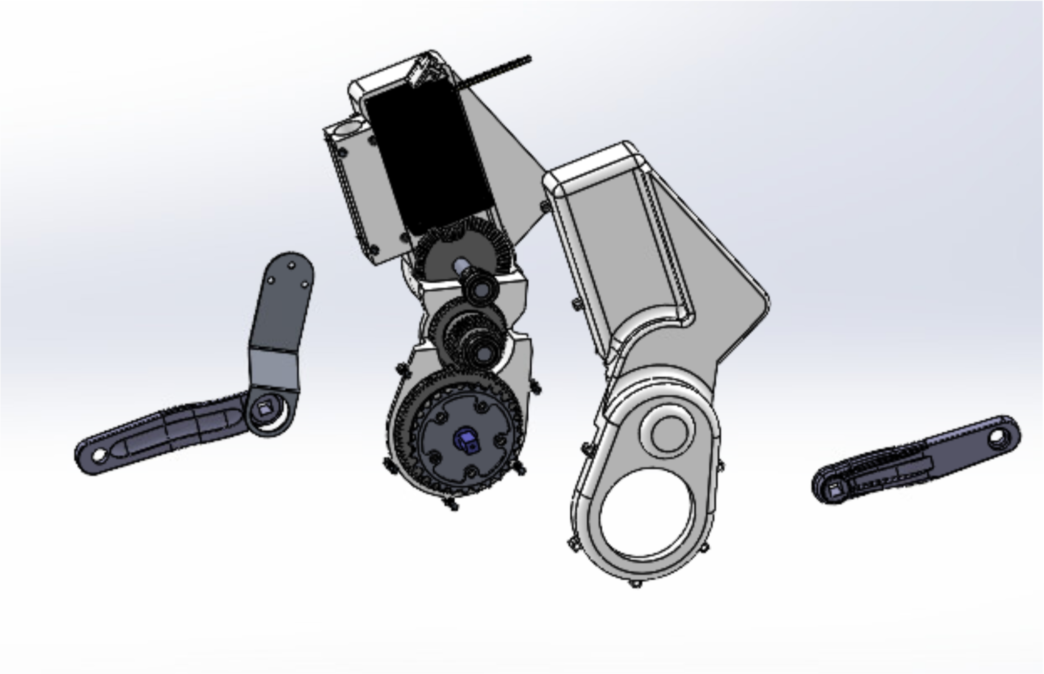
E-bike Engagement and Accessibility

Final Report



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EXECUTIVE SUMMARY

There is currently a large barrier of entry to the design space surrounding a DIY E-bike retrofit build. The combination of necessary knowledge regarding gearing and transmission, mechatronics and motor control, battery charge and capacity, and force analyses, all in addition to general bike-related knowledge can be completely overwhelming to a novice user. Our team approached this project through a Socially-Engaged Design strategy to provide access, regardless of mechanical ability and budget, to a low-cost and easily accessible E-bike. We defined requirements for our solution design to incentivize the use, purchase or build of E-bikes, to be usable without much background knowledge, to be safe, to be attractive and accessible to the user, and to be inexpensive. We began our design process by conducting research on existing designs solutions. From here, we conveyed every step that a user would go through to access an E-bike themselves and how they could optimize an E-bike or E-bike retrofit of their own.

Our theoretical stakeholder persona for this project is a University of Michigan student looking to commute across campus daily. This persona helped us build specifications such as hill climb ability, battery life and a target max flat ground speed. Primary subsystems were identified as system controls like throttling or pedal assist, motor and transmission, power supply, and the mounting interface. Our final CAD model of this design and its subsystems includes the motor, power supply, transmission, housing, and interfaces for any other subsystem. We also developed a model for a sustainable modular battery prototype design. This accomplishes our aim to make each battery cell replaceable while achieving a high cycle life compared to other batteries of similar size and cost. The transmission design solution provides a smooth ride up the steepest Ann Arbor hills and its mounting design provides easy access for maintenance and diagnosability. After completing the design, we evaluated it against our set specifications through physical testing and virtual analysis.

We also examined the effectiveness of our design solution by evaluating the gap between existing market solutions and the user needs. Through our analysis, we realized that our retrofit design is a helpful tool to convey our DIY decision making process, though its mechanical complexity prevented it from properly addressing our defined need for increased E-bike accessibility. To effectively address the needs of our problem space, we determined that we should communicate our process to users through inclusive web design, rather than only conveying it through the prototype design. We therefore developed a website which takes the user through several pages covering our mission statement, E-bike related background information, evaluation criteria for E-Bike selection, the design and decision-making process, maintenance guides and safety practices, end-of-life recycling details, and opportunities for further customization of a DIY retrofit build. We validated our website solution against several inclusive web design and educational guidelines which include the Nielsen Norman group and the US Department of Education. While the website needs further building and revision for optimal accessibility, these verification techniques indicate that its framework and existing structure will help users access, regardless of mechanical ability and budget, to a low-cost and easily accessible E-bike. In the future, we plan to finalize a website design with the use of HTML and CSS programming and conduct usability tests with potential users to iterate on our design and improve it further.

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PROBLEM DESCRIPTION

While as many as 90.5% of people rely on transport methods that burn fossil fuels as a primary method of transport, more people in urban areas have taken to biking and particularly E-biking as alternative methods of commuting. Encouraging E-biking could greatly reduce emissions and traffic congestion in urban areas. But, people who want access to E-bikes face a large barrier of necessary mechanical knowledge to do so. The combination of necessary knowledge regarding gearing and transmission, mechatronics and motor control, battery charge and capacity, and force analyses, all in addition to general bike-related knowledge is completely overwhelming to a novice user. A Socially Engaged Design approach is needed to determine a new strategy to provide access, regardless of mechanical ability and budget, to a low-cost and easily accessible E-bike.

Achieving this solution would increase the accessibility and democratization of E-biking as a whole. In the scope of this project we define these terms as not only to keep costs of biking and E-biking to a minimum, but to make the assembly, mounting, and operation of bikes and E-bikes accessible to all people, not only to those who may self identify as makers. This will enable most anyone to pick up E-biking and bike maintenance as an everyday hobby. A solution that provides access to low-cost, low-waste, E-bike retrofit alongside accessible educational materials and manuals is needed to allow individuals, regardless of mechanical ability, to incorporate an E-bike into their daily transportation. This would further enable individuals, especially those who don't cycle currently, to commit to lowering their carbon emissions by incorporating the use of an E-bike to their everyday travel. The solution is not limited to designing an E-bike retrofit, as other methods, such as the creation of a design process or model to follow when making choices about an E-bike, are also considered "solutions" to this problem.

Background and Design Process

In our design process, we have followed a cyclical path of problem-solution co-evolution. We began our ME450 design project with a specific goal in mind rather than a broad problem space because we knew that the scope of this course does not include enough time to fully explore the front-end of the design process. We defined our basic problem as "While it is one of the most carbon neutral ways of transportation, a very small percentage of people cycle as their primary method of transportation". We started by developing an E-bike retrofit kit designed to give people with very limited mechanical ability access to an E-bike. Doing this allowed us to gain all of the necessary knowledge to complete the design of an E-bike, all knowledge that would be useful to someone also trying to access an E-bike. During our design process, we realized that the most important aspect of our overall design solution was to address the need of expanding the access of E-bikes to non-makers and people normally excluded from technical learning. We also realized that we couldn't physically craft a design that would account for all the variations in bike designs. We determined that we really wanted to take our design process and knowledge of DIY decision-making and communicate it to any potential user through an inclusive web design, rather than solely communicating how to replicate and use our prototype design. The general steps in our design process to develop both an E-bike retrofit kit and a communication of our solution are outlined in this report with examples of our work to show how we worked through each step.

Stakeholder Mapping, Prioritization, and Engagement

In order to better scope our prioritized project requirements we used stakeholder mapping to identify our primary stakeholders: the Student Sustainability Coalition (SSC), a potential investor through grant application; the University of Michigan Board of Regents, publicly committed to the President's Commission on Carbon Neutrality's sustainability goals; the ME 450, outlining of the course syllabus from which this project is defined; Professor Steven Skerlos, the first specific representative of the user demographic; University of Michigan, to whom the SSC aims to benefit; and soon to be do DIYers, meaning hobbyists who enjoy do it yourself (DIY) projects. The stakeholder map in which these primary stakeholders were identified is shown in Figure 1.

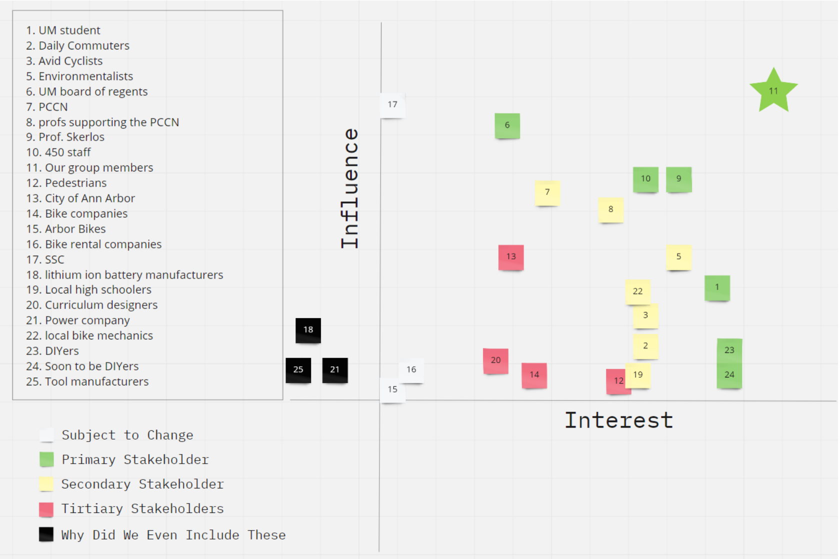


Figure 1. The stakeholder mapping process used to identify the primary stakeholders. The left list shows the stakeholders identified through brainstorming. Each stakeholder is associated with a number, placed onto a post-it, and qualitatively placed on the Influence versus Interest graph on the top right. Stakeholders were classified by priority seen in the legend at the bottom right. The categories include primary (green) , secondary (yellow), tertiary (red), and extraneous (black). A fifth group was identified as subject to change.

In order to address the lack of a predefined stakeholder we began by interviewing ten potential users and collecting pertinent information from them. While our original interviews provided fruitful potential user feedback, very few people have extensive knowledge of, or experience with, E-bikes. Further, our time constraints in this three month project limited our ability to pursue interviews as our only means of stakeholder engagement. As such, we pivoted to the reading of relevant amazon reviews. As our project lacks individual stakeholders, aside from Professor Skerlos, reading user reviews of E-bike products on Amazon was helpful in emulating stakeholder engagement. We found that many of the cheaper E-bike kits had unclear instructions, were not universally mountable, and built out of materials that failed after minimal use.

Retrofit Kit Requirements and Specifications

In order to design the E-bike retrofit, we first had to define requirements based on our identified primary stakeholders, and develop engineering specifications necessary to meet these requirements. The requirements and specifications we developed for our stakeholders are listed below. This list has guided all ideation and concept development for the use case of a full DIY E-bike retrofit build process. A table of the requirements and justifications can be found in Appendix A.1.

Safe to ride in Ann Arbor

Cannot travel faster than 20 mph without the assistance of pedaling on flat ground
Considering Michigan's safe riding policies, there are more stringent safety guidelines for E-bikes which travel faster than 20 mph than those whose maximum speed is 20 mph [24]. To streamline the user's transition from manual bike to E-bike riding, we capped the speed limit to 20 mph. This specification fulfills the requirement of "safe to ride in Ann Arbor" by ensuring that the user does not travel at speeds which are dangerous on a retrofitted bike.

Braking must disengage the powered drive system with less than 0.5 second response time or less
This is also in accordance with Michigan's safe riding policies [24]. This specification fulfills the requirement of "safe to ride in Ann Arbor" by ensuring that the E-bike will stop when the brake is engaged.

Includes features that allow the user to see >13.5 ft away in low light conditions and for the user to be seen >50 ft away
To encourage users to bike more regularly, including after the sun has gone down, we considered safety in low light situations. We followed a simplified formula to estimate the stopping distance, $d = \frac{s \cdot r}{3.6}$, where s is speed in km/h, r is reaction time in seconds, and d is stopping distance in meters [20]. For a top speed of 20 mph and a reaction time of half of a second (measured and including a safety factor), the stopping distance would be just under 13.5 feet [19]. This is the distance the user should be able to see in low light situations. To protect the user from oncoming vehicles, likely driving at faster speeds, the user should also be seen over 50 ft away. This specification fulfills the requirement of "safe to ride in Ann Arbor" by ensuring that the user will not hit or be hit by vehicles or other objects which they may encounter on their ride.

Good Range

Can travel >10 miles on a single charge over on flat ground
We considered the scope of our target customers', University of Michigan -- Ann Arbor students, commute to be approximately the distance from the southernmost part of campus to the North Campus Research Center and back. This distance is approximately 10 miles on flat ground [3]. This specification fulfills the requirement of "good range" by ensuring that the bike can travel as far as the user may need it to commute in Ann Arbor.

Can travel up a 9% gradient for 350 ft while maintaining 95% of the range of the bike.
We also have considered a single gradient rather than an averaged gradient. We chose to calculate the gradient of the hill on Broadway near North Campus. We found this gradient to be approximately 5% and we have set our single gradient specification to match this. This specification fulfills the requirement of "good range" by ensuring that the bike can make it up any hill it may encounter on a typical commute in Ann Arbor.

Fully rechargeable in ≤5 hours in a 120 V conventional outlet
Because the range of the modification is heavily reliant on the battery life, we also specified a charge time based on what we considered to be a minimum full nights sleep for a college student. This specification fulfills the requirement of "good range" by ensuring that it can travel it's full commuting distance on a charge that is completed in a reasonable amount of time the user would have to fully charge the power source.

Durable

Can withstand (safely operate after) impact of more than 5,541 N

Our E-bike weight is 305.7 lbs (the Cannondale bike weights 30.7 lbs [2], the retrofit mechanism should weigh at most 25 lbs, the additional load is at most 250 lbs) and the maximum velocity is 20 mph. With proper unit conversions,$KE = \frac{1}{2}mv^2$gets us 5,540.22 N. This specification fulfills the requirement of "durable" by ensuring that the bike will still function after an impact it would receive within reason.

No component fails under low-cycle fatigue where one cycle is one 10 mile ride (1<N<1,000)

To effectively scope this E-bike retrofit as a commuting vehicle, no components should fail within the scope of 1,000 10-mile rides on the E-bike [10]. This specification fulfills the requirement of "durable" by ensuring that the bike will continue to function after 1,000 uses of ten mile commutes.1,000 uses is a reasonable number because it is the equivalent of commuting seven days a week for 36 weeks (typical school year length) for four years.

Materials will not corrode with exposure to water, salt etc. (for 4 years or equivalent thereof)

This considers the Ann Arbor student user - in the context of typical Ann Arbor wet/winter road conditions and the four-year duration of an undergraduate program at the university. This specification fulfills the requirement of "durable" by ensuring that the bike's materials will last for the length of time a typical student commuter would use the bike.

Torque exerted onto the chain remains under 9000 N (otherwise a chain of higher force rating must be included in E-bike kit)

Lastly, the Cannondale bike has a rated chain tolerance of 9,000 N [28]. Our team is considering including a chain with a higher force rating with the E-bike kit given some complaints we found on E-bike forum sites [14]. This specification fulfills the requirement of "durable" by ensuring that the bike's chain will not break.

Usable in most conditions

Will keep traction with wet ground at a maximum speed of 20 mph

Considering our primary stakeholders and Ann Arbor users, we want to ensure that our E-bike is suitable for use in wet road conditions at the maximum use speed. This specification fulfills the requirement of "usable in most conditions" by ensuring that the E-bike is usable when riding on wet ground.

Power source performance can still last for at least 10 miles in 9-110 ºF

We also want to make sure that the performance is not drastically inhibited by fluctuations in heat. The specified high and low temperatures were determined by Michigan high temperatures (in-sun) and average low temperatures [30]. This specification fulfills the requirement of "usable in most conditions" by ensuring that the E-bike is usable in low and high temperatures.

Can reach a no pedal velocity of ≥15 mph in a range of 9-110 ºF

Temperature changes should not have a significant effect on the maximum velocity of the E-bike. Our team agreed that a reduction in speed of 5 mph is reasonable in extreme heat or cold. This specification fulfills the requirement of “usable in most conditions” by ensuring that the E-bike is usable in low and high temperatures.

Can reach a no pedal velocity of ≥15 mph against wind speeds of up to 25 mph
This specification is determined from the same reduction of speed as the previous specification and the Michigan average high wind speed [17]. This specification fulfills the requirement of “usable in most conditions” by ensuring that the E-bike is usable in windy conditions.

Pleasing user interface (in use)
Can operate with loads between 80 and 250 lbs placed on the bike without losing the ability to operate at top speed
In considering the typical load that the bike would have to support, we settled upon a range from 80-250 lbs being reasonable estimates for one rider and potentially extra attachments. This specification fulfills the requirement of “pleasing user interface” by ensuring that the E-bike is usable in its full capacity for a user of an 80 - 250 lbs weight range.

Power control system can be operated with at least one hand remaining on the handle bars
The user will most likely already be riding the bike when they choose to engage the power assist. So we added this specification to ensure the user can continue steering safely while operating the E-bike. This specification fulfills the requirement of “pleasing user interface” by ensuring that the E-bike assist can be engaged while the user is already operating the bike manually.

Maximum jerk during acceleration is 0.6 m/s3
For aesthetics, we considered the potential for rapid changes in acceleration to be uncomfortable. We researched what a comfortable level of change in acceleration would be for the average vehicle rider and found that the jerk, or derivative of acceleration, of our E-bike should be less than 0.6 m/s^3 [2]. This specification fulfills the requirement of “pleasing user interface” by ensuring that the user does not experience an uncomfortable ride due to changes in acceleration.

Rider has complete control over speed within the range of 0-20 mph (adjustable power draw)
We have previously specified this range in our explanation of the 20 mph speed limit. This specification fulfills the requirement of “pleasing user interface” by ensuring that the user has complete autonomy to choose any speed setting that user desires.

While running, E-bike produces sounds ≤50 dB
For the mechanism to not generate sounds that are too loud, we wanted the E-bike to produce sounds less than a conversation level, or 60 dB [29]. This is considered a safe noise level for continued exposure. We subjectively reduced the cap on sound level to 50 dB. This specification fulfills the requirement of “pleasing user interface” by ensuring that the user’s hearing is not at an uncomfortable level by using the E-bike.

Adding the retrofit will not interfere with already in place, back wheel shifting
Another logistical challenge that this retrofit poses is the possibility for it to interfere with other mechanisms already existing on the manual bike design, the most important one being gear shifting. This specification fulfills the requirement of “pleasing user interface” by ensuring that the user can keep their autonomy over their gear selections with the retrofit in place

Environmentally-conscious material selection

More than 80% of material by mass, excluding the motor and battery, is recyclable

80% is our target for making our design environmentally friendly in consideration of the environment, society, and economy. Because the motor and battery will be difficult to source while being economically cognisant of student users budgets, we excluded these from our benchmarks. This specification fulfills the requirement of "environmentally-conscious material selection" by ensuring that at least 80% of the material does not have to end up in a landfill and harm the environment in its end use.

100% of material, excluding the motor and battery, is sourced within the US

This metric will reduce our material sourcing emissions and stimulate the local economy by purchasing materials within the US. This specification fulfills the requirement of "environmentally-conscious material selection" by ensuring that materials do not travel farther than the boundary of the US to keep their carbon footprints minimal.

Lightweight

Does not add more than 25 lbs in additional weight to the bike

The FDA recommends that the maximum backpack weight be no more than 20% of your body weight [18]. For the added weight of our modification mechanism, we chose to consider 10% of our 250 lbs upper weight support limit to be a comfortable level of additional weight for the rider. This specification fulfills the requirement of "lightweight" by ensuring that the entire device weighs less than an amount that would be difficult for a typical user to carry.

No individual piece weighs more than 10 lbs

We wanted the user to easily hold the mechanism's parts and assemble them onto the bike without assistance. This particular weight was considered liftable with one hand by all project designers. This specification fulfills the requirement of "lightweight" by ensuring that each individual component of the device weighs less than an amount that would be difficult for a typical user to carry.

Minimized consumer cost

At a scale of 40,000 units, the per unit manufacturing costs must be ≤$500.00 USD

We considered a hypothetical scenario where our device could be mass manufactured. We chose a production unit size of 40,000 mechanisms to accommodate the entire University of Michigan -- Ann Arbor student population. We chose this cost of $500 because our research and interviews indicate that our primary stakeholders, Ann Arbor commuters, would not be willing to spend more than this. This specification fulfills the requirement of "minimized consumer cost" by ensuring that the entire device costs less than $500, a number below most E-bike modification device costs.

Can be adopted/used without extensive experience or education

Entire assembly can be assembled, mounted, and maintained using only a flathead screwdriver, a Phillips Head screwdriver, a hammer, and tools provided in the retrofit kit.

As indicated by the problem statement, a large focus of this project is centered around democratization of installation and use of the product. We believe that we can build a mechanism that would not require more than two generic screwdrivers, a hammer, and tooling we can provide. From our knowledge of student access to tools, we know that every college student will at least have access to borrowing a flathead, a Phillips Head, and a hammer. This specification fulfills the requirement of "can be adopted/used without extensive experience or education" by ensuring that the user can build the mechanism without uncommon or advanced tools.

Entire design is assembled in ≤6 hours
Given user feedback, we agreed that having to spend more than six hours on the assembly of the mechanism would likely reduce the user's willingness to complete the assembly. This specification fulfills the requirement of "can be adopted/used without extensive experience or education" by ensuring that the user can build the mechanism without spending multiple hours only learning how to build it.

Power source is removable in ≤5 minutes without tools
It will be important to charge the power source for the retrofit mechanism between uses. Therefore, it is important that it can be quickly and easily removed by the user. This specification fulfills the requirement of "can be adopted/used without extensive experience or education" by ensuring that it is straightforward for the user to remove and replace the power source to necessarily charge it.

Only uses 1 standardized fastener
Our design team rationalized that only one fastener would be necessary for the complete design so that we can streamline assembly time and decrease upfront and maintenance costs. This specification fulfills the requirement of "can be adopted/used without extensive experience or education" by ensuring that the user will not have to keep track of more than one fastener.

Able to mount to 3 or more bike designs
This specification ensures broad compatibility of the mechanism over bike frame variation. This specification fulfills the requirement of "can be adopted/used without extensive experience or education" by ensuring that the user is capable of mounting the device to the type of bike they own and will not have to troubleshoot the build to fit their particular style of bike.

PRELIMINARY MECHANICAL RESEARCH

To better understand the drive system, mechanical research was conducted. This research focused on understanding current E-bike retrofits that are on the market now, particularly their costs and their interfaces with the bicycles. Three main subsystems were identified, drive systems, power sources, and finally control systems. This research is summarized below.

Hub Drive

The first category of motors that are used in E-bikes are hub drive motors, which can be split into direct drive or geared motors. Hub motors are mounted within the rim of the wheel of the bike, and thus can either be on the front or back wheel. Each of these configurations have their advantages and disadvantages. Hub drive motors are said to feel awkward while riding, as they "push or pull" you along, which isn't as intuitive for new riders [13]. Direct drive hub mounted motors have the permanent magnets mounted in the rim of the wheel, and the electric current drives the wheel directly. They are more robust and can take greater loads than geared motors. Geared motors use planetary gears to drive the wheel, with the ring gear fitted to the rim of the wheel. These are shown below in Figure 2. They are normally a relatively cheap way to manufacture an E-bike, however, in the case of a retrofit, the entire wheel needs to be replaced. This makes it challenging to use on many different types of bikes, with different wheel sizes, fork separations, mounting mechanics, and brake types. This usually makes the retrofit "kit" more expensive, usually around $300-600. They are generally relatively light, with motors typically weighing around 10 pounds. [12]. Finally, hub mounted motors rank relatively low in efficiency and torque because they do not use the bikes already in place gearing to drive the bike [1].

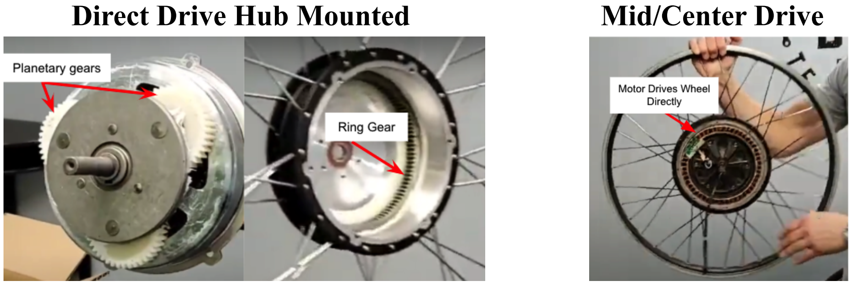


Figure 2. This figure shows images of the different types of motors used in drive systems of E-bikes.

Mid/Center Drive

Mid or Center drive motors are mounted elsewhere on the bike, and instead drive the chain of the bicycle rather than the wheel itself. Oftentimes they are connected where the cranks, or pedals, of the bike are located and incorporate the cranks into the design. This is shown in Figure 3 below. This drive system has a number of advantages over the hub mounted motor. First off, since it is not mounted in the wheel, there is a much greater variability in the bikes/mounting positions it can be used with. It is also easier to maintain, as it can easily be removed and inspected or replaced. They also have better performance with respect to the torque provided because they utilize the chain drive system already used in the bike. This also allows for changes in motor torque based on gear shifting, which can be very useful in hilly terrain [1]. This also makes them more efficient. Generally, they weigh about 10 pounds, and add the mass to the bike where it lowers the center of gravity.

Figure 3. This figure shows a typical mid/center drive mounted at the crankshaft

Friction Drive

A more simple method of electrically driving the bike's wheels forward, without the additions of chains or sprockets, is a rolling friction drive. This method employs a motorized roller which makes contact with the bike's wheel (generally the back wheel) and the friction between the driven roller and the wheel forces the wheel to spin. Therefore, adding a friction drive to a bike does not require any changes to gearing or replacements for the cranks or wheels. This greatly reduces the extra tooling required to mount a friction drive. There are a variety of rollers and mounting systems already on the market, and many require one or no tools to assemble and mount. The simplicity of the friction drive design makes it an ideal option for our democratized retrofitting project. However, there are limits to the maximum level of assist that friction drives can deliver to the user as the roller needs consistent traction with the wheel and too much power delivered to the roller can cause it to spin out. Further, it is possible that this traction can be lost in wet, muddy, or dusty conditions. This decreases the reliability of this drive system. There are a variety of ways to manage these pitfalls including using an “outrunner” motor which spins an outer shell, allowing the motor to be the roller. [11] It turns the wheel directly and the motor starting torque engages the wheel so that the drive does not have to be engaged when the power is not applied. This design does not fully address the weather issue nor the wear which extra friction puts on the bike tire. A German engineering company called *Velogical* has addressed these issues in their rim friction drive approach. They use two small “outrunner” motors, specially designed to induce a current and draw minimal power to run, which clamp together on the rim of a bike’s back wheel and create traction with the rim using rubber O-rings. These motors also self-regulate their contact pressure. [25]

Power Sources

The next subsystem researched was power sources, or the electric storage devices used in most E-bikes. Almost all E-bikes use a rechargeable Lithium Ion battery, that have different ranges of voltage and charge depending on the motor used and range of the bike. Typically, batteries are 36-52V, and provide a range of currents typically from 9-22 amps. We found these to generally be the most expensive part of a E-bike retrofit, with price ranges between $250-$800. This is a wide range related heavily to battery performance based on metrics such as voltage, amperage, single charge life, and cycle life. Because a quality battery can drastically increase the overall sustainability and user experience, it could be beneficial to build our own out of lithium ion battery cells to achieve high performance while maintaining a lower manufacturing cost than the bulk sale price of prebuilt lithium ion batteries.

Control Systems

Finally, we researched control systems for the E-bike retrofit. This included researching motor controllers, pedal assist systems, and other user interface based controls like throttles and LED displays. Motor controllers are a necessary part of any E-bike and act as the brain of the retrofit kit, transfering power from the battery to the motor given an input. This input can come directly from the user, in the case of a throttle, or from another sensor, like in the case of a pedal assist system. Usually, these would be sold with the motor. Pedal assist systems sense when the user is pedaling, and automatically activates the motor to help drive the bike. Additional user interfaces such as LED displays that show speed or battery charge can also be incorporated. The more features that are added to the E-bike, the higher the cost. Pedal assist systems might add around $80-200 to the price depending on the quality, and other other features can also sum to a large amount.

CONCEPT GENERATION AND DEVELOPMENT

To populate our design space with divergent brainstormed concepts for a mechanical solution, we first identified our functional subsystems, classified our requirements and specifications within them, and individually ideated before comparing concepts in a team setting. We focused primarily on concepts related to developing an E-bike retrofit kit, but we also brainstormed educational concepts and iterated through them toward an educational solution.

Subsystem Identification and Classification

Before beginning concept generation, our team decomposed our problem space into ten different subsystems based on functions desired in our final design. We sorted our E-bike retrofit kit requirements and specifications (Appendix A.1.) into each of the subsystems. These subsystems are listed and described in more detail in below.

> ***Primary Subsystems*** *encompass the subsystems that interface closely with one another therefore greatly impacting realization of each other:*
>
> > *Mechanical User Interface* - The Mechanical User Interface subsystem includes any concepts for a throttle or pedal-assist interface. This function amplifies the user's human-powered acceleration or fully substitutes the human input component of the bike's acceleration.
> >
> > *Power Delivery* - This subsystem focuses on the methods by which the motor delivers power to the bike or tires. This may include, for example, gearing or friction interfaces between the bike's moving parts.
> >
> > *Power Source* - The Power Source subsystem includes all battery concepts such as its assembly and the battery pack's mounting and removal from the bike.
> >
> > *Drive System* - The Drive System refers to the mechanical components of the E-bike kit. It also includes an exploration into the mounting and placement of the bike mechanisms.
>
> ***Secondary Subsystems*** *which may be influenced by the primary subsystems but do not do much influencing:*
>
> > *Feature to see and be seen* - As safety is a primary consideration throughout the entire design process and all subsystems, the user needs to see the path ahead and to be seen by other motorists while the bike is in use.
> >
> > *User Engagement* - The User Engagement subsystem includes how the user will interact with educational materials provided with the retrofit kit, as well as the user's interaction with construction of the assembly.
> >
> > *Materials* - Materials is an exploration into the materials which can be used during prototyping and scaled manufacturing, and also includes manufacturing processes in the case of mass production of our E-bike kit.
> >
> > *Braking* - This subsystem refers to motor disengagement and stopping concepts.

Divergent Brainstorming

Following the sorting of our requirements and specifications into the functional subsystems, each of our team members was tasked with individually brainstorming at least three divergent concepts underneath each subsystem. As a group, we then compared our individual concepts and sorted them into each of the subsystems while also eliminating any duplicate ideas, demonstrated in Appendix A.2. At this point, we also grouped together similar brainstormed ideas which allowed us to determine relationships between concepts and prepare to divergently explore them further.

Subsystem Ideation

The group ideation and organization session also helped our team identify the need for further research on each of the generated concepts. We divided the subsystems amongst ourselves and set the responsibility of conducting research on each of the concepts within the delegated subsystems. This helped us fully articulate and populate design elements of our concepts and identify if there was any additional divergent brainstorming we could do before moving to evaluate the concepts. A complete list of our subsystems and their justifications can be found in Figure 4. For the purpose of this report, we will fully explain the design process in the context of the drive system, the motor, and the education and engagement subsystems. The same process applies to the remaining subsystems.

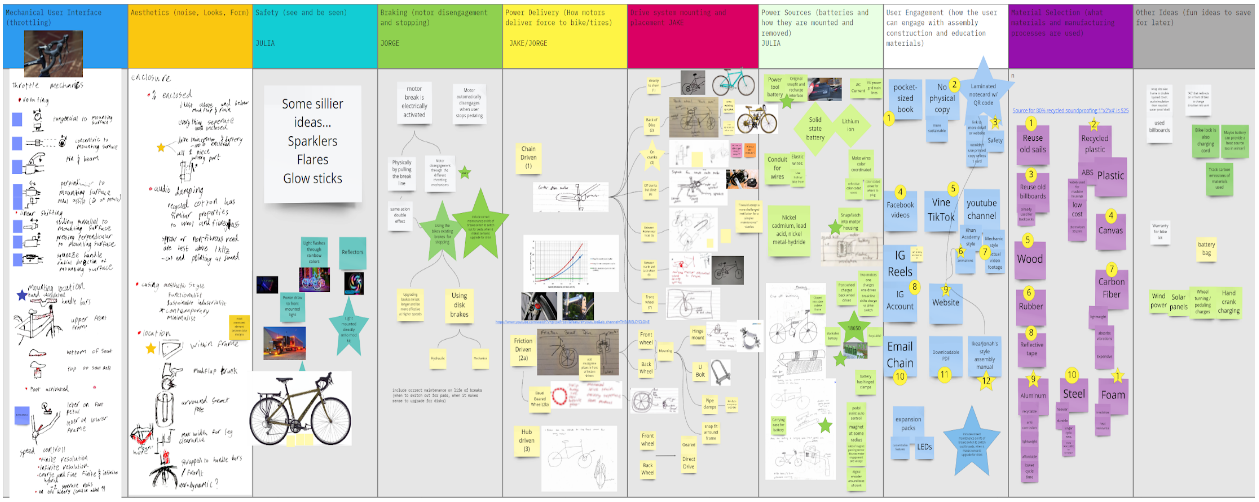


Figure 4. Screen capture of our Miro brainstorming organization within each of the ten subsystems. Similar concepts are grouped together and/or mapped with connecting lines between related concepts in different subsystems (i.e. power delivery concepts are linked to respective drive system concepts).

Drive System

In our brainstorming, we considered different locations for the retrofit device to mount to the bike, such as the back of the bike, in the frame of the bike, and on one of the wheels. We considered different components of the bike which the drive system would interface with, such as the existing chain, a sprocket which would be added to an existing wheel, and the existing chainring sprocket. We also considered whether the bike might be driven directly, with gear reduction, or even with friction. Additional ideas were also explored on our Miro board, found in Appendix A.2, which we kept for future reference.

Motor

Within our motor brainstorming, we ideated on the different types of motors that could be used in a retrofit kit, as well as the rated power consumption and voltage of the motors. For power consumption and voltage, we used benchmarks for current retrofit systems to guide our brainstorming. The different motor types that were discussed were ideas such as a brushless DC motor, a brushed DC motor, and an AC motor. Within this brainstorming session, we also discussed alternative methods of driving the bike, with more off-the-beaten-path ideas like adding a sail to a bicycle or using rockets as boosters. For brainstorming the rated power specifically for motors, we had a range that went from

250W on the low end to over 1000W on the high end, and for motor voltage the range went from 24V to 76V.

Education and Engagement

When brainstorming the format to engage and educate users, we developed several possibilities for conveying the content. We outlined these in our Miro brainstorming section, similar to the other subsystems. This identified solution concepts such as a website, a YouTube channel, a printed notecard with a quick start and troubleshooting guide, or a social media account. We also began brainstorming content which would be included in the solution format. This content included future modification opportunities, instructional mounting videos, and safety guidelines.

Concept Evaluation and Selection

In pursuit of leading solutions, we used subjective feasibility versus efficacy charts, objective research, and pugh charts to converge upon our final selections. Each of these processes helped us decide which of our mechanical solutions for each subsystem was best suited to meet our specifications. These processes are discussed in more detail below. We also used these to identify which educational engagement concepts were best as well.

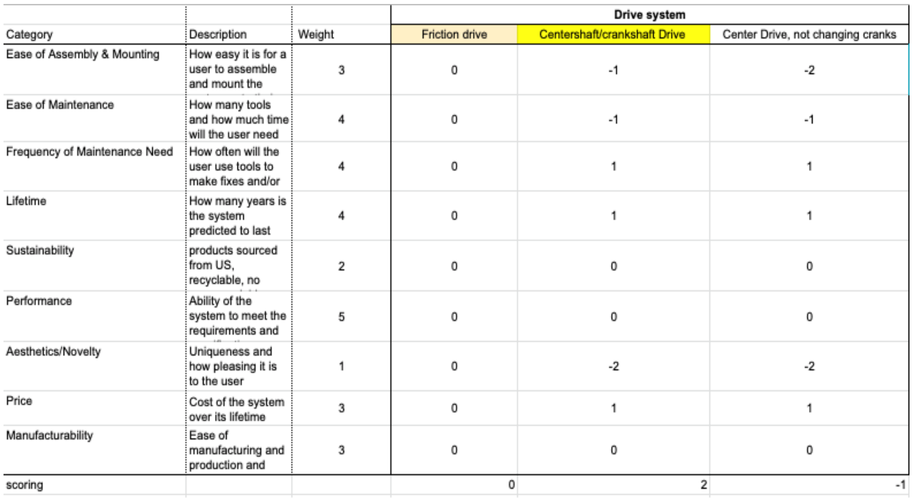
Solution Mapping

Heading into the convergent evaluation phase of concept exploration, we assembled feasibility versus efficacy charts for each of our subsystem solutions. On the x-axis, we subjectively arranged our concepts which seemed most difficult to manufacture (involved many parts, required many tools, would be less intuitive or seemingly more involved to the user) closest to the origin. On the y-axis, we arranged our concepts which seemed least likely to fulfill our outlined requirements and specifications closest to the origin. From here, we could eliminate the ideas which were placed nearest the origin and converge upon the solutions which were furthest away.

Research and Pugh Charting

For each subsystem that included multiple leading solutions, we generated a research matrix including criteria such as ease of assembly and mounting, ease of maintenance, frequency of maintenance needed, lifetime, sustainability, performance, aesthetics and novelty, price, and manufacturability. Within each of the criteria, our team members researched leading solutions and populated the matrices which were used to inform our concept evaluation and selection. Each of the generated research matrices can be found in Appendices A.3. through A.6.

Next, we converted the research matrices into evaluative Pugh Charts. First, we developed a ranking system from each of our previously outlined criteria. We ranked the most important criteria as “tier 1” and the next most important criteria “tier 2” and so on until each had a level of importance assigned to it. In the end, we had five tiers. And from here, we inverted the ranks to create a weighting system. “Tier 1” criteria received a weight of 5, (the heaviest weight), “tier 2” a weight of 4, and so on. With our weighting system established, we zeroed our left-most solution column and compared each other solution to that baseline. We chose a range of -2 to +2 for scoring how our concepts meet each criteria. This is visible in Figure 5 below.



			Drive system		
Category	Description	Weight	Friction drive	Centershaft/crankshaft Drive	Center Drive, not changing cranks
Ease of Assembly & Mounting	How easy it is for a user to assemble and mount the	3	0	-1	-2
Ease of Maintenance	How many tools and how much time will the user need	4	0	-1	-1
Frequency of Maintenance Need	How often will the user use tools to make fixes and/or	4	0	1	1
Lifetime	How many years is the system predicted to last	4	0	1	1
Sustainability	products sourced from US, recyclable, no	2	0	0	0
Performance	Ability of the system to meet the requirements and	5	0	0	0
Aesthetics/Novelty	Uniqueness and how pleasing it is to the user	1	0	-2	-2
Price	Cost of the system over its lifetime	3	0	1	1
Manufacturability	Ease of manufacturing and production and	3	0	0	0
scoring			0	2	-1

Figure 5. Pugh Chart populated with weights and scores for our drive system subsystem.

Adding up our final scores, we arrived at our leading solutions for each subsystem of our primary subsystems. Each of the Pugh Charts we created can be found in Appendix B.

Drive System

We evaluated our drive system mounting locations by using a feasibility vs efficacy chart described above which can be seen in Figure 6.

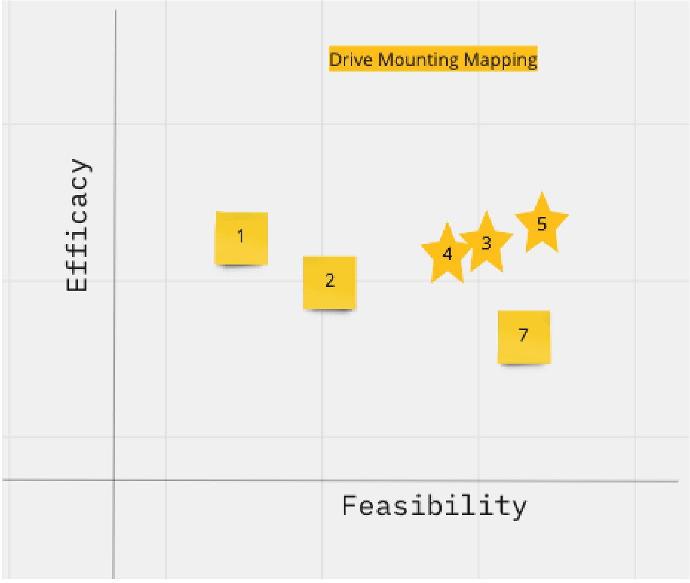


Figure 6. Mounting location feasibility vs efficacy chart.

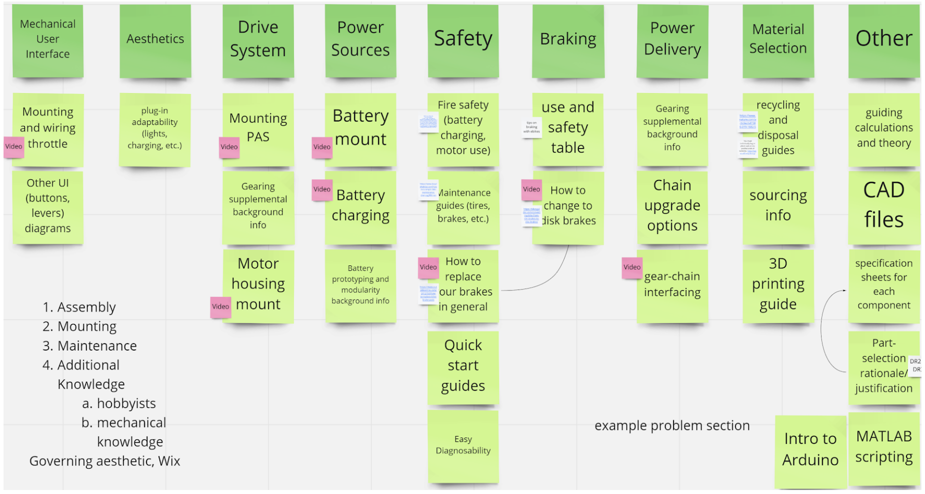
We subjectively evaluated the locations based on prior experience and basic engineering and biking knowledge. Our starred, three leading solutions were mounting either on the cranks, off the cranks but near the cranks, or on the frame between the cranks and the front wheel. However, we also needed to select the method of driving the bike. We completed another feasibility vs efficacy chart with our four brainstormed options, indicated in. Our three leading solutions included a chain drive (mid-drive), a friction drive, and a hub drive. We then populated a research matrix for each leading drive system to make an informed decision on how well each type would meet our requirements and specifications. The research matrix for our drive system can be found in Appendix A.3. Further, we created an evaluative Pugh chart for the drive system which can be found in Appendix B.1. From this Pugh chart, our leading solution was clearly a mid-drive.

Motor

Following the same method described above, we used a feasibility vs efficacy chart and research matrix to best quantify and rank our leading solutions. We also considered factors not mentioned in the concept generation section above, as they became relevant after continued research. This included using a motor with or without a pre-mounted gearbox, and using a motor with a pre-built motor controller or one without. After populating the research matrix shown in Appendix A.5 , we were able to make an informed decision on our leading solution, which turned out to be a 750+W Brushless DC geared motor with a pre-built motor controller.

Education and Engagement

After discussing our divergent brainstorming and concept evaluation using the processes described above, our team decided that a website was the most feasible and effective way to involve users in education and engagement materials. To develop the solution concepts within the user education and engagement subsystem, we used our other subsystems as categories to guide our brainstorming of what supplemental materials would be needed for the functions of the E-bike DIY build. For example, for the drive system, we considered that it would be beneficial to include videos on mounting the pedal assist sensor and motor housing. Our brainstorming also led us to incorporate supplemental background information on gearing so that the user can explore the significance of gear ratios, motor torque, and rotational speed. An outline of the brainstorming results is seen in Figure 7 below as a preliminary website content guide.



1. Assembly
2. Mounting
3. Maintenance
4. Additional Knowledge
    a. hobbyists
    b. mechanical knowledge

Governing aesthetic, Wix

Figure 7. Preliminary website content guide resulting from group brainstorming.

Technical Analysis (handwritten calculations)

To calculate how the component parts of an E-bike retrofit would work together and with the existing bike, we outlined equations which would consider external forces, mechanism specifications, and our design's engineering specifications.

Motor

There are many factors that go into the selection of a motor, and these parameters need to be calculated through an in depth analysis based on the individual specifications from the user. The primary factors that go into choosing a motor include the rated power consumption, rated torque, rotational speed (rpm), and rated voltage of the motor. These are all parameters that directly relate to the performance of the motor, and impact factors such as how fast the E-bike can go, the load the E-bike can handle, and the range of the E-bike. Based on user specifications, these parameters can be determined through an analysis, which we have outlined below. Other factors include the cost of the motor, size, and control mechanism. Users would input specifications into this analysis, such as their budget, bike load, desired speed, use cases that define things like hill-climbing, and desired control mechanisms. After the inputs are put in place, an analysis can be done that defines factors like external forces. This analysis would then output the parameters required by the motor based on the inputed specifications. Using Torque-Speed curves, power ratings, and other parameters that are typically defined on a motor supplier's website, we can pick a motor that fits our requirements. We used this style of technical analysis during the creation of our prototype retrofit. This allowed us to pick a motor that meets the engineering specifications developed from our stakeholder requirements.

Drive System

The drive system solution we developed was a mid-drive system. This system mounts to the crankshaft of the bike. To arrive at the necessary torque the motor transmission should exert on the crankshaft of the bike, we worked backward from the external forces exerted on the bike. Considering gravitational and air resistance forces at our engineering specifications' limits, we drew up the following diagram.

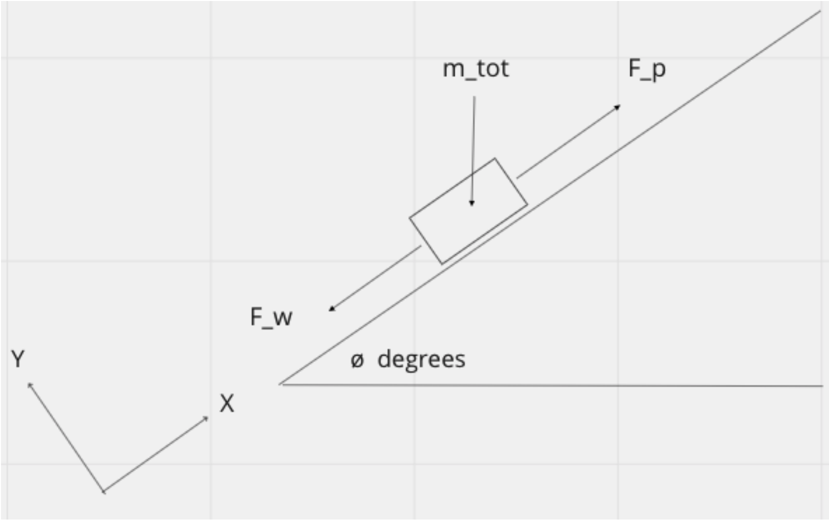


Figure 8. Hand drawn force calculation diagrams.

Under the least optimal conditions, the bike would have to drive a rider with a weight of 200 lbs up a 9% incline against wind speeds of 25 MPH. It was required that the bike function under these conditions by our set specifications. The 200 lbs rider, the 25 lbs that the device would weigh, at most, and the weight of the bike, combined would generate a cumulative downward force, m_{tot} in newtons. We estimated that this gravitational force would act at the bike's center of gravity and broke the force up into x and y components, using the slope of the incline as the x axis, as seen in Figure 8. Equation 1 calculates the x-component of this gravitational force.

$$F_{g,x} = m_{tot} * sin\,(ø) \quad \text{(Eqn. 1)}$$

Further, the wind speed would generate an excessive drag force on the bike and rider. Equation 2 was used to determine the air drag force which accounts for wind speed.

$$F_{w} = (1/2) \cdot \rho_{air} \cdot C_{d} \cdot A_{f} \cdot v_{w,true}^{2} \quad \text{(Eqn. 2)}$$

Here, F_w is the air drag accounting for wind speed.ρ_{air} is the density of air. C_d is the coefficient of drag which is determined mostly from an object's shape. The value used in our calculation comes from a study on professional bike performance [35]. $v_{w,true}$ (in m/s) is the relative wind speed, which is the summation of the speed of the bike ($v_{Bike,o}$) and the speed of the oncoming wind ($v_{w,true}$). We estimated the frontal area A_f (in m^2) by measuring the shoulder-to-shoulder width of our tallest team-member and their torso length from the top of their seat to the top of their shoulders. Then, we measured the distance from the ground to the height of his bike seat. Figure 9 shows our frontal surface area estimate articulating the added safety factor of using the riders shoulder as the width of the entire system.

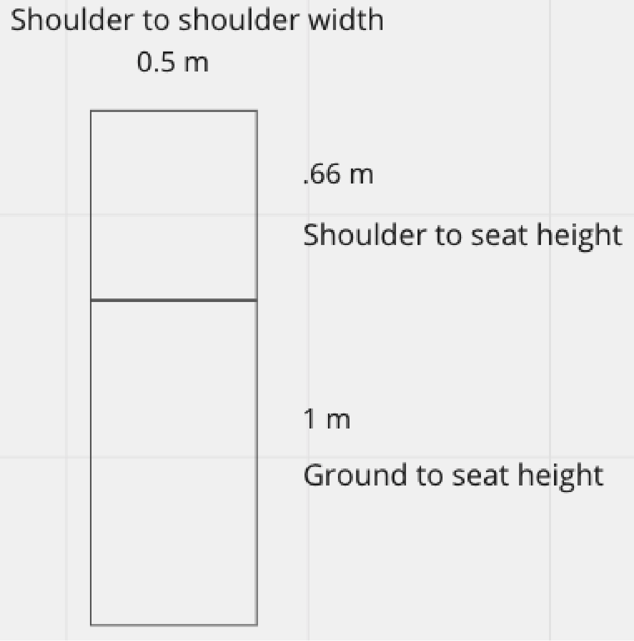


Figure 9. Frontal area estimation.

Equation 3 shows how the combined resistance forces of gravity, $F_{g,x}$, and drag, F_w, were set equal to the propulsion force which would be necessary for the bike to exert to drive forward.

$$F_{g,x} + F_{w} = F_{p} \quad \text{(Eqn. 3)}$$

We then used the required propulsion force to calculate the torque required from the back wheel. We also used the bike gear ratio (G_b) between the selected rear cog and ring gear to determine the torque required from the crankshaft. We considered the existing wheel dimensions and gearing combinations of a sample bike as seen below.

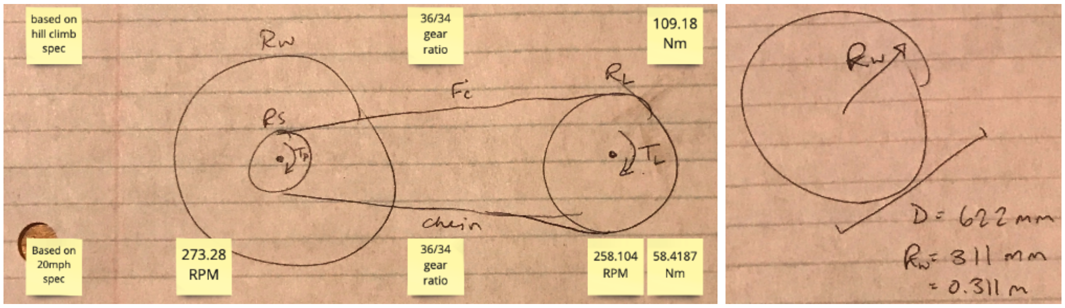


Figure 10. Torque calculation diagrams.

The equation below indicates how we incorporated the rear wheel radius (R_w), the bike gear ratio (G_b), and the propulsion force calculated previously (F_p) to solve for the required torque (T_L).

$$T_L = G_b * R_w * F_p \quad \text{(Eqn. 4)}$$

The torque required from the crankshaft (T_L) would determine the necessary gear ratio and torque delivery of the motor.

SOLUTION DEVELOPMENT & VERIFICATION

The decision to prioritize the educational model over the design of a retrofit for scale manufacturing was made from a re-evaluation of the existing design space. Evaluating the gaps between user needs and existing solutions, there is a much larger gap between the intended user's educational needs and existing educational solutions as opposed to the user's economic needs and existing E-bike and retrofit affordability solutions. The work we have done to create a theoretical DIY E-bike retrofit plays a significant role in how the user will interact with the educational model we develop. We will first outline our final retrofit design, then our detailed design solution for our educational model which will highlight how the retrofit design fits into the educational model.

Final E-bike Retrofit Design

The final design for our DIY E-bike retrofit kit is outlined in the sections below. We have split these up into the main subsystems we identified, and have explained our design decisions for each component or set of components. The final design will be the combination of all of these components to form a completed E-bike retrofit kit.

User Interface

The mechanical user interface subsystem involves the use of a rotational thumb throttle and a velocity input pedal assist system. Our team decided to move forward with a combination of both the throttle and PAS as it is an option found on some market E-bikes and would give the user more options for speed control of the bike. We wanted to select a combination that would be both low-cost and effective in providing engaging user interface and high levels of feedback between the user and the motor.

The rotational thumb throttle consists of a small lever that protrudes from the handlebars toward the user, and is operated by the user's thumb to control the power output of the motor while allowing the user the full range of power available to them. After extensive research, the thumb throttle was selected from three different E-bike throttle types. The thumb throttle was chosen largely due to its ability to be installed on both standard and non-standard handlebar shapes and grips, while also being less obtrusive than the other throttle types. The throttle is also relatively inexpensive as there are many existing models in the market. The throttle we selected, shown in Figure 11, has a 3LED display to show battery charge, on-off button, and the rotational lever. The LED battery indicator makes it more user-friendly at its cost point than other market options. There are more elaborate LCD models which offer better user interface and troubleshooting opportunities, but at a much greater cost.

Figure 11. Rotational thumb throttle with LED battery charge indicator and on-off switch.

The velocity input system is integrated into the crankshaft assembly of the bike and uses the speed at which the user is pedaling to control the power provided to the bike by the motor, without needing to use the throttle. This provides more comfort on a long trip by eliminating thumb fatigue and extending the battery life. The sensor was chosen from two types of pedal assist sensors as it is relatively inexpensive and would give the user control over the speed without having to worry about the force of their pedaling efforts. We are selecting the CSC KT-D12 sensor model, shown in Figure 12, which has 12 magnets allowing for a higher feedback rate while the user is pedaling, due to the smaller radial gap between the magnets. This particular model also comes as two pieces, which allows the user to easily snap it on around the crank spindle.

Figure 12. Velocity input pedal assist sensor model CSC KT-D12

Because we have two inputs into our motor controller, both the pedal assist and the throttle, our team will need to incorporate an arduino microcontroller into our motor controller schematic. This is because the motor controller only has one analog input, and doesn’t have the capability to read two inputs and make decisions on what to do in different scenarios. With our decision to use both a throttle and pedal assist sensor to control the motor, we'll use an arduino nano to resolve the two input signals and convert them into a single analog signal which will be read by the motor controller.

Motor Selection

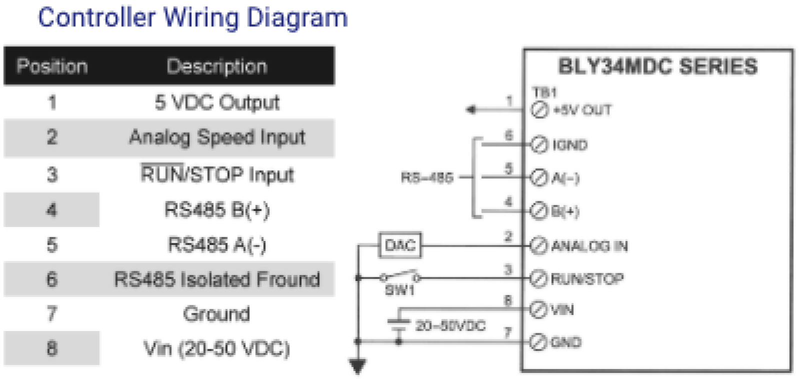
A crucial step in the process was picking a motor and motor controller that we would use to drive our power train. This required a lot of research, where we looked into many different aspects of the performance of motors. After our research, we decided on using a BLY34MDC3S motor with an integrated motor controller from a motor supplier called Anaheim Automation, shown in Figure 13. There were many criteria that went into selecting a motor and motor controller, which have been outlined under the *Technical Analysis* section. Based on our decisions earlier in the design process, we had decided to use a 48 volt motor, so this was a primary method to filter through motors. We also looked at the rated power and rated torque of these motors. We had a range of required power from 400-750W, and required torque between 300 and 650 oz-in, with a hope to be on the higher end of both ranges. This motor has a rated power of 440W and a rated torque of 595 oz-in. Another factor we looked at was the price when bought in bulk. This particular motor was $557 dollars bought as a single motor, but got cheaper than $300 dollars when over 100 were bought.

How the controller integrated with the motor was also a crucial factor. In this motor, a motor controller is already attached upon purchase, which allowed for us as designers to create a more compact design without having to house a motor controller separately from the motor. Finally, the last criterion, back EMF (electromotive force), was possibly the most important and complex. After speaking with an application engineer at Anaheim Automation, it became clear that the back EMF may cause a problem for us. When a torque is applied to the motor shaft the back EMF can become extremely high, and this motor controller does not have a protection circuit strong enough to prevent this from damaging the electrical components. This led us to a main conclusion, we must use a gear train that allows the motor to spin the chain without spinning the pedals, and the pedals to spin the chain without spinning the motor. This brought us to the idea of using sprag clutch bearings in our drive train, which will be talked about more in the transmission section.

Figure 13: This shows an image of the selected motor and attached motor controller.

Motor Control

Figure 14 below shows the pinout of the motor controller that is integrated onto the motor already. Because of this, it doesn't show the 3 motor phases or the hall sensors on this pinout because they are already attached to the motor upon purchase. Pin 7 and 8 are the 48V power supply which will be directly connected to our battery. Pin 3 us a simple on off switch, pin 2 is an analog input to control the speed of the motor. This will serve as our method of controlling the output of the motor using sensors, like the throttle and pedal assist sensor. Pin 1 is a 5V output from the controller we can use to power our sensors and microcontroller. Finally, this is a programmable motor controller. Pins 4, 5, and 6 are representative of a RS-485 cable that can be connected to a computer to program the controller. Through the programming software supplied by Anaheim Automation, we can set the direction of the motor, range limits for analog inputs and motor speed, as well as set the control gain to get an optimal response from our motor to different inputs. This makes the motor very easy to work with and also adjustable to better fit the needs of each biker.



Controller Wiring Diagram

Position	Description
1	5 VDC Output
2	Analog Speed Input
3	RUN/STOP Input
4	RS485 B(+)
5	RS485 A(-)
6	RS485 Isolated Fround
7	Ground
8	Vin (20-50 VDC)

Figure 14: This shows the pinout of the selected motor controller

Finally, a sample wiring diagram that we can use in our system is shown in Figure 15. Most parts of the circuit are included, but some things that aren't shown are, the battery management system, any LED lights we might want to add on, and also the motor wiring, again, because the wiring is done within the motor and integrated controller assembly. As highlighted in the wiring key, red wires are power, either 48 or 5V depending on what is required by the component, black is a ground bus, and green represents a wire that transmits a signal. The motor controller is shown on the right side of the screen, with the correct pins shown as being powered, grounded, and taking in a signal. As is shown, the 5V output powers the Arduino, and also the throttle and pedal assist sensor. These two components send analog signals to the Arduino, which translates them into a single analog signal that goes to the motor controller. This is done using Arduino code that is uploaded to the Arduino microcontroller, and can be adjusted with user preference. Because the throttle has a power button on it, the run/stop pin from the motor controller is wired to the throttle. The throttle also shows the battery level, so the 48V output from the BMS will also be wired to the throttle. This simple wiring diagram shows a straightforward path to motor control using our chosen sensors. Once our motor was chosen and the control mechanism figured out, we were able to move onto necessary analysis in order to design our transmission.

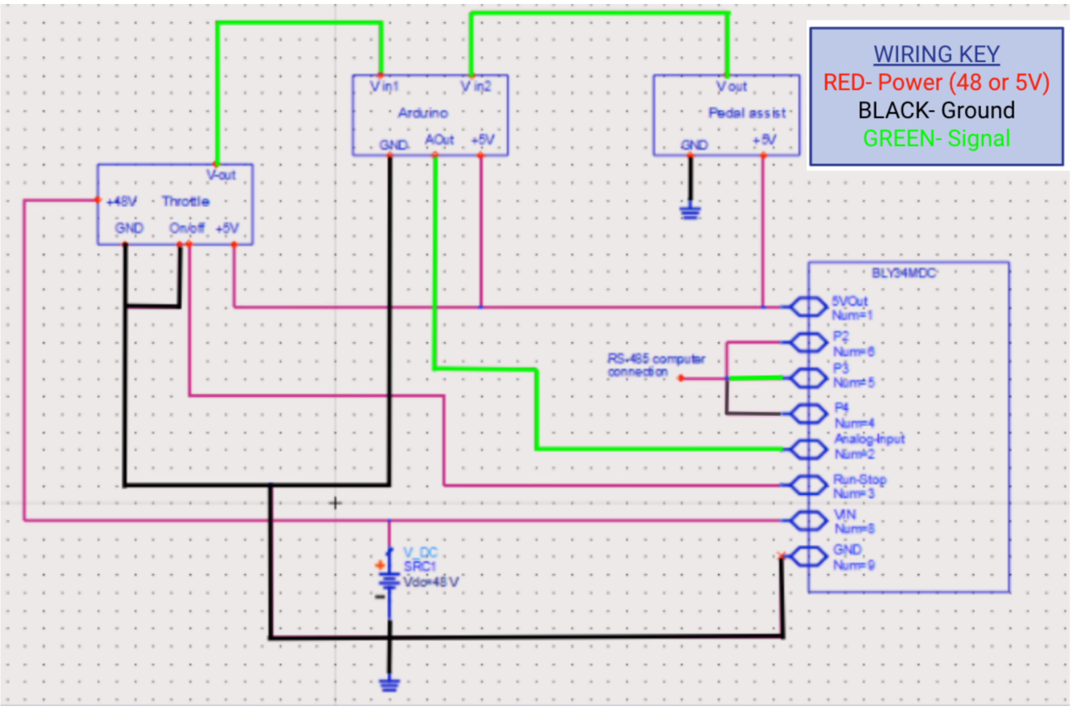


Figure 15. This figure shows the completed wiring diagram for the motor controller and sensors.

Transmission

From research into existing E-bike transmissions it was found that the most popular e bike transmissions used a two stage gear reduction either using gears and pinions transmission or a planetary gearbox and a belt drive. In addition to looking into gear reduction types we researched which types of gears would be best based on our application. We found that either a two or three stage gear reduction using pinions and gears would provide the simplest and most economical solution with helical gears being a close second because of their power transmission but ultimately cost was the deciding factor. Bevel gears were also kept in mind if motor placement were to become an issue.

The bottom bracket is important as it provides support for the crank spindle and allows it to rotate. The spindle diameter is based on the bottom bracket that is used and will need to be different for each bike. The bike that we are using to design our mod uses an older english threaded sealed cartridge bottom bracket with the spindle already attached. Because we would need to manufacture our own spindle for our mod we would need a bottom bracket that would allow us to do that. Because of that we have opted to use the english threaded GXP bottom bracket that allows for 24mm crank spindle. The figure below shows the CAD of our transmission to better illustrate our design.

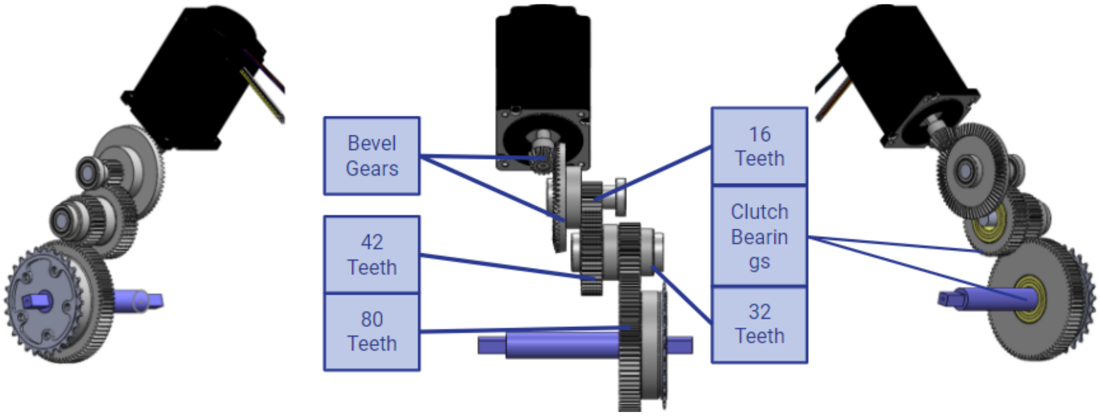


Figure 16. 30:1 three stage gear reduction. The First Stage of the transmission used bevel gears [33] to provide a gear reduction of 4:1 just as importantly the use of bevel gears allowed us to orient the motor upright to save space, without the use of bevel gears the motor would make the mod too wide and would interfere with the riders pedaling. The Second stage used spur gears [33] to give us a gear reduction of 3:1 with the use of a 16 tooth gear and a 48 tooth gear. The third and final stage also uses spur gears specifically a 32 tooth gear and 80 tooth gear to provide reduction of 2.5:1.

Another important part of our retrofit transmission system design is the incorporation of two clutch bearings. An issue we came across while designing the retrofit was the amount of back emf that would be produced by the rider, to overcome this issue we decided to add two clutch bearings. These clutch bearings would allow the rider and the motor-transmission to drive the E-bike separately. The figure below shows where the clutch bearings are located in our transmission design.

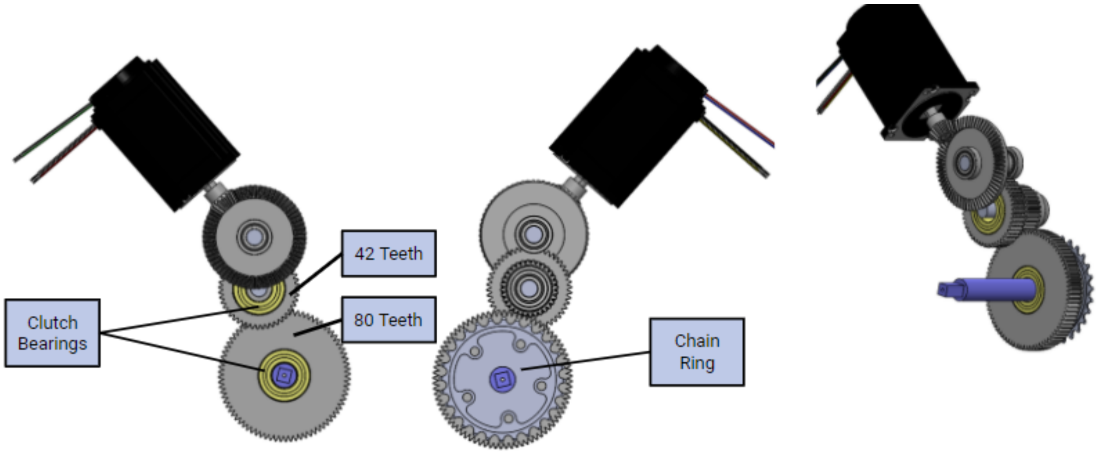


Figure 17. The clutch bearings highlighted in yellow are a solution to the back EMF issue. Clutch bearings only allow free motion in one direction, in the other direction of rotation the bearing locks and allow for torque transfer. Using clutch bearings would allow both the rider and motor to spin the spindle separately. The first clutch bearing is press fit to the 80 tooth gear allows for the rotation of the crank spindle by the cranks while the second clutch bearing placed midway through the transmission on the 42 tooth gear stops the rotation of gears in the transmission and any back emf from reaching the motor.

Battery Prototype

After we determined our motor and gearing ratio, we were able to define the specs of our power source. Starting from the Samsung INR21700-50E cells we were able to use battery cell specifications to govern the rest of the battery build. By integrating the battery and selected motor specs into our MATLAB script we were able to determine the battery dimensions to be 14 in series and 2 in parallel, or 14S2P. When accounting for resistance based voltage losses through the system's wiring leaves us squarely within the motor's 50V capacity while providing a safety factor of over 2 in order to increase cycle life.

The tac welded flatwire, or busbar, used to build the battery is nickel plated copper, in order to leverage the conductivity of copper and oxidation resistance of nickel.

A battery control system then had to be selected to provide protection to the battery, and control its cycling. The BMS is connected to the positive and negative terminals of the battery as well as each series junction. This allows the bms to levelize the charge and discharge of each parallel grouping in the battery individually. A veruzend 14S BMS was selected for its conformance to our 14S battery design as well as its well established documentation to aid in setup and operative troubleshooting.

Additionally a custom battery prototyping kit was developed and would be used to provide structure and form to the final battery build without requiring heat be applied to the lithium ion cells that could cause significant damage. An image of the selected 21700 lithium ion cell in a prototyping housing is depicted in 18 and 19 below.

Figure 18. A Samsung INR21700-50E lithium-ion battery cell in a custom prototyping housing connected to a voltmeter to test the connection of the battery to the nickel plated copper busbar via press fit housing to battery interface.

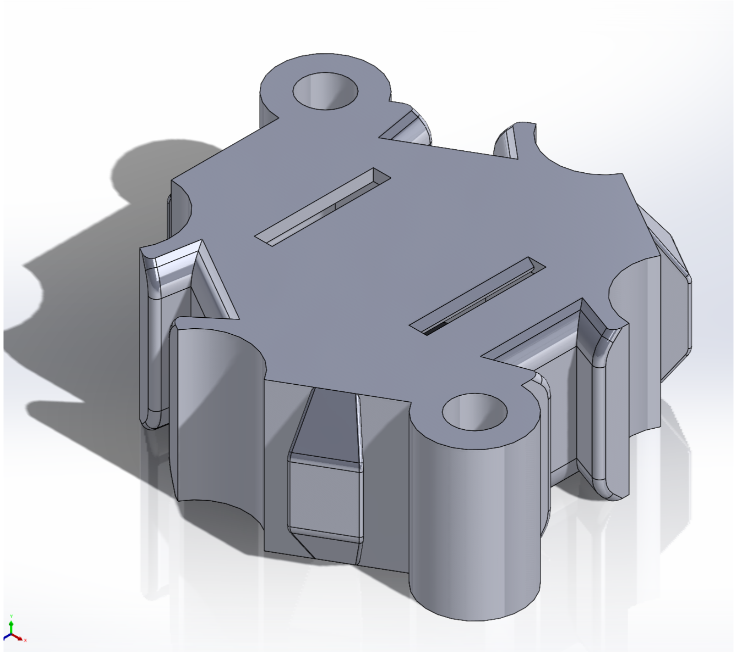


Figure 19. This shows a final, 8th iteration, 21700 cell prototyping kit cad model to better articulate the design details. The view seen here is of the exterior face of the housing. The cylindrical holes are for aluminum dowels used to provide structure and reduce potential compressive and tensile loading on the individual lithium ion cells within the battery.

When the prototyping kit is used to assemble the battery in a 14S2P fashion as described above, our final, 48V battery is complete and can be used to power our E-bike. There are a few main benefits to designing the battery this way. The first is that the battery is completely modular. This means that we can change the number of cells, orientation of the cells, and even shape of the entire battery very easily. This is great for a prototyping kit, and leaves a lot of options for changes in the future. Secondly, the battery we have designed also allows for the replacement of individual battery cells, which is not the case for almost all E-bike batteries that are sold today. This means a user could replace a few battery cells at a time if the battery life starts diminishing after many charging cycles, rather than throwing the entire battery out. This not only makes it a more cost effective solution from a users perspective, but also more sustainable than a typical lithium ion battery pack. A CAD model of the completed battery design is shown below in Figure 20.

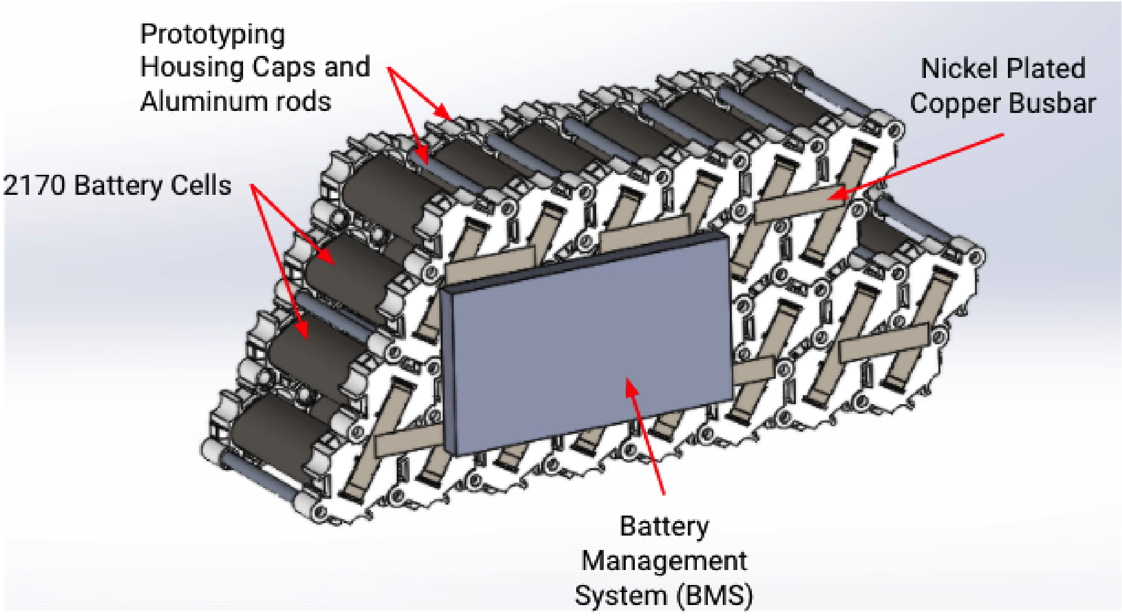


Figure 20. This shows the completed battery pack using the prototyping kit we have designed to reach the required specifications. The red lines indicate component call outs. For the sake of this model a rectangular simplification of the BMS was used to ensure geometric compliance between the battery housing and the battery assembly.

Housings and Mountings

After the design of our transmission and battery were complete, we needed to design a housing and mounting for both systems. These were designed sequentially to allow the housings and mounting systems to fit together on the bicycle frame. First, the housing for the battery was designed. For our prototype housings, we intend these to be 3D printed with PETG plastic. This allowed us to make them complex shapes that conformed with the bike frame well. The battery housing is shown in Figure 21. The housing consists of two pieces, a main casing and a hinged lid that latches closed once the battery is slid inside the casing. Also included in the design is a high density foam to hold the battery in place, as well as a rubber gasket at the seal between the two pieces to better weatherproof the housing. It has a semicircle shaped extrusion that allows it to be placed easily on the bike frame. This will also have rubber elastic straps (not shown in the CAD) that tightly wrap around the bicycle tube to help secure the battery to the bike. The final component of the battery housing is the snap fit electrical interface, shown on the top of the image in Figure X. This interfaces with the female side of the snap fit which is on the transmission housing. This allows all of the electrical connections that need to be made between the battery and the Arduino and motor controller in the transmission housing to be made in a single interface. This housing design not only for the battery to be removed from the bike so that it can be charged, but also for the battery pack to be removed from the housing so that the battery pack can be serviced when necessary.

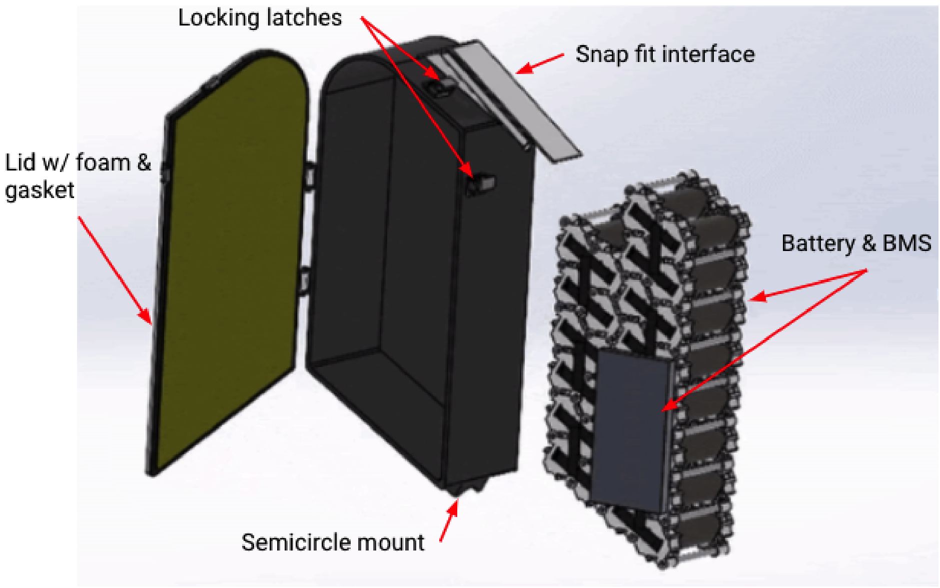


Figure 21. This shows a CAD model of the battery housing.

The transmission housing is shown below in Figure 22. As previously stated this housing would be 3D printed to allow for a more complex shape using PETG for its increased strength. The housing consists of two separate pieces that are bolted together to completely enclose our three staged transmission and vertically positioned motor. The inside of the transmission housing has enough clearance to allow the gears to spin freely with indentations to have the bearings pressed into the housing. The motor is also supported by the housing with an extrusion that distributes the motors weight equally on both sides of the housing. The outside of the housing has a unique shape to both minimize the amount of material used for the housing and to fit into the frame of the bike without any clearance issues. The amount of hard corners was also minimized through fillets to increase the housings strength. The housing also has fillets on each side of the housing for added support to the battery along with the female piece of the snap fit interface.

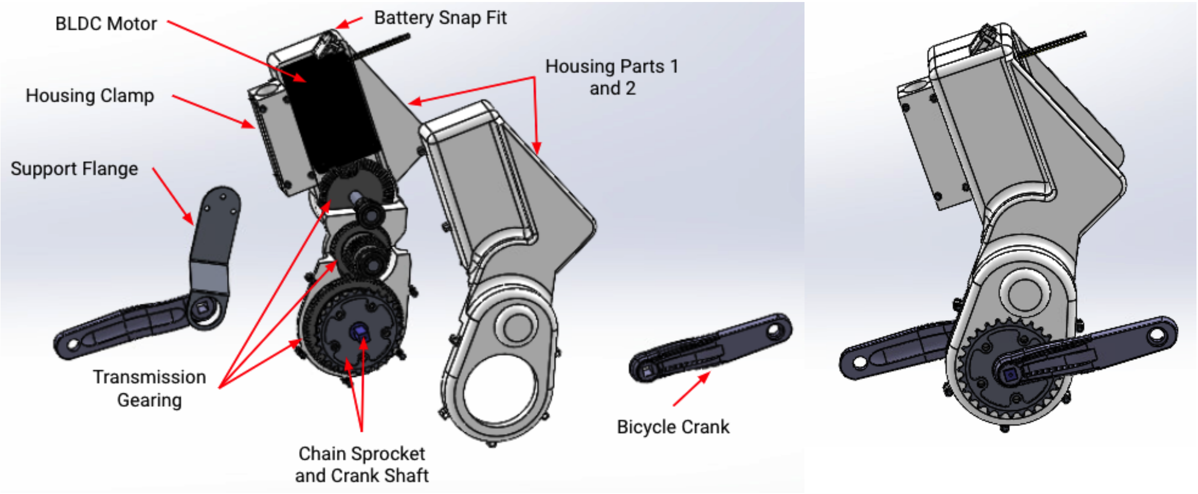


Figure 22. This figure shows an exploded view of the transmission housing, as well as an assembled view.

These two pieces, the battery housing and the transmission housing, mount together on the bicycle frame. Figure 23 below shows the housings secured onto the frame. The assembly process is relatively simple and should be able to be done fairly quickly and with minimal mechanical knowledge.

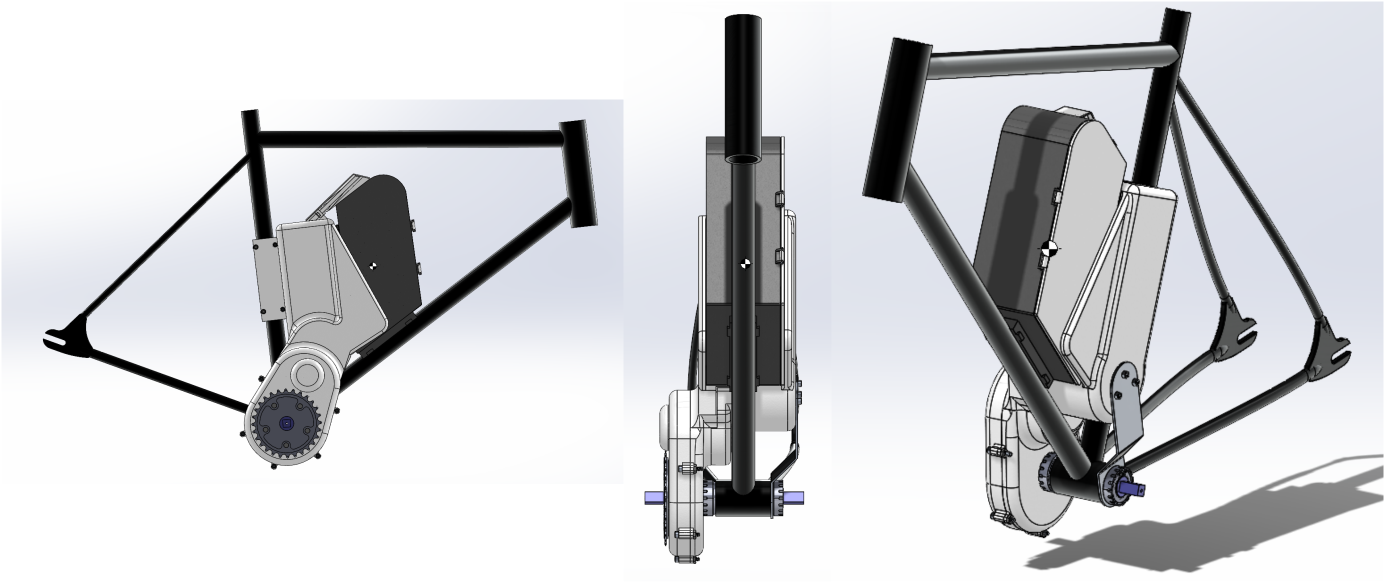


Figure 23. The screencaptures above are 3 views of a completed assembly onto a bike frame without the seat, tires, handlebars, or drive train. The assembly process consists of sliding the crankshaft and housing assembly into the bottom bracket of the bicycle frame, screwing together the housing clamp connected to the housing, attaching the support flange from the housing to the crankshaft, and finally, sliding in and securing the battery and battery housing assembly. An animation of this assembly process can be seen in Appendix C.1.

The final assembly above shows the completed design for the motor, transmission, battery, and mounting for the E-bike retrofit kit. This will interface with the other components of the design not shown, such as the thumb throttle mounted on the handlebars, and the pedal assist sensor located on the crank and crankshaft. These will interface with the design shown above electrically, using the wiring diagram illustrated and the manner described above in the Motor Control section. A final Bill of Materials and cost estimation for our single E-bike retrofit kit can be found in Appendix C.2.

Analysis and Verification

In the original process of designing a retrofit, we conducted multiple points of in depth analysis. Through the construction of a matlab model, conduction of secondary research, 3D CAD modeling, and physical testing, we were able to complete the analytical decision making and preliminary verification necessary to validate our retrofit design. This began from disparate theory-based calculations and concluded with the construction of a MATLAB script which is capable of outputting key multi-step calculations to approximate the retrofit's performance and adherence to the retrofit's design specifications. This code would also output an ideal gear ratio for the transmission system design, based on specifications and motor selection, which informed a 3D CAD transmission assembly.

After conducting the necessary analysis to construct our retrofit and communication website we continued the use of the Matlab Script and detailed CAD model along with secondary research and physical testing to preliminarily verify the effectiveness and general success of the project outcomes.

MATLAB Model

Building off of the drive system calculations described in technical analysis, we found that feedback loops necessarily exist between equation inputs and outputs. In analyzing the built system of equations, we realized that the gearing ratio, which is determined by the hill climb specifications, defines the speed of the theoretical hill climb. However, the gearing ratio is also based on the selected motor specifications, which changes the relative wind speed. Changing the wind speed changes the required torque which changes the gearing ratio. This change in gearing ratio signals the repetition of this looping cycle until hill climb speed and bike velocity converge to the same value. This relationship can be seen in the confluence of Equations 1 through 4 with equations 5 and 6 below.

$$G_m = T_L / T_{m,max} \qquad \text{(Eqn. 5)}$$

$$v_{Bike} = \frac{\omega_o \cdot G_B \cdot 2 \cdot R_B \cdot \pi}{G_m \cdot 60} \cdot 2.237 \qquad \text{(Eqn. 6)}$$

Here Z_m represents the gearing ratio. $T_{m,max}$ is the maximum continuous torque of the selected motor in Nm. v_{Bike} is the bike velocity in mph. ω_o is the motor speed at the motor's maximum continuous torque rating in rpm. R_B is the bikes rear wheel radius in m. G_b is the bike's sprocket ratio when in its lowest gear. Because T_L is dependent on relative wind speed, as seen from the aggregation of equations 4, 3, and 2, it is possible for the equation set to output a value for v_{Bike} which is different from that of the inputted bike velocity, $v_{Bike,o}$. This is unrealistic because this indicates that the bike is not actually travelling at the speed the user input into the equation set. $v_{Bike,o}$ is then updated to the previously output v_{Bike} value and the equation set is run again until the difference between $v_{Bike,o}$ and v_{Bike} is approximately zero. Upon convergence, the final G_m is the required motor transmission gear ratio for the bike to be able to climb the hill.

To validate the transmission ratio research was conducted on the transmission ratios used in other E-bikes that already exist in the market. From the research it was found that the transmission ratios were within the range of 18:1 to 45.8:1. From this research we concluded that our transmission ratio fit well with that range and that we would be able to use it in our retrofit. The table below summarizes the results of the research into E-bike transmission ratio and gear stages.

Table 1. Summary of research into transmission ratios and gear stages of popular E-bike transmission in the market. The table includes the name of the transmission, the total gear reduction, the number of stages in the transmission and the type of gear reduction used in each gear stage.

E-bike Transmission Market Options

Model Name	Final Ratio	Primary Reduction	Secondary Reduction	Tertiary Reduction
Yamaha PW	45.8:1	Pinion-Gear	Pinion-Gear	N/A
TQ Drive	37:1	Proprietary single-stage harmonic drive transmission	N/A	N/A
BROSE	30:1	Planetary Gear	Belt Drive	N/A
SHIMANO STEPS	Unknown	Pinion-Gear	Pinion-Gear	Pinion-Gear
BAFANG BBSHD	21.9:1	Pinion-Gear	Pinion-Gear	N/A
BOSCH	7.2:1	Pinion-Gear	Pinion-Gear	N/A

The transmission had to be further preliminarily verified against the flat ground no pedal velocity specification benchmark of a minimum of 10 mph. Because the flat ground distance specification was established in riding both to and from a location, the true wind speed can be set to zero making the relative wind speed the only factor affecting torque. Inputting a ø value of 0° and a $v_{w,true}$ value 0 mph we can determine the flat ground T_L from equations 1 through 4. With an updated T_L value we can now calculate flat ground torque and subsequent flatground speed for the given motor and transmission using Equation 7 below followed by Equation 6 above.

$$T_m = T_L / G_m \tag{Eqn. 7}$$

Equation 7 is simply a reconfiguration of Equation 5 in which T_L and G_m are used to calculate the applied torque on the motor when traveling on flat ground. The new T_m is used, in congruence with the selected motor's torque speed curve, to identify the flat ground motor angular velocity in rpm (ω_o).

In confluence with the selected motor's torque speed curve, we can then estimate the flat ground travel speed of the bike to evaluate it against the desired flat ground no pedal speed defined in a build's user specifications. If the output flatground speed is slower than the user's specified, desired, flatground, no pedal speed, the selected motor is not powerful enough. This indicates the need to select a motor with a higher power and torque rating. In the case of our example specifications the 30:1 transmission ratio needed for hill climbing using a BLY34MDC3S motor would produce a flatground speed of 10.6mph which is greater than the 10mph of the specified flat ground speed. This acted as preliminary verification of the motor and transmission design.

Using the newly defined flat ground speed and selected motor specifications, the number of battery parallel and series groups can be defined using Equation 8 and Equations 9 through 11, respectively.

$$S = V_m / V_b \quad \text{(Eqn. 8)}$$

$$P_i = \frac{x_{flat} \cdot i_{m,\,flat}}{V_{Bike,\,flat} \cdot q_{rated}} \quad \text{(Eqn. 9)}$$

$$P_{ii} = \frac{x_{climb} \cdot i_{m,climb}}{V_{Bike,\,flat} \cdot q_{rated}} \quad \text{(Eqn. 10)}$$

$$P_{iii} = i_{m,max} / i_{cell} \quad \text{(Eqn. 11)}$$

Here, S represents the battery build number of series groups. V_m represents motor rated voltage in volts. V_b battery cell rated voltage volts. P represents the battery build number of parallel groups. x represents the distance to be traveled in miles, either flat ground or climb. i_m is the motor's required input current in amps. v_{Bike} is the convergently calculated bike velocity of the given scenario in mph. q_{rated} is the amp hour rating of the selected battery cell. $i_{m,max}$ is the maximum rated current draw of the motor. i_{cell} is the maximum rated current of the selected battery cell. Each P value should be rounded up to the nearest positive integer and can then be compared to one another. The largest of P_i, P_{ii}, and P_{iii} should be used as the final battery build parallel count. For further optimization of battery cycle life, an additional safety factor may be applied to the P value calculation. Thus, the percent charge of the full range of every battery charge-discharge cycle may be reduced, which would increase theoretical battery cycle life [34]. This model not only acted as analysis, but was also used as verification as each P value corresponds to a different specification or expected functional limit of the designed retrofit. Based on the specifications defined in *Retrofit Kit Requirements and Specifications*, our analysis and verification model output a minimum parallel grouping of one applying an additional safety factor of two to in order to increase the potential single charge and cycle life of the battery.

To ease the analytical and verification processes described above, Equations 1 through 11 were built into a single MATLAB code. This code takes inputs including user defined performance specifications (such as the maximum incline, the maximum weight, and the desired flat ground no pedal speed), the specifications of the selected motor (such as the continuous torque rating, the rated power, the torque speed curve at max voltage, and the motor torque current ratio), the battery cell specifications (such as the Ah rating, the rated amperage, the voltage rating) and the dimensions of the bike and rider. This code produces a conservative motor to crankshaft transmission ratio as well as verification of whether the motor can meet the defined flat ground specification. The script in its earliest form can be seen in Appendix C.3.

CAD

A CAD design of the retrofit which includes the transmission, motor, housings, cranks, bottom bracket, was made in order to find estimations of different design components. The most important were an approximation of the Center of Gravity (CoG) of the design and the approximate weight of the retrofit. The CoG is an important aspect of the design in order to keep the rider safe as an unfavorable CoG would affect the rider. Figure 24 below illustrates where the CoG for our retrofit was approximated using our SolidWorks CAD model.

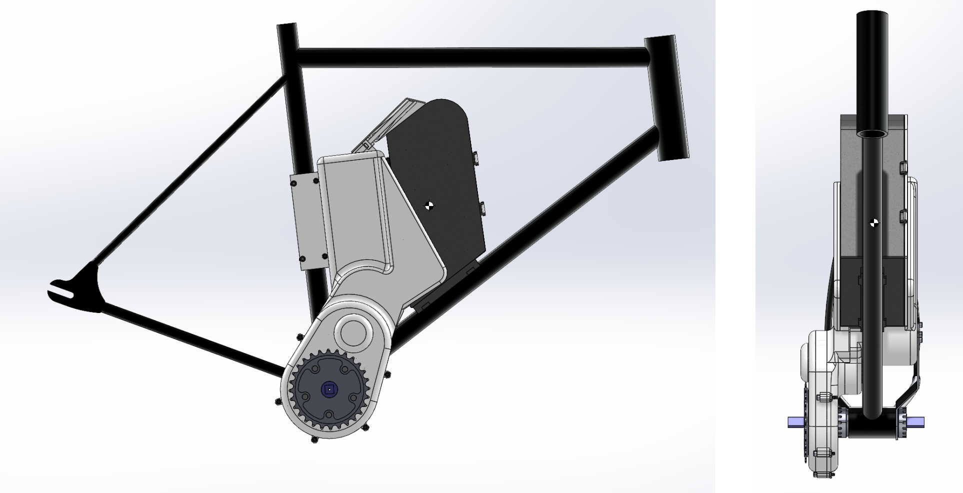
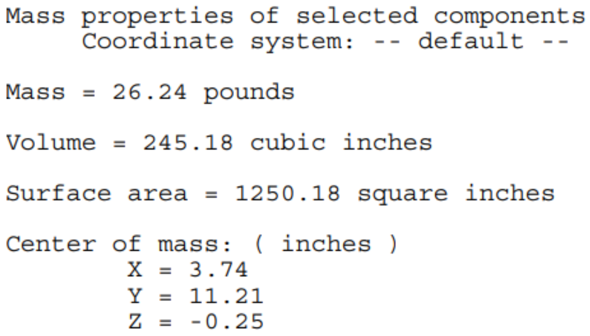


Figure 24. COG of the designed retrofit is marked by the checkered circle. As you can see the COG is relatively centered within the frame of the bike though shifted slightly up from where it was before the retrofit is attached. It is worth noting the COG will likely shift slightly forward and down as the remaining frame component's masses are accounted for.

To Validate that our model would meet the requirements and specifications that had been set for the center of gravity (COG) and weight of the retrofit we implemented the use of SolidWorks to approximate these values. By setting the material for each component of our retrofit we were able to use Solidworks weight analysis tool to approximate the weight of our retrofit. From the weight analysis tool the weight of the retrofit was approximated to be 30 lbs which is within the requirement that we had set. Solidworks also allowed us to find the COG of the retrofit, the figure below shows that the COG for our retrofit is within the bike frame. Having the COG within the bike frame meets the requirement we had set as having the COG outside the bike frame would be unsafe for the rider. The use of CAD software allowed us to find approximations for the weight and COG although these results are only approximations and carry with them some uncertainty. We were able to set the material properties for each component of the retrofit but those properties are not exact, for example the transmission housing is a significant source of weight but solidworks assumes the housing is a solid when in reality it is hollow which reduces the weight and changes our approximations. While the approximations made using Solidworks are not exact they do give us useful information on the weight of the retrofit and the location of the COG.

Another point of validation that we were able to get from the SolidWorks model is the weight approximation. Our E-bike retrofit specs have a weight requirement in order to minimize the weight that we would add to a potential user's bike. The solidworks model provided a good approximation for the weight of the retrofit design not including the battery. We found that the weight was approximately 30lbs. Figure 25 below shows all the information we gathered from this mass/weight analysis.



```
Mass properties of selected components
     Coordinate system: -- default --

Mass = 26.24 pounds

Volume = 245.18 cubic inches

Surface area = 1250.18 square inches

Center of mass: ( inches )
        X = 3.74
        Y = 11.21
        Z = -0.25
```

Figure 25. Weight Analysis using SolidWorks

In communicating our project CAD files will be provided to website users to enable them to design their own transmission from which they can find the center of gravity of their design. Beginning with the drive system analysis, which took into account the bike's speed, wind speed, weight, and incline angle, a transmission ratio was calculated. With this transmission ratio, the CAD files could be used to design a transmission with the necessary gear reduction which can be mounted onto the bike. Our CAD files will provide an example of what the fully designed transmission would look like once the motor and gear ratio are determined. Our fully designed CAD transmission assembly can be found in Appendix C6. With the user now having a fully designed transmission CAD assembly they would use it to find the center of gravity of the DIY retrofit. The center of gravity would then inform the user's safety considerations.

Physical testing

Three key subsystem functionality points were preliminarily verified using physical testing based on their compatibility with readily available manufacturing tools, primarily 3D printing.

The first subsystem to be functionally verified through physical testing was the power delivery subsystem. In order to easily and iteratively prototype a custom 21700 lithium ion battery we needed to design a custom 2170 cell prototyping kit. Based on existing 18650 prototyping kits a hexagonal cell was iteratively designed and tested for each housing's ability to interface with one another and interface with a respective battery cell. After successfully achieving those two functions a third test was run to verify if the noncommittal electrical interface could function as intended. An image of the voltmeter testing is shown in Figure X of the battery prototyping section.

The second functional feature that was preliminarily verified through physical testing is the tensile and material properties of 3D printed pETG components. In order to verify the functionality of the battery to motor housing buckle interface we drilled a hole near the center axis of the male component to which a tension force gauge was connected. With one team member holding the female housing another member pulled on the force gauge noting the maximum tensile force applied. A depiction of the test can be seen in Figure 26 below.

Figure 26. This figure shows a graphic representation of the tensile test conducted on the housing electrical interfacing components. The male buckle is mounted to the end of the tensile force gage connected to the female buckle grounded by a sufficient counter force. The close ups depict the max tension tested as well as a detail of the clasping arms of the buckle.

Given the testing constraints of not possessing proper equipment to run the ideal experiments testing was concluded after one trial noting the two 0.04 in thick buckle prongs showed no signs of critical failure under this loading. In order to achieve full validation we would need multiple trials verifying the tensile strength at maximum acceleration magnitude. Preliminary the 35lb trial is considered successful as the battery weighs well under this benchmark and the actual tensile forces will be mitigated by gravity as well based on the geometric configuration of the final model visible in Figure 24.

This second test also acted as preliminary verification of the sheer strength and resistance to bending moment failure of the 3D printing material as the thickness and relative geometric strength of the buckle prongs are less than half that of the next finest 3D printed retrofit component.

DESIGN COMMUNICATION

Our team discussed possible ways to better address the intended user’s need for an accessible tool which educates and encourages them to use an E-bike as a primary method of commuting. As outlined in the Education and Engagement sections through the Concept Generation and Solution Development sections of the report, we decided producing a website prototype would be the most socially engaged method to present the information we have collected through the development of our E-bike retrofit kit. This format was deemed the most accessible and had the most potential for environmental cost minimization, and still allows for diverse media options including both static text imagery and video capabilities. To ensure that we would meet the stakeholders requirements for this design, we developed a new set of requirements and specifications for the website, this time focusing on a larger, more broad subset of our identified stakeholders. These are outlined below. To determine specifications, we first brainstormed requirements. These included that the website be easy to navigate and approachable, comprehensive, succinct and easy to digest, and sustainable. We then populated quantifiable and verifiable specifications under each of these requirements as follows:

Easy to navigate and approachable - movement based

For users navigating through our website prototype, we have set the requirement that the website is easy to navigate and is approachable. The specifications derived from this requirement ensure that a user can move through the website structure without confusion and while being drawn into the content. The specifications for this requirement are:

- *Website includes clear hierarchical structure*
- *Website design includes less than or equal to 5 headers per page*
- *All buttons and website outline components feature boldface*
- *Website uses triad or adjacent tool of Paletton Live Colorizer tools to select color palette* [36]
- *Links to subsequent pages will not bring you to previously-visited pages*

Comprehensive

We have set a requirement for our website to be comprehensive. This means that the website content will be constructed in a way that does not require the user to do additional research before selecting an E-bike or retrofit option. The specifications that accompany this requirement are:

- *Includes information for "rules of the road" for all 50 states*
- *All necessary information for the included E-bike and E-bike retrofit devices will be included either on the site or in links to secondary sources, no external internet searches will be necessary*
- *Include at least 3 retrofit device options*
- *Include at least 3 E-bike options*

Succinct and easy to digest

For the user to easily understand technical content, there has been a requirement for the website content to be succinct and easy to digest. For this to be accomplished, the content must be adequately simplified and incorporate a format that is not overwhelming. The specifications for this requirement are:

- *Content has, at most, an 8th-grade reading level based on the Flesch-Kincaid grade-level index* [37]
- *Content has a 1:2 surface area ratio of images to blocks of text*
- *Includes a page defining all applicable technical jargon*
- *Each page introduces, at maximum, 5 new concepts or terms*

Sustainable

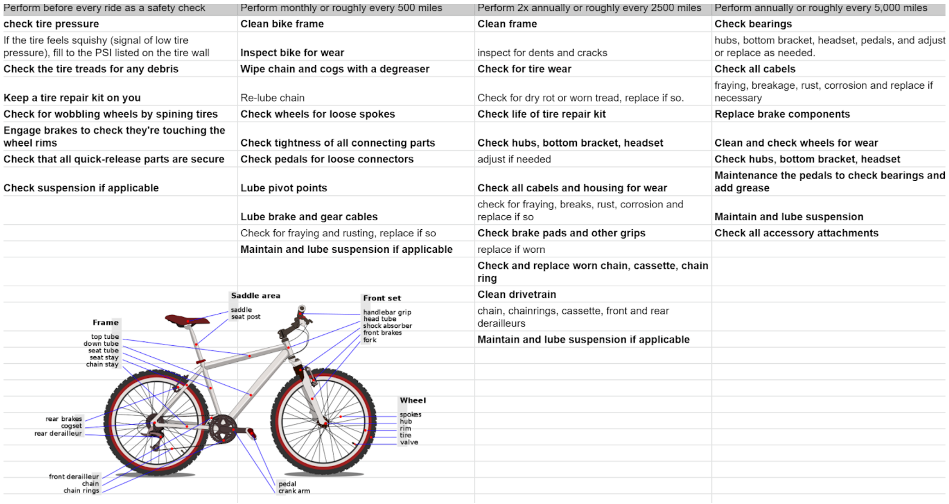
Our team has identified the requirement that the website be sustainable - both environmentally and socially. We recognize that some of these specifications are unable to be met by our prototype website design using the platform Wix; however, we intend to incorporate all specifications in a post-prototype website production scenario.

- *Minimize dark background to reduce energy footprint of website*
- *Include text summaries of all figures*
- *All content can be updated by site developers*

- *Animations will cycle for, at most, one loop without being further prompted by the user*
- *Post-prototype design must align with the Sustainable Web Manifesto* [38]

The first step in realizing this new objective was establishing outlines and wireframes for the website content and user flow through said content. Our current outline is broken up into six sections: Designing/Selecting your optimal E-bike, setting up your E-bike, maintaining your bike and E-bike, EOL considerations, general knowledge, and customization and further steps. Envisioning a linear user flow experience, we outlined what we imagined to be one of the most important pages; designing/selecting your optimal E-bike. Modeled directly from our own original retrofit design process, the page would take users through defining their own requirements and specifications as well as constraints. They could choose to explore either the purchase of a new E-bike or a complete retrofit kit, or they could choose to DIY their own retrofit. As the primary landing page for the site, this process will also lead users through however much or however little technical knowledge they may desire by linking to and from the other five website sections. The final objective is to allow users to visit a single site that can connect them to all of the information they might need in a predefined sequence. This will make the process as user friendly and engaging as possible. An outline of the design/selection process page can be seen in Appendix D. Each of the other five website sections will be similarly outlined.

To further develop the preliminary website solution, our team began researching scientific literature supporting our brainstormed website content. Based on our findings, we began the process of decomposing it into user-friendly guides that succinctly convey important information. Figure 27 shows an example of a simplified bike maintenance guide based on lifetime bike performance and maintenance research. This guide also includes a bike anatomy diagram to help beginners understand where key parts are located and what their technical names are.



Perform before every ride as a safety check	Perform monthly or roughly every 500 miles	Perform 2x annually or roughly every 2500 miles	Perform annually or roughly every 5,000 miles
check tire pressure	**Clean bike frame**	**Clean frame**	**Check bearings**
If the tire feels squishy (signal of low tire pressure), fill to the PSI listed on the tire wall	**Inspect bike for wear**	inspect for dents and cracks	hubs, bottom bracket, headset, pedals, and adjust or replace as needed.
Check the tire treads for any debris	**Wipe chain and cogs with a degreaser**	**Check for tire wear**	**Check all cabels**
Keep a tire repair kit on you	Re-lube chain	Check for dry rot or worn tread, replace if so.	fraying, breakage, rust, corrosion and replace if necessary
Check for wobbling wheels by spining tires	**Check wheels for loose spokes**	**Check life of tire repair kit**	**Replace brake components**
Engage brakes to check they're touching the wheel rims	**Check tightness of all connecting parts**	**Check hubs, bottom bracket, headset**	**Clean and check wheels for wear**
Check that all quick-release parts are secure	**Check pedals for loose connectors**	adjust if needed	**Check hubs, bottom bracket, headset**
Check suspension if applicable	**Lube pivot points**	**Check all cabels and housing for wear**	**Maintenance the pedals to check bearings and add grease**
	Lube brake and gear cables	check for fraying, breaks, rust, corrosion and replace if so	**Maintain and lube suspension**
	Check for fraying and rusting, replace if so	**Check brake pads and other grips**	**Check all accessory attachments**
	Maintain and lube suspension if applicable	replace if worn	
		Check and replace worn chain, cassette, chain ring	
		Clean drivetrain	
		chain, chainrings, cassette, front and rear derailleurs	
		Maintain and lube suspension if applicable	

Figure 27. Simplified bike maintenance guide and bike anatomy diagram as will be included in website deliverable.

After laying out the envisioned pages of our site in separate documents, we compiled them onto a Wix website titled “E-BIKE ACCESSIBILITY AND ENGAGEMENT”. The home page includes images of bikes and E-bikes along with an enticing line to excite the user about accessing an E-bike. It also includes our mission statement which reads, “We aim to provide you with access to a low-cost, low-waste, and easily accessible E-bike regardless of your mechanical ability and budget. We want to help you incorporate an E-bike into your daily transportation”. After reading the mission statement, the reader can click the link to “Get Started” which will take them to the “General Knowledge” page of the website. Each page of the website can be found in a drop-down menu as seen in Figure 28.

Figure 28. Wix website header for all pages which includes the website title and a drop-down menu to access all site pages.

Each page you access has a link to the next relevant page. The “General Knowledge” page explains bike anatomy and introductory motor and battery background knowledge so that users with minimal mechanical knowledge will completely understand this page and be prepared for references in subsequent pages. From here the user will be prompted to go to the “Selection & Design” page which will walk them through evaluation criteria to explain the differences between choosing to purchase an E-bike, an E-bike mid-drive retrofit, an E-bike hub-drive retrofit, an E-bike friction drive retrofit, or creating a DIY retrofit kit. The evaluation criteria on this page include price, quality, usability, sustainability, and customizability. After reading through the bulleted and image-accompanied evaluation criteria, the user can select to either access an E-bike, which will take them to an E-bike selection page and subsequently an E-bike setup page, or access an E-bike retrofit device. The option to access an E-bike retrofit will take them to a retrofit-focused evaluation page, and from here the user can select to either purchase or DIY a retrofit device.

In the “Design Your Own E-bike Retrofit” page, we take the user through the process we followed to create our retrofit prototype. We first indicate that the key focus areas of the design include the battery, the motor, the transmission, and the housing/mounting. The “Battery DIY” section, we explain the process for creating a modular battery for your E-bike using either 18650 lithium ion cells and a purchased kit from vruzend.com which is linked on the page, or using 21700 lithium ion cells and 3D printed pieces which this website section will house the CAD files for. Then, the “Motor Selection” section explains how to read a torque speed curve and use it in tandem with our Matlab script which will also be housed on this section. The “Transmission” section explains gearing, how to calculate gear ratios between sets of multiple gears to match the gear ratio which is an output of the Matlab code, and links McMasterCarr’s website as one means of purchasing gears. Finally, the “Housing/Mounting” recommends using Solidworks or another CAD software to model a housing which is suitable for their design and bike, but it also will link to our full CAD for our prototype which includes all of our own housing/mounting design. We are still in the process of building out this page further to be more accessible, but at this point we have geared this page toward an audience which already has experience with mechanical design.

Then, the user will be taken to a subsequent retrofit setup page. Setup pages include images and links to videos for setting up each type of device. After making their selections and learning how to set up their devices, the user will be taken to maintenance pages which use images and videos to explain regular, monthly, bi-annual, and annual maintenance techniques. The end of the “Maintenance” section will link the user to a “Safety Guides” section which will use images and videos to explain safety during setup and use of the E-bike as well as fire safety. The end of the “Safety Guides" section will link the user to an end-of-life “Recycling” section. Then, subsequently the user will be linked to a “Customization” section where further hobbyist E-bike customizations will be highlighted. The final section on our website is a “Watch” section where users can access all of the video content on the website.

Website Verification

To ensure that our website achieves its goal of educating users in an easily accessible way, we checked that the site met our original requirements and specifications, and then we tested it against established educational website guidelines. These guidelines were drawn from the Nielsen Norman Group [39], the US Department of Education [40], National Institutes of Health Web-Based Learning Guide [41], and 3 Media Web blog posts [42]. Table 2 indicates our progress on our compiled verification checklist.

Table 2. Compiled list of established educational website guideline verification tasks and their status.

Educational Website Guideline Verification Tasks

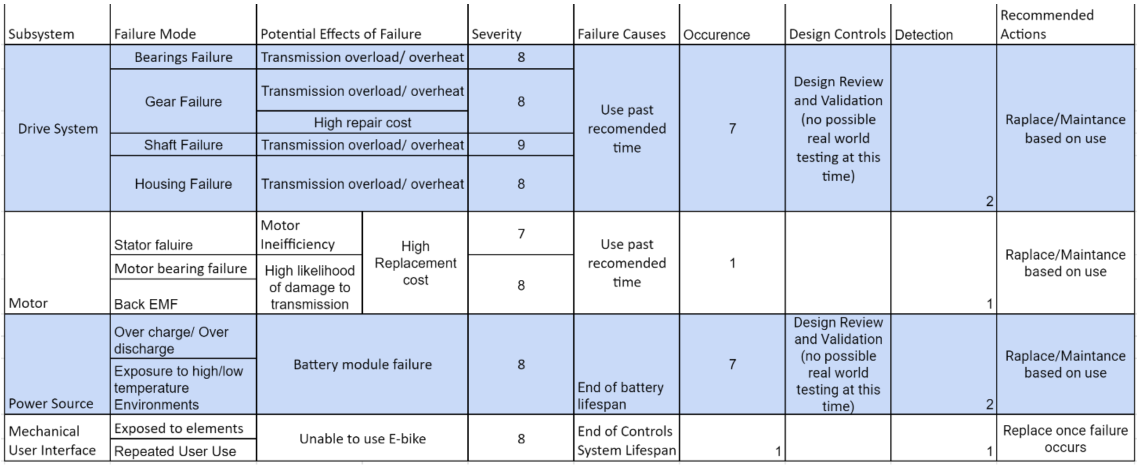
Task	Status
Perform a needs analysis and specify goals and objectives	Done
Evaluate pre-existing software and use it if it fully meets your needs	In Progress
Minimize the number of clicks on the site	In Progress
Create a path forward	Done
Include a search bar	Not Achievable
Consider your target audience - incorporate humor, formality, respectfulness, and enthusiasm in your tone	Done
Make certain the information you present is correct, complete, and up to date	Done
Design the site to present the most important information up front and center	Done
Use photos to demonstrate the experience is a "must-do" on your website	Done
Develop consistency across pages, even those with distinctly different audiences	Done
Before constructing a site, so a careful search of what is on the web already	Done
Do not alter file names after posting them on your site	In Progress
Have your education site page load in ≤ 3 seconds	Done
Optimize all videos, graphics, images	Done
Minimize the number of plug-ins your site uses	Done
Ask for feedback	Done
Use Nielsen Norman Group's 4 S's to improve link accessibility	Done
Use meta tags & bulleted lists wherever possible	Done
Provide text alternatives to images and graphics	In Progress
Provide high contrast to allow accessibility for visually impaired users	Done
Provide a simplified version of the website	Not Achievable
Provide a mobile version of the website	Not Achievable
Do not use flashing graphics	Done
Enable keyboard support	Done
Include ARIA Landmarks	Done
Use US Department of Education Style Guide	In Progress

As we built our website, using a Wix website building tool, we considered each of these guidelines and updated the color of their status accordingly. The most important verification technique we used was clearly defining our audience for the website. While the goal of our website is for visitors to end up with an E-bike, we cannot necessarily accommodate or target customers who would not have the time or money needed to invest in acquiring an E-bike. Therefore, we defined our audience as "People in the age range of 14-60 years old who do not already have extensive knowledge about E-bikes, who regularly travel distances of less than 15 miles by themselves, and who would be willing to invest more than 6 hours and more than $300 into accessing an E-bike". We did qualify that our DIY and Customization website pages could be targeted toward an audience who does have some making/machining experience. From here, we considered the US Department of Education's Website Simplicity guidelines to replace block text with bullets and images where appropriate. At this point, all of our verification checks have been considered, but as our website will continue to be built out over time, some checks need to be continually considered and are left highlighted as "needs attention". While the Wix website format provides many built in accessibility features such as meta tags and ARIA Landmarks, it does not interface easily with search bars or mobile website conversion. Therefore, these verification tasks are left highlighted as "likely not achievable".

Risk Assessment

As E-bikes are meant to be reliable forms of transportation, risk assessment of our design was important. This risk assessment included the failure mode of each subsystem of our E-bike along with the potential effects, severity, causes and the occurrence of failure. A summary of the retrofits risk assessment can be found in the design FMEA table below.

Table 3. Design FMEA table which summarizes the possible modes of failure for the most critical subsystems of the E-bike retrofit.



Subsystem	Failure Mode	Potential Effects of Failure	Severity	Failure Causes	Occurence	Design Controls	Detection	Recommended Actions
Drive System	Bearings Failure	Transmission overload/ overheat	8	Use past recomended time	7	Design Review and Validation (no possible real world testing at this time)	2	Raplace/Maintance based on use
	Gear Failure	Transmission overload/ overheat High repair cost	8					
	Shaft Failure	Transmission overload/ overheat	9					
	Housing Failure	Transmission overload/ overheat	8					
Motor	Stator faluire	Motor Ineifficiency High Replacement cost	7	Use past recomended time	1		1	Raplace/Maintance based on use
	Motor bearing failure	High likelihood of damage to transmission	8					
	Back EMF							
Power Source	Over charge/ Over discharge	Battery module failure	8	End of battery lifespan	7	Design Review and Validation (no possible real world testing at this time)	2	Raplace/Maintance based on use
	Exposure to high/low temperature Environments							
Mechanical User Interface	Exposed to elements	Unable to use E-bike	8	End of Controls System Lifespan	1		1	Replace once failure occurs
	Repeated User Use							

The important takeaways from the risk assessment is that within our transmission design the largest amount of risk is with the bearings that have a lower cycle life compared to the other components of the E-bike. As the bearings are part of the transmission subsystem that drives the ebike the failure of this substsem could be costly and more importantly dangerous for the user. To avoid this mode of failure the transmission housing was designed to be easily taken apart for any necessary maintenance along with safety guides that educate the user when certain components of the transmission should be maintained or replaced. For the E-bikes motor the largest source of failure would be continued use once it has reached the end of its lifespan. To accommodate for this mode of failure a motor that would meet our distance requirements, these requirements can be found in Appendix A. For the battery the largest source of risk is with one of the modules failing from overcharging or undercharging. This risk was addressed by designing a battery housing that allows for easy access to the battery and a battery design that allows the user to replace whichevery part of the battery has failed. Finally the risk assessment found that the failure of the mechanical user interface, throttle and pedal assist, would happen from exposure to the elements and from repeated user use. This possible mode of failure was addressed by designing the retrofit to allow for easy replacement of these parts. It is important to note that all of the proposed solutions to possible failure of our most critical subsystems were verified using models and partial physical testing and are at acceptable levels. We recommend that failure tests be done on each of the components.

DISCUSSION AND RECOMMENDATIONS

With the completion of our project, we have accomplished a few things. First, we have completed the design for a single E-bike retrofit kit. Secondly, we have developed an informational website meant to make E-biking more accessible to the greatest number of people using what we have learned from the design process. We believe that this is a robust solution to the problem that was posed to our team.

There are a number of critiques we can make about our final design, especially focusing on the prototype. When we began this project, we had hoped to make the E-bike retrofit design functional with as many bicycles as possible. We quickly realized that designing within this constraint was quite difficult. Because of this, we ended up focusing our design on a retrofit which is specific to a single bicycle, particularly one with very common attributes. We realize that this definitely makes our retrofit design less valuable. However, during our design process, we tried to make design decisions that would allow for a large amount of adjustability with the retrofit. For example, the angle at which the transmission is mounted can be changed for different bicycles, and the battery that snaps into the transmission housing is only mounted using rubber straps. This allows for minor adjustments, but ultimately widens the range of bicycles our retrofit kit can be applied to.

Other aspects of the design can be improved as well. The motor that was chosen was expensive, especially when bought as a single unit. This design decision was made because it, along with its motor controller, would be easy to interface with, and it met all of our engineering specifications after a thorough analysis. However, it is a very high quality motor meant for things like mechanical automation, that has features that wouldn’t be necessary on an E-bike. These added features are what made it more expensive. Finding a motor or working with a motor supplier to design a motor that still meets our specifications but doesn’t have extra features would have been more ideal and less expensive, but not possible in the time frame we were given.

Another improvement that could be made is in the transmission. While the transmission we designed is robust and of quality materials, it is also bulky and heavy. We could continue improvements on it by looking at other, more compact, lightweight, alternatives to a 3-stage metal gear transmission. We have considered looking into using belts or nylon gears in place of steel gears, but other changes to help this aspect of the design could also be investigated. Finally, a complete control algorithm wasn’t completed in its entirety due to the fact that we couldn’t build a complete functioning prototype. This would be an aspect of the design that would need to be developed further.

In terms of our website design, we have only been able to establish a framework for the full version of what we would plan to implement. Time constraints prevented our team from fully populating our website with all of the information we have collected through our research. For future work, we would recommend adding more descriptive information about bike anatomy, batteries, and motors on our "General Knowledge" page. We would also recommend compiling the safety guide information, recycling guide information, and customization recommendations we have collected to populate our "Safety Guides", "Recycling", and "Customization" pages. We also would recommend using our educational website verification table to continue our "In Progress" items. While Wix is a simple interface to work with and has many built-in accessibility features we have set specifications for, we would prefer to use a more technical development approach to building out our website design in the future. Ideally, we would utilize HTML and CSS to develop our site. Our team was not able to accomplish this because none of our team members have experience with these languages. We would hope to include features which we listed in our educational website verification as "Not Achievable" in this version of our website which is not limited by the Wix platform. We would also hope to streamline the interface between our site and attachments to our site like our Matlab code and our CAD files.

After completing this project, we believe that the best way to tackle the proposed problem is to continue focusing on the communication of the design process through our website design. In order for this to be the most robust and encompassing as possible, it would be helpful to look at more E-bike benchmarks than have already been discussed and explored in this project, possibly even designing another prototype retrofit kit. This will help make the communication of relevant information as complete as possible. A continuation on the prototype design to encompass more bike designs and make some of the possible improvements outlined above would also be desirable.

CONCLUSION

People who want access to E-bikes face a large barrier of necessary mechanical knowledge to do so. The combination of necessary knowledge regarding gearing and transmission, mechatronics and motor control, battery charge and capacity, and force analyses, all in addition to general bike-related knowledge can be completely overwhelming to a novice user. In this project, we took a Socially Engaged Design approach to determine a new strategy to provide access, regardless of mechanical ability and budget, to a low-cost and easily accessible E-bike. We approached this problem by defining requirements for a device or tool which would incentivize potential users to purchase or build E-bikes. We wanted our device or tool to be usable without much background knowledge, to be safe, to be attractive and accessible to the user, and to be inexpensive. We began our process by conducting research on existing E-bike designs and evaluating the existing solutions. From here, we designed our own E-bike retrofit device to deeply understand every step of the process that a user would go through to access an E-bike themselves and how they could optimize an E-bike or E-bike retrofit of their own.

When designing our retrofit we decided that our primary stakeholder would be students at the University of Michigan who would be using the E-bike daily around campus to get to class. From this theoretical stakeholder persona, we created specifications such as hill climb ability, battery life and a target max flat ground speed. We then broke the build down into primary subsystems to reduce the complexity of individual design decisions. Some of the subsystems included system controls like throttling or pedal assist, motor and transmission, power supply, and the mounting interface. We developed a final CAD model of our retrofit design which includes the motor, power supply, transmission, housing, and interfaces for all other subsystems. Our CAD model includes a sustainable battery design for our E-bike built from cells mounted in a custom prototyping kit. This was designed to make each individual cell replaceable while achieving a high cycle life compared to other batteries of similar size and cost. The CAD model also includes a motor and transmission that provide a powerful and smooth ride even up the steepest Ann Arbor hills. Additionally, its mount is designed to provide easy access to all primary systems for maintenance. After we had completed an e-bike design, we evaluated how well it met the desired specifications through physical testing with a force gauge and voltmeter, secondary research on existing retrofit designs, and models that were built out in Matlab code and CAD and digital drawings.

Moving forward, we examined our solution design by evaluating the gap between existing market solutions and the user needs. Our defined need was to expand accessibility to E-Bikes to non-makers and people normally excluded from technical learning. We realized that while the retrofit we designed was a helpful tool to teach our team about the E-bike building process, its high cost, specificity to one particular bike design, and mechanical complexity prevented it from properly addressing our defined need for increased E-bike accessibility. We determined that a better approach to addressing our need would be to take our design process and knowledge of DIY decision-making and communicate it to any potential user through an inclusive web design, rather than solely communicating how to replicate and use our prototype design. Therefore, we developed a website which sequentially steps the user through our mission statement on our home page, general E-bike-related background information, E-bike evaluation criteria which we defined based on our research, processes for purchasing or designing an E-bike or E-bike retrofit, maintenance guides, important safety considerations, end-of-life recycling, and further customization tips. To make sure that this website is as accessible as possible, and to democratize our making and learning guides as much as possible, we validated our website solution against several inclusive web design and educational guidelines which include the Nielsen Norman group and the US Department of Education. While the website needs further building and revision, these verification techniques indicate that its framework and existing structure will help users access, regardless of mechanical ability and budget, to a low-cost and easily accessible E-bike. In the future, we plan to finalize a website design with the use of HTML and CSS programming and conduct usability tests with potential users to iterate on our design and improve it further.

AUTHORS

Jacob Horcher (he/him) is a student at the University of Michigan pursuing his Master's Degree in Mechanical Engineering. He is an experienced mechanical designer, and has used these skills throughout his engineering career. He is passionate about renewable energy and sustainability, as well as environmental protection. He will be interning with Caterpillar this summer (2021) in the Large Power Systems division. He hopes his career takes him down a path where he can use his skills to innovate and make the world a better, more sustainable place.

Grace Hankes (she/her) is graduating with a B.S.E. in Mechanical Engineering from the University of Michigan College of Engineering. Along with this degree, she has also completed the International Minor for Engineers and the Program in Sustainable Engineering. Grace has furthered her interest and engagement with sustainable systems through her work with the Graham Sustainability Institute as a Collective Impact Coordinator. She hopes to apply this and her other leadership experiences through Theta Tau Professional Engineering Organization to a post-undergraduate career in sustainable technology consulting.

Julia Stuart (she/her) is graduating with a B.S.E. in Mechanical Engineering from the College of Engineering at the University of Michigan. She has also completed a minor in the Program in the Environment and concentrated in the Program in Sustainable Engineering. In her four years at this university, she has served as a Senator in the Engineering Student Government, completed research, taught and tutored, and taken many rock climbing and backpacking trips in her spare time. She is particularly passionate about applying her engineering knowledge toward environmental protection and education. She has recently accepted a position as a consultant with Remora Carbon and is very excited about the prospect of this position aligning well with her passions.

Jonah Shifrin (he/him) graduated undergraduate school at the University of Michigan in april of 2021 with 2 bachelors degrees. Jonah will be receiving a B.S.E. in Mechanical Engineering with a specialization in human centered design from the School of Engineering and a B.A. in Art and Design with a focus in human centered design from the Stamps School of art and design. Jonah has spent the majority of his undergraduate career working for startups around the United States as well as a teaching assistant consultant for a graduate multidisciplinary product design course Integrated Product Development, IPD. In his spare time, Jonah has done engineering outreach work with Chicago Public Schools and is a professional development committee chair for Theta Tau Professional Engineering organization. Jonah is planning on continuing work as an engineering/product design consultant for a California biomedical startup, Expanse Medical, as he searches for full time post undergraduate work.

Jorge Alfaro (he/him) is graduating from the University of Michigan with a B.S.E. in Mechanical Engineering. He is passionate about automotive engineering, specifically the impact that this sector has on the environment. As a Latino engineer, Jorge is also passionate about diversity and inclusion in the field of engineering. He believes that engineers from different backgrounds are the key to the future of engineering. Jorge hopes to take his interest and passions for automotive engineering, design, and diversity to a career in the automotive industry where he can further the industry.

ACKNOWLEDGEMENTS

Finally, the team would like to thank everyone that has helped us through this project and guided us to a successful, meaningful result. Specifically, we would like to thank our sponsor, mentor, and Professor, Dr. Steven Skerlos. He was an extremely valued member of our team, and we would not have been able to complete this project without his support, advice, and guidance. Thank you to our fellow classmates and the rest of the teaching staff, who constantly gave us feedback and asked truly meaningful questions that led us to look at our project from a different perspective. Finally, thank you to our friends, family, and peers who supported us, listened to us talk about our project and why we were passionate about it, and were there for us when we needed someone to help us through these trying times.

APPENDICES

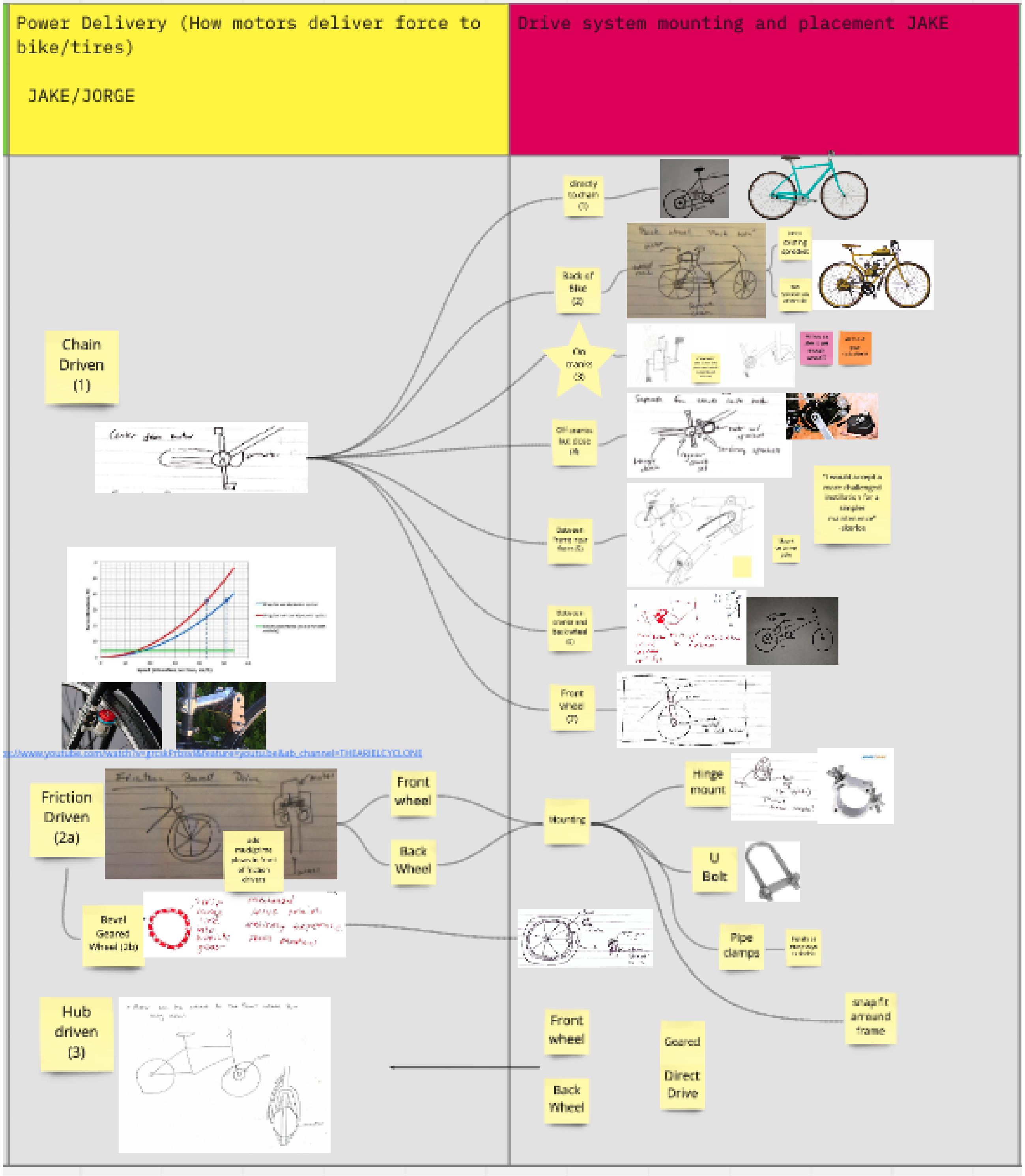
APPENDIX A: Model Prototype Design Process

A.1: Prototype Design Requirements and Specifications

Stakeholder Requirement	**Engineering Specification**
Safe to ride in Ann Arbor	Cannot travel faster than 10 mph without the assistance of pedaling on flat ground Breaking must disengage the powered drive system with less than 0.5 second response time or less Includes features that allow the user to see >13.5 ft away in low light conditions and for the user to be seen >50 ft away
Good Range	Can travel >10 miles on a single charge on flat ground *Can travel up a 11% gradient for 350 ft while maintaining 95% of the range of the bike.* Fully rechargeable in ≤5 hours in a 120 V conventional outlet
Durable	Can withstand (safely operate after) impact of more than 5,541 N No component fails under low-cycle fatigue where one cycle is one 10 mile ride. ($1<N<10^3$) Materials will not corrode with exposure to water, salt etc. (for 4 years or equivalent thereof) Torque exerted onto the chain remains under 9000 N. (otherwise there is potential for a chain of higher force rating to be included in E-bike kit)
Usable in most conditions	Will keep traction with wet ground at a maximum speed of 10 mph Power source performance can still last for at least 10 miles in 9-110 ºF Can reach a no pedal velocity of ≥10 mph in a range of 9-110 ºF Can reach a no pedal velocity of ≥10 mph against wind speeds of up to 25 mph
Pleasing user interface (in use)	Can operate with loads between 80 and 200 lbs placed on the bike without losing the ability to operate at top speed Power control system can be operated with at least one hand remaining on the handle bars Maximum jerk during acceleration is 0.6 m/s^3 Rider has complete control over speed within the range of 0-10 mph (adjustable power draw) While running, E-bike produces sounds ≤50 dB

	Adding the retrofit will not interfere with already in place, back wheel shifting
Environmentally conscious material selection	More than 80% of material by mass, excluding the motor and battery, is recyclable 100% of material, excluding the motor and battery, is sourced within the US
Lightweight	Does not add more than 25 lbs in additional weight to the bike No individual piece weighs more than 10 lbs
Minimized Consumer Cost	At a scale of 40,000 units, the per unit manufacturing costs must be ≤\$500.00 USD
Can be adopted/used without extensive experience or education	Entire assembly can be assembled, mounted, and maintained using only a flathead screwdriver, a Phillips Head screwdriver, a hammer, and tools provided in the retrofit kit. Entire design is assembled in ≤6 hours Power source is removable in ≤5 minutes without tools Only uses 1 standardized fastener Able to mount to 3 or more bike designs

A.2: Subsystem Identification and Justification



Power Delivery (How motors deliver force to bike/tires)

JAKE/JORGE

Drive system mounting and placement JAKE

Chain Driven (1)

Friction Driven (2a)

Bevel Geared Wheel (2b)

Hub driven (3)

s://www.youtube.com/watch?v=[illegible]&feature=youtu.be&ab_channel=THEARIELCYCLONE

Front wheel

Back Wheel

directly to chain (1)

Back of Bike (2)

On cranks (3)

Off cranks but close (4)

Between frame rear item (5)

Between cranks and backwheel (6)

Front wheel (7)

"I would accept a more challenged installation for a simpler [illegible]"
-[illegible]

Mounting

Hinge mount

U Bolt

Pipe clamps

snap fit around frame

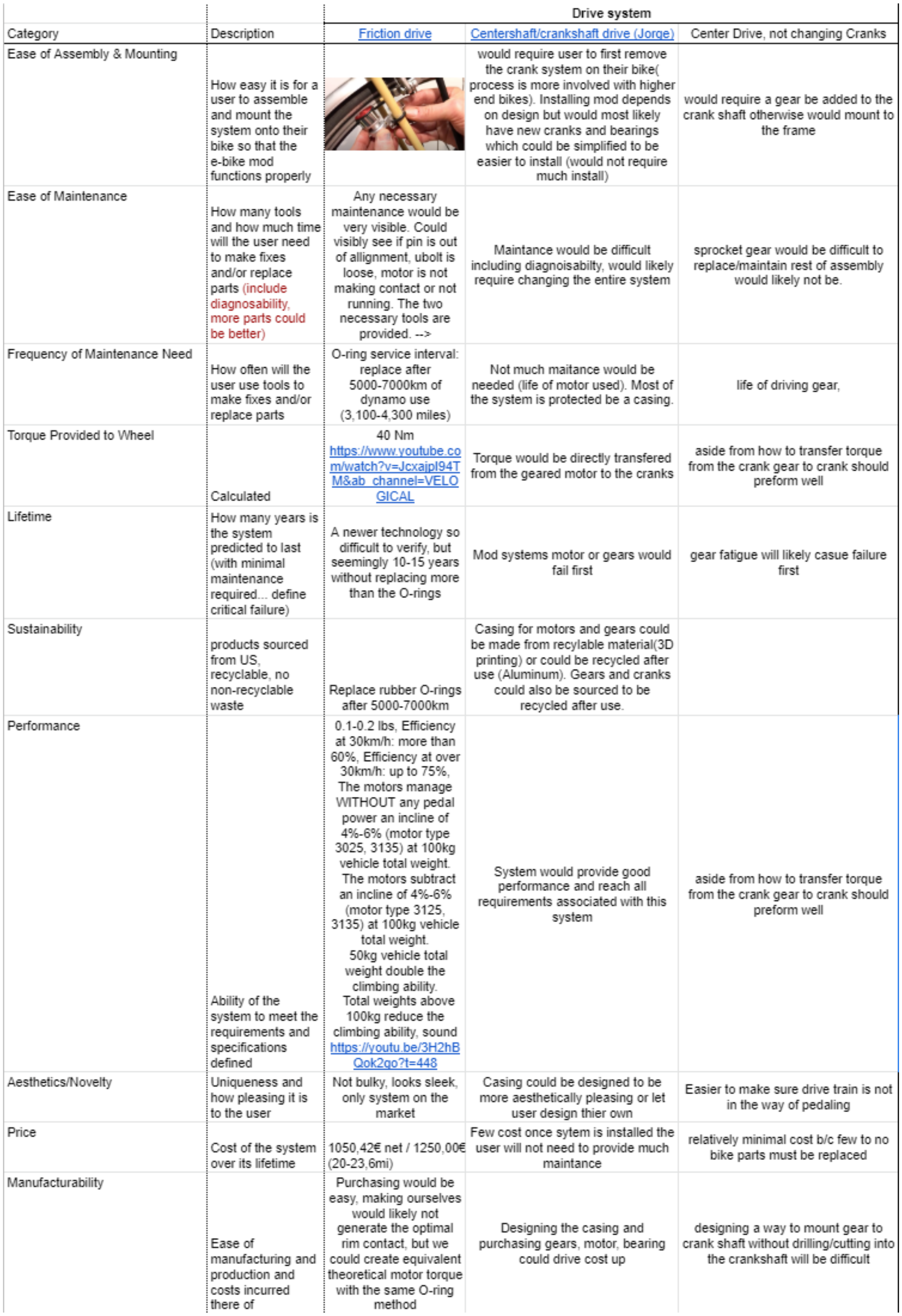
Front wheel

Back Wheel

Geared

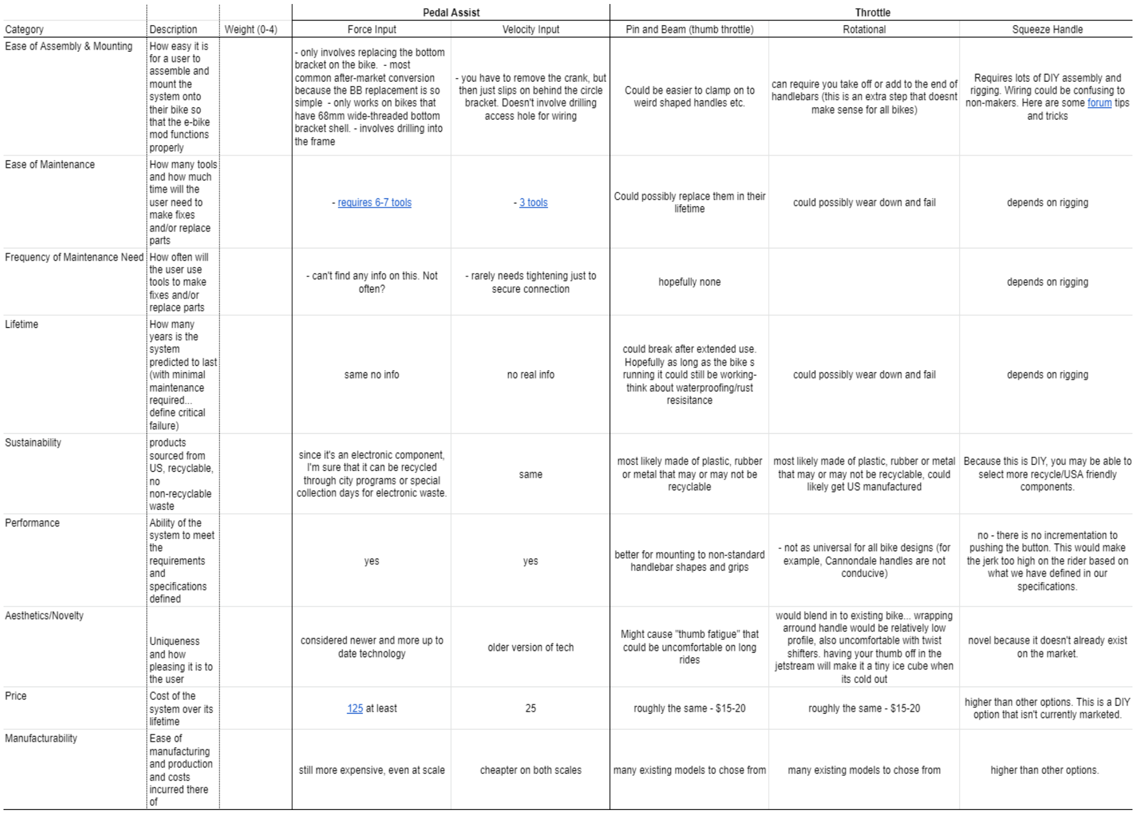
Direct Drive

A.3: Drive System Research Notes



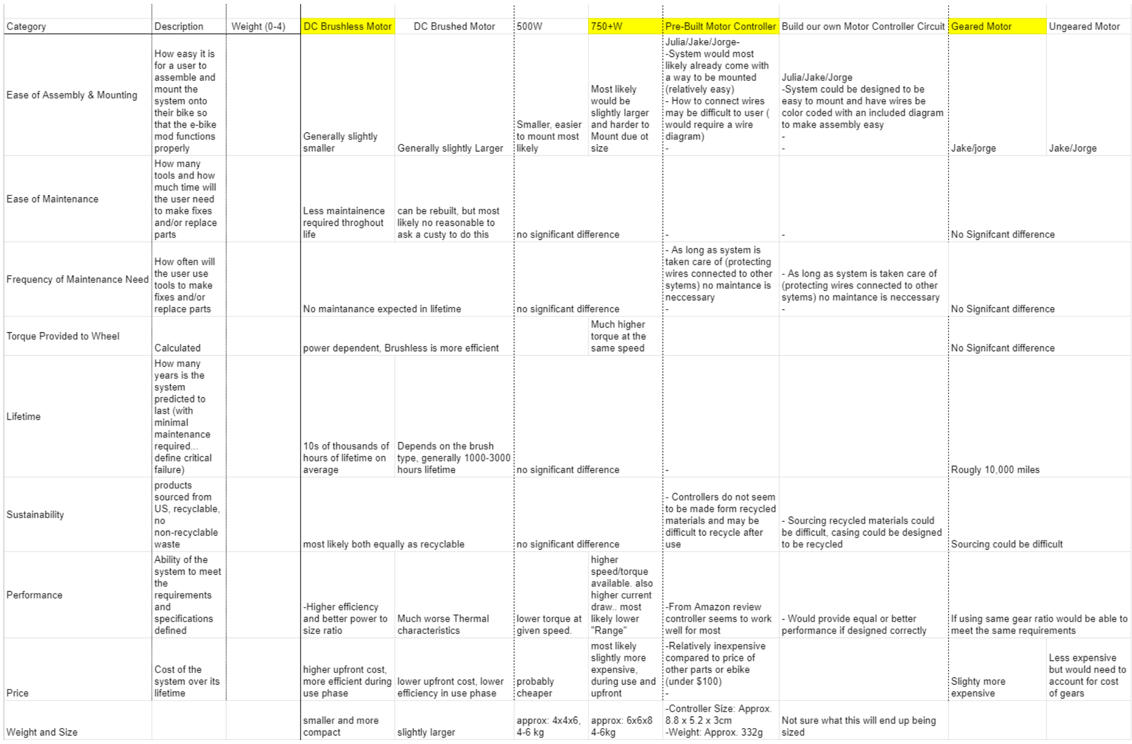
		Drive system		
Category	Description	Friction drive	Centershaft/crankshaft drive (Jorge)	Center Drive, not changing Cranks
Ease of Assembly & Mounting	How easy it is for a user to assemble and mount the system onto their bike so that the e-bike mod functions properly		would require user to first remove the crank system on their bike(process is more involved with higher end bikes). Installing mod depends on design but would most likely have new cranks and bearings which could be simplified to be easier to install (would not require much install)	would require a gear be added to the crank shaft otherwise would mount to the frame
Ease of Maintenance	How many tools and how much time will the user need to make fixes and/or replace parts (include diagnosability, more parts could be better)	Any necessary maintenance would be very visible. Could visibly see if pin is out of allignment, ubolt is loose, motor is not making contact or not running. The two necessary tools are provided. -->	Maintance would be difficult including diagnoisabilty, would likely require changing the entire system	sprocket gear would be difficult to replace/maintain rest of assembly would likely not be.
Frequency of Maintenance Need	How often will the user use tools to make fixes and/or replace parts	O-ring service interval: replace after 5000-7000km of dynamo use (3,100-4,300 miles)	Not much maitance would be needed (life of motor used). Most of the system is protected be a casing.	life of driving gear,
Torque Provided to Wheel	Calculated	40 Nm https://www.youtube.com/watch?v=JcxajpI94TM&ab_channel=VELOGICAL	Torque would be directly transfered from the geared motor to the cranks	aside from how to transfer torque from the crank gear to crank should preform well
Lifetime	How many years is the system predicted to last (with minimal maintenance required... define critical failure)	A newer technology so difficult to verify, but seemingly 10-15 years without replacing more than the O-rings	Mod systems motor or gears would fail first	gear fatigue will likely casue failure first
Sustainability	products sourced from US, recyclable, no non-recyclable waste	Replace rubber O-rings after 5000-7000km	Casing for motors and gears could be made from recylable material(3D printing) or could be recycled after use (Aluminum). Gears and cranks could also be sourced to be recycled after use.	
Performance	Ability of the system to meet the requirements and specifications defined	0.1-0.2 lbs, Efficiency at 30km/h: more than 60%, Efficiency at over 30km/h: up to 75%, The motors manage WITHOUT any pedal power an incline of 4%-6% (motor type 3025, 3135) at 100kg vehicle total weight. The motors subtract an incline of 4%-6% (motor type 3125, 3135) at 100kg vehicle total weight. 50kg vehicle total weight double the climbing ability. Total weights above 100kg reduce the climbing ability, sound https://youtu.be/3H2hBQok2go?t=448	System would provide good performance and reach all requirements associated with this system	aside from how to transfer torque from the crank gear to crank should preform well
Aesthetics/Novelty	Uniqueness and how pleasing it is to the user	Not bulky, looks sleek, only system on the market	Casing could be designed to be more aesthetically pleasing or let user design thier own	Easier to make sure drive train is not in the way of pedaling
Price	Cost of the system over its lifetime	1050,42€ net / 1250,00€ (20-23,6mi)	Few cost once sytem is installed the user will not need to provide much maintance	relatively minimal cost b/c few to no bike parts must be replaced
Manufacturability	Ease of manufacturing and production and costs incurred there of	Purchasing would be easy, making ourselves would likely not generate the optimal rim contact, but we could create equivalent theoretical motor torque with the same O-ring method	Designing the casing and purchasing gears, motor, bearing could drive cost up	designing a way to mount gear to crank shaft without drilling/cutting into the crankshaft will be difficult

A.4: Throttling Research Notes



			Pedal Assist		Throttle		
Category	Description	Weight (0-4)	Force Input	Velocity Input	Pin and Beam (thumb throttle)	Rotational	Squeeze Handle
Ease of Assembly & Mounting	How easy it is for a user to assemble and mount the system onto their bike so that the e-bike mod functions properly		- only involves replacing the bottom bracket on the bike. - most common after-market conversion because the BB replacement is so simple - only works on bikes that have 68mm wide-threaded bottom bracket shell. - involves drilling into the frame	- you have to remove the crank, but then just slips on behind the circle bracket. Doesn't involve drilling access hole for wiring	Could be easier to clamp on to weird shaped handles etc.	can require you take off or add to the end of handlebars (this is an extra step that doesnt make sense for all bikes)	Requires lots of DIY assembly and rigging. Wiring could be confusing to non-makers. Here are some forum tips and tricks
Ease of Maintenance	How many tools and how much time will the user need to make fixes and/or replace parts		- requires 6-7 tools	- 3 tools	Could possibly replace them in their lifetime	could possibly wear down and fail	depends on rigging
Frequency of Maintenance Need	How often will the user use tools to make fixes and/or replace parts		- can't find any info on this. Not often?	- rarely needs tightening just to secure connection	hopefully none		depends on rigging
Lifetime	How many years is the system predicted to last (with minimal maintenance required... define critical failure)		same no info	no real info	could break after extended use. Hopefully as long as the bike s running it could still be working- think about waterproofing/rust resisitance	could possibly wear down and fail	depends on rigging
Sustainability	products sourced from US, recyclable, no non-recyclable waste		since it's an electronic component, I'm sure that it can be recycled through city programs or special collection days for electronic waste.	same	most likely made of plastic, rubber or metal that may or may not be recyclable	most likely made of plastic, rubber or metal that may or may not be recyclable, could likely get US manufactured	Because this is DIY, you may be able to select more recycle/USA friendly components.
Performance	Ability of the system to meet the requirements and specifications defined		yes	yes	better for mounting to non-standard handlebar shapes and grips	- not as universal for all bike designs (for example, Cannondale handles are not conducive)	no - there is no incrementation to pushing the button. This would make the jerk too high on the rider based on what we have defined in our specifications.
Aesthetics/Novelty	Uniqueness and how pleasing it is to the user		considered newer and more up to date technology	older version of tech	Might cause "thumb fatigue" that could be uncomfortable on long rides	would blend in to existing bike... wrapping arround handle would be relatively low profile, also uncomfortable with twist shifters. having your thumb off in the jetstream will make it a tiny ice cube when its cold out	novel because it doesn't already exist on the market.
Price	Cost of the system over its lifetime		125 at least	25	roughly the same - $15-20	roughly the same - $15-20	higher than other options. This is a DIY option that isn't currently marketed.
Manufacturability	Ease of manufacturing and production and costs incurred there of		still more expensive, even at scale	cheapter on both scales	many existing models to chose from	many existing models to chose from	higher than other options.

A.5: Motor Research Notes



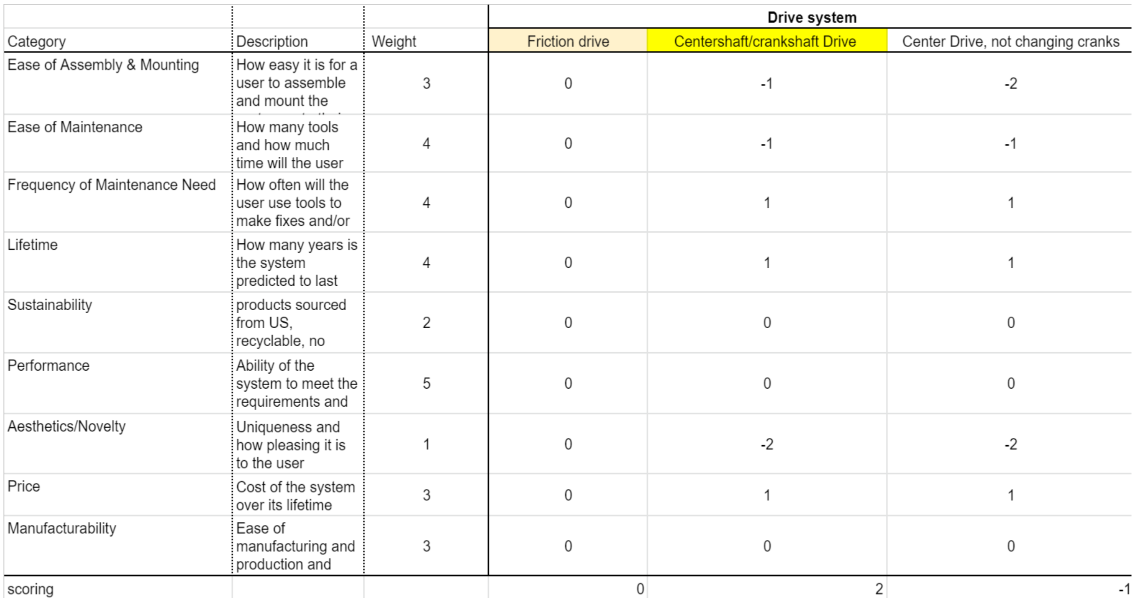
Category	Description	Weight (0-4)	DC Brushless Motor	DC Brushed Motor	500W	750+W	Pre-Built Motor Controller	Build our own Motor Controller Circuit	Geared Motor	Ungeared Motor
Ease of Assembly & Mounting	How easy it is for a user to assemble and mount the system onto their bike so that the e-bike mod functions properly		Generally slightly smaller	Generally slightly Larger	Smaller, easier to mount most likely	Most likely would be slightly larger and harder to Mount due ot size	Julia/Jake/Jorge- -System would most likely already come with a way to be mounted (relatively easy) - How to connect wires may be difficult to user (would require a wire diagram) -	Julia/Jake/Jorge -System could be designed to be easy to mount and have wires be color coded with an included diagram to make assembly easy - -	Jake/jorge	Jake/Jorge
Ease of Maintenance	How many tools and how much time will the user need to make fixes and/or replace parts		Less maintainence required throghout life	can be rebuilt, but most likely no reasonable to ask a custy to do this	no significant difference		-	-	No Signifcant difference	
Frequency of Maintenance Need	How often will the user use tools to make fixes and/or replace parts		No maintanance expected in lifetime		no significant difference		- As long as system is taken care of (protecting wires connected to other sytems) no maintance is neccessary -	- As long as system is taken care of (protecting wires connected to other sytems) no maintance is neccessary -	No Signifcant difference	
Torque Provided to Wheel	Calculated		power dependent, Brushless is more efficient			Much higher torque at the same speed			No Signifcant difference	
Lifetime	How many years is the system predicted to last (with minimal maintenance required... define critical failure)		10s of thousands of hours of lifetime on average	Depends on the brush type, generally 1000-3000 hours lifetime	no significant difference		-		Rougly 10,000 miles	
Sustainability	products sourced from US, recyclable, no non-recyclable waste		most likely both equally as recyclable		no significant difference		- Controllers do not seem to be made form recycled materials and may be difficult to recycle after use	- Sourcing recycled materials could be difficult, casing could be designed to be recycled	Sourcing could be difficult	
Performance	Ability of the system to meet the requirements and specifications defined		-Higher efficiency and better power to size ratio	Much worse Thermal characteristics	lower torque at given speed.	higher speed/torque available. also higher current draw.. most likely lower "Range"	-From Amazon review controller seems to work well for most	- Would provide equal or better performance if designed correctly	If using same gear ratio would be able to meet the same requirements	
Price	Cost of the system over its lifetime		higher upfront cost, more efficient during use phase	lower upfront cost, lower efficiency in use phase	probably cheaper	most likely slightly more expensive, during use and upfront	-Relatively inexpensive compared to price of other parts or ebike (under $100) -		Slighty more expensive	Less expensive but would need to account for cost of gears
Weight and Size			smaller and more compact	slightly larger	approx: 4x4x6, 4-6 kg	approx: 6x6x8 4-6kg	-Controller Size: Approx. 8.8 x 5.2 x 3cm -Weight: Approx. 332g	Not sure what this will end up being sized		

A.6: BMS Research Notes

			BMS	
Category	Description	Weight (0-4)	Smart BMS	Vruzend BMS
Ease of Assembly & Mounting	How easy it is for a user to assemble and mount the system onto their bike so that the e-bike mod functions properly		Wiring, more wires because bluetooth connection, securing to battery pack. Only option 4 has heavy gauge silicone wires already connected. Less clear wiring diagram	Wiring, securing to battery back: "Most BMSs are hard to install because you have to solder on the wires yourself. Our BMSs come with 6" high quality, heavy gauge silicone wires already connected, making it much easier to install. " More clear wiring diagram
Ease of Maintenance	How many tools and how much time will the user need to make fixes and/or replace parts		No difference in maintenance methods	No difference in maintenance methods
Frequency of Maintenance Need	How often will the user use tools to make fixes and/or replace parts		A bit more wiring for bluetooth connection, ideally no maintenance needed, frequency unknown	Ideally no maintenance needed, frequency unknown
Lifetime	How many years is the system predicted to last (with minimal maintenance required... define critical failure)		N/A	N/A
Sustainability	products sourced from US, recyclable, no non-recyclable waste		Metal components in these devices can be broken down, recycled and reused	Metal components in these devices can be broken down, recycled and reused
Performance	Ability of the system to meet the requirements and specifications defined		Hard to find many reviews (especially unbiased), youtube videos rave, one man had to fix his bluetooth connection to the device	Again, hard to find many reviews, highly recommended by ebikeschool youtuber
Aesthetics/Novelty	Uniqueness and how pleasing it is to the user		App connection, interactive, potentially difficult to navigate interface	Not interactive, aesthetically simple
Price	Cost of the system over its lifetime		~$70	~$40
Manufacturability	Ease of manufacturing and production and costs incurred there of		We'll buy it	We'll buy it

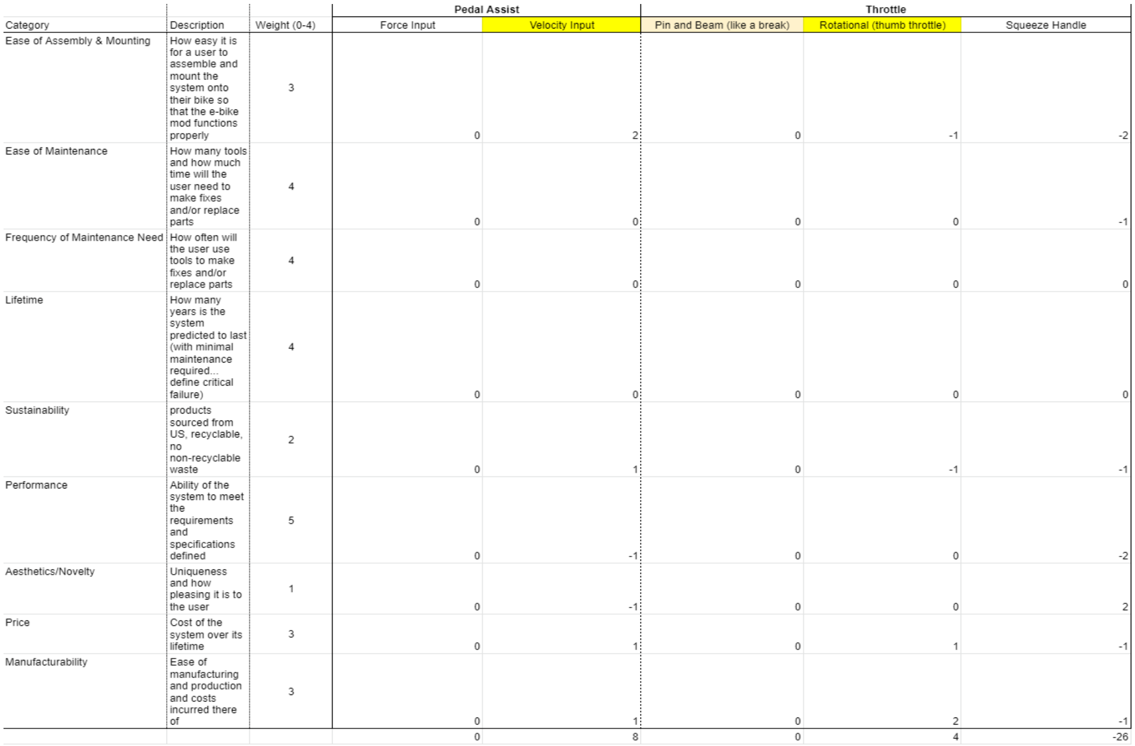
APPENDIX B: Pugh Charts

B.1: Drive system Pugh Chart



			Drive system		
Category	Description	Weight	Friction drive	Centershaft/crankshaft Drive	Center Drive, not changing cranks
Ease of Assembly & Mounting	How easy it is for a user to assemble and mount the	3	0	-1	-2
Ease of Maintenance	How many tools and how much time will the user	4	0	-1	-1
Frequency of Maintenance Need	How often will the user use tools to make fixes and/or	4	0	1	1
Lifetime	How many years is the system predicted to last	4	0	1	1
Sustainability	products sourced from US, recyclable, no	2	0	0	0
Performance	Ability of the system to meet the requirements and	5	0	0	0
Aesthetics/Novelty	Uniqueness and how pleasing it is to the user	1	0	-2	-2
Price	Cost of the system over its lifetime	3	0	1	1
Manufacturability	Ease of manufacturing and production and	3	0	0	0
scoring			0	2	-1

B.2: Throttling Pugh Chart



			Pedal Assist		Throttle		
Category	Description	Weight (0-4)	Force Input	Velocity Input	Pin and Beam (like a break)	Rotational (thumb throttle)	Squeeze Handle
Ease of Assembly & Mounting	How easy it is for a user to assemble and mount the system onto their bike so that the e-bike mod functions properly	3	0	2	0	-1	-2
Ease of Maintenance	How many tools and how much time will the user need to make fixes and/or replace parts	4	0	0	0	0	-1
Frequency of Maintenance Need	How often will the user use tools to make fixes and/or replace parts	4	0	0	0	0	0
Lifetime	How many years is the system predicted to last (with minimal maintenance required... define critical failure)	4	0	0	0	0	0
Sustainability	products sourced from US, recyclable, no non-recyclable waste	2	0	1	0	-1	-1
Performance	Ability of the system to meet the requirements and specifications defined	5	0	-1	0	0	-2
Aesthetics/Novelty	Uniqueness and how pleasing it is to the user	1	0	-1	0	0	2
Price	Cost of the system over its lifetime	3	0	1	0	1	-1
Manufacturability	Ease of manufacturing and production and costs incurred there of	3	0	1	0	2	-1
			0	8	0	4	-26

B.3: Safety Considerations

Ensuring the safety of the user is more important than ensuring that our design is educational and democratized. Safety is considered in every aspect of our design process so we can achieve our design goals of creating an educational and democratized E-bike retrofit mechanism. We plan to incorporate safety into user engagement solutions through the addition of a braking use case and maintenance diagram and various safety manuals. The following safety considerations heavily influenced our specification definitions and concept evaluation process:

Center of Gravity (CoG)

A typical rider may weigh at the lightest about 80 lbs. To keep the center of gravity between the seat and handlebars of the bike which typically weighs 20-30 lbs, to prevent flipping, the weight of the device and horizontal distance from the bike's CoG must be considered. [27] In the most extreme scenarios, the rider will sit straight above the seat or lean most of their weight on the handlebars. Given that the rider will shift greater than 80 lbs of weight between the seat and handlebars between extremes of positions, it is necessary that the center of gravity of the retrofit device and bike combination remain also between the seat and handlebars.

Friction

With the addition of an electric motor driving a manual bike, the tire pressure should stay within the bike tire manufacturer's recommendations to optimize a balance between rolling resistance and inducing premature fatigue on the tires. However, the pressure should be reduced from the upper limit of inflation due to the excess weight of the retrofit device and added speed. Reducing the tire pressure slightly will increase traction with the ground by increasing rolling resistance. Reducing tire pressure within manufacturer's specifications will also help the bike keep traction with the ground in wet conditions and in rugged terrain. [7]

Accelerating

A common trait of high speed electric vehicles is the rapid change in acceleration or the jerk. This feeling is uncomfortable but in larger vehicles like cars it is not a safety risk. In E-bikes, however, this can be dangerous. The effects of unexpected jerk while operating an E-bike could cause the user to fall off of their bike and injure themselves and possibly others. This is why we have to take into account the possibility of jerk occuring when the E-bike is in operation.

Braking

Braking performance in a bike is an important mechanism used to stop the bike in an emergency event. Commonly available rubber brake pads (RBP) have low friction and low braking performance. The poor performance leads to a lack of power in braking and as a result, slippage. Sliding may occur during braking [15], and this is especially true if used during nonideal conditions such as while riding on wet roads. This effect is more pronounced in E-bikes which travel at higher speeds (with more momentum) for longer periods of time, this is why brake maintenance is important and necessary for our E-bike retrofit users to understand.

APPENDIX C: Models

C.1: CAD Assembly Animation

The Figure below is a looping animation of the assembly process of the designed retrofit onto a naked bike frame.

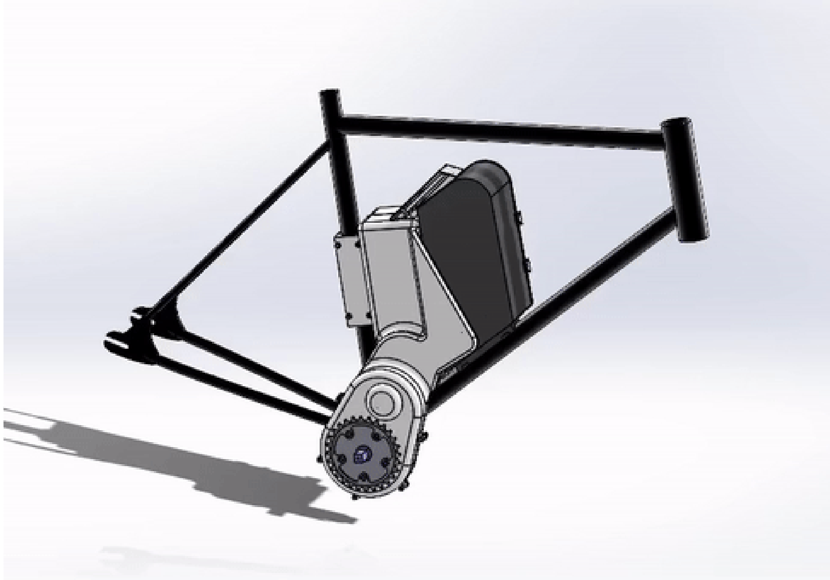
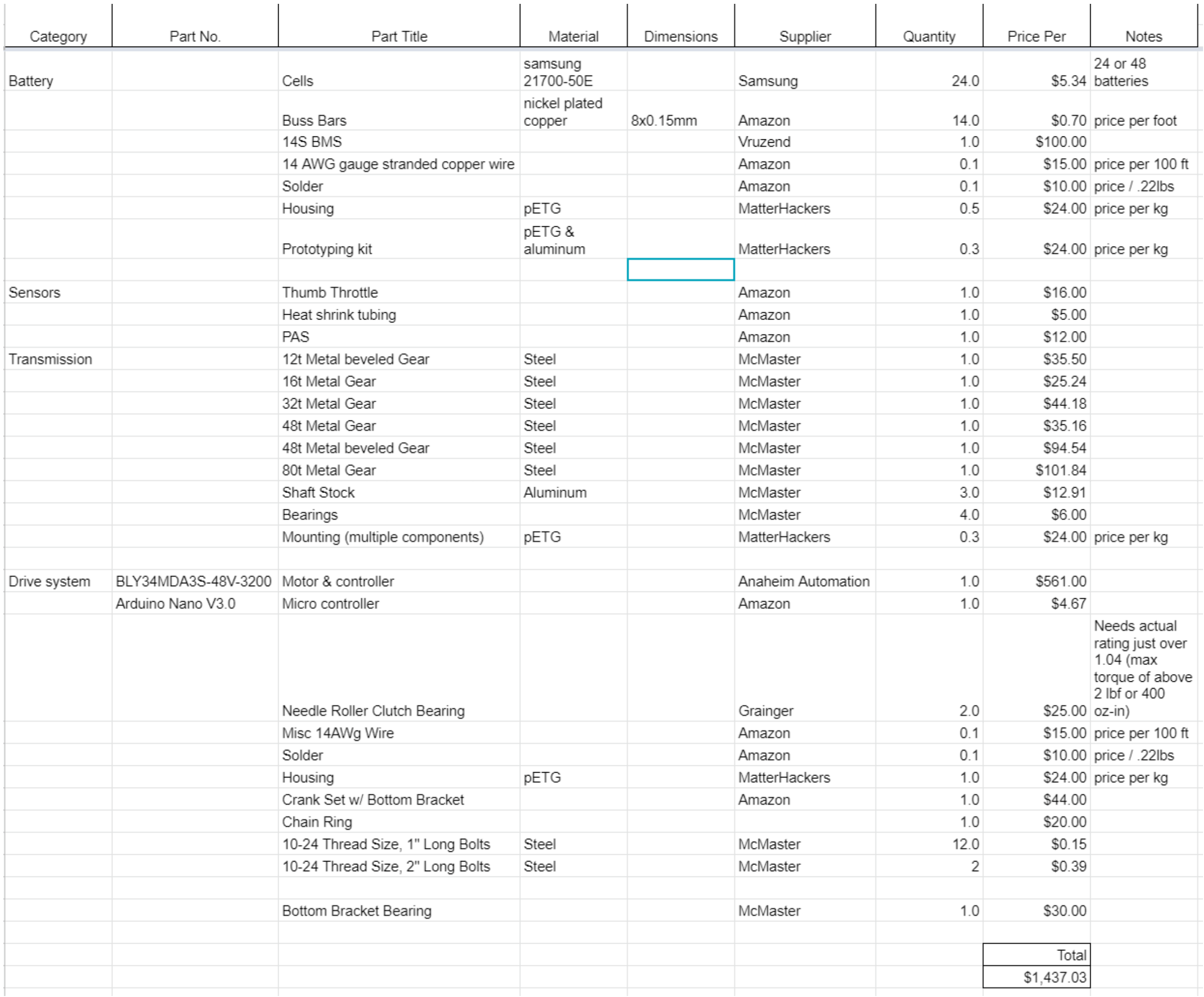


Figure C.1. This figure shows an animation of the retrofit mounting process. This animation is not representative of the entire assembly process nor the use of any hardware.

C.2: Final Bill of Materials



Category	Part No.	Part Title	Material	Dimensions	Supplier	Quantity	Price Per	Notes
Battery		Cells	samsung 21700-50E		Samsung	24.0	$5.34	24 or 48 batteries
		Buss Bars	nickel plated copper	8x0.15mm	Amazon	14.0	$0.70	price per foot
		14S BMS			Vruzend	1.0	$100.00	
		14 AWG gauge stranded copper wire			Amazon	0.1	$15.00	price per 100 ft
		Solder			Amazon	0.1	$10.00	price / .22lbs
		Housing	pETG		MatterHackers	0.5	$24.00	price per kg
		Prototyping kit	pETG & aluminum		MatterHackers	0.3	$24.00	price per kg
Sensors		Thumb Throttle			Amazon	1.0	$16.00	
		Heat shrink tubing			Amazon	1.0	$5.00	
		PAS			Amazon	1.0	$12.00	
Transmission		12t Metal beveled Gear	Steel		McMaster	1.0	$35.50	
		16t Metal Gear	Steel		McMaster	1.0	$25.24	
		32t Metal Gear	Steel		McMaster	1.0	$44.18	
		48t Metal Gear	Steel		McMaster	1.0	$35.16	
		48t Metal beveled Gear	Steel		McMaster	1.0	$94.54	
		80t Metal Gear	Steel		McMaster	1.0	$101.84	
		Shaft Stock	Aluminum		McMaster	3.0	$12.91	
		Bearings			McMaster	4.0	$6.00	
		Mounting (multiple components)	pETG		MatterHackers	0.3	$24.00	price per kg
Drive system	BLY34MDA3S-48V-3200	Motor & controller			Anaheim Automation	1.0	$561.00	
	Arduino Nano V3.0	Micro controller			Amazon	1.0	$4.67	
		Needle Roller Clutch Bearing			Grainger	2.0	$25.00	Needs actual rating just over 1.04 (max torque of above 2 lbf or 400 oz-in)
		Misc 14AWg Wire			Amazon	0.1	$15.00	price per 100 ft
		Solder			Amazon	0.1	$10.00	price / .22lbs
		Housing	pETG		MatterHackers	1.0	$24.00	price per kg
		Crank Set w/ Bottom Bracket			Amazon	1.0	$44.00	
		Chain Ring				1.0	$20.00	
		10-24 Thread Size, 1" Long Bolts	Steel		McMaster	12.0	$0.15	
		10-24 Thread Size, 2" Long Bolts	Steel		McMaster	2	$0.39	
		Bottom Bracket Bearing			McMaster	1.0	$30.00	
							Total	
							$1,437.03	

C.3: Matlab Analysis

The figure below depicts screenshots of the MATLAB code used to streamline the analytical process. Many of the variables listed in the analysis section are hardcoded to fit the specific retrofit design case for the Diamondback Trace ST bike and the BLY34MDC3S brushless DC motor from anaheim automation as well as inputs from the original requirements and specifications.

```
%%finding motor gearing ratio

RatioB = 28/34; %Input ring gear over rear cog ratio

BikeV = 5.6699; % Input velocity of bike [MPH]
incline = 10; % Input incline of road [degrees (0-90)]
loading = 1360; % total bike+mod+rider weight [N]
WindV = 16; % average windspeed [MPH]
Vwind = (BikeV+WindV)/2.237; % relative velocity of the wind [m/s]

Fres = (1.32*0.8*.83*Vwind^2)/2; % force of wind resistance [N]
Fgrav = loading*sind(incline); % force of gravity resistance up incline [N]
R_backW = .311; % Radius of the back wheel [m]
Tl = RatioB*R_backW*(Fres+Fgrav); % Load Torque [Nm]

MotT_cont = 2.09728; % [Nm]
contT_speedM = 3200; % [rpm] at max continuous torque
RatioM = Tl/MotT_cont; % motor gearing ratio for running at continuous torque
speedl = contT_speedM/RatioM; % if ratioB num > denom then change the last *
speedBh = speedl*RatioB*R_backW*2*pi/60*2.237; % [MPH]

disp (RatioM)
disp (speedBh)
```

```
%% can this ratio acheive the flat ground speed of 20 MPH given bike gearing options

Ratio = round(RatioM);
BikeVf = 15; % [MPH]
loading = 1360; % total bike+mod+rider weight [N]
WindV = 0; % because wind is at your back for as long as at your front on the whole [m/s]
incline = 0; % flat ground [degrees]
RatioBf = 28/34; % Input ring gear over rear cog ratio
Fgrav = loading*sind(incline); % force of gravity resistance up incline [N]

Vwind = (BikeVf+WindV)/2.237; % relative windspeed [m/s]
Fres = (1.32*0.8*.83*Vwind^2)/2; % force of wind resistance [N]
Tl = RatioBf*R_backW*(Fres+Fgrav); % [Nm]
TM = (Tl/Ratio)/0.0070615518333333; % [Oz-in]
disp(TM)% we need to find motor speed at this torque use this to update speedM below

speedM = 3500; %enter rated speed [RPM] at 40.11212 Oz-in;
speedBf = (speedM/(RatioM*RatioBf))*R_backW*2*pi/60*2.237;

disp(RatioBf)
disp(speedBf)
```

```
%% Battery specs calc


num_Pf = (10/BikeVf)*3/4.9; %flat
num_Ph = (0.0662879/speedBh)*594.6/20.4*20/4.9; %incline

disp(num_Pf);
disp(num_Ph);
```

Figure C.2. A screengrab of early draft MATLAB code used for streamlining the analytical process.

APPENDIX D: Website Prototype Design Process

Below is a preliminary wireframe for the user process flow of the website's design selection feature. This page will likely act as the landing page for the cite as well.

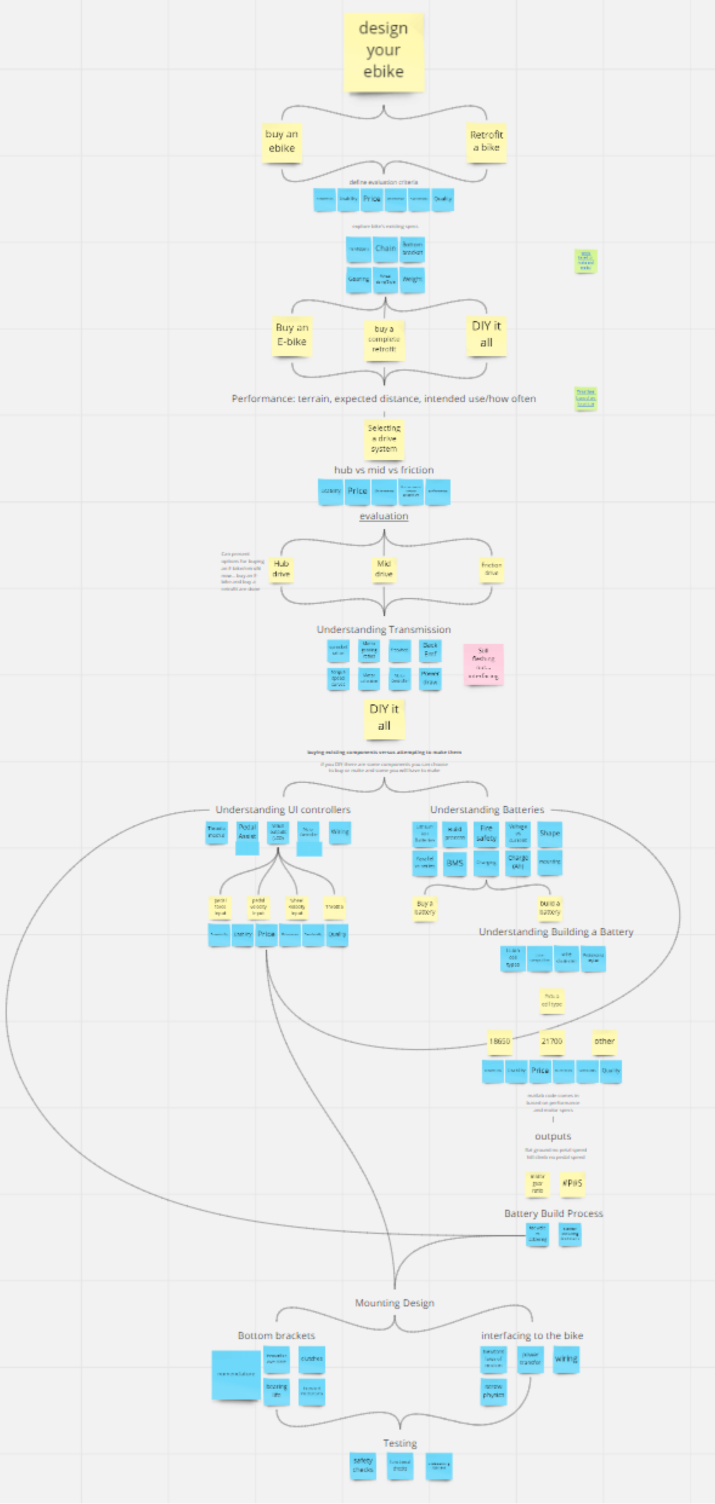


Figure D.1. A screengrab of a miro outline for the design page of the educational system

APPENDIX E. Engineering Standards

This section describes how we have incorporated appropriate engineering standards in the design development of our project.

Engineering Standards in our Prototype:

Standards are guidelines set by a reputable body which are reviewed and updated regularly to consistently keep in line with advances in society and technology. Standards promote safety and are informed by regulatory and market needs [43]. To guide our mechanical prototype design we looked into all E-bike standards and regulations that could be used to inform any design decisions we made about the retrofit. We found that regulations can vary depending on the U.S state and because of this we chose to follow the State of Michigan's regulations for E-bikes [44]. Using these regulations for a Class 2 E-bike, we were able to set motor, speed, and user interface engineering specifications for our E-bike. These informed settings for our motor's power and the maximum speed of the E-bike then informed our battery and transmission design accordingly.

Educational Standards in our Educational Website:

While engineering standards were important to follow in terms of our mechanical prototype design, we also considered educational standards in terms of our educational website design. The Nielsen Norman group is a well established web-based user experience consulting firm which has conducted extensive research and set standards for website accessibility, navigation, eye-tracking/content consumption, and others. We followed standards set by the Nielsen Norman group for creating descriptive links on our website and using language which is appropriate for our audience. The US Department of Education also had set style guidelines for "Web Writing". Their standards also reference the Nielsen Norman group. The guidelines set forth by the Nielsen Norman group and the US Department of Education formed our set standards for building our website in the most accessible and educational way possible.

APPENDIX F. Engineering Inclusivity

Throughout the design process, our team made sure to engage in inclusive design practices in order to best accommodate our stakeholders and provide an effective design solution. Our project itself is aimed at inclusivity, in that we should design a way for increased participation in E-bike making and learning regardless of background or identity. To achieve this goal we developed a democratized learning guide through an inclusive website design. Our website communication design features plain language, void of technical jargon where possible, important terms and diagrams, and comprehensive informational sourcing so that any user or stakeholder is able to engage with technical information. Also included in the accessibility of our design are figure descriptions on all website images, so that a vision-impaired user can still experience the images, and keyboard support shortcuts such as up and down arrows rather than requiring the mobility associated with using a trackpad or mouse. These design decisions, amongst others, were conducted so that our solution is as inclusive as possible for the users and stakeholders of our project.

To make our design process more inclusive, our team should have consulted with stakeholders more directly and more often. Due to the short timeframe of this course, we were unable to conduct surveys or usability tests for our website design, and we were only able to engage in a minimum number of interviews with stakeholders and potential users. As a result, our team used online reviews of products such as Amazon user reviews and other manufacturer ratings to guide stakeholder satisfaction or dissatisfaction with existing products and technologies similar to some of our ideated concepts. This stand-in method for stakeholder interaction worked well in reducing any power dynamic biases in the feedback we received. Whereas positive positive reviews could potentially have been coerced out of a user through the influential power of a company/seller, the negative reviews we collected were the honest and unbiased opinions of customers. Given a more flexible timeline our team would have engaged more directly and more often with users and stakeholders in our problem space to better understand the problem space and more accurately assess the efficacy of our design solution and website communication.

APPENDIX H. Environmental Context Assessment

Included in the evaluation of our design solution, we must consider assessing the environmental context of the solution space. This includes considering if our solution meets the first two necessary criteria for sustainable technologies: (1) Does the system make significant progress toward an unmet and important environmental or social challenge? And (2), Is there potential for the system to lead to undesirable consequences in its lifecycle that overshadow the environmental or social benefits?

First, our DIY E-bike retrofit design and website communication both support progress toward the environmental challenge of the University of Michigan 2025 goals for Carbon Neutrality, amongst other national and international carbon reduction goals. Personal transportation via E-bike commuting is less carbon intensive than commuting by traditional combustion engine vehicles. Research has shown that if fifteen percent of all automobile travel was replaced with E-bike travel, overall carbon emissions could be reduced by twelve percent [45] and lead to multiple benefits, including better air quality in urban areas such as Ann Arbor. When considering a single commuter, E-bikes are also less energy intensive than electric passenger vehicles with E-bike battery capacities averaging 500-800 Watt hours [46] and electric vehicle battery capacities around 66 kWh [47]. Our design communication and engagement solution also represents progress toward the social challenge of providing democratized access to making and learning guides for individuals who identify as non-makers, or otherwise would not have access to the making and learning space.

Second, we do not anticipate that our retrofit design, nor our communication and engagement thereof, will lead to undesirable consequences throughout its lifecycle that will overshadow the benefits of this solution. While our design is not currently manufactured, it has been designed so that its production involves maximized recyclability of the materials. Considering the housing of our design, for example, it may be entirely produced by 3D printing with PET-G filament, which can both be recycled and can be sourced from recycled content itself. We do, however, recognize the conflict materials included in Li-ion battery production, and the social costs associated. We still believe that the benefits of our design outweigh the costs, as we are confident in current progress toward more ethical mining practices [48].

APPENDIX I. Social Context Assessment

Included in the evaluation of our design solution, we must consider assessing the social context of the solution space. This includes considering if our solution meets the remaining necessary criteria for sustainable technologies: (1) Is the system likely to be adopted and self-sustaining in the market? (2), Is it so likely to succeed that planetary or social systems will be worse off? And (3), is the technology resilient to disruptions in the market?

Due to existing products in the market, we anticipate that it may be difficult for users to be adopting our design solution. This is not because the existing products already address the problem space, but rather it will require advertising our solution to spread awareness of our learning resource and design. Based on early stakeholder research and engagement, our design offers a solution that is not currently on the market of a concise and understandable guide to E-bike retrofitting that does not require the user to conduct separate research. This was determined through stakeholder mapping and development of user requirements. This was conducted to characterize the potential societal implications and drivers of specific technologies, and increased our awareness of cost/benefit analysis across users. Once our design is adopted by users, the system should be easily self-sustaining due to our website design. Not only does it allow users to return indefinitely to learn more supplemental content or pursue other DIY modifications to their own design, but our website is an editable domain which can be re-published as new material becomes available. In this way, our design is self-sustaining as users continue to explore it, and sustaining as we are able to update the content as needed.

As mentioned previously in the consideration of our solution as a self-sustaining system, our website design communication format is easily editable and can regularly be updated to suit user and market needs. If there is a disruption in “business as usual”, users will be able to navigate through our design process according to what suits themselves and the market most appropriately. We will also be able to provide recommendations and guidance based on dynamic market conditions.

The way that we designed our final solution is to provide each individual with a making guide to accomplish a fully DIY E-bike retrofit build. In this scenario we are not marketing a final product kit, but rather allowing the users to make their own design decisions and construct their own solution. Due to this framework, our solution will never be more economically successful than individual components which already exist on the market such as the motor, sensors, and battery cells. As explained in Appendix H, the most significant contributor to unintended costs for social or planetary systems is the mining of conflict materials for the production of Li-ion battery cells. Our design process encourages the use of these cells due to end-of-life sustainability considerations, modularity, and diagnosability for learning and safety. Advocating the use of these batteries in the promotion of widespread use of E-bikes for commuting would increase the demand of conflict material mining. However, electric vehicle manufacturers such as Tesla use the same battery cells as our design but at a larger scale [49]. If our design communication inspires use of E-bike commuting over individual EV transportation, the number of Li-ion battery cells per user would be reduced.

APPENDIX J. Ethical Decision Making

While our team did not encounter any ethical dilemmas in our design process, we did have to evaluate several decisions based on ethical factors to ensure that we hold ourselves professionally responsible for any unintended consequences of our design decisions. The first of these was the consideration of the usability of our website design. Our goal was to craft a design that is aimed to make E-bike learning and E-bike making as democratized as possible. An ethical dilemma lies in the potential for exclusion from the educational space of our project. As explained in Appendix F, we proceeded to design with accessibility in mind and are confident that our website communication does not directly exclude any group from being able to participate in our making and learning guide.

A second ethics scenario which we navigated involved the sourcing of materials and energy. Our design motivation includes improving the environment through carbon reduction and increasing ethical education and engagement practices. One of our concerns in this space was involving conflict materials or unethically-produced components into our final design. We recognize that Li-ion battery cells involve the mining of conflict materials, as explained in Appendix H, and are confident in our decision to continue their use only due to the fact that our design uses magnitudes fewer than electric vehicle battery designs. We are currently largely unaware of the manufacturing practices of some of our component sources. In the solution context of our team proceeding with the prototype build of our DIY design, we would plan to conduct additional research into our component sources' company ethics to minimize any concerns or unintended consequences. Lastly, our team also considers the sourcing of the energy that charges our battery design. While we aim to reduce carbon emissions, it is likely that the energy powering our retrofit design comes from the combustion of fossil fuels. In this scenario, our impact contradicts our motivation and leads to an unethical practice. However, we are confident that creating a demand for systems that are powered by renewable energy through our retrofit design and communication will lead to more ethical energy sourcing in the future.

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