Kohler gasoline engine Command Pro Small Horizontal series CH440 Model. This is the engine that SAE specifies Baja Racing Teams must use.

The MBR Team transfers the power and torque output of this Kohler CH440 engine to the CVT, then the gearbox, and finally to the wheels. This engine must be the sole method of power production for the car, and must not be modified. SAE limits this engine to 10 horsepower from the 14 horsepower that it comes standard with. The Kohler Command Pro CH440 is a gasoline engine with head valve, a cast iron interior, and an aluminum base. This single cylinder engine has a peak power of 3.5 kW, with a horizontal output shaft [4]. Measuring the torque and RPM output of the engine using a dyno would provide the team with an accurate power-speed curve, and thus allow us to design the components in our drivetrain to a more accurate maximum torque. It would also allow us to identify variabilities between each engine and select the engine that outputs the most power to use for competition.

2.3.3 Continuous Variable Transmission (CVT) Overview. The continuously variable transmission (CVT) is the transmission used to route power from the engine crankshaft to the input of the gearbox, through an infinite number of gear ratios. A CAD model for the MBR CVT from the previous year's car is shown below in Figure 2.3.3.

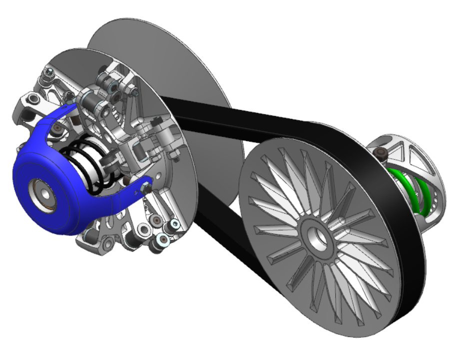

Figure 2.3.3. Custom CVT developed by the MBR Team. This CVT consists of two pulleys, called the primary and secondary sheaves, joined with a rubber v-belt.

The MBR CVT contains a proprietary design configuration that maximizes towing force through the use of an additional set of weights, called flyweights. This method of transmission requires no driver input but requires extensive tuning based on the power-speed curve of the engine to determine the optimal configuration to maximize engagement time, towing capacity, and overall performance. On a dynamometer, we would measure the torque and RPM at the primary sheave (where it connects to the engine) and at the secondary sheave (where it connects to the gearbox) in order to determine the peak efficiency range of the CVT and to identify where the series of pulleys reaches steady-state RPM. We would also measure the temperature of each of the sheaves to determine how the efficiency of the CVT changes with temperature.

2.3.4 Gearbox Overview. The gearbox receives input power from the CVT and its output power is routed to the wheels. A CAD model for the MBR CVT from the previous year's car is shown below in Figure 2.3.4.

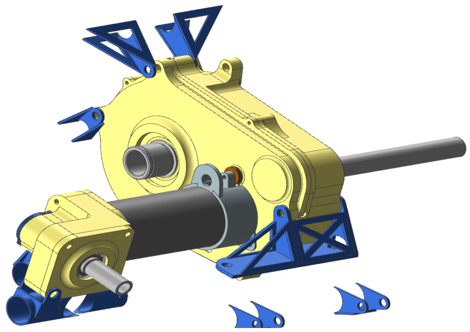

Figure 2.3.4. Custom gearbox developed by the MBR Team. The gearbox consists of a single-speed, double reduction gear set.

The gearbox's single-speed double reduction gear set is designed to act as final drive for the CVT. The gearbox's reduction box contains oil and is sealed using a precision o-ring. The gearbox also has a split of power at the intermediate stage to a transfer case that connects to the propshaft. The transfer case and main reduction box are joined through the use of dog clutches and driver-actuated shifter fork.

2.3.5 Brakes Overview. The brakes are the method of stopping the car. A CAD model for the MBR CVT from the previous year's car is shown below in Figure 2.3.5.

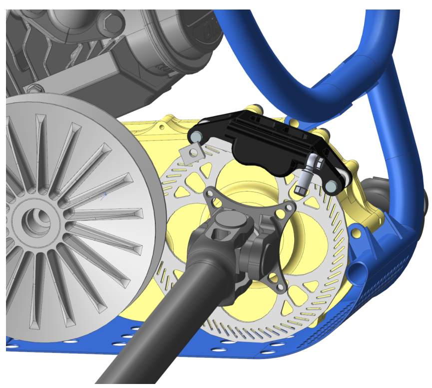

Figure 2.3.5. Custom rear brakes developed by the MBR Team. The brakes consist of a disk-shaped rotor, brake pads forced by the pistons, and calipers which hold these brake pads in place.

They consist of a disk shaped rotor that spins with the front and rear wheels. This disk has pads on either side that can be pressed into the rotating disk with a piston, creating friction to slow the vehicle down. Typically the layout of brakes on MBR's car is a single inboard rear caliper and two outboard front calipers. All of the calipers slide on shoulder bolts to allow for proper alignment of the caliper on the rotor as the pads wear.

2.3.6 Problem Statement. Previously, the Michigan Baja Racing team had not fully understood the torque, RPM, and temperature performance of the entire car and individual components (engine, CVT, gearbox, and brakes). Historically, the team has had to “guess and check” the capabilities of these components when knowing exact data for the car would yield higher performance. The team needs a multifunctional dynamometer to gather data on these individual systems. Measuring torque and RPM of the engine and gearbox will allow the team to optimize the CVT to the power curve of the engine, and improve lifespan of the gearbox by determining proper oil weight. Measuring temperature, torque, and RPM of the CVT and brakes will allow the team to optimize performance of these systems and understand how they are affected at various operating temperatures. Collecting this data will allow the team to yield overall higher car performance in events at competitions via an increase in speed and durability.

2.4 Project Goals

This project exists in order to assist our sponsor, the Michigan Baja Racing team, make better-informed design decisions on their race car. The motivation for this project is to improve the performance of the car by creating a better understanding of all its components. By understanding the torque, speed, and temperature of the car MBR will be able to make better informed decisions when designing and tuning the car. For example, if the MBR team has three engines labeled as identical, but one outputs marginally more power the team could put that one in the final car to improve performance.

The major objectives of this project are to design a multifunction dynamometer for the MBR car and develop plans for its manufacture. A successful outcome for this project will be determined by a completed design for the dynamometer and a plan in place for the construction of the final design.

2.5 Information Sources

Our main information was drawn during interviews with our primary stakeholders consisting of the main subsystem leads being tested, who are the main beneficiaries of our project (more information on stakeholders' identities in section 3.2). In addition, previous internal Baja projects and documentation are other primary information sources, including past dyno designs outlined in sections 3.1.2 and 3.1.3 below. We also conducted extensive research on market solutions to our design problem, including dynos on the market and the different possible options of sensors we could use. These sources are more closely outlined in our benchmarking process in Section 3. The Baja SAE rules are a source of standards that need to be followed by our requirements and specifications. These include HROE requirements for safety guarding that give more information on protection. We have also referenced information from the ME 450 course content. This has helped us find a design process framework that works for our team as well as information on stakeholder analysis and problem definition. In the future, we anticipate considering standards for several different materials, fasteners, and other components common to mechanical engineering design. As we get further into the design and analysis stages, these sources will be identified in more detail as we use them.

2.6 Design Process

At this stage in the design process, we have followed the ME Capstone design process framework [5] described by the ME 450 instructional team. The framework diagram is shown below in Figure 2.6:

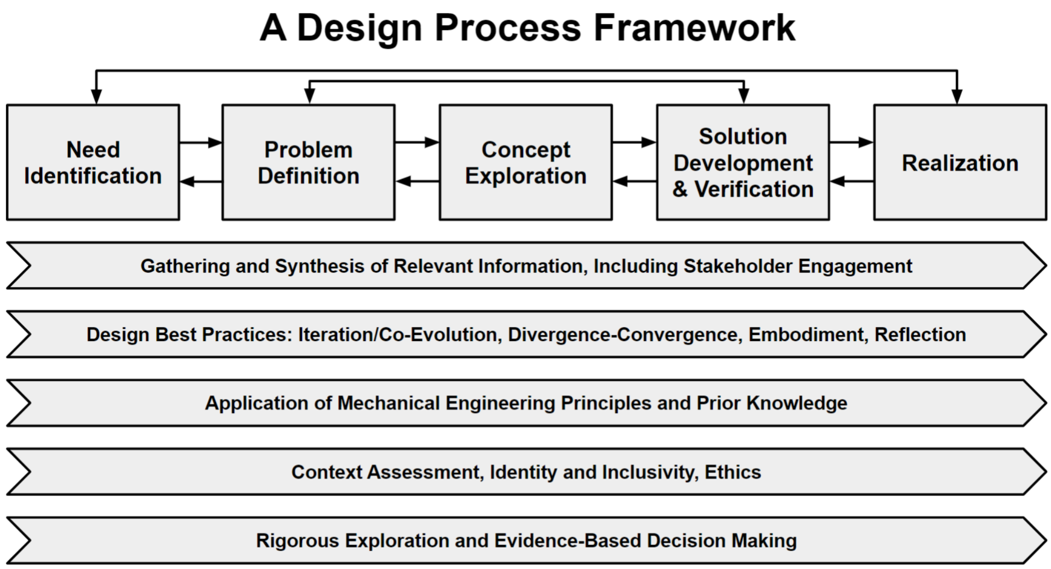

Figure 2.6.1. A diagram showing the ME Capstone Design Process Framework outlined in the learning blocks for ME 450 [6]. The iterative, solution-based system matches MBR's process closely.

Our team has found that this framework works well with our project due to its emphasis on solution-based design. There have been past MBR projects that have involved different types of dynos making it possible to iterate on those designs. With these resources available, the proposed solution of a dynamometer will be repeatedly modified throughout the design process as requirements are further evaluated, making our approach solution-oriented [7]. To get to this framework, the team also considered several others described in the ME 450 learning blocks. We also evaluated the possibility of using the five-stage Dym and Little design process model, which is a more linear and chronological sequence from need identification to the final design [8]. These steps were not cyclic in nature with more of a problem-based approach.

With the considerable amount of resources available to us, we decided to adopt the ME Capstone Design Process Framework with an emphasis on iteration between concept exploration and solution development. This works well with our project since we already have a start from the previous MBR dyno projects, so we will mostly be improving on their design. Since we want the dyno to be multifunctional and able to test multiple subsystems, we expect to be continuously changing our requirements and specifications throughout the design process. Considering this, we find the ME Capstone Design Process Frame a good fit for our team and what we want our project to achieve.

3 Research and Benchmarking

3.1 Current Dynamometer Benchmarking Standards

To evaluate what options exist on the market for our problem, we did research into the other dynos currently in existence in our local community as well as professionally fabricated ones. Table 3.1 below summarizes the pros and cons of the dynamometers we researched.

Table 3.1. Benchmark dynos pros and cons. This table summarizes the pros and cons of each of the dynos we explored during benchmarking.

Existing Solution	Pros	Cons
Previous MBR Projects (CVT and Brake Dynos)	Usable parts and inspiration for our project.	Not functional (CVT dyno) or never built (brakes dyno). Each only measures one component.
MRacing Engine Dyno	In the Wilson Center, similar to previous MBR dynos.	Only measures the engine, meant for engines much larger than the Kohler.
Washtenaw Community College Engine Dyno	Sturdy and reliable. Close to Wilson Center.	Cost of renting builds over time; not able to use on a whim. Only measures one component.
Professionally Fabricated Dynos on the Market	Sturdy and reliable.	Above our budget, only measures one component.
DIY Dyno Projects	Compatible with multiple components. Low cost to make.	Unable to purchase.

3.1.1. Dynamometers on the Market

On a high level, current dynamometers on the market all contain a power source and a braking source, and a method to measure RPM and torque. They also largely focus on one of two categories: the engine or the chassis/drivetrain. Engine dynos are largely used to tune the performance of the engine by producing a power-speed curve. They come in a variety of sizes depending on the displacement of the engine, from small 6 HP lawn mower engines to large 5000 HP locomotive engines. Figure 3.1.1 below shows Moran Motorsports' engine dyno, which is located in Taylor, MI.

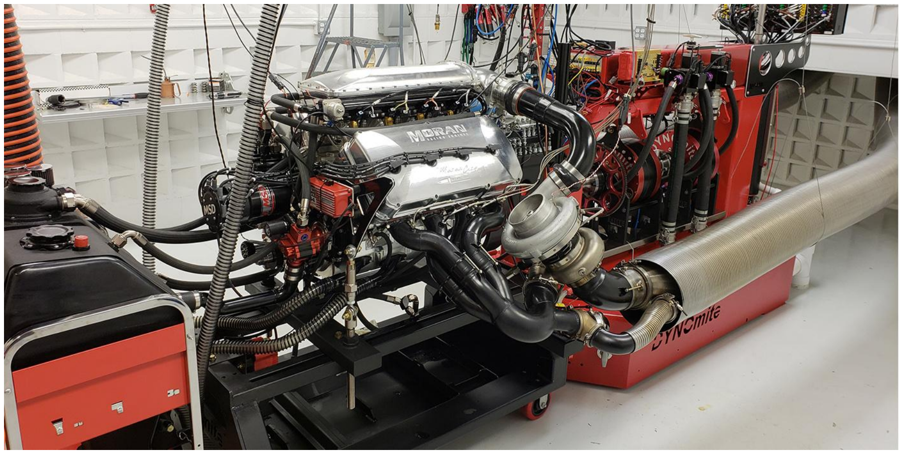

Figure 3.1.1. An automotive-sized engine dyno [9].

The other main type of dyno used in industry is a chassis or drivetrain dyno. This type of dyno focuses on the system as a whole rather than one individual component, and usually includes the entire vehicle. Chassis dynos typically measure the torque and power output at the vehicle's axles and can be used to tune the overall vehicle. It provides a consistent environment that replicates driving on the road, allowing the user to perform repeatable tests in a more controlled environment. Figure 3.1.2 shows Land and Sea's DYNOmite Truck Chassis Dynamometer.

Figure 3.1.2. An automotive-sized chassis dyno [10].

3.1.2. Existing Baja CVT Dynamometer

In 2013 the MBR team designed a CVT dynamometer for a ME 450 project. Since then it has been subject to wear during its use and is now currently unusable. The CVT dynamometer's electronics are currently outdated and would need to be replaced. Several of the sensors on the dyno are broken, the ones that are not are uncalibrated and are not able to be recalibrated by members of the MBR team.

However while the dyno itself cannot be used, there are some components from the project that we could use for this project. The most important part we can use is the absorber, which would cost $3,800 to buy and would not be able to be made in-house. Additionally the CVT dyno is mounted on a frame which can be used to mount the components of our project [11][12].

3.1.3. Existing Baja Brake Dynamometer Design

In 2020, a dynamometer used to measure brake drag and pad wear was developed by a member of the team, but was never constructed due to time constraints. All of the components were purchased and are stored in the team's workspace. These parts can be utilized in the new multifunction dyno, and inspiration can be taken from the design for overall packaging of the brakes system on the dyno [13].

3.1.4. DIY Dynamometer Project

In 2020, a do-it-yourself (DIY) dynamometer was developed by a man with a website and youtube channel called "Megoingfast". The dynamometer he built used a hydraulic pump connected by a chain to the engine. The dynamometer measured engine power by measuring hydraulic pressure produced by the engine turning the input of the hydraulic pump. He also had a tachometer measuring RPM of the engine output shaft. The designer stated that this dyno was only meant for comparing an engine to another engine on the same dyno, or comparing an engine to itself after making modifications. This dynamometer setup has no way of actually measuring horsepower, unless significant testing was done to correlate hydraulic pressure to torque output of the engine [14].

3.2 Current Sensors Benchmarking Standards

3.2.1. Torque Sensors

There are broadly speaking two main types of torque sensors. The first type we could use is a **rotary torque sensor**. They are used to determine the torque being applied to a shaft while it is rotating. They measure this torque through a strain gauge which measures the deformation of the shaft due to the applied torque. They are sometimes combined with an optical encoder in order to create plots of shaft data. This could be very useful for our project because the components could be operated normally while hooked up to the dynamometer [15][16].

The second type of torque sensor is a **reaction or static torque sensor**. Reaction torque sensors are sometimes called flange-to-flange sensors because they are mounted between two flanges, one stationary, one rotating. These sensors are typically not as complex as rotary torque sensors and are usually cheaper as a result. However, because they measure a stationary shaft, they are not very applicable to our design [15].

3.2.2. Temperature Sensors

There are four main types of temperature sensors, the first of which are **negative temperature coefficient (NTC) thermistors**. NTC thermistors measure temperature by using resistors which change the resistance they apply depending on the surrounding temperature. NTC thermistors have higher resistances at lower temperatures and lower resistances to higher temperatures. NTC thermistors can operate in environments as low as -50 [°C] and as high as 250 [°C]. This means that NTC thermistors cannot operate within our required max temperature of 600 [°C] and will not be able to be used in our project [13].

The second main type of temperature sensors are **resistance temperature detectors (RTD)**. Similar to NTC thermistors, RTDs have a resistance that varies with temperature. They are typically constructed by wrapping a wire around glass or ceramic. RTDs can be made out of different materials that correspond to different levels of accuracy in measurement. RTDs have a range of -200 [°C] to 600 [°C] which fits within the range of temperatures our dynamometer will experience.

The third type of temperature sensor are **thermocouples**. Thermocouples measure temperature by using wires made of two different metals. The difference in voltage between the two metals correlates nonlinearly to the temperature of the surroundings. The accuracy of thermocouples is low compared to the other sensors, but they have a much higher operating range. They can measure temperatures as low as -200 [°C] and as high as 1750 [°C].

The final type of temperature sensor is **semiconductor-based temperature sensors**. They use two diodes that measure the current vs. temperature relationship and how it associates to temperature change. Unfortunately semiconductor-based temperature sensors have low accuracy and a small range of temperatures that can be measured (-70 [°C] to 150 [°C]). This means that semiconductor-based temperature sensors will not be good for our dynamometer [17].

An additional type of temperature sensor the group could use on the dynamometer is an **infrared (IR) thermometer**. Surfaces will emit infrared radiation corresponding to how quickly their molecules are moving which itself is related to temperature. An example of this is how in cases of extreme heat metals can appear red, orange, or white. IR thermometers use integrated thermocouples and lenses to read this radiation and calculate the temperature associated with it. They can be extremely easy to use because they do not have to be attached to the dynamometer in order to be used. [27]

3.2.3. RPM Sensors

One way to measure angular speed is by using a **hall effect sensor**. Hall effect sensors employ semiconductors and magnets to gather data. Once placed in a magnetic field they measure speed by observing a change in voltage as something, in this case an output shaft, rotates. Members of the MBR team already have experience with hall effect sensors, which means there will be little if any learning curve associated with their use if they are selected for this project [18].

Another way to measure angular speed is by using a **tachometer**. There are three types of tachometers, the first of which is a **mechanical tachometer**. Mechanical tachometers are reliant on the rotating component making contact with the tachometer. The tachometer analyzes this contact through the use of electronics and determines speed. Because mechanical tachometers in our dynamometer would require up to twelve thousand contacts a minute it would likely not be durable long term. Additionally, they have difficulty measuring the angular speed of smaller objects [19].

The second type of tachometer is a **digital tachometer**. Digital tachometers do not use physical contact, instead they use the reflection of infrared light to measure angular speed. Digital tachometers require the use of reflective tape for the light to reflect off of, which may be difficult to apply. These are very similar to the optical encoders used in ME 350 which means several stakeholders will have experience using a similar device if it is used on our project.

The final type of tachometer is a **stroboscopic tachometer**, which as their name suggests uses the stroboscopic principle to measure angular speed. At a high level, this principle states that objects that are rotating will appear stationary when a light strobes at the same frequency as the rotating object. Stroboscopic tachometers use a light flashing at a set frequency in order to determine the speed of the object the light is hitting. However, this type of sensor may be impractical for our application. However, this dynamometer will be used while the engine is increasing/decreasing its power output, meaning the RPM of our components will vary as the engine accelerates/decelerates, which would make this type of sensor impossible to use in the required scenarios [19] [20].

3.2.4. Absorbers

Dynamometers require that a braking force is applied to the moving components in order to get the desired measurements. For this project the team looked at three different types of absorbers to provide this force, the first of which is a **friction-based absorber**. Friction-based absorbers use friction to apply a load to the moving components. This is similar to how cars and trucks stop on the roads.

The second type the team considered is a **hydraulic absorber**. These absorbers use hydraulics to apply the load experienced by the rotating components of the dynamometer. Hydraulics can also be used in these absorbers to change the load being applied which can be useful for this project.

The final type of absorber the team considered was the **magnetic particle absorber** from the preexisting MBR CVT dynamometer. When connected to the absorber, the moving parts of the dynamometer can rotate freely, but when a current is applied to the absorber a magnetic field is generated which provides the resistance required. These absorbers are easily controlled and are extremely reliable. Additionally, by using the preexisting absorber the team will save thousands of dollars in component costs. [11]

3.2.5. Non-Engine Power Sources

When speaking with stakeholders, it was suggested that we run as many trials as possible off of a non-engine power source due to the uncertainty associated with the MBR engine. The importance of having an exact torque-speed curve for each trial was discussed in section 2.3.2.The first and most obvious of these was a **DC motor**. A DC motor would be able to be programmed to give the same torque-speed output for every trial. The same cannot be said for the several engines MBR uses on their cars. It is entirely possible that the different engines, or the same engine over two different trials would supply a different power. Using a DC motor would remove any variation in observed torque and speed coming from components other than the ones being tested. For example, if the purpose of a trial was to observe the difference in shaft output for a new CVT setup, using an electric motor would guarantee the only differences in results between trials would be coming from the different CVTs, not the engine. [22]

Another non-engine power source that could be used is an **air motor**. At a high level, air motors function by using compressed air to provide power. They are beneficial in areas where traditional power cannot reach. The compressed air available to the MBR team is not strong enough to power an air motor. Additionally, they have less control than a DC motor. For this project, these motors would not be as useful as a DC motor. [28]

Another type of electric motor that could be used is an **AC motor**. AC motors operate similarly to DC motors, and typically have higher efficiencies. However, they are not typically as controllable. Due to our requirements, which require a high level of control, an AC motor will not be as useful as a DC motor.

Because both of the other options explored for non-engine power source can provide as much control as a DC motor, a DC motor will be used to supply the non-engine power. [22]

3.3 Stakeholder Analysis and Interviews

Our stakeholder map includes primary stakeholders who would be most affected by our design, secondary stakeholders who may be indirectly affected by our solution due to being part of the problem context, and tertiary stakeholders who are outside of the problem context but may still have some influence on the problem. Our stakeholder map also includes another categorization system, that system including Resource Providers, Supporters & Beneficiaries of the Status Quo, Complementary Organizations and Allies, Beneficiaries and Customers, Opponents & Problem Makers, and Affected or Influential Bystanders. Resource Providers may provide financial aid, knowledge or expertise, or technological resources. Supporters & Beneficiaries of the Status Quo who benefit from there being no change (i.e. no new solution). Complementary Organizations and Allies may have some influence on the process and also may be working to solve the same problem. Opponents & Problem Makers are those who play a part in the problem and actively work against any solution being designed. Affected or Influential Bystanders who currently do not have influence over the solution but may have influence and could be affected in the future [21].

Our stakeholders are largely in support of our design, all of them are actively in support of our design or ambivalent to it unless otherwise stated. Our primary stakeholders are our 450 project team as Resource Providers due to our design work along with the most relevant MBR subsystem leads as Beneficiaries & Customers. The CVT, testing, engine, and gearbox MBR subsystem leads are considered the most relevant ones; these subsystem leads will be directly interacting with our design which will collect data for them and then help to set ideal parameters to do best at the events during SAE Baja Racing competitions. Our secondary stakeholders include Baja alumni and the ME 450 Instructional Staff as resource providers due to providing knowledge and financial support by the latter, along with the other MBR Subsystem Leads as Affected or Influential Bystanders who will be affected if the solution causes MBR to perform better at competitions. Our tertiary stakeholders largely are against any solution, those include Washtenaw Community College and Dynamometer Manufacturers as Supporters & Beneficiaries of the Status Quo as MBR currently relies on them for using their dynamometers and provides these stakeholders with financial compensation, and the ETS Baja Team and Cornell Baja Team as Opponents and Problem as they are the direct competition of MBR and big rivals. Our other tertiary stakeholders are the New MBR Members as Affected or Influential Bystanders and the UIUC Formula Team and MRacing Team as Complementary Organizations & Allies as they could also benefit from an improved dynamometer to perform better at their respective competitions. Our stakeholder map can be seen below in Figure 3.3.1.

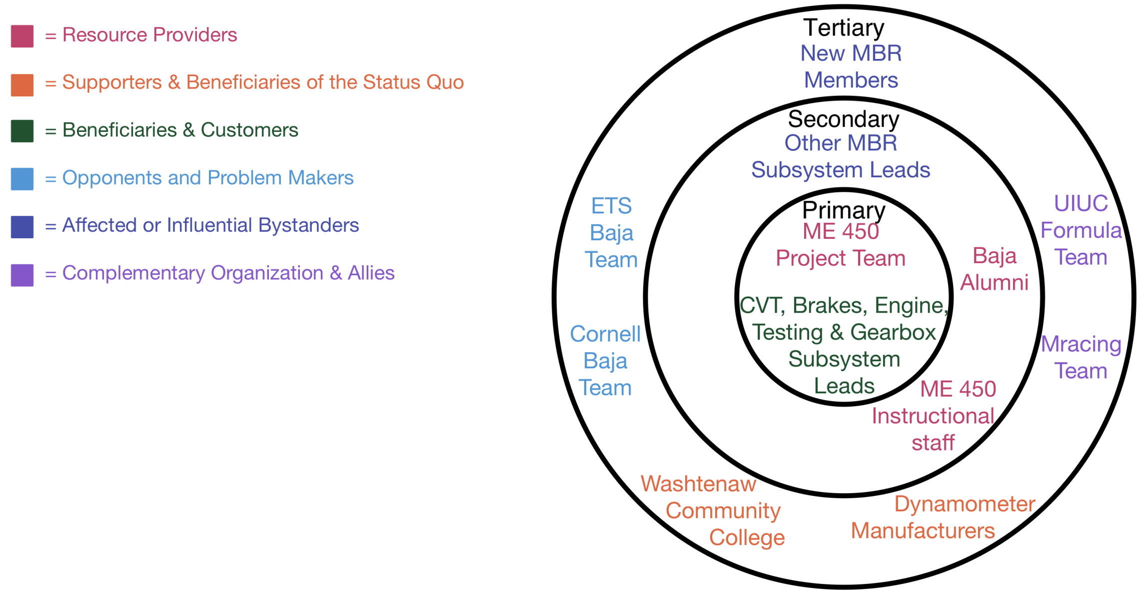

Figure 3.3.1. Our stakeholder map in which we analyzed all of our stakeholders and thought about their relevance and influence on this multifunctional dynamometer solution and on MBR performance at competitions. We only interviewed the primary stakeholders as they are the only ones who will be directly affected by this solution as they will be the current primary users of this solution and will use the collected data to drive design decisions to improve overall car performance at competitions.

3.3.1. CVT Subsystem Lead. According to the MBR CVT lead, in order for the dyno to be usable there needs to be an input shaft attached to the engine, variable resistance force approximating the drag of brakes and friction of the ground, and the ability to simultaneously dyno the connected engine and CVT. The CVT lead believes the most important data for their subsystem to get out of the dyno would be RPM and torque of the primary and secondary sheaves, and temperature data would also be helpful. The collected data would help to better understand the CVT (e.g. how the CVT shifts) and find efficiencies in the CVT and the whole drivetrain [engine, CVT, gearbox, and propshaft], which would allow the lead to tune the CVT so that the car will be faster. Specifically, the relationship between temperature and RPM could be found so that it is better understood what the best RPM would be in every situation [so that the car is faster and more durable]. The collected data could also be used to modify helix angles based on the found relationships. In order to properly design the CVT needs the relationship between peak power/torque and RPM. They believe some additional uses for this dyno would be to validate a lot of parameters [e.g. load cases] in the drivetrain (especially the gearbox) and accurately find maximum torque and power of the engine [12].

3.3.2. Brakes Subsystem Lead. According to the MBR Brakes lead, in order for the dyno to be usable/accessible it must have ways to easily mount and replace both rotors and calipers, and the rotors must be connected to a power source, most likely attached to the gearbox, with power coming from the engine and then going through the CVT and gearbox. The most important data to collect would be cycles to failure (warping of the rotors) which would allow them to fully utilize rotors and replace them just before failure, the maximum temperature the rotors experience which would allow them to ensure the chosen materials are proper and guide future design, and how long different brake pad materials can last while continuously engaged so that the best brake pad material is chosen. Something that is not essential but would be helpful is to change the RPM and measure the loads experienced on caliper pistons and caliper casing. Some other ideas for this dyno would be including a master cylinder in order to measure force on the pedal/into the piston and locating the failure point as this is currently unknown and would help bleed brakes more effectively and identify what should be improved. Another thought would be adding a rotational torque gauge to measure stress on steering or find the failure points on the throttle and brake pedals [13].

3.3.3. Engine Subsystem Lead. According to the MBR Engine lead, in order for the dyno to be usable/accessible it must be easy to set-up and run, not require extensive EE and CS to gather and interpret data, and be reliable with easily replaceable parts. The most important data to gather from this dyno would be the engine's RPM and torque output, which would be used to find its peak power and power curve. With this data the highest performance [peak power, peak torque, and highest RPM] of the engines can be found, meaning the team can identify its highest performing engine and then use this engine at competitions and perform better, as the car will be capable of more power, torque, and RPM. This data could also be used to accurately find the power curve which would be very helpful in CVT tuning. They believe another use of this dyno would be to determine cycle count and cycle to failure for drivetrain components [19].

3.3.4. Testing Subsystem Lead. According to the MBR testing lead, in order for this dyno to be usable/accessible it needs to have wireless sensors whose output can be easily converted into usable data (i.e. RPM, torque, etc.). The wireless sensors need to be easy to attach and replace, and ideally their outputs are similar. They believe collecting torque and RPM data of the engine is most important as this will identify the highest performing engine which would greatly affect the car's overall performance (speed, possible torque output). With the collected data they are hoping that the whole team will get a better understanding of the capabilities of the drivetrain system as a whole and its individual components. With this better understanding it will be possible to properly tune the components and system (for maximum speed of the car and durability), and future design decisions can be made using this data and not just simply using blind assumptions [22].

3.3.5. Gearbox Subsystem Lead. According to the MBR gearbox lead, the most promising use for a dyno for the gearbox is for oil level and efficiency testing, as well as testing various gear ratios in conjunction with the CVT. They would get the most value out of having temperature data from inside the gearbox, as well as RPM and torque data at both the input and output to quantify efficiency. It is not essential, but this lead expressed desire to include fatigue cycle testing in order to validate the team's calculations for safety factors on gears. This lead expressed concern in the ability to easily mount different shaped gearboxes on the dyno, as this is a critical part in testing multiple gear ratios. They also emphasized the importance of quantifying the engine power-speed curve to drive gear ratio design, and the need for the engine to be the primary power source for the gearbox so that the data is as accurate as possible [23].

3.4 Broader Design Context

Our design most directly affects those who are included in our stakeholder map in Figure 3.3.1., but it will still minorly affect others. Our sponsor is not very concerned with the social impacts of our design, nor the economic and environmental impacts, functionality and speed of the delivery of our design are far more important to them. Our design will be used in a very small-scale capacity, it will just be used by the MBR Team, so there will be minimal societal and economic impacts on the broader scale including the local community, society, and value chain actors. This design will just be an internal tool for the MBR team and thus will not affect the local community much, it will not have a cultural impact, largely impact access to resources, or affect living conditions. In regards to society, there will be minimal impact on society due to the design being internal thus not causing conflicts, leading to societal technology development, largely affecting the economy. There will be a bit of an impact on the environment as this design will use a combustion engine and pollute, but the MBR Team currently runs the whole car to gather this data so there would most likely be a net decrease in pollution. It would be best to not pollute and to have a more sustainable design, but there is little that can be done due to the requirements of the sponsor. For the small number of parts that must be manufactured we can try to limit the number of operations and use scrap material in order to minimize the environmental impact. Our team would like to prioritize the environment but the sponsor does not consider it to be important. Due to this design being internal it will not really affect value chain actors (besides intellectual property rights which is explored in the next paragraph), it will not affect fair competition, supplier relationships, or social responsibilities.

There are not official intellectual property protections in place for our design, but there is an agreement that this product is to be used exclusively by the MBR Team. This means that anything that is designed this semester is the intellectual property of the MBR team, meaning this design cannot be used for profit and should not be given to others including our direct competitors.

Our design will have some effect on both consumers and workers, but as mentioned previously this is on a small scale and internal. The consumer in this instance would be the user or members of the MBR team. The privacy of the MBR team will be ensured by keeping the design internal and not sharing information. As we will be able to speak directly with the consumers there will be complete transparency and we will collect feedback during this design process. The goal is to replace components and maintain the design so that this design will be long lasting and there will not be a large end-of-life cost. The design will be made with the health and safety of the consumers and workers in mind, adding in proper guarding, making pieces safely manufacturable, etc., in order to guarantee their safety. Most of the work on this design, including manufacturing, will be done by us (Project Team 20) during this semester or in the future, so there is not much worry about the impact on workers. We will make sure that we are not overworked and take care to not overwork the CNC operators. There will be no child labor or forced labor during our design, all work will be done by us or the MBR Team [21][24].

It is important to reflect on the power dynamics between the team and our sponsor, the MBR team, and within our team. It is important to note that our sponsor and end user are one and the same. Our project team is comprised of seniors, several of whom are members of the MBR team, one being the team's captain. This means that a power dynamic exists between our project team and the MBR team, and we will take care to not cause a power imbalance. Those of us who are on this project team and the MBR Team will make sure to keep our roles as designers of the solution and as members of MBR Team separate. We will make sure to listen to the MBR team and provide much time for feedback, and make sure to gather all this information before making design decisions so that the sponsor has much influence. We will work to ensure that unconscious bias does not affect our decisions and we thoroughly listen to all members of the MBR Team. The sponsor has told us it is essential to include certain components (the ones listed as our primary stakeholder) which has the potential to create some power imbalances between the subsystem leads of these components and other subsystem leads, but we will make sure to separate the leads from their components and listen to all members of the MBR equally. Within our project team itself we are not worried about power imbalances, although one member is the captain and two others are on the MBR Team, we are making sure that all of us have a voice and impact.

As discussed above, social, environmental, global, political, cultural, and economic factors did not significantly affect our final design because of it being a one-off part and because the design is contained to our team. Stakeholder factors had the majority of the influence over our final design, due to our stakeholders also being our sponsor.

4 Requirements and Engineering Specifications

4.1 Requirements and Specifications and Verification and Validation Plans

After speaking with the sponsor and stakeholders of our project during the interview process described in section 3.3, our group developed a list of high level requirements. These high level requirements are listed in table 4.1 below. The high level requirements were each expanded into multiple sub-requirements, each with a corresponding specification and justification. Each specification was driven by either external research relating to the system being analyzed, or internal research relating to one of the subsystems that makes up the MBR race car. The sub-requirement breakdowns may be found in tables 4.1.1-4.1.23. Sub-requirements that have an asterisk* next to them are "nice to have" requirements. Our group decided that these are beyond the scope of what we can complete and are not necessary for the first iteration of the dynamometer design that we will produce during this semester. For each sub-requirement, we also developed a verification/validation plan that we will use to confirm whether or not our project meets the requirements we set for it. Some of the verification plans may be more suitable for checking on a functional dynamometer prototype, however we will also outline plans for checking them without a fully built model. Tables 4.1.1 - 4.1.23 describe the verification/validation plans for all requirements that were outlined previously.

Table 4.1.1 Stakeholder requests and high level requirements with sub-requirements

High level requirements (prioritized high to low) with sub-requirements (prioritized high to low)

Requirements for the MBR dynamometer

- Measure, withstand, and apply up to max RPM
  - Must be accurate
  - Engine
  - CVT (input and output)
  - Gearbox (input and output)
  - Brakes
- Measure, withstand, and apply up to max torque
  - Must be accurate
  - Engine
  - CVT (input and output)
  - Gearbox (input and output)
  - Brakes
- Measure and withstand max temperature
  - Must be accurate
  - CVT
  - Brakes
  - *Engine*
  - *Gearbox oil temp*
- Maintainable/easy to use
  - Maintainable
  - Easy to use
- Portable/Storable
  - Fit within specified MBR area in WSTPC
  - Can move around the WSTPC
- Safe
  - All components are rigidly attached and contained
  - All liquids and gasses used or released by the dyno are managed safely
- Cost Effective
  - Stay within MBR Budget
- Manufacturable
  - In-house manufacturing
  - Must be weldable if welding is necessary
- Reconfigurable
  - Must be able to set up dyno in multiple different testing configurations
- Must be able to integrate with the Data Acquisition System (DAQ)
  - Wirelessly communicate sensor data
- Timeline
  - Must be able to complete project deliverable within fall semester

4.1.2. Dynamometer must be able to measure, withstand, and apply up to max RPM. This requirement is ranked as the most important because it is the one of the main drivers of the dynamometer's importance. Without measuring RPM of selected components, the dynamometer would be essentially useless to the team. The dynamometer must measure RPM so that we can combine this with torque and optimize power delivery throughout the drivetrain.

Table 4.1.2. Requirements and specifications for able to measure, withstand, and apply up to max RPM requirement

Sub-requirement	*Specification*	*Justification*
Must be accurate	<2% error (of max reading)	2% of the highest speed required to measure is 76 RPM, and based on sponsor interviews any more than this makes the data less useful [12].
Engine RPM	Measure, withstand, and apply up to 3800 RPM	This is the maximum speed of the engine output shaft [19].
CVT (input and output) RPM	Measure, withstand, and apply up to 3800 RPM	This is the maximum speed of the CVT [12].
Gearbox (input and output) RPM	Measure, withstand, and apply up to 3080 RPM	This is the maximum speed of the gearbox [23].
Brake rotor RPM	Measure, withstand, and apply up to 590 RPM	Our vehicle's maximum speed is roughly 40 mph, with 23" inch front tires the maximum brake rotor RPM can be calculated.

Table 4.1.3. Verification/Validation plans for measure, withstand, and apply up to max RPM requirement

Sub-requirement	*Specification*	*Completed Verification*
Must be accurate	<2% error (of max reading)	Sensor's maximum operating frequency is 15 kHz which is 900000 RPM. The operating frequency is greater than maximum speed of our components so error is negligible [31].
Engine & CVT RPM	Measure, withstand, and apply up to 3800 RPM	Sensor's maximum operating frequency is 15 kHz which is 900000 RPM and greater than 3800 RPM [31].
Gearbox (input and output) RPM	Measure, withstand, and apply up to 3080 RPM	Sensor's maximum operating frequency is 15 kHz which is 900000 RPM and greater than 3080 RPM [31].
Brake rotor RPM	Measure, withstand, and apply up to 590 RPM	Sensor's maximum operating frequency is 15 kHz which is 900000 RPM and greater than 590 RPM [31].

4.1.4. Dynamometer must be able to measure, withstand, and apply up to max torque. This requirement is also ranked as one of the most important because it is the one of the main drivers of the dynamometer's importance. Without measuring torque of selected components, the dynamometer would be essentially useless to the team. The dynamometer must measure torque so that we can combine this with RPM and optimize power delivery throughout the drivetrain.

Table 4.1.4. Requirements and specifications for the measure, withstand, and apply up to max torque requirement

Sub-requirement	*Specification*	*Justification*
Must be accurate	<2% error (of max reading)	2% of the highest torque required to measure is 12 ft lbs, and based on sponsor interviews any more than this makes the data less useful [23].
Engine torque	Measure, withstand, and apply up to 20.4 ft-lbs	Engine torque reaches a maximum of 18.5 ft-lbs and we must be able to measure this with a 10% safety factor [19].
CVT (input and output) torque	Measure, withstand, and apply up to 59.2 ft-lbs	CVT torque reaches a maximum of 53.8 ft-lbs and we must be able to measure this with a 10% safety factor [12].
Gearbox (input and output) torque	Measure, withstand, and apply up to 385 ft-lbs	Gearbox torque reaches a maximum of 350 ft-lbs and we must be able to measure this with a 10% safety factor [23].
Brake rotor torque	Measure, withstand, and apply up to 564 ft-lbs	Brake torque reaches a maximum of 512 ft-lbs and we must be able to measure this with a 10% safety factor [13].

Table 4.1.5. Verification/Validation plans for measure, withstand, and apply up to max torque requirement

Sub-requirement	*Specification*	*Completed Verification*
Must be accurate	<2% error (of max reading)	Error at the maximum reading is ±0.4% which is less than 2% [29]
Engine torque	Measure, withstand, and apply up to 20.4 ft-lbs	$M = 20.4\ ft\ lbs, D = 1", L_{pipe} = 18" \rightarrow \theta_{max} = 0.2303°$ $Longitudinal\ Deflection\ Ratio\ Experienced = \frac{\frac{\theta_{max}}{360°}*\pi D}{L_{pipe}}$ $Longitudinal\ Deflection\ Ratio\ Maximum = \frac{strain\ range*W_{overall,pattern}}{L_{overall,pattern}}$ $\frac{\frac{0.2303°}{360°}*\pi(1\ in)}{12\ in} = 0.000112 < \frac{0.05*(0.82\ in)}{0.7\ in} = 0.0586$ [29][32]
CVT (input and output) torque	Measure, withstand, and apply up to 59.2 ft-lbs	$M = 59.2\ ft\ lbs, D = 1", L_{pipe} = 12" \rightarrow \theta_{max} = 0.4455°$ $Longitudinal\ Deflection\ Ratio\ Experienced = \frac{\frac{\theta_{max}}{360°}*\pi D}{L_{pipe}}$ $Longitudinal\ Deflection\ Ratio\ Maximum = \frac{strain\ range*W_{overall,pattern}}{L_{overall,pattern}}$ $\frac{\frac{0.2303°}{360°}*\pi(1\ in)}{12\ in} = 0.000324 < \frac{0.05*(0.82\ in)}{0.7\ in} = 0.0586$ [29][32]
Gearbox (input and output) torque	Measure, withstand, and apply up to 385 ft-lbs	$M = 385\ ft\ lbs, D = 1", L_{pipe} = 19" \rightarrow \theta_{max} = 2.1729°$ $Longitudinal\ Deflection\ Ratio\ Experienced = \frac{\frac{\theta_{max}}{360°}*\pi D}{L_{pipe}}$ $Longitudinal\ Deflection\ Ratio\ Maximum = \frac{strain\ range*W_{overall,pattern}}{L_{overall,pattern}}$ $\frac{\frac{0.2303°}{360°}*\pi(1\ in)}{12\ in} = 0.00211 < \frac{0.05*(0.82\ in)}{0.7\ in} = 0.0586$ [29][32]
Brake rotor torque	Measure, withstand, and apply up to 564 ft-lbs	$M = 564\ ft\ lbs, D = 1", L_{pipe} = 9" \rightarrow \theta_{max} = 3.1831°$ $Longitudinal\ Deflection\ Ratio\ Experienced = \frac{\frac{\theta_{max}}{360°}*\pi D}{L_{pipe}}$ $Longitudinal\ Deflection\ Ratio\ Maximum = \frac{strain\ range*W_{overall,pattern}}{L_{overall,pattern}}$ $\frac{\frac{0.2303°}{360°}*\pi(1\ in)}{12\ in} = 0.00309 < \frac{0.05*(0.82\ in)}{0.7\ in} = 0.0586$ [29][32]

4.1.6. Dynamometer must be able to measure and withstand max temperature. This requirement is one of the more important requirements in terms of data collection, but is not as crucial as RPM or torque measurement collection. The dynamometer must be able to collect temperature data in order for the team to understand CVT and brakes performance changes at operating temperatures.

Table 4.1.6. Requirements and specifications for the measure and withstand max temperature requirement

Sub-requirement	*Specification*	*Justification*
Must be accurate	<2% error (of max reading)	2% of the highest temperature required to measure is 9 degrees, and based on sponsor interviews any more than this makes the data less useful [13].
CVT temperature	Must measure up to 253°F	Historical CVT temperatures reach a maximum of 230°F so we must be able to measure this with a 10% safety factor [12].
Brakes temperature	Must measure up to 441°F	Historical brake pad temperatures reach a maximum of 401°F so we must be able to measure this with a 10% safety factor [13].
Engine temperature*	Must measure up to 330°F	Historical engine temperatures reach a maximum of 300°F so we must be able to measure this with a 10% safety factor [19].
Gearbox oil temperature*	Max temperature unknown	Our team has never measured gearbox oil temperature before, so there is no specification for this requirement. Further testing would need to be done with a dyno to establish a temperature range before setting a specification for this requirement.

Table 4.1.7. Verification for the measure and withstand max temperature requirement

Sub-requirement	*Specification*	*Completed Verification*
Must be accurate	<2% error (of max reading)	Maximum error of the sensor is 0.5℃ and maximum temperature the sensor can read is 85℃, so the error is 0.6% which is less than 2% [30].
CVT	Must measure up to 253℉	The maximum temperature the sensor can read is 380℃ which is 716℉ and more than 253℉ [30].
Brakes	Must measure up to 441℉	The maximum temperature the sensor can read is 380℃ which is 716℉ and more than 441℉ [30].
Engine	Must measure up to 330℉	The maximum temperature the sensor can read is 380℃ which is 716℉ and more than 330℉ [30].

4.1.8. Dynamometer must be maintainable/easy to use. The dynamometer must be able to be maintained and operated by members of the Baja team with resources easily available to us. If the dyno is not maintainable, it will be neglected if it breaks at some point during its lifespan. The dynamometer also must be easy to use by members of the team with very little background knowledge about the dyno, so that its use does not diminish after members of this ME 450 team graduate and leave the team.

Table 4.1.8. Requirements and specifications for the maintainable/easy to use requirement

Sub-requirement	*Specification*	*Justification*
Maintainable	Sensors must be able to be calibrated in house, never sent out to external companies	The previous dyno lacked this requirement and included sensors which had to be specifically calibrated by an external company. This is part of the reason why this dyno got shelved, we would like to avoid this and have the simplicity of in-house calibration.
	All spaces where tools need to be used must be big enough for a 95% male human hand Breadth: 3.84 in Circumference: 9.07 in. Height: 8.29 in	All spaces for maintenance or repair must be accessible to the majority of the team. The volume correlating to the 95 percentile human male hand will be the largest size needed on the team. [26]
	Dyno must not require extensive EE and CS knowledge to gather and interpret data	The 450 team does not have extensive EE or CS knowledge or skills to create an electrically complex dyno, and the team is historically not made up of EE or CS students.
	Can be serviced with tools found in WSTPC	We must be able to repair the dyno in our own shop, as requested by the sponsor. This will reduce repair time and repair costs.
	Can be run with power sources found in WSTPC (480V AC max or 90psi max air pressure)	All power sources (besides the engine) must be from the available energy sources in the Wilson Center.
Easy to Use	Must be able to install or replace each car subsystem component on dyno in less than 10 minutes by 2 or more people	If changing setups takes too long, users may become discouraged and not use the dyno for small tests they want to do if it is too much work to set up.
	Must be able to set up each test in the computer in less than 10 minutes	If setting up a program to run each dyno test takes too long, users may become discouraged and not use the dyno for small tests they want to do if it is too much work to set up.

Table 4.1.9. Verification/Validation plans for the maintainable/easy to use requirement

Sub-requirement	*Specification*	*Completed Verification*
Maintainable	Sensors must be able to be calibrated in house, never sent out to external companies	All sensors used in this assembly are ones the team already owns and has used before. The team currently uses these sensors and calibrates them in house.
	All spaces where tools need to be used must be big enough for a 95% male human hand Breadth: 3.84 in Circumference: 9.07 in. Height: 8.29 in	Put a 3D CAD hand model of one of MBR's drivers into our dynamometer assembly and moved it around places which need to be worked during assembly and didn't encounter interference issues.
	Dyno must not require extensive EE and CS knowledge to gather and interpret data	The dynamometer only requires knowledge of a wheatstone bridge and how to go between different parameters (such as voltage and resistance to torque) using found transfer functions. All of this content is covered in EECS 314 and EECS 215 and all members of MBR have taken or will take one of these courses.
	Can be serviced with tools found in WSTPC	The dynamometer can be assembled using sockets and wrenches found in MBR's tool cabinet.
	Can be run with power sources found in WSTPC (480V AC [single or 3 phase] max or 90psi max air pressure)	All sensors and desktop used to collect the data can be powered using the WSTPC's 480V AC power [29][30][31].
Easy to use	Must be able to install or replace each car subsystem component on dyno in less than 10 minutes by 2 or more people	(1 minute to move engine) + (4 bolts) * (44 seconds to tighten each bolt) + (2 minutes to align holes with bolts) + (3 minutes for user movement) = 8.93 minutes
	Must be able to set up each test in the computer in less than 10 minutes	(1 minute to boot desktop) + (½ minute to select power source) + (1 minute to select components used) + (2 minutes to add data being measured) + (1 minute waiting for computer) + (1 minute for computer to connect with sensor assembly) + (2 minutes to troubleshoot) = 8.5 minutes

4.1.10. Dynamometer must be portable/storable. We must be able to store the dynamometer at our facility and also move it around within our facility. This is ranked relatively high in priority because if we cannot store the dynamometer at our facility for a majority of the time, it will not be used.

Table 4.1.10. Requirements and specifications for the portable/storable requirement

Sub-requirement	*Specification*	*Justification*
Fit within specified MBR area in WSTPC	Height < 60”, Width < 30”, Length < 48”	Needs to fit within the area or else it will be kept elsewhere and potentially forgotten about.
Can move around the WSTPC	Moved with < 70 lbs of lateral force	The dyno must be mobile in order to be moved to temporary storage if needed. On average, a 105 lbs female who is a novice at bench pressing can safely bench press 70 lbs (we imagine the dyno will be moved by pushing). This would be the weakest member in terms of bench pressing on our team [25]

Table 4.1.11. Verification for the portable/storable requirement

Sub-requirement	*Specification*	*Completed Verification*
Fit within specified MBR area in WSTPC	Height < 60”, Width < 30”, Length < 48”	CAD model is within 45.74” x 29” x 48”
Can move around the WSTPC	Moved with < 70 lbs of lateral force	At most the dynamometer takes 68 lbf to move (math in section 9)

4.1.12 Dynamometer must be safe to operate. We must ensure that the dynamometer is safe for all users and bystanders. It is not acceptable to create something which may harm someone without following protocols and putting measures in place to keep people safe.

Table 4.1.12. Requirements and specifications from safety requirement

Sub-requirement	*Specification*	*Justification*
All components are rigidly attached and contained	Powertrain guards shall safely dissipate a sudden, hazardous release of energy from powertrain components in the radial and tangential directions. Hazardous Release of Energy (HROE) guards shall be durable and mounted with sound engineering practices. HROE guards shall extend around the entire periphery of the guarded components. Constructed out of: Steel, at least 1.5 mm (0.06 in.) thick, meeting or exceeding the strength of AISI 1010 steel. Aluminum, at least 3.0 mm (0.12 in.) thick, meeting or exceeding the strength of 6061-T6 aluminum. [3]	These specifications are provided by SAE for the development of our team's baja car, and so to ensure our dynamometer is as safe as our car, we will follow these requirements.
All liquids and gasses used or released by the dyno are managed safely	No hazardous liquids (oils, fuels, etc.) or gasses (exhaust) released from dynamometer into Wilson Center	We are responsible for keeping a clean and safe area in the Wilson center, and releasing toxic or messy gasses and liquids into our area will not allow us to keep the area safe and clean.

Table 4.1.13. Verification for the safety requirement

Sub-requireme nt	*Specification*	*Completed Verification*
All components are rigidly attached and contained	Steel, at least 1.5 mm (0.06 in.) thick, meeting or exceeding the strength of AISI 1010 steel. Aluminum, at least 3.0 mm (0.12 in.) thick, meeting or exceeding the strength of 6061-T6 aluminum. [3]	In the CAD model, all steel is at least 0.06 in thick and all aluminum is at least 0.12 in thick. All components are attached using bolts and nylon loctite nuts. Additionally, plexiglass goes around the frame.
All liquids and gasses used or released by the dyno are managed safely	No hazardous liquids (oils, fuels, etc.) or gasses (exhaust) released from dynamometer into Wilson Center	Dynamometer will only be run in the WSTPC's paint booth which has a ventilation system or will be run outside which is the environment that our engine on the car is safely run in.

4.1.14 Dynamometer must be cost effective. We must be able to afford the production of the dynamometer or it will not be a feasible project for the team.

Table 4.1.14. Requirements and specifications for cost effective requirement

Sub-requirement	*Specification*	*Justification*
Stay within MBR Budget	Total cost within $6000 budget, using parts from previous dynos if necessary	The sponsor gave a set budget and the cost of the dyno must stay within this budget or else it can not be built

Table 4.1.15. Verification for the cost effective requirement

Sub-requirement	*Specification*	*Completed Verification*
Stay within MBR Budget	Total cost within $6000 budget, using parts from previous dynos if necessary	Total cost is $2,686.05 which is less than $6000

4.1.16 Dynamometer must be manufacturable. We cannot fabricate parts outside of the Wilson Center machine shop, all fabrication must be done within the Wilson Center.

Table 4.1.16. Requirements and specifications for the manufacturable requirement

Sub-requirement	*Specification*	*Justification*
In-house manufacturing	Manufacturable with regular manual Mills and Lathes, or 4 axis CNC (< 3 CNC parts total, no 5-axis mill parts)	Our sponsor has requested that we do not outsource manufacturing for this project, so we must use the manufacturing center we have available to us at the Wilson Center
Must be weldable if welding is necessary	No welded aluminum parts, only low-medium carbon steels	Welders on the team do not have the experience to weld aluminum

Table 4.1.17. Verification for the manufacturable requirement

Sub-requirement	*Specification*	*Completed Verification*
In-house manufacturing (WSTPC and Taubman)	Manufacturable with regular manual Mills and Lathes, or 4 axis CNC (< 3 CNC parts total, no 5-axis mill parts)	Pieces of the dynamometer and the assembly can be made using the waterjet in Taubman and the welder and manual mill and lathe in the WSTPC.
Must be weldable if welding is necessary	No welded aluminum parts, only low-medium carbon steels	All welded pieces are made of A513 1"x0.065" Square Steel Tube

4.1.18 Dynamometer must be reconfigurable. We must be able to set up different configurations of subsystems within the dynamometer in order to recreate the drivetrain of the car.

Table 4.1.18. Requirements and specifications for reconfigurable requirement

Sub-requirement	*Specification*	*Justification*
Must be able to set up dyno in multiple different testing configurations	Engine → CVT → Gearbox → Absorber	Testing this setup allows us to tune for final drive torque out of the gearbox. This setup also allows us to measure total drivetrain efficiency from the engine to the gearbox output
	Engine → Absorber	This setup will allow us to develop a motor torque vs speed curve, which is important to know to be able to properly design the CVT shift rates
	Engine → CVT → Absorber	This setup allows us to directly tune the CVT, which is important for high performance drivetrain events such as acceleration or sled pull
	Non-Engine Power Source → Gearbox → Absorber	Testing this setup allows us to isolate the gearbox to test gear fatigue and gear oil lifespan. Having this setup powered by a non-engine power supply will be simpler than running it off the engine because it would not produce exhaust and would not consume gas during lengthy gearbox fatigue testing
	Non-Engine Power Source → Brakes	Testing this setup allows us to isolate the brakes to test rotor deflection and pad wear due to heating at routine loads. Having this setup powered by a non-engine power supply will be simpler than running it off the engine because it would not produce exhaust and would not consume gas during lengthy endurance testing for brakes

Table 4.1.19. Verification for the reconfigurable requirement

Sub-requirement	*Specification*	*Completed Verification*
Must be able to set up dyno in multiple different testing configurations	Engine → CVT → Gearbox → Absorber	All components have mounting points. The dynamometer can be used with all components and with only some components. Chains and sprockets with the same gear ratios as components can replace these components.
	Engine → Absorber	
	Engine → CVT → Absorber	
	Non-Engine Power Source → Gearbox → Absorber	
	Non-Engine Power Source → Brakes	

4.1.20 Dynamometer must be able to integrate with the DAQ system. We must ensure that the sensors we choose for the dynamometer can be compatible with our data acquisition system in order to use collected dynamometer data.

Table 4.1.20. Requirements and specifications for the integrate with the DAQ system requirement

Sub-requirement	*Specification*	*Justification*
Wirelessly communicate sensor data	Must be able to transmit data from sensor system to analysis system without the use of wires	The subject matter expert on testing for the team has a great deal of experience in data acquisition using wireless sensors, so in order to make it useful for him we must follow this specification [22].

Table 4.1.21. Verification for the integrate with the DAQ system requirement

Sub-requirement	*Specification*	*Completed Verification*
Wirelessly communicate sensor data	Must be able to transmit data from sensor system to analysis system without the use of wires	All sensors are wireless and are compatible with the DAQ system [29][30][31].

4.1.22 Dynamometer deliverables must be accomplishable within a timeline. We must complete our dynamometer deliverables within the semester in order to satisfy the requirement of the course, and also to put the team on schedule for building the dyno before testing season.

Table 4.1.22. Requirements and specifications for timeline requirement

Sub-requirement	*Specification*	*Justification*
Must be able to complete project deliverable within fall semester	Must complete a CAD model of the final design and have manufacturing drawings complete by December 12th, 2023	If our group completes CAD and manufacturing drawings by the end of the semester, we not only have created a substantial deliverable for this class, we will also be able to manufacture the dyno after the semester in time for testing season.

Table 4.1.23. Verification for the timeline requirement

Sub-requirement	*Specification*	*Completed Verification*
Must be able to complete project deliverable within fall semester	Must complete a CAD model of the final design and have manufacturing drawings complete by December 12th, 2023	CAD model and drawings are completed

Table 4.1.24. Validation Plans for Built Dynamometer

Objective	*Validation Plan*
Ensure ease of component attachment	Ask members of MBR to detach and reattach components and ask about the experience, highlighting the ease of the process and any improvements
Ensure ease of computer setup	Ask members of MBR to set up a test using the computer and ask about the experience, highlighting the ease of the process and any improvements
Ensure ease of data collection	Ask members of MBR to run a test and ask about the experience, highlighting the ease of the process and any improvements

4.2 Weighted Sub-Requirements

From the preceding tables of requirements we created a table which weighted some of our sub-requirements that will be used in decision matrices later in the document. Each weight has an associated justification that explains why that weight was chosen for that sub-requirement. The weights are 1-5, with 5 being more important than 1. The sub-requirements in this chart may not match requirements in decision matrices word for word but mostly cover what sub-requirements will be used in later decision matrices.

Table 4.2.1. Sub-requirements with respective weights and justifications.

Sub-requirement	*Tentative Weights*	*Weight Justification*
Measure max torque, RPM, and temperature, withstand and apply max torque and RPM	5	Measuring these types of data is crucial to the useful output of the dynamometer. Withstanding the loads from the dynamometer is also crucial, without withstanding these loads it would break and become useless to the team.
Portable/Storable	5	The dynamometer must fit in our space at the Wilson Center, otherwise it will need to go into permanent storage offsite and will not get used. Frequent use of the dynamometer is very important for collecting a large portfolio of subsystem data.
Cost effective	4	This requirement falls to the next ranking of importance, although it is still important. If we exceed our budget in designing this dynamometer, we will not be able to build it and it will always remain just a plan on a shelf. This would not be useful to the team.
Reconfigurable	4	This requirement is ranked slightly higher here than compared to its ranking above in the master list of requirements. This is because in this context it will be used for justifying concept decisions in decision matrices later on. It is more important when ranked with these other sub-requirements.
Maintainable	3	Maintainable is the first of the sub-requirements in this list to be at a weight of 3, this is because it is simply not as crucial for performance as collecting data and applying loads. If the dynamometer is not easily maintainable, we will just have to spend more time working on repairing it, whereas if the dynamometer is poor at applying and measuring loads on our components, we will likely not use it.
Manufacturable	3	Manufacturable is another sub-requirement in this list to be at a weight of 3, this is because it is simply not as crucial for performance as collecting data and applying loads. If the design of the dynamometer is not manufacturable, we will have to change the design before we can manufacture it anyway, which is less detrimental than if the dynamometer cannot collect or withstand loads.
DAQ integration	3	Integration of the Data Acquisition System is not as important as the previous sub-requirements mentionioned. Our team's testing lead is going to lead this aspect of the dynamometer, our job is simply to ensure that the sensors we use are compatible with the way he plans to complete the DAQ for the dynamometer.

5 Concept Generation

5.1 Concept Generation Process

To begin our concept generation process, each member of the team generated at least 40 concepts individually. At this stage, we intentionally avoided filtering out any ideas, so that we could explore the solution space as thoroughly as possible and break away from conventional solutions. Each of us used tools such as heuristic cards and morphological analysis with our own concepts to expand our breadth of ideas. After this individual divergent thinking exercise, we held a group brainstorming session to describe our ideas to each other so that we could build on them and introduce even more concepts. This generated an extremely diverse and comprehensive set of over 50 unique solutions, a few of which are shown in Figure 5.0.l below and the rest of which can be found in Appendix B.

Our concept generation process had both collaborative and individual components. Figure 5.1.1 below shows our concept generation process.

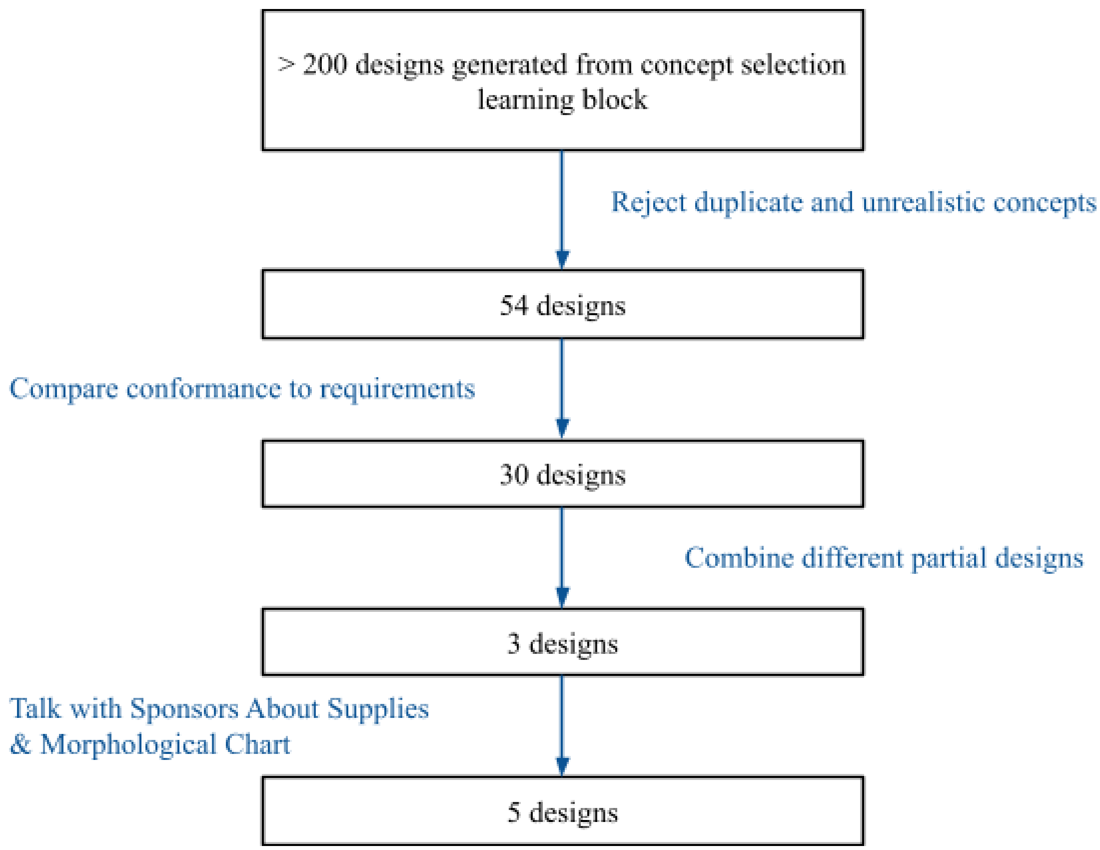

Figure 5.1.1. Our concept generation process. It started out with us brainstorming individually, then getting together to analyze our proposed designs and to build off of all proposed designs. The process ended with talking with the sponsors to make sure our design would work for them.

First, each member of the team was tasked with individually creating at least 40 unique concepts which in turn gave us more than 200 designs. For this brainstorming we used techniques such as design heuristics and morphological analysis to iterate off of our ideas as some members got stuck before reaching 40 unique concepts. During this stage we encouraged each other to focus on quantity rather than quality or feasibility; at this time we encouraged divergent thinking.

After our individual brainstorming sessions, we got together to go through all of our designs. At this point we got rid of any duplicate designs we had and filtered out any unrealistic designs. Figure 5.1.2. below shows some ideas that were filtered out as they were deemed unrealistic.

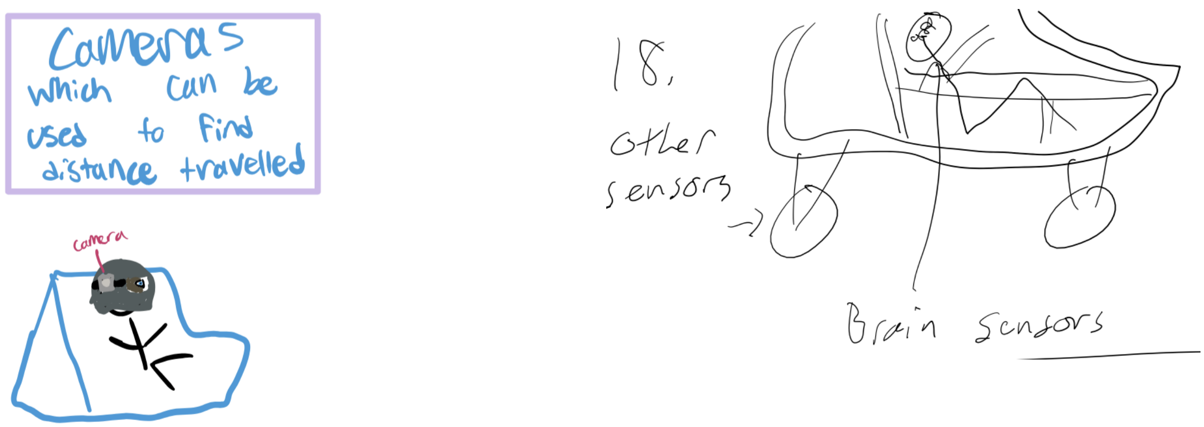

Figure 5.1.2. Some unrealistic designs from our individual brainstorming session.

In the figure above, the design on the left has a camera on the driver's helmet which could be used to collect the distance traveled and the path taken by the driver, at this point though the technology is probably not good enough to accurately calculate these parameters. The design on the right has a driver who communicates with the car with their mind (mind-reads the car) to know what data to collect and what to improve

After we filtered out the unrealistic and repetitive designs, we were left with 54 ideas. We next compared our designs with our specifications and requirements and got rid of any which were found to not adequately meet these specifications and requirements. Figure 5.1.3. on page 32 below shows some of the designs which were found to fall short of the requirements and specifications.

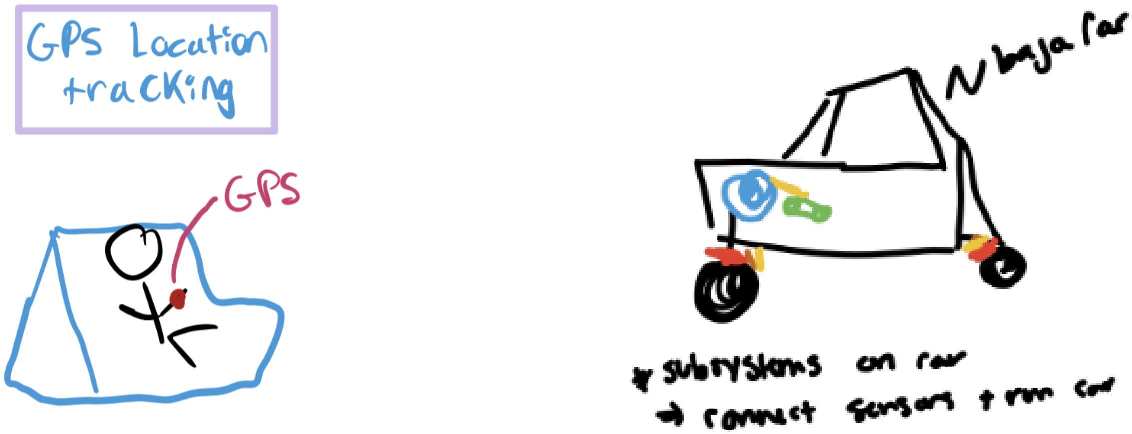

Figure 5.1.3. Some designs which were found to not fully address our requirements and specifications.

In the figure above, the design on the left has a GPS tracker on the driver so that the design would be able to collect the location the driver, this design does not collect input or output RPM of the gearbox or CVT, or output RPM of the gearbox, so although it tracks location it would not truly give any relevant data. The design on the right just has us test the components on the car which does not utilize space well and would not meet our spatial requirements.

After we filtered out the concepts which inadequately addressed our requirements and specifications we were left with 30 ideas. During our brainstorming process we emphasized divergent thinking and not getting stuck on ideas, and due to the complexity of the design problem most of our ideas only partially addressed our specifications and requirements. Thus we next began to combine our not fully-fledged designs into more complete designs. After combining designs we were left with the three designs below in figure 5.1.4.

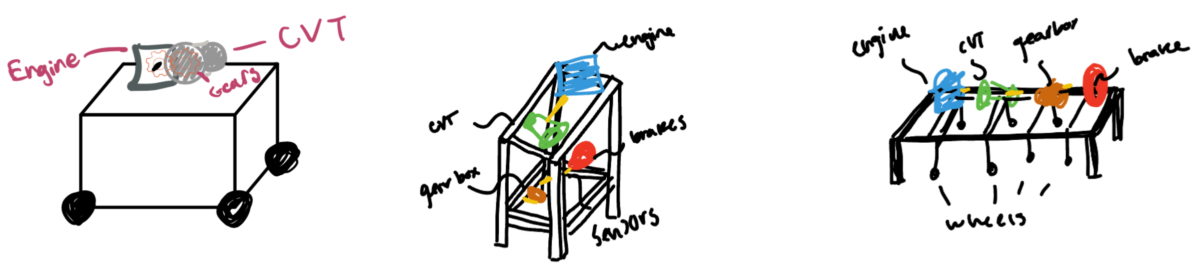

Figure 5.1.4. The three complete designs we were left with after combining our ideas.

In the figure above, the design on the left is a welded steel frame with components resting on the top with wheels on the bottom for mobility. The design in the middle is a bolted Al frame with components bolted to it. The design on the right was one level with each component on its own set of wheels so that the components are easily detachable.

After our collaborative brainstorming and analysis session, we met with our sponsors. We walked our sponsors through our three designs and asked them about which supplies would be readily available. With this information we constructed morphological charts which are explored in sections 5.2 and 5.3, and then came up with the two designs which are discussed in section 6.2.

5.2 Options of Data Acquisition

The functional decomposition of the data acquisition system is included below in Figure 5.2.1.

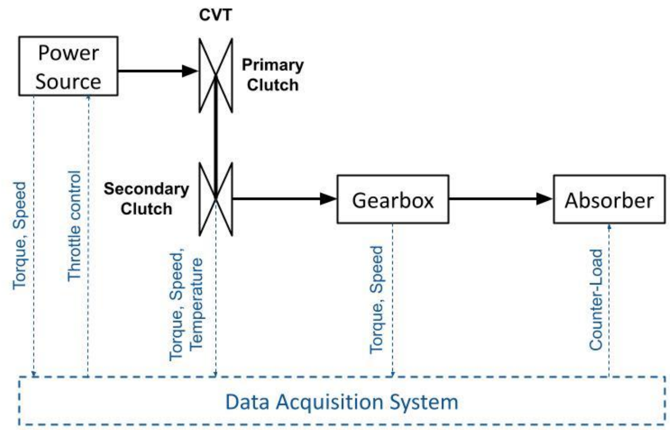

Figure 5.2.1. Functional decomposition for the data acquisition system.

The figure above shows one of the possible component arrangements with a power source providing input torque to the primary clutch of the CVT which transfers torque to the secondary clutch of the CVT, the output torque of the secondary clutch is transferred to the gearbox and its output torque is absorbed by the absorber. The blue text and dotted arrows show what data is being collected and from which components, with the power source providing a throttle control and the absorber providing a counter-load.

The different options for data acquisition consisted of various types of sensors that would be used to collect our desired data as well as the absorber that would provide the counterload. The different types of sensors and absorbers were outlined individually in section 3.2 and are organized in a morphological chart below. Notably, semiconductor-based temperature sensors are absent from the temperature sensor row because of their low accuracy and small operating window. The types of non-engine power sources were also not included because a DC motor was clearly the best option as highlighted in section 3.2.5. Table 5.2.2 below shows the morphological chart for the data acquisition system.

Table 5.2.2: Morphological chart of sensors and absorbers considered for this project. Types of data needed are listed below "subfunction" as well as "counterload" for the force required from the absorbers. Ways these forces could be measured or supplied are listed to the right of the subfunction under "solutions."

Subfunction	**Solutions**			
Temperature	NTC	RTD	Thermocouple	Infrared Thermometer
RPM	Hall Effect	Digital Tachometer	Physical Tachometer	Stroboscopic Tachometer
Torque	Rotary Sensor	Static Sensor	–	–
Counterload	Friction-Based Absorber	Magnetic Particle Absorber (CVT Dyno)	Hydraulic Absorber	–

5.3 Options of Mechanical Setup

The mechanical setup for the dyno consists of the components that are not used to collect the data from the subsystems or the systems being tested. Similar to the data acquisition system, a variety of methods were used to come up with solutions for our mechanical setup. One method used was a functional decomposition, which is shown in Figure 5.3.1 below:

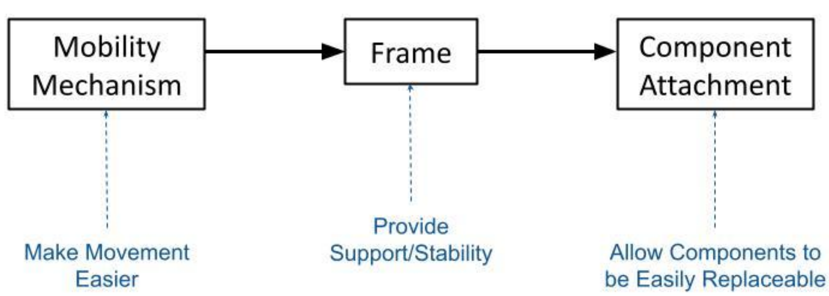

Figure 5.3.1. The functional decomposition of our mechanical setup. The subfunctions are shown in the black boxes. The blue dotted line leads to the specific requirement for each subfunction. The black arrow shows the flow of material regarding all the mechanical setup subfunctions.

The decomposition broke the mechanical setup into different subfunctions including the mobility mechanism, frame, and component attachment. From our list of requirements acquired from our stakeholders described in Section 4 above, the subfunctions need to be easily portable, provide support and stability, and be easily reconfigurable, respectively. After that, we further broke down the subfunctions of the mechanical setup using a morphological chart, shown in Table 5.3.2 below:

Table 5.3.2. A morphological chart of the different solution options for the mechanical setup subfunctions. The subfunctions of the mechanical setup are listed below "subfunction" and the possible solutions we generated are listed below "solutions" to the right.

Subfunction	Solutions		
Frame Material	80/20 Al	6061 Al	1020 Steel
Frame Attachment	Bolted together	Welded	Screwed together
Frame Configuration	Two rows	Three rows	Four rows
Component Attachment	Bolted to fixed plate	Bolted to removable plate	Bolted to frame itself
Mobility	4 Wheels	Track	Treads

For this morphological analysis, we broke down the frame subfunction further into three integral components, material, attachment methods, and configuration. Furthermore, we included the component attachment and mobility subfunctions that are outlined above in our functional decomposition. The right side of the morphological chart lists the potential solutions we generated for each subfunction, which were derived using information from discussions with our stakeholders. For the frame material, the three options are 80/20 aluminum, 6061 aluminum, and 1020 steel. These options were chosen after consulting our sponsor, as they are the most available and practical while still providing the necessary durability [19]. The attachment solutions include bolting, welding, or screwing the frame together. These methods were generated through stakeholder interviews taking into account MBR's skills and experience [19]. To best utilize the space the dyno takes up, the options for the frame configuration include 2 to 4 rows. The dyno has spatial constraints it must fulfill for it to satisfy the storable requirement, so there must be more than 1 row to fit all the subsystems. In addition, the frame must provide stability for the dyno to meet the stable requirement, making more than 4 rows impractical. The components could be bolted to a fixed plate, bolted to a removable plate, or bolted to the frame itself regarding the attachment methods. Lastly, the potential mobility options include 4 wheels, tracks, or treads, allowing for adaptability.

6 Concept Selection

After concept generation, we stepped into selecting our final designs. By combining the options for the data acquisition system, the braking force, and the mechanical setup through the morphological analysis done, we were provided with 28 strong concepts. To select these down into a final design concept, we first selected the best options for components within each of our high level concepts and then evaluated these top concepts to determine the best one to move forward with.

6.1 Component Selection

6.1.1. Data Acquisition

The sensors and absorbers from the morphological chart in section 5.2 were put in a decision matrix to select the components that will be used in the dynamometer. The decision matrix determined how well each of the components could meet the requirements, sub-requirements, and specifications outlined in section 4. The information from section 4 was condensed to five different criteria: data collection, accuracy, cost-effectiveness, maintainability, and ability to be integrated with the data acquisition system.

The criteria were all given a weight from 1-5 corresponding to how crucial they were to our design, with 5 representing the most important weighting. Data collection was deemed the most important and received a weight of 5 as a result. Cost-effectiveness was determined to be equally important and was given a weight of 4. Maintainability and integration with the data acquisition system were noted as being less important than the other three, but still crucial to the design as a whole, because of this they both received a weight of 3.

All sensors and absorbers were given a score out of 5 for each of the above categories, where 5 is best and 0 is worst. The scores were then multiplied by the weight of the category to determine the weighted score for that section. The weighted scores were then added up to provide a final score for each component.

The chart with the weighted scores is included below. Physical and stroboscopic tachometers were both determined to be unrealistic for this project, so they were removed from consideration and not included in this analysis.

Table 6.1.1. The decision matrix used to determine which sensors and absorber will be used on the final dynamometer. Unweighted scores are included first with the weighted score in parentheses following it. The total weighted score in the rightmost column to show each component's "total score." The highest "final score" for each category is highlighted to show which components were selected.

	Category	Collect All Necessary Data Values	Cost Effectiveness	Maintainable	Daq Integration	Total Score
	Weight	5	4	3	3	N/A
RPM	Hall Effect [18]	5 (25)	5 (20)	4 (12)	5(15)	72
	Digital Tachometer [20]	3 (15)	3 (12)	5 (15)	4 (12)	54
Temp. Sensors [17]	NTC	0 (0)	4 (16)	4 (12)	5 (15)	32
	RTD	3 (15)	2 (8)	4 (12)	5 (15)	50
	Infrared Thermometer	5 (25)	3 (12)	4 (12)	5 (15)	64
	Thermo-couple	3 (15)	3 (12)	4 (12)	4 (12)	51
Torque	Rotary [15] [16]	5 (25)	4 (16)	4 (12)	5 (15)	68
	Stationary [15]	0 (0)	4 (16)	4 (12)	5 (15)	43
Counter-load [11]	Friction-based	4 (20)	1 (4)	2 (6)	5 (15)	45
	Magnetic Particle Brake	4 (20)	5 (20)	4 (12)	5 (15)	67
	Hydraulic	4 (20)	1 (4)	3 (9)	5 (15)	48

From this table we determined that the sensors we will be using on this dynamometer are: a hall effect RPM sensor, an infrared thermometer, and a shear/torque strain gauge. These sensors will be purchased from digikey. The hall effect RPM sensor we selected to meet our requirements is the Honeywell ZH10 hall effect speed sensor [31]. The infrared thermometer sensor we have selected to meet our requirements is the Melexis Technologies MLX90614ESF-BAA-000-TU infrared digital temperature sensor [30]. The torque strain gauge we selected to meet our requirements is the Micro-Measurements MMF404946 strain gauge [29]. The counterload will be applied using the preexisting magnetic particle brake and the power to the components being tested when applicable will come from a DC motor as discussed in section 3.2.5.

6.1.2. Mechanical Setup

The mechanical setup morphological chart and conversations with our stakeholder were used to determine which options would be the best to include in our final design. For both the frame material and attachment methods, we developed two different options based on the characteristics of each material and manufacturability considerations. We decided one option would use the 1020 steel and be welded together considering the weldability of steel, which would ensure structural stability. The second option uses the 80/20 aluminum bolted together based on aluminums difficulty to weld and the flexibility this method would allow for reconfiguration. These two materials are readily available to Michigan Baja Racing and these combinations would allow the frame to be manufactured based on the skill level of the team. The remaining subfunction decisions would be included within both design options. For the component attachment method, the bolted removable plate was chosen because it is the most adaptable for reconfiguration while still giving support to the subsystems on the dyno. Furthermore, we decided three rows was our optimal frame configuration based on the spatial constraints to meet the storable requirement while maintaining stability, which could be compromised by adding more rows. For mobility, four wheels gives the dyno the best portability and is the most practical option for ease of movement. These choices were made to maximize the functionality of the mechanical setup while keeping in mind the available resources available and the skills of our sponsors.

6.2 Top Concept Selection

As mentioned in Section 5.1, after we combined our partial designs and were left with three designs we created two more designs collaboratively. In order to make these designs we first created the functional decomposition for the data acquisition system in system 5.2 and for the mechanical system in 5.3, and then created a morphological chart for the data acquisition system in sections 5.2. The sensors used in our data acquisition system were chosen in section 6.1.1.. The two new designs which became our top concepts focus just on the mechanical setup. Our first concept is a welded 1020 steel frame, with 3 rows of bolted plates to the frame and 4 wheels. Our second concept is a bolted 80/20 Aluminum frame, with 3 rows of bolted plates to the frame and 4 wheels. Figure 6.2.1. below shows these two concepts.

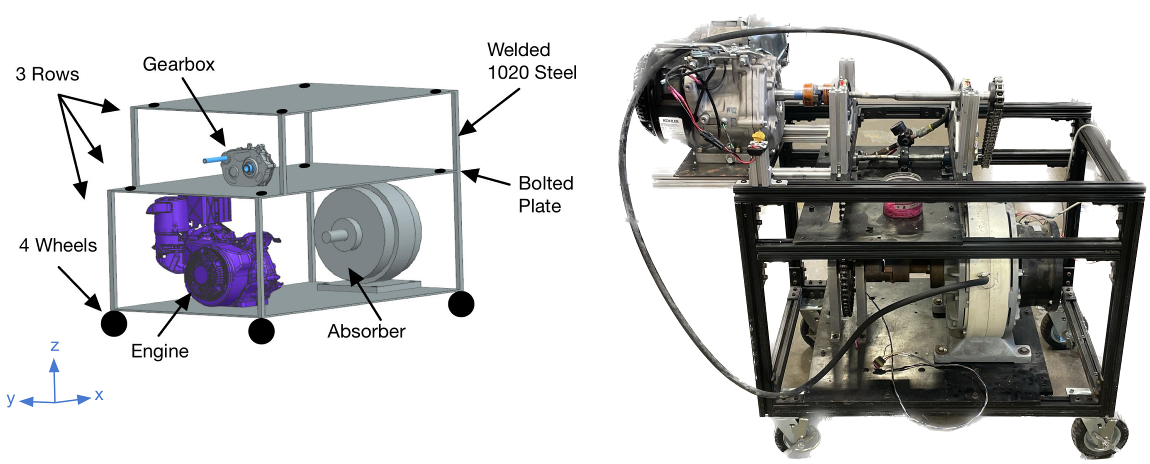

Figure 6.2.1. Our top two concepts during our concept selection process.

In the figure above, the concept on the left is our first concept of a welded 1020 steel frame, its bottom row has a height of 18 inches and top row has a height of 12 inches (with respect to the z-axis), the bottom row has a length of 42 inches and top row has a length of 48 inches (with respect to the x-axis), and both rows have a width of 30 inches (with respect to the y-axis). The rows are ¼" thick. The concept on the right is our second concept of a bolted 80/20 Aluminum frame.

We used a Pugh chart to decide between our top two concepts, which is table 6.2.2 below.

Table 6.2.2. Pugh chart analysis for our top two design concepts.

		Portable /Storable	**Withstand Loads**	**Reconfigurable**	**Cost Effective**	**Maintainable**	**Manufacturable**	**Total Score**
	Weight	5	5	4	4	3	3	
Concept 1: Welded 1020 Steel Stand	**Raw Score**	4	5	3	4	4	4	25
	Weighted Score	**20**	**25**	**12**	**16**	**12**	**12**	**97**
Concept 2: Bolted 80/20 Aluminum Stand	**Raw Score**	5	1	5	3	4	5	25
	Weighted Score	**25**	**5**	**20**	**12**	**12**	**15**	**89**

Our criteria for the Pugh chart were derived from the requirements that are affected by design decisions at this level. The rest of our requirements would be affected by lower level design decisions, but are not very relevant to this choice and would have very little variation in scoring across concepts, so we decided not to include them in this chart. Our highest weights are for Portable/Storable and Withstand Loads, followed by reconfigurable and cost effective, with maintainable and manufacturable as the lowest weight. Even though reconfigurable is relatively low on our high level requirements it has a greater weight as the chosen designs largely affect reconfigurability. We assigned scores on a scale from 1 to 5, with high point values indicating good performance.

Our two concepts performed similarly with the first concept (1020 steel) having a total score of 97 and the second concept (80/20 Aluminum) with 89, we decided on the first concept which performed slightly better. When we initially took on this project, we inherited some ideas and components from a previous ME 450 team that worked with Michigan Baja Racing. That team also pursued a dynamometer specifically for the CVT, so we already had some resources to help us. Specifically, we had an 80/20 Aluminum bolted frame which we attached to a new engine and through this test found this frame to be inadequate due its shaking while the motor was powered on. We attempted to solve this issue by adding in more supports, but ultimately ended up having an experienced welder on our team weld the 80/20 together, which eliminated the shaking. Despite the 80/20 Aluminum performing similarly to the 1020 steel it was declared as an improbable solution due to the results of this test and the difficulty of welding 80/20/aluminum together. With the 1020 steel outperforming the 80/20 Aluminum and the 80/20 Aluminum having issues with withstanding loads–thus not being super maintainable–1020 steel was chosen as our final concept.

As we explained in sections 5 and 6, through extensive brainstorming and several layers of concept selection we arrived at the 1020 steel as a top concept. This does give us reason to pause and consider whether or not our brainstorming was sufficient, whether or not we were biased in our selection, as we ended up with a very common frame shape which is similar to the CVT dynamometer. However, we believe that our process gave us an accurate depiction of what options were strongest, and the fact that we ideated a similar solution to the CVT dynamometer just shows that these parameters have been well studied and the prior CVT team and the industry in general well understand what is ideal. As such, we are confident that we are pursuing a very strong solution for this problem.

7 Alpha Design

Our top concept following the concept selection process outlined in section 6.2 is a welded 1020 steel frame, with 3 rows of bolted plates to the frame and 4 wheels. An early stage of our selected design can be seen in figure 7.1 below.

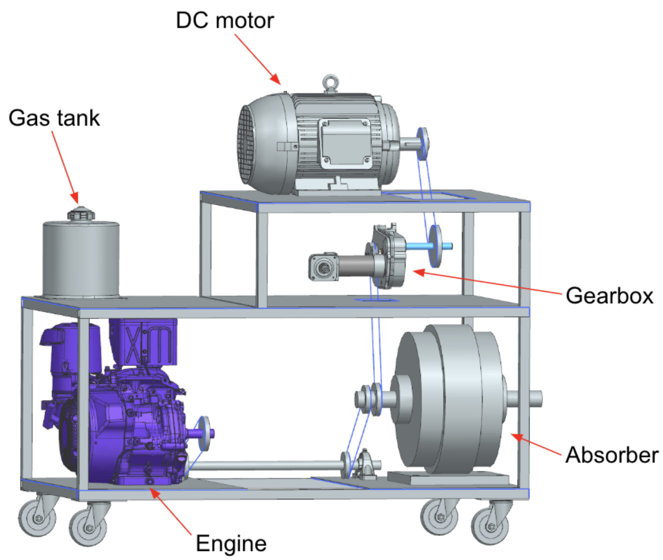

Figure 7.1. Alpha Design (early version) of the dynamometer.

The maximum dimensions of the frame in the figure above are 30” by 48” by 30” (with additional height due to components on top) which are within the space requirements of 30” by 48” by 60”. The DC motor lies on the top shelf with space for the CVT to attach and go to the middle row which holds the gearbox and gas tank, and the absorber and engine are on the bottom row. The gas tank is above the engine so that gravity will feed the gas into the engine. The same principles are used in the MBR car.

If possible, this frame will later be trimmed once the necessary space for each of the component assemblies is defined. The 1020 bars will be welded together to make the frame, with plates which will be bolted onto the frame, along with support blocks bolted to the plates and support blocks, and the critical components (gearbox, brakes, absorber, CVT, motor, and engine) will be bolted to these support blocks. The plates will have holes so that the dynamometer can be arranged in all the configurations described in section 4.1., the support blocks may have multiple sets of holes so that they are multifaceted and as few blocks need to be manufactured as possible. This design has parts which are easy to manufacture as the stakeholders have emphasized manufacturability and maintainability. In preparation for moving into true design and manufacturing, we compiled manufacturing plans for challenging components in each concept which are shown in table 7.2 below.

Table 7.2. Preliminary materials and manufacturing plans. Includes plans for our chosen concept.

Component	*Material*	*Manufacturing Operations*
Frame	1020 Steel	(1) Cut using horizontal band-saw (2) Use mill to drill holes used to affix plate to frame (3) Weld frame together
Plates	Steel sheet metal, ¼" thick	(1) Waterjet outline and holes used to attach components to plate
Support Blocks	Aluminum	(1) Mill shapes and drill holes
Bolts	Grade 8 Steel	Buy
Lock Nuts	Nylon Insert, Grade 8 Steel	Buy
Shaft Attachment Mechanism	Unknown	Buy

This design was a great start but had some issues. Firstly, without a lot of complicated routing it would be very difficult to test components with the engine due to its location on the bottom level. Additionally, there is no way to test the CVT without also using the gearbox which would put a lot of unnecessary wear on the gearbox. As can be seen in figure 7.1., there is a lot of unused space which means this design uses more material than is necessary. The information in table 7.2. is relevant, but the exact information is somewhat outdated. The components and stock we plan to buy are in section 10. The updated manufacturing plans are included in section 8.

8 Build and Final Design

The build and final CAD design are identical for our dynamometer solution, so this section will describe both the build and final design. The maximum dimensions of the frame and maximal height of the assembly can be seen in figure 8.1 below.

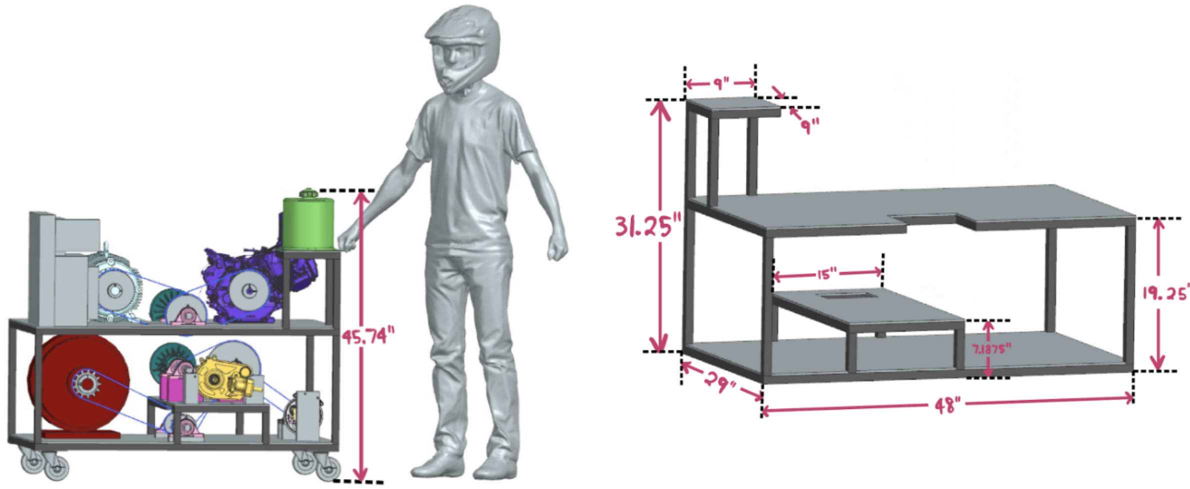

Figure 8.1. The dimensions of the final frame and assembly.

The final frame is within 29” x 48” x 31.25” effectively meeting our size requirement. Including the wheels and gas tank to the assembly, the maximal height is 45.73” which makes the dynamometer serviceable when adding gas to the gas tank. One of MBR’s drivers from the 2023-2024 season is shown next to the full assembly in order to give context as to the size of the dynamometer.

Our design with all major components highlighted is shown in figure 8.2. below.

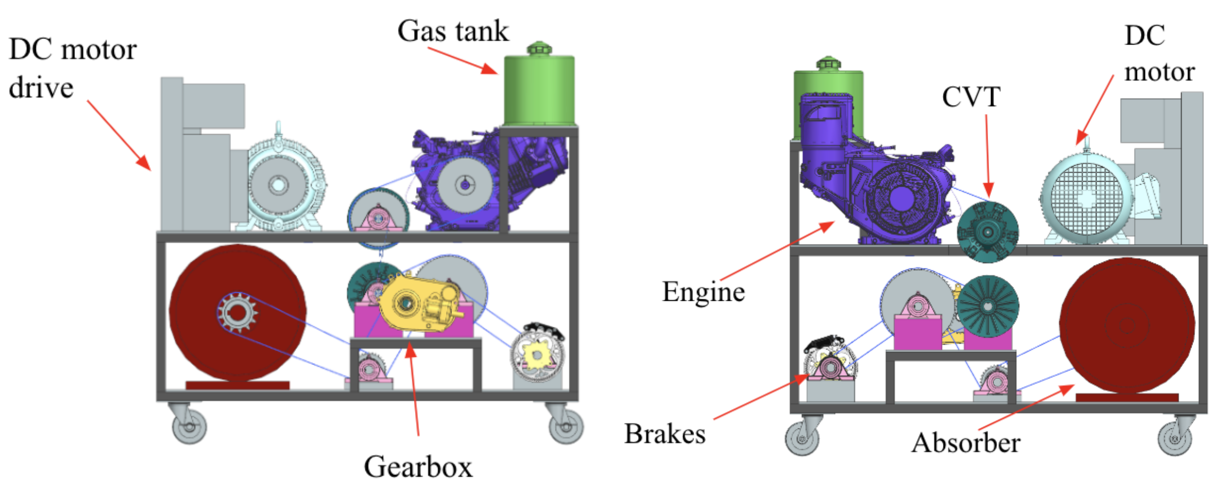

Figure 8.2. The current CAD model for the dynamometer.

In the current CAD model there is a little shelf on top for the gas tank so that gravity will feed gas into the engine just as in the MBR car. The top plate contains the components generating motion–DC motor and engine–along with the DC motor drive. The CVT runs from the top plate to the middle shelf where it can connect to the gearbox. The absorber and the brakes are on the bottom plate. There are shafts before and after each component so that configurations can be made without using components. On the top shelf there is an input shaft to the CVT which is equidistant from the DC motor and engine so that it is easy to switch between the power source. When the CVT and gearbox are not in use they are replaced with chains and sprockets to reduce wear on these components. Using sprockets the torque is geared down before reaching the absorber or brakes in order to stay below their maximal threshold.

The frame is made out of A513 1”x0.065” Square Steel Tube. The square steel tube is welded together to form the frame and then detachable sheet metal plates can be bolted into place. This design has four plates: bottom, middle, top, and gas tank. The bottom plate is made of 4130 Steel ⅛” thick sheet metal. The three other plates are made of 6061 Aluminum ⅛” sheet metal. The gas tank, DC motor, DC motor drive, engine, and absorber are bolted directly to the sheet metal. The brakes and CVT are mounted on the shafts placed before and after components. These shafts are supported by pillow blocks on top of support blocks which are bolted to the sheet metal. The gearbox is attached to a support block which is bolted to the sheet metal. Additionally, we will bolt 0.125” plexiglass shields to the outside of the stand to act as HROE guarding and protect the user from any hazards. The manufacturing plans for these components are seen below in table 8.3.

Table 8.3. Manufacturing plans

Component	*Material*	*Length/Area*	*Manufacturing Operations*
Frame	1020 Steel 1-inch square tube	21 ft	(1) Cut using metal chop saw (2) Weld frame together (3) Use mill to drill holes used to affix plate to frame
Bottom (Absorber) Plate	4130 Steel sheet metal, 1/8” thick	48” x 29”	(1) Laser cut outline and holes used to attach components to plate
Other Plates	6061 Aluminum sheet metal, 1/8” thick	Gas Tank Shelf: 9” x 9” Top Plate: 48” x 29” Middle Shelf: 15” x 29”	(1) Laser cut outline and holes used to attach components to plate
Support Blocks	6061 Aluminum	2 ft^3	(1) Mill shapes and drill holes
Plexiglass Shields	0.125” Plexiglass	20 ft^2	(1) CO2 cut outline and holes

We will make sure to take proper safety measures and use proper protective equipment while manufacturing. While using the metal chop saw, laser cutter, CO2 cutter, and mill that means wearing safety glasses, close toed shoes, long pants, and no long sleeves. When welding we will wear safety glasses, close toed shoes, long pants, leather shoes or covers, fire-resistant clothing, and a welding helmet. Additionally, for all these processes we will ensure there is proper ventilation.

The entirety of our manufacturing work will be completed in the Wilson Student Team Project Center (WSTPC) and Ford Robotics Building Makerspace (FRB). In WSTPC, we will be using the manual mills, metal chop saw, handheld drills, and the welder to build the frame, support blocks, and assemble everything. In the FRB, we will be using the Fablight laser cutter and CO2 cutter to cut out all the metal plates and plexiglass shields. Tolerances are around 0.025” for the stand since we will be welding the components together which will cause warping, and match drilling all of the holes to ensure the plates line up well with the square tube frame. The tightest tolerances will be on the support blocks, which will have a squareness tolerance of 0.003" and dimensional tolerances of 0.005" as these will interface with the most components and are critical in ensuring everything is mounted in the correct place. All laser cut sheets will have tolerance of 0.002" as well since that is the tolerance the laser cutter is able to hit, which ensures that all the pillow blocks and shafts will be adequately aligned.

As specified in our requirements and specifications in table 4.1.9. in section 4.1., the dynamometer must be reconfigurable to cover different testing scenarios. The same setups must be possible using the engine and DC motor as the power source. The four configurations with the engine as the power source are shown in figure 8.4 below.

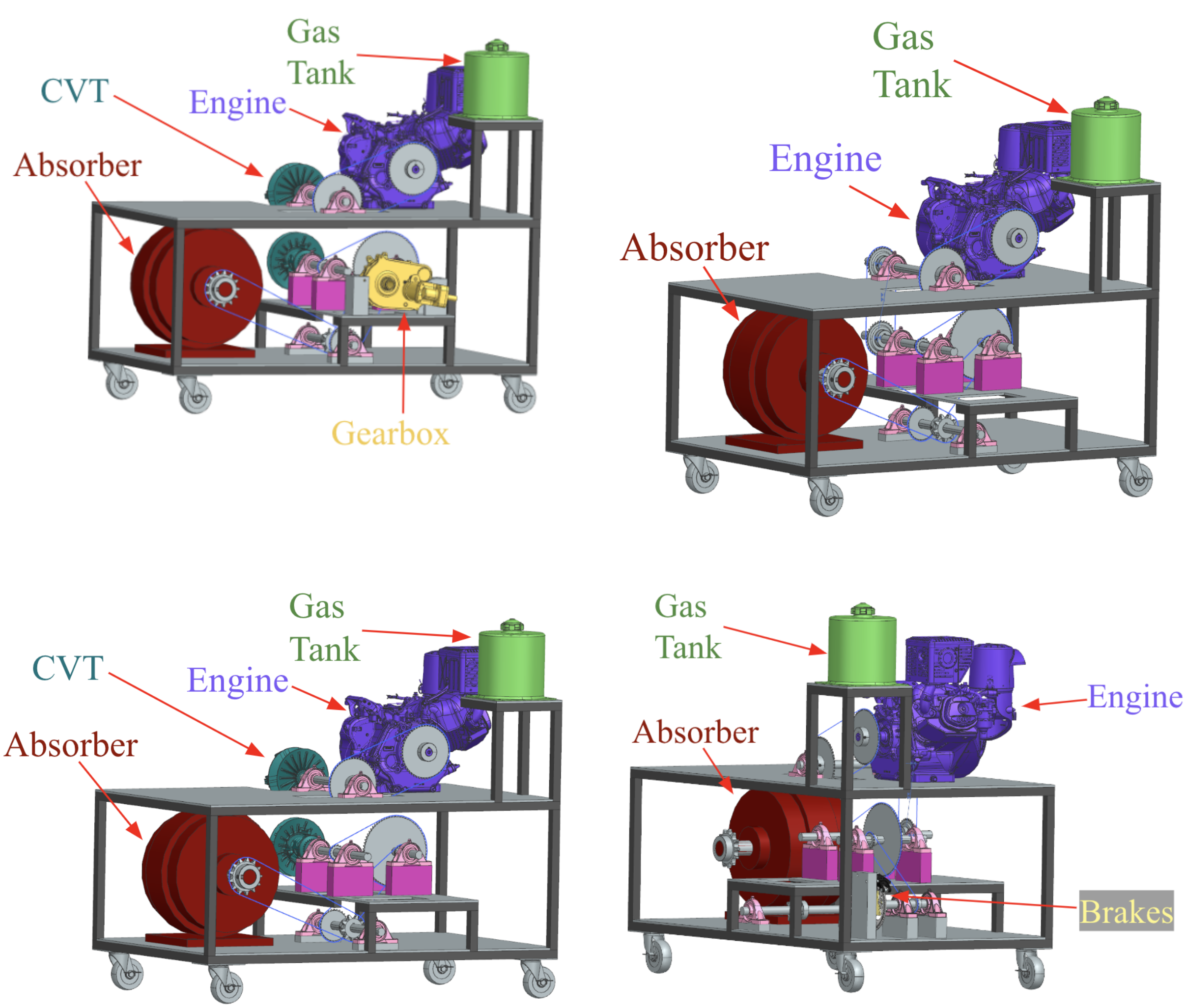

Figure 8.4. Configurations of the dynamometer using the engine as the power source.

In the figure above, the configuration in the top left has torque going from the engine to the CVT to the gearbox to the absorber. This configuration best represents MBR's car and can be used to find final drive torque out of the gearbox and measure drivetrain efficiency. The configuration in the top right has torque going from the engine to the absorber. This configuration can be used to find the torque power curve to better understand each engine and identify the engine with highest torque output to use at competitions. The configuration in the bottom left has power going from the engine to the CVT to the absorber and can be used to directly tune the CVT. The configuration in the bottom right has torque going from the engine to the brakes. This configuration isolates the brakes so that pad wear can be studied and the maximal temperature experienced can be found.

9 Analysis

To verify our design has met all of our requirements, we performed a variety of analysis on the frame, shafts, and system as a whole. The team has all of the required knowledge to complete these analyses, namely solid mechanics and dynamics, as most of it was learned in ME 240 and ME 211. The quickest and easiest way to determine if our selected concept will meet our specifications is by creating a mock-up of the stand in CAD and performing FEA. We performed a linear static analysis in Altair Hyperworks using an Optistruct solver on the frame to ensure that it can handle the loads of all components without yielding. We set up our model by treating each component as a 2D element and creating a 2D mesh, and applying a thickness to it in the material properties. We applied our loads via a pressure that covered the area of the component that had a total magnitude equal to the components mass. Based on our FEA we had to change our frame (sheet metal plates and square tubing supports) so that all components could be supported. Our FEA results can be seen in figure 9.1. below.

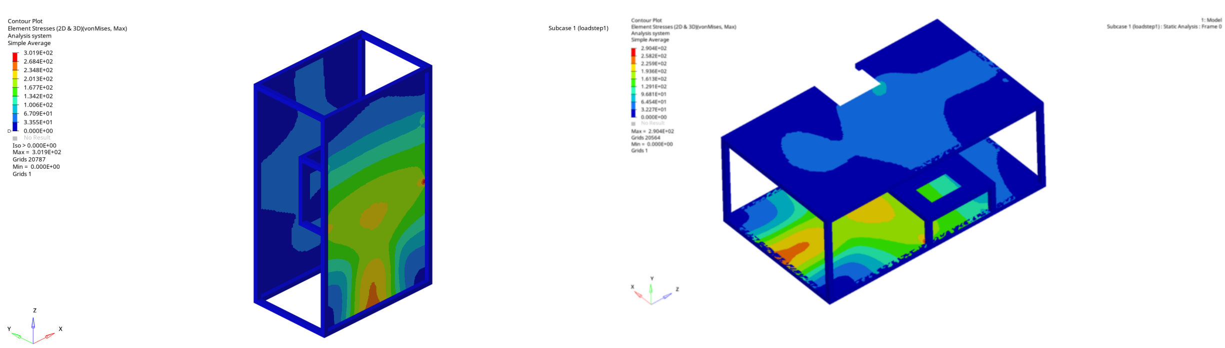

Figure 9.1. The results from our FEA of the frame. The first frame iteration is on the left and the final is on the right.

Initially, we decided to make all plates and shelves out of ⅛" 6061 aluminum sheet metal. The first iteration–which is on the left in the figure above– is run with 6061 aluminum plates. With all of the weight of the components on this frame, the aluminum is found to be inadequate (the stresses experienced are greater than the material can handle. The bottom plate experiences a maximum stress of 301.9 MPa while 6061-T6 Aluminum has a yield strength of 276 MPa meaning this frame would yield. After this analysis we decided to change the bottom plate to ⅛" 4130 steel and add in supports (1020 Steel 1-inch square tube) at the bottom of the plates to help handle stress. With these changes we ran FEA on the final frame iteration and received the results on the right in the figure above. The maximum stress experienced by the bottom plate is 290.4 MPa and the maximum yield strength of 4130 steel is 435 MPa, which means the frame has proper strength for the weights it must endure. The top plate experiences a maximum stress of 106 MPa, which is well below the maximum stress. In the final design the bottom absorber plate has a 1.5 safety factor and the other plates have a 2.6 safety factor.

The dynamometer must be reconfigurable, which means the assembly must be usable without the CVT and Gearbox. The CVT operating ratio ranges between 1:1 and 2.7:1. For most testing we will be using the max gear ratio of 2.7. In order to achieve this ratio with a chain and sprocket replacement, we will use a 40 tooth and 15 tooth sprocket to achieve a 2.67 gear ratio.

CVT Gear Replacement Calculation: (40/15) = 2.67

The gearbox's gear ratio is 10.55. In order to achieve this ratio with a chain and sprocket replacement, we will use a 15 and 60 tooth sprocket and an 11 and 72 tooth sprocket in a double reduction configuration to achieve a 10.54 gear ratio.

Gearbox Gear Replacement Calculation: (60/15) * (72/11) = 10.54

Additionally, the maximum torque the absorber can handle is 300 ft-lbs as detailed in its specifications data sheet, while the maximum torque output of the gearbox is 350 ft-lbs. The torque is transferred from the gearbox or its chain and sprocket replacement to the absorber. To reduce this torque to below 300 ft-lbs, we used a 13 tooth sprocket on the gearbox output and 9 tooth sprocket on the absorber. This gear reduction has a 1.23 safety factor for the absorber.

Absorber Gear Reduction: (9/13) * 350 = 242 ft-lbs

We also performed torsion and bending calculations on each shaft that transfers torque. We plan to use shafts with a 1" outer diameter which fit into the pillow blocks MBR already owns. The set up for these shaft bending moment calculations is shown in figure 9.2. below.

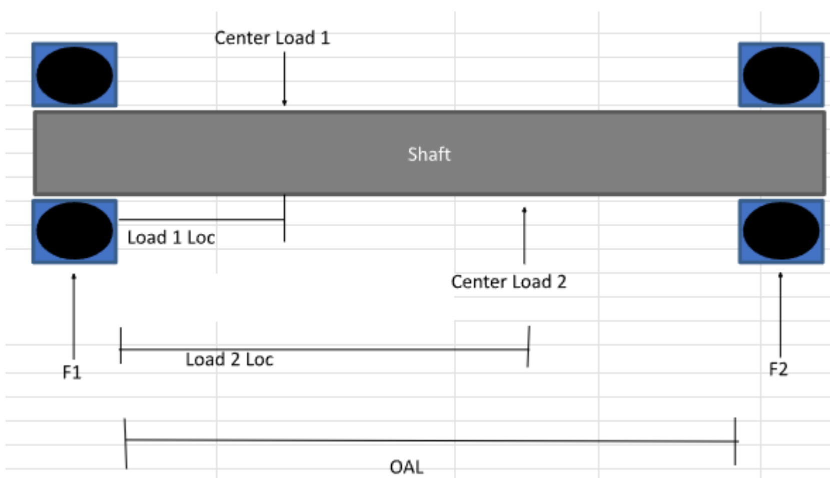

Figure 9.2. The first principle model for our maximum bending moment calculations. This model shows the two reaction forces F1 and F2 at the shaft's ends. Center Load 1 and Center Load 2 represent the two applied forces with their locations.

When analyzing the shafts using a first principle model, we assumed that all loads applied to the shaft would be radially and thus there would be no axial load acting on it. We would add in snap rings to stop the shaft from moving horizontally, but these snap rings do not affect the maximum stress calculations and were not considered.

With our first principle model we performed calculations to find the maximum bending moment experienced by the shafts during the dynamometer's usage. We also found the maximum torque experienced by the shafts. With the maximum bending moment and torque we found the maximum shear stress experienced by the shafts. These calculations can be seen in Figure 9.3. below.

Absorber Input Shaft		
Sprocket 1 diameter	2.02	in
Torque	525	N-m
Center Load 1	129.950495	N
Center Load 1 Loc	5.7	in
Sprocket 2 Diameter	2.02	in
Center Load 2	129.950495	N
Center Load 2 Loc	12.74	in
Overall Length	17.4	in
F1 (left bearing)	52.57767156	N
F2 (right bearing)	-52.57767156	N
Max Von Mises Stress (Mpa)	10.19784204	PASSES
	SF Grade 5 Ti Annealed	50.01058045
	SF 300M Hardened	77.7615496
	SF 1045 Carbon Steel	29.4179885

Multifunction Dyno Combined (Torque + Bending) Calcs

Inputs	Outer radius	R	1	inches	0.0254000508	meters
	Torque	T	525	ft-lbs	711.8044229	N-m
	Cross sectional area	A	3.141592654	inches^2	0.0020268339	m^2
	Polar moment of inertia	J	1.570796327	inches^4	0.0000006532	m^4
	Shear stress	τ	27.67568864	MPa		
	Bending Stress	σ	-10.19784204	MPa		
	Mohr's circle center	C	-5.098921022			
	Mohr's circle radius	R_M	28.14147717	MPa		
Outputs	Max stress	σ_{max}	-33.24039819	MPa		
	Material:					
	1045 Carbon Steel					
	Yield stress	σ_{yield}	300	MPa	Safety factor	9.025162642

Figure 9.3. The shaft stress calculations we performed to decide the shafts used in the dynamometer. The table on the left shows the calculations performed to find the maximum bending moment in the shaft without torque. The table on the right shows the calculations performed to find the stress in combined torque and bending.

With 1045 carbon steel's maximum yield stress of 300 MPa and the calculated maximum bending stress of 10.19 MPa is found using the Von Mises criterion, a safety factor of 29.42 is found in bending. The maximum torque is found through the gear reduction calculations, which are derived from the highest torque output of components of MBR's car historically with a 1.2 SF. With the maximum bending moment stress and torque, the maximum stress experienced was found using Mohr's circle. This maximum stress was found to be 33.24 MPa, meaning these shafts have a safety factor of 9.05 in combined loading.

Based on the calculations performed and specifications it was found that 1045 carbon steel with a 1" outer diameter would be the cheapest material capable of handling operating torques and forces. The pillow blocks altogether are rather expensive as shown in section 10. Due to MBR's possession of these pillow blocks we will use shafts with a very large safety factor for cost savings. These shafts will be keyed to allow for attaching sprockets and dogs (placed on when not using the gearbox or CVT).

Additionally, we drew a free body diagram of the stand to determine the pushing force required to move it. This free body diagram is shown in Figure 9.4 below.

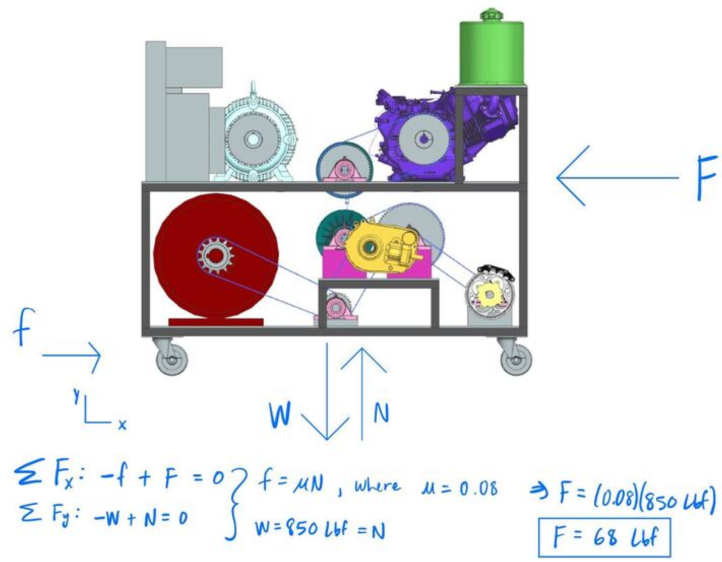

Figure 9.4. Shows required force for moving cart.

The mass of frame and unknown components (sprockets, pillow blocks, etc) was found to be 850 lbs using CAD. The caster wheels made of polyurethane on the frame have a coefficient of friction of 0.08. Through using the weight and the coefficient of friction, the calculated frictional force is 68 lbf. This is less than our requirement of the pushing force being less than 70 lbf so that one person can easily push this assembly. Although these two parameters are close, it is very unlikely that one member of the team would have to push this up an incline or use this assembly alone and two people can push this cart easily.

Prototyping is not feasible for our project as a scaled down or simplified version of our design would not be beneficial or provide us with further understanding and validation. Therefore, upon completion of the dyno, we can perform empirical testing to validate our analysis by measuring the maximum torque through the shafts during operation using strain gauges, measuring the maximum pushing force required to move the dyno using a force transducer, and verify the stand can withstand the maximum loadcase exerted on it by each component.

10 Bill of Materials

From the final design, the following bill of materials was made:

Table 10.1. Bill of materials for the final design. The total cost of parts that the team already owns are marked with an asterisk (*) and will not be counted towards the total cost at the bottom of the table.

Component	Supplier	Manufac. Part #	Unit Price	Quantity	Total Cost
32-Tooth 1” Sprocket (ANSI 35)	McMaster-Carr	6236K119	$52.60	4	$210.40
9-Tooth 1” Sprocket (ANSI 80)	McMaster-Carr	6280K267	$43.75	1	$43.75
13-Tooth 1” Sprocket (ANSI 80)	McMaster-Carr	6280K3	$66.73	1	$66.73
54-Tooth 1 ⅞” Sprocket (ANSI 35)	McMaster-Carr	2737T524	$74.62	2	$149.24
54-Tooth ⅜” Sprocket (ANSI 35)	McMaster-Carr	2737T526	$74.62	1	$74.62
18” Keyed Rotary Shaft (1045 Carbon Steel)	McMaster-Carr	1497K961	$38.39	3	$115.17
1” Shaft Coupling	Grainger	29HY90	$17.43	1	$17.43
¾” Shaft Coupling	Grainger	29HY88	$17.79	1	$17.79
12” Keyed Rotary Shaft (1045 Carbon Steel)	McMaster-Carr	1497K281	$29.83	1	$29.83
9” Keyed Rotary Shaft (1045 Carbon Steel)	McMaster-Carr	1497K145	$26.06	1	$26.06
15-Tooth 1” Sprocket (ANSI 35)	McMaster-Carr	6280K375	$18.21	3	$54.63
72-Tooth 1” Sprocket (ANSI 35)	McMaster-Carr	2737T543	$88.04	1	$88.04
1” Pillow Blocks	McMaster-Carr	6494K14	$47.97	10	*
Caster Wheels	Caster Supply	CSK20-40S-A1-PB	$7.85	4	$31.40
ANSI 35 Chain	McMaster-Carr	6261K172	$5.07/ft.	22 ft.	$111.54
ANSI 80 Chain	McMaster-Carr	6261K177	$17.81/ft.	4 ft.	$71.24
Baldor 10 HP DC Motor	Compressor Source	L1512T	$1,349.95	1	$1,349.95

Component	Supplier	Manufac. Part #	Unit Price	Quantity	Total Cost
9" Keyed Rotary Shaft (1045 Carbon Steel)	McMaster-Carr	1497K145	$26.06	1	$26.06
Baldor DC Motor Drive	Baldor Reliance	BC20H210-CL	$4,500.00	1	*
Magnetic Particle Clutch	Placid Industries	POC-400F	$3,000.00	1	*
A513 1"x0.065" Square Steel Tube	Online Metals	10301	$146.94	1	$146.94
0.125" Aluminum Sheet	Online Metals	N/A	$676.00	1	*
0.125" Steel Sheet	Online Metals	N/A	$389.97	1	*
⅜"-16 Bolts -25 Count	McMaster-Carr	92965A632	$21.50	2	$43.00
⅜"-16 Nuts - 100 Count	McMaster-Carr	95615A105	$16.03	1	$16.03
Temperature Sensor Digital, Infrared	Digikey	MLX90614ESF-BAA-000-TU	$18.53	3	$55.59
Shear/Torque Strain Gauge	Digikey	MMF404946	$410.75	3	*
Digital Hall Effect Sensor	Digikey	ZH10	$187.50	3	*
Total Cost					$2,686.05

The cost of all components required to build the dynamometer was calculated to be $11,731.72. Fortunately, the Baja SAE team already owns $9,045.67 worth of the necessary materials so the final cost to the team will be $2,686.05, which is $3,313.95 under budget. The rest of the budget will be returned to the Baja SAE team to help them in building their racecar.

11 Project Plan

Our key milestones and tasks are outlined in our project plan in the form of a Gantt chart, shown in Figure 11.1 below. This includes detailed steps in addition to the course deadlines that are specific to our project. The delegation of responsibilities is also included in our project plan. Higher level tasks that still remain after DR2 are broken down further in Table 11.2 below including due date, responsible personnel, and the resource or critical path contributor.

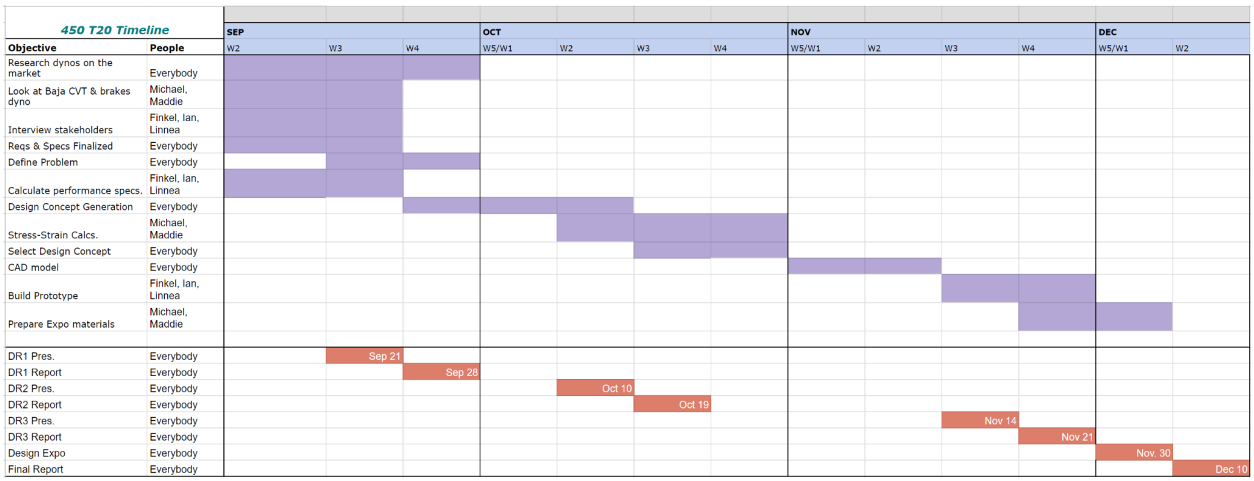

Figure 11.1. A high-level timeline of our project plan.

As shown above, our timeline consists of the ME 450 deliverables with hard deadlines below and further detailed steps including team member responsibility above. The more team-specific tasks are both a breakdown of the requirements for the deliverables for ME 450 and the details for our project in particular

Table 11.2. Task delegation, expected time and resource costs. Since we are unsure if we will be able to deliver a functional prototype within the timeline constraints, the expected cost is listed as TBD.

Task	Due Date	Responsible Personnel	Resource/Critical Path Contributor (expected time, cost)
Engineering Analysis	10/26	Maddie M./Ian	Yield, torsion, bending calculations, free-body diagram (2 days, $0)
CAD Model of Final Design	11/1	Maddie F.	Mock up of stand, subsystems (5-10 days, $0)
Frame FEA	11/9	Linnea	Altair Hyperworks (3 days, $0)
Manufacturing	11/20	All	(1-2 weeks, $ 0)

Task	Due Date	Responsible Personnel	Resource/Critical Path Contributor (expected time, cost)
Materials	12/10	All	All stock material & components (3 days, $2,686.06)
Assembled Functional Prototype	11/30	Michael	(1-2 weeks, $ 0)

While making this timeline, the team acknowledged the difficulty in the scope of a semester-long project. With this in mind, we kept the definition of a prototype unspecific considering the time constraints of our project. As described in Section 5 above, having a goal of a manufactured prototype was initially what our team wanted our final deliverable to be; however, we realized that it was not a reasonable goal within the time constraints of a full semester. In light of this, our final deliverable for the design expo is a fully developed CAD model and analysis with a proof of concept visual model as our prototype. With this deliverable, we are confident the scope of our project is reasonable.

An analysis of previous dyno projects on MBR has revealed to us that we will need to spend a considerable amount of our budget on testing sensors and electronics. From these past projects, we also have different components that could be used in our design, saving some of our budget. In addition, we will have to spend a large part of our prototyping phase in our timeline testing the past dynos to find the best possible design going forward. Considering the previous components available to us, and the manufacturing resources and sponsors able to manufacture complex machining at little to no cost, we expect to stay within our budget requirement.

We have thoroughly defined the design problem, generated requirements through stakeholder and sponsor interviews, and extensively generated and narrowed down potential concepts for the design solution. We are now working on our CAD model focusing on integrating all the different components, focusing on establishing the optimal locations for alignment holes to allow for reconfiguration of the subsystems. This will be an iterative process throughout the prototyping and testing phase, and will be completed by DR3. In addition, we will continue to access the previous MBR dynos to look into possible options to incorporate the old components into our design or to refurbish them.

After DR2, the following schedule was made for the months of November and December.

Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
			1	2	3	4
5	6	7	8	9	10	11
				Sprockets/Chains ordered, choose caster wheels	First Principles Analysis finished	
12	13	14	15	16	17	18
Frame cut		DR3 Presentation	Finish Cutting Frame			
19	20	21	22	23	24	25
		DR3 Report due	Frame welded Laser cut plates	Thanksgiving		
26	27	28	29	30		
		Poster due at 8AM	Frame Assembled	Design Expo		

December						
Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
					1	2
3	4	5	6	7	8	9
		Final CAD Model complete		Verification and Validation testing complete		
10	11	12	13	14	15	16
		Final Report due				

Figure 11.3. A specific timeline of our project plan for the month of November and December. This has been, and will continue to be used to keep the team on schedule.

The project plan outlines the start of the manufacturing process for a functional dynamometer, starting with the frame. While a functional prototype is not within the scope of this project (only CAD models are required), the team has decided to start early on its construction to make the design more clear during the design expo. Following the expo the team will continue working on the dynamometer by starting to attach the components being tested and the sensors measuring them. After this semester is over, we will continue to manufacture the dyno through the winter. Once it is finished, we will perform additional verification and validation testing outlined above in Section 4 that was not possible without a physical prototype.

12 Discussion

12.1 Problem Definition

If we had more time and resources to collect data and better define the problem, we likely would have explored the data acquisition system more. In the current scope of the project, the team was not responsible for integrating the sensors to the data acquisition system, nor coding the program that reads the data. If we had more time we would have reached out more to members of the MBR team with electrical engineering experience so we could create a system to read the data being produced by our design, and properly integrate it within the mechanical systems on the dyno.

12.2 Design Critique

The greatest strengths in our design come from its configurability. The ability to use any number of several combinations of different parts means the MBR team can easily test whichever components they want data for without adding unnecessary fatigue to others. Specifically, the ability to power the dynamometer with a DC motor will help deliver more accurate results by supplying a consistent torque and speed for each trial.

The design was an overall success, however there is still room for improvement. One area for improvement would be the shaft on the bottom plate. In the current design the shaft is under a smaller plate in a way that will make it difficult to replace if it was to break. Another area for improvement would be adding a way for parts of different sizes to be added to the dynamometer. If, for example, the center-to-center distance of the CVT was to change next year, multiple components on the dynamometer would have to be rearranged. If we could design the frame differently, we might have added an adapter plate for the components so different designs can be used in the years to come as the component sizes change.

12.3 Risks

The largest challenge we encountered in the design process was designing the dynamometer to be used in different combinations. For example, the team had to design a system of chains and sprockets so the gearbox could be removed but the output shaft would still be rotating at the correct speed and torque for the brakes or absorber. When starting the design, we did not account for having to create the gearbox's ratio with different components, nor did we account for having to fit that system in our frame. Additionally, this ratio may need to change over time. We addressed this by creating a system of shafts that several different sprockets can be attached to to create the required gear ratio.

The largest risk moving forward is the integration of electrical components into the design. This was intentionally left out-of-scope for this project because of the fast pace of the project and the team members' inexperience in the field. Right now, we are confident that the mechanical components in the design will all work as intended, but are less sure of the effectiveness of the sensor suite and data acquisition system. This poses a risk to the end user because if the components are integrated poorly, the data the system reads will likely be incorrect. To make sure the electrical components measure the data successfully, we will stay in contact with members of the MBR team with electrical engineering experience and use their input when constructing the final design.

13 Reflection

Although our project is fairly unique among ME 450 groups in that our sponsor and stakeholders were the same individuals (MBR), as well as our design was contained within the team as we are only building our design once exclusively for team use, there were still various factors that were relevant to our final solution.

13.1 Public health, safety and welfare

For our project, the considerations of public health, safety, and welfare were derived from the extent that the public interacts with our product. We deemed this to have slight relevance for our product as other individuals and teams in the Wilson Center will be in the presence of our design during operation, and have designed safety measures accordingly, as outlined in Section 8.

13.2 Global context

We did not deem global context to have a large relevance for our product, as there are no intentions of bringing our design to market.

13.3 Social Impacts

The largest social impact comes in the upkeep and use of the dyno by the younger members of the team. After the COVID-19 pandemic, the Michigan Baja Racing team underwent an immense loss of knowledge transfer which is continuing to affect the team, especially concerning previous test stands and data acquisition systems. To ensure that the final design can be sustained by future teams, it was critical to make the final design simple to use, with only basic knowledge learned in freshman and sophomore level classes required to operate the dyno.

As the project progressed, it was also clear that initial intuitions that the social impact of the project was very much limited to the stakeholders mentioned in Section 3.3 were correct, in addition to all personnel in the Wilson Center.

13.4 Economic Impacts

Similar to the other impacts of the project, the economical impacts of the design were limited to the Michigan Baja Racing team. Throughout our design process, we aimed to reuse as many parts as possible from previous test stands and MBR projects so as to reduce the financial cost of the dyno. We were able to save $9,045.67 by reusing components, as discussed in Section 10. We also determined that sourcing materials from local suppliers and sponsors would greatly reduce the cost, and used the resources available to use to drive the material selection.

13.5 Inclusivity, Power Dynamics, and Equity

All five of the team members working on the design project come from backgrounds of very similar cultures, privileges, and identities. Three of us are also experienced members of the Michigan Baja Racing team with very similar styles, although having two members that aren't on the team provided differing perspectives. To ensure that unique concepts were generated and to ensure no concepts were prematurely discarded, the team placed a heavy emphasis on stakeholder meetings and using requirements to drive concept generation and selection.

The project's primary sponsor was a member of the 450 team, and all of the secondary sponsors were members of Michigan Baja Racing, meaning there were many stylistic similarities between the 450 team and sponsor. Although this meant that all personnel involved with the project were accustomed to solving problems in similar ways, having members that specialize in different parts of the vehicle provided a well-rounded perspective and ensured no part of the project was overlooked.

Although stakeholders were influential due to stylistic similarities, there was a clear power difference between the design team and the rest of the Michigan Baja Racing team, due to members of leadership and other MBR upperclassmen being on the 450 team. Additionally, the fast pace of the project meant that design decisions were often made in closed spaces without any stakeholder input. We attempted to limit this by asking team members to attend the design reviews and Design Expo already held by the ME 450 schedule to gain feedback during each stage of the design.

13.6 Ethical Dilemmas

During the design of our project, our team did not face many ethical dilemmas. On a very small scale, we had to make ethically influenced decisions, such as how we would deal with the release of hazardous materials from our device into the environment. We considered the serious nature of these decisions and weighed the ethical effects of our decision against the benefits that our team would gain from the decision and chose a correct outcome as a group. If our team's project entered the marketplace, one ethical issue that may arise could include material sourcing and ethical component production further up the supply chain. We would manage this by re-evaluating our suppliers for components based on ethical manufacturing practices.

As a whole, our group's personal ethics are similar to those that we are expected to uphold in a professional environment. The Michigan Baja Racing team, who this project is sponsored by, strives to uphold a professional environment. This also includes a professional set of ethics that reflect what would be expected by the University of Michigan, as the team is directly affiliated with the university.

14 Recommendations

We have several recommendations for MBR to ensure completion, safe, and successful usage of our design. Our first recommendation is to find a more cost effective DC motor that is compatible with the motor drive we have, as this will allow the team to use the dyno for extended periods of time without creating a hazardous environment or having to run the dyno outside. Additionally, the team should explore alternative options for mounting the gearbox system as it uses a large quantity of stock and would have to be remade each year when a new gearbox is designed. Finding an alternative that would allow for easier adjustability and can support multiple gearboxes with minimal modifications would reduce the amount of stock used and time needed to reconfigure the dyno each year. We also recommend performing further finite element analysis, including modal vibration analysis, to determine areas of the stand that are overbuilt to reduce the weight of the stand. Lastly, obtaining and integrating additional TECAT boards is recommended so that there is a permanent set of boards that stay with the dyno, rather than swapping the testing boards between on car and dyno testing. There are no improvements we recommend to make on the design process used and the verification and validation processes.

15 Conclusion

Michigan Baja Racing has asked our team to design a multifunction dynamometer to gather RPM, torque, and temperature data for a variety of subsystems in order to make better informed design decisions and more accurately and quickly tune each component. This problem was broken down into a set of specifications and corresponding numerical requirements based on the desires of our most important stakeholders, including the MBR admin team, and the engine, gearbox, CVT, and brakes leads. We noticed a particular emphasis in the design being multifunctional, portable, easy to use, and within team budget. In order to meet these requirements, extensive research across the pre-existing design space and dyno market was done. Successful completion of this project is defined as a detailed CAD model in Siemens NX that shows each configuration the dyno can be used in, as well as the required sensors identified and ordered. We have completed these deliverables, and following the end of the semester we will continue the fabrication of the final design. This will be done in Wilson Student Team Project Center. Once the final design is complete we will install the sensors on the rotating shafts and write the code to read the data provided by the sensors. Finally, once all of this is complete we will be able to test our design and use the data to create a better car for competitions.

16 Acknowledgement

We would like to thank our course instructor, Randy Schwemmin for all the guidance he provided throughout the semester. We also acknowledge the members of the Michigan Baja Racing team for all they did to help us complete this project.

Appendix A - References

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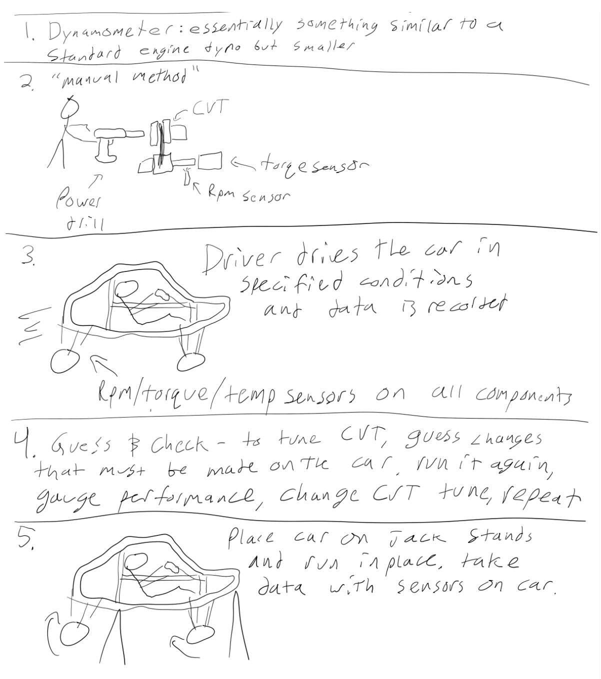
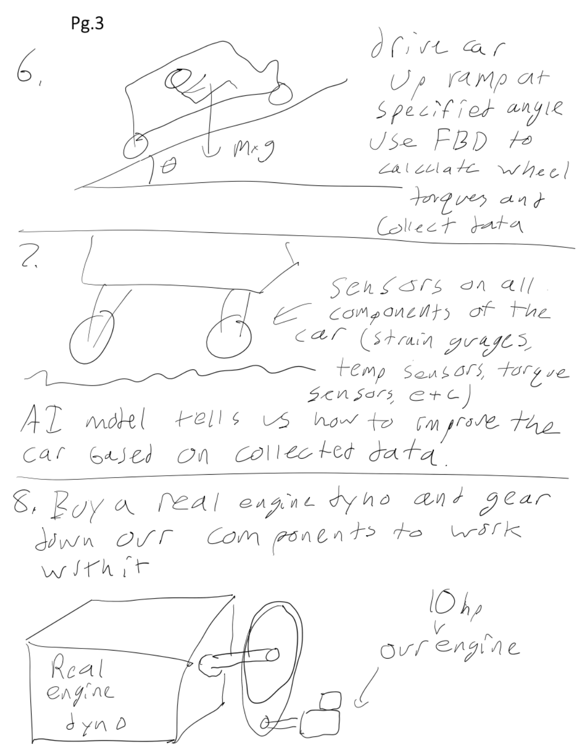
Appendix B - All Generated Concepts

B.1. Ian Beaufait's Concepts

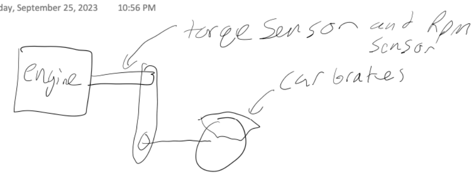




Pg4 Concepts

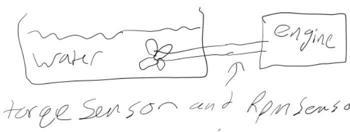
Monday, September 25, 2023 10:56 PM

9.)



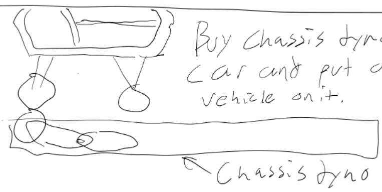
Use car brakes as a braking force on the engine and collect data. Perform similarly with other systems.

10.



Use water as a braking force on the engine and collect data.
Perform similarly with other systems

11.

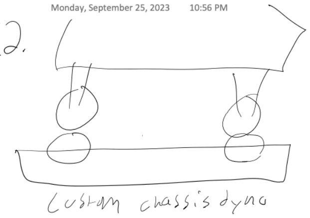


Buy chassis dyno for regular car and put our small vehicle on it.

Pg5 Concepts generated

Monday, September 25, 2023 10:56 PM

12.

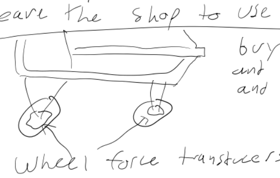


design/make custom chassis dyno for entire car

13. Buy pre-existing small dyno online and modify it to suit our needs

14. Move the shop to WCC where they have a dyno and then we don't have to leave the shop to use it.

15.



buy 4 wheel force transducers and put 1 on each wheel and collect data

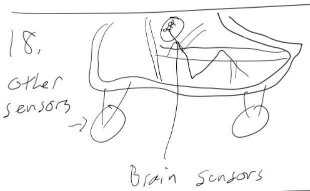
16. Have a dyno custom made for the team by dynocom, a commercial dynamometer company

Pg6 Concepts generation

Monday, September 25, 2023 10:56 PM

17. Buy dyno kit from dynomitedyno and use kit for dyno

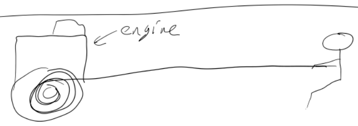
18.



Driver communicates with car with mind to collect data and know what to improve

19. Move Dyno at WCC to our shop - maybe "borrow" it in the middle of the night :)

20.

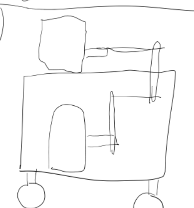


team pulls on rope to apply load to engine, measure tension in rope and retraction speed.

Part II

1. Inspired from Part I concept generation Custom built chassis dynamometer with water brake

2)



Reuse dyno from 11 years ago with modification to make it relevant

3.

Inspired from part 1, buy regular car dyno and modify it, then build false floor and lifting mechanism to store it in the wilson center

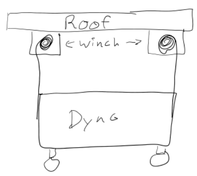
Pg9 Concepts generatron

Monday, September 25, 2023 10:56 PM

4.) inspired by previos idea #6, but with an adjustible ramp height

5. Inspired by idea #7 and #1, AI model reads sensor data and helps us improve car

6. Inspired from #1, build small multifunctional dyno but have winches to lift it to the roof

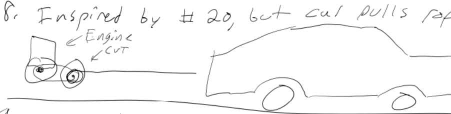


7. Inspired by #17 from previous generation, dynomite dyno makes custom dynos so have them make a custom dyno for our team (also inspired by #16)

Pg10 Concepts generatron

Monday, September 25, 2023 10:56 PM

8. Inspired by #20, but car pulls rope instead



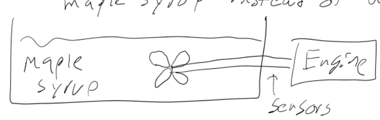
9. Inspired by #19, contact WCC and purchase their old dyno if they ever get rid of it

10. Buy a used dyno on FB marketplace or Ebay

11. Inspired by #18, but instead driver communicates telepathically with car to collect load data

12. Inspired by #11 from previous, buy a small chassis dyno from dynamite dyno (just found out they sell them)

13. Inspired by #10 from previous, but using maple syrup instead of water for more braking force



Pg11 Concepts generatron

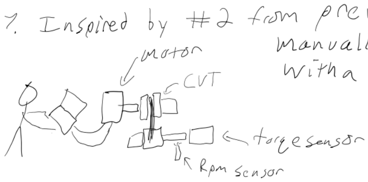
Monday, September 25, 2023 10:56 PM

14. Inspired by #5 from previous but hang car from ceiling instead of on jack stands

15. use a torsion spring as an energy absorbing method for the dyno

16. Use an air compressor as an energy absorbing method for the dyno. The drive train components would recieve load based on how much air is let out from the valves

17. Inspired by #2 from previous, operator manually runs dyno with a laptop controlling a motor

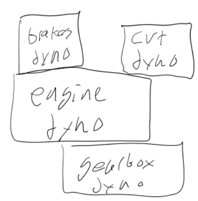


Pg12 Concepts generatron

Monday, September 25, 2023 10:56 PM

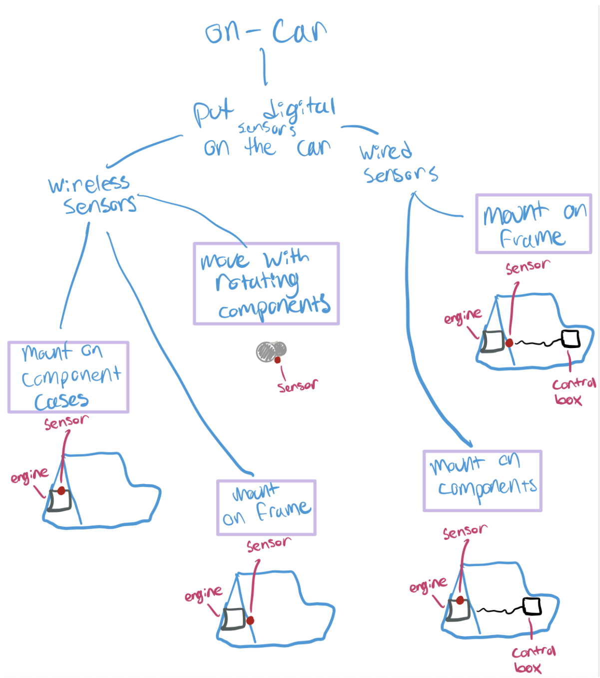
18. Inspired by #4 from previous, but operator uses a spreadsheet to input data and return optimal changes to make to system

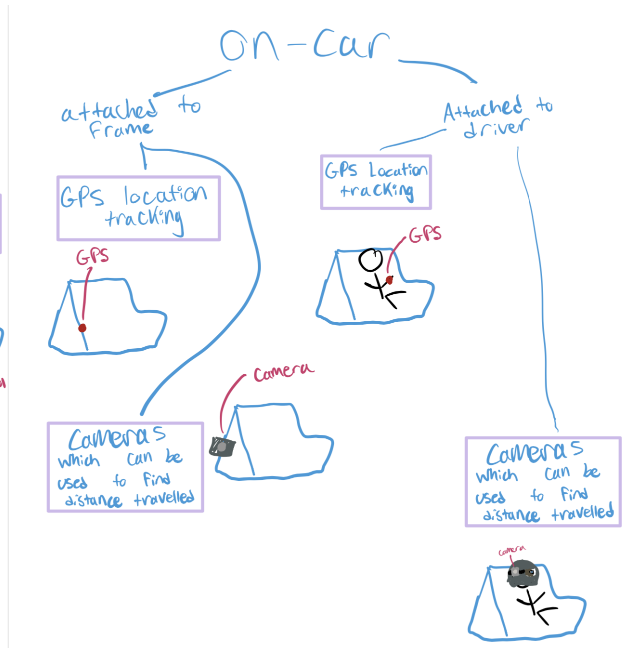
19. "Frankenstien" dyno of all dynos we currently have, mashed together

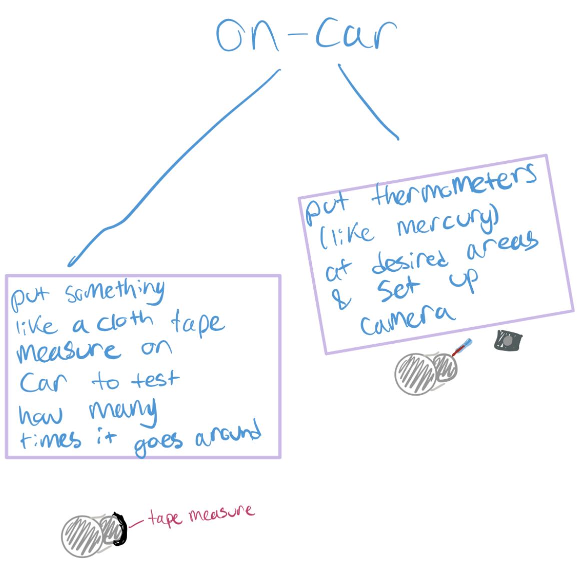


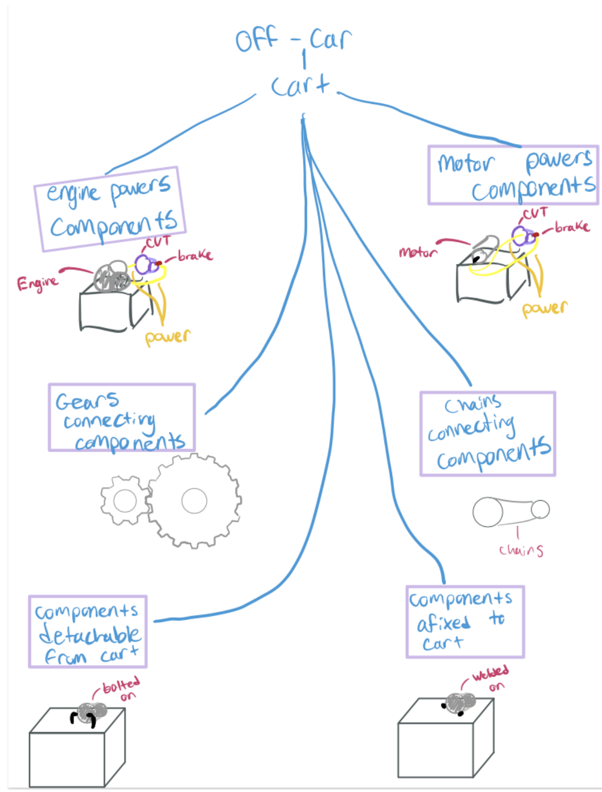
20. Inspired by the idea above I have 1 separate dyno for each subsystem that needs to be tested.

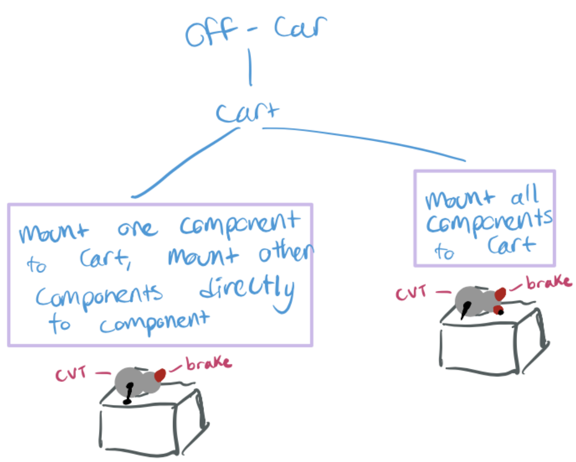
B.2. Maddie Finkel's Concepts

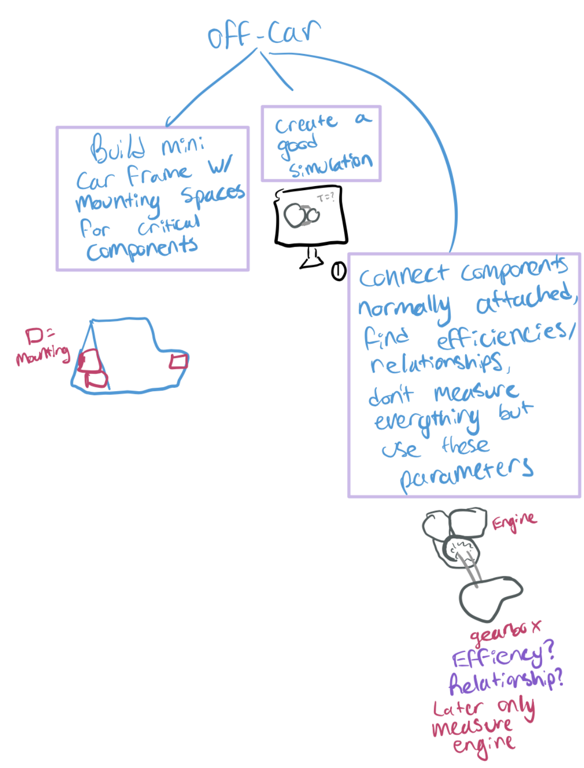


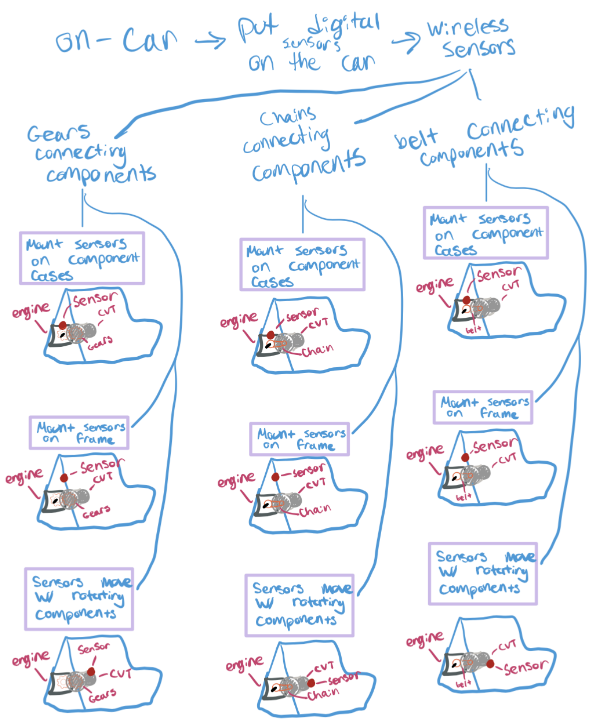


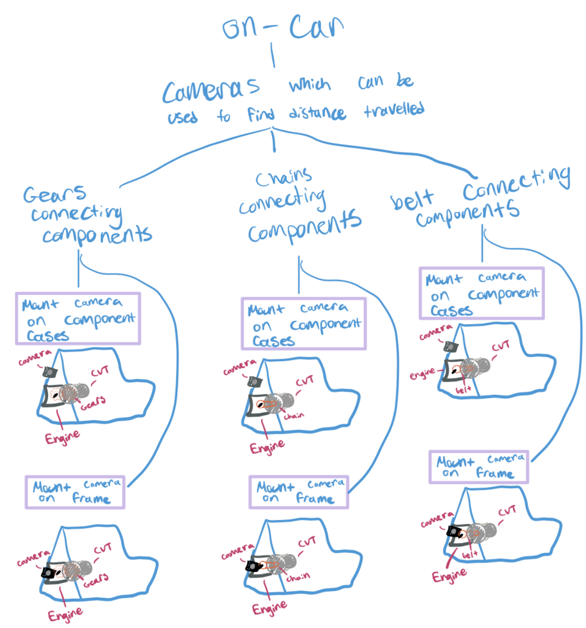


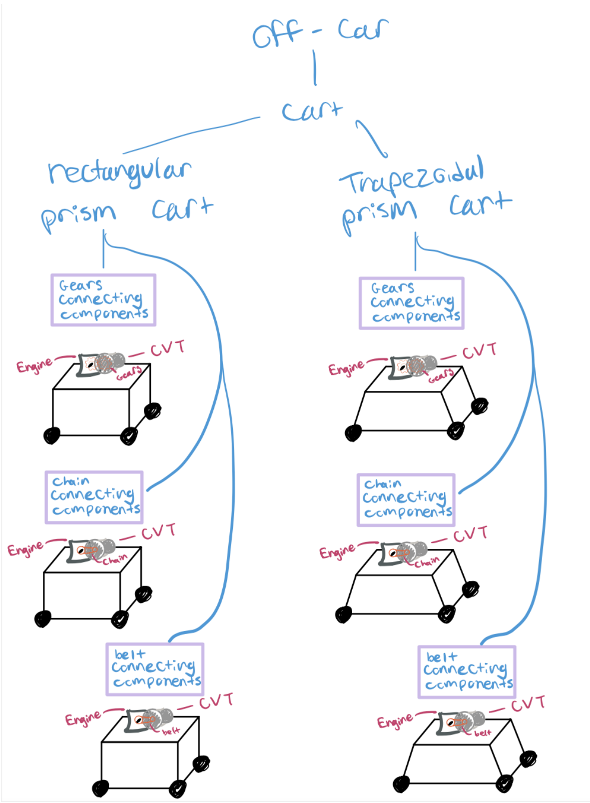



Off - Car
cart
Mount one component to cart, mount other components directly to component
Mount all components to cart
CVT
brake


Off-Car
Build mini car frame w/ mounting spaces for critical components
Create a good simulation
Connect components normally attached, find efficiencies/ relationships, don't measure everything but use these parameters
Mounting
Engine
gearbox
Efficiency?
Relationship?
Later only measure engine


On-Car → Put digital sensors on the car → Wireless sensors
Gears connecting components
Chains connecting components
belt connecting components
Mount sensors on component cases
Mount sensors on frame
Sensors move w/ rotating components
engine
sensor
CVT
gears
chain
belt


On- Car
Cameras which can be used to find distance travelled
Gears connecting components
Chains connecting components
belt connecting components
Mount camera on component cases
Mount camera on frame
camera
CVT
gears
chain
belt
Engine



Off - Car
cart
rectangular prism cart
Trapezoidal prism cart
Gears connecting components
Engine
CVT
Chain connecting components
belt connecting components

B.3. Linnea Lindblom's Concepts

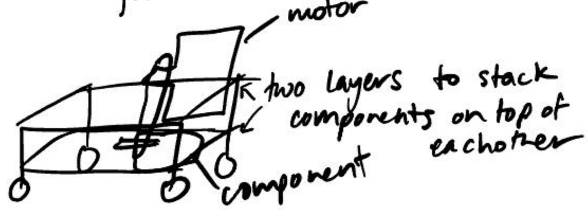
1. EM absorber
2. water brake
3. eddy current
4. hand brake

(items 1–4: absorber types)

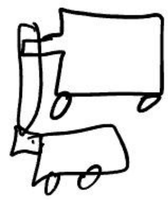
5. Kohler engine
6. electric motor
7. pedal bike

(items 5–7: power sources)

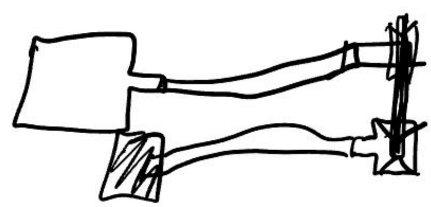
8. hamster wheel w/ hamsters
9. 80-20 stand
10. wooden shop table w/ casters



11. put engine & brake on wheels
12. mount system to wall

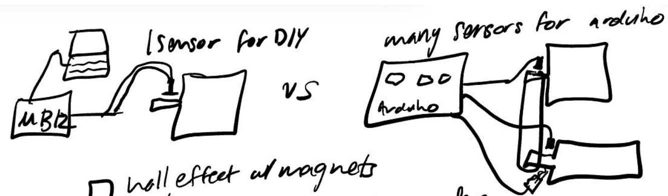


13. chain & sprocket to connect components
14. belt & pulley system
15. series of shafts & dog clutches

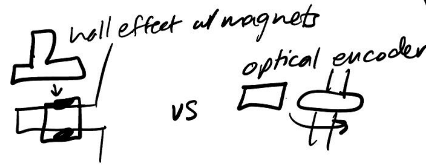


16. direct connection
17. friction clutches to link everything
18. bendy shaft to link everything
19. custom aluminum jig blocks to mount
20. jig plate on wheels

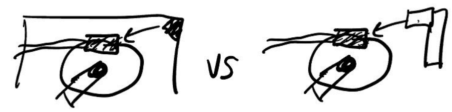
21. hall effect sensor w/ arduino
22. optical encoder w/ arduino
23. hall effect w/ DIY daq
24. optical encoder w/ DIY daq



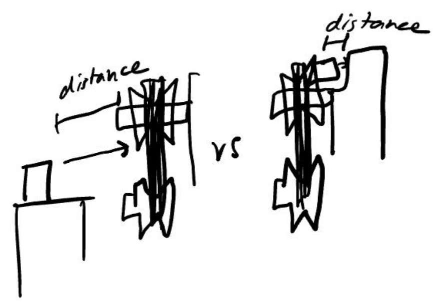
25. rotary torque sensor on engine
26. rotary torque on brake
27. reaction torque on engine
28. reaction force on brake



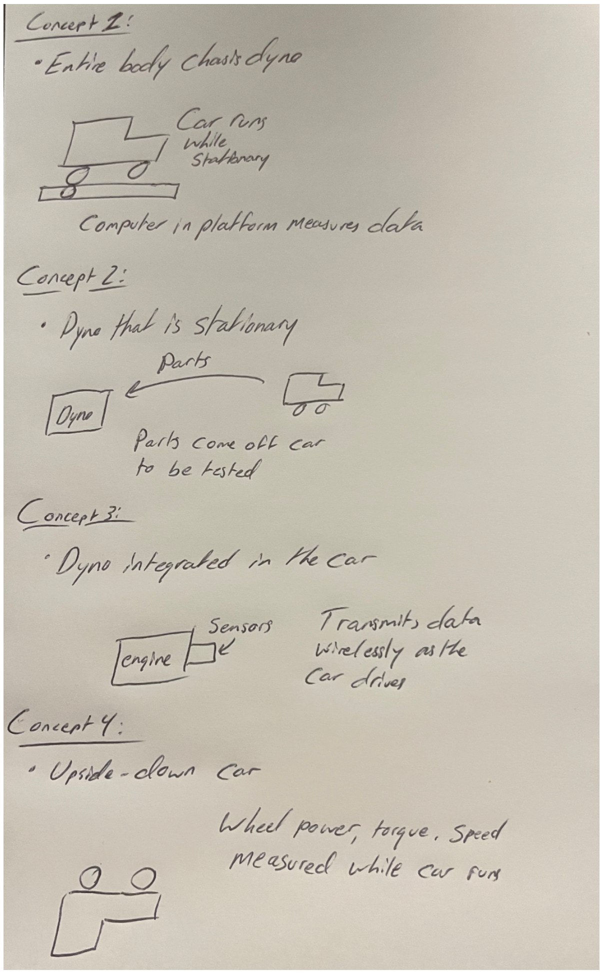
29. thermocouple with case/covering
30. thermocouple without case/covering

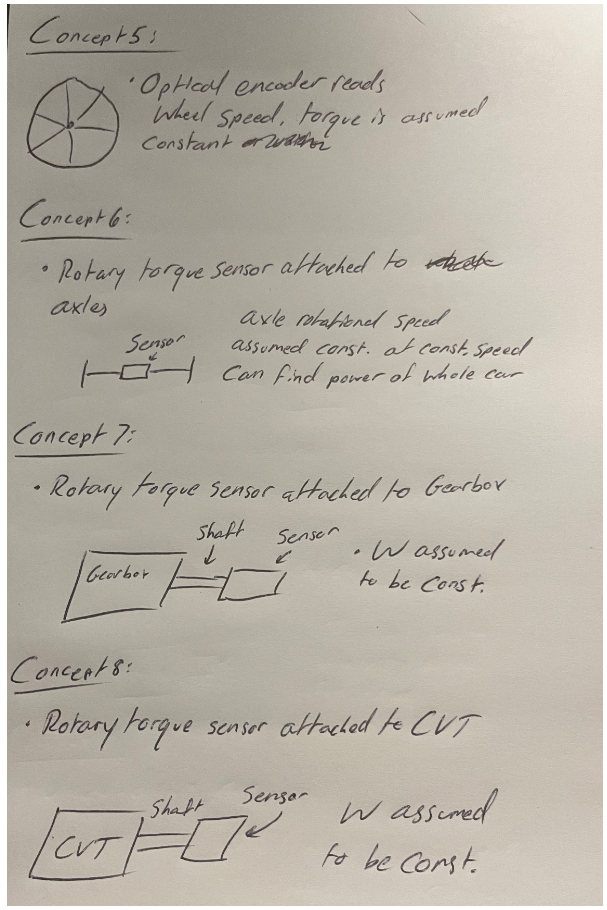


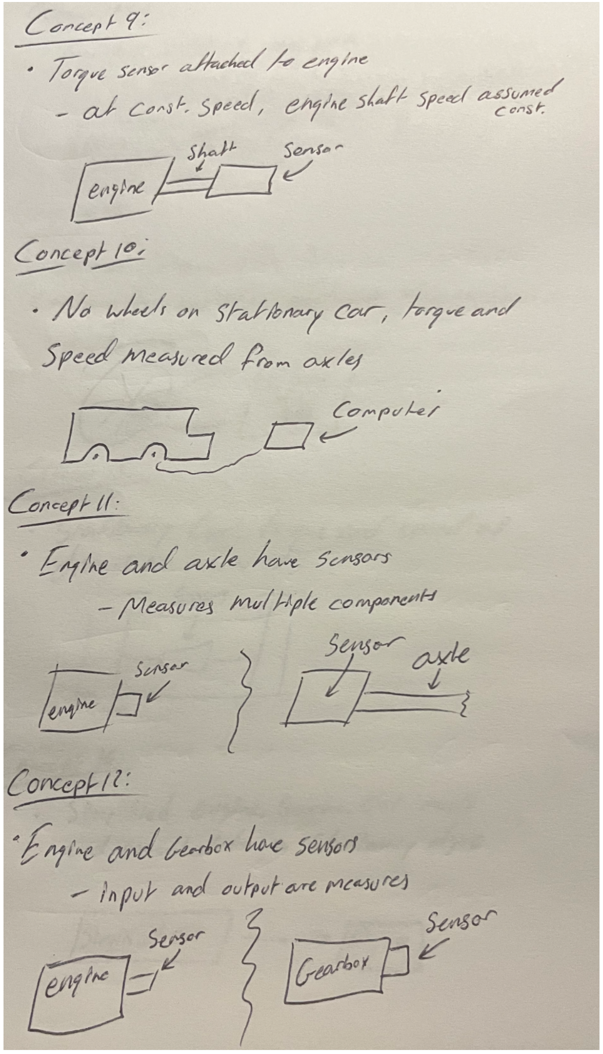
31. thermistor on metal component
32. thermistor on plastic/composite component
33. hand-held heat gun without case/covering
34. frame mounted heat gun
35. infrared sensor for temperature
36. silicon diode sensor
37. gyroscope sensor
38. time of flight sensor
39. proximity sensor mounted to frame
40. proximity sensor mounted to sheave



B.4. Michael McCallig's Concepts






Concept 9:

- Torque sensor attached to engine
  - at const. speed, engine shaft speed assumed const.

Concept 10:

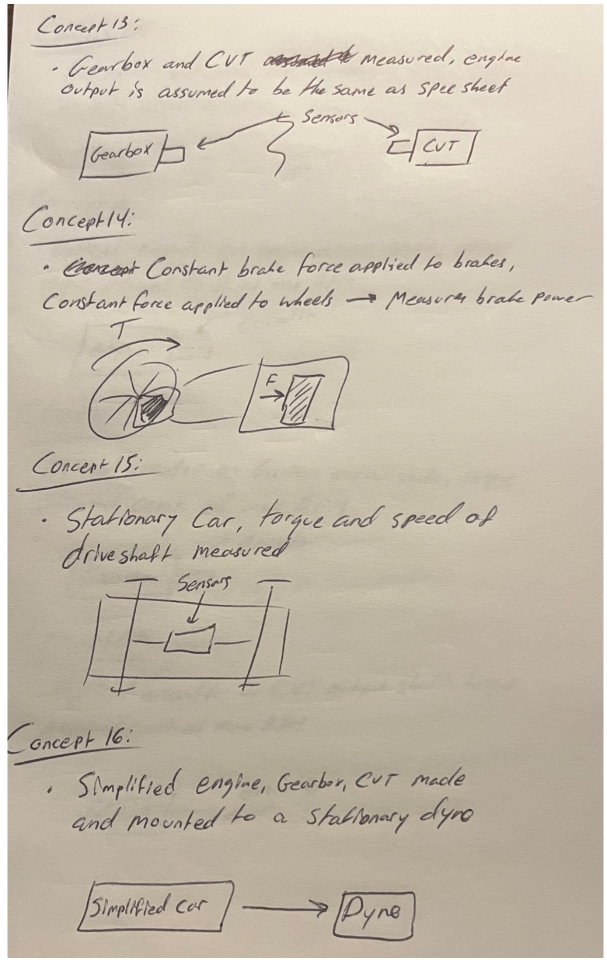
- No wheels on stationary car, torque and speed measured from axles

Concept 11:

- Engine and axle have sensors
  - Measures multiple components

Concept 12:

- Engine and Gearbox have sensors
  - input and output are measures


Concept 13:

- Gearbox and CVT ~~assumed to~~ measured, engine output is assumed to be the same as spec sheet

Concept 14:

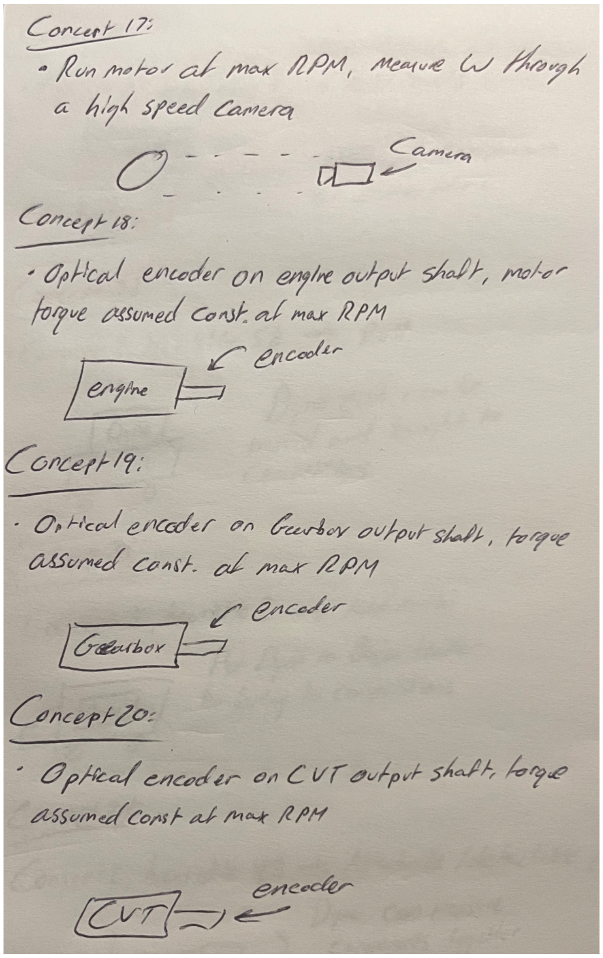
- ~~Concept~~ Constant brake force applied to brakes, Constant force applied to wheels → Measures brake power

Concept 15:

- Stationary Car, torque and speed of driveshaft measured

Concept 16:

- Simplified engine, Gearbox, CVT made and mounted to a stationary dyno



Concept 17:

• Run motor at max RPM, measure ω through a high speed camera

Camera

Concept 18:

• Optical encoder on engine output shaft, motor torque assumed const. at max RPM

engine
encoder

Concept 19:

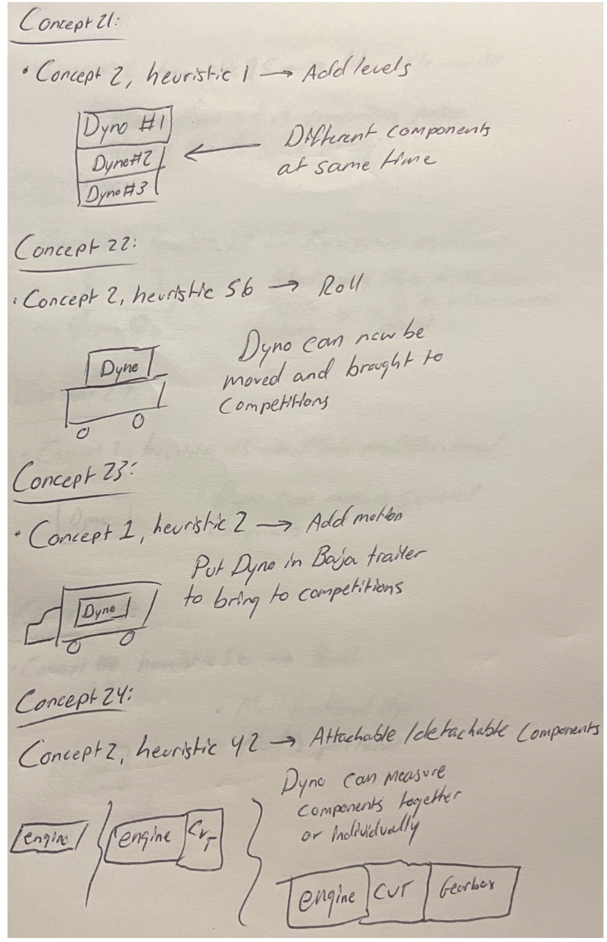
• Optical encoder on Gearbox output shaft, torque assumed const. at max RPM

Gearbox
encoder

Concept 20:

• Optical encoder on CVT output shaft, torque assumed const at max RPM

CVT
encoder



Concept 21:

• Concept 2, heuristic 1 → Add levels

Dyno #1
Dyno#2
Dyno#3
Different components at same time

Concept 22:

• Concept 2, heuristic 56 → Roll

Dyno
Dyno can now be moved and brought to competitions

Concept 23:

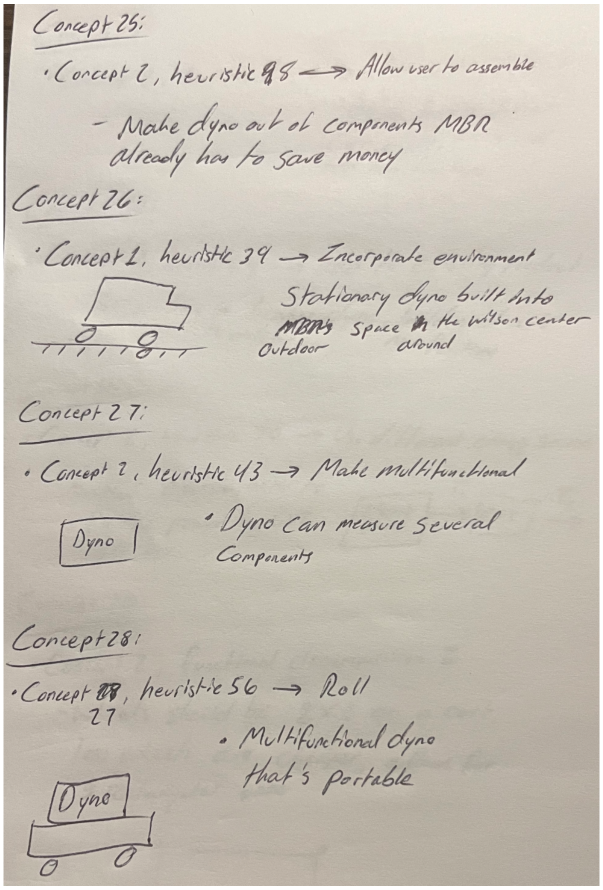
• Concept 1, heuristic 2 → Add motion

Dyno
Put Dyno in Baja trailer to bring to competitions

Concept 24:

Concept 2, heuristic 42 → Attachable/detachable Components

engine
engine CVT
Dyno can measure components together or individually
engine CVT Gearbox



Concept 25:

- Concept 2, heuristic 8 ⟶ Allow user to assemble
  - Make dyno out of components MBR already has to save money

Concept 26:

- Concept 1, heuristic 39 ⟶ Incorporate environment

Stationary dyno built into ~~MBR's~~ outdoor space ~~in~~ around the wilson center

Concept 27:

- Concept 2, heuristic 43 ⟶ Make multifunctional

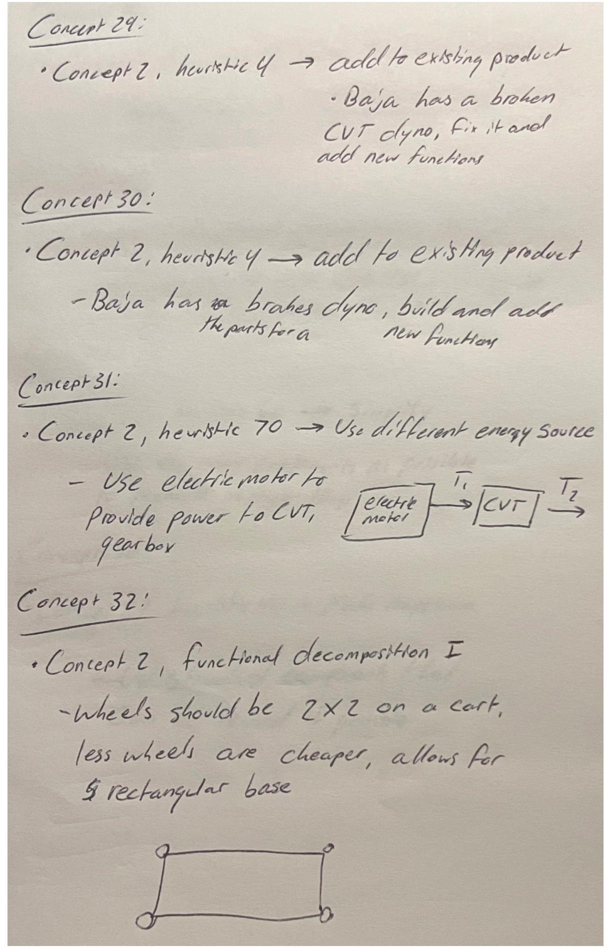
Dyno

- Dyno can measure several components

Concept 28:

- Concept ~~28~~ 27, heuristic 56 ⟶ Roll
  - Multifunctional dyno that's portable

Dyno



Concept 29:

- Concept 2, heuristic 4 ⟶ add to existing product
  - Baja has a broken CVT dyno, fix it and add new functions

Concept 30:

- Concept 2, heuristic 4 ⟶ add to existing product
  - Baja has the parts for a brakes dyno, build and add new functions

Concept 31:

- Concept 2, heuristic 70 ⟶ Use different energy source
  - Use electric motor to provide power to CVT, gearbox

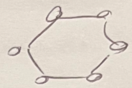
electric motor ⟶ T_1 ⟶ CVT ⟶ T_2

Concept 32:

- Concept 2, functional decomposition I
  - wheels should be 2 x 2 on a cart, less wheels are cheaper, allows for ~~$~~ rectangular base

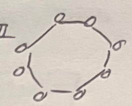
Concept 33:

- Concept 2, functional decomposition II
  - Hexagon base for more stability



Concept 34:

- Concept 2, functional decomposition III
  - Octagon base for more stability



Concept 35:

- Concept 27, heuristic 60 → Simplify
  - Use as many components as possible to measure multiple things

Concept 36:

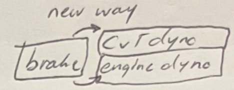
- Concept 27, heuristic 44 → Make recyclable
  - Use standard components that can be reused if possible

Concept 37:

- Concept 27, heuristic 49 → optional components
  - design for several components, make the final dyno according to budget

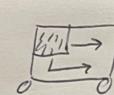
Concept 38:

- Concept 27, heuristic 13 → existing mechanism in new way
  - CVT dyno brake used for all components



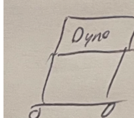
Concept 39:

- Concept 27, heuristic 11 → allow user to reorient
  - Components can move to be more accessible

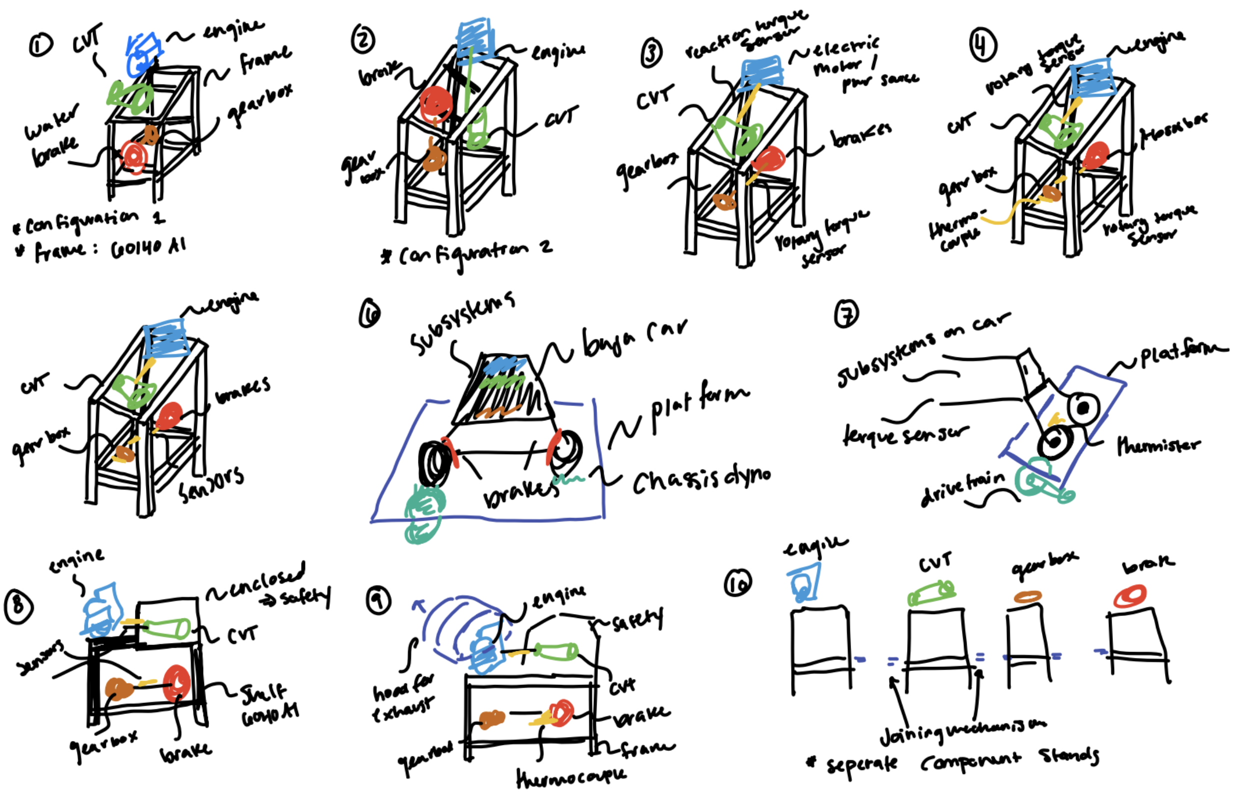


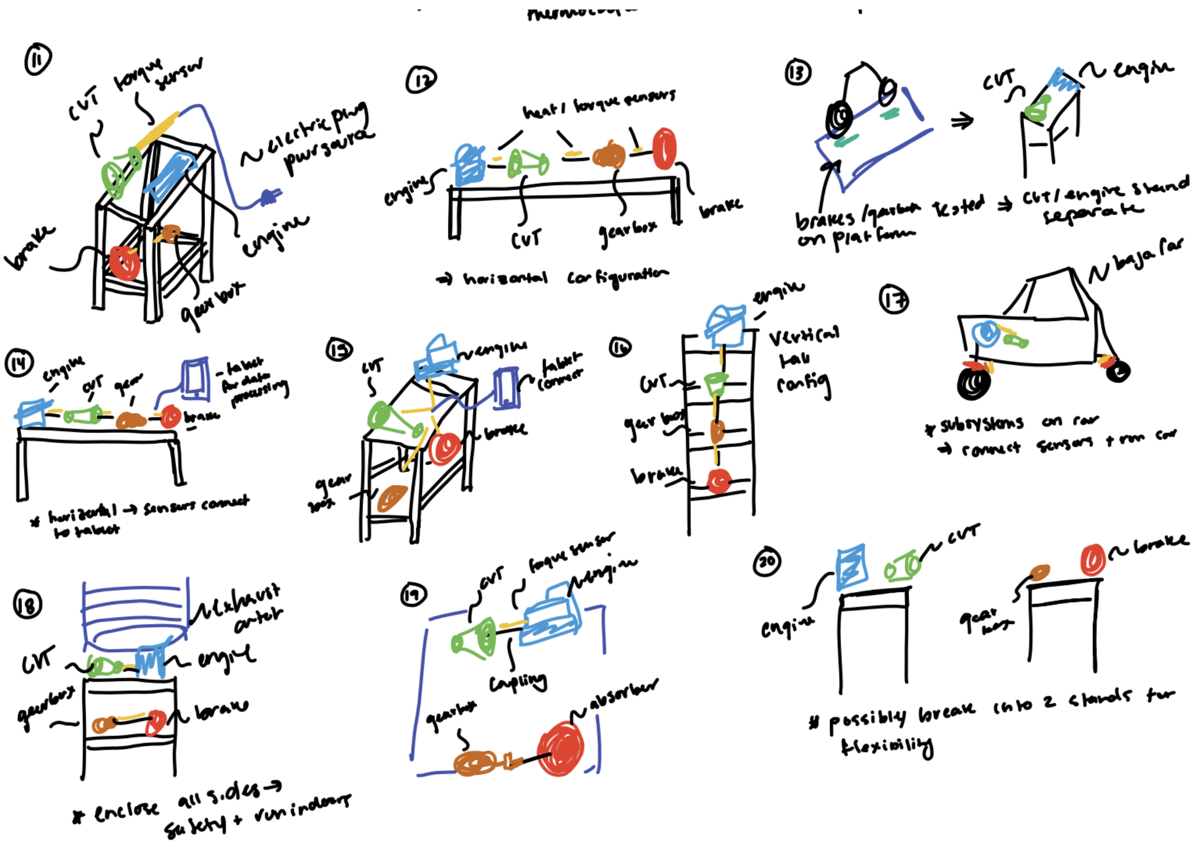
Concept 40:

- Concept 31, heuristic 31 → elevate or lower
  - Elevate dyno to be more accessible

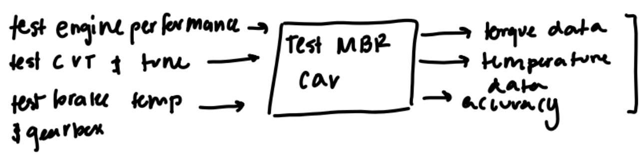


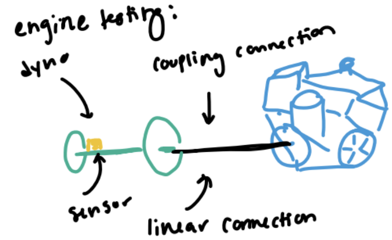
B.5. Madelyn Moore's Concepts



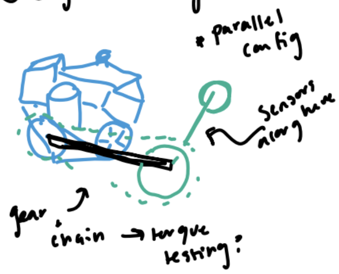

11
CVT
torque sensor
electric plug power source
engine
brake
gearbox
12
heat / torque sensors
engine
CVT
gearbox
brake
→ horizontal configuration
13
CVT
engine
brakes / gearbox tested on platform
→ CVT / engine stand separate
14
engine
CVT
gear
brake
tablet for data processing
* horizontal → sensors connect to tablet
15
CVT
engine
tablet connect
brake
gear box
16
engine
vertical config
CVT
gear box
brake
17
baja car
* subsystems on car
→ connect sensors from car
18
exhaust outlet
CVT
engine
gearbox
brake
* enclose all sides → safety + reminders
19
CVT
torque sensor
engine
coupling
gearbox
absorber
20
CVT
brake
engine
gear box
* possibly break into 2 stands for flexibility

㉑ Functional decomposition:

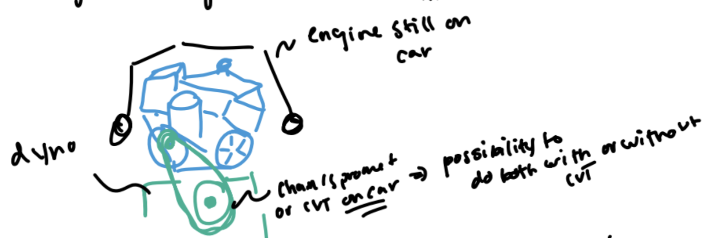




㉒ engine testing:

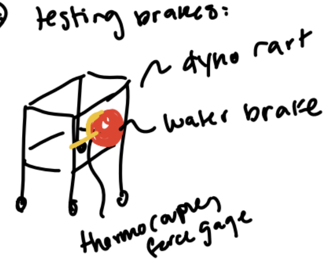


㉓ engine testing:

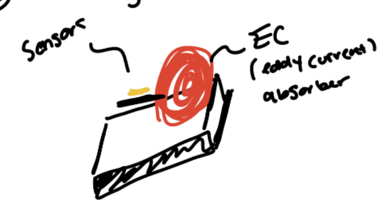


㉔ testing brakes: on car

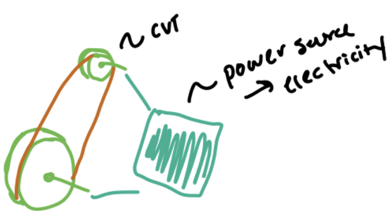
㉕ testing brakes:



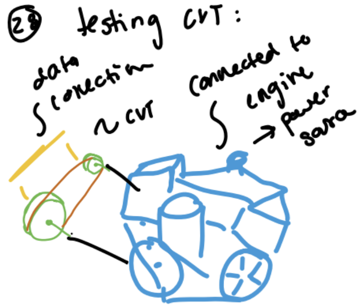
㉖ testing brakes:



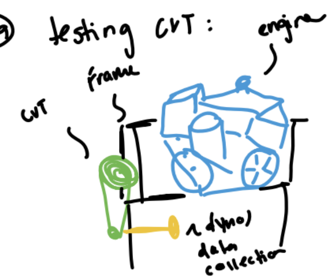
㉗ testing CVT:



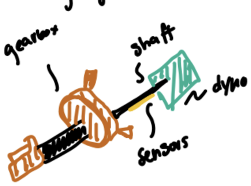
㉘ testing CVT:



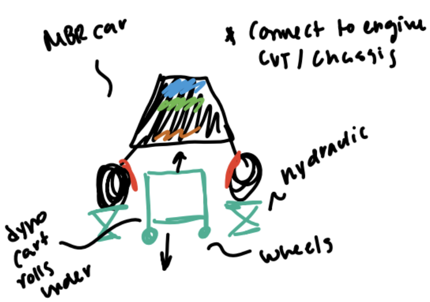
㉙ testing CVT:



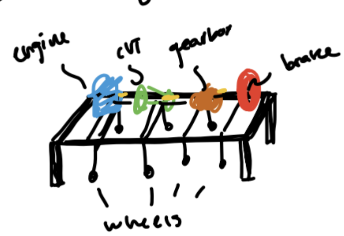
㉚ testing gear box:

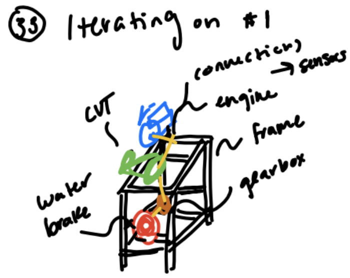


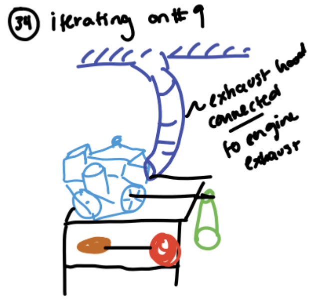
㉛ Iterating on #6

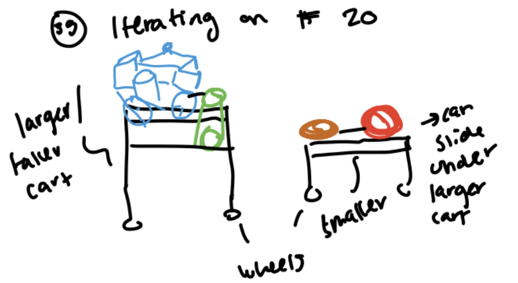


㉜ Iterating on #12:

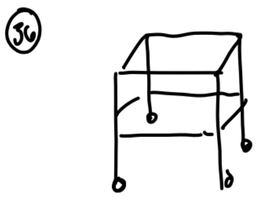


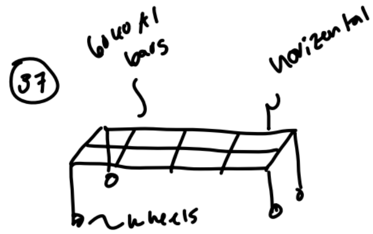


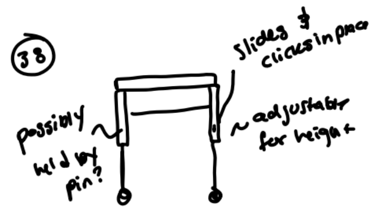


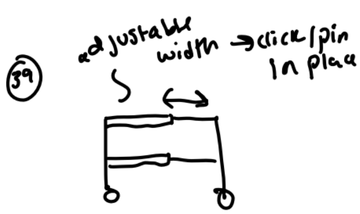


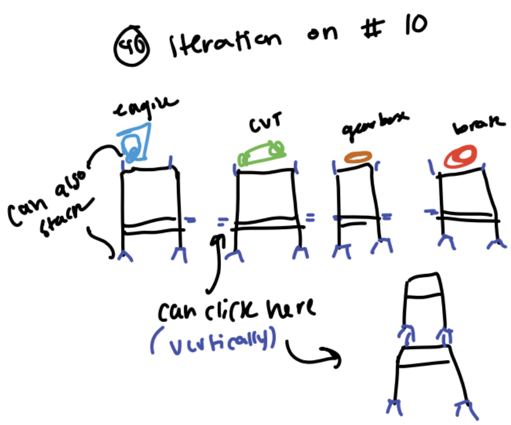
Used Morphological Chart
⇒ Frame configurations







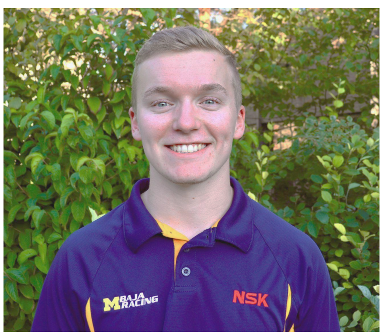




Appendix C - Author Bios

Linnea Lindblom
B.S.E Mechanical Engineering Winter '24

Linnea is a senior in mechanical engineering with a minor in multidisciplinary design. She grew up in Menlo Park, California, and spent her time after school playing on the varsity basketball team. From the first time she played with legos and robotics kits as a kid, she was hooked on the idea of being an engineer, and spent her childhood building everything, from go karts to tree houses. On the Baja Racing team, the notable roles she held were the rear frame lead for MBR32, the gearbox lead for MBR33, and the captain for MBR34. Her current interests involve gear train design and structures analysis. After graduating, Linnea will be moving to Orange County, California to work as a mechanical design engineer for Anduril Industries.



Ian Beaufait
B.S.E Mechanical Engineering Winter '24

Ian is a senior in mechanical engineering with a concentration in manufacturing systems. He grew up in Columbus, Michigan as the son of two mechanical engineers. Ian has always enjoyed taking apart/fixing things and working on home renovation projects. In high school he was a member of the FRC robotics team, and was specifically involved in the design subteam. Coming into U of M he wanted to study aerospace engineering, but switched to mechanical engineering after realizing the prevalence of mechanical engineering in all industries, including the aerospace industry. Ian is participating in his second year on the Baja Racing team, and holds the role of half shaft and hub lead for MBR34. In his free time, Ian enjoys camping, hiking, woodworking, and working on any project involving building things.

Maddie Finkel
B.S.E Mechanical Engineering Winter '24

Maddie is a senior majoring in mechanical engineering with minors Multidisciplinary Design Program (MDP) Minor and International Minor for Engineers, with a concentration in manufacturing systems. Maddie grew up right outside of Chicago, Illinois in Evanston, Illinois, which is near Northwestern University. In her childhood she was fascinated by science and math, and participated in clubs, Center for Talent Development (CTD) courses at Northwestern, and took STEM classes. She enjoyed fixing and assembling designs and her family quickly became dependent on her for assembling purchased assemblies. She enjoyed making and assembling her own designs in her science olympiad club, and also in her woodworking, engineering, and geometry courses. At the University of Michigan she has been a participant of the MBR team for 4 years, working as a driver controls lead previously and a composites lead currently.

Madelyn Moore
B.S.E Mechanical Engineering Winter '24

Madelyn is a senior in mechanical engineering. She grew up in Saugatuck, Michigan where she spent her childhood playing sports and swimming in Lake Michigan. Growing up, Madelyn and her dad completed several projects together sparking her interest in engineering, including building a treehouse and rebuilding her first car, a '61 Chevy. During her first year at the University of Michigan, Madelyn was part of the varsity rowing team and enrolled in LSA. She then transferred to the College of Engineering after realizing her large interest in mechanical design. She has a large interest in sustainability and renewable energy technology. She would like to pursue a full-time job after graduation. She enjoys hiking and playing tennis in her free time.

Michael McCallig
B.S.E Mechanical Engineering Winter '24

Michael is a senior pursuing a B.S.E. in mechanical engineering. He grew up in Niskayuna, New York where he spent his time after school playing on the varsity hockey and baseball teams. His interest in science and engineering started in middle school when he was given the opportunity to learn about chemistry and physics. He originally enrolled in The University of Michigan's college of Literature, Science, and the Arts pursuing a degree in physics before transferring to the College of Engineering after realizing he had more interest in engineering design than physics research. He is interested in finding a full-time job in either power generation or automotive engineering after he graduates this May. In his free time he enjoys hiking, golf, and woodworking.