Green Go-Kart Dyno

FDR Report

Tim Morris

Victor Tishkevich

Jenna Chinn

Ryan Doherty

Zach Delahunty

ME 463 – Senior Design

Professor Eric Holloway

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Executive Summary

This report covers the Final Design Review for the Green Go Kart Dyno, focusing mainly on the improvements made to the design from CDR, the production of the final prototype, and the testing of the prototype.

The Green Go Kart Dyno team wants to make the testing of small engines more accessible to people, while making tests easier to conduct and environmentally friendlier. To do this the team will fabricate a comparably inexpensive small engine dyno that will be able to safely filter engine exhaust. This would give small engine builders and hobbyists easier access to testing equipment, reducing the barrier of entry into the sport.

The FDR phase was focused on the physical implantation of the design. The first step was to manufacture and modify parts for the dyno. Manufacturing drawings and operation sheets were drafted to ensure these parts were manufactured to standard. Three parts were fabricated, and a further two purchased parts were modified to match the design.

The assembly of the dyno was broken into three areas, the hydraulic system, filtration system, and electronic system. **Figure E.1** shows the final prototype with these sub-systems labelled. Assembly of the hydraulics included affixing components such as the hydraulic tank, oil cooler, and pump to the modified cart and assembling the rest of the hydraulic system around these items. The filtration system used 3-D printed parts and hose clamps to mount an in-line ducting fan and tubing to the cart before being released into the filters. The electronics were mounted in such a way where wiring could be kept out of the way of the other sub-systems and were all run to the electrical housing which contained the power supply, electric terminals, and buck converter. The final step was to install plywood guards along the side of the cart to prevent injury in the event of chain snappage.

The dynamometer was able to record some data from the engine running while the hydraulic flow valve was fully open. This was not indicative of true engine performance because of the lack of load on the engine, but due to safety concerns with the pump shelf lifting and the fear of failure in the hydraulic lines, not all the planned validation tests were able to be performed. Three validation tests were not able to be performed due to failures upstream in the system or changes in the design. Three tests failed, those being ones who relate to an actual dyno test, and the failure of filtration tubing to withstand exhaust temperature and pressure.

Some changes made to the design from CDR are the arrangement of the hydraulic lines, further modification to the frame to support switches in the electronic system, and a fan attached to the oil cooler. The CAD model used to represent the dyno's digital twin shown in **Figure E.2** was modified to reflect these changes. Further iterations the team would like to make include reinforcement for the pump shelf, better tubing for the upper part of the hydraulic system, a universal engine mount, and noise reduction.

The final prototype built in FDR used a budget of $860.42, lower than the anticipated budget from both PDR and CDR, both of which were around $900. This cost reduction was thanks to a few design simplifications, and an abundance of resources available from the Purdue ME department.

The current design for the Green Go Kart Dyno shown in **Figure E.1** uses 24 purchased parts and 4 manufactured parts, the cost of which would be $2,084.11. With a markup of about 50% the anticipated sales price of the Green Go Kart Dyno will be $3,100. This is similar in price to competitors while also providing more value to the consumer. According to Market Research Future, only a few thousand small engine dynos are sold annually. If the product can capture around 7% of this market, 200 Green Go Kart dynos will be sold annually, resulting in an annual gross profit of $203,178.

The prototype design meets most of the engineering requirements, with the exception of some requirements for the filtration system, and requirements pertaining to engine tests in the Performance/Accuracy category, as the validation tests relating to these requirements could not be conducted.

With the completion of FDR, the team would like to validate system reliability and durability for long term use as well as refine the design further to improve usability, routing and noise reduction.

We encourage you to read the rest of the report for more detailed information about the state of the design and ask that the Green Go Kart Dyno be given approval to continue to extended testing, implantation of final design refinements, and to begin low volume production and market launch.

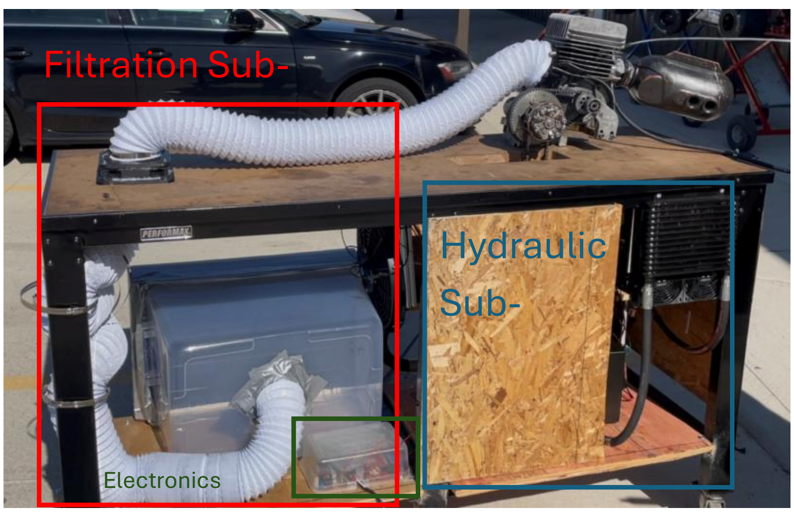

Figure E.1: Green Dyno Final Prototype

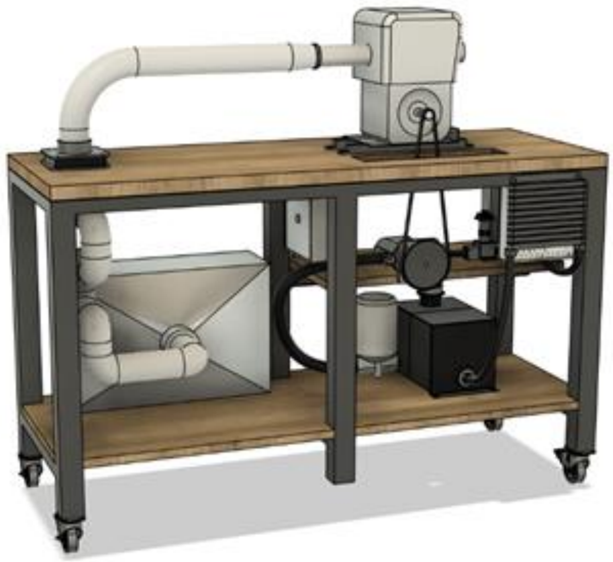

Figure E.2: Green Dyno Finalized Digital Twin CAD Model

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I. Introduction

The Green Go-Kart Dyno project was developed to address a critical gap in the market for small displacement engine testing: the lack of an affordable, compact, and environmentally responsible dynamometer solution. Traditional dynos are often cost-prohibitive, occupy significant space, and fail to include exhaust filtration, posing challenges for hobbyists, educators, and small-scale engine builders who require precise engine validation without compromising on safety or sustainability. The Green Go-Kart Dyno integrates performance testing with built-in exhaust filtration in a portable, user-friendly platform. This report details the progress made during the Final Design Review (FDR) phase, which included manufacturing the system components, completing both mechanical and electrical assembly, and conducting validation testing to confirm system functionality. These efforts build on the foundation established in the Preliminary and Critical Design Reviews (PDR and CDR), which guided component selection, system layout, and failure mitigation strategies. The result is a fully assembled, operational prototype that meets the majority of the team's engineering requirements for reliability, accuracy, and environmental safety.

II. Problem

Many builders of small displacement engines need a dyno to test their engines but lack the funds or space to incorporate exhaust filtration systems. When rebuilding small displacement motors, particularly 2-stroke engines, precision is crucial, as these engines can experience catastrophic failures within the first few minutes of operation if the tolerances are incorrect. Running the engine on a dyno helps prevent these failures before the engine reaches the consumer. However, most dynos are expensive, large, and lack built-in exhaust filtration.

To address this challenge effectively while staying within the team's time and resource constraints, vision and mission statements were developed and included in the charter in Appendix A to ensure the team remains focused and on track. The vision is as follows: To revolutionize small displacement engine testing with solutions that are accurate accessible and environmentally sustainable, with the mission statement being: To create cutting-edge, eco-friendly testing systems for small displacement engines, delivering precision and affordability to empower users while promoting environmental responsibility.

III. Results of PDR and CDR

The Preliminary and Critical Design Reviews (PDR and CDR) confirmed strong design readiness and validated the core functionality of the Green Dyno system. The PDR phase successfully demonstrated accurate and repeatable power measurement in small displacement engines through the "Pressure Dyno System." Key achievements included the validation of a flow control system integrating a stator motor, flow control valve, and Arduino-based pressure feedback loop, enabling real-time regulation for optimal dynamometer performance. The encoder-mounted pump provided RPM measurements, which, combined with known pump displacement, enabled accurate flow rate and engine power calculations. These results affirm the system's capability to consistently measure horsepower and support reliable engine testing. The integrated "Snake Filter with Fan" exhaust system also met design expectations. Its ducting and convection-enhanced cooling design reduce filter degradation risk by lowering exhaust temperature, contributing to the system's durability. Additionally, the PDR confirmed proper housing fitment within the go-kart and provided insights for hydraulic line routing and component placement, such as the pump and hydraulic tank, improving system integration.

During the CDR phase, a Failure Mode and Effect Analysis (FMEA) identified 15 potential failure points, prompting design improvements including a chain guard, oil cooler, heat-resistant wiring, and improved routing. CAD modeling supported component fitment and informed layout refinements such as repositioning the electronics box, adding a larger exhaust shroud, and including a wooden pump-mounting platform. Finite Element Analysis (FEA) guided material selection, confirming steel as an optimal choice for the pump bracket with a high factor of safety. Plans to weld casters and modify the table further support system mobility and integration. Together, these results from PDR and CDR reflect a robust, functional design, with validated core systems and targeted refinements that position the team for successful implementation in the Final Design Review (FDR) phase.

IV. Technical Approach

The Green Go-Kart Dyno project prioritizes rigorous engineering analysis to ensure the reliability and efficiency of its components. Finite Element Analysis (FEA) played a crucial role in validating key structural elements, including the sheet metal pump bracket. FEA simulations were conducted to assess stress distribution and structural integrity, ensuring the bracket met strength and durability requirements under operational loads. Similar FEA evaluations were applied to other brackets and load-bearing components to verify their performance and longevity.

For the hydraulic system, as seen in Figure M.1, component selection was driven by precise calculations. The hydraulic pump was chosen based on pressure and flow rate requirements, ensuring it could compensate for head losses and maintain system efficiency. Hydraulic tubing was selected based on pressure ratings and flow characteristics to minimize energy loss and maintain optimal fluid dynamics. Bernoulli’s equation was applied to evaluate pressure and energy losses, confirming the pump’s capacity to sustain the necessary outlet pressure of 11,407.84 kPa, or 1654.6 psi.

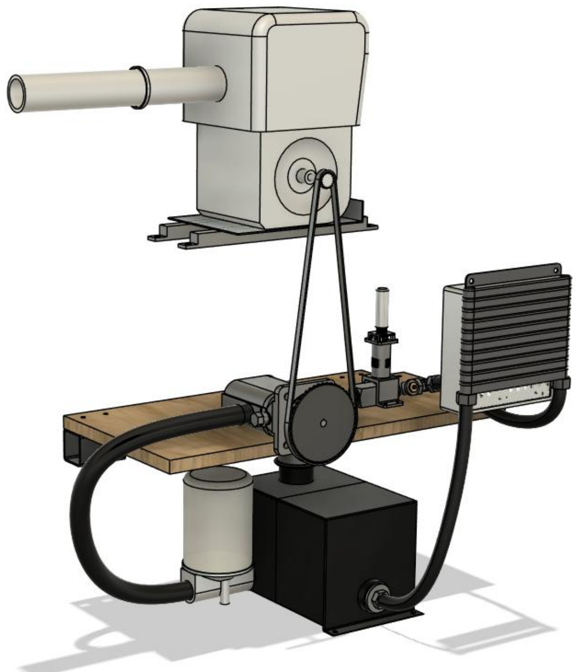


Figure M.1: Hydraulic System Sub Assembly

Cooling and exhaust system components, as displayed in Figure M.2 below, were also carefully analyzed. The exhaust cooling fan size was determined based on airflow requirements and thermal dissipation needs, ensuring adequate cooling efficiency. Exhaust tubing dimensions and length were selected to optimize flow characteristics while maintaining proper backpressure. Heat exchanger calculations, utilizing energy balance equations, validated the system's heat dissipation capabilities, with a heat transfer value of 1.92 kW and an effectiveness rating of 90%. Material choices for other components were based on availability and budget constraints while maintaining structural and functional integrity. This analytical approach ensured that all selections met performance expectations, contributing to the overall success and efficiency of the Green Go-Kart Dyno system.

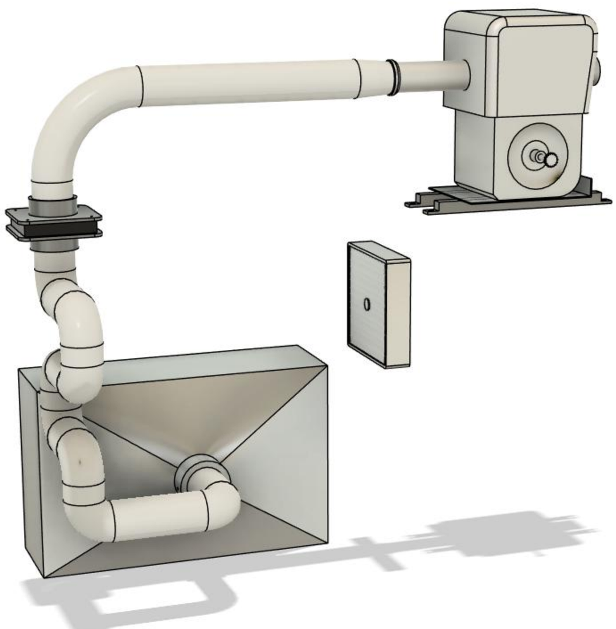


Figure M.2: Filter System Sub Assembly

The approach to collecting engine data involves using an Arduino to collect sensor data, recording time, and sending those values into Excel for data processing. The code uploaded into the Arduino has it record time, which it uses to find the RPM of the gear on the pump when the proximity sensor detects a full revolution. The Arduino uses the Serial.print command which is used to upload the measured time, RPM, and pressure data to Excel with Excel's built in function Data Streamer. To process the data, values from the pressure sensor need to be converted to psi, and the RPM of the pump needs to be converted into engine RPM by applying the gear ratio between the two devices. The volumetric flow rate through the pump needs to be identified using the maximum pump operation values, and finally these values are used to calculate the engine's horsepower. If testing a power run on the dyno, the gear motor will close the flow valve, building up back pressure in the hydraulic system, applying load to the engine and reducing RPM. In this case the flow valve is closed until the target RPM is reached, allowing for the dyno to measure performance data.

V. FDR Results

Prototype Part Manufacturing

Before full Assembly of the prototype could begin, the team manufactured various parts, some of which were modified purchased parts. All manufacturing drawings and operation sheets can be found in Appendix N. The final Green Go-Kart Dyno prototype was assembled using a total of 28 components, including 24 purchased parts and 4 custom-manufactured components.

The cart frame was modified by cutting slots into the tabletop for the chain path and duct fan, drilling precise holes to mount the oil cooler, and welding wheels and reinforced shelving to support system components. A purchased pump gear was modified by using a milling machine to add a key slot that allowed for secure connection to the drive shaft of the hydraulic pump. In addition, the team 3-D printed a flow valve bracket, designed to hold the gear motor in proper alignment with the valve for precise flow control, and a fan adapter, used to interface the duct fan with the exhaust tubing.

Prototype Assembly

The assembly process involved closely mirroring the CAD models, as all distances between each component to ensure a proper arrangement were meticulously calculated and laid out in the CAD design. The assembly features three main subassemblies: the hydraulic system, exhaust filtration system, and data acquisition system.

The hydraulic system was constructed using a hydraulic tank, hydraulic filter, fluid lines, oil cooler, and a pump driven by the engine through a chain connection. A gear motor was mounted to control a flow valve, allowing the team to regulate back pressure within the hydraulic system and apply varying loads to the engine. A pressure sensor was installed to monitor system pressure, and a proximity sensor was used to detect the gear's revolutions. Worm clamps and brackets were used throughout the hydraulic subsystem to ensure all components were securely mounted and properly aligned, which was critical for maintaining safety and performance under operating conditions.

The exhaust filtration system included ducting that was connected to the engine's exhaust port and routed underneath the tabletop, where it was secured in a snake pattern down the side of the frame using worm clamps. The ducting was clamped to the 3-D printed fan adapters allowing a duct fan to move the exhaust through the tubing. A cooling fan was mounted to the underside of the table to blow air directly across the snaked ducting, and the ducting was then routed to a filtration case housing MERV-16 filters.

The data acquisition system included a 12 V supply wired to a switch, then to a 12 V terminal to power all the electronics in the sub assembly. Wired connections ran from the 12 V terminal to the proximity sensor, gear motor, motor controller, and through a buck converter to step down to 5 V. The pressure sensor and all three fans were connected to the 5 V terminal. The sensors and controller were then wired to the Arduino and housed in an electrical box attached to the base plate of the frame. The detailed final prototype assembly in Figure M.3.

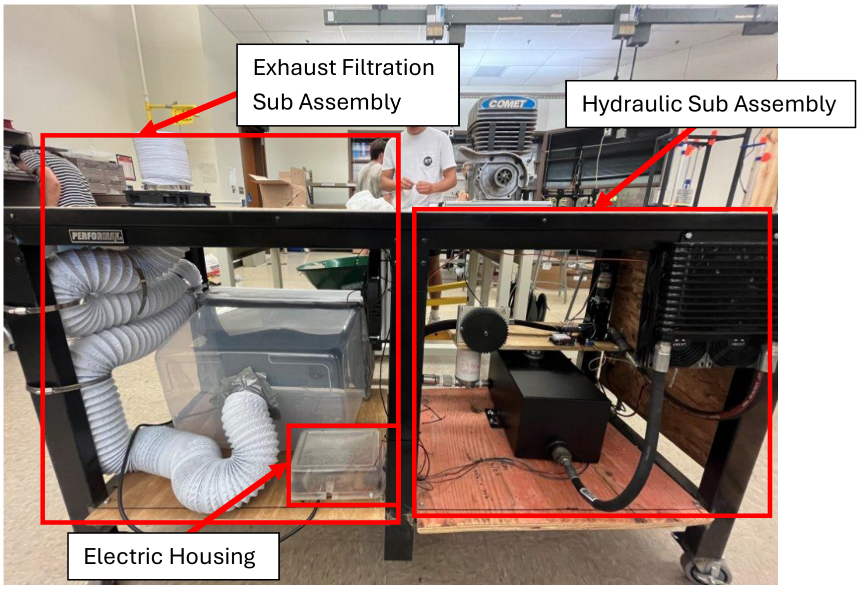
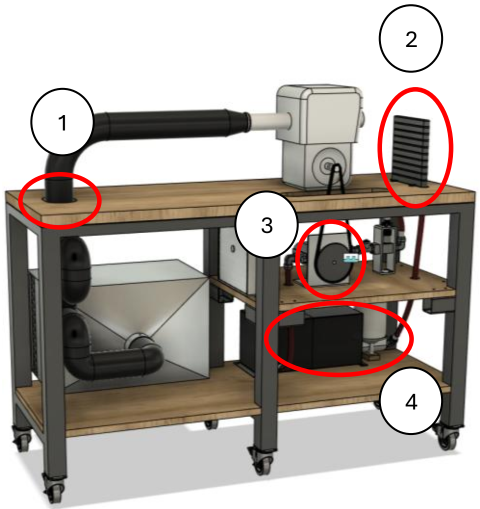


Figure M.3: Final Green Dyno Prototype

<u>Prototype Iterations</u>

Multiple iterations were done to the design during the assembly process due to strength, integrity and budgeting. The main assembly-based iteration was the rearrangement of the hydraulic system layout. The initial assembly included an oil cooler that was attached to the top of the tabletop, and a hydraulic tank orientated parallel to the frame as seen below in Figure M.4 by **2** and **4**. With this configuration, there would be more parts needed to attach the system, and longer hydraulic lines to and from the oil cooler, ultimately increasing the budget significantly. In addition, there would be high tension within the hydraulic lines due to this configuration. The arrangement of the system was eventually iterated to the one shown in Figure M.5 by **2** and **4**, which features the oil cooler bolted to the front side of the frame, and the hydraulic tank rotated 90 degrees.

The addition of a fan and the adapters, as displayed below by **1**, allowed for better movement of exhaust gases through the ducting. Finally, the pump mounting was updated to ensure better stability of the pump to the wooden shelf as seen below by **3,** as the pump will be reaching high RMP speeds and must be able to withstand high torque produced by the engine.



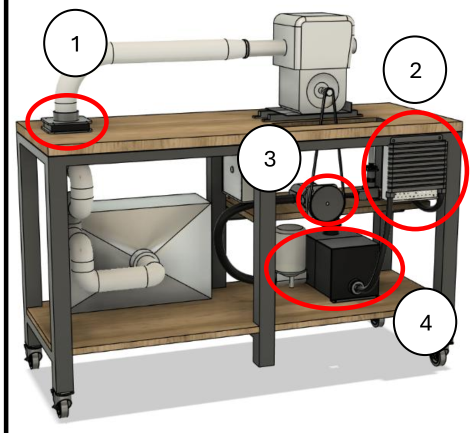


Figure M.4: CAD without Updated Iterations **Figure M.5**: CAD with Updated Iterations

<u>Prototype Validation</u>

The Green Go Kart Dyno Project included multiple tests to ensure performance and reliability. The electrical components were each tested individually before being assembled into a full circuit. It was verified that the motor controller could turn the flow valve into the fully on and fully off positions when given signal through the Arduino, and that the pressure sensor was able fully operational. In addition, all three of the fans on the dyno were tested and ensured they could be powered on and off through a switch. Finally, the proximity sensor was calibrated to and tested to ensure it would detect the magnet when it was spinning on the pump gear.

After the component tests were all validated, a small engine was hooked up to the Green Dyno, and multiple system tests were performed. A rolling and stability test confirmed the ease of movement of the cart with unlocked casters, and stability of the cart with locked casters. A filtration test was used to assess the prototype's ability to properly route exhaust gases through the filter, although, this test failed as the exhaust gases melted through the filtration ducting.

In addition, a fluid flow test validated that the hydraulic system was able to move the hydraulic fluid through the lines without any leaks or failures in the lining while the flow valve was fully open (no resistance on motor). A performance test was used to evaluate if the prototype would be able to close the flow valve, building up pressure, and measuring the horsepower of the engine. Unfortunately, this test failed as the pump had already begun lifting the shelf with it during a fully open valve test, and any more pressure in the lines would cause the entire hydraulic system to fail. Finally, a data acquisition sub system test verified that the sensors and controllers were working properly together, and the horsepower and torque of an open valve test run can be seen below in Figure M.5.

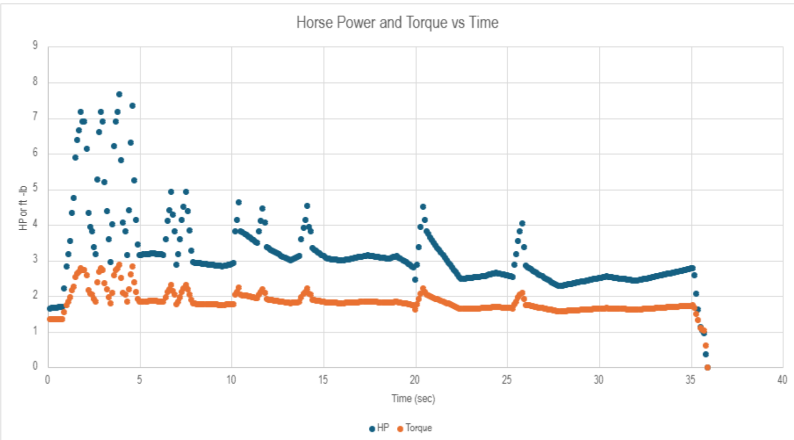


Figure M.6: Horsepower and Torque versus Time Output

VI. Market Analysis

Commented [CJ1]: Ryan Update

There is currently no all-in-one small engine dynamometer filtration device on the market, so team Green Go Kart dyno aims to fill this niche with a product that is accessible to hobbyists and small engine builders. The first consideration was to ensure that the idea does not infringe upon any patents. No patent exists for a dynamometer that filters engine exhaust, however the main patents considered are patent US3289471A which encompasses dynamometers typically used in small engine testing. This patent is expired, allowing for free use of the idea. For the filter system, the closest existing patent is patent US11047276B2 which is an attachment to engine exhaust systems, however it is only for use on vehicles that have a catalytic converter. The closest benchmark to the Green Go Kart is the Fast Factory small engine dyno shown in Appendix E. This dyno costs $2,999 and is a reasonable benchmark due to its similar size and testing capabilities. The sales price decided for the Green Go Kart dyno is $3,100. This price was selected to keep the price around that of the benchmark, allowing for product to be accessible to consumers the added value of the included filtration system. The $3,100 price tag allows for a roughly 50% markup from the estimated $2,084.11 cost of production. This estimate comes from the $1,231.77 cost of materials, $204.35 manufacturing costs and $648 labor cost. For a more detailed breakdown of this price, refer to Appendix F. According to Market Research Future in reference 15, only a few thousand small engine dynos are sold annually. With this volume in mind, it is expected that up to 200 Green Go Kart dynos will be sold annually. At this volume, the product would return an annual gross profit of $203,178.

Commented [CJ2]: $3,000 - $3,500?

Commented [CJ3]: 50%

VII. Conclusion

Commented [CJ4]: Update

The successful completion of the Final Design Review (FDR) phase marks a significant milestone in the Green Go-Kart Dyno project. The team translated conceptual designs and prior phase learnings into a fully assembled and operational prototype that meets the project's core objectives: affordability, portability, and environmental responsibility in small displacement engine testing. Through detailed manufacturing, assembly, and validation testing, the system's hydraulic load application, exhaust filtration, and real-time data acquisition were proven functional and reliable. Key design elements, such as the 3D-printed flow valve bracket, cooling-enhanced exhaust system, and Arduino-based performance tracking, were implemented and verified through practical testing. The FDR phase confirmed that the system not only meets critical engineering requirements but is also safe, effective, and user-friendly. This achievement demonstrates the project's readiness for potential field use, and it sets the stage for future refinement, commercialization, or expanded testing across a broader range of engine types.

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Appendix 1 – Project Management

A. *Charter (Click here to access ME463_Charter.xlsx)*

The challenge involves designing an all-in-one dynamometer that allows users to accurately measure the power output of small engines while effectively capturing and filtering harmful combustion emissions. The solution must function efficiently in enclosed environments without the need for an external ventilation system. Team Green Go-Kart Dyno aims to revolutionize small-engine testing by providing solutions that prioritize accuracy, accessibility, and environmental sustainability. The team's mission is to develop advanced, eco-friendly testing systems for small displacement engines, delivering precision and affordability while promoting environmental stewardship. Due to the expensive nature of small engine testing, Team Green Go-Kart Dyno had originally considered the budget out of scope for the project. During the CDR phase of the project many materials were sourced without needing to pull from the budget. This has substantially reduced the expected cost of the project. While the budget is still higher than the team hoped, as the design was further refined, we managed to stay within the budget and expect to complete the project using no more than the allotted $1,000. The size of the project remains out of scope due to the fact that the device will be built, stored, and tested in the MMRL facilities.

B. *Schedule (Click here to access ME463_Project Schedule.mpp)*

Throughout the Preliminary Design Review (PDR), Critical Design Review (CDR), and Final Design Review (FDR) phases, the Green Go-Kart Dyno team maintained a disciplined and adaptive schedule, successfully meeting all major project milestones on time. During the PDR phase, the team focused on concept development, design selection, market analysis, and early evaluations of materials and cost. Feedback during this stage highlighted the need for a more detailed timeline, prompting the team to revise their schedule ahead of CDR. The updated schedule improved clarity and accountability, keeping the team on track through the CDR phase, where efforts centered on design finalization, analytical validation, and preparation for manufacturing. Key deliverables, such as the bill of materials (BOM), sourcing plans, risk assessments, and prototype planning, were completed slightly ahead of schedule. The FDR phase marked the transition to physical implementation. The team successfully manufactured and assembled the final prototype, followed by validation testing to confirm performance and safety. Final documentation, safety reviews, and project deliverables were completed on time. The team’s consistent adherence to the schedule reflects strong project management and positions them well for post-review improvements and continued testing.

C. *Budget (Click here to access ME463_Budget.xlsx)*

Commented [CJ5]: Zach update

The total budget to produce the green go kart dyno is $1000. In the PDR phase, the team is trying to keep the budget low, leaving almost $100 free in case of problems that were not foreseen in this phase. The current estimated cost of materials for the dyno is $903.36, but the actual cost of production will likely be more due to parts breaking or not working as planned. A document detailing the budget can be found in ME463_Budget.xlsx. During the CDR phase the budget was reduced to $840.95. While the decrease in cost from PDR is good, this is still higher than the team would like, as the budget may increase if parts fail or if other problems arise. The team has already sourced parts in ways that do not impact the budget and plans to continue doing so wherever possible to potentially further decrease the budget. Finally, after the completion of FDR, the total cost of the entire project is $860.42. This price decreased significantly from CDR due to eliminating unnecessary parts. The two most significant parts that were removed from the budget were sheet metal from Home Depot which cost over $60 and ducting filter which cost roughly $50. To balance out the budget, some items had to be reordered which led to them being more expensive, but overall, the prices ended up being $40 less than CDR and $140 under the budget limit.

D. *Risk Register (Click here to access ME463_RiskRegister.xlsx)*

Commented [CJ6]: Update

Following the Final Design Review (FDR), the Green Go-Kart Dyno team updated its risk register to reflect new challenges and mitigation strategies identified during the final stages of the project. The team initially identified six key risks, including moderate concerns such as part delays, manufacturing issues, and component failures. Among these, budget overrun was classified as the most critical risk due to the project's high cost. To mitigate this, the team emphasized strict financial oversight, strategic purchasing, and responsible component handling. Minor risks like team illness and prototype testing issues were considered insignificant but still tracked with backup planning in place. One earlier concern about unfiltered exhaust gas during dyno testing was addressed by planning outdoor tests at the MMRL facility, approved by Mike Sherwood to prioritize safety.

During the Critical Design Review (CDR), seven new risks were identified, including one insignificant risk, unexpected purchase conditions such as minimum order requirements, which briefly impacted the budget but were quickly resolved. Moderate risks included potential welding issues, limited ME shop inventory, and loose wiring during operation. These were proactively managed through early part acquisition, having multiple team members trained in welding, and securing wiring once finalized. Critical risks at that stage focused on part availability, fitment issues, and potential power supply failures. To mitigate these, the team committed to verifying all component specifications and stock status before purchase or assembly.

During FDR, the team identified an additional nine risks, bringing the total to 25. These included both operational and safety-related concerns. Critical new risks included a clogged filter during extended testing, potential sensor disconnections, gear motor stalls, and data logging failures, each of which could jeopardize test results or system accuracy. The team addressed these through enhanced specifications, redundancy, rigorous pre-test checks, and backup systems. Other notable risks involved overheating of the duct fan, excessive dyno noise, pressure-related hose detachments, and fire hazards due to fuel spills. Each was mitigated with targeted engineering controls such as thermal cutoffs, acoustic insulation, double clamps, and spill containment procedures. Lastly, documentation and long-term usability were considered, and a modular cart design for easier storage. These comprehensive updates reflect the team's proactive and structured approach to risk management throughout the project lifecycle.

Appendix 2 – Business / Marketing

E. *Market Analysis*

Commented [CJ7]: Ryan Update

There are no patents specifically for go kart dynamometers, as patent US3289471A encompasses dynamometers typically used in go kart engine testing. This patent does not include filtration of the engine being tested, meaning that to safely test their equipment the customer needs a source of external ventilation, which differentiates our product to the market. The patent is currently expired.

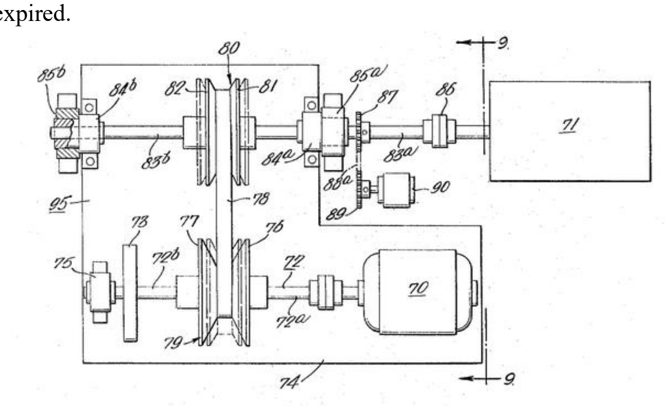


Figure A.1: Patent US3289471A Dynamometer

For exhaust filtration, many similar products are attached for car and truck exhaust systems, such as Patent US7877989B1. This patent is meant to reduce emissions from internal combustion engines with a catalytic converter, so this type of filter would not be as effective for the uses of this team. The patent is also expired.

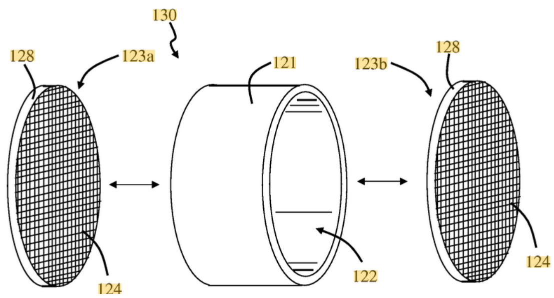


Figure A.2: Patent US7877989B1 filter system

Patent US11047276B2 is closer to the team's goal, with one filter attached to the exhaust. These filters are only rated for systems that have catalytic converters, which the small engines our product will test do not. Our design will have a system attached to the exhaust pipe, with fans to keep the air moving. The system will use multiple filters to ensure air quality.

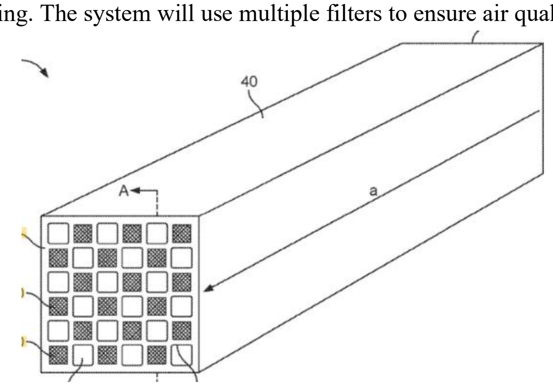


Figure A.3: Patent US11047276B2 Gasoline Particulate Filter

Currently no filtering dynamometer exists on the market, so this product will be compared to two benchmarks, small engine dynamometers and vehicle exhaust filters. Small engine dynos measure data directly from the engine. A close benchmark to the green go kart dyno is the Fast Factory small engine dyno shown Figure A.4. This is the benchmark that the project will primarily be compared to.

Figure A.4: Fast Factory Small Engine Dyno Benchmark

This dyno costs $2999 and is able to determine clutch engagement rpm, lock up and slippage ratio, compare 6 dyno pulls at once, and has precision data down to 30 rpm increments. Our goal is to be able to produce an accurate dyno that is competitive to ones that currently exist, and this is a good benchmark for that.

Chassis dynamometers, rather than testing the engine, test the kart at the wheel with drums to identify horsepower, speed, and rpm. The chassis dyno shown in reference 10 can measure with the accuracy of 1 microsecond and $1/10^{th}$ of an rpm. Using chassis dynos may lead to more accurate knowledge of what the whole kart is capable of, but they are more difficult to use, takes up more space, and are far more expensive. It will likely not be feasible to create such a complex dyno with the budget and time constraints.

Figure A.5: Dynojet Chassis Dyno Benchmark

A typical exhaust system used for indoor dynamometers is an exhaust removal unit can be seen in reference 12. These systems require additional ductwork which may or may not filter the exhaust. This solution limits the usability range of the dyno, and it is not as environmentally friendly as the team's solution. Exhaust attachment filters can be used to reduce toxins in exhaust gas. The filter seen in reference 11 has particle separation of over 99% and can withstand temperatures up to 200°C. The green go kart dyno design hopes to achieve similar filtration levels, but the anticipated temperature it will be subject to is much higher. This filtration system will have to be bigger, with fans to facilitate airflow, and it will allow for the filters to be changed.

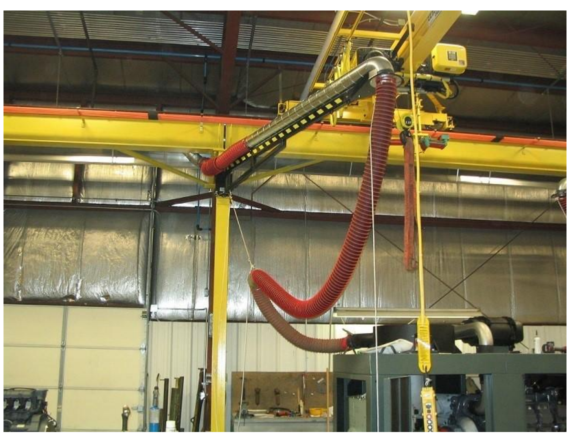


Figure A.6: Exhaust Removal System Benchmark

The green go kart dyno will provide a combined testing and exhaust filtration unit, having one product which allows for easier purchasing and wider usability, while not compromising measurement quality. The dynamometer will function with similar quality to ones currently on market, while also filtering exhaust. The goal is to make the filtered exhaust fully safe to breathe so that it can be used indoors. There is currently no dynamometer that filters engine exhaust on the market.

The research and analysis phase of this project involved extensive outreach to over 50 companies, where a Google Form survey was distributed to gather insights on engineering requirements and constraints. These companies primarily consisted of small engine manufacturers, as they represent the target customer base for the team's product. The survey data provided valuable feedback, as illustrated by the pie charts below, which helped Green Go-Kart Dyno develop a clearer understanding of industry constraints and refine their engineering requirements accordingly.

One key takeaway from the survey was the importance of maintaining the product's weight within a 20-35 lb range, as this was the most preferred specification among small engine companies. As a result, the team is confident in adhering to this target weight during the design process. Additionally, the survey revealed that 15,000 RPM is a suitable maximum rotational speed for the dynamometer to withstand, aligning with industry expectations.

Temperature considerations were also critical, with the survey indicating that operating temperatures for small engines generally range from 800 to 1500 degrees Fahrenheit, a broad margin that must be carefully factored into the design. Furthermore, small engine companies typically conduct tests lasting between 5 to 20 seconds and perform 1 to 5 RPM sweeps per test cycle. These insights will help the team design a product that meets industry demands while maintaining functionality and efficiency across various testing conditions.

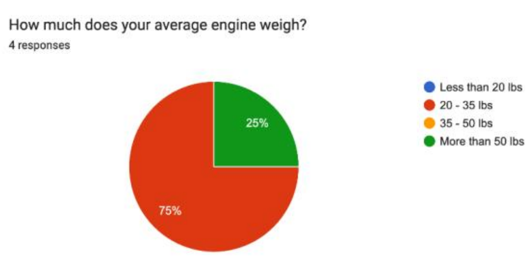


Figure A.7 average engine weight

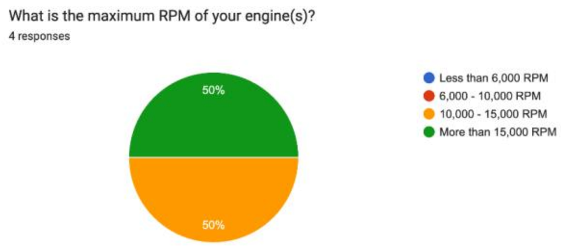


Figure A.8 maximum RPM for engine

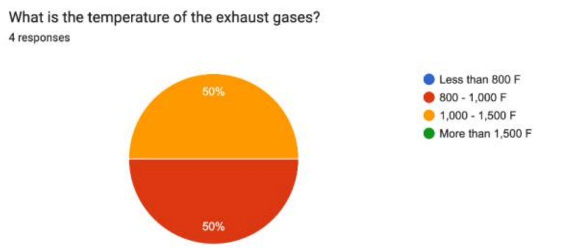


Figure A.9 exhaust gas temperature

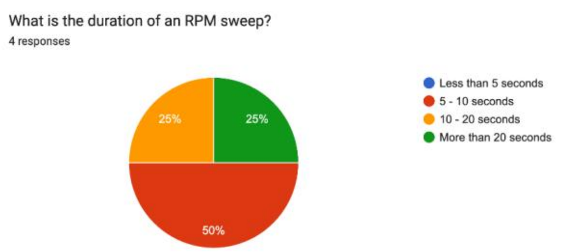


Figure A.10 duration of an RPM sweep of surveyed companies

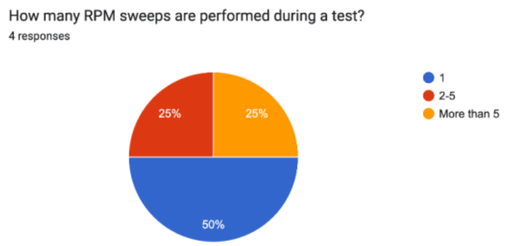


Figure A.11 RPM sweeps performed during test of surveyed companies

Commented [DR8]: Update with new figures - discuss new results

For the FDR phase, 19 responses were recorded, which is much higher than the 4 responses from PDR. Comparing the results from PDR and FDR, the average engine weight appears to be in the same range for both results with a weight of 20-35 lbs. Next, for the maximum RPM, the results were tied between 10,000 – 15,000 RPM and more than 15,000 RPM for PDR, which is also the case for FDR. For PDR, the exhaust gas temperature was tied between 800 – 1000 F and 1000 – 1500 F. For FDR, 1000 – 1500 F was by far the most popular response. Next, looking at duration of an RPM sweep, 5 – 10 seconds was the most popular result for PDR and FDR. Lastly, the number of RPM sweep tests performed was 1 for PDR and 2-5 for FDR. Overall, the majority of the results stayed the same, which confirms that the requirements and constraints for the team's project were valid from PDR.

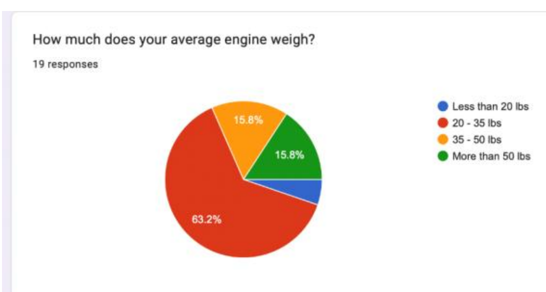


Figure A.12 FDR average engine weight survey

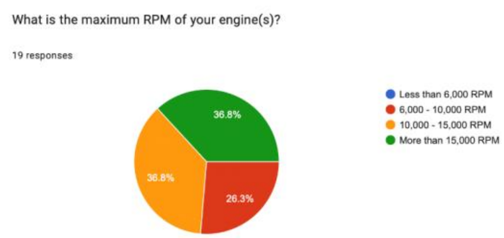


Figure A.13 FDR maximum RPM of engine survey

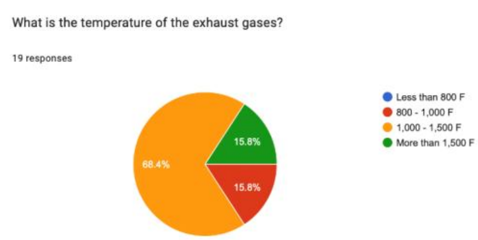


Figure A.14 FDR exhaust gas temperature survey

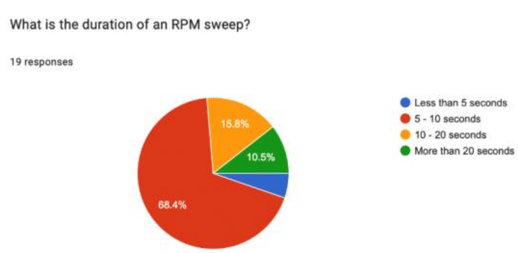


Figure A.15 FDR duration of RPM sweep survey

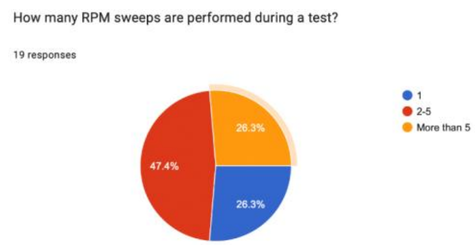


Figure A.16 FDR RPM sweeps performed during test survey

Considering that the green go kart dyno aims to be a more affordable alternative to other small engine dynos, the goal is for the sales price to be around $3,000, the cost of the Fast Factory small engine dyno benchmark. To achieve this goal, it was decided that a suitable price for the green go kart dyno is $3,100. This price is not considerably higher than the benchmark, and the added value of the filtration system means that the product could justify a higher cost. The green go kart dyno will attempt to capture more of the market with its additional value and comparable price.

Commented [CJ9]: $3,100?

F. *Value Proposition*

Commented [CJ10]: Ryan Update

It is expected that the product will cost $3,100 based on the results of the market analysis. This will allow a markup of 50% due to the construction costs of $2084.11 based on the estimation of the material costs in the bill of materials and the cost of labor in construction. According to the cost tables, the cost of materials will be $1,231.77. The green go kart dyno will be a complex project, so the labor hours are expected to be large. There will not be many parts that will need manufacturing, so the majority of labor cost will come from assembly of the assembly. The cost tables seen in ME_463_Cost_Tables break down the hours and costs required to manufacture the product.

The frame will be made by modifying a table, cutting holes for the parts and welding caster wheels to the base. This will likely take 4 hours. The construction of the filtration system contains the exhaust connection, tubing, mounting a large fan to the frame, and smaller fans and filters mounted in the tubing. This sequence will likely take 1 hour to assemble. The sub assembly for the filtration system consists of the 5-gallon tank to store hydraulic fluid, the pump, the piping, and the sensors. Based on the estimation of similar homemade dynos that have been made before, this system will take 1.5 hours to assemble. The wiring and placement of all electronic components will likely take 1.5 hours. The total estimated time it would take to construct the green go kart dyno is 8 hours. This estimate is for assembling the dyno for sales, it took far longer for the team to fabricate the prototype, and this estimate might not be accurate. With a labor rate of $60 per hour assembly will cost $480, and with a 35% overhead it will be

$648. Adding the cost of machining the pump bracket, motor bracket, and filter casing which will cost $48.32, $63.14, and $92.88 respectively, making the total cost $2056.23 This cost is less than the $2,999 Fast Factory small engine dynamometer benchmark. We believe that the product will be functionally competitive while including extra features, and with the cost of production, a markup of about 50% leading to a sale price of $3,100 is justifiable.

There are not published records of how many small engine dynos are sold annually, but based on industry trends, it is likely that. According to Market Research Future in reference 15 the dynamometer industry had $2.15 billion of market value in 2024. Engine dynamometers take up about one third of that market, and small engine dynamometers a smaller percent of that. Only a few thousand small engine dynos are sold annually, but these are typically sold to larger engine builders, while the green go kart dyno team aims to be a viable option for smaller builders and hobbyists. This product targets smaller consumers and it is likely that less than 200 green go kart dynos would sell annually. Using the optimistic sales target of 200 sold annually the product would return an annual gross profit of $203,178.

Appendix 3 – Design Process

G. *Engineering Requirements and Constraints*

Table A.2 Engineering Requirements

Design Specifications				
Category	**Specification**	**Measurable Criteria**	**Source**	**Weight**
	Withstand Weight of Small Engine	dyno chasis has to withstand 50 lb max weight	Customer Requirement	7
	Withstand Engine rotation speed	withstand 16,000 rpms	Customer Requirement	9
	Withstand Heat	exhuast piping must withstand max 1200 F due to exhaust gasses,	Customer Requirement	6
	Withstand Time	withstand up to 20 seconds of a consecutive run	Functionality	9
Durability	Withstand Cycles	withstand 5 to 7 RPM sweeps before needing a cooldown	Customer Requirement	7
Maintenance	Easy to replace filters	must have access panel to be able to	Functionality	5

		replace filters in less than 60 seconds		
	Easy to replace chain	must have access panel to be able to replace engine chain In less than 60 seconds	Functionality	5
	Easy to place in/take out and secure engine	must be able to place in/ take out and secure engine in less than 3 minutes	Functionality	6
	Provides gas to small engine while testing	have a minimum of a 1 gallon gas tank in design	Functionality	7
Cost	Be able to be constructed within budget	product must be less than $1000	Project Viability	7
	Measures and graphs engine RPM sweep, torque, horsepower	final measurements should be within 5% of catalog data	Market competitivity	10
	Repeatable, accurate measurements	Same tests return values within 5%	Market competitivity	10
	Harness various types of small engines	be able to fit 60cc to 300cc engine sizes into dyno design	Functionality	7
	Adaptable engine exhaust tube	be able to connect to max 4 inches diameter exhaust	Functionality	8
Performance/Accuracy	Filter combination must be able to filter out all produced exhaust compounds	Filtered air contains less than 50 ppm of exhaust pollutants	Market differentiation / Risk assessment	9
Safety	Filtered air quality	Filtered air contains less than 50 ppm of exhaust pollutants	Risk assessment	9

	Exhaust temperature caution	provide adequate shielding and warning for hot exiting exhaust gasses coming from engine	Risk assessment	9
	Injury prevention	Guards in case of chain snapping	Risk assessment	9
	Portable, but remains stationary during testing	Device moves less than 4 inches in any direction while testing engines	Functionality	5
Portability	Size	2 ft x 6ft x 40 in	Functionality / Customer	3

The Green Go-Kart Dyno team evaluated and assigned weights to engineering requirements based on their importance and customer needs. These weights were determined through a collaborative group discussion, taking into account the functionality, market competitiveness, and safety considerations of each requirement. Weights were assigned on a scale of 1 to 10, with 1 indicating a low level of importance and 10 indicating a high level of importance.

For the Durability requirements, the dyno chassis must support up to 50 pounds to accommodate various engines. Motors in this weight range, such as the Briggs and Stratton LO206 (36 lbs) [4], the Yamaha KT100 (21 lbs) [5], and the Predator 212 (37.5 lbs) [6], all fall within the required 50 lb limit, earning a weight of 7. This ensures the dyno can withstand all major hobbyist motors.

The dyno must also handle engine speeds up to 16,000 RPM, as seen in the KT100 engine. This high-speed capability earned a weight of 9, as it is essential for the intended use of the dyno by Purdue Grand Prix teams, which primarily use the KT100 engine.

The exhaust piping must withstand temperatures up to 1,200°F, the maximum exhaust gas temperature (EGT) of the KT100 engine [7]. Since other hobbyist engines typically have lower EGTs, this requirement was assigned a weight of 6, reflecting its lower criticality but still an important factor in design.

The dyno must operate continuously for up to 20 seconds for full RPM sweeps, a functional requirement that earned a weight of 9 due to its direct impact on the dyno's core function. Additionally, the dyno must handle 5 to 7 sweeps before requiring a break, also earning a weight of 7 to ensure it meets the demands of repeated engine testing.

Ease of maintenance is a key concern. The dyno must allow for filter replacement within 60 seconds, earning a weight of 5. The chain, being a wear item, must be easily adjustable or replaceable, also earning a weight of 5. The dyno must support easy engine mounting within 3 minutes to ensure efficient testing, which earned it a weight of 6. The cost constraint for the project is to keep the build under $1,000, which is a critical project viability requirement, earning a weight of 7.

For Performance/Accuracy, the dyno must measure and graph the engine's RPM sweep, torque, and horsepower within 5% of catalog data, a key market competitiveness requirement that earned a weight of 10. Repeatability is also crucial; any difference greater than 5% between consecutive tests would undermine the dyno's utility, earning this requirement a weight of 10.

The dyno should support a range of small engines from 60cc to 300cc, which earned a weight of 7 for its functional importance. It must also accommodate exhaust systems up to 4 inches in diameter, receiving a weight of 8 for functionality. The filtration system must ensure the air contains less than 50 ppm of pollutants, in line with OSHA standards for indoor work environments [8], earning a weight of 9 as a market differentiation and safety feature.

Safety requirements are critical, including proper shielding from exhaust gases (weight of 9) and a fully enclosed chain guard to prevent accidents (weight of 9). The dyno must also remain stationary during operation, moving no more than 4 inches, with a weight of 5 due to its importance in maintaining stability during testing. Lastly, the dyno's footprint must be compact yet accommodate necessary components, such as the filtration system and hydraulic pump, within a 12" x 72" x 40" space. This requirement received a weight of 3, as it is flexible and can be refined further in the design.

The final prototype design meets most of the engineering requirements, the exceptions being "the easy to replace filter" requirement which due to cutting costs in the filter casing, the "withstand heat" requirement which will be addressed with more durable tubing, the "filtered air quality" requirement due to the withstand heat requirement failing this could not be tested, and requirements pertaining to engine tests in the Performance/Accuracy category, as the validation tests relating to these requirements could not be conducted.

H. *Concept Sketches*

The team followed a structured concept generation process to develop potential solutions for the dynamometer and filter selection, ensuring the designs met all customer and project requirements. The primary focus was on maximizing durability, functionality, cost, safety, and performance accuracy. Engineering challenges, such as load capacity, heat resistance, exhaust filtration, and measurement accuracy, were identified early in the process to guide the development of viable solutions. Each team member created three initial design sketches representing different approaches to the dynamometer and exhaust filtration systems. These sketches were reviewed collaboratively, and the team refined and integrated the best elements of each to enhance the feasibility and effectiveness of the concepts. To evaluate the concepts, the team used a risk-reward decision matrix (**Figure A.9**) to assess the viability of each design. The concepts were categorized as "Pursue," "Further Study," or "Drop," ensuring that only the most promising designs moved forward for further analysis.

Figure A.17 concept generation exercise

For the dynamometer, the team considered three concepts: a hydraulic pressure-based system, a flow rate measurement system, and a generator-based system. The hydraulic pressure-based system (**Figure A.14**) utilized hydraulic resistance to measure torque and power output. This system was designed to withstand high RPM (up to 16,000) and extreme temperatures (up to 1,200°F), ensuring durability. Maintenance was simplified through quick-access panels, and the system met the accuracy requirement of performance measurement within 5% of catalog data. The flow rate measurement system (**Figure A.13**) relied on hydraulic fluid resistance to calculate engine performance by measuring the flow rate. This design also handled high RPMs and temperatures, with easy maintenance and built-in safeguards against pressure surges. Its performance accuracy was ensured with precise flow meters. The generator-based system (**Figure A.15**) converted rotational energy into electrical resistance, similar to a recumbent bike mechanism. This system could withstand the required RPM and temperature conditions, with a self-cleaning mechanism and cooling fans to maintain performance accuracy within 5% of catalog data.

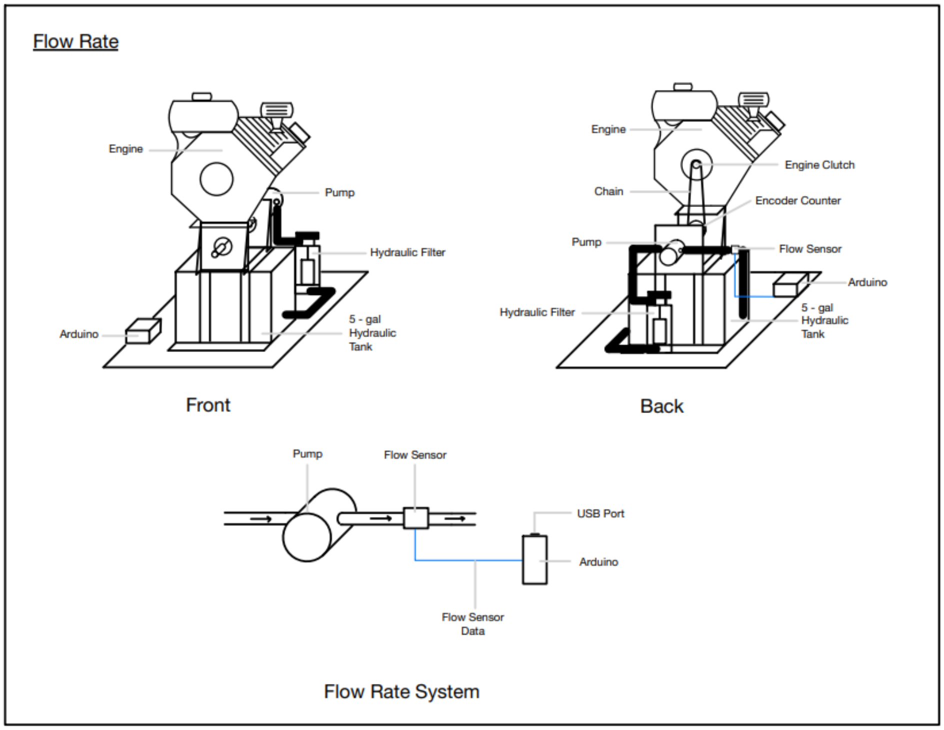


Figure A.18 Concept Generation: Flow Rate Dyno System

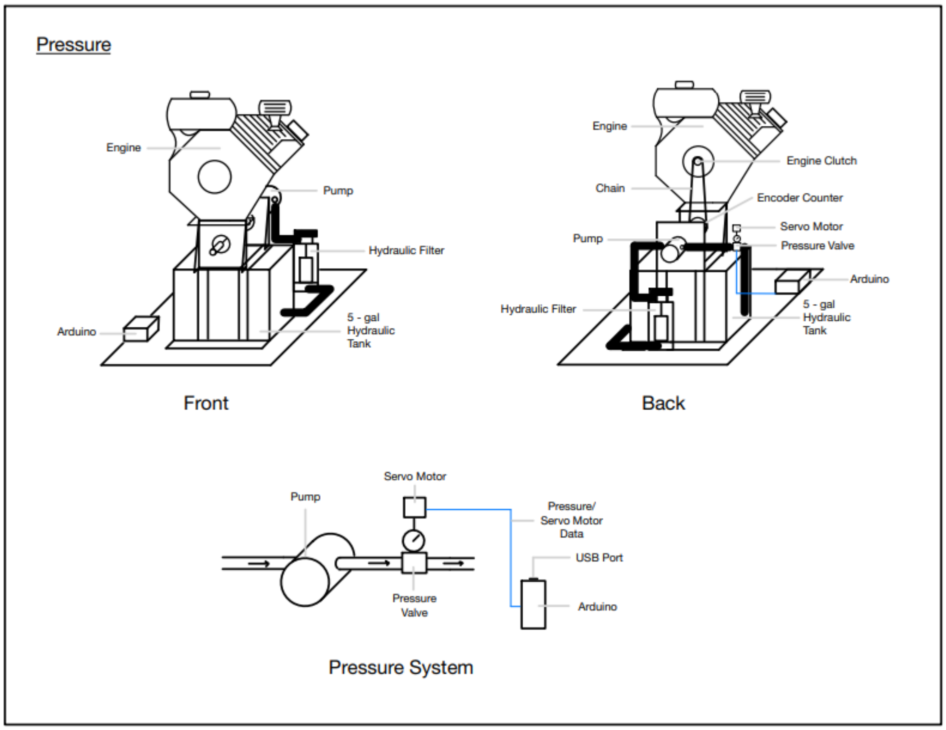


Figure A.19 Concept Generation: Pressure Dyno System

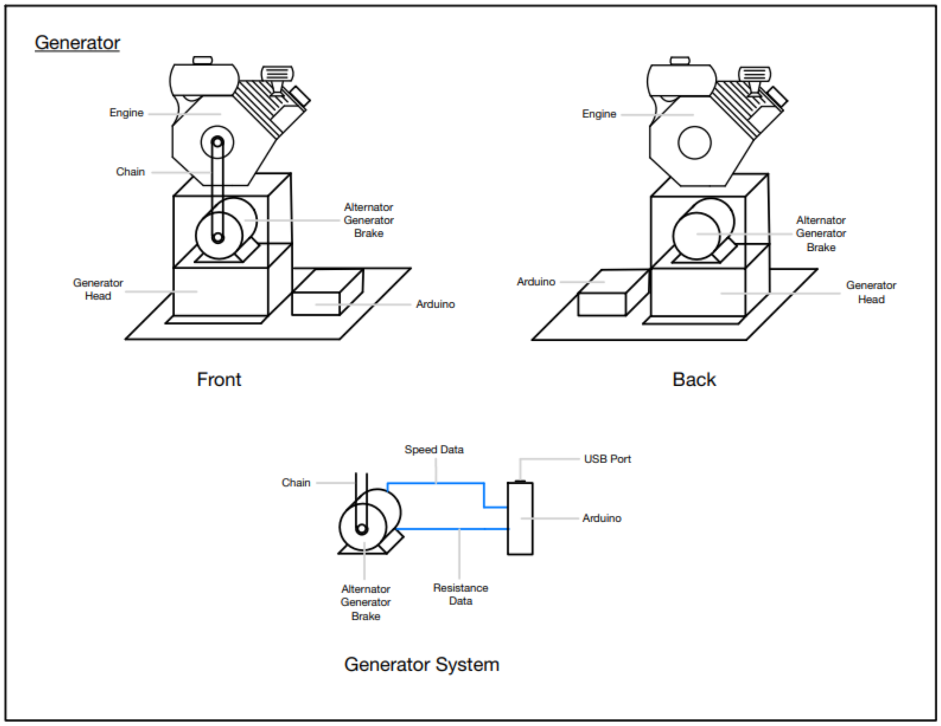


Figure A.20 Concept Generation: Generator Dyno System

For the filtration system, three concepts were explored: a cross-airflow filtration system, a passive filtration system, and a direct exhaust connection system. The cross-airflow filtration system (**Figure A.16**) used two fans to enhance air purification while cooling combustion products. This system was designed to keep pollutant levels below 50 ppm, and it withstood temperatures of up to 1,200°F, with easy maintenance features such as replaceable filters. The passive filtration system (**Figure A.17**) utilized two fans and two filters but relied on natural convection instead of cross-airflow to cool the combustion products. This design also met the pollutant filtration requirements, with heat-resistant materials and accessible filters for maintenance. The direct exhaust connection system (**Figure A.18**) featured a fan-filter sequence to maintain pollutant levels below 50 ppm. It included safety features such as a chain guard and exhaust shielding, designed to protect users from heat and debris, while also meeting the high-temperature and rotational speed requirements.

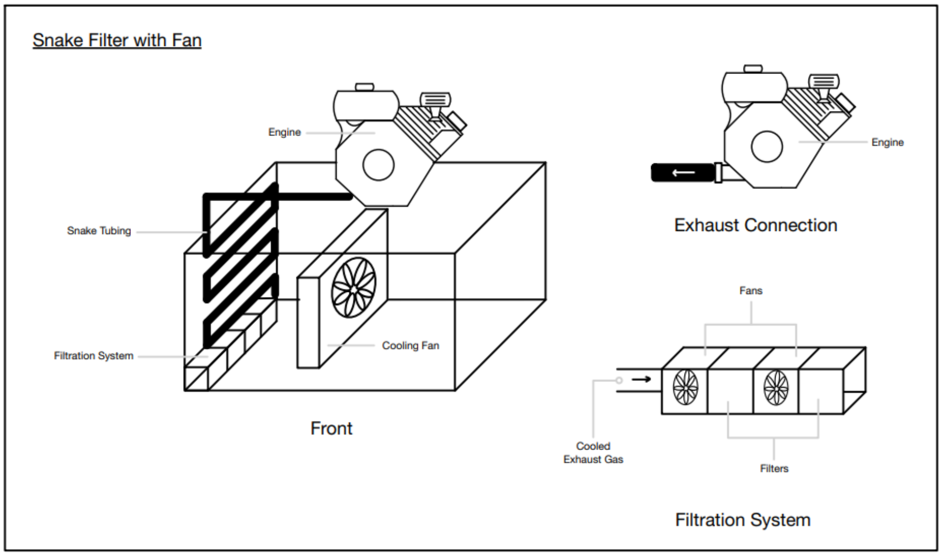


Figure A.21 Concept Generation: Snake Filter with Fan

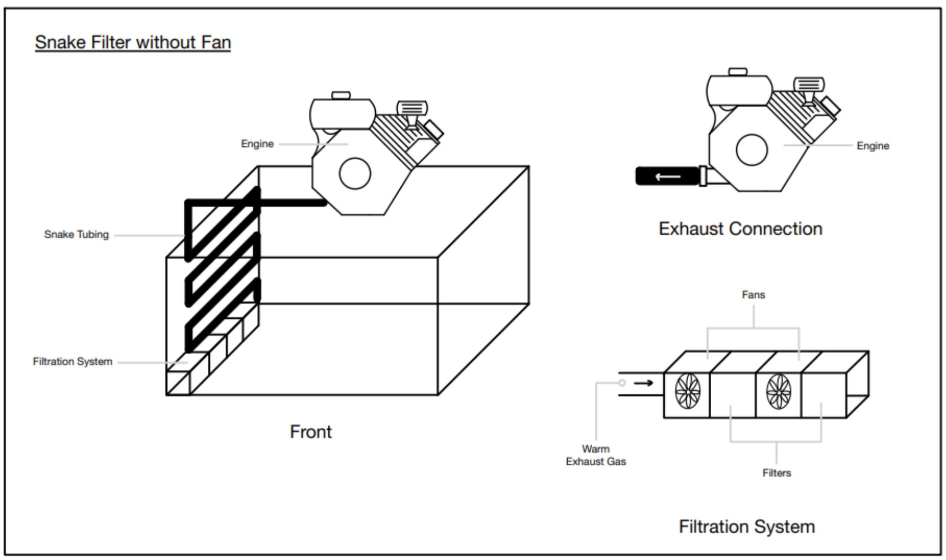


Figure A.22 Concept Generation: Snake Filter without Fan

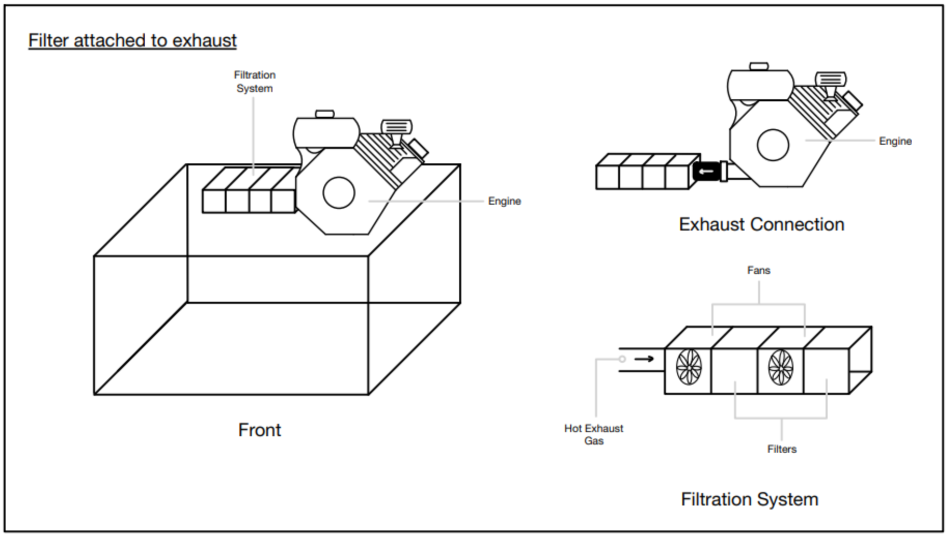
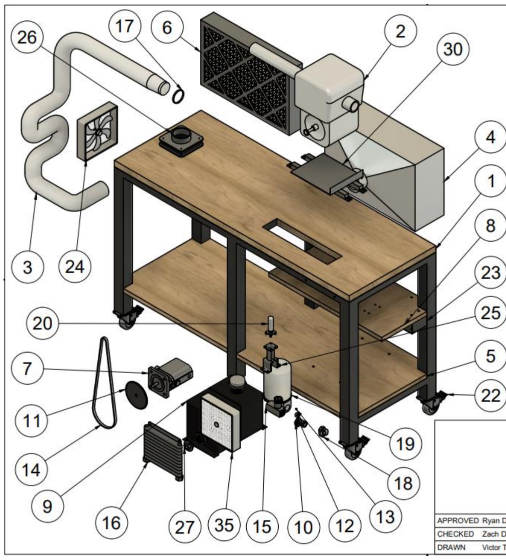


Figure A.23 Concept Generation: Filter Attached to Exhaust

Each concept was carefully assessed against engineering requirements, including load capacity, heat resistance, performance accuracy, and safety. The most feasible designs were selected for further testing and refinement, with the aim of developing a prototype that would meet or exceed customer and project specifications. The engineering requirements were fully addressed by each concept, ensuring durability, accuracy, and safety across both the dynamometer and filtration systems.

I. CAD

The images below showcase the CAD design the team developed to refine key design concepts. In Figure A.19, component number 19, the oil cooler, was strategically positioned using CAD. Additionally, CAD was instrumental in determining the precise lengths of the hydraulic lines and optimizing the placement of various components. **Figures A.20** and **A.21** below show certain parts of the design in more detail. Lastly, **Figure A.22** shows the tolerance and fits for all of the manufactured portions of the project.

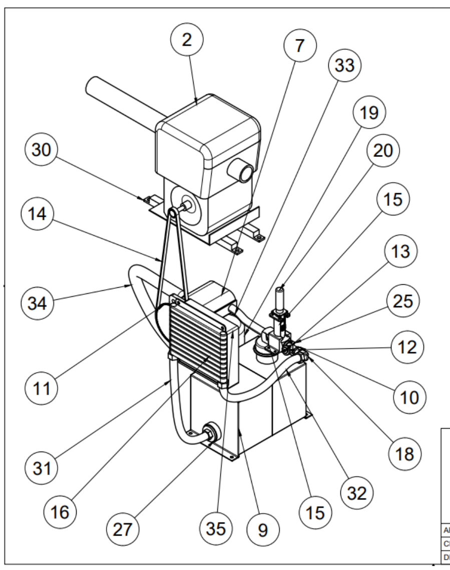


PARTS LIST			PARTS LIST		
ITEM	QTY	PART NUMBER	ITEM	QTY	PART NUMBER
1	1	FRAME	17	1	DUCT CLAMP
2	1	KT100 ENGINE	18	1	ELBOW 3/4"
3	1	DUCT LINE	19	1	HYDRAULIC FILTER
4	1	FILTER CASING	20	1	MOTOR
5	1	WOOD BASE	21	1	COVERS
6	1	3881T189_PANEL AIR FILTERS	22	4	2702T71_CART-KING CASTER
7	1	VEVOR HYDRAULIC LOG SPLITTER PUMP	23	3	SHELF WELDED BRACKET
8	1	PUMP SYSTEM WOOD BASE	24	1	CROSS FLOW FAN
9	1	5 GALLON HYDRAULIC RESERVOIR TANK OPEN	25	1	FLOW VALVE MOTOR BRACKET
10	1	TEE	26	2	FAN ADAPTER TOP
11	1	PUMP CHAIN SPROCKET	27	1	TANK ADAPTER
12	1	3/4" TO 1/8"	28	1	BACK PANEL
13	1	PRESSURE SENSOR	29	1	SIDE PANEL
14	1	SPROCKET CHAIN	30	1	ENGINE RAILS
15	1	1042K21_FLOW-ADJUSTMENT INLINE HYDRAULIC VALVE	31	1	TANK - COOLER LINE
16	1	OIL COOLER	32	1	COOLER-VALVE LINE
			33	1	VALVE-PUMP LINE
			34	1	PUMP-TANK LINE
			35	1	OIL COOLER FAN

PROJECT
Green Dyno
TITLE
Green Dyno Exploded

APPROVED Ryan Doherty 4/27/2025 SIZE B CODE DWG NO REV
CHECKED Zach Delahunty 4/28/2025
DRAWN Victor Tishkevich 4/24/2025 SCALE 1:10.5 WEIGHT SHEET 2/8

Figure A.24 Exploded Green Dyno CAD Model with Part List



PARTS LIST		
ITEM	QTY	PART NAME
2	1	KT100 ENGINE
7	1	VEVOR HYDRAULIC LOG SPLITTER PUMP V13
9	1	5 GALLON HYDRAULIC RESERVOIR TANK OPEN V4
10	1	TEE
11	1	PUMP CHAIN SPROCKET
12	1	3/4" TO 1/8"
13	1	PRESSURE SENSOR
14	1	SPROCKET CHAIN
15	1	1042K21_FLOW-ADJUSTMENT INLINE HYDRAULIC VALVE
16	1	OIL COOLER
18	1	ELBOW 3/4"
19	1	HYDRAULIC FILTER V1
20	1	MOTOR
25	1	FLOW VALVE MOTOR BRACKET V7
27	1	TANK ADAPTER
30	1	ENGINE RAILS
31	1	TANK - COOLER LINE
32	1	COOLER-VALVE LINE
33	1	VALVE-PUMP LINE
34	1	PUMP-TANK LINE
35	1	OIL COOLER FAN

PROJECT
Green Dyno
TITLE
Hydraulic System Sub Assembly

APPROVED Ryan Doherty 4/27/2025 SIZE B CODE DWG NO REV
CHECKED Zach Delahunty 4/27/2025
DRAWN Victor Tishkevich 4/24/2025 SCALE 1:7 WEIGHT SHEET 3/8

Figure A.25 Hydraulic System Sub Assembly and Parts List

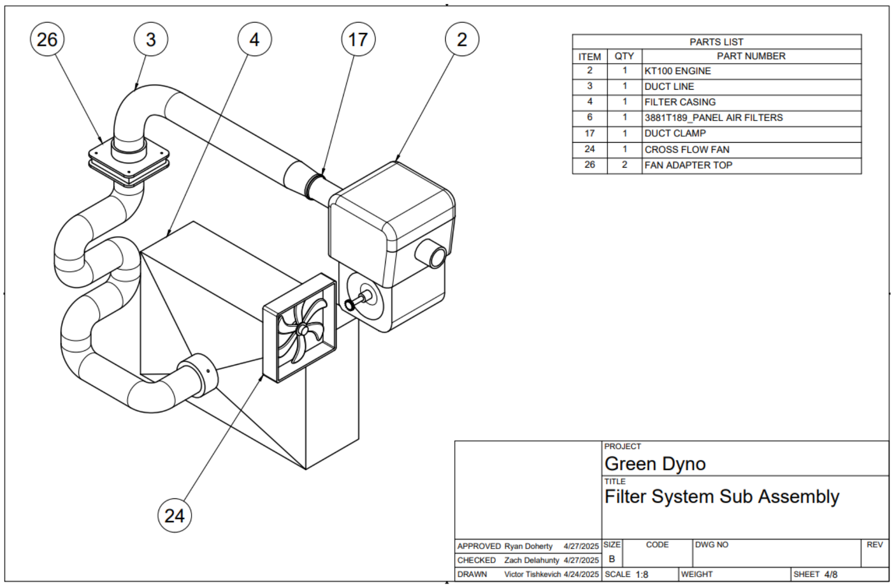


Figure A.26 Filter System Sub Assembly and Parts List

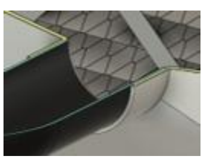
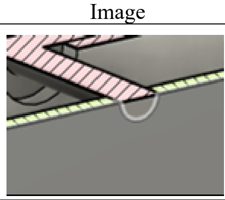
Filter Casing/ Duct - LC3					
Image		Filter Casing (Hole)	Size/Tolerance	Duct (Shaft)	Size/Tolerance
	MMC	4.1	4.1 ± 0.05	4	3.95 ± 0.05
	LMC	4.2		3.9	
Pump Gear/ Pump Shaft - RC5					
Image		Pump Gear (Hole)	Size/Tolerance	Pump Shaft	Size/Tolerance
	MMC	0.497	0.5 ± 0.003	0.502	0.5 ± 0.002
	LMC	0.503		0.498	

Figure A.27 Tolerance of Fits

The Green Go Kart Dyno uses a 12 volt power supply to power the electronics in the dyno. The power supply is wired to a ground terminal and a switch, so that all the electronic systems can be turned off, before going to a 12 volt terminal. The 12 volt terminal powers the proximity sensor, gear motor, and motor controller. It is also run through a buck converter to convert the 12 volts to 5 volts for the 5 volt terminal. The 5 volt terminal powers the pressure sensor and all three fans, which are also connected to a switch. The Arduino is powered by the 5 volt USB connection to a computer. The Arduino sends signals to the motor controller to have the gear motor open and close the flow valve in the hydraulic system, and it receives signals from the gear motor's encoder, the pressure sensor, and proximity sensor. The wiring diagram detailing this is shown in **Figure A.28**.

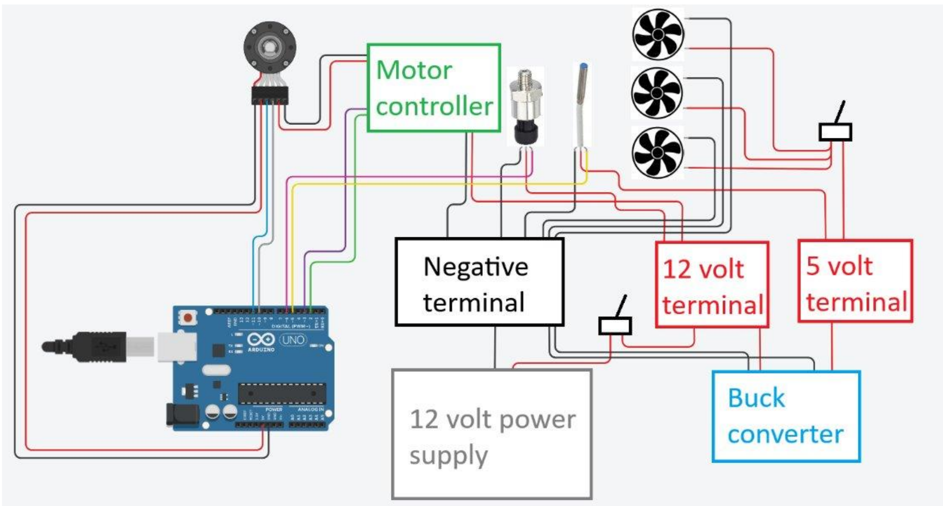


Figure A.28 Wiring Diagram

J. Down Selection

Once the team outlined all potential concepts for the filtration and dynamometer systems, a down-selection process was employed to identify the most suitable design for the final prototype. To guide this down-selection, the team used the engineering requirements as a framework to develop a selection criterion. As detailed in the down-selection tables below, the criterion consisted of six key categories: Durability, Maintenance, Cost, Performance/Accuracy, Safety, and Portability. These categories correspond to the engineering requirements outlined in Appendix G.

To ensure a fair and objective down-selection, the team first assigned weights to each category. These weights were derived by averaging the values of the design requirements within each category from the engineering requirements and constraints table (Appendix G). The weighted averages for each category were as follows: Durability = 7.6, Maintenance = 5.75, Cost= 7, Performance/Accuracy = 8.8, Safety = 9, and Portability = 4. A 10-point rating scale was then developed to evaluate how each concept performed within each category (as shown in **Table A.3**). This rating scale allowed for a quantitative assessment of each concept's strengths and weaknesses. The team calculated the weighted totals for each concept by multiplying the score for each category by the category's assigned weight and summing the results to determine the overall score.

Table A.3: Down Selection Rating Scale

Rating Scale (1-10)	
1-2	Poor: Does not meet requirements, significant issues
3-4	Fair: Meets Basic Requirements, several limitations
5-6	Good: Meets Most Requirements, minor issues
7-8	Very Good: Meets all Requirements, few minor issues
9-10	Excellent: Exceeds Requirements, no issues

The down-selection process was conducted collaboratively, with each team member contributing to the ratings and discussions. The scores were determined through group consensus, ensuring a balanced perspective on each concept’s merits. After completing the scoring process, the team reviewed the results to determine which concepts best aligned with the engineering requirements.

The first step in the down-selection was choosing the dynamometer system. Three proposed design concepts were compared (as seen in **Table A.4**), and after applying the selection criteria, the pressure gauge system emerged as the winning concept. The pressure gauge system was chosen due to its high performance in key areas such as durability, accuracy, and cost-effectiveness, with minimal maintenance requirements compared to the other systems. The ability of this design to perform accurately within the 5% tolerance and its ease of integration with the filtration system were decisive factors. Next, the filtration system concept was down-selected by comparing two designs (as shown in **Table A.5**). The "duct snake" filtration system was chosen due to its superior performance in filtering exhaust gases, its efficiency in maintaining pollutant levels below 50 ppm, and its compatibility with the dynamometer system. Its design also offered ease of maintenance with simple access to the filter for replacement.

Once the winning dynamometer and filtration concepts were selected, they were combined into a single prototype design. This prototype was compared to the Fast Factory small engine dynamometer, as seen in **Table A.6**. The combined design scored highly in all key categories, particularly in durability, performance, and portability, which contributed to its selection as the final design. The weighted totals for both the prototype and the Fast Factory dynamometer are shown in **Table A.6**.

After completing the Critical Design Review (CDR) phase, the team developed a preliminary prototype based on the down-selected concepts. The preliminary prototype was a scaled-down model that included all the critical components and key features of the design. The prototype incorporated a scaled-down model of a pressure gauge dynamometer with exhaust filtration, quick-access features for filter and chain maintenance, secure mounting for engine various sizes, and a portable yet stable framework. The team performed several analyses to validate the prototype's capabilities. These analyses included FEA structural load testing of the sheet metal pump bracket, calculations for tubing and pump selections, and airflow and filtration effectiveness evaluations. The team's goal was to finalize the prototype to meet all customer and engineering requirements, thus laying the groundwork for the final design validation.

		Concepts		
Design Requirements	Weight	Flow Rate Gauge	Generator	Pressure Gauge
Durability	7.6	7	5	7
Maintenance	5.75	7	7	7
Cost	7	5	8	5
Performance/Accuracy	8.8	6	5	8
Safety	9	8	3	8
Portability	4	5	7	5
	Weighted Total	273.25	233.25	290.85

Table A.4 Dynamometer System Down Selection

		Concepts	
Design Requirements	Weight	Duct Snake	Instant Widen
Durability	7.6	6	8
Maintenance	5.75	8	8
Cost	7	7	8

Performance/Accuracy	8.8	9	6
Safety	9	8	5
Portability	4	7	7
	Weighted Total	319.8	288.6

Table A.5 Filtration System Down Selection

Customer Requirements	Weight	Final Design Pressure Gauge + Duct Snake	Benchmark Fast Factory Dynamometer
Durability	7.6	7	7
Maintenance	5.75	7	7
Cost	7	8	5
Performance/Accuracy	8.8	8	8
Safety	9	7	4
Portability	4	5	4
	Weighted Total	302.85	250.85

Table A.6 Final Design Down Selection

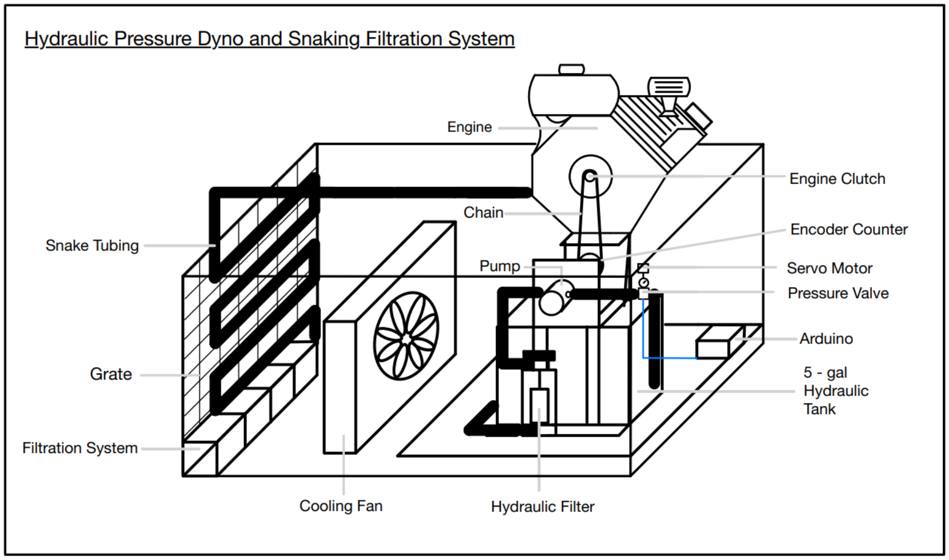


Figure A.29 Final Green Dyno Design

Figure A.30 Fast Factory Small Engine Dynamometer Benchmark

K. Analysis

The Green Go-Kart Dyno project utilized a detailed and structured approach to ensure all components met the necessary engineering requirements for strength, safety, and performance. A Finite Element Analysis (FEA) was performed on the pump bracket (**Figure A.24**), the primary load-bearing component, to assess its structural integrity under expected loading conditions. The bracket, which supports a cast iron pump base and an aluminum upper body, was subjected to a 32.373 N load applied at its center. The FEA was conducted in Fusion 360, with the pump-bracket assembly isolated from the full system to streamline the analysis. Boundary conditions included fixed supports at the mounting points, and the model was meshed with 17,502 nodes and 9,796 elements to ensure high accuracy. The results indicated a maximum stress of 0.015 MPa (**Figure A.25**), well within safe limits, and a factor of safety of 15.0, providing a substantial margin of safety (**Figure A.26**). The analysis concluded that the pump-bracket assembly is structurally sound with no risk of deformation or failure under operational loads.

Commented [DR11]: From CDR feedback: the FEA discussion is not adequate. It lacks all of the boundary conditions, meshing, etc. (it takes about 6 images to set up and describe an FEA as detailed in Dr. Jensen's lecture). Finally, make sure that the calculations and FEA discussions include how the results relate back to engineering requirements (i.e., conclusions about materials/components and how these relate to the engineering requirements).

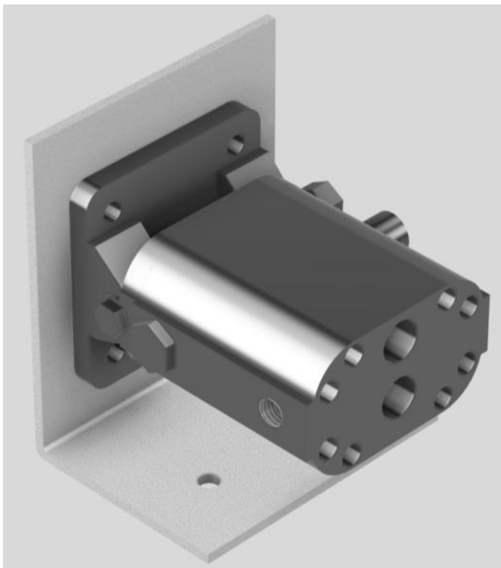


Figure A.31 Pump-Bracket System Rendering

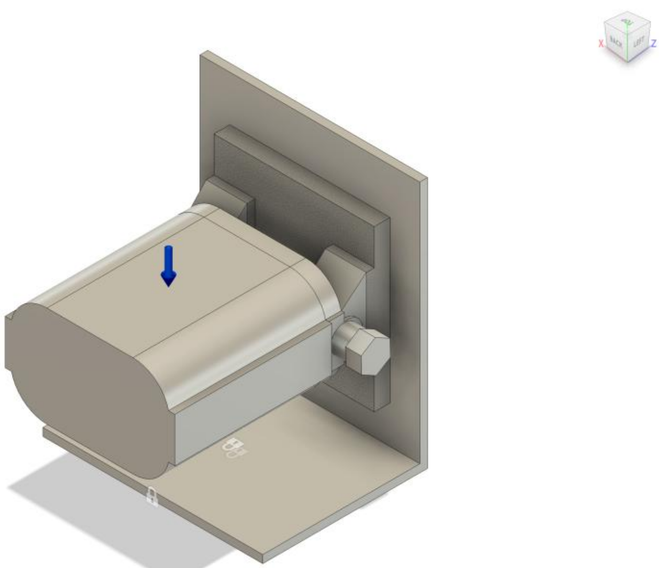


Figure A.32 Pump-bracket FEA simplified geometry with force applied at center of mass

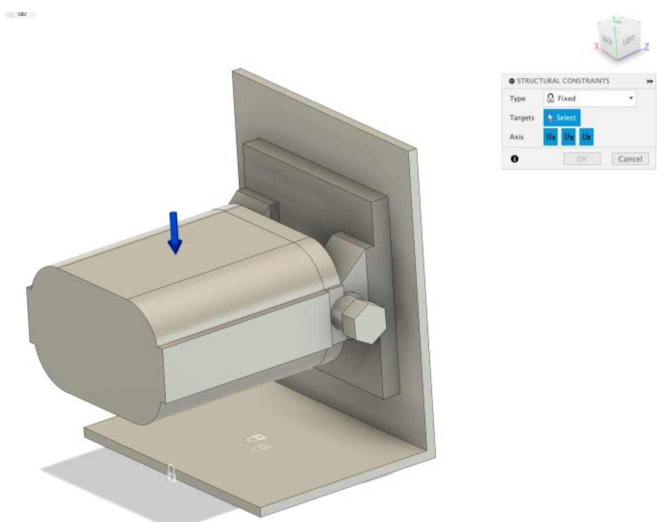


Figure A.33 applied constraints making bracket rigid

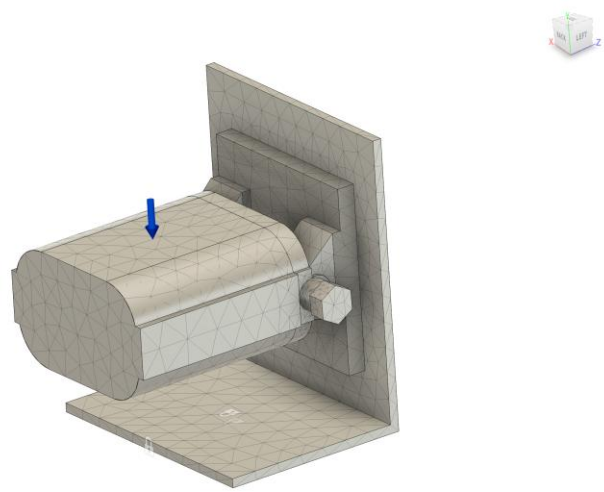


Figure A.34 Pump-bracket system with mesh

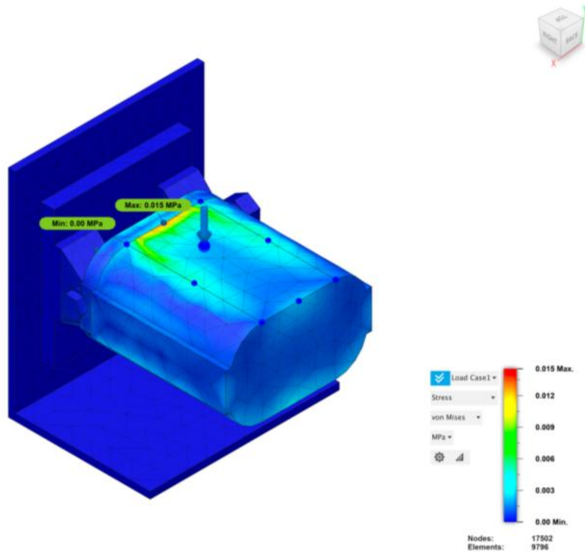


Figure A.35 Pump-Bracket FEA Static Stress Results

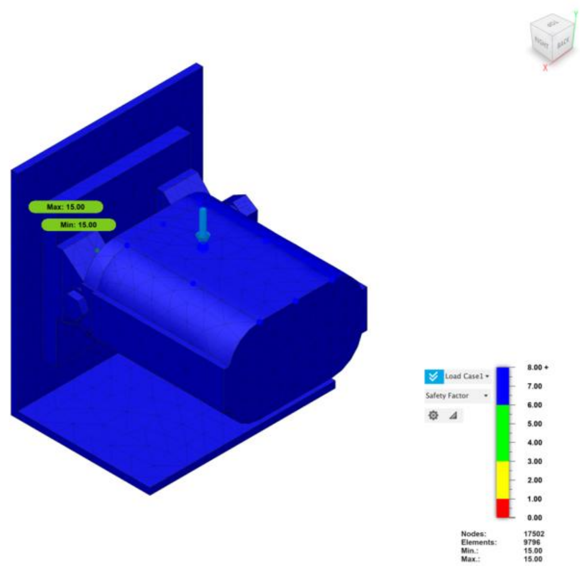
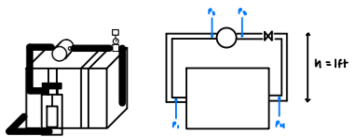


Figure A.36 Pump-Bracket FEA Factor of Safety Results

For the boundary conditions of the FEA, the pump has a load placed at its center of gravity to simulate the most accurate weight distribution. The bracket itself is rigid and therefore will not movement other than deformations that take place. The meshing used for the FEA analysis is 5% since this is a perfect combination between accuracy and quick results.

Given the high factor of safety and minimal deformation, the FEA concluded that high-strength aluminum is the best design decision for this component. This component will fulfill the engineering requirement of having RPM's of up to 16,000 since the strength of the bracket will be adequate to hold down the pump at such high vibrations.

For the hydraulic system, the team utilized Bernoulli's equation and head loss calculations to select the appropriate hydraulic pump. These calculations confirmed that the pump would maintain the required outlet pressure of 11,407.84 kPa (1654.6 psi), while minimizing energy loss through properly sized tubing. These hydraulic flow and pressure calculations are detailed in **Figure A.37**.



Commercial steel : 0.045 mm
reg 90° elbow square : k = 1.3
Kentrance , sharp-edged : k = 0.5
Diaphragm valve, ½ open : k = 4.3
Kexit , sharp-edged : k = 0.5

$$\left(\frac{P}{\rho g} + \alpha \frac{\bar{V}^2}{2g} + z\right)_2 = \left(\frac{P}{\rho g} + \alpha \frac{\bar{V}^2}{2g} + z\right)_1 - H_{L12} + H_{s12}$$

$P_1 = P_4 = P_{atm} = 101.3\ kPa$
$P_2 = ?\quad ,\ P_3 = ?$
$z_1 = z_4 = 0\quad ;\ z_2 = z_3 = 1ft = 0.305\ m$
$H_s = z_2 - z_1 = 0$
$Q = 16\ gpm = 0.001\ m^3/s$
$D_1 = 1\ in = 0.0254\ m$
$D_2 = 1/2\ in = 0.0127\ m$
$\rho = 0.865\ kg/L = 865\ kg/m^3$
$\mu = 32\ cSt = 0.032\ Ns/m^2$
$g = 9.81\ m/s^2$
$L = 7ft = 2.134\ m\ ,\ L_{12} = 2ft = 0.61\ m\ ,\ L_{34} = 5ft = 1.524\ m$

$\dot{W}_s = 11\ kW$
$A_1 = \frac{\pi}{4} \cdot D_1^2 = 0.0005\ m^2$
$A_2 = \frac{\pi}{4} \cdot D_2^2 = 0.00012\ m^2$

$$Re_{12} = \frac{\rho \bar{V} D}{\mu} = \frac{(865)(2)(0.0254)}{0.032} = 1373.19 \rightarrow \alpha = 2\ (\text{laminar})$$

$$\frac{\varepsilon}{D_1} = \frac{0.045}{25.4} = 0.0017 \longrightarrow f = 0.025$$

$$Re_{34} = \frac{\rho \bar{V} D}{\mu} = \frac{(865)(8.3)(0.0127)}{0.032} = 2849.36 \rightarrow \alpha = 2\ (\text{laminar})$$

$$\frac{\varepsilon}{D_2} = \frac{0.045}{12.7} = 0.0035 \longrightarrow f = 0.028$$

$$\bar{V}_{12} = \frac{Q}{A} = 2\ m/s$$
$$\bar{V}_{34} = \frac{Q}{A} = 8.3\ m/s$$

$$\dot{W}_s = \rho Q g H_s \longrightarrow H_s = \frac{\dot{W}_s}{\rho Q g} = \frac{11}{(865)(0.001)(9.81)} \longrightarrow H_s = 1.3$$

$$H_{L12} = \Sigma_i k_i \frac{V_i^2}{2g} = f\left(\frac{L_{12}}{D}\right) \cdot \frac{\bar{V}^2}{2g} + k_{entrance} \frac{\bar{V}^2}{2g} + k_{elbow} \frac{\bar{V}^2}{2g} = \left[f\left(\frac{L}{D}\right) + K_{entrance} + 2K_{elbow} + K_{valve} + K_{exit}\right] \frac{V_i^2}{2g}$$

$$H_{L12} = \left[0.025\left(\frac{0.61\ m}{0.0254\ m}\right) + 0.5 + 2(1.3)\right] \cdot \frac{(2\ m/s)^2}{2(9.81\ m/s^2)} \longrightarrow H_{L12} = 0.75$$

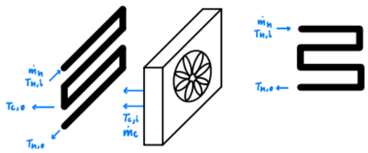
$$\left(\frac{P}{\rho g} + \alpha \frac{\bar{V}^2}{2g} + z\right)_2 = \left(\frac{P}{\rho g} + \alpha \frac{\bar{V}^2}{2g} + \cancel{z}\right)_1 - H_{L12} + H_{s12}$$

$$\left(\frac{P_2}{(865\ kg/m^3)(9.81\ m/s^2)} + 2 \cdot \frac{(2\ m/s)^2}{2(9.81\ m/s^2)} + 0.61\ m\right)_2 = \left(\frac{101.3\ kPa}{(865\ kg/m^3)(9.81\ m/s^2)} + 2 \cdot \frac{(2\ m/s)^2}{2(9.81\ m/s^2)}\right)_1 - 0.75 + 1.3 \longrightarrow \underline{P_2 = -407.84\ kPa} = \underline{-59.15\ psi}$$

$$\dot{W}_s = Q \Delta P \longrightarrow \dot{W}_s = Q(P_3 - P_2) \longrightarrow 11kW = 0.001\ m^3/s\ (P_3 - 407.84\ kPa) \longrightarrow \underline{P_3 = 11407.84\ kPa} = \underline{1653.7\ psi}$$

Figure A.37 Hydraulic Pump Calculations

The exhaust cooling and filtration system was also analyzed to ensure proper heat dissipation and filtration performance. An energy balance around the heat exchanger yielded a heat transfer rate of 1.92 kW and 90% effectiveness, meeting the engineering requirement for keeping the exhaust gases below degradation temperatures before entering the filtration unit. The cooling fan and tubing dimensions were chosen to optimize airflow and reduce thermal loads on the filter, as detailed in the calculations found in **Figure A.38**.



$T_{cold,in} = 294.26\ K$

$T_{cold,out} = ?$

$T_{hot,in} = 922.04\ K$

$T_{hot,out} = ?$

$c_{p,h}\ (@\ 922.04K) : 1.125\ kJ/kg \cdot k$

$c_{p,c}\ (@\ 294.26K) : 1.006\ kJ/kg \cdot k$

$\dot{m}_c = 0.966\ kg/s$ (12 in fan)

$\dot{m}_h = 0.003\ kg/s$ (exhaust)

$D = 4in = 0.1016\ m$

$A = 26.18\ ft^2$ (SA of tube) $= 7.98\ m^2$

$@\ T = 950\ k$:

$\mu = 4.113 \times 10^{-5}\ \frac{N \cdot s}{m^2}$

$\rho = 0.3666\ \frac{kg}{m^3}$

$k = 0.0643\ \frac{W}{m \cdot K}$

$\alpha = 0.000155\ \frac{m^2}{s}$

$$Re_D = \frac{4\dot{m}_h}{\pi D \mu} = \frac{4(0.966\ kg/s)}{\pi(0.1016m)(4.113 \times 10^{-5}\ \frac{N \cdot s}{m^2})} \rightarrow Re = 921.14 \text{ (laminar)}$$

$$\overline{Nu}_D = \frac{\bar{h}_i D}{k_i} = 3.66 \rightarrow h_i = \frac{(0.0643\ W/m \cdot k)}{(0.1016m)}(3.66) \rightarrow h_i = 2.316\ \frac{W}{m^2 \cdot K}$$

$$U = \frac{h_i}{2} = 1.16\ \frac{W}{m^2 \cdot K}$$

$$C_h = \dot{m}_h \cdot c_{p,h} = \left(0.003\ \frac{kg}{s}\right)\left(1125\ \frac{J}{kg \cdot k}\right) = 3.4\ \frac{W}{k}$$

$$C_c = \dot{m}_c \cdot c_{p,c} = \left(0.966\ \frac{kg}{s}\right)\left(1006\ \frac{J}{kg \cdot k}\right) = 971.8\ \frac{W}{k}$$

$$C_{min} = 3.4\ \frac{W}{k}\ ;\ C_{max} = 971.8\ \frac{W}{k}$$

$$NTU = \frac{UA}{C_{min}} = \frac{(1.16\ W/m^2 \cdot k)(7.98m)}{3.4} = 2.72$$

Fig. 11.14 : $\varepsilon\ (NTU \approx 3\ ;\ C_r \approx 0) = 0.9$

$$\varepsilon = \frac{q}{q_{max}} \rightarrow \varepsilon = \frac{C_h(T_{h,i} - T_{h,o})}{C_{min}(T_{h,i} - T_{c,i})} = \frac{C_c(T_{c,o} - T_{c,i})}{C_{min}(T_{h,i} - T_{c,i})}$$

$$\hookrightarrow 0.9 = \frac{3.4(922.04k - T_{h,o})}{3.4(922.04k - 294.26k)} \rightarrow \underline{T_{h,o} = 357.04\ K \rightarrow 183\ F}$$

$$\hookrightarrow 0.9 = \frac{971.8\ W/k\ (T_{c,o} - 294.26K)}{3.4(922.04k - 294.26k)} \rightarrow \underline{T_{c,o} = 296.24\ K \rightarrow 73.5\ F}$$

$$q = \dot{m}_h c_{p,h}(T_{h,o} - T_{h,i}) = \left(0.003\ \frac{kg}{s}\right)\left(1.125\ \frac{kJ}{kg \cdot k}\right)(316.48K - 922.04K) \rightarrow \underline{q = -2.044\ kW}$$

$$q = \dot{m}_c c_{p,c}(T_{c,o} - T_{c,i}) = \left(0.966\ \frac{kg}{s}\right)\left(1.006\ \frac{kJ}{kg \cdot k}\right)(296.24K - 294.26K) \rightarrow \underline{q = 1.924\ kW}$$

Figure A.38 Exhaust Heat Dissipation Calculations

The Arduino used to collect data in the dyno has it record time, which it uses to find the RPM of the gear on the pump when the proximity sensor detects a full revolution. The Arduino uses the Serial.print command which is used to upload the measured time, RPM, and pressure data to Excel with Excel's built in function Data Streamer. After the test, the data was processed in Excel using the equations in **Figure A.39**. These equations convert values from the pressure sensor to psi and convert the RPM of the pump into engine RPM by applying the gear ratio between the two devices. The volumetric flow rate through the pump is identified using the maximum pump operation values, and finally these values are used to calculate the engine's horsepower. If testing a power run on the dyno, the gear motor will close the flow valve, building up back pressure in the hydraulic system, applying load to the engine and reducing RPM. In this case the flow valve is closed until the target RPM is reached, allowing for the dyno to measure performance data.

Finding RPM:

$$\mathrm{RPM_{gear}} = \frac{60}{t_{\mathrm{prox}} - t_{\mathrm{prev}}}$$

$$\mathrm{RPM_{engine}} = \frac{\mathrm{RPM_{gear}}}{\text{Gear Ratio}}$$

Finding Pressure:

$$\text{Pressure} = \left(\frac{S_{\mathrm{read}} \cdot V_{\mathrm{ref}}}{S_{\mathrm{max}}}\right) \cdot \left(\frac{P_{\mathrm{max}}}{V_{\mathrm{max}}}\right)$$

$$\text{Pressure} = \left(\frac{S_{\mathrm{read}}}{1023}\right) \cdot 10000$$

HP Conversion:

$$HP = \frac{(GPM \cdot P(psi))}{1714 \cdot \eta}$$

Finding Flow Rate:

$$\mathrm{GPM} = \mathrm{GPM_{max}} \cdot \frac{\mathrm{RPM}}{\mathrm{RPM_{max}}}$$

Figure A.39 Data Processing Equations

More information about the data from the dyno tests can be found in Appendix L.

In terms of material selection, the team employed CAD modeling to verify the fit of all components within the go-kart chassis and the tabletop structure. Key design changes included adding a wooden platform for mounting, resizing tubing paths, and modifying table cutouts to accommodate all components effectively. Material choices were made to balance cost-efficiency, strength, and temperature tolerance, particularly for the brackets, tubing, and sensor mounts, ensuring both functional and structural integrity.

L. FMEA (Click here to access ME463_FMEA.xlsx)

Commented [CJ12]: Update

17 total failures were identified through FMEA. Critical failures, defined by high RPNs include the filters catching on fire, hydraulic fluid boiling, hydraulic leaks, exhaust tubing melting, pump breakage, and pump shelf lifting. Some of these were already addressed in parts of the design, with the snake exhaust tubing to cool exhaust gases to temperatures the filters can withstand and using a gear to reduce the RPM experienced by the pump. The FMEA did refine the Green Go Kart Dyno, as 4 improvements were made to the design. A chain guard was added to reduce the severity of the chain snapping. An oil cooler was added to the hydraulic system to reduce hydraulic fluid temperature so the fluid would not boil from the use of the dyno. The wiring used with the sensors will be routed away from hot temperature areas and heat resistant casing will be used to ensure the wires don't melt. Of the critical failures, the only one not explicitly accounted for in the design is hydraulic leaks. This will be addressed during the construction of the dyno, with the use of thread sealing tape and ample testing to ensure the system does not leak. The FMEA was a helpful exercise in identifying weak points in the design and improving it by reducing the severity of occurrence of failures. During FDR the two additions to the FMEA are wiring shorts and the pump shelf lifting. The first is accounted for by keeping the wiring secured and by ensuring that no wiring work was done while the power

supply was plugged in. The pump shelf lifting was the reason the dyno could not test a power run, as we were afraid that this would cause a catastrophic failure in the hydraulic system. This would be remedied by adding supports from the table to the top of the shelf to keep the shelf in place, rather than the reinforcements we had placed below.

M. BOM & Sourcing Plan

Commented [CJ13]: Zach Update

The following section provides an updated overview of the BOM and Sourcing Plan (**Table A.7**) for the selected concept, detailing the make-vs.-buy strategy and sourcing locations for each component. The Bill of Materials (BOM) consists of components that are either owned, purchased, or fabricated in-house. Some components, such as the engine, Arduino, and electrical wires, are already owned and will not need to be sourced. Several parts, including the servo motor, hydraulic fluid pump, encoder counter, and pressure valve, are precision-engineered components. These will be outsourced to reliable industrial suppliers, ensuring both quality and cost-effectiveness. Other parts, such as hydraulic tubing, tubing connectors, hydraulic filters, and exhaust tubing, are standard items that will also be sourced externally from established suppliers for greater cost-efficiency.

Table A.7 BOM and Sourcing Plan

Assembly/Sub - Assembly	Material	Quantity	Make/ Buy	Notes on Sourcing Decision
Engine	Engine	1	Own	Already owned, no sourcing needed.
Hydraulics	Chain	1	Buy	Standard component, cost-effective to purchase.
Hydraulics	Hydraulic Fluid Tubing	1	Buy	Specialized material, better to source externally.
Hydraulics	Tubing Connectors	1	Buy	Standard fittings, cheaper and easier to procure.
Hydraulics	Hydraulic Fluid Pump	1	Buy	Precision component, best sourced from a supplier.
Sensors	Proximity Sensor	1	Buy	Electronic component, complex to manufacture in-house.
Hydraulics	Servo Motor	1	Buy	Requires precision engineering, best purchased.
Sensors	Pressure Sensor	1	Buy	Requires precision engineering, best purchased.
Hydraulics	Pressure Valve	1	Buy	Requires precision engineering, best purchased.
Sensors	Arduino Mega	1	Own	Already owned, no need to buy.
Sensors	Electrical Wires	1	Own	Already available, no sourcing needed.

Hydraulics	5 Gallon Hydraulic Fluid Tank	1	Buy	Standard industrial item, not cost-effective to make.
Hydraulics	5 Gallon Hydraulic Fluid	1	Make/ Buy	Standardized filtration component, best purchased.
Hydraulics	Hydraulic Filter	1	Buy	Standardized filtration component, best purchased.
Filteration	Cooling Fan	1	Make	Could be fabricated if simple, but complex designs are better bought.
Filteration	Exhaust Tubing	1	Make	Standard piping, more efficient to buy.
Filteration	Exhaust Attachment	1	Make	Custom component, better suited for in-house fabrication.
Filteration	Grate	2	Buy	Can be fabricated in-house for specific needs.
Filteration	Duct Fan	2	Buy	Precision component, better sourced from manufacturers.
Filteration	MERV 16 Filter	1	Make	Specialized filtration component, best to purchase.
Cart	Rolling Cart	1	Own/Make	Custom design, making it in-house ensures exact specifications.
Hydraulics	VEVOR Hydraulic Log Splitter Pump	1	Buy	Contains multiple moving components, best purchased
Filteration	Steel housing	1	Own	Was donated by Motorsports at Purdue
Cart	Plywood	1	Own/Buy	Depends on how much the Machiene shop has
Hydraulics	3/4" NPT Tee	1	Buy	Standard fittings, cheaper and easier to procure.
Hydraulics	3/4" NPT to 1/8" NPT	1	Buy	Standard fittings, cheaper and easier to procure.
Hydraulics	Oil Cooler	1	Buy	Requires precision engineering, best purchased.
Hydraulics	48 Tooth gear	1	Buy	Standard component, cost-effective to purchase.
Filteration	6pcs Adjustable Stainless Steel Hose Clamps	1	Buy	Standard component, cost-effective to purchase.
Hydraulics	1/2" NPT (12") Hose	1	Buy	Standard component, cost-effective to purchase.
Hydraulics	90 deg Fitting	1	Buy	Standard component, cost-effective to purchase.
Hydraulics	1/2" NPT (24") Hose	1	Buy	Standard component, cost-effective to purchase.
Hydraulics	Male to Male 3/4" NPT	1	Buy	Standard component, cost-effective to purchase.

Hydraulics	3/4" NPT Male x 1" NPT Female Straight 5405-12-16 Adapter	1	Buy	Standard component, cost-effective to purchase.
Hydraulics	1/2" NPT Tee	1	Buy	Standard component, cost-effective to purchase.
Hydraulics	1/2" NPT to 3/8" NPT	1	Buy	Standard component, cost-effective to purchase.
Sensors	Proximity Sensor	1	Buy	Standard component, cost-effective to purchase.
Hydraulics	Flow Valve	1	Buy	Standard component, cost-effective to purchase.
Filteration	PVC Air Duct Ventilation Hose, 4 Inch x 25 Feet	1	Buy	Standard component, cost-effective to purchase.
Filteration	4.3" Compact Inline Ducting Vent	1	Buy	Standard component, cost-effective to purchase.
	Total Purchased Parts	**33**		
	Total Made Parts	**9**		
	Total Parts	**42**		

For custom components, the exhaust attachment, grate, and rolling cart will be fabricated in-house to meet exact specifications. This approach allows for greater design flexibility and ensures compatibility with the overall system. The cooling fan is considered a hybrid sourcing decision, as simpler versions may be fabricated, while more complex designs will be purchased. The sourcing strategy aims to balance cost, lead time, and quality. Hydraulic and mechanical components, including tubing, connectors, pumps, valves, and filters, will be sourced from suppliers such as Hydraulics Direct, Amazon, and Tractor Supply. Electronic components like the servo motor and encoder counter will be purchased from Amazon or TEMU, while HVAC-related components, including duct fans, MERV 16 filters, and exhaust tubing, will also be obtained from Amazon.

To mitigate supply chain risks, backup suppliers have been identified for critical components. Long-lead items such as the servo motor, encoder counter, and hydraulic pump will be prioritized for procurement to ensure timely availability. Frequently consumed items, such as hydraulic tubing and filters, will be bulk purchased to reduce costs and guarantee stable availability. Quality control measures will be implemented for both procured and in-house-fabricated components to ensure that all parts meet the required performance standards. This comprehensive sourcing plan ensures that all necessary materials are acquired in an efficient manner, balancing cost, quality, and lead-time constraints.

The BOM & Sourcing Plan summary includes a total of 33 purchased parts, 9 made parts, and 42 total parts. Any changes to the BOM and sourcing strategy are highlighted in yellow in the Appendix, as part of the CDR report.

Table A.8 FDR BOM and Sourcing Plan

Assembly/Sub - Assembly	Material	Quantity	Make/Buy	Notes on Sourcing Decision
Engine	Engine	1	Own	Already owned, no sourcing needed.
Hydraulics	Chain	1	Buy	Standard component, cost-effective to purchase.
Hydraulics	Hydraulic Fluid Pump	1	Buy	Precision component, best sourced from a supplier.
Hydraulics	Fluid Pump Mount	1	Make	Custom Design, easy to manufacture
Sensors	Proximity Sensor	1	Buy	Electronic component, complex to manufacture in-house.
Hydraulics	Servo Motor	1	Buy	Requires precision engineering, best purchased.
Sensors	Pressure Sensor	1	Buy	Requires precision engineering, best purchased.
Hydraulics	Pressure Valve	1	Buy	Requires precision engineering, best purchased.
Sensors	Arduino Mega	1	Own	Already owned, no need to buy.
Sensors	Electrical Wires	1	Own	Already available, no sourcing needed.
Hydraulics	5 Gallon Hydraulic Fluid Tank	1	Buy	Standard industrial item, not cost-effective to make.
Hydraulics	5 Gallon Hydraulic Fluid	1	Buy	Standardized filtration component, best purchased.
Hydraulics	Hydraulic Filter	1	Buy	Standardized filtration component, best purchased.
Filteration	Cooling Fan	1	Own	Could be fabricated if simple, but complex designs are better bought.
Filtration	Cooling Fan Mount	1	Make	Custom design, using stock material already in ME building
Filteration	Exhaust Tubing	1	Own	Standard piping, more efficient to buy.
Filteration	Exhaust Attachment	1	Own	Custom component, better suited for in-house fabrication.

Filteration	Duct Fan	2	Own	Precision component, better sourced from manufacturers.
Filteration	MERV 16 Filter	1	Buy	Specialized filtration component, best to purchase.
Hydraulics	VEVOR Hydraulic Log Splitter Pump	1	Buy	Contains multiple moving components, best purchased
Filteration	Steel housing	1	Own	Was donated by Motorsports at Purdue
Cart	Plywood	1	Own	Depends on how much the Machiene shop has
Hydraulics	3/4" NPT to 1/8" NPT	1	Buy	Standard fittings, cheaper and easier to procure.
Hydraulics	Oil Cooler	1	Buy	Requires precision engineering, best purchased.
Hydraulics	48 Tooth gear	1	Make/Buy	Standard component, cost-effective to purchase.
Filteration	6pcs Adjustable Stainless Steel Hose Clamps	1	Buy	Standard component, cost-effective to purchase.
Hydraulics	1/2" NPT (12") Hose	1	Buy	Standard component, cost-effective to purchase.
Hydraulics	90 deg Fitting	1	Buy	Standard component, cost-effective to purchase.
Hydraulics	1/2" NPT (24") Hose	2	Buy	Standard component, cost-effective to purchase.
Hydraulics	1/2" NPT Male x 1 1/2" NPT Female Straight 5405-12-16 Adapter	1	Buy	Standard component, cost-effective to purchase.
Hydraulics	1/2" NPT Tee	1	Buy	Standard component, cost-effective to purchase.
Sensors	Proximity Sensor	1	Buy	Standard component, cost-effective to purchase.
Hydraulics	Flow Valve	1	Buy	Standard component, cost-effective to purchase.
Hydraulics	Flow Valve Bracket	1	Make	Custom design, easy to manufacture
Filteration	PVC Air Duct Ventilation Hose, 4 Inch x 25 Feet	1	Buy	Standard component, cost-effective to purchase.
	Total Purchased Parts	**24**		
	Total Made Parts	**4**		
	Total Parts	**28**		

In contrast to CDR, 9 purchased parts and 5 made parts were removed from the BOM. The purchased parts removed include sheet metal and duct venting, which were discussed in the budget section, hydraulic fittings, and plywood, since there was plenty in the ME machine shop scrap area. For the made parts, or the parts that required an operation sheet, these were reduced to the pump mount, fan mount, key slot for the gear, and flow valve bracket. Overall, the total purchased parts is 24 and the total made parts is 4 which leads to the total parts being 28.

N. *Validation Plan (Click here to access ME463-Validation Plan.xlsx)*

Commented [CJ14]: Tim, include validation testing results here too?

This validation plan outlines the 17 testing procedures for each critical function of the Green Go Kart Dyno Project. The plan details what will be tested, how the tests will be conducted, and where they will take place. Measurement systems are clearly defined to ensure credible data collection for each test. The sheet Validation Tests in ME463-Validation Plan.xlsx displays how these tests relate to the engineering requirements of the Green Go Kart Dyno.

The validation plan for the Green Go Kart Dyno Project includes multiple tests to ensure performance and reliability. For the dyno platform, a rolling test will assess the ease of movement with unlocked wheels, scoring the difficulty from 1 to 3. A lock test will confirm the wheels remain stationary when locked, also scored on a 1-3 scale. The hydraulic pump setup will include a fluid flow test to verify fluid movement through the system and a leak test to check for leaks at all connections, both assessed on a Pass/Fail basis. The gear motor's valve control ability will be tested using Arduino to confirm it can open and close the valve (Pass/Fail).

Sensor validation involves a proximity sensor test to ensure the sensor detects a magnet via Arduino and a pressure sensor test to verify the recording of pressure changes, both evaluated on a Pass/Fail basis. Fan testing includes verifying the cooling fans operate correctly and blow air in the proper direction, while the suction fan test will confirm it creates suction and only operates in the designated switch position (Pass/Fail).

The motor mount evaluation includes a mounting test to assess ease of motor installation (scored 1-3), a stability test to confirm the motor remains securely mounted (Pass/Fail), and an adjustment test to ensure the motor slides properly for chain tension adjustments (Pass/Fail). Finally, dyno testing will involve a performance test where the motor runs for 90 seconds at 10,000 RPM without leaks or failures (Pass/Fail).

During FDR 14 of the 17 validation tests were able to be completed. The three validation tests that were not able to be performed were due to failures upstream in the system, the filters could not be tested due to the tubing melting, or changes in the design, both tests involving the engine mount could not be conducted due to a different setup of engine that was run on the dynamometer. Three of the conducted tests failed, those being ones who relate to an actual dyno test, those being the accurate measurements withstand cycles tests. The filtration tubing was also not able to withstand exhaust temperature and pressure, failing the validation test.

Figures A.37, **A.38**, and **A.39** display the results of an engine driving fluid through the hydraulic system with the flow valve fully open. These figures display RPM, Pressure, and Horsepower and Torque vs time graphs respectively. The test used to get this data was not indicative of true engine performance because of the lack of back pressure in the hydraulic system, and thus, load on the engine, but due to safety concerns with the pump shelf lifting and the fear of failure in the hydraulic lines, validation tests involving power runs and RPM sweeps were not able to be performed.

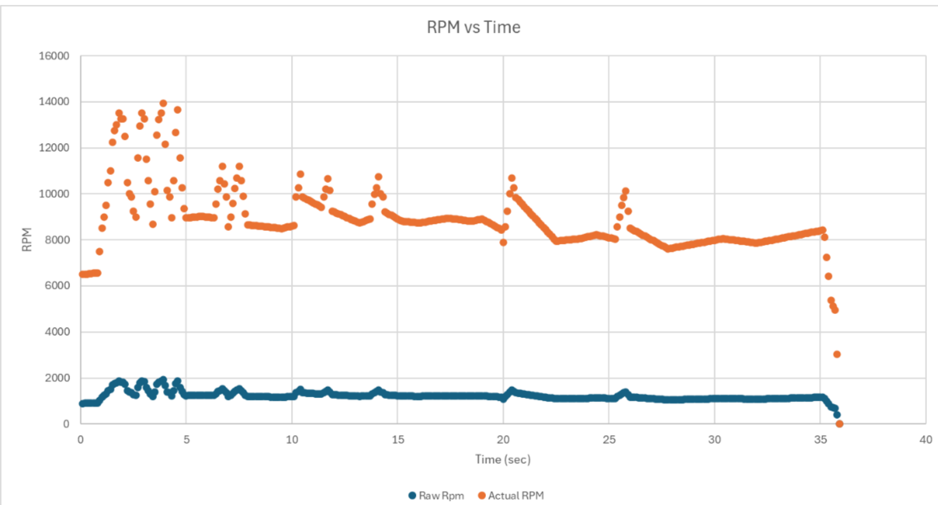


Figure A.40 Pump and Engine RPM vs Time

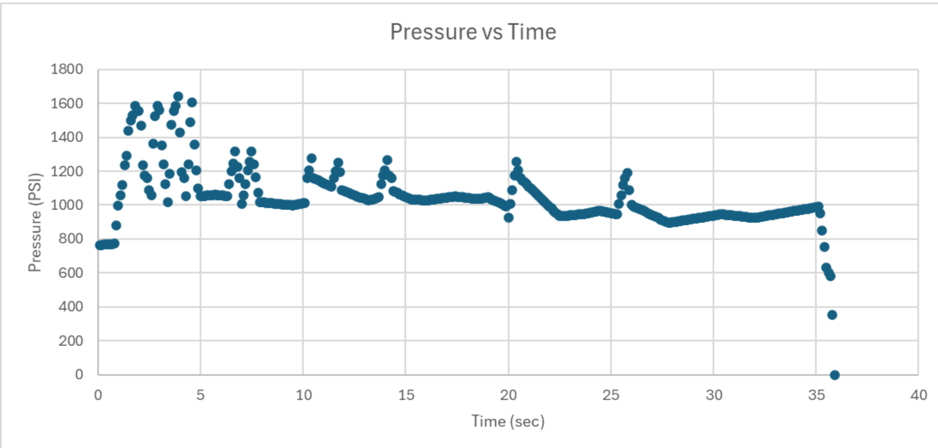


Figure A.41 Pressure vs Time

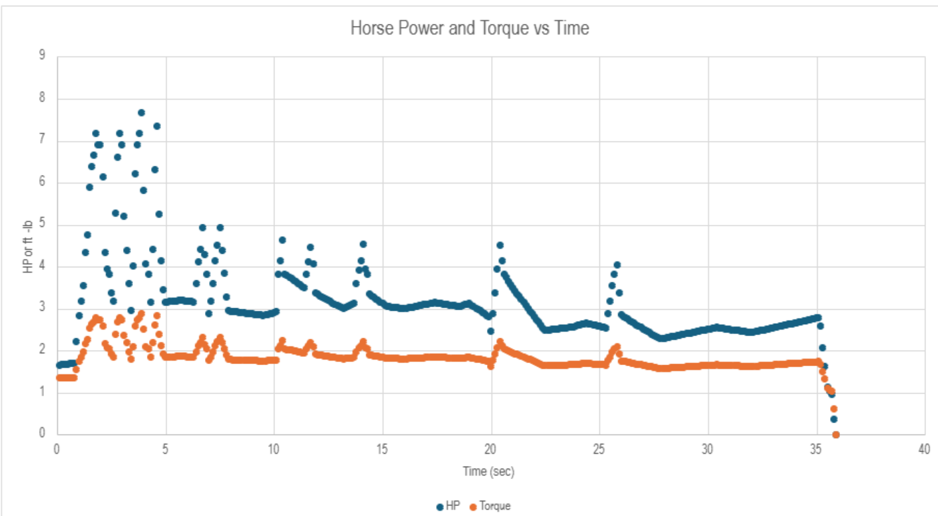


Figure A.42 Horsepower and Torque vs Time

O. Manufacturing and Assembly Process

The final Green Go-Kart Dyno prototype was assembled using a total of 28 components, including 24 purchased parts and 4 custom-manufactured components. Assembly was completed following the Critical Design Review (CDR) and served as a key deliverable for the Final Design

Review (FDR). The prototype consists of three major subsystems: the hydraulic dynamometer, the exhaust filtration system, and the data acquisition system.

The hydraulic dynamometer was constructed using a hydraulic tank, hydraulic filter, fluid lines, oil cooler, and a pump driven by the engine through a chain connection. A gear motor was mounted to control a flow valve, allowing the team to regulate back pressure within the hydraulic system and apply varying loads to the engine. A pressure sensor was installed to monitor system pressure, and a proximity sensor was used to detect the gear's revolutions. The proximity sensor was positioned to register each full rotation of the pump gear, enabling the Arduino to calculate real-time RPM. Worm clamps and brackets were used throughout the hydraulic subsystem to ensure all components were securely mounted and properly aligned, which was critical for maintaining safety and performance under operating conditions. The hydraulic system underwent several layout iterations to improve space utilization and minimize interference between components.

In parallel, the team assembled an exhaust filtration system to manage and filter engine emissions during testing. Ducting was connected to the engine's exhaust port and routed underneath the tabletop, where it was secured using worm clamps. This ducting led to a sealed container housing MERV 16 filters to capture particulate matter. The team designed and 3D printed adapters to connect the ducting to both the exhaust port and the duct fan, ensuring airtight seals and smooth airflow. To manage heat buildup, a cooling fan was mounted to the underside of the table to blow air directly across the snaked ducting, reducing the temperature of the exhaust gases before filtration and thereby extending the life of the filters.

Four custom parts were manufactured in-house. The first was a modified cart frame (**Figure A.40** and **Table A.9**), which involved cutting slots into the tabletop for the chain path and duct fan, drilling precise holes to mount the oil cooler, and welding wheels and reinforced shelving to support system components. The second part was a modified pump gear (**Figure A.41** and **Table A.10**), which was machined using a milling machine to add a key slot that allowed for secure connection to the drive shaft. The third was a 3D-printed flow valve bracket (**Figure A.42**), designed to hold the gear motor in proper alignment with the valve for precise flow control. The fourth was a fan adapter (**Figure A.43**), also 3D-printed, used to interface the duct fan with the exhaust tubing.

To complete the system, an Arduino microcontroller was integrated for real-time data acquisition. The Arduino recorded time intervals and used input from the proximity sensor to calculate RPM. It also captured pressure data from the hydraulic sensor. These values were streamed to Microsoft Excel via the Serial.print function and the built-in Data Streamer plugin. Post-test, performance data were processed using defined equations (refer to **Figure A.30**). During power runs, the flow valve was gradually closed by the gear motor to increase system back pressure, reducing the engine's RPM and simulating load. This controlled resistance allowed for accurate performance testing and power output measurement.

The assembly process concluded with successful prototype validation, with most subsystems operating as intended. The system's modular design, clear documentation, and iterative improvements made the final product robust, testable, and ready for further development.

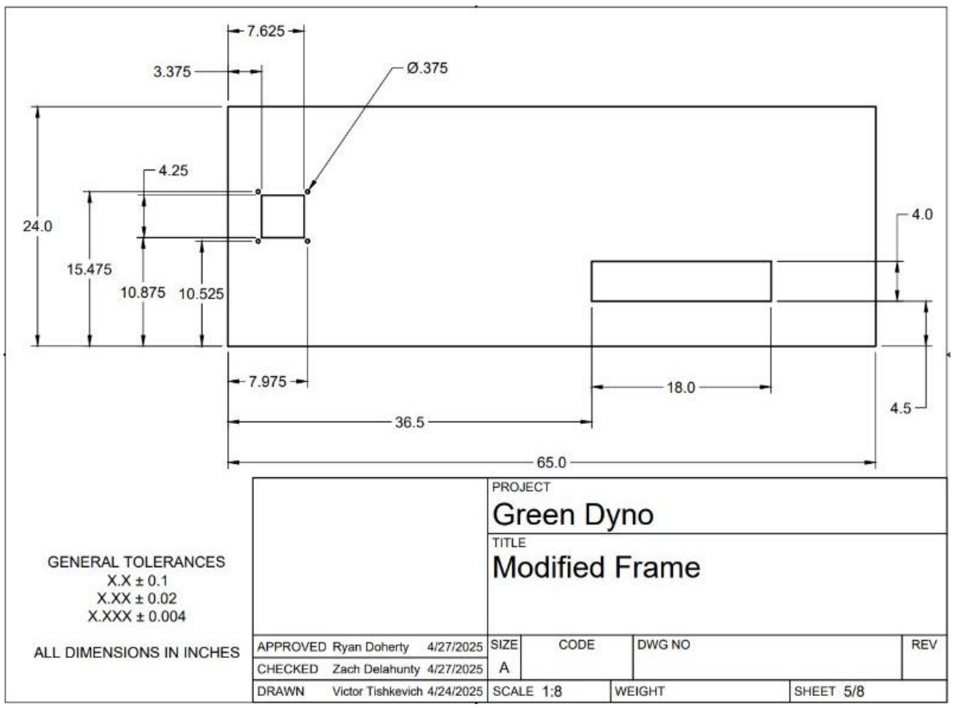


Figure A.43 Modified Frame Manufacturing Drawing

Table A.9: Modified Frame Operation Sheet

Modified Frame				
Step	Operation	Description	Equipment	Notes
1	Setup	Secure the table top onto two stable platforms on either side. Ensure the table is strapped down.	Handheld Electric Saw; Jigsaw	Utilize a ruler and circle tool for measurements. High tolerance since holes are not meant for fittings.

2	Draw Duct Fan Hole	Sketch a 4.25" square hole centered in the 24" width of the table, 4" into the side of the table.	Compass & Ruler	Double-check measurements before cutting.
3	Cut Duct Fan Hole	Cut along the trace of the 4.25" square hole markings for the duct fan.	Jigsaw	Higher tolerance needed for accurate cuts.
4	Draw Chain Slot	Sketch an 18" length X 4" width rectangle hole, 4.5" into the 24" width table, for the chain slot.	Compass & Ruler	Double-check alignment and measurements.
5	Cut Chain Slot	Cut along the trace of the markings for the 18" x 4" rectangle hole for the chain slot.	Jigsaw	Ensure the cut is clean and precise.
6	Draw oil cooler holes	Take circle drawer tool and create two vertically aligned 0.5" holes. Proceed to draw two vertically aligned semi-circles with radius of 0.75"	Compass & Ruler	Ensure symmetry in hole placement.
7	Cut oil cooler holes	Drill through trace of the markings created in step 6	Drill with 0.5" Drill Bit	Accuracy is important to avoid misalignment.
8	Smooth	Take sandpaper and smooth along the edge of the cuts	Sandpaper	Aesthetically better and reduced risk of splinters

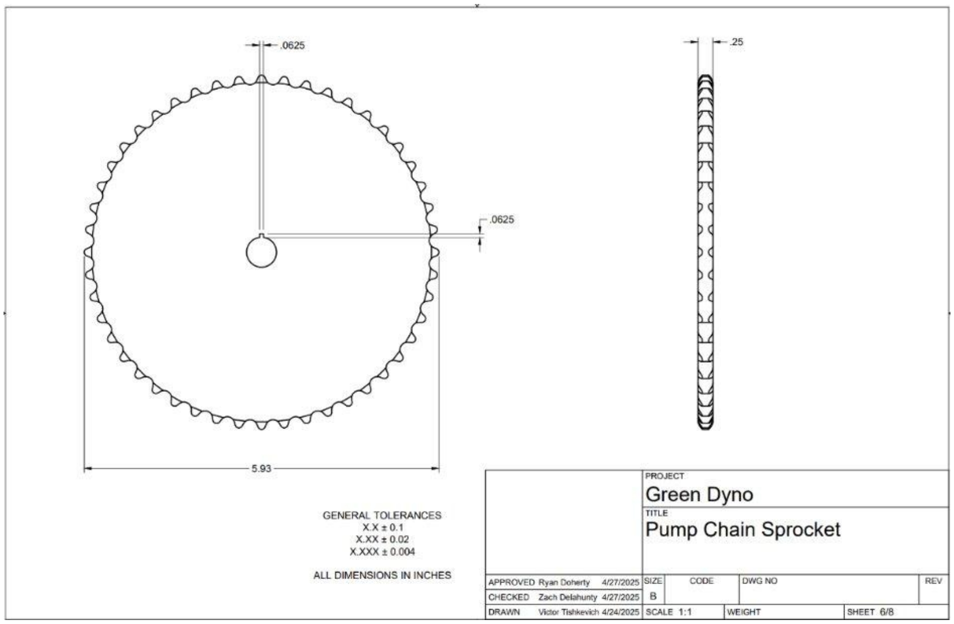


Figure A.44 Modified Pump Gear Manufacturing Drawing

Table A.10: Modified Pump Gear Operation Sheet

Modified Pump Gear				
Step	Operation	Description	Equipment	Notes
1	Setup	Secure the gear in a precision vise or fixture on the milling machine table. Ensure the part is flat and centered.	Milling machine, Vise/Fixture, Dial indicator	Use an edge finder to locate the center hole.
2	Locate Key Slot Position	Use digital readout (DRO) or manual measurement to position the cutter at the correct slot location relative to the center hole.	DRO, Edge Finder, Dial Indicator	Double-check measurements before cutting.
3	Select Cutting Tool	Install a 0.0625" end mill in the collet and set the appropriate spindle speed for material.	End Mill (0.0625"), Collet, Wrench	High-speed steel (HSS) or carbide end mill recommended.

4	Mill Key Slot	Move the end mill to the correct starting position and gradually plunge to 0.0625" depth. Then, feed the cutter along the slot length using a slow, controlled feed rate.	Milling machine, End Mill (0.0625")	Use cutting fluid for better tool life and surface finish.
5	Deburr	Use a small file or deburring tool to remove sharp edges and burrs from the key slot.	File, Deburring tool	Ensure smooth edges to fit the key properly.
6	Inspection	Measure the key slot dimensions using calipers and check alignment with the center hole.	Calipers, Gauge Pin, Key Stock	Ensure slot width and depth meet design specs.

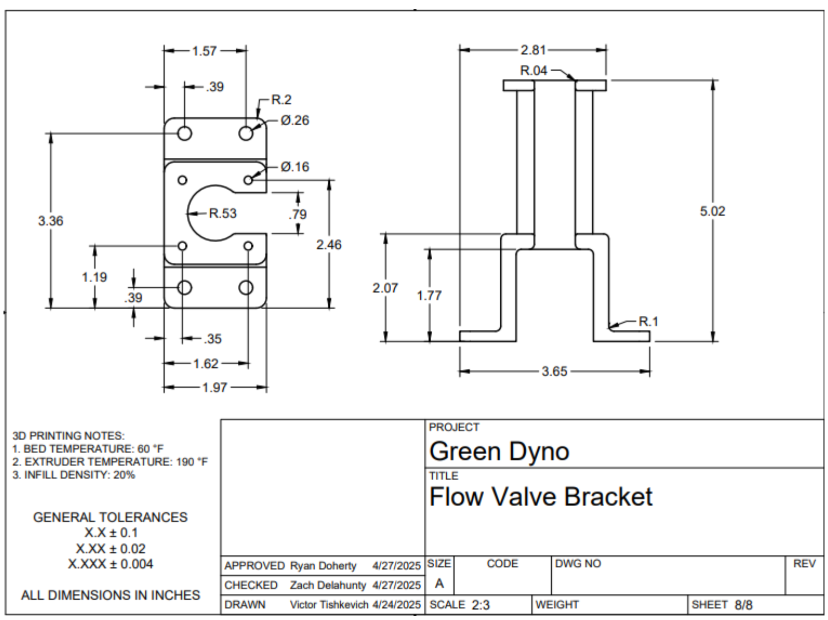


Figure A.45 Flow Valve Bracket Manufacturing Drawing

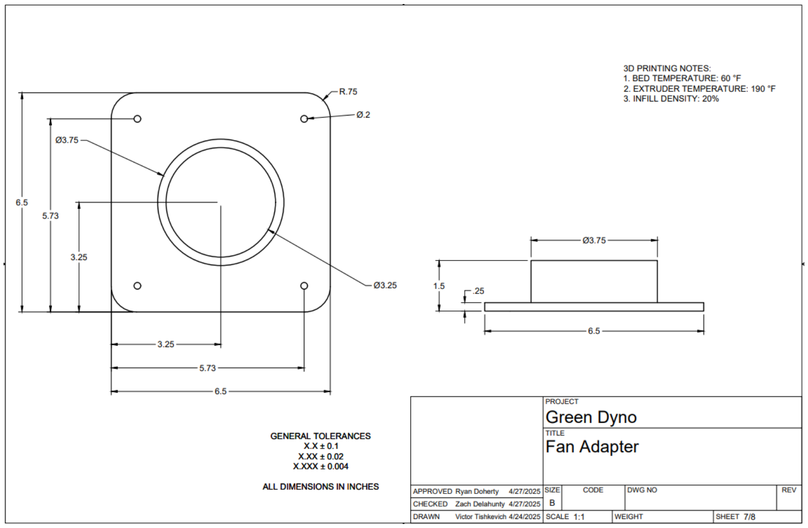


Figure A.46 Exhaust Duct Fan Adapter Manufacturing Drawing

P. Standards Applied

Commented [CJ15]: Victor

Nominal Size Range, Inches		Class RC 5		
		Clear-ance[a]	Standard Tolerance Limits	
Over	To		Hole H8	Shaft e7
0 –	0.12	0.6 1.6	+0.6 0	− 0.6 − 1.0
0.12 –	0.24	0.8 2.0	+0.7 0	− 0.8 − 1.3
0.24 –	0.40	1.0 2.5	+0.9 0	− 1.0 − 1.6
0.40 –	0.71	1.2 2.9	+1.0 0	− 1.2 − 1.9
0.71 –	1.19	1.6 3.6	+1.2 0	− 1.6 − 2.4
1.19 –	1.97	2.0 4.6	+1.6 0	− 2.0 − 3.0
1.97 –	3.15	2.5 5.5	+1.8 0	− 2.5 − 3.7
3.15 –	4.73	3.0 6.6	+2.2 0	− 3.0 − 4.4

Table A.47 ANSI Running and Sliding Fits

The pump shaft to pump gear shaft in the prototype has an RC 5 medium running fit.

Nominal Size Range, Inches	Class LC 1			Class LC 2			Class LC 3		
		Standard Tolerance Limits			Standard Tolerance Limits			Standard Tolerance Limits	
	Clear-ance[a]	Hole H6	Shaft h5	Clear-ance[a]	Hole H7	Shaft h6	Clear-ance[a]	Hole H8	Shaft h7
Over To	Values shown below are in thousandths of								
0– 0.12	0 0.45	+0.25 0	0 −0.2	0 0.65	+0.4 0	0 −0.25	0 1	+0.6 0	0 −0.4
0.12– 0.24	0 0.5	+0.3 0	0 −0.2	0 0.8	+0.5 0	0 −0.3	0 1.2	+0.7 0	0 −0.5
0.24– 0.40	0 0.65	+0.4 0	0 −0.25	0 1.0	+0.6 0	0 −0.4	0 1.5	+0.9 0	0 −0.6
0.40– 0.71	0 0.7	+0.4 0	0 −0.3	0 1.1	+0.7 0	0 −0.4	0 1.7	+1.0 0	0 −0.7
0.71– 1.19	0 0.9	+0.5 0	0 −0.4	0 1.3	+0.8 0	0 −0.5	0 2	+1.2 0	0 −0.8
1.19– 1.97	0 1.0	+0.6 0	0 −0.4	0 1.6	+1.0 0	0 −0.6	0 2.6	+1.6 0	0 −1
1.97– 3.15	0 1.2	+0.7 0	0 −0.5	0 1.9	+1.2 0	0 −0.7	0 3	+1.8 0	0 −1.2
3.15– 4.73	0 1.5	+0.9 0	0 −0.6	0 2.3	+1.4 0	0 −0.9	0 3.6	+2.2 0	0 −1.4
4.73– 7.09	0 1.7	+1.0 0	0 −0.7	0 2.6	+1.6 0	0 −1.0	0 4.1	+2.5 0	0 −1.6
7.09– 9.85	0 2.0	+1.2 0	0 −0.8	0 3.0	+1.8 0	0 −1.2	0 4.6	+2.8 0	0 −1.8
9.85– 12.41	0 2.1	+1.2 0	0 −0.9	0 3.2	+2.0 0	0 −1.2	0 5	+3.0 0	0 −2.0
12.41– 15.75	0 2.4	+1.4 0	0 −1.0	0 3.6	+2.2 0	0 −1.4	0 5.7	+3.5 0	0 −2.2
15.75– 19.69	0 2.6	+1.6 0	0 −1.0	0 4.1	+2.5 0	0 −1.6	0 6.5	+4 0	0 −2.5

Table A.48 ANSI Clearance and Location Fits

All duct to ducting adapter connection in the prototype have a tolerance of LC3 fits.