Aftermarket Hybrid Solution for Light-Duty Trucks

Senior Design Proposal submitted to the
Department of Mechanical and Materials Engineering
College of Engineering and Applied Science
University of Cincinnati

in partial fulfillment of the
requirements for the degree of

Bachelor of Science

in Mechanical Engineering Technology
Mechanical Engineering
Computer Engineering

by

F. Casey Wolnitzek
Freddy Mazza
Max Scholtes
Mikey Krebs

April 2024

Thesis Advisor:

Professor Chris Calhoun

TABLE OF CONTENTS

ABSTRACT

This report outlines the research, design, and implementation of an aftermarket hybrid system for light-duty trucks. Considering the poor fuel efficiency of existing light-duty trucks on the road and the exuberant cost of new fuel-efficient vehicles, our team set out to integrate new electric propulsion and energy storage technologies so existing truck owners can experience fuel savings at a fraction of the cost. The initial efficiency increase we set out to achieve was 30% with a payback period of 50,000 miles. To ensure we were able to achieve that efficiency increase we started using a vehicle dynamics simulator (Autonomie) which allowed us to model various hybrid system configurations. The results from this test showed we could theoretically achieve 20-30% fuel efficiency increase. Our proposed system will integrate an electric motor into the drivetrain of the existing vehicle. We then incorporated the motor controller, wiring, and energy storage into the vehicle needed for proper operation. In order to have seamless integration of hybrid system into the vehicle we connected a microcontroller to the vehicles OBD-2 port. This connection allows the system to take engine parameters and use those to fully control the electric motor. This project not only showcased the feasibility of incorporating new technology to older vehicles for performance improvement but also provided proof that vehicles can be improved long after they leave the production line. This senior design project reflects a comprehensive effort in applying engineering principles to solve practical, real-world problems.

PROBLEM STATEMENT

The push for electrical vehicles is growing stronger every year. Automakers are working tirelessly to deliver these new vehicles to fit customers' needs. Although they are making great strides year after year, there is currently a gap in the market when it comes to electric and hybrid light-duty trucks. Our solution is to develop an aftermarket hybrid system that can be applied to any consumer's internal combustion engine truck and provide them with the fuel efficiency and cost savings that any other EV or hybrid provide.

BACKGROUND

As the awareness of environmental issues increased, air pollution, and fuel consumption led to stricter emissions regulations and incentives for cleaner vehicles. This environment encouraged the development of hybrid technology. In the early 2000s, other automakers like Honda, Ford, and General Motors introduced their hybrid models, further popularizing the technology. The 2010s witnessed the introduction of plug-in hybrid vehicles (PHEVs) and electric vehicles (EVs). PHEVs featured larger battery packs and the ability to charge from external power sources, allowing for extended electric-only driving ranges. EVs operated solely on electricity stored in large battery packs. Today, lithium-ion battery technology has greatly improved the efficiency and electric-only range of hybrid and electric vehicles. This technology made EVs more practical for everyday use. (1) (2) Governments around the world introduced incentives, rebates, and regulations to encourage the adoption of cleaner vehicles, spurring further development of hybrid and electric vehicles. Automotive manufacturers committed to reducing their carbon footprint and invested heavily in electric and hybrid technologies. Today, hybrid vehicles have become a mainstream choice for those seeking to reduce fuel consumption and emissions, and they continue to play a pivotal role in the ongoing transition to more sustainable transportation options. This technology has evolved significantly, with a wide range of hybrid and electric models available to consumers.

RESEARCH

SCOPE OF THE PROBLEM

We see an opportunity to improve on the current state of hybrid vehicles. Decreasing fuel emissions is a current push in society, so we know increasing fuel efficiency to decrease emissions is of high concern. Before we get into the hybrid solution there are key concepts the reader must know before.

LIGHT DUTY TRUCKS

Light-duty trucks, commonly known as pickup trucks, constitute a crucial segment within the automotive industry. These vehicles are designed to offer a versatile solution for transporting cargo or passengers, balancing efficiency, and functionality. Light-duty trucks are characterized by their smaller size and weight compared to their heavy-duty counterparts, making them adept at navigating urban environments while maintaining fuel efficiency. With a payload capacity ranging between 1,500 to 3,000 pounds, they provide a flexible platform for various transportation needs. (1)

The light-duty truck market in 2022 is valued at 7.2 trillion dollars globally. When focusing on the United States auto market, the love for trucks becomes much clearer. In 2021 there were 11.6 million trucks sold to consumers compared to 3.3 million cars sold. Although light truck sales have slightly declined over the past couple years due to increased fuel costs, there's no doubt in the consumer demand for these vehicles. Automobiles are the main form of transportation in the United States with over 76% of the population reporting they have access to their own vehicle. (3)

INTERNAL COMBUSTION ENGINES (ICE)

The history of internal combustion engines spans over a century, beginning with early experiments in the late 18th century. The pivotal moment came in the 1860s when Nikolaus Otto invented the first practical internal combustion engine, known as the four-stroke engine. This innovation ushered in the era of automobiles, with Karl Benz producing the first gasoline-powered car in the 1880s. Internal combustion engines proliferated, revolutionizing transportation and industry in the early 20th century. They played crucial roles in the aviation and marine sectors during this period. Post-World War II, advancements in turbocharging, fuel injection, and emissions control technologies emerged. Today they are highly refined machines that are vital to transportation, energy production, and all-around mechanical application. (2)

The physics of internal combustion engines is rooted in the principles of thermodynamics and fluid dynamics. These engines operate through a series of well-defined processes, adhering to thermodynamic cycles like the Otto and Diesel cycles. During the power or combustion phase, a precisely controlled mixture of air and fuel ignites, generating a high-pressure, high-temperature gas that pushes the engine's piston and converts chemical energy into mechanical work. The compression ratio, spark timing, and air-fuel mixture play pivotal roles in engine efficiency and performance. Heat transfer and fluid dynamics are also fundamental aspects of engine operation, as heat must be efficiently dissipated to prevent overheating, and airflow within the engine is optimized to enhance performance. The physics of internal combustion engines also extends to emissions control, where catalytic converters and other technologies mitigate harmful exhaust emissions. (4)

Spark ignited (SI) internal combustion engines are the propulsion systems used in most consumer automobiles in the U.S. These engines operate using the otto cycle which consists of four processes. The first being the induction stroke; during this step the piston travels downwards in the cylinder pulling the air and fuel mixture into the combustion chamber. The combustion stroke follows; this step involves the compression of the air/fuel mixture where the intake and exhaust valves are closed. Once the piston reaches top dead center (TDC (Top Dead Center)), the cycle moves into the next step. The expansion stroke also known as the power stroke, is where explosion of the air/fuel mixture pushes the piston down creating linear force that translates to rotation force at the crankshaft. The final step is the exhaust stroke. This is where the exhaust valve opens and the piston moves upward in the cylinder, pushing the exhaust gases out of the combustion chamber. This cycle can occur in multiple cylinders almost simultaneously, providing propulsion for the vehicle. (2)

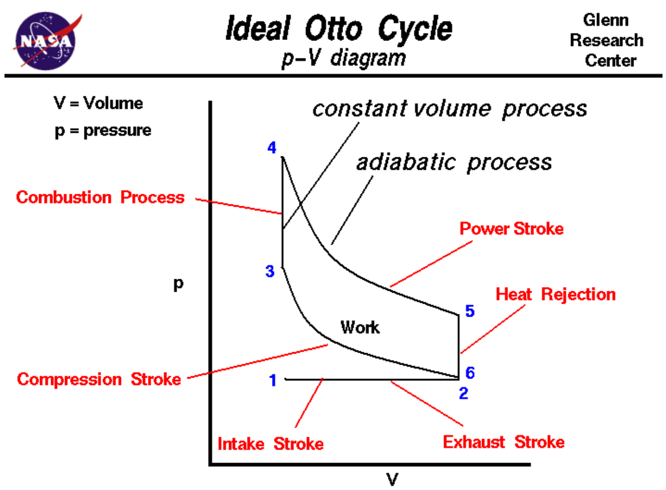


Figure 1 Ideal Otto Cycle (18)

One of the most important metrics for vehicle propulsion is the system's efficiency. ICEs are notorious for poor efficiency when looking at total energy in and out. In general, the efficiency is around 30%. Much of this efficiency loss is due to energy converted to heat via combustion and friction. Automakers have been working for decades to improve this number to as high as 50%. Although this is promising, it requires a highly complex system to reach this number, sacrificing power and longevity. (2)

ELECTRIC VEHICLES (EV) AND HYBRID VEHICLES (HV)

An electric vehicle (EV) is an automobile that operates solely on electricity as its primary source of power for propulsion. Unlike traditional internal combustion engine (ICE) vehicles, which rely on gasoline or diesel fuel, electric vehicles are powered by electricity stored in rechargeable batteries. These batteries supply electricity to an electric motor, which drives the vehicle's wheels, making them highly efficient and environmentally friendly.

EVs offer several advantages, such as reduced greenhouse gas emissions, lower operating costs due to the lower cost of electricity compared to gasoline, quieter operation, and regenerative braking, which can recover energy during braking and improve overall efficiency. As technology continues to advance, electric vehicles are playing a pivotal role in the transition to more sustainable transportation solutions.

While electric vehicles undeniably offer a promising path towards a more sustainable and environmentally friendly future of transportation, it's essential to recognize that they are not the sole solution to the complex challenges faced by the automotive industry. As we shift our focus, we must also consider the role played by hybrid vehicles in this transformative landscape.

A hybrid vehicle represents the convergence of traditional internal combustion engines with innovative electric propulsion systems. This union of technologies revolutionizes the way we think about transportation, compromising the convenience and range of conventional vehicles and the eco-friendly attributes of pure electric cars.

As electric vehicle technology is optimized, hybrid vehicles can use it as well as the co-existing conventional engine technology to create multiple different hybrid vehicle configurations. There is the full hybrid which uses the ICE, an electric motor, and a rechargeable battery pack. A mid hybrid uses the same components on a smaller scale. Last, the plug-in which allows the users to externally charge the battery pack. We will go into further detail and discuss the advantages and disadvantages next.

TYPES OF HYBRID VEHICLES

Full Hybrid

The full hybrid systems have both an internal combustion engine (ICE) and an electrical motor. Compared to a mild hybrid the electrical components in a full hybrid are capable of handling far more of the workload. During city driving, a full hybrid system can operate for some distance solely on electric power. This is why City MPG is higher than Highway MPG in a full hybrid vehicle. The contrary is true for internal combustion engines. Like mild hybrids, full hybrids charge their batteries through the ICE and regenerative braking. (5)

Mid Hybrid

The mild hybrid does not operate the vehicle on electric power alone. Its purpose is to give a small boost to the vehicle's gasoline engine. This is achieved by reducing the engine's load during acceleration from a dead stop. A typical mild hybrid system often uses a 36 to 48-volts (6) electric system that does not need to be plugged in. The batteries are recharged through a combination of power from the gasoline engine and regenerative braking. (5)

Plug-in Hybrids

The plug-in hybrids can charge their batteries via external chargers as well as internal. This allows the vehicle to have greater electric-only range. A plug-in hybrid system falls in between full hybrid and full electric systems. (5)

HYBRID CONFIGURATIONS

A hybrid configuration, in the context of automotive technology, refers to the specific arrangement and combination of power sources and propulsion systems in a hybrid vehicle. Hybrid configurations are designed to optimize fuel efficiency, reduce emissions, and enhance overall vehicle performance by integrating multiple power sources, typically an internal combustion engine (ICE) and one or more electric motors. These configurations can vary in complexity and the way they operate. Here are some common hybrid configurations.

Integrated Started Generator (ISG) System

The ISG system functions as a traditional starter as well as an alternator. The system typically uses a 48-volt battery to provide the initial power needed to crank the engine. Once the engine is running, the ISG can operate as a generator to recover and store energy during deceleration and braking, regenerative braking. The ISG system has the feature of idle stop-start. The system also provides an electric power boost to assist the ICE during acceleration and provide additional power.

Series Hybrid

A series hybrid configuration is a type of hybrid vehicle setup in which an internal combustion engine (ICE) is used solely to generate electricity, rather than directly powering the wheels. In a series hybrid, the ICE operates as a generator, producing electricity that is then used to power an electric motor or motors which drive the vehicle's wheels. This setup allows for flexibility in the choice of the ICE's operating point, enabling it to run at its most efficient RPM range, which can enhance fuel efficiency. Series hybrids often have a high-capacity battery pack to store electricity for use when additional power is required, such as during acceleration or hill climbing. This configuration is known for its potential to reduce emissions and improve fuel economy, especially in urban and stop-and-go driving conditions. (7)

Parallel Hybrid

In a Parallel hybrid, the internal combustion engine is the main source of power while the electric motor generates torque to assist in propulsion. Both the ICE and electric motor are connected to the transmission and coordinated through I process called *torque coupling* (See Figure 2). Torque coupling monitors the vehicle's speed, load, and driver inputs through a control system to blend the two torques together seamlessly and efficiently. Couplers can be pulleys, gears, or chain assembly. The ICE and electric motor can operate separately or as one. (7)

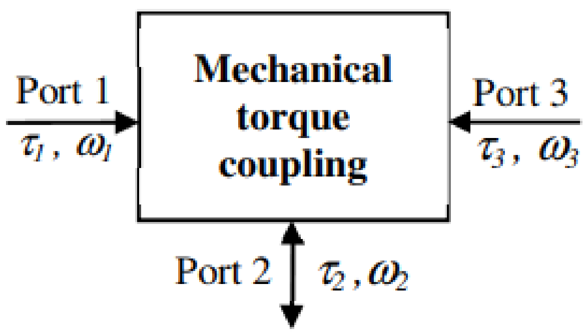


Figure 2 Torque Coupling Visual (8)

TORQUE COUPLING

Figure 2. A parallel hybrid drivetrain represented by a 3-port, 2-degree-of-freedom mechanical system. Port 1 is a unidirectional input (connected to the ICE), while port 2 (connected to the motor) and port 3 (connected to the wheels) are bidirectional input or output of the system (at least one must be an output at any time)

$$\tau_3\omega_3 = \tau_1\omega_1 + \tau_2\omega_2$$

Figure 3 Parallel System Equation (8)

Equation. Ignoring losses, power input to the torque coupler is equal to its power output. τ_3 is the torque output of the mechanical coupling. Considering the structural parameters, k_1 and k_2, of the coupling system, which fixed parameters of the system, τ_3 can be expressed as Equation 4.

$$\tau_3 = k_1\tau_1 + k_2\tau_2$$

Figure 4 Structural Torque Parameters Equation (8)

The contributing torques τ_1 and τ_2 are independent of each other and thus, can be individually controlled. However, due to power conservation, Eq. (5) leads to the constraint that speed of the power sources are linked together and governed by the relationship (8):

$$\omega_3 = \frac{\omega_1}{k_1} = \frac{\omega_2}{k_2}$$

Figure 5 Power Conservation Equation (8)

Pre-trans Parallel Hybrid

The pre-transmission layout is a specific configuration of a hybrid vehicle where the internal combustion engine (ICE) and an electric motor are both mechanically connected to the vehicle's transmission but are located before the transmission (figure 6). This setup allows both the ICE and the electric motor to contribute directly to powering the wheels. Pre-transmission hybrids may have a slight advantage in terms of regenerative braking efficiency because the electric motor can directly engage the wheels to recover kinetic energy during braking. (8)

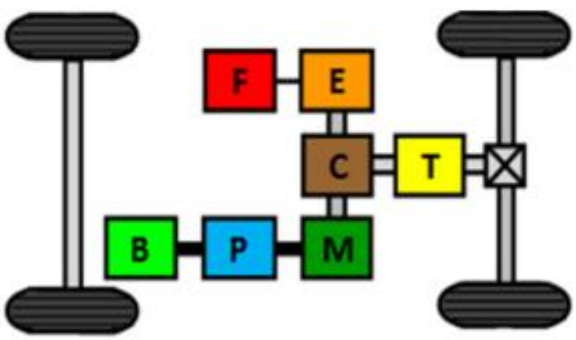


Figure 6 Pre-trans Parallel Hybrid Diagram (8)

Post-trans Parallel Hybrid

The post-transmission layout is a specific configuration of a hybrid vehicle where the internal combustion engine (ICE) and an electric motor are both mechanically connected to the vehicle's transmission but are located after the transmission. This setup allows both the ICE and the electric motor to contribute directly to powering the wheels. (8)

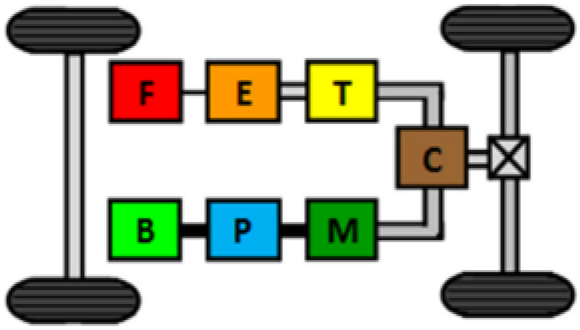


Figure 7 Post-trans Parallel Hybrid Diagram (8)

Series Parallel Hybrid

In a series-parallel hybrid, both an internal combustion engine and electric motor work together to provide propulsion. The ICE generates power to drive the wheel and generate electricity. During low-speed city driving, the electric motor can provide most of the power, with the ICE acting as a generator to supply electricity. At higher speeds, the ICE can directly drive the wheels, assisted by the electric motor. This configuration provides greater flexibility, allowing the vehicle to adapt to various driving conditions and optimize fuel efficiency.

Dual Mode Hybrid

The Dual-Mode or Two-Mode hybrid system is an infinitely variable speed hybrid transmission that works with the engine and battery system and automatically chooses to operate in a parallel or series hybrid path to maximize efficiency and minimize emissions, fuel consumption and noise. The first mode works like a full hybrid vehicle. In the second mode the system adjusts varying amounts of engine and motor functions to meet requirements. This system is found in buses and large SUVs. (9)

ELECTRIC MOTORS

An electric motor is a device that converts electrical energy into mechanical energy, typically in the form of rotational motion. It operates based on the principles of electromagnetic induction, using the interaction between electric current and magnetic fields to generate mechanical force. One major difference between an electric motor and an internal combustion engine is the Power vs Rpm curve. For an electric motor maximum torque is reached at 0 rpm and will be maintained until the motor reaches maximum power. Maximum torque for an internal combustion engine is reached between rpms of 1500 and 6500, quickly falling towards redline. In hybrid vehicles, it's a specialized electric motor designed to work in conjunction with an internal combustion engine to provide additional propulsion power and increase overall vehicle efficiency. These motors are powered by high-voltage batteries and can operate independently or in tandem with the ICE, helping to reduce fuel consumption and emissions, especially during low-speed driving or acceleration. Electric motors in hybrid vehicles play a crucial role in enabling regenerative braking, where they convert kinetic energy into electricity to recharge the battery, further enhancing the vehicle's energy efficiency. When selecting an electric motor for an application multiple variables must be considered.

When picking the right motor for the vehicle, there are a few variables that all depend on each other. One must consider the vehicle's weight, drive cycle, the battery size and capacity, and where all the parts fit. The next characteristic to consider is the output torque and speed needed. While considering the size of the electric motor, one must keep in mind the battery size as they both influence each other. To appropriately size the system, we need to determine the voltage needed for the system. This will determine the size of the battery pack and the current that it needs to enable the motor to deliver the necessary torque. Commercial EV's run around 350-400V, but some cars run as high as 800V. The higher the voltage the less current that is needed to reach a desired power. A high voltage system is more expensive and runs at higher rpms which will impact the transmission. They state, "That many electric car conversations run on a low voltage, 100-150V." Broadly speaking, lower voltage motors and accessories are cheaper. (10)

$$Power = Voltage\ x\ Current$$

ELECTRIC BATTERIES

To combat the poor efficiency of internal combustion engines, engineers started to shift their focus to electric powered vehicles. Surprisingly electric vehicles (EV's) have been around almost as long as ICE vehicles. In 1881, Gustave Trouve built an electric drive tricycle using a 0.1 hp DC (Direct Current) motor fed by lead-acid batteries. Although electric vehicle discovery has existed for so long, it has not been a viable solution until very recently. The core reason for that is the technology of energy storage. Retaining the amount of energy to propel a vehicle in a reasonable size and doing it safely has been the largest opponent of electric vehicles.

The turning point of introducing electric propulsion in vehicles successfully is the introduction of the Toyota Prius. Released in 1997, although not fully electric, the Prius revolutionized efficient vehicle propulsion. The NHW11 model consisted of a 1.78 Kwh battery, 70 hp gasoline engine, and a 33kW electric motor. This vehicle was capable of 42 mpg city, 41 mpg highway, and 41 mpg combined. Up to this point, these fuel efficiency numbers were unheard of in passenger vehicles and pushed other automakers to adopt a hybrid system in their vehicle lineup. Given that ICEs are wildly inefficient, adding an electric motor and energy storage system allowed the vehicle to utilize the electric motor for propulsion during low efficiency conditions. The Prius drivetrain can operate in full gas, mix of gas and electric, and fully electric depending on the propulsion scenario. Power for the system is accumulated using electric generation by the gas engine and via regenerative braking. (2)

Around a similar time, General Motors unveiled the first fully electric production vehicle, the EV1. The push for this vehicle was derived from California Air Resources Board's (CARB) mandate that made the production and sale of zero-emission vehicles a requirement for major automakers to continue to sell vehicles in California. The EV1 offered a range of only 70-90 miles, providing seating for just 2 passengers. Although well received by the public, the EV1 quickly prevailed as an automotive flop. The limited range and 15-hour charge time was just not adequate for most American consumers. Fast forwarding a decade, almost all major car manufacturers offered either a Hybrid or fully electric vehicle for consumers. At this point battery technology and engineering capacity allowed for relatively successful electric infused vehicles that were useful enough for the average consumer. (11)

BRAKING

During the use of conventional braking in a conventional engine car, the sole purpose of the brakes is to stop the vehicle. This is achieved through a hydraulic system. Once brakes are initiated, the hydraulic system connects the brake pedal to the disc brakes. Once the brake pedal is applied the master cylinder pushes fluid to the slave cylinder(s), forcing the pads of a disc brake inward. The vehicle decelerates due to the friction between the pads and the discs. This process transfers all the energy of the vehicle's motion into kinetic energy, expunging it as heat. One advantage of an electric or hybrid system is that it can capture and store that kinetic energy into potential energy. This is carried out through a process called regenerative braking. (12)

REGENERATIVE BRAKING

Regenerative braking is a technology used in hybrid and electric vehicles, vehicles that use an electric motor and battery, which allows the vehicle to capture and convert the kinetic energy generated during braking into electric energy. When the brakes are applied, the polarity of the electric motor is reversed, which causes the output shaft to turn the motor like a generator (See figure 8). The energy generated is then stored in the battery system and can be used to power the electric motor when driving the vehicle. By capturing the energy that would otherwise be lost during braking, regenerative braking helps to increase the energy efficiency of hybrid and electric vehicles, reducing the amount of energy needed to power the vehicle and extending the vehicle's range. Additionally, regenerative braking also reduces wear and tear on the brakes, extending the life of the pads and reducing maintenance. (12)

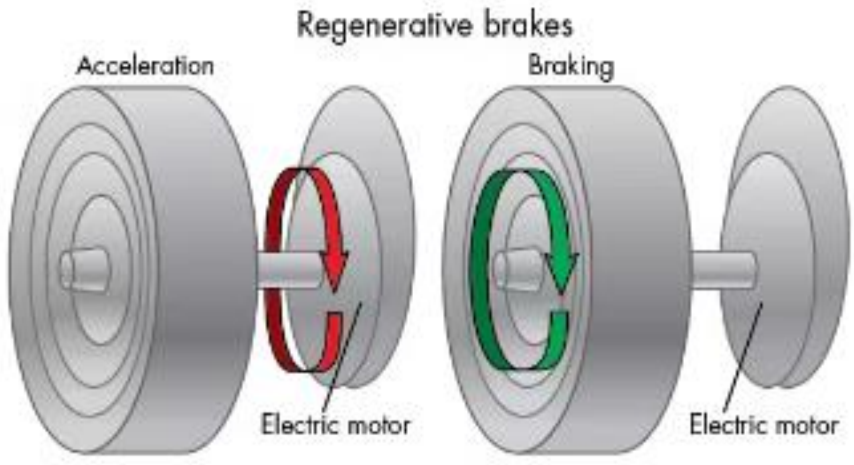


Figure 8 Regenerative Braking Visual (12)

As we delve into the remarkable technology of regenerative braking and its capacity to harness and store energy during deceleration, it becomes evident that this innovation requires a carefully orchestrated ensemble of components to function seamlessly. The transition from conventional friction-based braking to regenerative braking necessitates a well-coordinated integration of electric motors, high-capacity batteries, sophisticated control systems, and advanced sensors. These crucial components work in harmony to not only optimize energy recovery but also ensure the safety and efficiency of this transformative braking system. These are the components needed to successfully create a regenerative braking system.

Electric Motor/Generator

In an electric vehicle (EV) or hybrid electric vehicle (HEV), the electric motor(s) used for propulsion can also function as generators during regenerative braking. When the driver lifts off the accelerator pedal or applies the brake pedal, the motor switches to generator mode, converting the kinetic energy of the moving vehicle back into electrical energy. These are the components that are active when the electric motor switches from motor to generator.

Inverter

The inverter is responsible for controlling the electric motor's operation. During regenerative braking, it reverses the motor's role from propulsion to generation, and it also converts the generated electrical energy from alternating current (AC) to direct current (DC) if necessary.

Battery Pack

The captured electrical energy is typically sent to the vehicle's high-voltage battery pack for storage. Lithium-ion batteries are commonly used in electric and hybrid vehicles. The battery stores the energy as chemical potential energy for later use in powering the vehicle.

Brake Control System

The vehicle's brake control system plays a crucial role in coordinating regenerative and friction braking. It determines the appropriate balance between regenerative and friction braking based on factors like driver input, vehicle speed, and battery state of charge. When regenerative braking alone cannot provide enough deceleration or the battery is fully charged, friction brakes may be applied in conjunction with regenerative braking.

Energy Management System (EMS)

The EMS is responsible for optimizing the energy flow in the vehicle, including controlling regenerative braking. It determines when to activate regenerative braking, how much energy to capture, and when to use friction brakes. It also manages the distribution of energy between the battery and the electric motor.

Control Electronics

Various sensors and control units monitor vehicle speed, throttle position, brake pedal input, and other parameters to ensure that regenerative braking is applied smoothly and effectively.

CAN-BUS SYSTEM

In short, the CAN (Controller Area Network) Bus system is the nervous system of the car. It connects all the ECU's (electronic control units), sensors, peripherals, and miscellaneous electronics of the car, and ensures that they are all communicating with each other. All modern cars run a CAN bus system. Before the CAN system, cars ECUs were much simpler, less reliable, and required extremely complex point-to-point wiring. (13)

Below is a diagram that shows a typical CAN bus system, along with the LIN Bus system, which operates at a lower speed "Local interconnect network". The lower speed, cost-effective communication of the LIN bus controls the lower priority systems that don't rely on real-time fast response (i.e. door locks, windows, power seats, heater, etc.). (14)

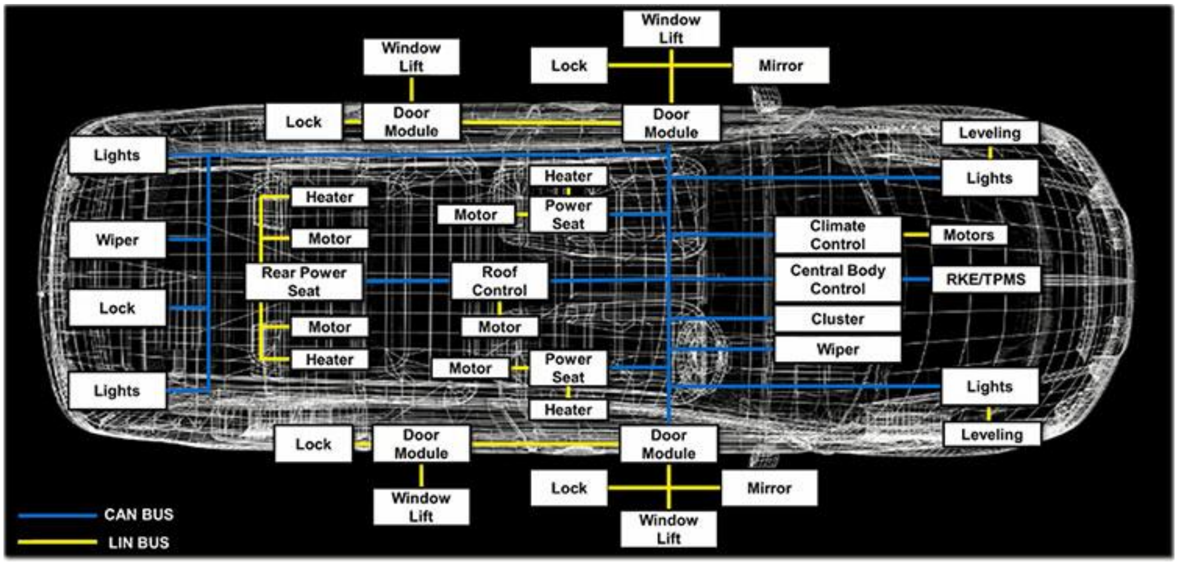


Figure 9 CAN bus Vehicle Layout (13)

The CAN bus offers several key advantages. Firstly, it simplifies communication between Electronic Control Units (ECUs) by replacing complex analog signal lines with a single CAN system, reducing errors, weight, wiring, and overall costs, thanks to its requirement of only two communication wires (CAN High and CAN Low). Secondly, it provides a centralized point of entry for communication with all network ECUs, facilitating central diagnostics, data logging, and configuration. Additionally, the CAN bus is exceptionally robust against electric disturbances and electromagnetic interference, making it highly suitable for safety-critical applications like vehicles. Finally, it ensures efficiency by prioritizing data frames based on their ID, allowing high-priority data to access the bus without causing interruptions to other frames or CAN errors. The CAN bus uses terminated, twisted pair wiring, and nodes are drop connected. Each node has a CAN transceiver and a microcontroller unit (MCU) with CAN functions. (13)

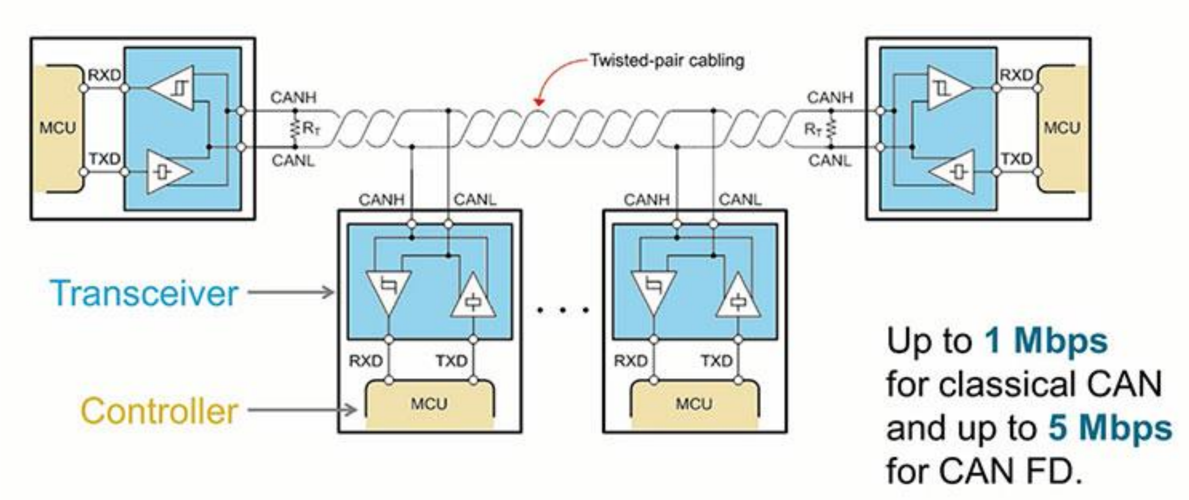


Figure 10 CAN bus Microcontroller Unit (13)

The future of CAN Bus systems may be impacted by the development of non-compatible technologies (such as AI and IOT technologies in automotives). It may also be made obsolete by the need for increasingly advanced vehicle functionality. (13)

CAN systems can be customized using specific companies' systems that allow modular systems/ programmability. This allows the user to add sensors they need, see raw data of vital systems (RPM's, fluid temperatures/ pressures, speed, throttle positions). This is extremely important for our specific situation, as we will need to know exactly how our bolt on hybrid impacts the rest of the engine's internals.

ELECTRONIC COMPONENTS

Automotive sensors are electronic devices that monitor performance and provide data for various vehicle parts. They measure temperature, pressure, speed, airflow, and more. These sensors analyze data and send the information to a car's computer, allowing the computer to make adjustments to ensure optimal engine performance, fuel efficiency, and safety.

Sensors play a pivotal role in various aspects of the automotive industry due to five primary reasons. Firstly, they are essential for safety, ensuring the well-being of drivers, passengers, and pedestrians by enabling vehicles to react swiftly to potential threats through sensors like anti-lock brake system sensors, lane departure warning system sensors, blind spot detection sensors, and tire pressure sensors, thus averting accidents. Secondly, sensors contribute to fuel efficiency by continuously monitoring and adjusting engine parameters, such as air-fuel ratios, throttle position, and spark timing, to optimize fuel consumption. Thirdly, they aid in emissions control, ensuring that harmful emissions remain within acceptable limits, with sensors like oxygen sensors, catalytic converter sensors, and exhaust gas temperature sensors working together to detect and notify the driver of emissions-related issues. Additionally, sensors assist in performance optimization by constantly monitoring various vehicle parameters, providing crucial data to the engine control unit (ECU) to optimize fuel injection, valve timing, and ignition timing. Lastly, sensors are crucial for vehicle diagnostics, identifying issues before they escalate into major problems. Most modern vehicles are equipped with an onboard diagnostics system that employs sensors to monitor various vehicle components, alerting the driver to malfunctions and enabling timely corrective actions to avoid costly repairs. The most basic sensors include temperature (oil, coolant, engine, etc.), throttle position, oxygen in each cylinder, and mass airflow. (15)
Here is a list of the most common types of automotive sensors, plus their uses:

Airflow Sensor

The airflow sensor measures the air entering the engine and helps determine the appropriate fuel-to-air ratio for efficient combustion.

Engine Knock Sensor

The engine knock sensor detects unusual vibrations, which indicate that the engine is experiencing detonation (also known as knocking or pinging). This allows the engine control module to make adjustments to prevent engine damage.

Engine Speed Sensor

The engine speed sensor detects the rotational speed of the engine's crankshaft, which helps the control module manage the timing and fuel delivery.

Camshaft Position Sensor

The camshaft position sensor helps the control module determine the position of the camshaft, which is essential for synchronizing the engine's valves with the fuel injection cycle.

Manifold Absolute Pressure (MAP) Sensor

The manifold absolute pressure sensor measures the air pressure in the intake manifold to help the control module manage the air/fuel ratio.

Throttle Position Sensor

The throttle position sensor indicates how far the throttle valve is open, which allows the control module to manage fuel delivery and engine performance.

Voltage Sensor

The voltage sensor measures the vehicle's electrical energy to help the control module prevent overcharging or undercharging the battery.

Oxygen Sensor

The oxygen sensor measures the oxygen content in the exhaust gas to help the control module manage fuel delivery and ensure efficient combustion.

NOx Sensor

The NOx sensor measures the amount of nitrogen oxide in the vehicle's exhaust, which helps the control module manage emissions.

Temperature Sensor

The temperature sensor helps the control module manage engine temperature and prevent overheating.

Fuel Temperature Sensor

The fuel temperature sensor helps the control module determine the vehicle's fuel temperature, affecting fuel delivery and engine performance.

Speed Sensor

The speed sensor detects the rotational speed of the vehicle's wheels, which helps the control module manage anti-lock braking systems and traction control.

Parking Sensor

The parking sensor uses ultrasonic or electromagnetic technology to detect nearby objects while parking to prevent collisions.

Rain Sensor

The rain sensor automatically adjusts windshield wiper speed and frequency based on the rainfall detected on the windshield.

APPLICABLE STANDARDS

Over the last decade of innovating hybrid and electric vehicles, standard practices and rules have been established to regulate emission, to ensure safety to the consumer, and to guarantee a reliable product. Here are various standards to that have put in place for the hybrid and electric vehicle industry:

BATTERY STANDARDS

UN Regulation No. 100

This regulation, established by the United Nations Economic Commission for Europe (UNECE), set forth uniform provisions for the approval of electric and hybrid vehicles concerning the electric powertrain components. It covers aspects like electrical safety, battery durability, and electric propulsion system performance.

IEC 62660-1

Developed by the International Electrotechnical Commission (IEC), this series defines performance and testing requirements for lithium-ion batteries used in electric and hybrid vehicles. These standards cover safety, environmental testing, and performance testing.

ISO 6469 Series

The Internal Organization for Standardization (ISO) has established a series of standards that address the safety of electric and hybrid road vehicles.

Safety and Environmental Standards

There are general safety and environmental regulations related to safe handling, recycling, and disposal of high-voltage batteries to minimize environmental impact.

Testing and Certification

Battery packs and systems used in electric and hybrid vehicles undergo various tests and certifications to ensure they meet safety and performance requirements. These tests consist of assessments of thermal management, short-circuit protection, and crash safety.

ELECTRIC POWERTRAIN STANDARDS

IEC 61851 Series

The International Electrotechnical Commission (IEC) has established a series of standards for electric vehicle conductive charging systems. These standards govern charging infrastructure and include safety requirements for power transfer systems between the infrastructure and the vehicle.

IEC 62196 Series

This series addresses the dimensions and general requirements for vehicle couplers used in charging. This standard helps ensure compatibility between charging infrastructure and electric vehicles.

Testing and Certification

Electric powertrain components and system undergo testing including the assessment of electrical system integrity, thermal management, and crash safety.

ENERGY EFFICIENCY AND TEST

Energy efficiency standards for hybrid vehicles vary by country and region. These standards primarily focus on fuel efficiency and reducing greenhouse gas emissions. They encourage the development and adoption of hybrid vehicles.

Corporate Average Fuel Economy Standards (CAFÉ)

These standards regulate how far a vehicle must travel on a gallon of fuel. This is an average MPG rating across a manufacturer's whole fleet. These standards are broken up into cars and light-duty trucks, medium-duty trucks, and heavy-duty trucks.

ENVIRONMENT STANDARDS

The United Stated Environmental Protection Agency (EPA) has reducing greenhouse gas emission as a top priority. They have rules and standards in place for 2027 (16) to further reduce harmful air pollutants from light-duty and medium duty vehicles. Hybrid vehicles help reduce output emissions of vehicles. Hence, passing the emission standards for a conventional engine vehicle.

INTEROPERABILITY STANDARDS

Standards for communication protocols and data exchange between different EV and HV components and systems. This includes standards for vehicle-to-charger communication and data exchange. Different regions may have their own specific standards and initiatives.

Charging Connector Standards

Charging connection standards vary in different regions and countries. For example, Europe and North America used a Combined Charging System (CCS) that combines AC and DC charging into a single connector. Second, Japan uses a fast-charging system call CHAdeMO.

ISO 15118: Vehicle-to-Grid Communication

This international standard defines communication between electric vehicles and charging infrastructure, including smart grid applications. It allows for bi-directional energy flow.

Open Charge Point Protocol (OCPP)

This is a communication protocol used to manage electric vehicle charging stations. This allows different charging stations to interoperate and communicate with various electric vehicles.

Manufacturer-specific Standards

On top of all these organizational standards, automotive manufacturers often have internal standards and specifications for all their products that are shipped to the customer. These standards are developed to meet or exceed regulatory requirements and ensure product quality.

Federal Motor Vehicle Safety Standards (FMVSS)

Title 49. Subtitle IV. Part C. Improved Vehicle Tech. SEC. 131. Transportation Electrification

This essentially states to ensure that the truck's original safety standards are maintained whilst installation of new hybrid system.

STATE OF THE ART

The current state of hybrid vehicles is bought directly from the automotive manufacturer. One can either buy a hybrid or electric truck. Major vehicle manufactures like Ford, Toyota, Douge, Honda, and Hyundai have at least one hybrid truck in their 2024 fleet. Compared to conventional engine trucks, these hybrid trucks have a major increase in city miles per gallon through the process of regenerative braking and the idle-off feature. Some companies have created a fully electric truck, Ford with the F-150 Lighting and Telsa's impending Cybertruck. The electric truck has multiple drawbacks. (1)

A truck is known for its long range, high tow capacity, and durability. The electric truck brings question to else key features. Since it only uses batteries as a power cell, there is a limited range, out-of-the-way charging ports, and a long charge time. An electric truck is much heavier than a conventional engine truck because of the weight of the batteries. The weight of 30 gallons of gas is about 180 lbs. while the battery pack of the Ford F-150 Lighting is 1800 lbs. This added weight reduced its payload capacity. The battery pack has a negative effect on the extreme durability of a truck. In severe cold weather, the range of the battery will decrease. Since the battery pack of a hybrid is much smaller and is in combination with an ICE, these flaws are much more negligible.

One feature that can be improved for the hybrid truck is its ability to integrate. Currently, all hybrid trucks are bought from its manufacturer. What if the system could be retrofitted into an existing ICE and achieve the same performance as a hybrid truck?

END USER

The end users for the retro-fitted hybrid system are anyone with a current light-duty truck looking to increase fuel efficiency without buying a new vehicle. There are many businesses that have light duty trucks for their employees to commute to job sites and haul around tools and light equipment. Converting these trucks would decrease their fuel consumption, increasing profits for the company.

SUMMARY OF RESEARCH

In conclusion, our exploration of hybrid and electric vehicles (EVs) illuminates a path towards a more sustainable and efficient future in the automotive industry. We began by recognizing the enduring importance of light-duty trucks and their dominant role in the global market.

The journey led us through the historical and technological evolution of internal combustion engines (ICEs) and their quest for enhanced efficiency. Simultaneously, the emergence of electric propulsion, fueled by innovation and environmental consciousness, offered a promising alternative.

We delved into the heart of these advancements—electric motors, their selection criteria, and the paramount role they play in reshaping transportation. Hybrid configurations emerged as versatile solutions, offering adaptability to diverse driving scenarios. Regenerative braking showcased its energy-saving potential, while the Controller Area

Network (CAN) Bus system underlined the backbone of modern vehicles, ensuring seamless communication between electronic control units and sensors.

Throughout our research we discovered how far electric and hybrid vehicle technology has become and how innovation in this space will allow us to achieve our hybrid system. Looking into previous EV's and Hybrids we now have a better scope on our component sizing which we will be able to narrow down further once we run simulations. Our electric motor will have to be sized appropriately with keeping cost, reliability, and power in mind. The electric motor is the component of our design that is the keystone for its operation. The motor will both propel the vehicle while also recapturing energy through regenerative braking. With an important aspect being regenerative braking, we focused a lot of research on how it functions and how it can be optimized. This information is crucial to both system viability as well as system performance. We will be focused heavily on maximizing our design to recapture as much energy as possible. Another key component of our research was figuring out the automotive CAN Bus system. This system, which is present in every modern vehicle, allows all the vehicles' computers to communicate with each other. We will be utilizing this system by tapping into the OBD2 port on our truck and pulling important real time information from the vehicle. This information will be used to control every aspect of our system as well as supplying us with useful data. Lastly, we looked at current hybrid solutions which we believe are not up to par and are too costly for the average consumer. We will be analyzing those hybrids to utilize what they did right and correct the things they did wrong to accomplish our design goals.

QUALITY FUNCTION DEPLOYMENT

CUSTOMER FEATURES

As we considered the features for our retrofitted hybrid system, we presented a survey to people who currently own a light duty truck, conventional or hybrid. (The survey results can be found in Appendix A.) The survey asked what current vehicle one owned, the amount one drives, what features are important in a hybrid truck on a scale of 1-5, and how well their current vehicle achieves those features on a scale of 1-5. The survey received 50 participants. The data was analyzed to give "Weighted Importance" to each customer requirement of the HoQ. The customer requirements that we focused on were:

- High Fuel Efficiency – Weighted Importance: 0.132
- Vehicle Reliability – Weighted Importance: 0.177
- On Board Power – Weighted Importance: 0.112
- Low Cabin Noise – Weighted Importance: 0.127
- High Horsepower/Torque Rating – Weighted Importance: 0.147
- Smooth Driving Experience – Weighted Importance: 0.148
- System Cost – Weighted Importance:0.157

PRODUCT OBJECTIVES / ENGINEERING CHARACTERISTICS

To address the customer features, we developed engineering characteristics to give quantitative objectives for the product to achieve.

Fuel Efficiency (Percent MPG increase)

The system must increase fuel efficiency with a target value of 30%.

Power Recovery (kW)

The system must recover power through regenerative braking.

System Failure (Yes/No)

The system reliability must return stock vehicle reliability.

Electrical Output Power (Amps)

The system has useful external power output.

Battery Capacity (kW)

The battery is sized correctly based on power needs.

Noise (dB)

The interior noise must remain the same.

Theoretical Propulsion Output (HP/ft-lbs)

This value is calculated to determine what our theoretical power output through mechanical coupling.

Satisfactory ride quality (Yes/No) – Relative Weight: 7.8

Ride quality must remain the same.

Cost ($)

System cost meets target value.

Payback Period (miles)

The system's payback period through fuel savings is 50,000 miles. Based on the results of the survey and our House of Quality, we have assigned relative weight ratings to each engineering characteristic. The characteristics and their associated ratings are listed below. We will use this data to move through the design to justify our decisions.

HOUSE OF QUALITY

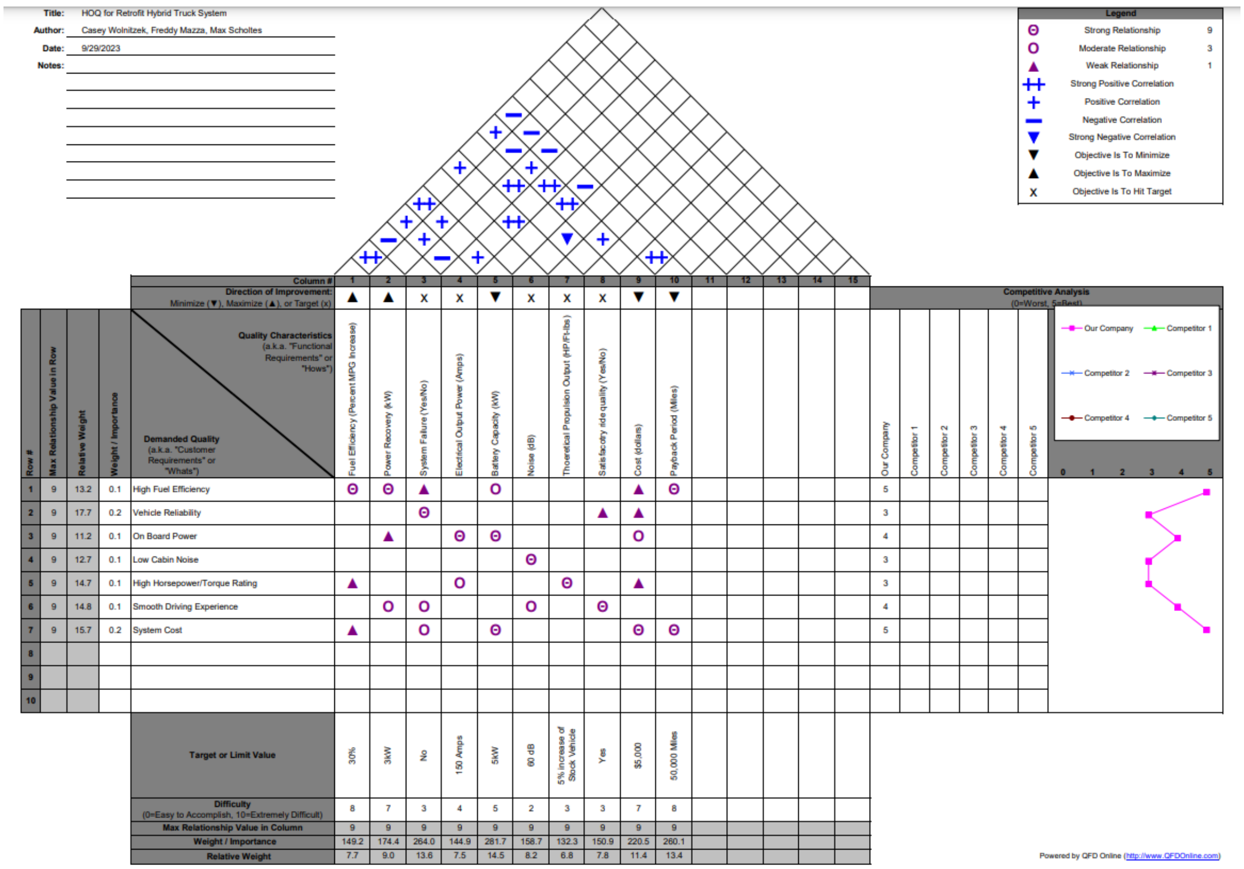


Figure 11 House of Quality

KEY DESIGN FEATURES

Here is a breakdown of the important features of our design:

Electric Motor

The motor is what will assist the gasoline engine during vehicle propulsion to achieve higher operating efficiency.

ECU (Electronic Control Unit)

The ECU will be the brains of our system. It will take engine data and inputs from the vehicle and will tell the motor when and how to operate. This will be programmed to optimize the system based on the vehicle.

Battery

The battery will provide power for the system to operate. It will accumulate power via the regenerative braking and store it for when the motor needs power.

DC to DC Converter

The converter will be used to alter the voltage coming out of the battery to change to the voltage needed for the system.

TEAM MEMBERS AND RESPONSIBILITIES

Freddy Mazza – Will be responsible for team meetings organization, regenerative braking system analysis, and idler pulley design and assist in harmonic balancer coupling designs.

Max Scholtes – Will be responsible for electrical layout design, system to vehicle communication, and system controls.

Casey Wolnitzek – Will be responsible for vehicle system simulation, battery and ECU mounting, and overall system integration.

Mikey Krebs – Will be responsible for document control and creation of motor mount design and fabrication and assist in overall integration and build of the system.

CONSTRAINTS

Economic

The budget of 5000 is based on main required components to achieve efficiency. The theoretical efficiency gain is 20-30% which gives a payback period of 50,000 miles after purchase.

Environmental

In terms of the surrounding environment of the system, the electric motor size is a major design constraint as it drives how big to make the motor mount and consider the space in the engine bay. Which brings up another constraint: engine bay space. This space is very tight and limited, so deciding where to place the electric motor is a crucial design aspect and necessity as the hood needs to be able to remain closed as the truck is moving. The internal temperature of the bay will be hot so the inserted components will need to be able to withstand higher temperatures. Some components are recyclable such as the lithium-ion battery, but hazardous chemicals are involved with the recycling process and chemical waste is produced.

Sustainability

Lithium-ion batteries are a concern as they are made from non-renewable resources, however a size of this battery is fraction of what EVs have today. The motor mount will be made from metal which involves metal wear over time, especially at the mounting points and faces. There will also be welds on the motor mount which hold it together which may deteriorate over time. In general, there are a lot of metal components that will wear overtime.

Manufacturability

There is slight in-depth machining processes that need to be done for the motor mount and motor coupler, however they are not too complex to render it a major concern for the project's feasibility. Parts to be machined in house at Victory Parkway Campus and some out of house at former employer's shop.

Ethical

The system claims to achieve 20-30% efficiency improvements, but in the scenario where a particular driver is a little more reckless than not, they may not achieve as good as efficiency as claimed. This presents a potential dilemma where the customer is not getting the expected savings in the timespan claimed for this product.

Health and safety

A 48-volt electrical system will be in use which is a high point of low voltage systems, so risk is a possibility for personal injury and/or fire hazards. With that, Lithium-ion batteries have some risk potential in associating with fire starting.

Welding has some risks associated with it as well with arc flashes, etc. if proper safety PPE is not used. This goes with while working in the shop building the system, proper PPE needs to be worn to ensure safety when utilizing metal cutting machines or simply building the system in the existing truck.

The system will be used to decelerate the vehicle, which can instigate risks if the system fails to brake, and a person who fails to brake manually could cause an accident. Essentially, if the system fails it can affect the dynamics of vehicle deceleration.

Specifications

Material needs to withstand high stress and oscillating stresses (cyclic loading).

CONCEPT DRAWINGS

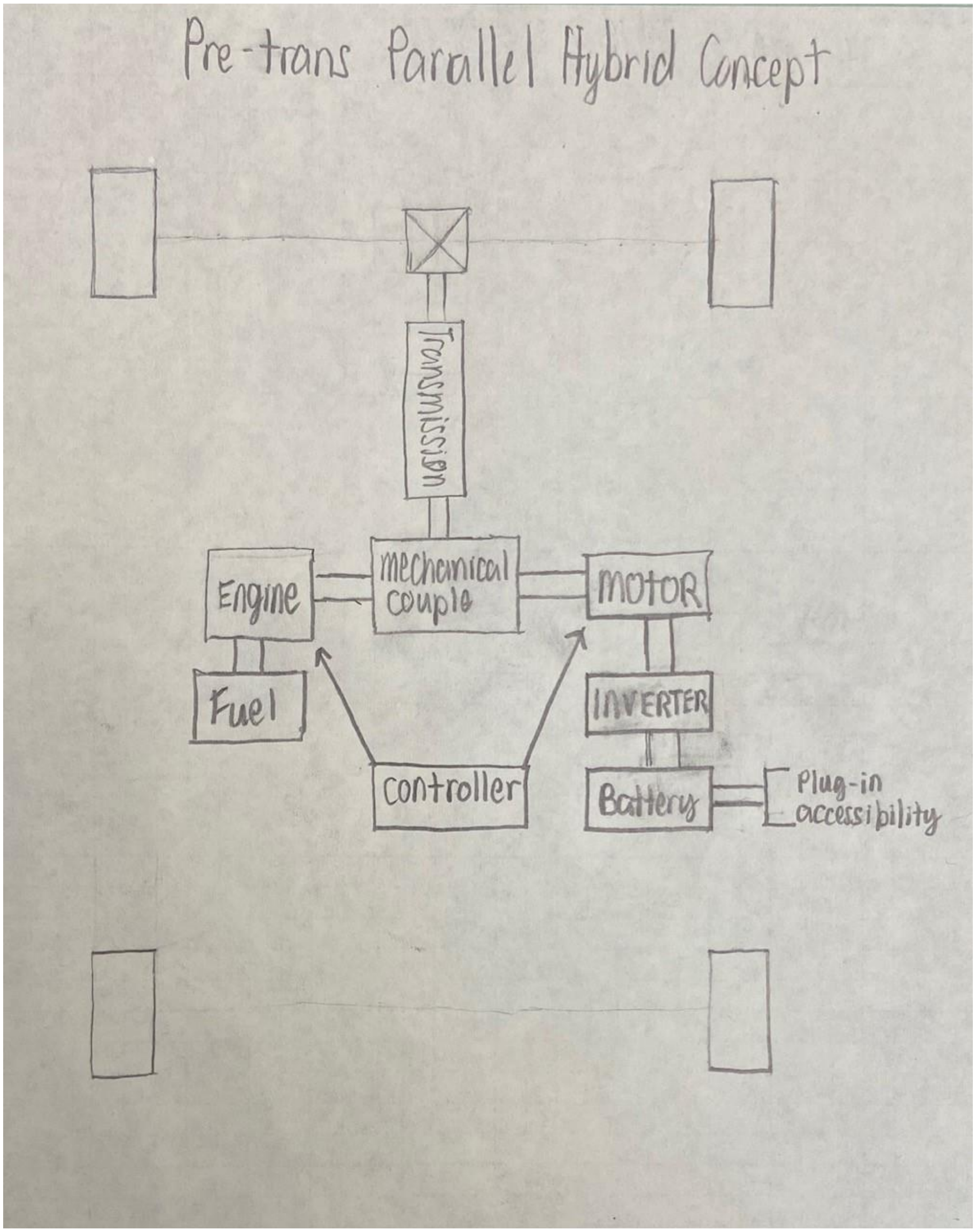


Figure 12 System Configuration Concept

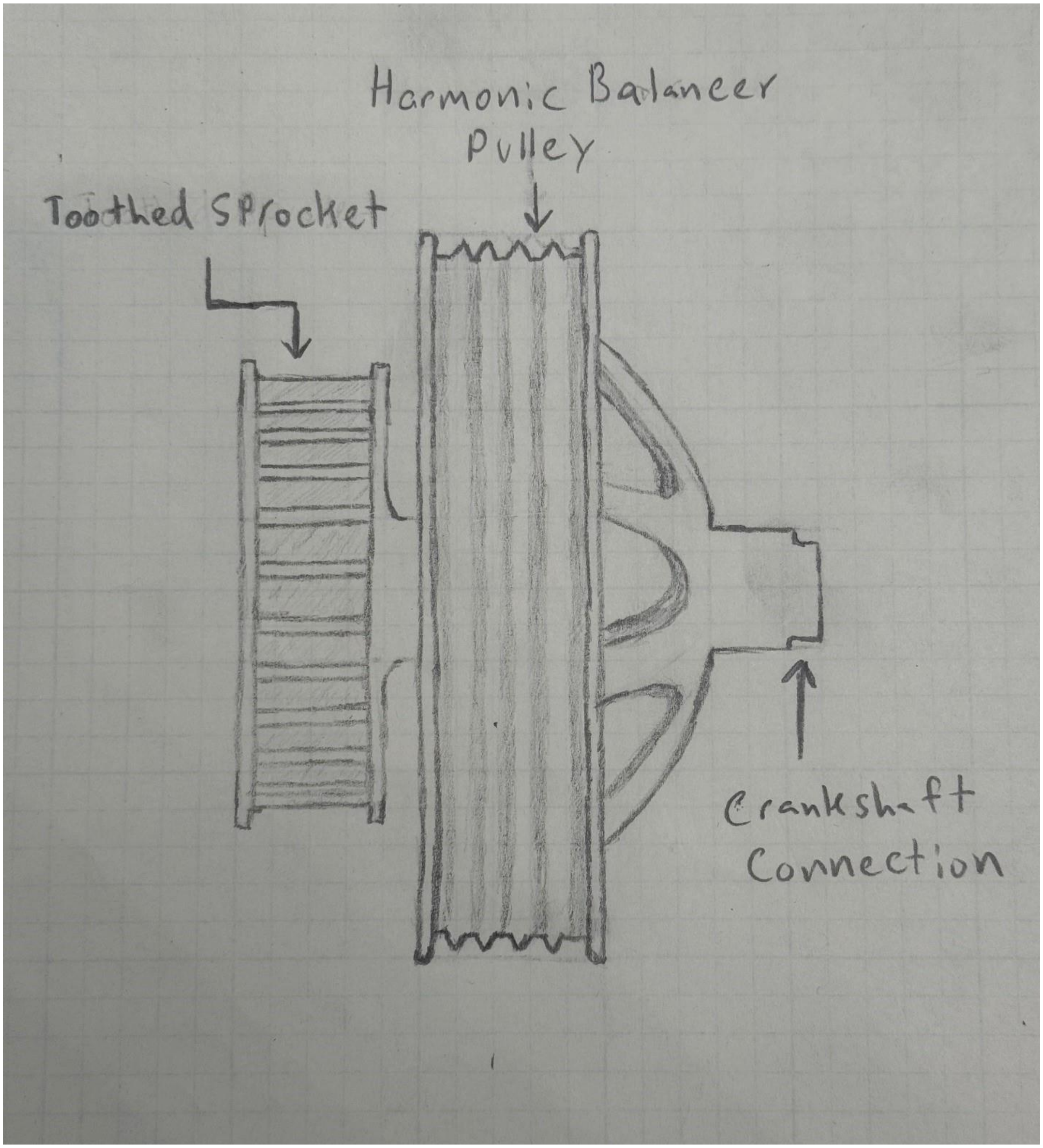
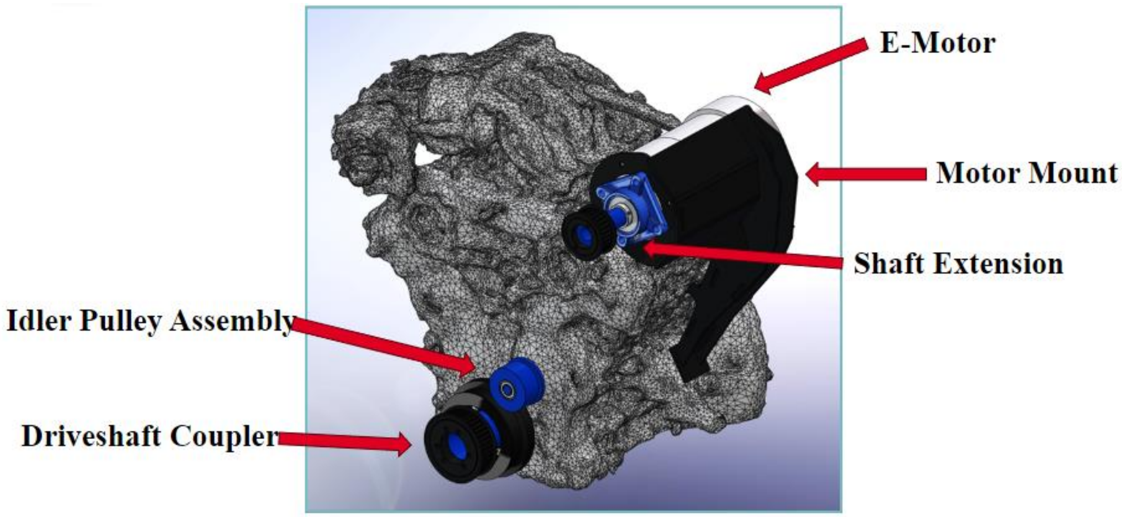


Figure 13 Mechanical Coupler Concept

DESIGN



Motor Mount

One of the most crucial components of this system is the mounting of the electric motor. Based on our decision to go with the P0 hybrid position, we needed to mount the motor such that the shaft is in line with the harmonic balancer of the engine. This proved to be a difficult task having to work with the limited space in the engine compartment and the limited mounted points available. Another key design factor is the motor must be mounted directly to the engine since it has slight movements independent of the rest of the truck during operation. Based on the space available in the engine bay, the right side of the engine is the only place where enough space can be made. (Figure 14) shows the tight space that the motor needs to fit in.

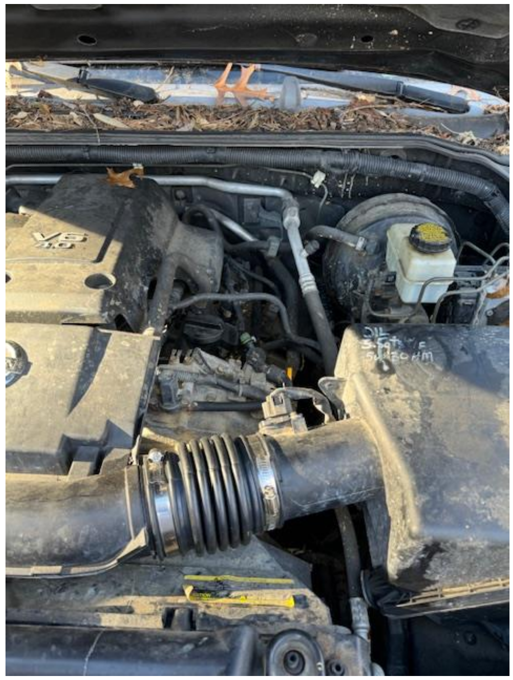


Figure 14 Nissan Frontier Right side of engine bay

A few modifications need to be made to allow the motor to fit properly. The first being the engine's air filter and intake. This will be solved by downsizing the overall size of the airbox and shifting it forward. There is also an air conditioning line that runs directly in the space needed. Until we have everything in during our construction, we plan to remove this line. The last consideration is the engines dip stick. Once the motor is in the dipstick will be inaccessible; this will be solved by extending the dip stick and moving it further towards the right.

When it comes to how we will mount the motor to the engine we began by locating existing bolts or unused threaded holes on the right, front and back of the engine. We were looking for any bolt or hole that was M12 or larger. We were successful in finding three unused bolt holes on the right side of the engine on the cylinder head. Due to the lack of additional high strength fixturing points we began to look at the right-side engine mount.

Figure 15 contains two red X’s; this is where we will connect the top side of the motor mount. Figure 16 contains an X where we will drill two holes into the motor mount to use as our bottom fixture point.

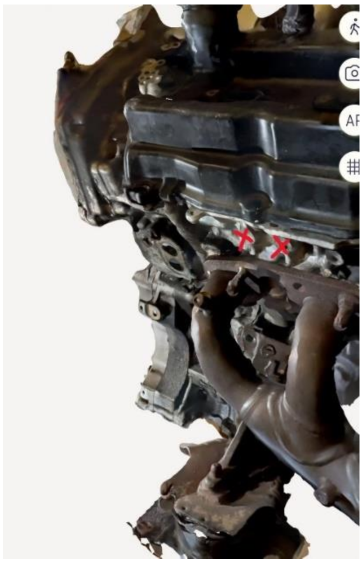


Figure 16

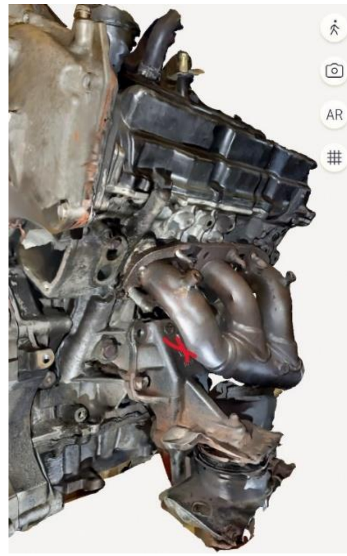
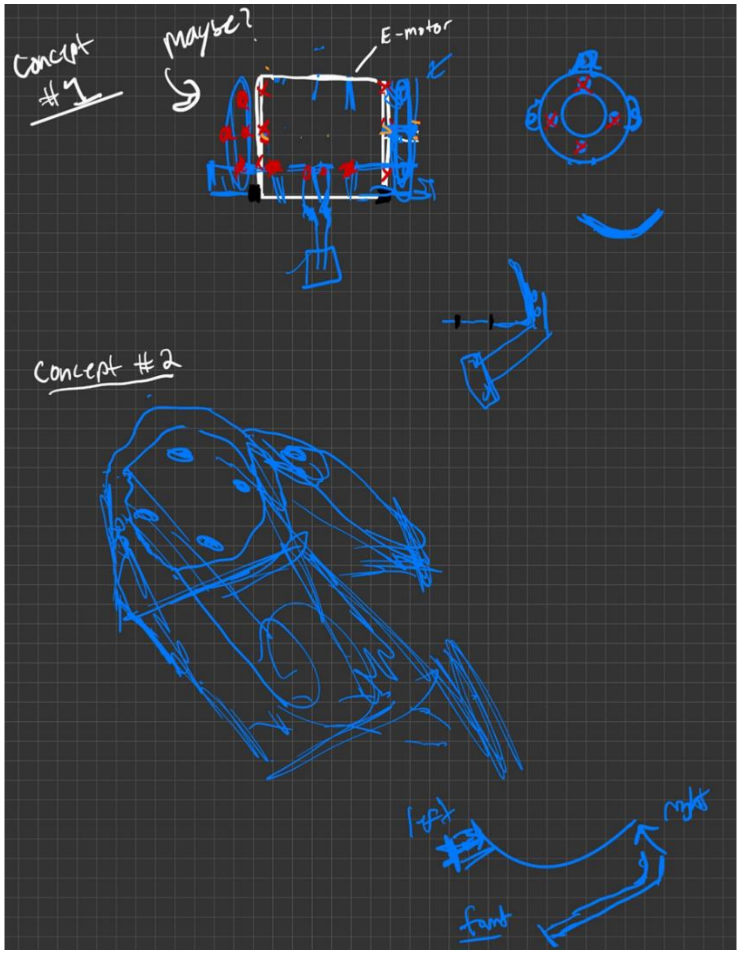
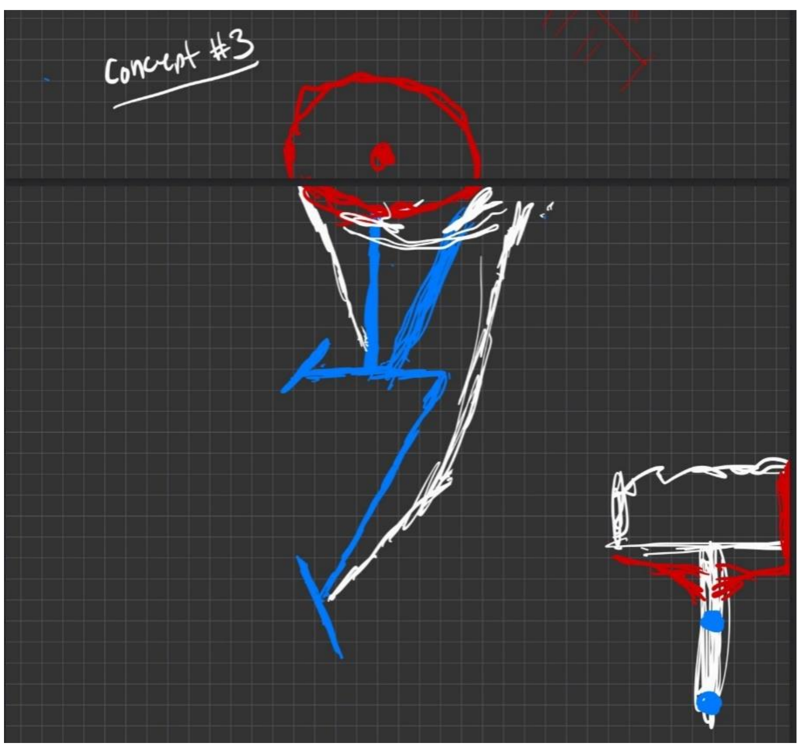
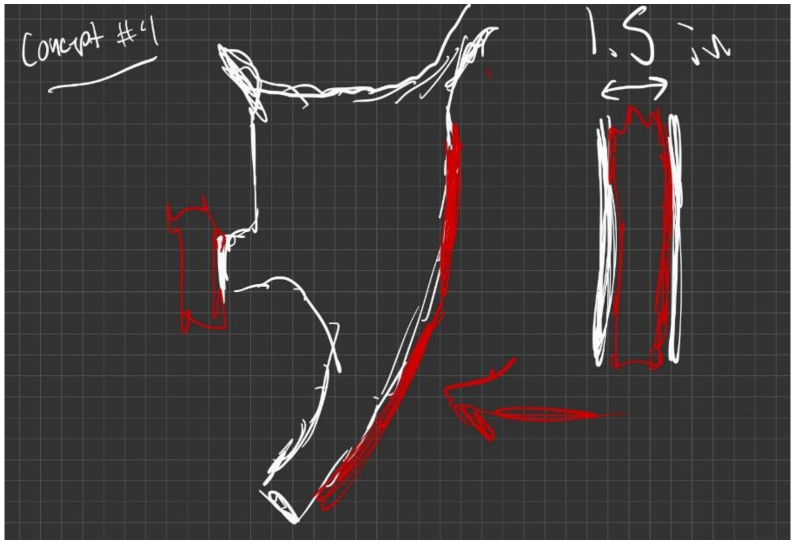


Figure 15

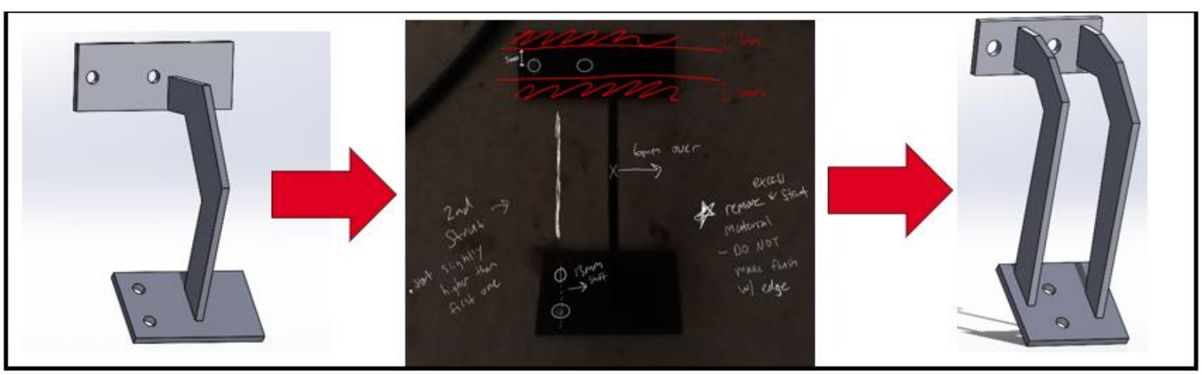
Now that we have our mounting points selected, we can begin designing the motor mount itself. We first had to figure out what the motor mount is going to be made of. There were only two options to choose from, machined or sheet metal. Due to the overall size of the motor mount and trying to limit the total weight of the system we decided to use sheet metal. Below are the initial process design ideations through the complete final design of the motor mount.

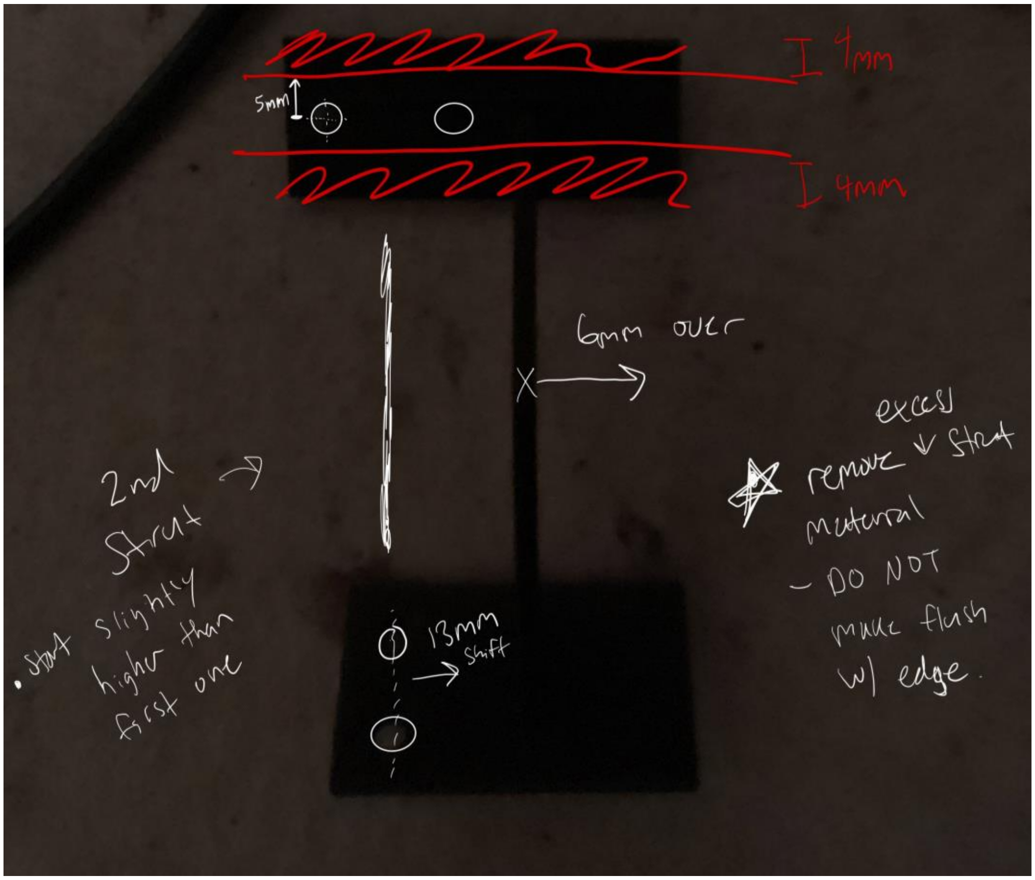

Concept #1
maybe?
E-motor
Concept #2
left
right
front


Concept #3



Concept 4 was the design that ended up being used as the basis of ideation going forward. Of course, there were smaller changes within this concept that were handled in the 3D modeling workspace. This design has a more organic shape for the support struts which is due to the limited space between the engine mounting block and the top of the engine bay. Within this concept, a crucial area of interest was the mounting plates where the mount connected to the engine. This critical feature had its own set of design iterations to capture the perfect angle and position of the mount. This was accomplished by 3D printing prototypes, capturing these critical features of interest.





Enlarged Photo of Previous Progression Image

During this process a full model was developed for preliminary FEA tests as well. Ensuring that the supports would sustain enough force from the motor weight and torque applied from the pulley of the motor coupler.

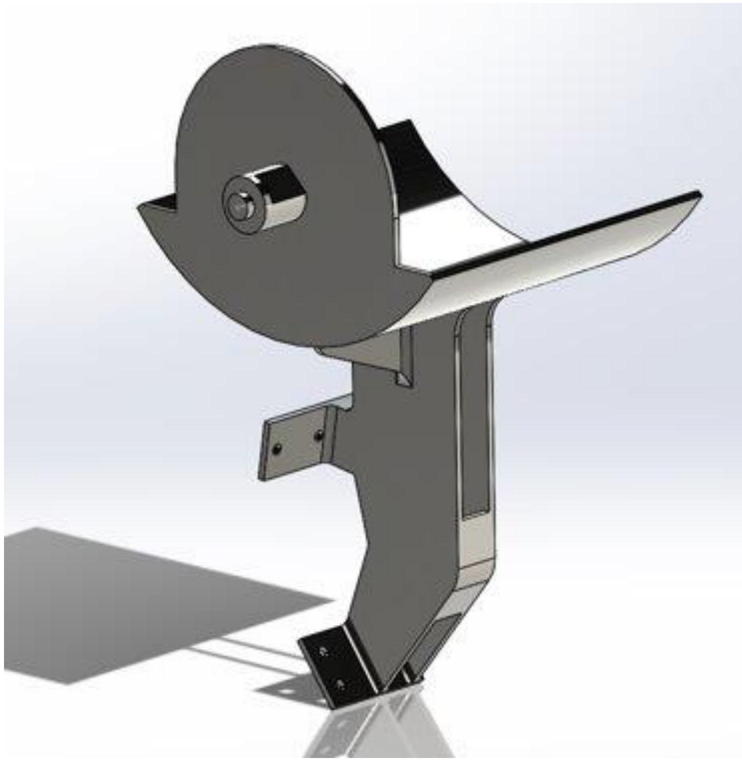


Figure 17 Initial Motor Mount Design

The motor mount consists of two metal plates that reach from out two mounting points up to the crest of where the motor needs to be. They sandwich flanges between them to allow bolts to fit in the mounting plate and add extra strength. The top half is shown as a round cradle which will be made using multiple bends. The cradle is just below the bottom of the motor and contains a mounting face on the front edge where it will mount to.

After designing the mount, we needed to know if the design will be structurally sound and which material will need to be used. An FEA simulation was run using the three forces the mount will encounter. The face plate will experience 3558.58 N of force pulling down towards the engine's crankshaft. It will also experience a maximum torque of 88.128 Nm. in the clockwise direction. Finally, the weight of the motor will exert a constant downward force on the mount. Based on these three values the FEA results are as shown.

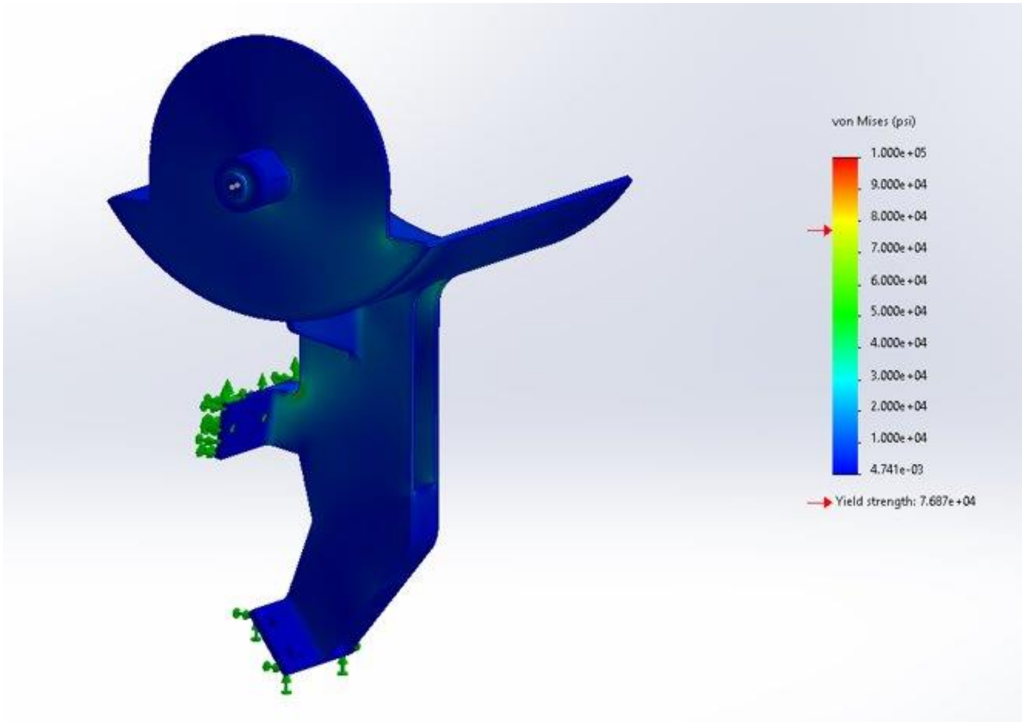


Figure 18 Motor mount FEA Results

The FEA results were promising. Based on the maximum stress experienced by the motor mount of 524 MPa, we chose 689.5 MPa steel for the material. By selecting this material this gives us a factor of safety of 1.3. Although that seems like a low factor of safety, this is based on the maximum torque our motor is capable of. We will be able to limit the max torque the motor can output via our microcontroller. A 6-7 factor of safety will be aimed for in the final iteration of the design.

The final design was realized once the truck was moved into the workspace area at Victory Parkway Campus. Once there, more accurate measurements were taken within the actual truck's engine bay itself and from the disconnected mock engine display. This allowed the team to obtain proper size requirements and better locate the constraints within the engine bay. After a series of measurements were obtained, the final design was completed, and FEA was revisited to obtain the new data which can be seen below.

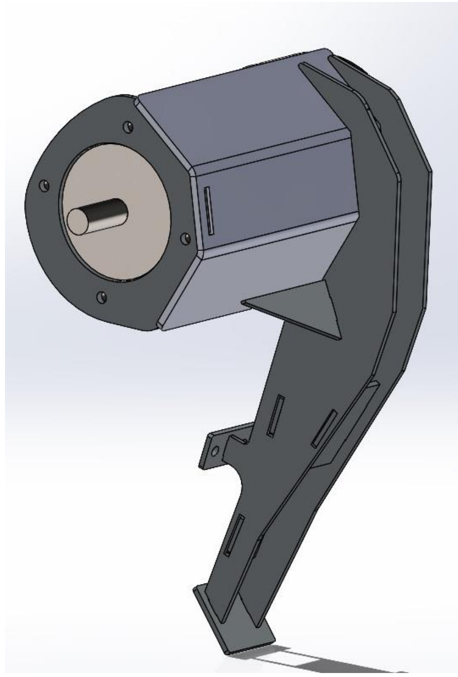


Figure 19 Final Motor Mount Design

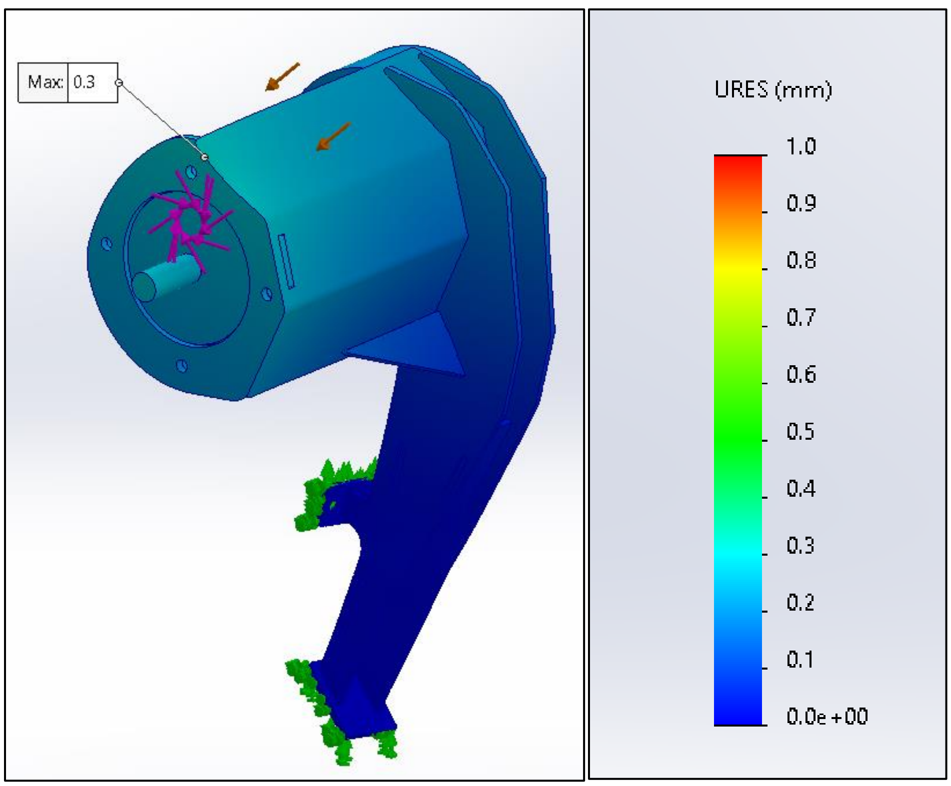


Figure 20 Displacement FEA Results

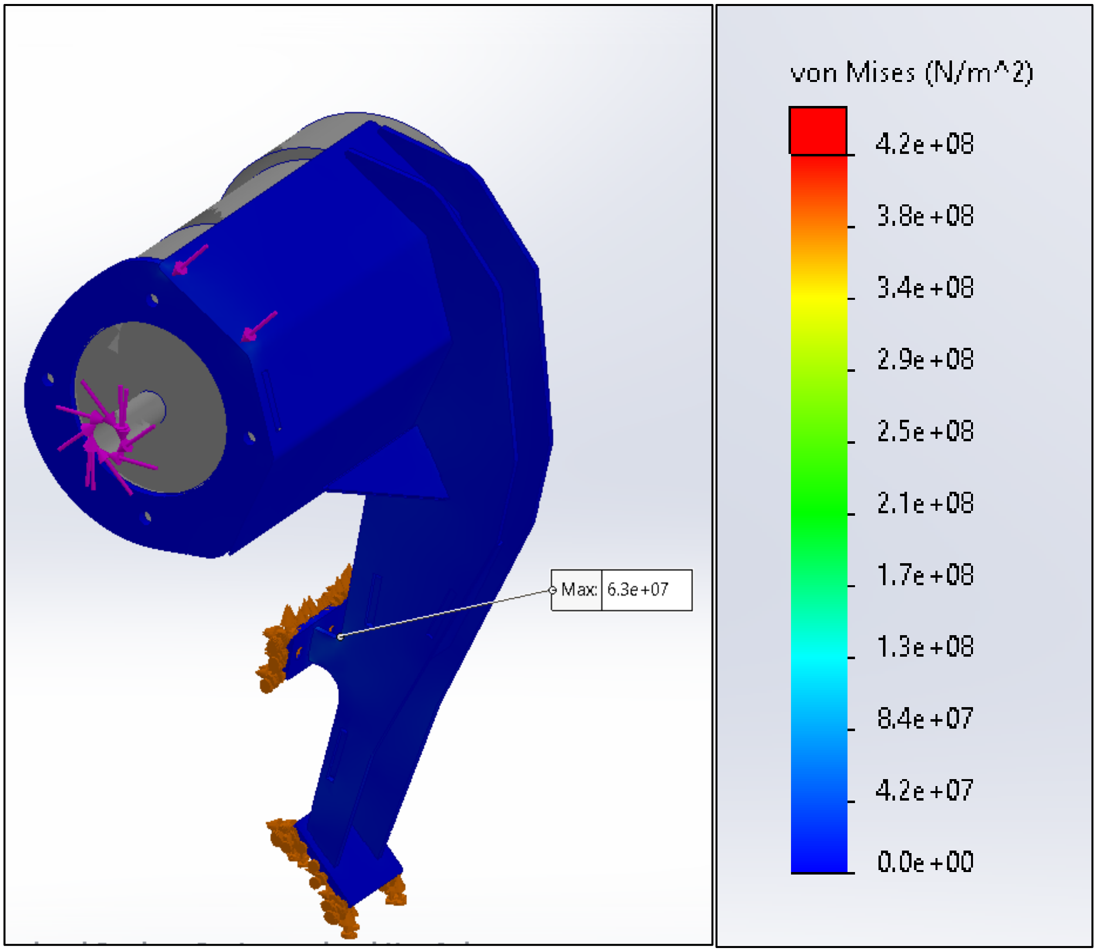


Figure 21 Highest Stress Point Results

From the final design alone, a massive jump in the appearance and structure has changed, making it sleeker to fit within the tight engine bay and more supportive to be able to withstand the tension forces from the motor coupler.

Continuing from the forces from the belt, pulley, and motor coupling, in Figure 20, it can be seen that a maximum displacement of 0.3mm was discovered. This is a very positive value because that means that under the tension forces applied from the engine's torque at 88Nm and a belt tension of 700N that the motor mount itself is barely moving when the engine is running with the harmonic balancer coupled to the electric motor.

Similarly, from the same loading conditions (88Nm Max torque on motor shaft and

700N Max belt tension) the highest stress point was discovered to be 6.3x$10^7 \frac{N}{m^2}$ or 63MPa at a point of the top mounting plate where it was mounted directly to the engine's unused bolt holes. This is sensible as this point was closer to the area of applied force, which was the electric motor's shaft, so it is expected that that area would receive a higher value due to the mount wanting to twist in the direction of the tension. However, although it was the highest stress point, it was well within the maximum tensile stress of the steel which was indicated by the red zone in Figure 21 at 4.2x$10^8 \frac{N}{m^2}$ or 420MPa. With that, the resulting safety factor obtained was 6.6 which is a great improvement from the original designs 1.3. Overall, this final design and simulation proved that the motor mount was well-designed and is structurally sound to operate under the truck's real loading conditions and engine bay environment.

MECHANICAL COUPLER

Task: Design a coupler to connect to electric motor drive pulley to the harmonic balancer.

There are multiple design considerations to examine during the design process of the coupler. One, how far away does the Electric Motor Output Pulley EMOP from the harmonic balancer align with the electric motor? Two, how will the EMOP couple to the harmonic balancer? How much torque will the pulley experience? How much shear force will the bolt experience?

The harmonic balancer has available space between the spokes to introduce a coupler (Figure 20). There are multiple designs we developed to couple the two together. In each design, a custom crankshaft bolt (Figure19) is needed to center the crankshaft, harmonic balancer, and electric motor drive pulley. The bolt slides through EMOP and balancer then fastens to the crankshaft. The bolt holds the EMOP in the correct position, but a coupler is needed to join the balancer and EMOP together. This allows the power from the electric motor to transfer to the crankshaft. The bolt will have the same threads and same diameter. The length will be extended to account for the added pulley.

Figure 19 Harmonic Balancer

Figure 20 Crank shaft bolt

Design Alternative 1 – Twist and lock

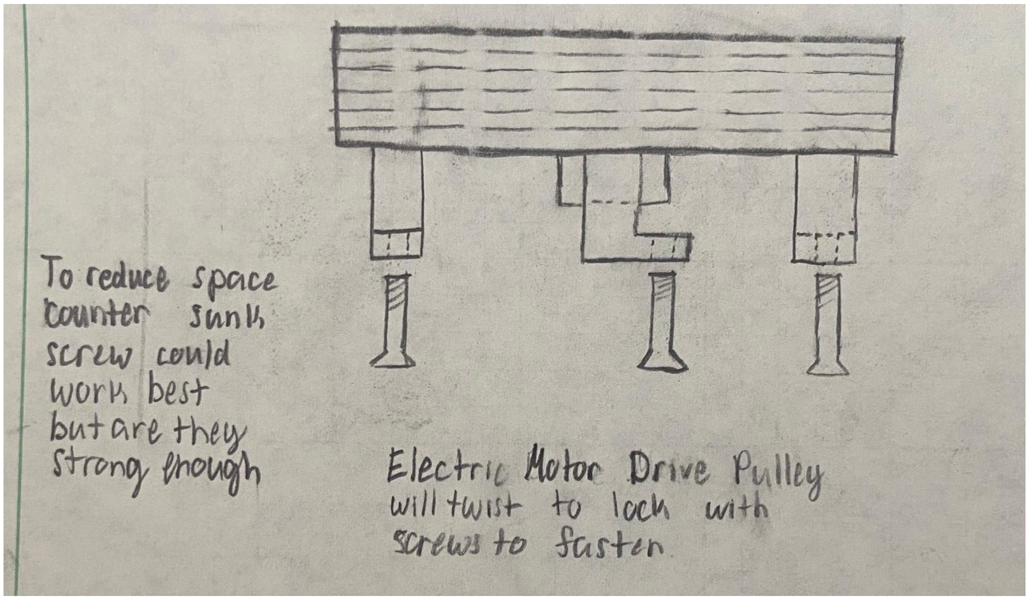


Figure 22 Alternative Design 1: Twist to Lock

Description: Alternative 1 couples to the harmonic balancer via connecting arms. The custom crank bolt is used to center the EMOP. Once the EMOP is centered, the EMOP rotates until the connecting arms wrap around the harmonic balancer spoked. A washer is then placed over the bolt hole on the open ends of the arms. The bolt runs through the arms and the washer then tightened. Thus, the EMOP is coupled to the harmonic balancer.

Advantages: One advantage to this design is that the harmonic balancer does not need to be manipulated.

Disadvantages: The inside of the connecting arms and washers need to sit flush with the balancer spoke. Any play in the coupling will result in a loss of energy, making the system less efficient. Designing and machining these parts are difficult and may take several tries. Also, if the EMOP needs to extend the connecting arms will need to extend as well, creating a larger moment. Hence, the arms will be a weak point. For installation, the harmonic balancer needs to be removed.

<u>Design Alternative 2 – Pegs</u>

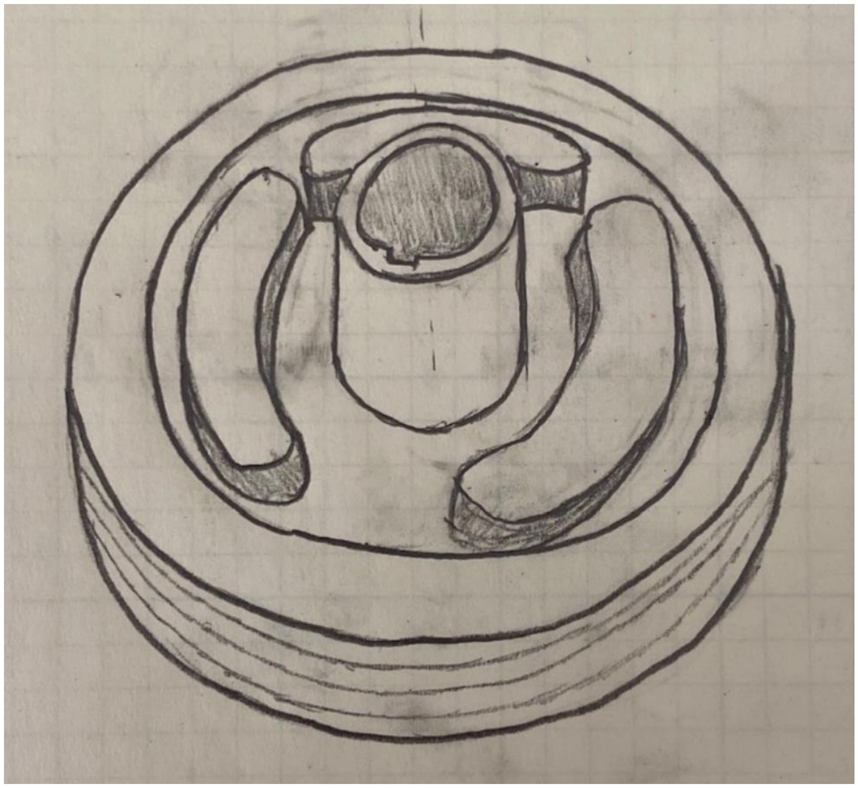


Figure 23 Alternative Design 2: Press Fit

<u>Description:</u> Alternative 2 couples to the harmonic balancer via pegs. The pegs are designed to press fit into the space between the balancer spokes. The custom crank bolt is used to center the EMOP to the crankshaft.

<u>Advantages:</u> Minimum work required for installation. No manipulation of the harmonic balancer. The pegs will over satisfy the torque requirements needed.

Disadvantages: The space between the balancer spokes is irregular. Designing a peg for an irregular space is difficult. If the fit is not perfect, there will be energy loss in the system. Also, there is no fastener, so even if the fit was "perfect" there would still be some loss in the system. Long design time.

Design Alternative 3 – Keys

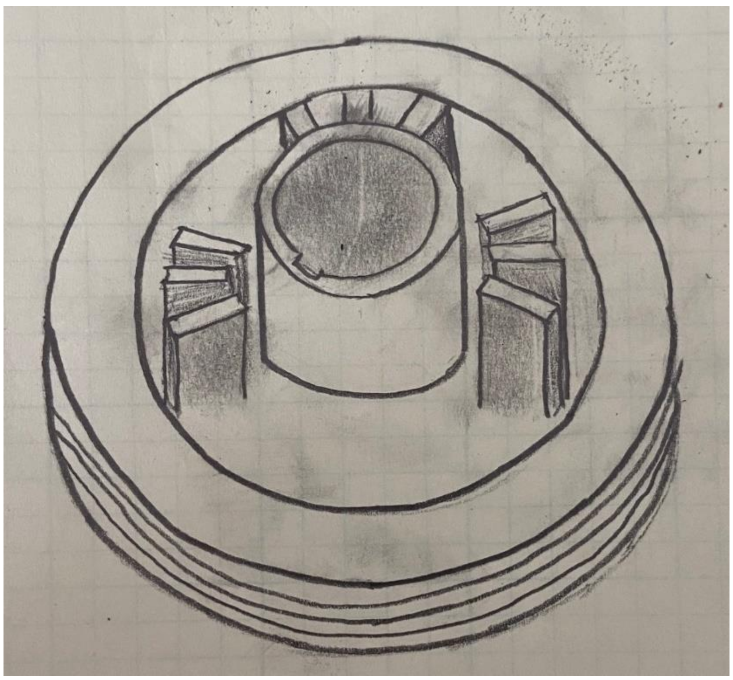


Figure 24 Design Alternative 3: Multiple Keys

Description: Alternative 3 couples to the harmonic balancer via keys. The custom crank bolt is used to center the EMOP. The number of keys needed will be determined by the maximum torque experienced by the pulley. The keys are designed to fit equally spaced in the gaps between the spokes. Keyways need to be machined in the harmonic balancer to accommodate from the keys. Once the balancer is manipulated, the EMOP will press fit in.

Advantages: The required number of keys can be easily added to the design. With three separate sets of keys, the play in the system will be minimum, resulting in the least amount of energy loss.

Disadvantages: The harmonic balancer needs to be removed and manipulated. There are many keys, so the manipulation is major. High probability of a mistake. Also, if the EMOP needs to extend the keys will need to extend as well, creating a larger moment. Hence, the keys have a possibility to break. This will be accounted for during the final design.

Design Alternative 4 – Keyways and Keys

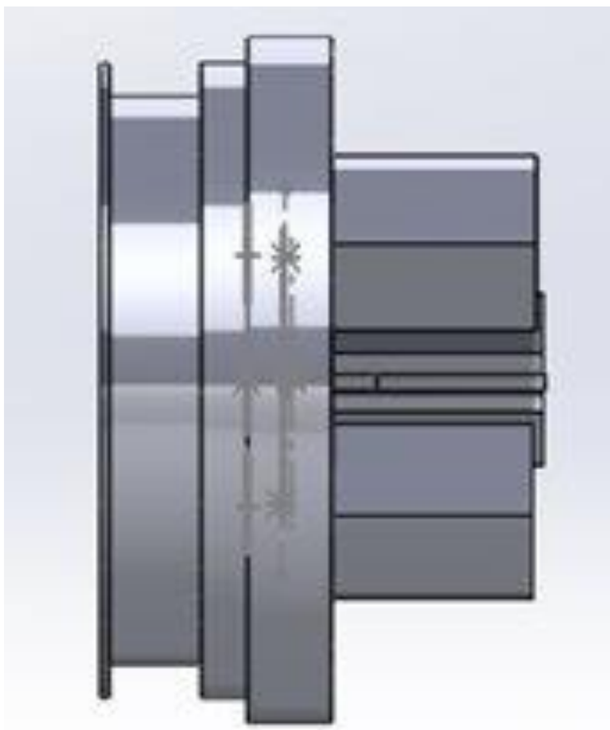


Figure 25 Design Alternative 4: Side View

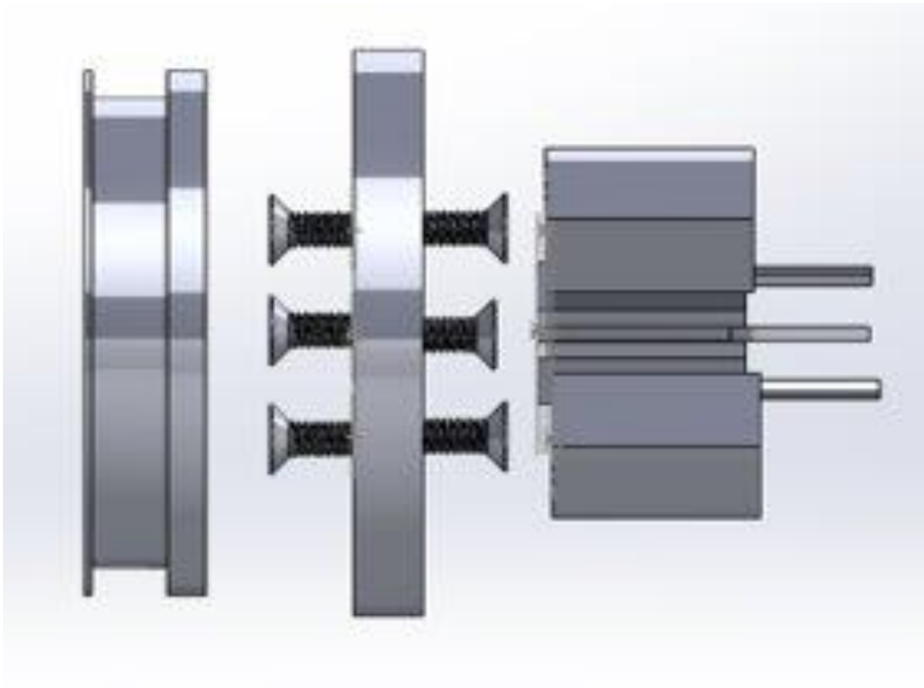


Figure 26 Design Alternative 4: Exploded View

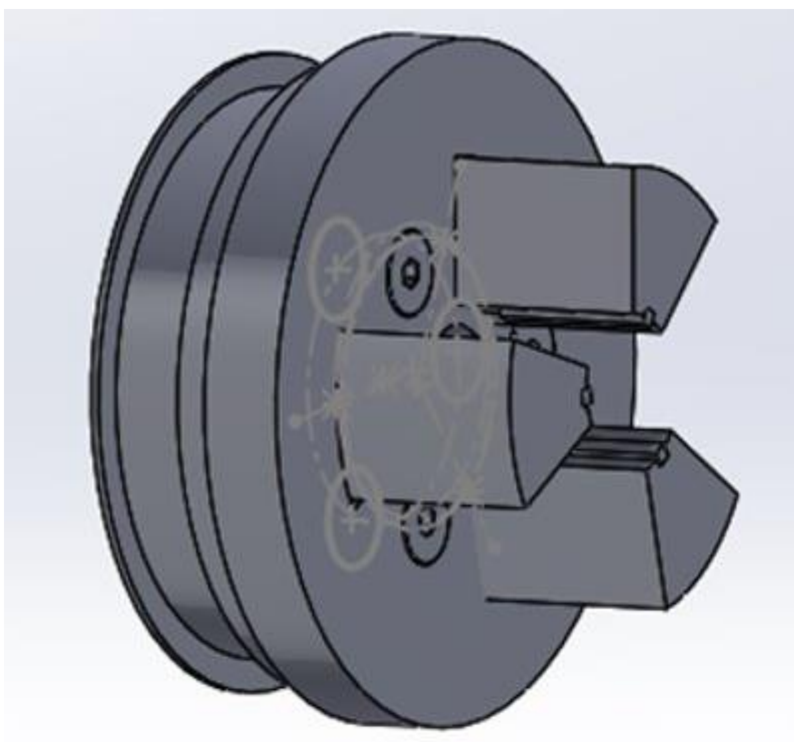


Figure 27 Design Alternative 4: Isometric

Description: Alternative 4 couples to the harmonic balancer via keys ways in the EMOP and balancer with a key locking them together. The EMOP has pegs shaped as wedges to fit in the gaps of the balancer. When the pegs are inserted into the balancer, there is contact between the walls. This provides support and friction to help prevent slipping. Once the EMDP is inserted the keys ways will align. A key of a stronger material will be used to secure the two pulleys together.

Advantages: Using a separate key of a stronger material will result in a high yield strength in the system. A weaker, cheaper material is used to machine the pulley; a harder, more expensive material is used for the keys, decreasing the total material cost. This design locks the two pulleys tightly together with minimum play in the system.

Disadvantages: Manipulation to the harmonic balancer is needed and high in weight.

Design Alternative 5 (Selected Design)

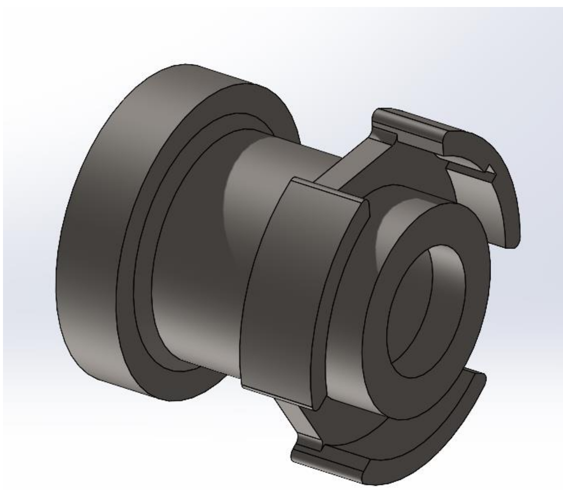


Figure 28 Coupler

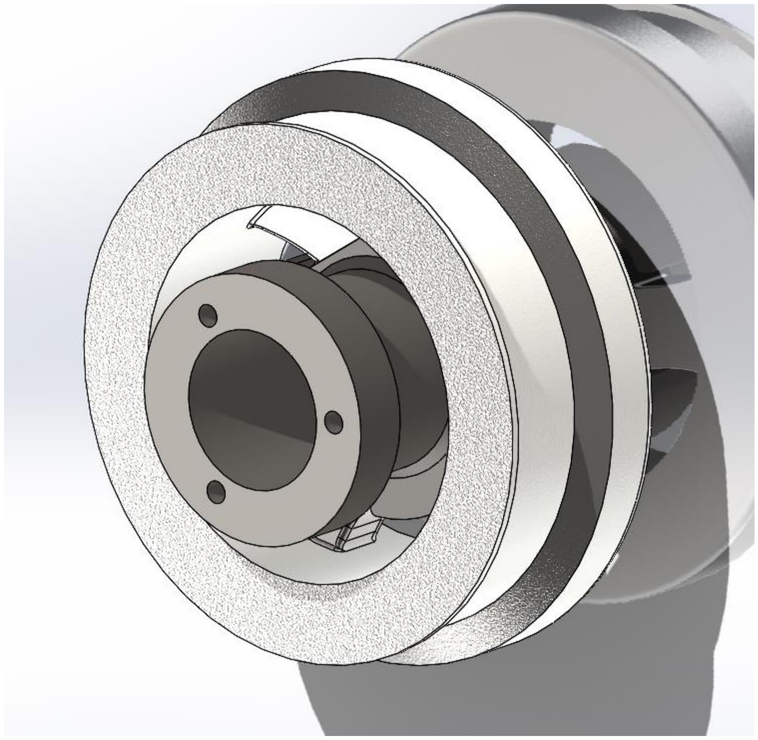


Figure 29 Coupler attached to Harmonic Balancer

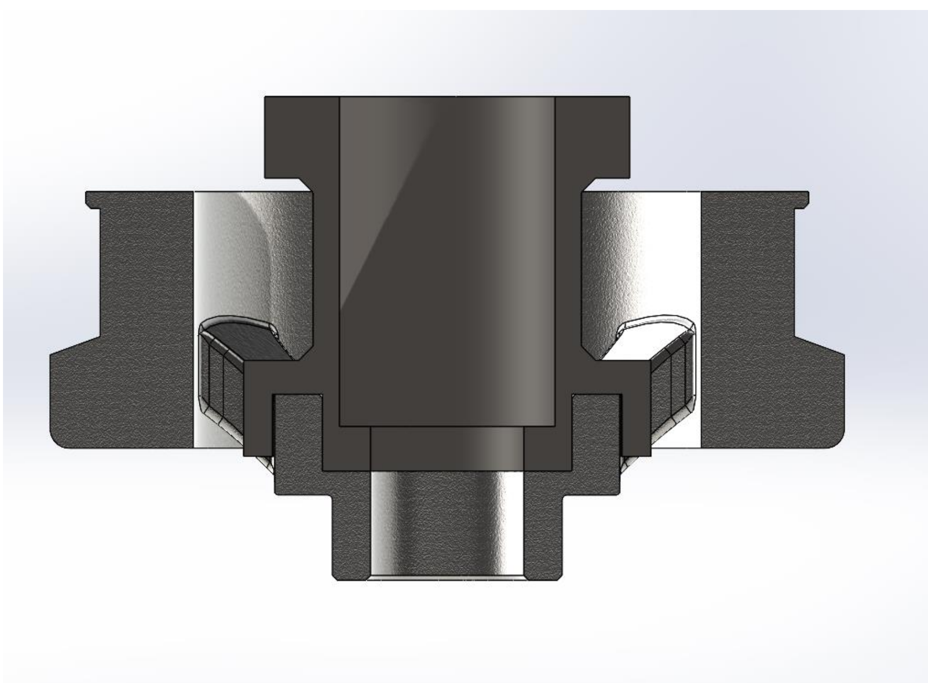


Figure 30 Coupler and Harmonic Balancer side view

Description: Design option 5 consists of a center hub that seats into the bore of the harmonic balancer. This is important to maintain concentricity with balancer to remain stable at higher RPM. The coupler then has three arms that fit around the outside of the balancer with one containing a keyway. This keyway matches up with the keyway cut in the harmonic balancer. This key is crucial for withstanding the rotational forces that the coupler needs to transfer into the harmonic balancer. The existing balancer center bolt will be used to secure the coupler to the balancer. The end of the coupler allows the pulley to fit snuggly on the end and secured by three bolts.

Advantages: Reliably connects coupler to harmonic balancer and is rated with withstand expected forces. It is the lightest in weight of the design options.

Disadvantages: This design requires machining to be done to the harmonic balancer which adds to the complexity and creates possible weak points.

Idler Pulley

Task: Design an idler pulley for the new pulley system to improve belt performance by increasing the angle of wrap and ensuring that the belt is properly routed, avoiding any interference with the engine.

The new idler pulley will be attached to the idler pulley for the serpentine belt. One challenge to designing this part is that the new idler pulley has to rotate clockwise, and the serpentine pulley rotated counterclockwise. To achieve this function a shaft, two bearings, and a pulley were used (Figure 30). These parts are fastened together with a press fit. The pulley is press fitted around the bearings, and the bearings are press fitted around the shaft.

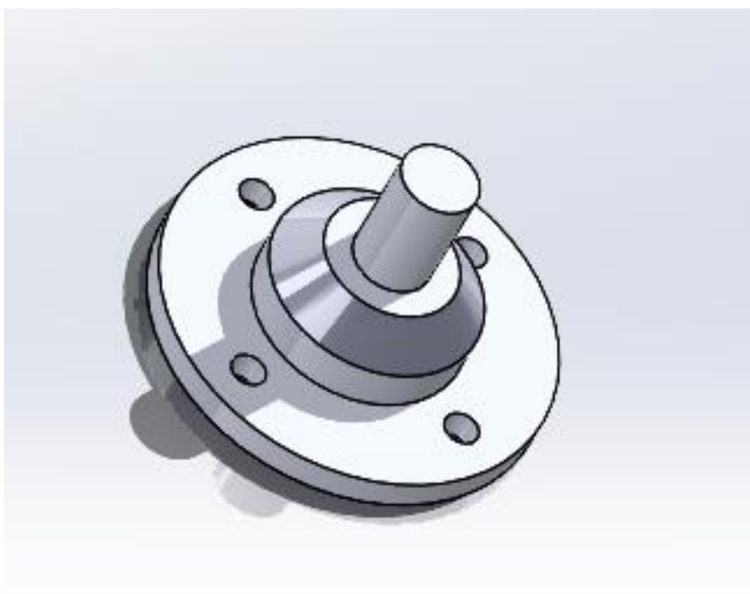


Figure 31 Mounting Shaft

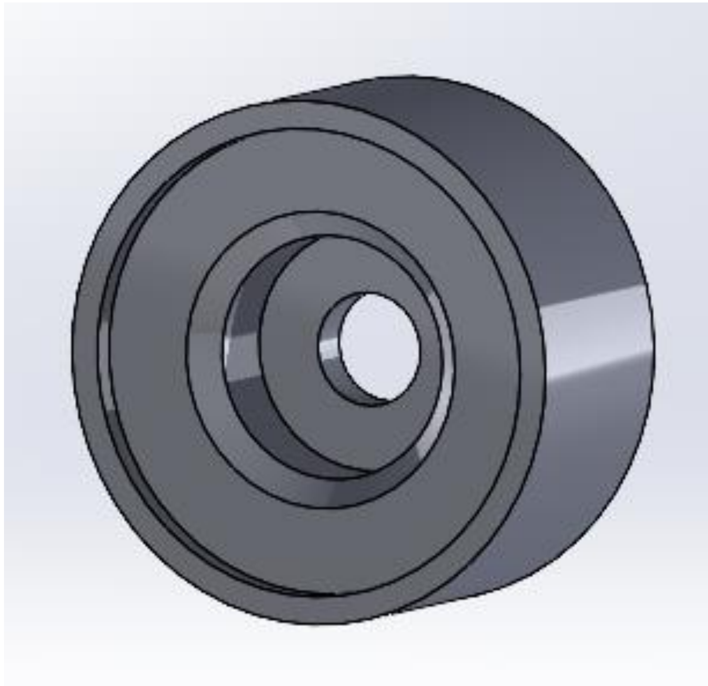


Figure 32 Idler Pulley

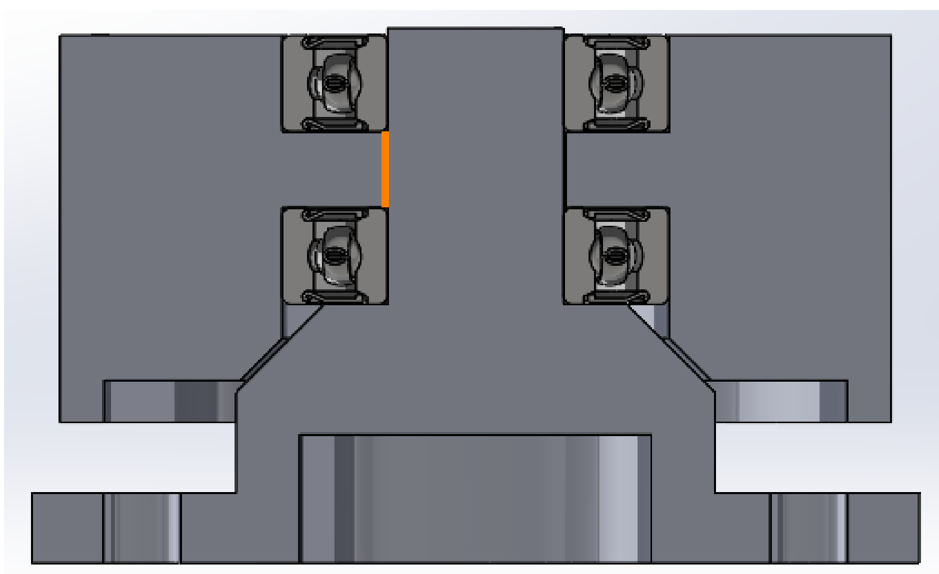
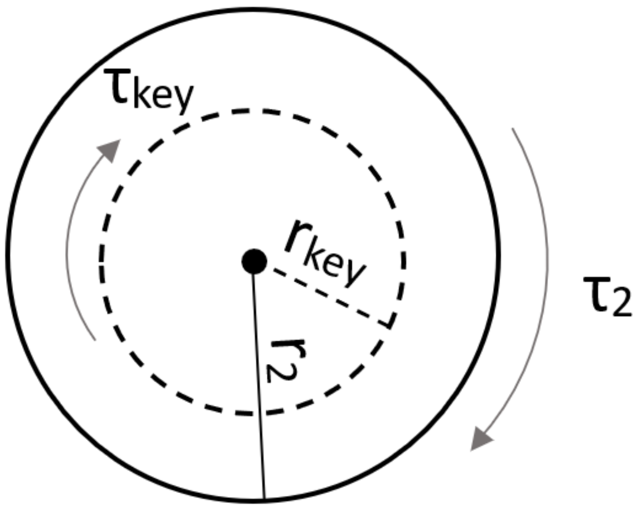


Figure 33 Section Cut of Idler Pulley Assembly

Finding the reaction forces on the key:



Known Variables:

1. τ_2 =
2. r_2 = 50.925 mm
3. r_{key} =36.5 mm

Unknown Variables:

1. τ_{key} =

Figure 34 Diagram of load conditions of key

Torque on the key:

$$\tau = f * r$$

$$f = \frac{\tau}{r}$$

$$f = \frac{Nm}{0.050925\ m}$$

$$f = N$$

$$\tau key = f * r$$

$$\tau key = N * 0.0365\ m$$

$$\tau key = Nm$$

Shear Force on the key:

$$shear\ force = \frac{applied\ force}{cross\ sectional\ area}$$

$$shear\ force = \frac{N}{0.00476\ m * 0.00476\ m}$$

$$shear\ force = N/m^2$$

Factors of Safety

In the mechanical system, the key serves as a critical component that facilitates the transfer of rotational motion between interconnected harmonic balancer and the coupler. While the key plays a crucial role in maintaining synchronization and transmitting torque effectively, they also represent a potential point of failure. The reliance on a small, slender piece of material to withstand the forces of rotation makes it susceptible to wear, fatigue, or shearing under excessive loads. Additionally, the precision and tight tolerances required for proper key functioning can be compromised over time due to factors such as corrosion or misalignment. Consequently, the vulnerability of the key to wear and tear makes them a key point of failure in mechanical systems. To account for these vulnerabilities a factor of safety will be accounted for. Through our research equation # (17) will determine our material selections.

$$shear\ force = 0.4(yield\ strength)$$

$$shear\ force = 0.4(yield\ strength)$$

$$shear\ force =$$

Press fit Calculations

$$P = \frac{\delta}{\frac{d}{E_o}\left(\frac{d^2{}_o + d^2}{d^2{}_o - d^2} + v_o\right) + \frac{d}{E_i}(\frac{d^2 + d^2{}_i}{d^2 - d^2{}_i} - v_i)}$$

$$P = \frac{0.0000762m}{\frac{0.05207m}{210000\ Pa}\left(\frac{0.073m^2 +.05207m^2}{0.073m^2 -.05207m^2} + 0.292\right) + \frac{0.05207m}{210000\ Pa}(\frac{0.05207m^2 + 0.045m^2}{0.05207m^2 - 0.045m^2} - 0.292)}$$

$$P = 29.11\ Pa$$

$$Force = \frac{Torque}{\frac{d}{2}}$$

$$Force = \frac{88Nm}{\frac{.05207m}{2}}$$

$$Force = 3380.1\ N$$

$$Engagment\ Length = \frac{Force}{\pi * d * P * f}$$

$$Engagment\ Length = \frac{3380.1N}{\pi * 52.07mm * 29.11Pa * 0.4}$$

$$Engagment\ Length = 1.77\ mm$$

Factors of Safety

$$Factor\ of\ Safety = \frac{Actual\ Engagement\ Length}{Required\ Engagment\ Length}$$

$$Factor\ of\ Safety = \frac{14.41\ mm}{1.77\ mm}$$

$$Factor\ of\ Safety = 8$$

COMPONENT SELECTION

MOTOR SELECTION

To begin with motor selection there are some non-spec constraints that need to be addressed. The first constraint is cost, since we are working with a limited budget the price of the motor cannot exceed $1700 dollars. The second constraint is motor availability. Due to the short timeline of this project we need to look only at off-the-shelf motors which can be received quickly. The next constraint will be motor envelope size. Since we are installing this motor inside the engine bay, we are limited to 254mm x 304.8mm x 355.6mm (10"H x 12" W x 14" L). Lastly, we will need to decide between water cooled and air cooled. Since the motor is going to be inside the engine bay which can be a hot environment, it would stand to reason we should select a water-cooled motor. However, selecting a water-cooled motor would require us to establish a cooling system which adds complexity, cost, and added power draw.

Selecting the motor for our system will be based on the additional torque and the rotational speed needed to achieve the efficiency increase we are targeting. Based on the Autonomie simulation we the engine experienced a max RPM of 3,200, the median RPM was 2,500, and there needs to be 16.948 Nm of torque applied to the engine to increase the fuel efficiency by 22.5%. Based on this data most motor we were looking at we unable to provide that much continuous torque and if we were to incorporate a large pulley ratio to increase the torque, the maximum motor speed would be exceeded, and the motor would be operating less efficiently. After applying all of these specifications in looking for the right motor we found the HPEVS AC-9 Brushless Induction motor. Below is the continuous performance chart of the motor.

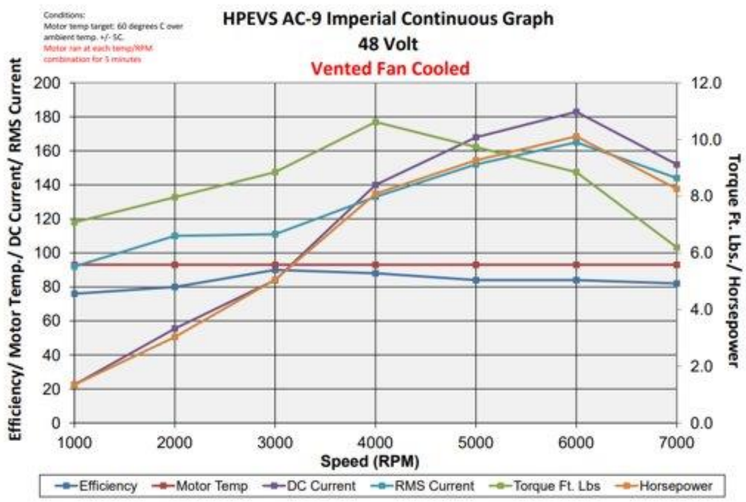


Figure 35 Motor Performance Chart

The chart shows that using a 1.25:1 torque ration we can provide 13.558-16.27 Nm (10-12 ft-lbs.) of torque in the bounds of the RPM data stated previously. This motor also comes with a Curtis 1236SE-5621 motor controller. This leaves all the work out of selecting one as we are now sure that the motor and motor controller are compatible. The motor also fits with our envelope better than we had planned for. The motor is 48 volts with the controller allowing 60-volt input. This allows us to determine that our battery will be between 48-60 volts.

BATTERY SELECTION

The constraints regarding our battery size and specs are very well defined at this point. Based on our motor selection the battery will need to be between 48-60 volts, fit in a 762mm x 457.2mm x 304.8mm (30” x 18” x 12”) space, and will need enough power to provide the system to considerable increase efficiency. From the simulation results it was found that the energy expenditure the system needs to be capable of is 1100 watts per hour. Based on our limited selection of batteries and the refined constraints we found the LG Chem

Lithium Ion Battery. The battery module is a 60.8V 2.6kWh and fits well within the space available. The usable capacity of the battery will be between 20-80% SOC to limit battery degradation. Based on this SOC window the battery we chose will be able to output 1500 watts per hour, which lands very much into total power needed.

Figure 36 LG CHEM Lithium ION Battery

Before purchasing the battery shown above, we were presented with a great opportunity to acquire a similar battery system at a fraction of the cost. We were able to find someone selling ram Etorque batteries for $15 dollars apiece. Each module is a 12-series comprised of lithium-ion cobalt cells. Each module was 48 volts 9.8 amp. To achieve our needed battery compacity we wired four modules in parallel to get our total pack capacity to ~2000-watt hours. However, these batteries did not come with BMS modules, so we had to wire in our own. For many lithium-Ion battery packs it is common for them to be wired in 13 series but the modules we found were only 12 series. This presented a problem for finding the proper BMS modules. After much research we acquired 4 DALY BMS protection boards that were compatible with our pack. These BMS boards are rated at 50-amp continuous discharge, maintain cells voltage levels across pack, and will shut down the battery if there are any shorts. These were a must have regarding battery pack safety.

Figure 37 DALY 12 Series BMS Board

After every BMS board was wired to each module we stacked the modules on top of each other and utilized through holes on each corner of the pack to run threaded rods through to secure them together. To properly wire the packs in parallel we needed to connect every positive and negative to their own BUS bar. We decided to use aluminum bar stock that we sized using our max discharge rating of the pack. The BUS bars had 5 holes equally spaced to ensure that each pack would be discharged and charged equally. The main positive and negative wires were connected to the center of the bus bar and then ran to the controller.

Figure 38 Finished Battery Modules

PROJECT MANAGEMENT

PROJECT BUDGET LIMITS

Below is the preliminary budget set at the beginning of the project. It comprises of general expense that we expected. This gave us a general starting point which was further refined as we dug deeper into the project.

Senior Design Project Budget

SUMMARY

Expense	Amount
System Components	$5,000
Labor	$300
Expo Display	$200
Vehicle Rehab	$600
Total	$6,100

Figure 39 Initial Project Budget

The next budget was produced after we finalized most of the specific components needed at the end of the design period. The items that are not highlighted had already been purchased or finalized at the time of making the budget.

Senior Design Project Expenses

Item	Cost
VQ40 Long Block Engine	$100
Engine Stand	$40
iKKEGOL OBD OBDII J1962 Male Connector	$7.99
iKKEGOL 30cm/12 Right Angle OBD2 OBD II Y Splitter Cab	$9.99
WWZMDiB 3Pcs MCP2515 CAN Bus Module Board	$9.99
HPEVS AC-9 Induction Motor and Controller	2,625.00
LG Chem Battery	$799.00
Microcontroller	$150
Pulleys and belt	$200
Wires and Connectors	$500
Harmonic balancer coupler	$70
Miscallaneous	$300
Total	$4,812

Figure 40 Mid Term Project Expenses

BILL OF MATERIALS (ACTUAL)

The final budget below is the exact list of all purchased components we made throughout the project. The total expenses are compared to our finalized budget at the bottom. Fortunately, we were able to get our expenses around $1000 less than our budget. Much of this was due to the batteries we sourced as well as a few components we were donated throughout the project.

Senior Design Project Expenses	
Item	**Cost**
VQ40 Long Block Engine	$100
Engine Stand	$40
iKKEGOL OBD OBDII J1962 Male Connector	$7.99
iKKEGOL 30cm/12 Right Angle OBD2 OBD II Y Splitter Cable	$9.99
WWZMDiB 3Pcs MCP2515 CAN Bus Module Board	$9.99
HPEVS AC-9 Induction Motor and Controller	$2,625.00
LG Chem Battery	$100.00
Harmonic Balancer	$205.66
Microcontroller	$30
Pulleys and belt	$220
Wires and Connectors	$30
Harmonic balancer coupler	$0
Miscallaneous	$300
Idler Pulley	$0
4 BMS Boards	$105
Fasteners	$250
Total	$4,034
Budget	$5,000

Figure 41 Final Materials List and Expenses

Schedule and Key Milestones

Senior Design Shedule

Select a period to highlight at right. A legend describing the charting follows.

ACTIVITY	PLAN START	PLAN DURATION	ACTUAL START	ACTUAL DURATION	PERCENT COMPLETE
Design I					
Project Selection	1	3	1	3	100%
Research	2	7	3	7	100%
Customer and Product Objectives	6	2	6	2	100%
Design II - Design Development					
Design Decision	10	4	10	4	100%
Simulation/Calculations	10	5	11	7	100%
Final Design/Drawings	12	6	13	7	100%
Design III - Manufacturing					
Order Materials	18	2	18	4	100%
Manufacture	19	4	19	4	100%
Build	19	6	21	5	100%
Testing	22	3	24	0	30%
Tech Expo	26	1	26	1	100%

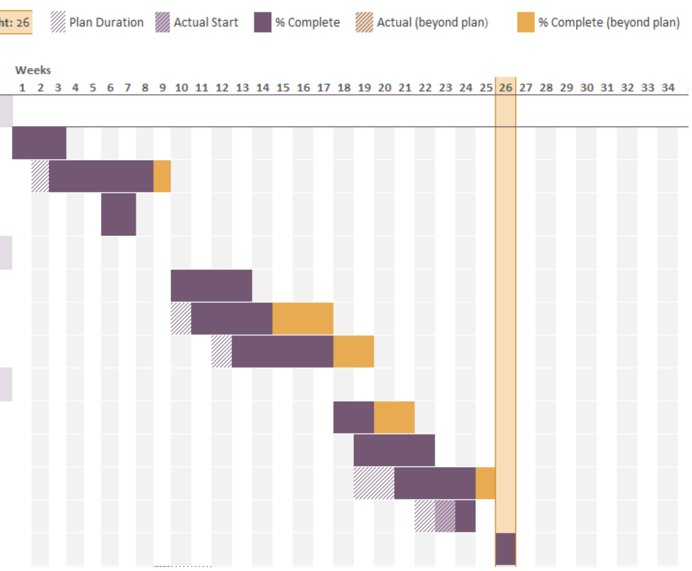


Figure 42 Project Schedule

Sustainability and Material Usage

During prototype construction we see no issue with the sustainability of materials selected for the system. Further research will be done to determine the sustainability of our system if we were to start producing these in a larger quantity.

MANUFACTURING, FABRICATION, AND ASSEMBLY

All drawing can be found in Appendix C

MOTOR MOUNT

The manufacturing of the motor mount was accomplished in a multitude of steps, beginning with several small sample 3D printed iterations of the mounting plates to establish the correct angle and plate position as these were the most critical factors of the design. Once the final positioning of the plates was determined, the rest of the model was constructed after obtaining measurements of the limited space within the engine bay. This includes how much space between the exhaust manifold to build between, the horizontal space from the engine to the other side of the bay's components, and the maximum height of the mount to ensure hood closure. After the final model was created based off these parameters, the model was deconstructed into individual components and slots and tabs were added for future reinforcement during the welding stage. After the individual components were complete, DXF drawings were made so that the pieces could be laser cut from sheet metal. The parts were then MIG welded together to create the mount. The fabricated mount was then fastened to the two previously mentioned mounting positions: one on the engine itself and one on the engine mounting block. Two unused holes were used on the engine while two new holes were drilled into the engine block. These holes were located once the mount was placed on the mock block and space constants for installation were determined. Grade 8 bolts were utilized for the mounting application. Once installed onto the truck's engine, the electric motor was then placed into the mount and fastened together using Grade 8 bolts.

Figure 43 Slotted Sheet Metal

Figure 44 Motor Mount after Fabrication

Figure 45 Close up of Mount Plates

Figure 46 Motor Mount mounted of Mock Block

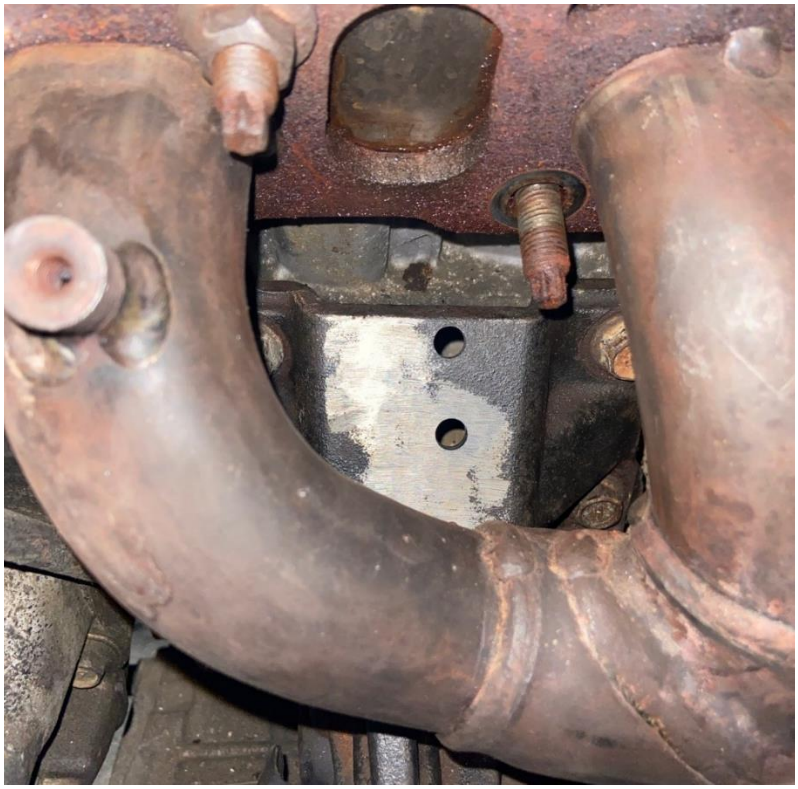


Figure 47 Engine Motor Mounted after Drilled and Installed

DRIVE SHAFT AND BEARING

To align the electric motor pulley with the belt path, a shaft extension was needed. To achieve this, the shaft was milled with a so that a pulley could be mounted on one end and the other hollowed to slide on to the motor shaft. To constraint the rotation between the two, a key matching the existing keyway on the motor shaft was cut into the shaft. To cut the blind keyway, the shaft had to be cut and welded back together. The selected key was 3/16 by 54.61mm in length. Due to the extension of the shaft, the forces acting on the internal bearing of the motor increase. To compensate for this, a pillow block bearing to the face of the motor mount. This will allow the motor to run more efficiently and help increase the longevity of the motor.

IDLER PULLEY AND SHAFT

To machine the idler pulley and shaft we started with two stock cuts of 1023 steel to be machined on a lathe. The parts were machined to the dimensions and tolerances of the drawings. It was important to pay close attention to the dimensions of the shaft, the inner bore of the shaft, and bearing in lays of the pulley to keep the diameter or holes within press fit tolerances. The shaft was heated and press fitted to the bearing of the serpentine idler pulley and fastened with 4 M6 bolts. To press the bearings into the idler pulley, the pulley was heated, and the bearings were set and cooled. Finally, the pulley with bearings was heated and pressed onto the shaft.

Figure 48 Machined Components for Idler Pulley

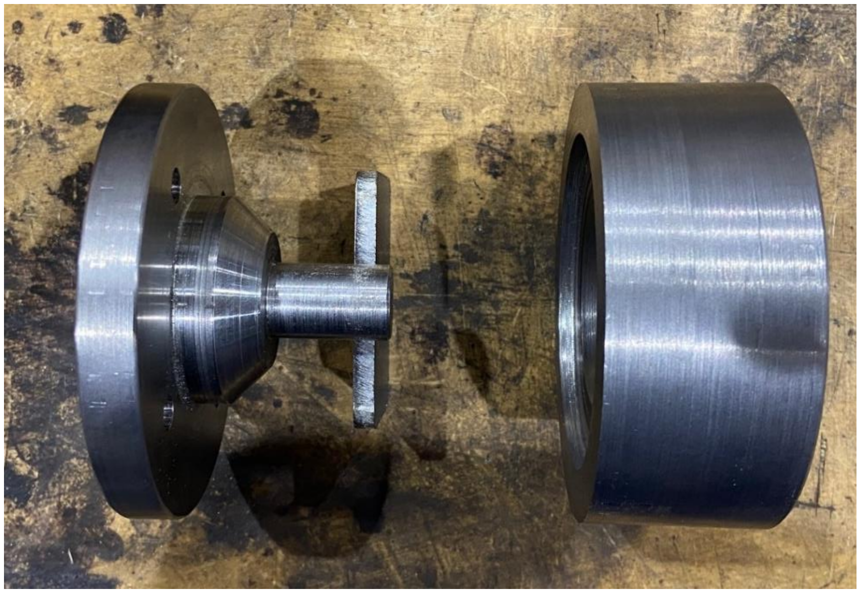


Figure 49 Order of Installation

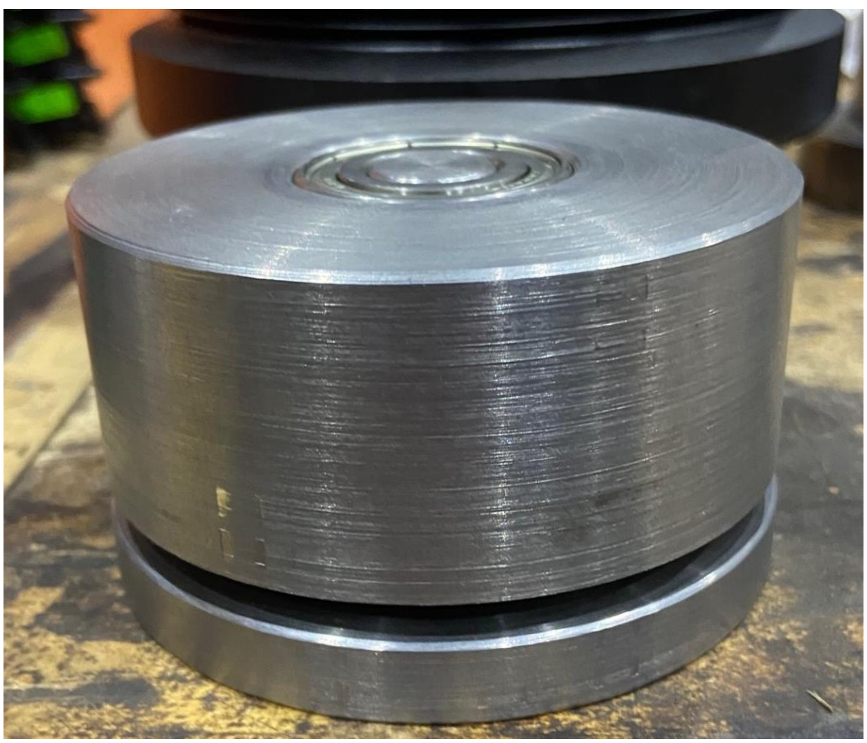


Figure 50 Idler Pulley Assembly

COUPLER

Figure 51 Machined Harmonic Balancer

Figure 52 Harmonic Balancer Coupler

Figure 53 Harmonic Balancer Coupler


Figure 54 Order of Assembly Installation

ELECTRICAL COMPONENT

The electrical components utilized in this project can be separated into three categories: General, Power, and Control. General components include electrical enclosures, miscellaneous wires, connectors, terminals, DIN rail, etc. The power components include power cables (low gauge), the motor contactor, various fuses and circuit breakers, batteries, etc. Finally, the control components are made up of the microcontroller (Arduino Uno), the CAN-Bus shield, the motor controller, shielded cables and harnesses, etc.

Most notably in the “General” category are the three electrical control boxes we used to contain various systems (all NFPA rated). The first was used to house the motor contactor. We decided to use a small enclosure to house the contactor for two reasons: it has live wires connected to exposed contacts, and it emits a fair amount of heat. The first reason was obvious, we needed to ensure that contact with the high amperage wires was impossible, as it was a serious safety hazard. The second reason was addressed by cutting out ventilation holes into the enclosure and inserting 2 fans (intake and exhaust) which served to dissipate heat from the contactor. The second enclosure contained the motor controller, which again, was done to eliminate accidental contact with live contacts. The final enclosure contained all the CAN-related control components (terminals, microcontroller, CAN shield, 12V power, etc.)

The major Power components were the batteries (which have already been discussed at length), BMS modules, and power-related wires. The most notable of these that have not been discussed is the power wires, which were extremely large (1/0 AWG). These were necessary to comply with NFPA regulations regarding wire cross sectional area and maximum amperage allowed.

The control components are the most important in bringing the project to life. The most notable of these are the Arduino Uno microcontroller, the Sparkfun CAN-Bus shield mated to it, and the electric motor controller supplied with the motor. Utilizing CAN communication, we were able to read data from the ECU via the shield, interpret and manipulate it via the Arduino, and then send corresponding commands to the motor controller. This whole process relies heavily on our ability to manipulate CAN data.

` Some of CAN Identification information is standard across all vehicle manufacturers (as per SAE J1979/ISO 15031-5) so that governmental agencies can perform emissions tests across all vehicles in the same manner (i.e. being able to read fuel consumption, oxygen sensors, throttle position, rpm in all vehicles using the same CAN ID's). This is fortuitous in regard to our project, as these are the kinds of values we use to calculate the corresponding control variables of the electric motor, and a majority of CAN ID's that are non-emissions related are proprietary and require a tedious guess and check process to identify.

The CAN bus of the light duty truck was accessed via the OBDII port underneath the driver-side dashboard. Using an Arduino Uno and a Sparkfun CAN-Bus Shield, we can send an “OBDII Frame” of data to the car. This consists of an 11 bit CAN ID followed by 8 bytes of data and is represented in hexadecimal form.

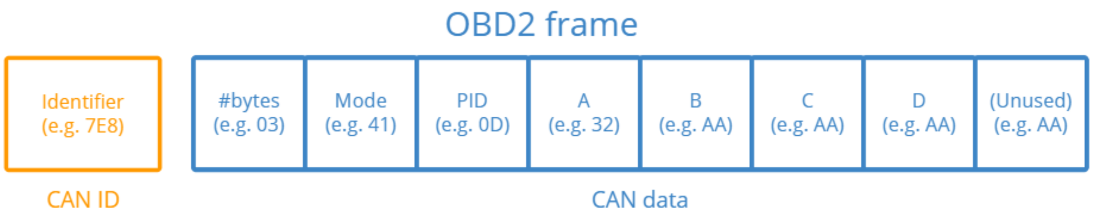


Figure 55 Typical OBDII Data Frame (response)

The two notable parts of this data frame include the CAN ID and the PID. The former is generally always “7DF”, which is the CAN ID that tells the ECU we are requesting data, and therefore, expect a response, which will begin with the CAN ID of “7E8” as shown in figure 11. The latter (PID) is the variable we are requesting – some of these values are listed below (according to SAEJ1979).

- 0A – fuel pressure
- 0C – engine speed
- 0D – vehicle speed
- 11 – throttle position

Following the PID are up to 4 data bytes (represented by A, B, C, and D), that give the raw values of the PID. These values then need to be converted using a standardized formula, according to which PID is being addressed. An example of a typical request/response exchange is shown below (**Error! Reference source not found.**).

	CAN ID	Byte 0	Byte 1	Byte 2	Byte 3	Byte 4	Byte 5	Byte 6	Byte 7
Request	7DF	02	01	0C	AA	AA	AA	AA	AA
Response (example)	7E8	04	41	0C	12	34	AA	AA	AA
Physical value (DEC)	= 0	+	0.25	*	4660	=	**1165**	**rpm**	

Figure 56 OBDII Request/ Response for engine speed (RPM)

As we can see above, we requested “0C” which is engine speed, and the response contained data bytes with values A=12, and B=34 (AA signifies an “unused” data byte). After converting A and B into decimal (A = 18, B = 52), the value of the PID is calculated according to the standardized formula for engine speed:

$$\frac{(256 \times A) + B}{4} = \frac{(256 \times 18) + 52}{4} = 1165\ RPM$$

Thus, we have easy access to the real time engine data, and we then utilize these values to adjust the parameters of the electric motor accordingly.

The actual control of the electric motor was done by taking data via the process described above, manipulating it via the Arduino, then sending corresponding commands to the motor controller to change the motor speed. An example of such a cycle is shown below:

- Input from ECU
  - Vehicle Throttle pos $= 50\% \ (\geq 10\%)$
  - RPM $= 1500 \ (\geq 750)$
- Output to motor controller
  - Electric motor throttle pos = 50% (adjusted to match vehicle throttle)
  - If electric motor torque $< 0.75\ (T_{max})$, increase throttle

A very basic description of the control structure is as follows.

1. **Get and interpret CAN data – occurs every ~ 5ms**
    a. Request the engine RPM, throttle position, and vehicle speed from the ECU.
    b. Receive the response, interpret the data, and store into variables.
2. **Analyze, manipulate data – occurs between CAN requests**
    a. **Accelerating:** If the RPM is above 750 (idle speed), the throttle position is above 10% (i.e. the driver is pressing on the accelerator, and the vehicle speed has increased since the last request → electric motor speed increase until rpm matches engine
    b. **Regenerative Braking**: If the RPM is above 750, the throttle position is below 10%, and the vehicle speed is has decreased since the last request → electric motor set to regenerative braking
    c. **No change**: If the previous 2 conditions are not met, the motor controller stays in its current state.

Thus, we can control the electric motor via a simple CAN request to the ECU and the appropriate command sent to the motor controller via our microcontroller.

CUSTOMER FEATURES

With our system the customer will experience improved fuel efficiency through various driving cycles. With the fully integrated system the customer will lose no functions of their vehicle and mostly not even know the system is there. The only factor that might feel different for the customer is the braking interaction. Since the system utilizes regenerative braking for slowing the vehicle down and recuperating the energy back into the battery back, they may feel more aggressive braking when compared with a stock vehicle.

SUMMARY AND CONCLUSION

As we stand, we have successfully attached an electric motor to the side of the engine. We have coupled the electric motor to the drivetrain of the vehicle. We have also completed the wiring of the electrical system to operate the motor using a throttle. In terms of full project completion, we have failed to use engine parameters from the vehicles computer system to control the hybrid system. The reason for this is that it has been difficult to overcome proprietary communication blocks due to limited access given from the manufacturer. Without this communication we are unable to control the electric motor so that it can work seamlessly with the vehicle’s engine. This is the reason for the lack of testing data we were hoping to collect. We are confident that once this communication problem is solved, we will be able to achieve a drastic fuel efficiency increase.

Moving forward we plan to dig deeper into communication alternatives. After further discovery if we are unable to get the required values through the OBD-2 port, the next option would be to hardwire our microcontroller to specific CAN bus wires that contain the information we are looking to acquire. The reason we did not go this route earlier is because modifying these wires in certain ways could affect other computer systems or vehicle components that would alter its operation.

All things considered; we could not be happier with the progress we have made over the past 9 months. This project started as a simple idea 2 years ago and is nearly completed. We firmly believe this system could save consumers billions of dollars per year which is still very much in the realm of possibility.

WORKS CITED

1. **Wadhwani, Preeti.** Light Duty Truck Market. *Gobal Market Insight.* [Online] August 2023. [Cited: October 9, 2023.] https://www.gminsights.com/industry-analysis/light-duty-truck-market.

2. **Ehsani, Mehrdad.** *Modern Electric, Hybrid Electric, and Fuel Cell Vehicles.* Boca Raton : CRC Press LLC, 2005. 0-8493-3154-4.

3. **Carlier, Mathilde.** U.S. car and truck retail sales from 2011-2021. *Statista.* [Online] January 2021 . [Cited: October 9, 2023.] https://www.statista.com/statistics/199981/us-car-and-truck-sales-since-1951/.

4. **Britannica, The Editors of Encyclopaedia.** four-stroke cycle. *Britannica.* [Online] August 31, 2023. [Cited: October 1, 2023.] https://www.britannica.com/technology/supercharger.

5. **Understanding Hybrid Vehicles: The 4 Main Types .** ***motorlease.*** **[Online] [Cited: September 25, 2023.] https://motorlease.com/article/hybrid-vehicle-types/.**

6. Mild hybrid. ***Wikipedia.*** **[Online] [Cited: August 30, 2023.] https://en.wikipedia.org/wiki/Mild_hybrid.**

7. Hybrid Electric Vehicles. ***Alternative Fuels Data Center.*** **[Online] [Cited: September 1, 2023.] https://afdc.energy.gov/vehicles/electric_basics_hev.html.**

8. ***Comparative Analysis of Torque and Acceleration of Pre- and Post- Transmission Parallel Hybrid DriveTrains.*** **Saiful A. Zulkifli, Nordin Saad, A. Rashid A. Aziz. s.l. : MATEC Web of Conferences, 2016.**

9. Dual-Mode Hybrid/Two-Mode Hybrid Accomplishment. ***energy.gov.*** **[Online] [Cited: September 1, 2023.] Dual-Mode Hybrid/Two-Mode Hybrid Accomplishment .**

10. Choosing a Motor. ***Electrogenic.*** **[Online] [Cited: September 3, 2023 .] https://www.electrogenic.co.uk/under-the-bonnet/technology/choosing-a-motor/#:~:text=The%20properties%20of%20the%20vehicle,torque%20of%20the%20original%20motor.**

11. The History of the Electric Car. ***Energy.gov.*** **[Online] 2014.**

12. What is the Difference Bewteen Friction and Regenerative Brakes. ***MachineDesign.*** **[Online] March 2, 2016. [Cited: Septmeber 3, 2023.] https://www.machinedesign.com/mechanical-motion-systems/article/21831982/whats-the-difference-between-friction-and-regenerative-car-brakes.**

13. Falch, Martin. CAN Bus Explained - A Simple Intro (2023). ***CSS electronics.*** **[Online] April 2022. https://www.csselectronics.com/pages/can-bus-simple-intro-tutorial.**

14. Pini, Art. The Basics of the Controller Area Network (CAN bus) and its Use in Automotive Applications. ***DigiKey.*** **[Online] January 26, 2023. https://www.digikey.com/en/blog/the-basics-of-the-controller-area-network.**

15. Muscad, Ossian. The Eyes and Ears of Your Car: A Comprehensive Guide to Automotive Sensors. ***Datamyte.*** **[Online] April 17, 2023. https://datamyte.com/automotive-sensor/#:~:text=Automotive%20sensors%20are%20the%20eyes,fuel%20temperature%2C%20and%20throttle%20position..**

16. Agency, Environmental Protection. United States Environmental Protection Agency . ***epa.gov.*** **[Online] April 12, 2023. [Cited: September 2, 2023.]**

https://www.epa.gov/regulations-emissions-vehicles-and-engines/regulations-greenhouse-gas-emissions-passenger-cars-and#regulationssafety.
17. Engineering Product Design. ***Shaft key selection & shaft keyway design guide.*** **[Online] February 13, 2021. https://engineeringproductdesign.com/knowledge-base/shaft-key-selection-keyway-design-guide/.**
18. Glenn Research Center. ***Ideal Otto Cycle*** **. [Figure] s.l. : NASA, 2021.**

APPENDIX A

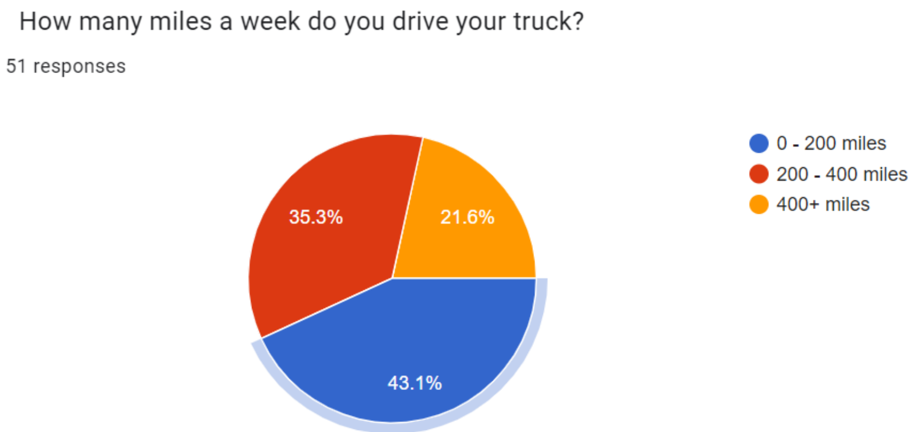


Figure 57 Weekly Miles Survey Results

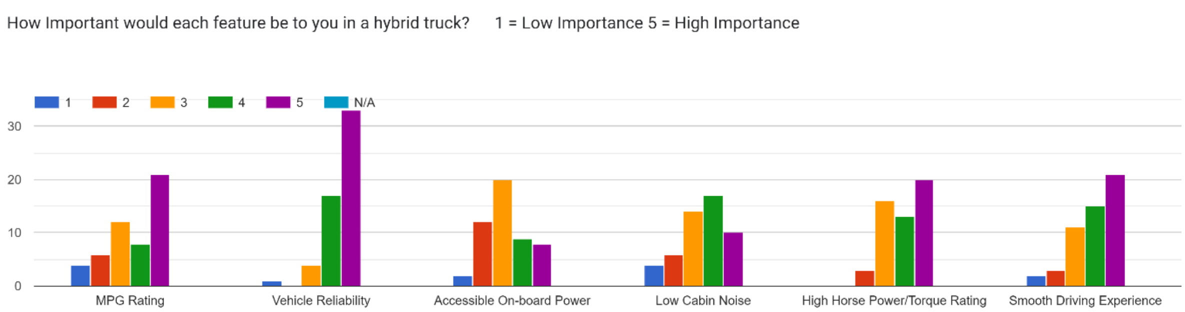


Figure 58 Feature Importance Survey Results

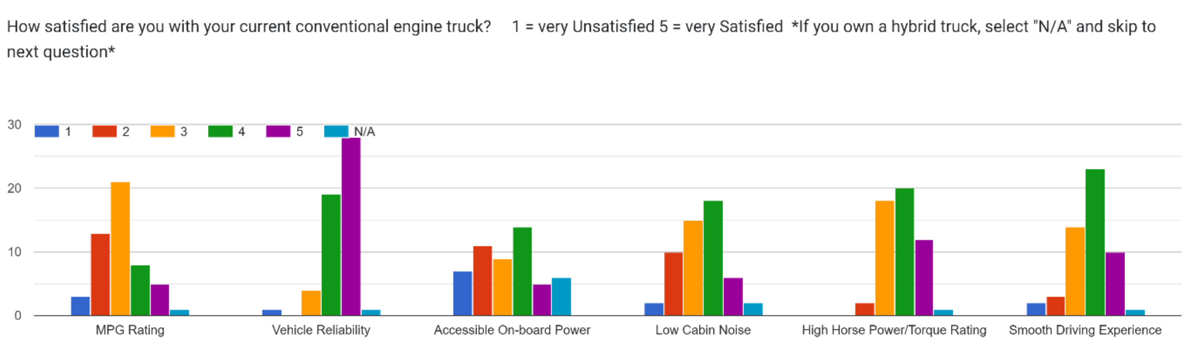


Figure 59 Vehicle Satisfaction Survey Results

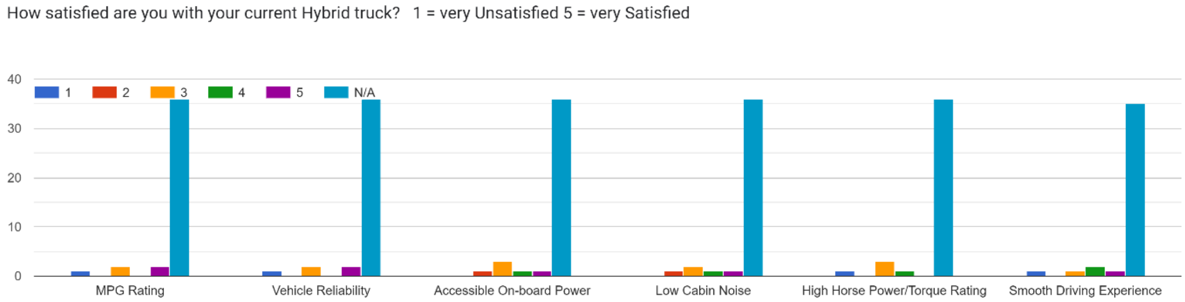


Figure 60 Hybrid Vehicle Satisfaction Survey Results

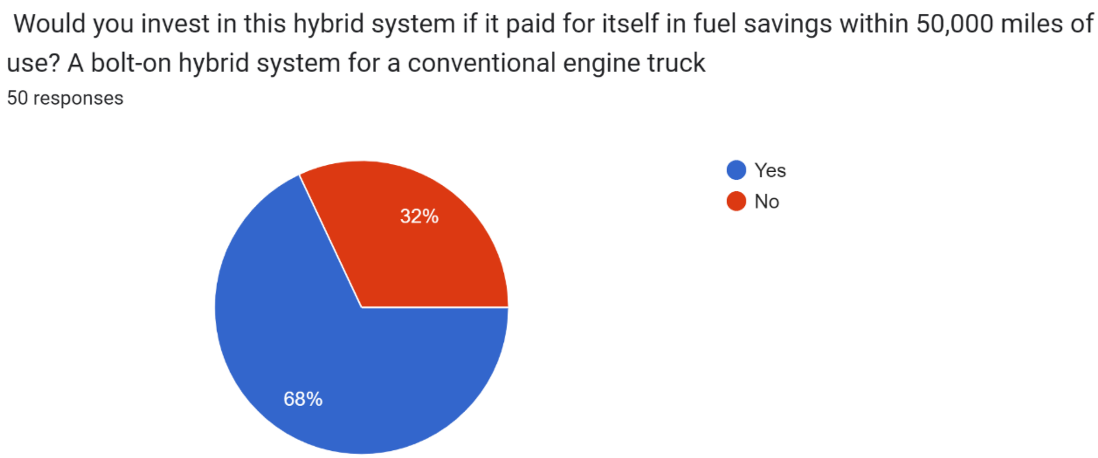


Figure 61 System Interest Survey Results

APPENDIX B

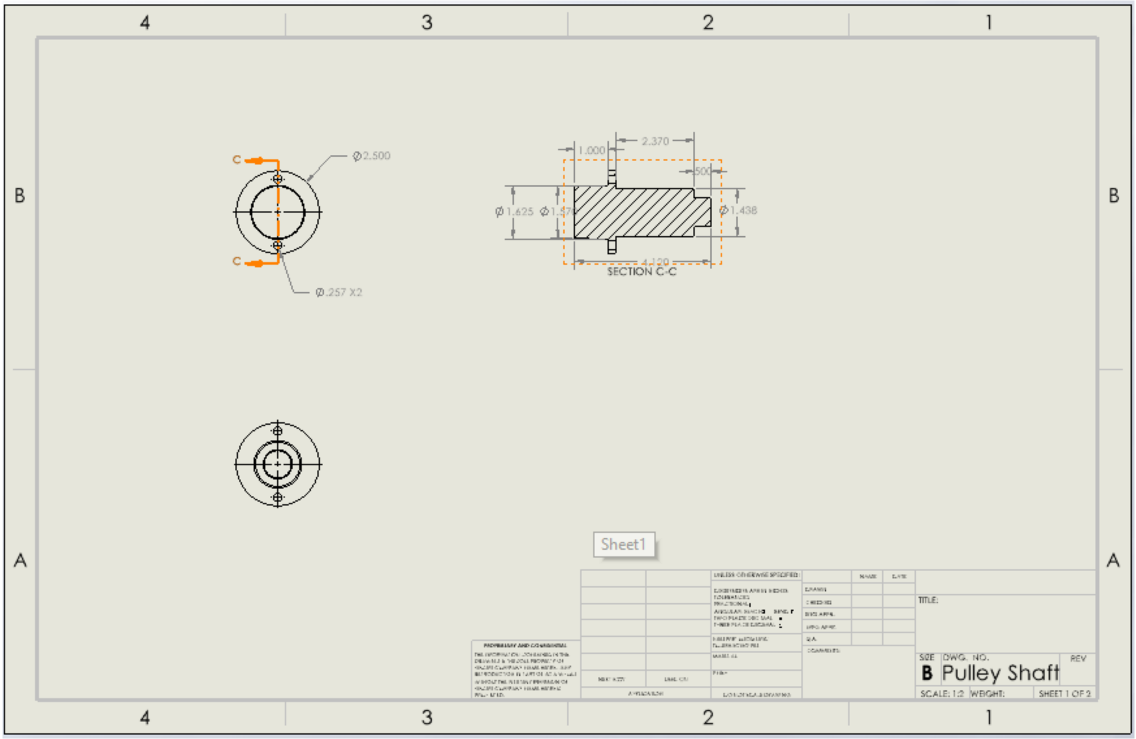


Figure 62 Motor Shaft Extension pt.1

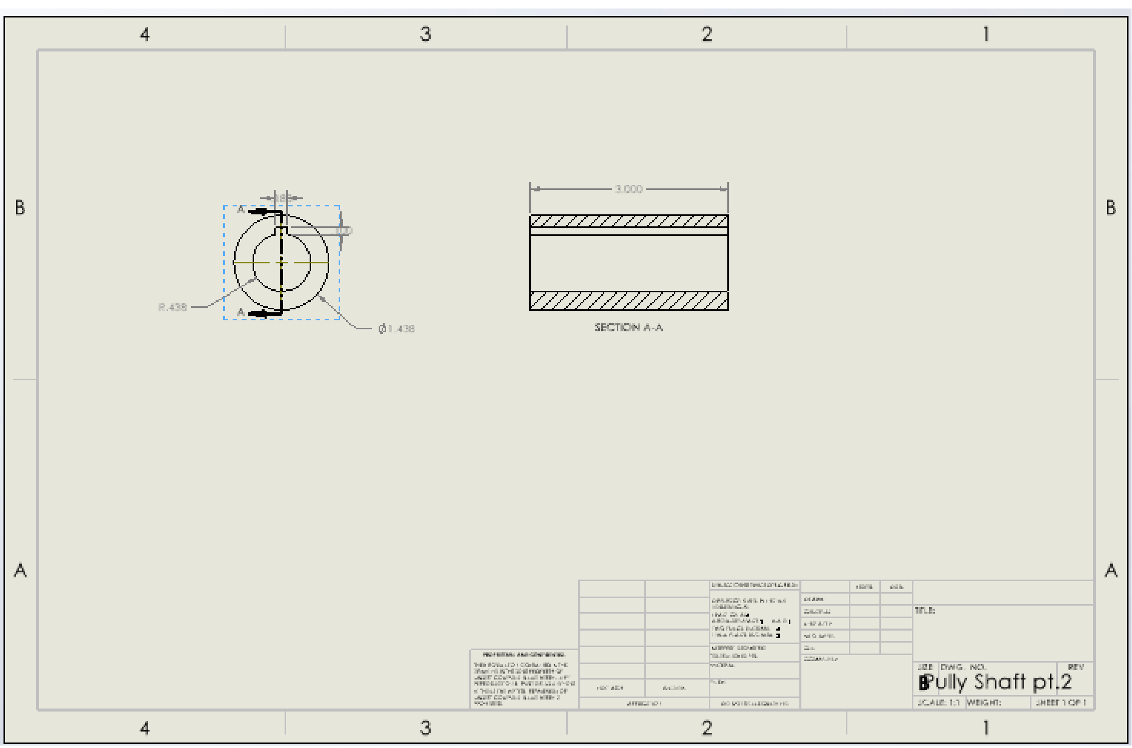


Figure 63 Motor Shaft Extension pt.2

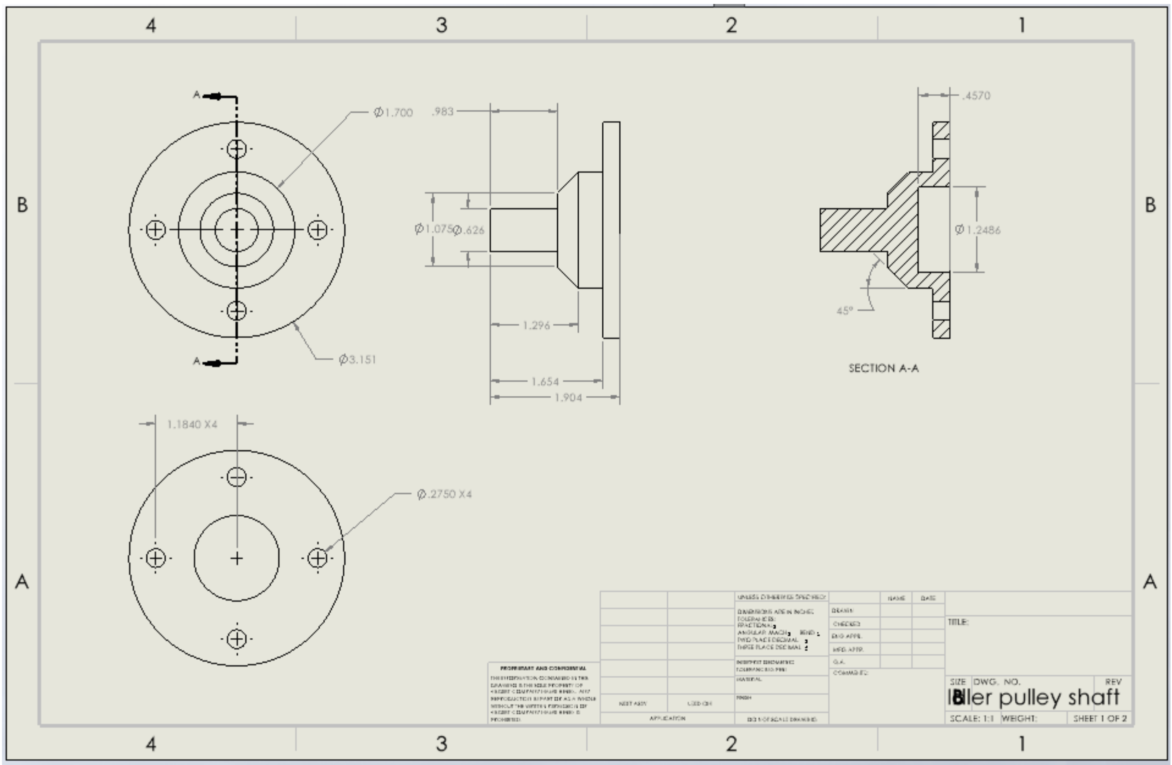


Figure 64 Idler Pulley Shaft

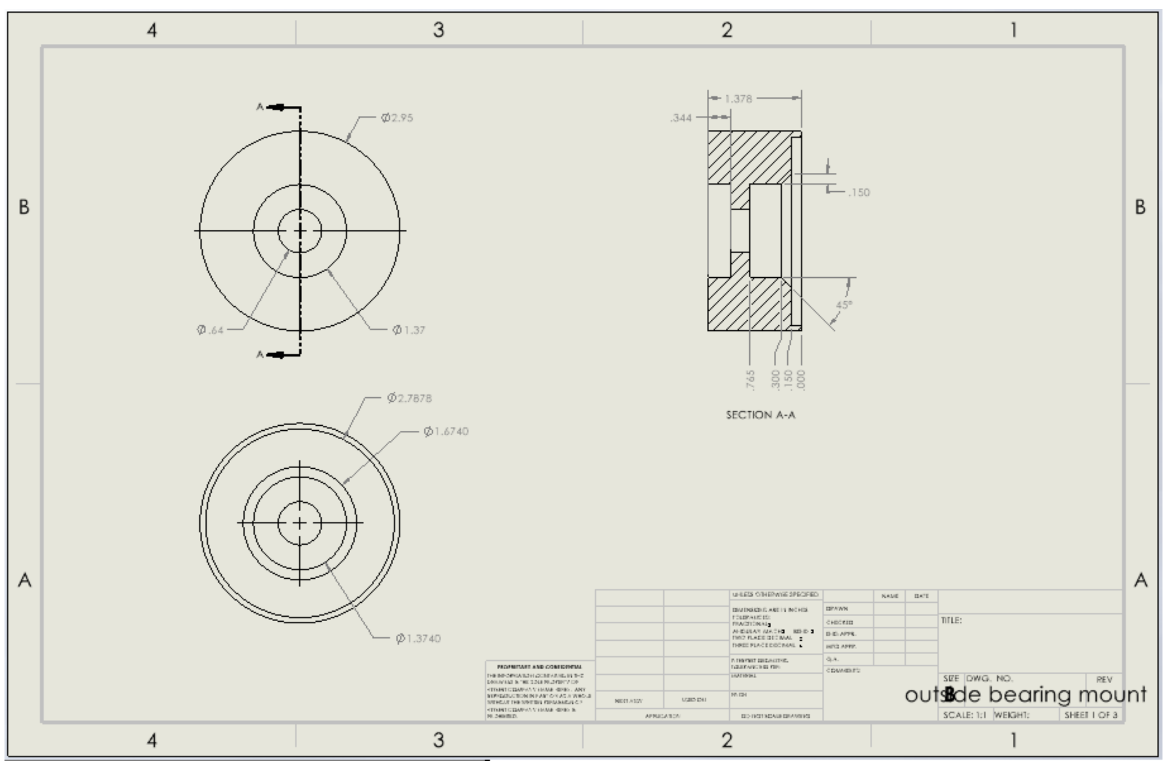


Figure 65 Idler Pulley

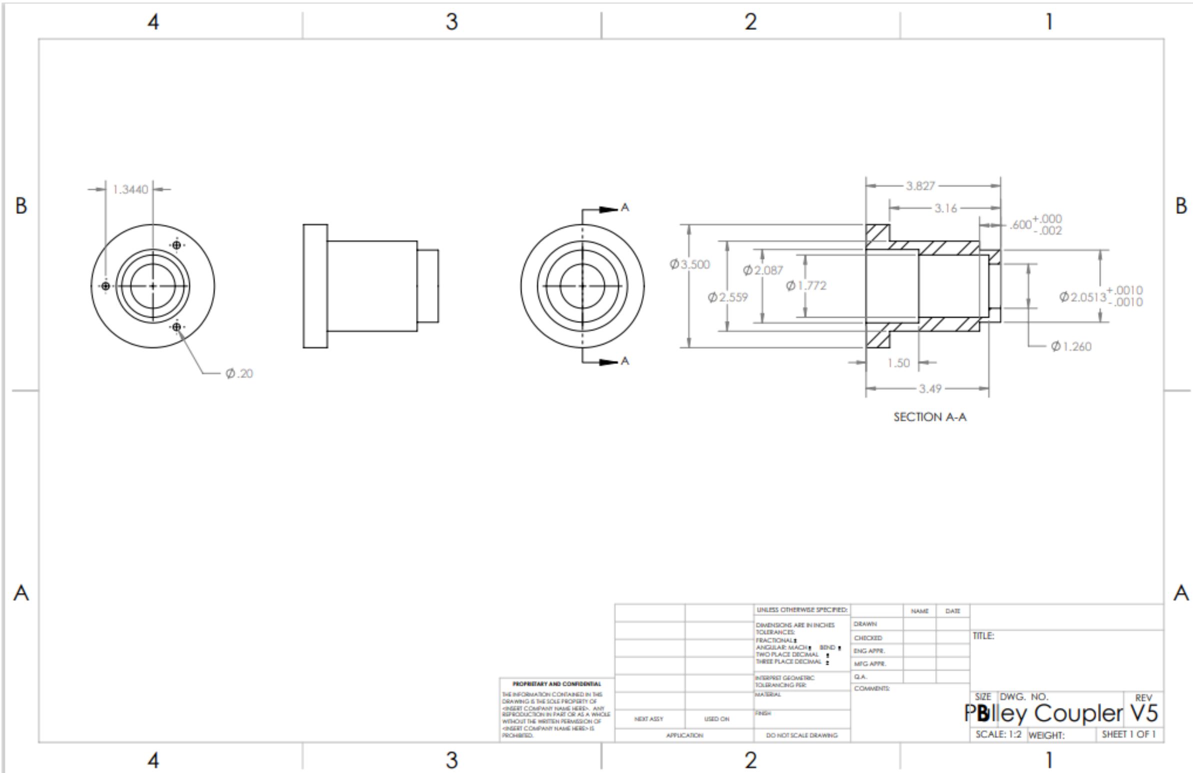


Figure 66 Pulley Coupler Drawing

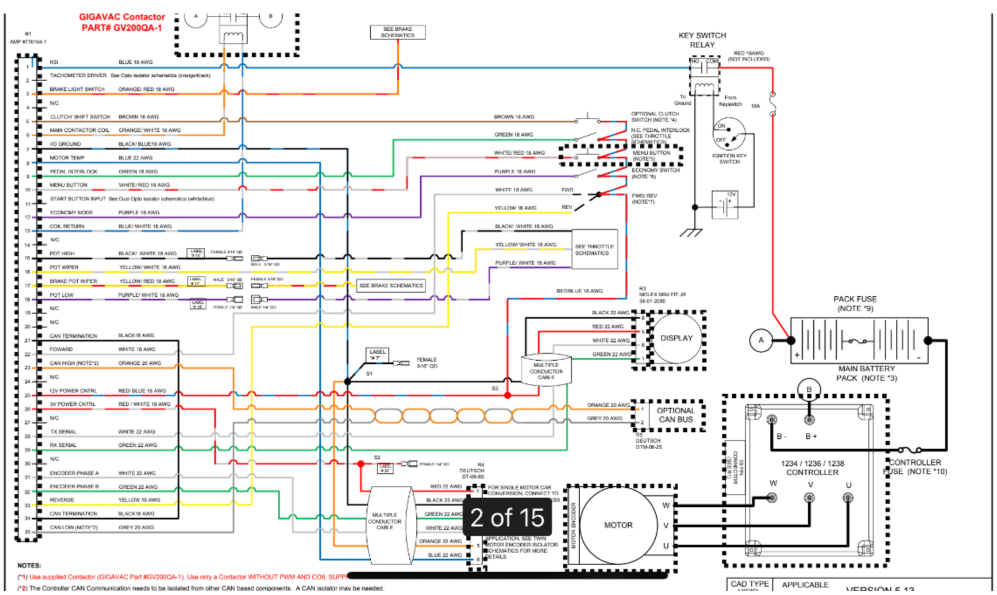


Figure 67 Overview of Electrical Control Schematic