ME450
MRacing Variable Valve Timing

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Executive Summary

Problem Statement

MRacing, Michigan's Formula SAE team, is tasked each year to create the fastest, most efficient car possible. MRacing's Honda CBR600RR engine uses a dual-overhead camshaft system to control intake and exhaust valve actuation. The valve timing of this system is fixed relative to engine speed and is therefore only optimized for a singular engine speed. The purpose of this project is to develop a mechanism to optimize the valve timing of MRacing's Honda CBR600RR engine, for each engine speed, resulting in significant gains in torque and efficiency of the engine and therefore improve MRacing's performance in Formula SAE dynamic events. The goal for our team is to design, manufacture, and test a mechanical system that can be assembled directly to the existing MRacing engine. Our manufactured product is required to optimize valve timing, increase torque, and package with the existing powertrain.

Requirements and Specifications

Throughout the process of doing research on existing solutions for variable valve timing, meeting with subject expert Harvey Bell, and keeping in mind of the competition's restrictions, overall user requirements and respective engineering specifications have been determined which address or tackle issues like continuously varying the valve timing, manufacturability, packaging in engine and ECU compatibility. Detailed explanation and justifications of the requirements and specifications have been provided in the respective section (Page 8-12) of the report.

Concept Generation, Evaluation, and Selection

Using examples from industry, as well as various brainstorming activities, numerous design concepts were generated to solve the problem statement set forth by MRacing. A flowchart was created using design selections starting from the most broad, such as whether to use a camshaft or not, narrowing down to the individual concepts. This flowchart was used to help do an initial screening to remove the least feasible designs. Using sub-functions developed from a functional decomposition of our project, each of the remaining designs were ranked either good, bad, or neutral at fulfilling the systems sub-functions. This ranking was used to select a final design that we moved forward with.

Design Solution

After selecting a hydraulically actuated cam phaser, first we created CAD of the engine head and camshaft so to have a better understanding of our packaging requirements. Next we spent a lot of time solving the problem of getting oil pressure from the engine, to the rotating camshaft phaser. This was the first of the bigger challenges we had to overcome. Next was the challenge of a design that packages well in the engine. Our design did not package in the head and will require further modification in a future project to achieve packaging requirements. We were successful in manufacturing our design solution using only machines available to us at the wilson center.

Engineering Analysis

Our design solution is operating in the harsh conditions inside of an engine, so we needed to ensure that it would function properly. We analyzed the life of the bearings providing oil to our phaser to ensure that they would meet the durability requirements set by MRacing, as well as analyzing the torques and stresses experienced by the phaser to ensure none of the parts were in danger of failure. Oil flow through the system was analyzed using some simplified analysis. The oil pressure generated by the pump was determined to be adequate to rotate the phaser even in the worst case scenario.

Validation

Due to the dangers of operating a prototype using a running engine and oil pump, we decided to use a 12v oil pump to attempt to validate our design. First we validated the weight and degrees of motion requirements, which our system achieved. Then we attempted to use the oil pump to validate the continuous motion requirement, which due to some unsolved leaking issues we were unable to verify. Finally, due to not operating the system on an engine, we validated our torque requirements using GT-Power simulations.

Conclusion

MRacing desired a solution to change their fixed timing Honda CBR engine into an engine that can vary its valve timing continuously. We provided what we consider to be a big first step in achieving this goal, and provided some next steps for MRacing to take to fix the bigger problems with this project, and actually succeed in implementing this design into their vehicle.

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Background

Formula SAE is a collegiate design series that challenges students to conceive, design, fabricate, develop, and compete with small, single-seat open wheel race cars as can be seen in figure 1 below. A large part of the competition is centered around four dynamic events: autocross, skid pad, acceleration, and endurance. Placing first in all these events would reward the team with a total of 575 points in the competition. Our sponsor, The University of Michigan's Formula SAE team known as MRacing, currently uses a Honda CBR600RR engine with fixed valve timing in their vehicle. They have identified this fixed valve timing as a potential area for performance gains to garner more competition points.

Figure 1: MRacing Vehicle

The valvetrain of an engine consists of the valves themselves, the camshafts, and the timing chain. Valves are the engine's way of controlling air flow into the engine, as well as the exhaust flow out of the engine. The valves are controlled via the lobes on the camshaft. The rotation of the camshaft forces the lobes to actuate the valves allowing air to flow through the valves into the engine cylinder[1]. The rotation of the camshaft is typically driven via a chain connecting the crankshaft (the shaft that the pistons are attached to, as seen in Figure 2 below) to the camshaft. As the crankshaft directly drives the camshaft in that typical scenario, the shafts rotate at a constant speed relative to each other. This means the valves always open at the same time relative to the location of the piston. This timing is what is known as valve timing and is measured in degrees of rotation relative to "top dead center" which is the crankshaft position that places the first piston in the engine at the top of its stroke.

Figure 2: Typical Fixed Timing Valvetrain[17]

Valve timing can have a significant impact on an engine's performance. Often the limiting factor in how much power an engine can produce is the amount of air an engine is able to get into its cylinder. As valves are what control the air allowed into an engine, the timing of valve opening, and closing are a large contributor to the power output of an engine. For engines with fixed valve timing, the valve timing is optimized for maximum power at a specific engine RPM, typically the engine RPM that the engine is most frequently operating at. However, this leaves a lot of room for improvement at other engine operating conditions. Therefore, implementations of variable valve timing can typically produce 5-10% increases in torque across the engine's rev range[1][2].

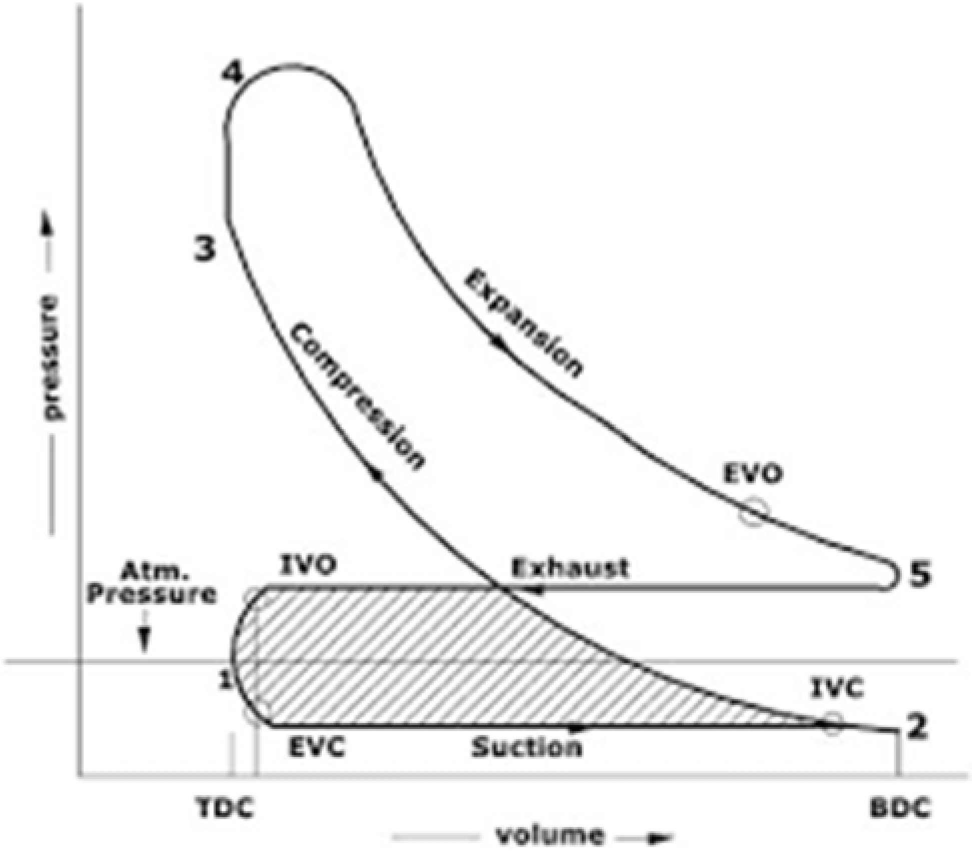


Figure 3: Typical In-Cylinder Pressure vs. Volume Diagram of a Throttled Engine

In engines that use a throttle-based load control, like MRacing and most gasoline engines, the engine uses some of the work it produces to intake the air it needs for combustion. This work is known as pumping work and reduces the usable work an engine produces[1]. This pumping work is represented by the shaded area of the in-cylinder pressure vs. volume diagram shown in Figure 3 above. Research has shown that the pumping work experienced by a throttled engine can be reduced by varying an engine's valve timing[1]. With fixed valve timing, pumping losses can only be optimized at a specific operating condition. Variable valve timing allows for pumping losses to be reduced across the entirety of operating conditions, resulting in an increase in the usable power out of an engine.

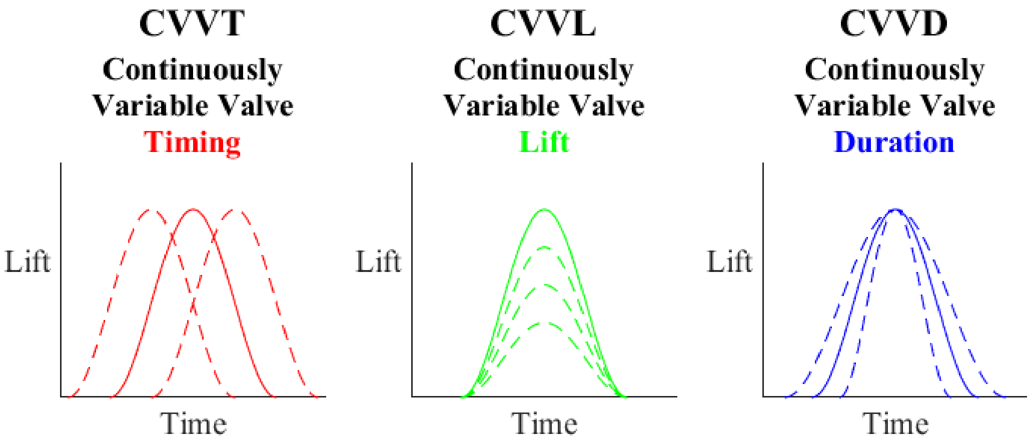


Figure 4: Valve Timing/Lift/Duration Visualization

Along with valve timing, valve duration and lift can also be varied by engine speed to optimize torque output as shown in Figure 4. While creating systems to vary all three of these parameters would be ideal, the systems necessary to do so would be extremely complex and require significant modifications to the overall MRacing powertrain design. For this reason we limited the scope of this project to valve timing.

Problem Statement

Internal combustion engines, especially in motorsports applications, are very complex and utilize many intricate systems to enhance their performance. Chief among these systems is the valvetrain of the engine which controls the flow of fluids in and out of the engine's combustion chamber. MRacing's engine, sourced from a Honda CBR600RR motorcycle, has a displacement of 600cc, 4 cylinders, and makes use of a 16 valve dual-overhead camshaft setup. In this setup one camshaft controls the eight exhaust valves with the second camshaft controlling the eight intake valves. Figure 5 (p. 9) shows the entire head and valve train assembly currently used by MRacing.

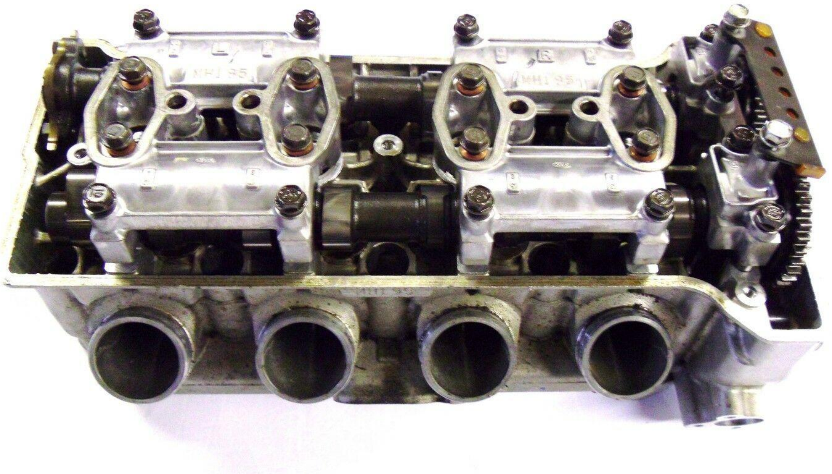


Figure 5: Honda CBR600RR head used by MRacing

While this valvetrain is advanced and robust, it is still wanting in terms of optimizing the flow of fluid through the combustion chamber as the valve timing, lift, and duration are fixed throughout the engine's operating range. When valve timing is not variable, it can only be optimized for a single engine speed, therefore compromises in torque and efficiency are being made during the majority of engine operation.

For this reason, the objective of our project was to develop a mechanism which can be attached to the existing MRacing powertrain and is able to vary valve timing in order to optimize the torque output of the engine across its entire operating range.

Requirements and Specifications

Throughout the process of doing research on existing solutions for variable valve timing, meeting with subject expert Harvey Bell, and keeping in mind of the competition's restrictions, we created various requirements and specifications we needed to achieve in order to consider the project a success.

Table 1: Requirements and Specifications

System Requirement	Specification
Optimize valve timing for greater torque output	Optimize valve timing in increments of 200 RPM
Powertrain Requirements	
Increase Torque	VVT system must increase low-end torque by at least 3.5 % across the engine's entire rev range
Controllable and compatible with the current ECU (Engine Control Unit)	VVT system must vary timing by no more than 16° from the nominal orientation.
Mechanical Design Requirements	
Packages with Existing Powertrain	VVT system should have ≥ 0.1 in. clearance to all existing powertrain components
Compatible with Current Engine	VVT system must attach to CBR600RR engine without any required machining to the engine head
Continuously Vary Valve Timing	VVT system must be able to vary valve timing with continuous camshaft phase angle adjustment
Machineable with UMich Facilities	Any machining must able to done with: CNC 4-axis mill, CNC lathe
Lightweight	VVT system must add ≤ 7.5 lbs. mass
Reliable for 4 Weeks of Driving	VVT system must be able operate ≥ 1,700,000 revolutions at an average engine speed of 8200 RPM

Optimize Valve Timing

We aimed to optimize valve timing in increments of 200 RPM which is the industry standard[2] and having smaller increments would give diminishing returns in performance as the ECU interpolates between these points which acts a control (electric) system constraint.

Increase Torque

Existing variable valve timing implementations typically increase the low-end torque approximately by 5-10% across the entire engine rev range. However, the MRacing team's engine has a limit on the amount of air that can be taken in by the engine which affects the overall performance and torque outputs and, therefore, a conservative increase in torque output was expected. Hence, our VVT implementation targeted an increase in the torque output by at least 3.5% across the entire range.

Controllable with current ECU

The ECU used by MRacing has limits on its control functionality. Specifically, it does not let the valve timing change by more than 16° from the nominal orientation. It was very crucial that the solution was compatible with this ECU as creating a custom control system was outside the scope of this project. Hence, our VVT system was designed to vary the valve timing in accordance with the ECU.

Packages with Existing Powertrain

The VVT system must not interfere with existing powertrain packaging shown in figure 6 (p. 12). As a result, the VVT system must have at least 0.1 in. clearance to all existing powertrain components. This amount of clearance is based upon previous MRacing powertrain packaging requirements and the variability within the powertrain system. This will allow for MRacing to utilize the VVT system on existing vehicles for testing. This will help reduce the overall test effort as the system is validated. Most importantly, it will allow MRacing to build confidence in the system prior to implementing the system on future iterations of the MRacing vehicle.

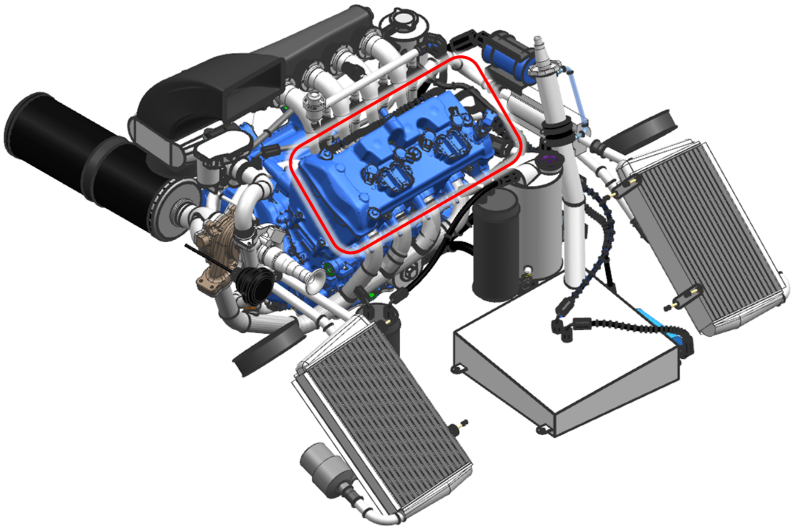


Figure 6: Location of Existing Valvetrain on MR21 Powertrain

Compatible with Current Engine

The VVT system must attach to the Honda CBR600RR engine without any required machining to the engine head. The engine head is an intricate component as seen in figure 5 (p. 6). As a result, any modification would require extensive machining that likely cannot be performed with UMich facilities. Additionally, a new design would require significant design effort on top of the VVT system. Thus, modification or a redesign of the engine head is outside the scope of this project.

Continuously Vary Valve Timing

We designed our VVT system to be able to vary valve timing with continuous camshaft phase angle adjustment. Continuous camshaft phase angle adjustment offered optimal performance benefits at each operating speed across the engine speed range. Additionally, continuous adjustment allowed for the system to follow the continuous valve timing map that the ECU interpolates.

Machineable with UMich Facilities

Any necessary machining must be able to be completed with a CNC 4-axis mill and CNC lathe. Due to the current COVID circumstance, university and state regulations discourage us from interacting with outside companies for physical parts. Therefore, it is important that we limit the complexity of our design to that which can be machined with the 4-axis mill and CNC lathe in the Wilson Center.

Lightweight

The VVT system must add less than 7.5 lbs. of total mass. The negative effect of the system's added mass of total competition points must not outweigh the benefit from the increased torque.

Figure 9 (p. 13) shows a full vehicle sensitivity analysis conducted by MRacing in VI-CarRealTime looking at the sensitivity of total competition points to torque and mass. The positively sloped torque sensitivity and negatively sloped mass sensitivity creates the inequality relationship shown in Figure 10 (p.13). With an average torque increase of five percent across the entire operating range, the system must stay under 7.5 lbs. to remain at least point neutral.

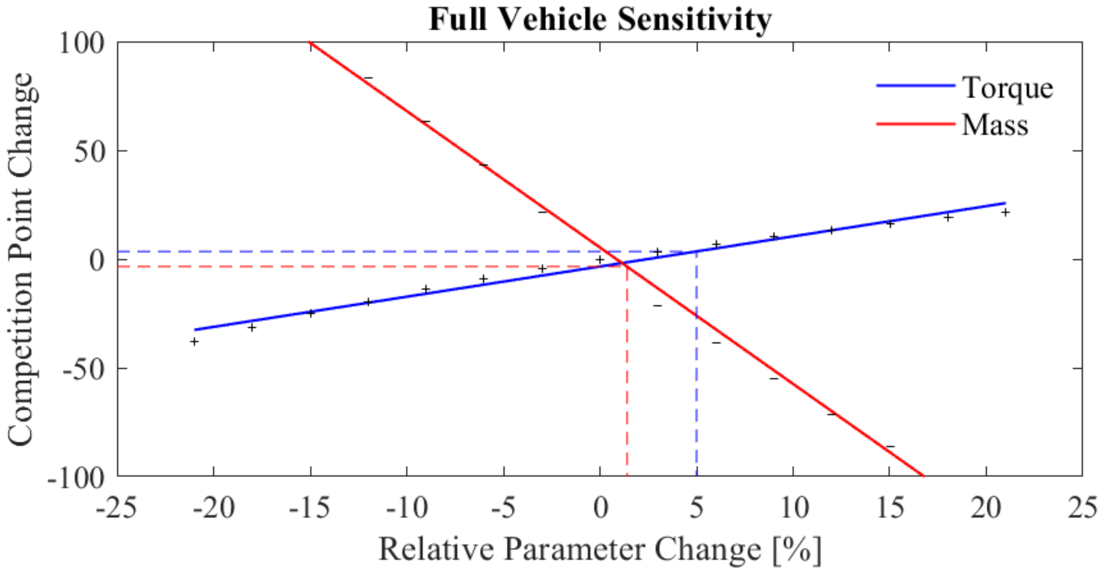


Figure 9: Competition Point Sensitivity to Torque and Mass

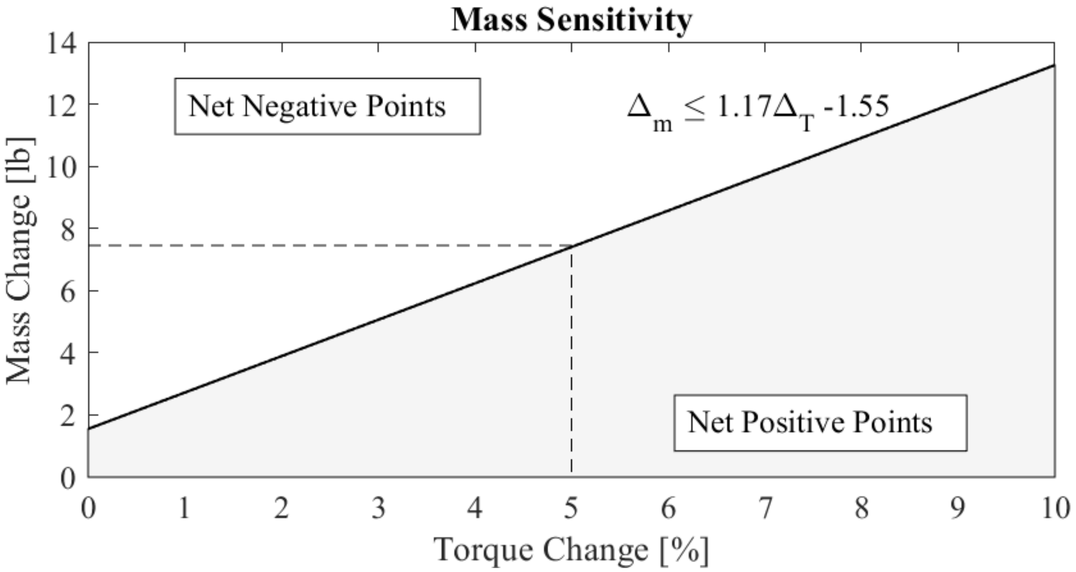


Figure 10: Mass Sensitivity to Average Torque Changes

Reliable for 4 Weeks of Driving

The VVT system must be able to operate at least 1.7 million revolutions at an average engine speed of 8200 rpm. The system must be reliable for the extent of its use during a season, which estimates to approximately 28 endurance events, the most strenuous Formula SAE dynamic event. The average engine vehicle speed during the event was used to find the engine speed and total number of revolutions over the 22 km. events.

Simulation

Besides mechanical design, a complex factor in developing a variable valve timing system for an internal combustion engine is determining actual valve timing targets for your optimal system. Even if you can successfully vary intake and exhaust valve timing at every engine speed, it will not be useful unless you know what update timing to set your system to.

The way optimal valve timing is traditionally determined is through physical testing of the variable valve timing system on an engine attached to a dynamometer. The method used is to reach a steady-state engine speed and then vary valve timing in sweeps until maximum torque is reached. This is repeated for every desired engine speed and is common practice for optimizing ignition timing and fuel injection as well. Methods like this are very costly in terms of fuel used, time spent, and potential for total failure of the system and require a physical system to exist already.

Luckily, software exists that has the capability to simulate engine performance and can be used to optimize valve timing. The added benefit of this is to find the potential performance gains prior to designing and manufacturing a physical VVT system. There are many engine simulation software available but for our project we decided to use GT-Power as it is free to use through the University of Michigan's CAEN network and because MRacing has prior experience and knowledge of the GT-Power.

To set up a GT-Power model, all relevant engine components are created using visual code and connected to one another then any cases the user would like to explore are input. MRacing's GT-Power model, as well as other relevant figures can be found in Appendix F.

Along with modeling engine performance GT-Power has built in optimization tools that can be used for a large number of parameters. In our case, we wanted to optimize intake and exhaust timing in order to maximize torque in 200 RPM increments from 3,000 to 10,000 RPM with a limit on the timing to be plus or minus 16 degrees from the nominal orientation. When the variable valve timing solution we developed eventually is implemented into the MRacing vehicle, the results from this optimization will be used as initial targets for the valve timing of the engine.

Concept Generation

After establishing a well defined set of requirements and specifications, our group started generating concepts to address our problem. Our goal was to develop a diverse set of ideas that address our requirements and specifications and are within the scope of our project. To aid in the development of these ideas, we used a functional decomposition with a series of ideation flowcharts, these flowcharts and functional decompositions can be seen in Appendix E.

Functional Decomposition

In order to expand upon our requirements and specifications, our group developed a functional decomposition tree. The decomposition would serve as a tool to guide our concept generation phase. The decomposition focused on our overarching requirement to optimize valve timing and branched down to the important sub functions and considerations that must be made to meet that requirement.

Design Ideation Flowchart

After clearly establishing the important functions for our project, our group then started to generate ideas. Due to the complexity of variable valve timing systems, it is unlikely that our group develops a novel solution for the problem of varying valve timing. Additionally, there are many connections between the different functional solutions. For instance, a particular valve timing solution will only integrate into the engine one particular way. As a result, more traditional concept generation techniques that emphasize more free connections between the different functions are not well suited for our project. For these reasons, our group opted to develop our own ideation flowchart to better highlight these connections and ideas. Before going deep into the concept generation phase, our group first made a high level ideation flowchart. This helped further establish the scope of our project as many of our functional decisions were limited by the complexity of the resulting system.

Our group limited the scope of our valve timing controller options to only the existing ECU as a part of our requirements and specifications. A custom electronic controller to control engine valve timing at the high rotational speeds of the camshaft would constitute an entire project on its own. A driver-aided mechanical controller that would take the form of a button or dial on the steering wheel was also considered. However, this solution likely would not have been continuous and would be subject to driver error. Our group also limited the scope of our engine integration to solutions that don’t require a completely custom engine head. The engine head on the Honda CBR600R is very complex as seen on Figure 5 (p. 9). Designing and manufacturing an engine head would require extensive design effort and manufacturing processes that are likely outside of our capabilities on campus. As a result, we only considered solutions that can be implemented with our existing engine head.

After screening our valve timing and integration options, we further investigated the design space for mechanisms that can vary valve timing. From this investigation, we developed the low level design ideation flowchart that can be seen in appendix E.

Our mechanism concept generation was divided into two basic subcategories: with the camshaft and without the camshaft. One can vary the valve timing of the engine without using a camshaft by changing how the valves actuate. The valves are usually lifted the camshaft, but the camshaft and valve actuation can be decoupled. This idea leads to the free valve solution where a physical actuator is used to lift the valves and let air in and out of the cylinder. Solutions that still utilize a camshaft can be further subdivided into solutions that use the existing camshaft design and a new, custom camshaft design. One can vary valve timing with the existing camshaft design by decoupling the intake and exhaust camshafts. This is called a cam phaser since it creates a relative phase angle between the two camshafts. There is more freedom to vary valve timing with a custom camshaft. One can use a 3D camshaft lobe that varies along its length to allow for different effective camshaft lobe profiles as the speed varies. One can also alternate between two or more camshaft profiles for a particular valve. These resulting concepts were further explored to determine the best concept for our problem.

Concept Exploration

Free Valve

The first concept our team explored was a free valve mechanism. Free Valve is a fully variable valve actuation system that provides independent control of the intake and exhaust valves. A free valve VVT can be actuated by either a pneumatic, hydraulic, or electrical system Instead of a camshaft, each valve is controlled by an independent actuator and spring system. This idea has been around for many years, but supercar maker Koenigsegg was the first car company to develop a free valve engine. Visuals showing how free valve works can be found in Appendix D.

The biggest advantages to the free valve VVT is the complete control over air in every individual cylinder to optimize engine efficiency and emissions. The engine is free of the mechanical constraints of a steel camshaft. The other big advantage is that you do not have to make sacrifices with some parameters to optimize others. You can simultaneously control timing, lift, and duration of each individual valve. Each spring system can open or close the valve when it wants (timing), as much as it wants (lift) and for as long as it wants (duration). The computer controlling all this can decide to run the engine on whatever cycle it wants, to optimize power, efficiency, or emissions. Another pro is its compact size and weight. Free valve cylinder heads are shorter, narrower and thinner. There is also no chain drive to run the camshafts, as well as no camshafts or lifters. There is only the valve, spring, and actuator system.

While the advantages of a free valve seem like the ideal variable valve system, the cons far outweigh the pros in the scope of our 450 design project. The biggest problems are cost and complexity. You are replacing pieces of metal that our team could potentially fabricate and manufacture with advanced electronics and high pressure seals for both air and oil controls. Seals can and do wear, and when they do, they leak. When failure occurs within the system, it's likely very expensive to fix.

Updated Ideation Flowchart

After evaluating the free valve design, our team decided to update our ideation flowchart to only include designs that contain a camshaft, this can be seen in Appendix D. Designs without a camshaft are out of the scope of our project. They would be very costly, complex to both design and manufacture, and involve varying timing, duration, and lift. We are just attempting to vary valve timing. Concepts that require a camshaft better meet our engineering requirements and specifications.

Multiple Camshaft Profile per Valve

The first camshaft concept explored was the multiple camshaft profile. A multiple camshaft profile involves having lobes connected to the camshaft that vary in size and orientation. Lobes that are larger or smaller would create a longer or shorter duration that the valve is open. Lobes that are angled higher or lower than the original would give the valve opening a different timing than the original orientation. The use of different lobes would be able to optimize performance and efficiency. The engine would be able to switch between the different lobe styles based on what RPM the engine is functioning at. This VVT mechanism uses an actuator that controls a rocker shaft. This slides a pin that slides in and out based on what lobe style is chosen. This style of design is commonly seen in Honda's VTEC, developed in 1980. [10]

The biggest advantages of using a multiple camshaft profile VVT is that it improves overall engine efficiency and performance. Similar to all VVT designs, this concept allows you to vary valve timing at different speeds to improve performance. This concept also allows you to vary timing, duration, and lift, instead of just timing. The multiple camshaft profile will give the engine higher performance at high RPM and lower fuel consumption at lower RPM. The major disadvantage to this design is that the system is not continuous. The continuity of the design is solely dependent on how many different camshaft profiles you add to the camshaft. When this design is used in industry, it usually has two different cam lobe profiles, low RPM and high RPM. One of the requirements of our project is that the mechanism be able to vary continuously. This design would only allow us two different timings if we included two cam profiles. The other con of this concept is the packaging of it. Our current engine is designed for specific camshafts. This design would involve attaching more lobes to the camshaft, and there is limited space within the engine.

3-D Camshaft Lobes

This mechanism was introduced by Ferrari but is still not used in any production car mainly due to its much higher cost and complexity compared to the existing solutions. This system consists of a cam lobe with a three- dimensional profile that varies along its length[12]. At one end of the cam lobe is the least aggressive cam profile, and at the other end is the most aggressive. The shape of the cam smoothly blends these two profiles together. A mechanism can slide the whole camshaft laterally so that the valve engages different parts of the cam. The shaft still spins just like a regular camshaft but by gradually sliding the camshaft laterally as the engine speed and load increase, the valve timing can be optimized. This system brings major wear and reliability issues which make it not ideal given our durability requirements[13].

Cam Phaser

Most common VVT systems are the cam phasing type which an actuator to radially adjust the camshaft position relative to the timing chain and hence optimize the valve timing. This allows continuous adjustment of the cam timing (cam position), however the lift and duration cannot be adjusted. There are two major types of actuators and mechanisms used in the cam phasing type VVT systems: Hydraulic Actuator and Electrical Actuator.

Hydraulic Actuation

The hydraulic system uses a pressure control valve and oil flow to optimize the valve timing. The cam phaser has two basic components: an outer sprocket (connected to the timing chain) and an inner rotor (connected to the camshaft) that varies the valve timing by adjusting the rotation angle of the cam[14]. This inner rotor consists of a set of lobes, and oil fills the space (phaser cavity) between the outer housing and the lobes. Adding oil to one side of the cavity and removing it from the other creates a pressure difference which moves and hydraulically locks the phaser in position. These systems require an upsize oil pump to produce the extra pressure that is required to work the cam phasers, which saps some of the fuel-economy gains of VVT. With a mechanical oil pump, these systems do not work well at low engine speeds because the pump doesn’t build pressure and volume until the revs get higher[14].

Electric Actuation (E-CVVT)

This system uses a brushless direct current (BLDC) motor paired with a cycloid reducer (gearbox) to rotate the inner rotor and adjust the cam timing[16]. A detailed configuration of the E-CVVT system, which can be seen in appendix D, consists of an E-CVVT controller, servo motor, BLDC motor, motor control unit, and cylinder head block. The phase variable part consists of a BLDC motor and a two-stage gearbox[16]. The BLDC motor rotates to adjust the phase of the cam shaft through the cycloid reducer. The gearbox has a high reduction ratio which amplifies the output torque of the BLDC motor. The cylinder head block includes a camshaft and a cam position sensor, and it is possible to measure the phase change between the camshafts by the speed control of the BLDC motor. The cam shaft is connected to the medium servo motor of the drive by a chain and rotates at a constant speed. The speed of the servo motor measures the cam phase (position) and controls the valve opening and closing time by feedback control to the E-CVVT controller hence optimizing the valve timing[16].

Concept Selection

To narrow down and select a final concept to move forward with we used a modified chart to aid us in our decision-making process, this chart can be seen in appendix G. First, based on the functional decomposition we created four requirements to help compare the concepts we had remaining. These requirements were to be able to continuously vary valve timing, ease of manufacture, ability to package well in the engine, and ECU compatibility. We then rated each concept based on how well it was able to meet these requirements and placed them in a chart to compare. The 3D camshaft lobe design rates well in varying timing and packaging, however there are serious concerns over manufacturability due to the precision machining needed to create the custom 3D cam lobe. The multiple camshafts profiles per valve solution rates either bad or neutral in every category essentially eliminating it from consideration. And both cam phasers rated well in varying valve timing, ecu compatibility, and manufacturability, with their only downside being possible engine packaging issues.

Final Design Selection

After analyzing all the options from the table (found in appendix G), our team decided to pursue a hydraulically actuated cam phaser. This decision was driven by cost, availability, and functionality. Hydraulic cam phasers are commonplace in modern cars and are used by almost every manufacturer. For this reason there is a very large selection of aftermarket cam phasers used as replacements that are very affordable and are sold at most auto part stores. In contrast, electrically actuated cam phasers are made for very specific engine applications, are much more expensive, and are not sold at most retailers. Hydraulic cam phasers use a solenoid which takes an oil input from the engine and redirects it to the actual cam phaser which means it can be mounted away from the camshaft and more easily packaged where as electric cam phasers use an electric motor mounted directly to the camshaft. For this reason, there are no “off the shelf” options available for electric cam phasers meaning we would have to design an entire electric motor system ourselves. Additionally, our engine already has a substantial oiling network that can readily be adapted to an oil cam phaser unit whereas an electric actuator would require substantial electrical wiring labor and packaging.

The hydraulically actuated cam solenoid we chose is the Duralast Engine Variable Timing Solenoid TS1013. This solenoid was available at Autozone for $34.99 and has adequate functionality for our usage. It is capable of controlling oil flow to both sides of the cam phaser, and can precisely control phase via a 12v PWM signal from the ECU. A photo of this solenoid can be found in appendix G.

Design Solution

We started the design process by first modeling the relevant components of our engine's camshaft and engine head. This would allow us to parallelize the detailed model with our actuation investigation. Since we do not have a detailed model or scan of our engine, it was important that we capture enough fidelity to understand our packaging limitations. However, since the engine head consists of many complex cast aluminum surfaces, we could not model the clearance surfaces with 100% accuracy. To account for this, we modeled all clearance surfaces of the engine head conservatively, meaning the modeled surfaces would provide less clearance than the actual surfaces on the engine. Despite this, we were still able to model the comparatively simple camshaft end with enough fidelity to ensure an accurate mating connection.

Cam Phaser Design

After completing our representative model in parallel to our actuation investigation, we then started the detailed design of our system. Our design solution focused on providing the simplest solution to avoid significant downstream effects associated with other modifications. Our design solution, both attached and unattached from the camshaft, can be seen in Figure 11 below.

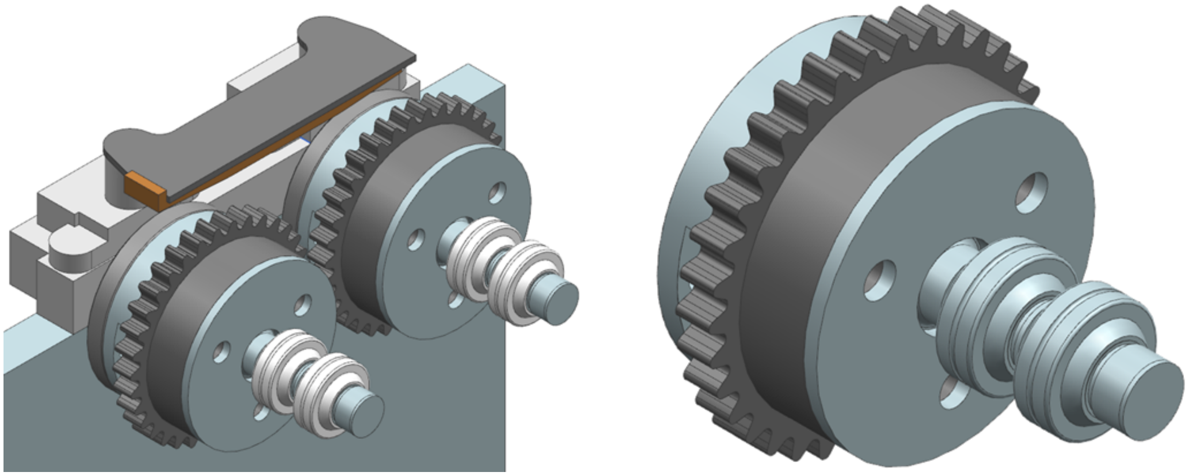


Figure 11: Initial design solution for variable valve timing cam phaser. Cam phasers attached to intake and exhaust camshaft (left)

The cam phaser assembly is attached to the end of the camshaft and constructed of 7 different parts: camshaft coupling plate, outer rotor, inner rotor, chamber seals, retaining plate, oil supply bearings, and oil passage closeout as shown in Figure 12.

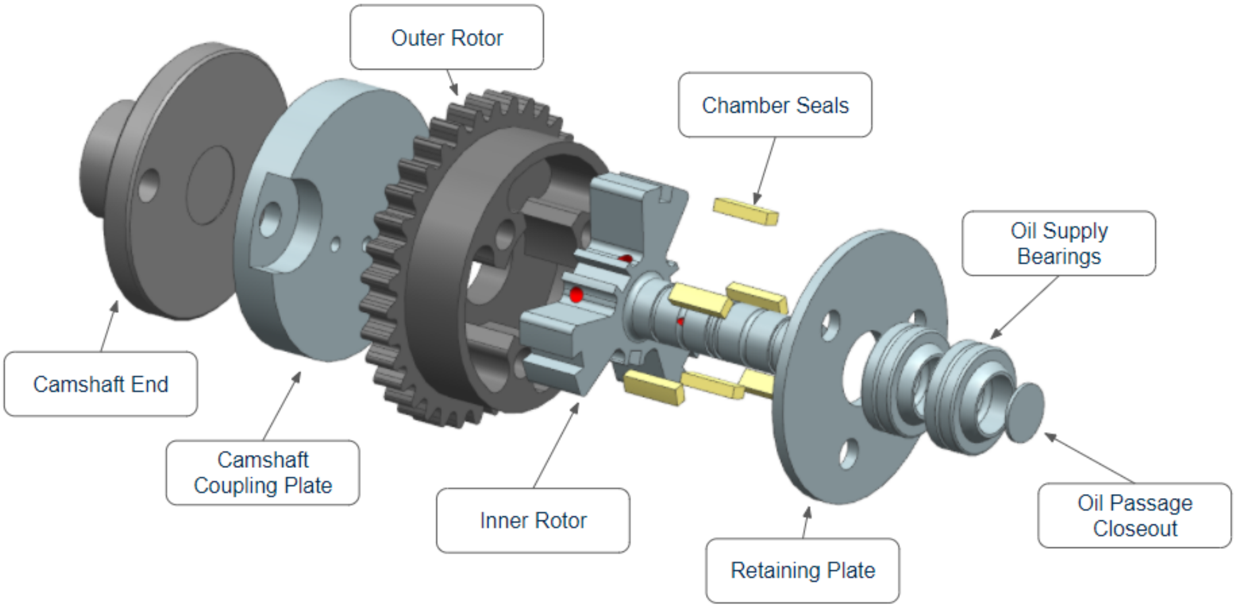


Figure 12: Exploded view of cam phaser assembly.

The 6061-T6 Aluminum camshaft coupling plate attaches to the end of the camshaft with the M7 bolts holes that are used to fasten the current camshaft sprocket as shown in Figure 13(page 22). Additionally, these M7 bolt holes are counterbored to provide enough axial clearance to the outer rotor and enough radial clearance for a socket to fit around the bolt head. Two holes are located eccentrically to allow for press fit ⅛” dowel pins to rigidly connect the coupling plate to the inner rotor.

The outer rotor is attached to the chain drive that determines nominal valve timing, but can spin relative to the inner rotor and camshaft coupling plate via hydraulic fluid as shown in Figure 13(page 22). The outer rotor uses the camshaft sprocket’s existing gear tooth profile to keep the gear ratio between the crankshaft and camshaft consistent. The outer rotor has chambers that allow hydraulic fluid to accumulate pressure and spin the inner rotor relative to it. Additionally, there are three ¼”-20 threaded bolt holes that allow the retaining plate to close off the section. The outer rotor was made of a 4340 for its excellent strength and toughness.

The 6061-T6 Aluminum inner rotor rigidly attaches to the camshaft coupling plate via press fit ⅛” dowel pins located on the bottom face of the inner rotor as shown in Figure 13(page 22). As a result, the camshaft will spin with the inner rotor instead of the chain driven outer rotor. The inner rotor has three ears that fit into the three respective chambers of the outer rotor. As hydraulic pressure builds up in the three chambers, a relative moment is applied between the outer rotor and inner rotor. This relative moment is what turns the inner rotor and allows for the continuous phase angle adjustment. Figure 14(p. 22) below shows this relative phase angle adjustment with the nominal position and extreme advanced and slowed positions.

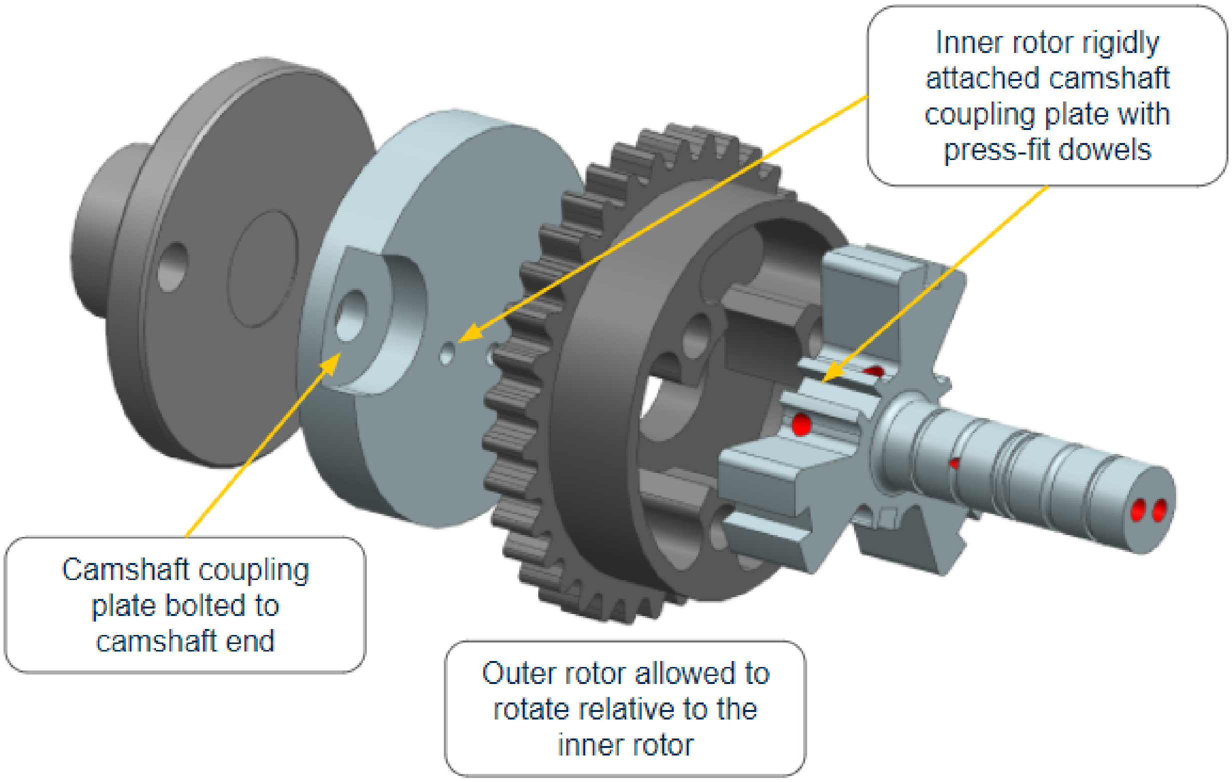


Figure 13: Camshaft-to-rotor attachment strategy

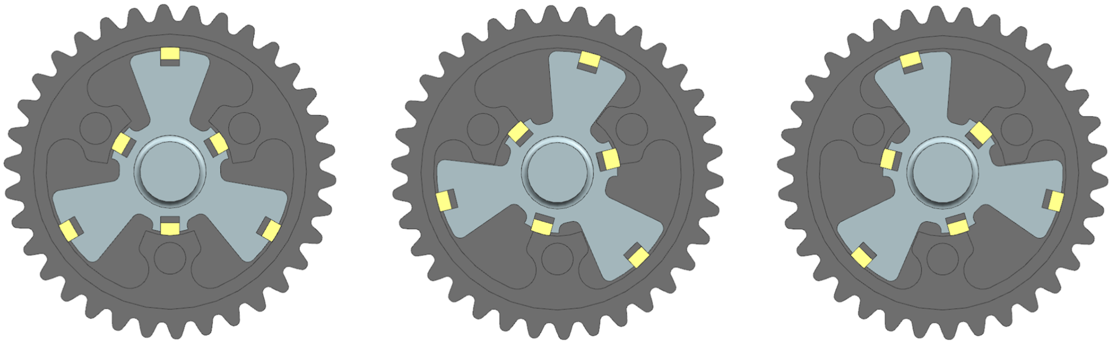


Figure 14: Cam phaser with nominal timing (left), 16° advanced timing (middle), and 16° slowed timing (right).

Cam Phaser Oil Supply

To achieve this relative moment between the inner and outer rotor, oil is sent through passages shown in Figure 15 (page 23) below to pressurize the individual chambers. Oil is delivered to the inner rotor via the bearings on the inner rotor shaft. The bearings have radial holes and grooves that allow oil to flow through them and into the inner rotor. After flowing through the bearings, the oil then enters the two axial passages, one for advancing and slowing timing, that flow into the body of the cam phaser. Once into the body of the cam phaser, the oil flows outward into the three parts of the rotor chambers. These oil passages can be seen more clearly in the section views in Figure 16 (p. 23). After entering the chambers, the oil is sealed with acrylic chamber seals and a 6061-T6 Aluminum retaining plate.

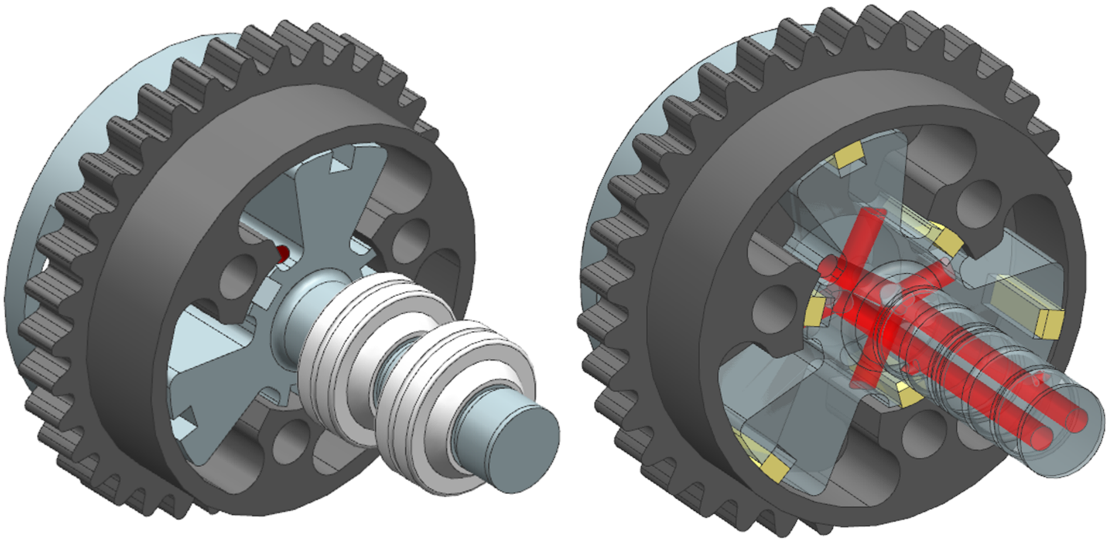


Figure 15: Cam phaser oil supply bearing and oil passages.

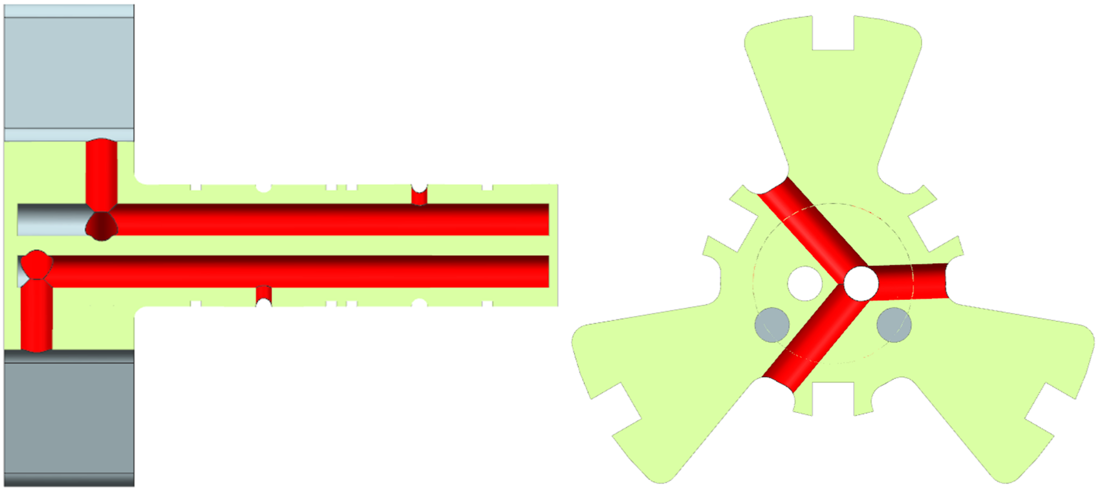
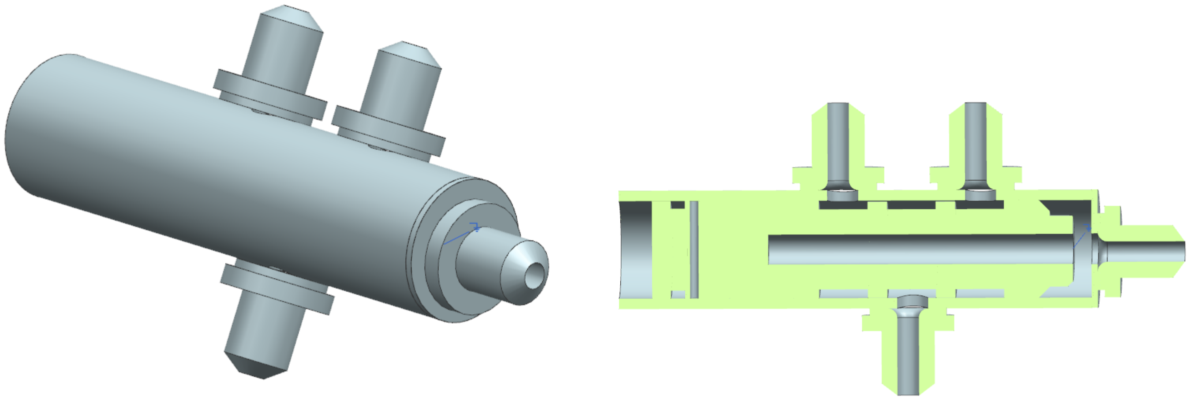


Figure 16: Section view of cam phaser oil passages.

Along with the cam phase assembly, additional fittings had to be designed to route oil from our engine, to the Duralast solenoid, and then to the cam phaser. The requirements for these fittings were to be lightweight, manufacturable, and to have good sealing.

The first fitting we designed will be used to take an oil input from the engine and to then route it to the two bearing passageways on the cam phaser. This fitting uses a simple design of an 6061-T6 Aluminum sleeve with 4AN bungs welded to it. Aluminum was chosen for it’s low weight and 4AN bungs were chosen because they geometrically match the oil passage size and are used elsewhere on the MRacing vehicle. Sealing would be covered by using Permatex RTV Silicone Sealant on the rings of the solenoid. This fitting has 4 orifices which are used for oil input to the solenoid, oil pressure relief back to the engine, oil out to cam advance, and oil out to cam retard.



Figures 17: Fitting for Duralast TS1013 solenoid.

The second fitting we designed receives oil from the solenoid and routes it to the camp phaser. This solenoid was also designed using 6061-T6 Aluminum and 4AN weld bungs. Because this fitting is mounted directly to highly sensitive bearings, it utilizes a more robust design where two opposite pieces are bolted together around the receiving end of the cam phaser.

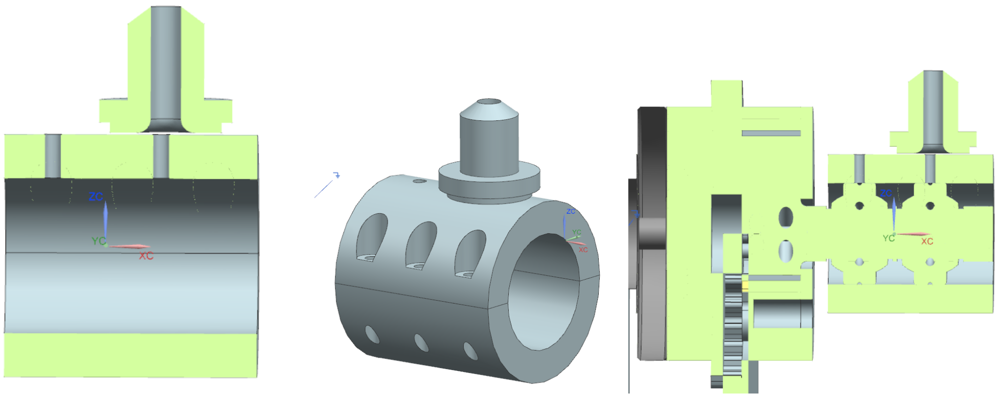


Figure 18: Fitting for cam phaser oil input.

Cam Phaser Packaging

One of our design requirements is for our VVT design to be compatible with the current engine design meaning it must be attached to the engine head without any machining. Meeting this requirement was a significant challenge for the team. Prior to cam phaser design we underestimated the available space within the engine head to mount phasers. Our final design had issues with packaging as shafts needed to supply oil interfered with the engine head as can be seen in figure 19 (p. 25) below. This was an issue that was unable to be resolved during the duration of this project, however we have provided some insight into the problem, and next steps for MRacing to take going forward to address this issue in the Discussion and Recommendations section of the report.

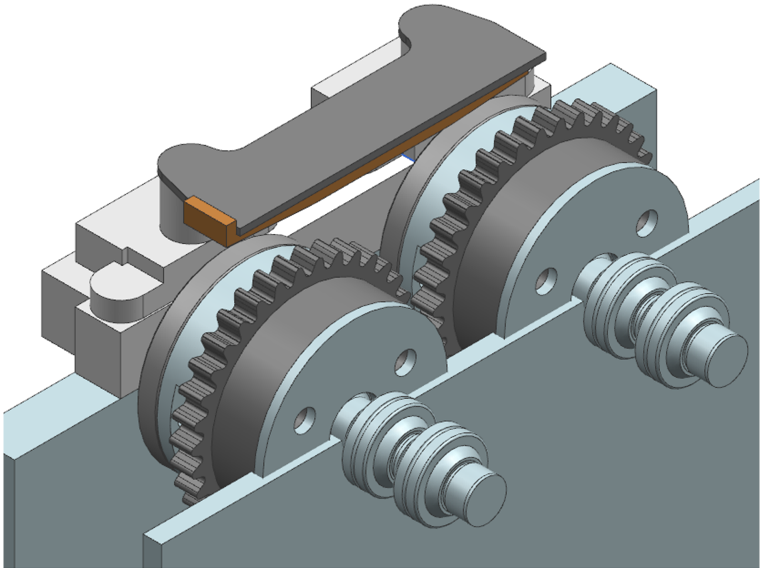


Figure 19: Cam phaser engine head packaging

ECU Implementation

Another important aspect of our design solution is controlling the oil flow to the cam phaser. This is done using the Duralast TS1013 solenoid in conjunction with MRacing's Bosch MS6 ECU. The MS6 controls all aspects of the engine including spark timing, fuel flow, and all sensors and data logging. This MS6 has built in functions to control these devices so that no custom code has to be written. In the same way the MS6 is able to control a hydraulically actuated solenoid with built-in functions. To set this up, many inputs are defined by the user such as oil pressure, number of camshafts actuated, and cam gear size and then the user fine tunes a PID controller within the ECU to reach cam timing targets. These cam timing targets, which we have found using GT-Power are input as degrees from nominal based on engine speed and throttle position. Because our project is for a racing application we focused on the wide open throttle portion of the map and at timing increments of 200 RPM according to our requirements and specifications.

Engineering Analysis

Camshaft Stress Analysis

As we are replacing the existing camshaft gear with a new part, we wanted to ensure that we fully understand the torques and stresses that are experienced by the camshaft. Camshaft torque can be calculated based on the equations shown below.

$$T = (J_C + My'^{2})\alpha'' + My'y''\alpha^{2} + ky''(y - x) + y'(y'\alpha' - x')$$

Eq. 1

J_C = Camshaft Moment of Inertia (Kg×m^2)
α = Camshaft Angular Displacement (Rad)
M = Mass of the valve (Kg)
y = Vertical displacement of valve 1 (m)
x = Vertical displacement of valve 2 (m)

The camshaft's moment of inertia was found using the CAD of the MRacing camshaft, the mass of the valve is a known value for the Honda engine. The vertical displacement x and y are functions of the angular displacement of the engine, and the valves lift, which is a known value. We assume worst case scenarios for the angular velocity and acceleration of the engine, and then solve for the camshaft torque. Camshaft torque plotted versus its angular displacement can be seen in Figure 20 (p. 20).

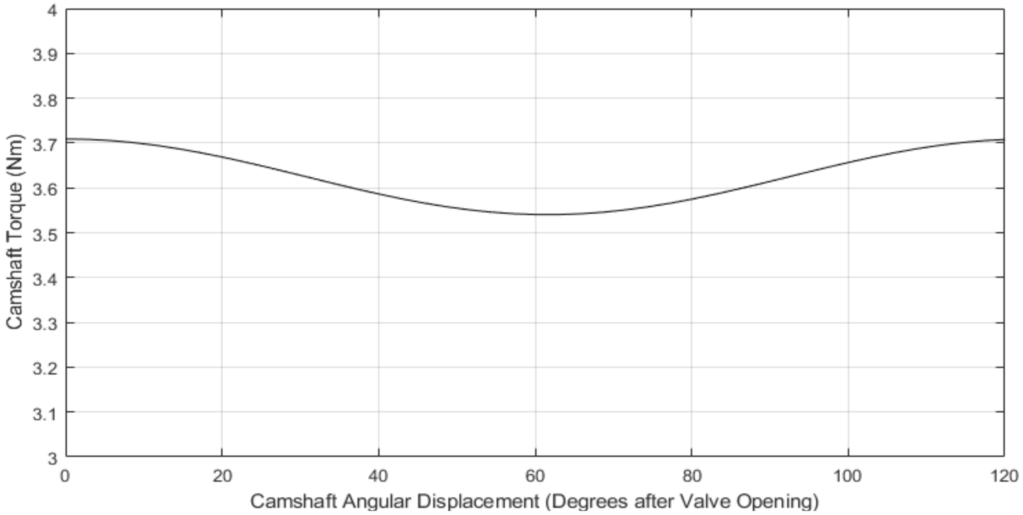


Figure 20: Camshaft torque plotted versus angular displacement after valve opening.

The equations for camshaft torque were obtained from a research paper[16] into electronic control of cam phasers. In the paper the researchers were measuring torque from a DOHC 4-Cylinder engine very similar to the MRacing engine, so it could be assumed that the equations would hold true when used in our situation. The researchers validated the equations by driving the camshaft assembly with a large electric motor through a torque sensor. MRacing does not have access to the equipment that would be necessary to accurately measure the true torque experienced by the camshaft during operation. Therefore, these equations are the best estimate we have available at estimating the torque for our other calculations.

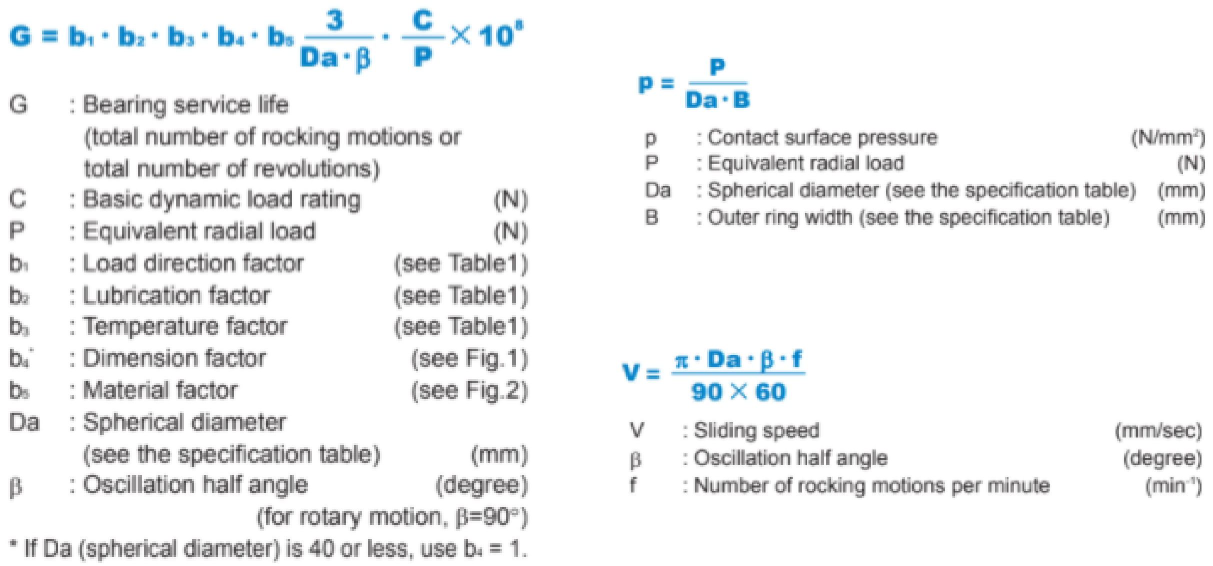
After obtaining the maximum amount of torque that the engine places on the camshaft, we were able to do stress calculations on the dowel pins that attach our new part to the camshaft. These calculations were fairly straightforward, and involved using moment arm equations to calculate the force on the dowels based on the maximum camshaft torque. These forces are in shear, and the dowel supplier provides a maximum shear force that the dowel can tolerate. As can be seen from Table 2 below, the safety margins on the dowel stress are above 40, and are not a cause for concern at all.

Table 2: Dowel Stress Analysis

Dowel Stress Analysis	
Dowel Ultimate Shear Force [lb]	2600
Camshaft Torque [N-m]	3.7
Camshaft Torque [lb-in]	33
Dowel Distance-to-Center [in]	0.26
Dowel Shear Force [lb]	63
Margin of Safety	**41**

Bearing Selection and Life Analysis

Using a hydraulically actuated cam phaser presented the unique problem of getting oil pressure from the engine into the rotation cam phaser. We solved this problem by using spherical plain bearings with oil passageways to transmit oil from the solenoid to the rotating phaser, however we needed to ensure that the bearings would survive the rotational speeds of the phaser. Using equations provided by the bearing manufacturer, we were able to determine that the bearing would survive to approximately 2.3 x 10^{11} revolutions at an operating condition of 6000 RPM, the worst case scenario for the camshaft. This exceeds the durability requirement set by MRacing of a lifetime of 1,700,000 revolutions.



$$G = b_1 \cdot b_2 \cdot b_3 \cdot b_4 \cdot b_5 \frac{3}{Da \cdot \beta} \cdot \frac{C}{P} \times 10^6$$

G	: Bearing service life (total number of rocking motions or total number of revolutions)	
C	: Basic dynamic load rating	(N)
P	: Equivalent radial load	(N)
b_1	: Load direction factor	(see Table1)
b_2	: Lubrication factor	(see Table1)
b_3	: Temperature factor	(see Table1)
b_4^*	: Dimension factor	(see Fig.1)
b_5	: Material factor	(see Fig.2)
Da	: Spherical diameter (see the specification table)	(mm)
β	: Oscillation half angle	(degree) (for rotary motion, β=90°)

* If Da (spherical diameter) is 40 or less, use $b_4 = 1$.

$$p = \frac{P}{Da \cdot B}$$

p	: Contact surface pressure	(N/mm^2)
P	: Equivalent radial load	(N)
Da	: Spherical diameter (see the specification table)	(mm)
B	: Outer ring width (see the specification table)	(mm)

$$V = \frac{\pi \cdot Da \cdot \beta \cdot f}{90 \times 60}$$

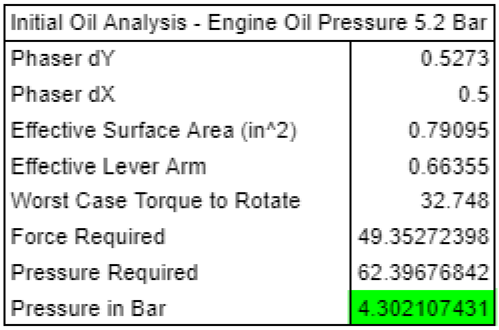
V	: Sliding speed	(mm/sec)
β	: Oscillation half angle	(degree)
f	: Number of rocking motions per minute	(min^{-1})

Figure 21: Bearing Life Equations

Oil Analysis

Our final cam phaser design solution relies on oil pressure in the phaser in order to rotate the phaser and adjust cam timing. Thus we must ensure that MRacing's engine oil pump is capable of creating adequate oil pressure for the design. Oil flow and pressure through an engine is determined by the oil pump, and the passageways that the oil passes through. Oil pressure specifically is built by the restrictions of flow that the small oil passageways create. The phaser is essentially the ultimate restriction to flow. It will build oil pressure in the chambers until the pressure is enough for the phaser to rotate. As long as the oil pump is capable of generating enough pressure to rotate the phaser, the phaser should operate correctly. Using the maximum torque the phaser would experience, and making some calculations about the phaser's inner area, we can calculate the oil pressure necessary to rotate the phaser, these calculations can be seen in Table 3 (p. 29). This pressure comes about to around 4.3 bar of pressure, significantly less than the 5.2 bar of pressure the oil pump is already generating at operating conditions. Thus, assuming no leakage in the phaser assembly, the oil pump will have the pressure to rotate the phaser.

Table 3: Oil Pressure Analysis



Initial Oil Analysis - Engine Oil Pressure 5.2 Bar	
Phaser dY	0.5273
Phaser dX	0.5
Effective Surface Area (in^2)	0.79095
Effective Lever Arm	0.66355
Worst Case Torque to Rotate	32.748
Force Required	49.35272398
Pressure Required	62.39676842
Pressure in Bar	🟩 4.302107431

Manufacturing

Because of the complex geometry of our mechanism, designing for manufacturability was an important aspect of our project. When machining such a complex shape from billet it is important to consider how many work holdings and operations will be needed to complete the manufacturing. Manufacturing for our final design solution was done using a horizontal bandsaw, horizontal lathe, and a Haas CNC VF2 vertical mill with 4-axis attachment. To make the inner rotor of the mechanism, the first step in the process was using a bandsaw to cut a ⌀2.5 in. extruded aluminum stock to length. That stock was then turned down to the largest OD using the horizontal lathe followed by turning the smaller OD to length. Next, the part was secured in the 4th axis attachment of the VF2 where the grooving operations. peripheral pockets, and peripheral holes were machined. A photo of the toolpath used for the peripheral packets is show in Figure 22 (p. 30), below:

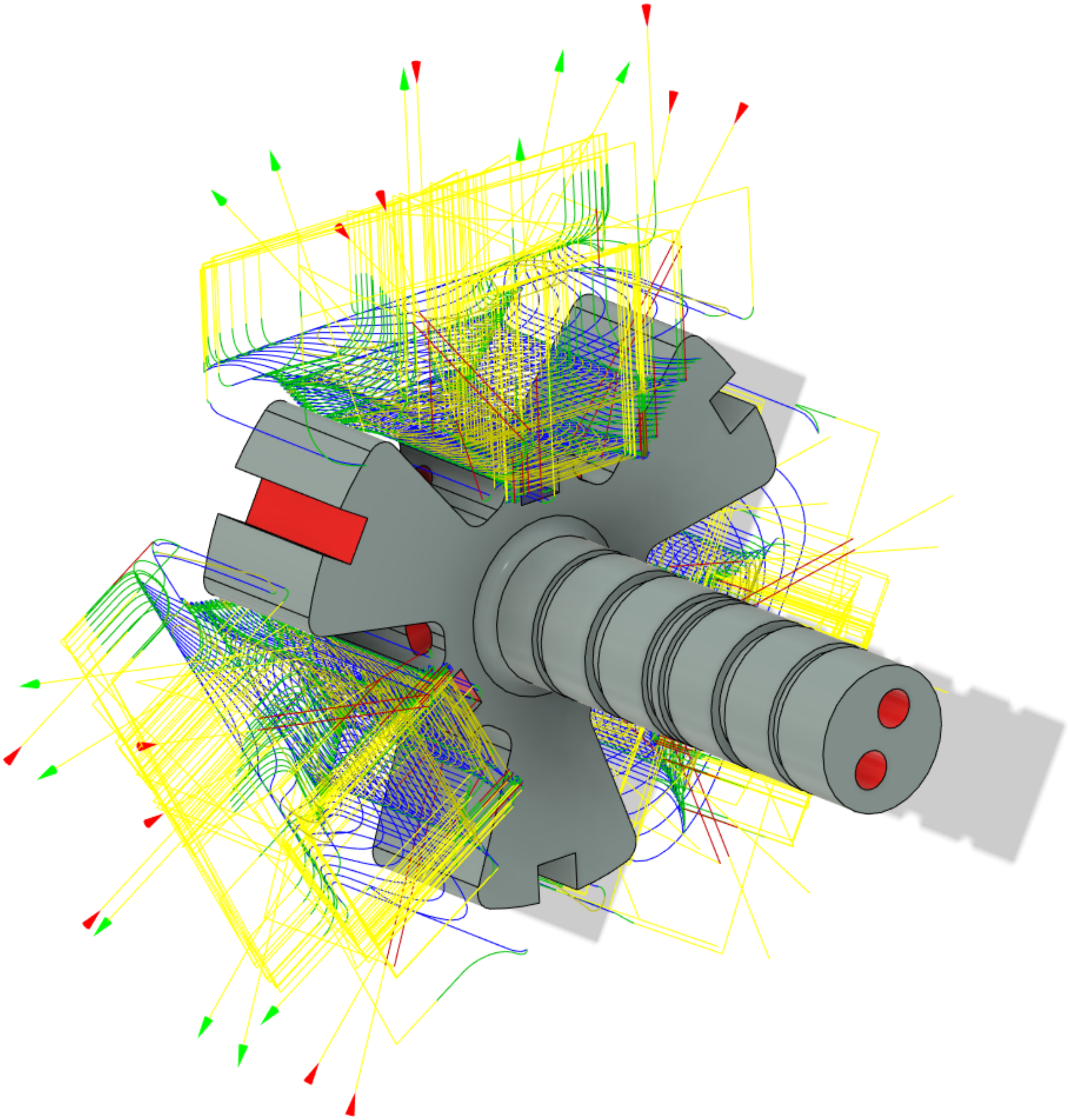
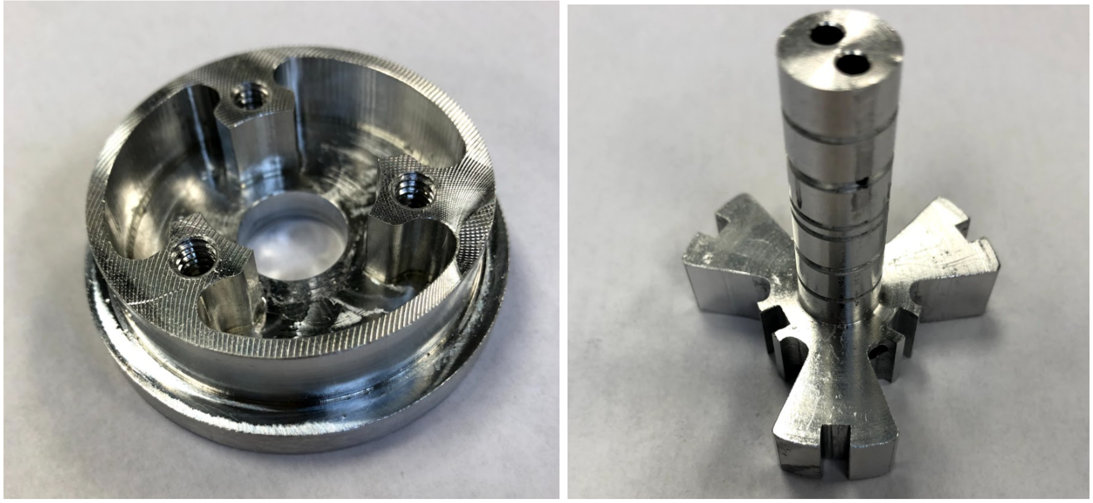


Figure 22: Toolpath for 4th axis pocket machining designed in Fusion 360.

After these operations were complete, the part was secured vertically in the mill and the vertical drilling operations were performed. Finally, the part was flipped 180°, faced, and slotted. This amounted to a total of 4 workholding setups. This would normally be a lot for a mass-produced part, but was more than acceptable for a prototype. After this, the outer rotor and adapter plate were machined with two vertical workholdings each on the VF2 and the cover plate was cut from polycarbonate. Pictures of the finalized part are shown in the figure 23 and 24 (p.31) below.



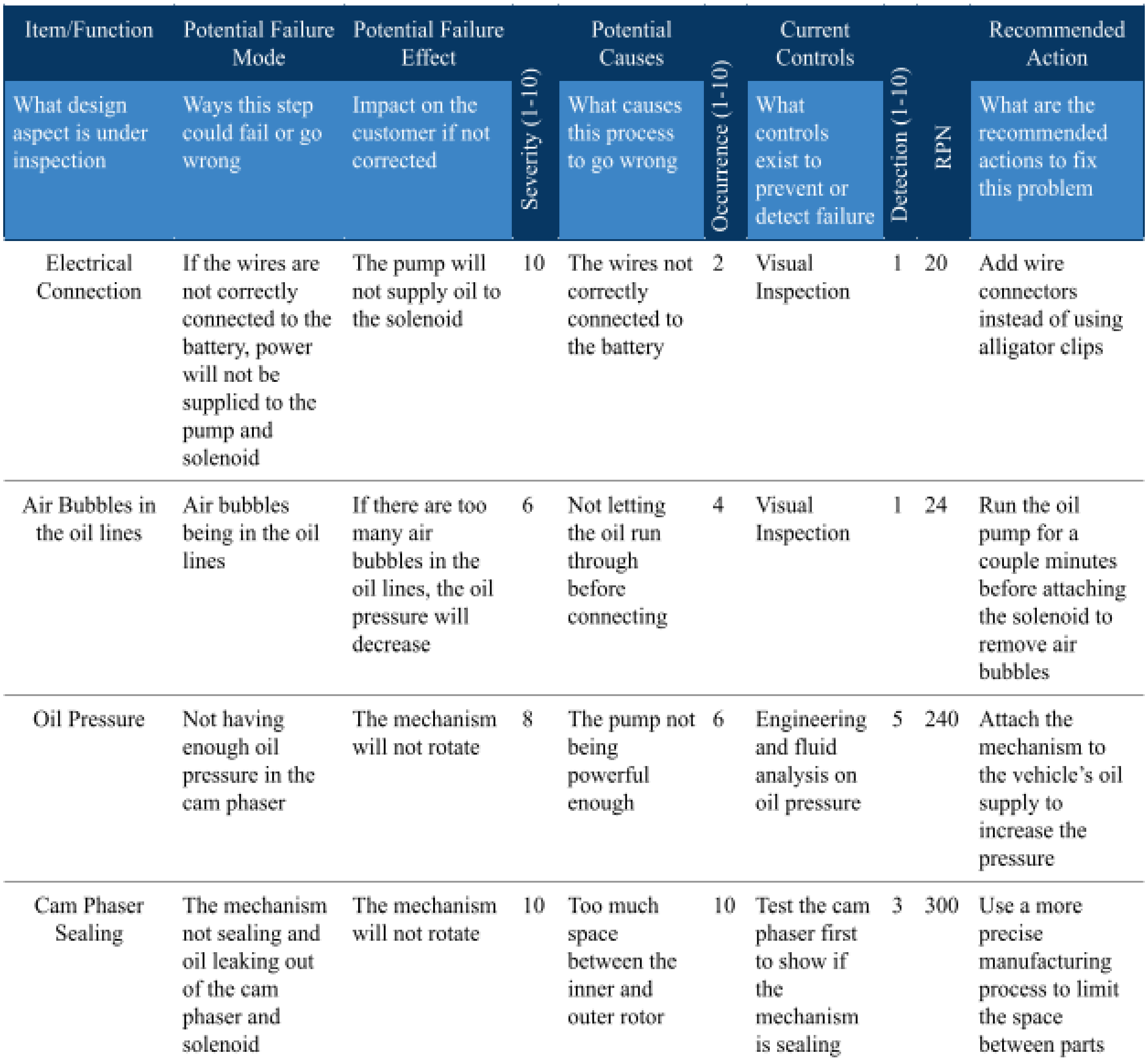
Figures 23 and 24: Machined inner and outer rotors.

The other components of the cam phaser were manufactured in parallel with the inner and outer rotor and the coupling plate. Specifically, the phaser seals were routed out of an acrylic sheet. Additionally, the rotor closeout was waterjet out of a polycarbonate sheet to allow for inspection during operation. After all components were manufactured, the cam phaser was then assembled onto a camshaft as shown below in Figure 25.

Figure 25: Assembled cam phaser

Risk Assessment

For our team to analyze the risks associated with our design and decrease potential errors within the device, we conducted a risk assessment using a Failure Modes and Effect Analysis. FMEA is a process used to find the different ways or modes an idea, product or design may fail. A failure is any effect or defect from the mechanism that impacts the overall performance. The ‘effect analysis’ is a way of studying the consequences of each possible failure. Each potential failure of our design was prioritized based on how serious the consequences, how frequently they occurred, and how easily they can be detected. Our FMEA helped us decide what the problems in our design were, and how to prioritize them.



Item/Function	Potential Failure Mode	Potential Failure Effect	Severity (1-10)	Potential Causes	Occurrence (1-10)	Current Controls	Detection (1-10)	RPN	Recommended Action
What design aspect is under inspection	Ways this step could fail or go wrong	Impact on the customer if not corrected		What causes this process to go wrong		What controls exist to prevent or detect failure			What are the recommended actions to fix this problem
Electrical Connection	If the wires are not correctly connected to the battery, power will not be supplied to the pump and solenoid	The pump will not supply oil to the solenoid	10	The wires not correctly connected to the battery	2	Visual Inspection	1	20	Add wire connectors instead of using alligator clips
Air Bubbles in the oil lines	Air bubbles being in the oil lines	If there are too many air bubbles in the oil lines, the oil pressure will decrease	6	Not letting the oil run through before connecting	4	Visual Inspection	1	24	Run the oil pump for a couple minutes before attaching the solenoid to remove air bubbles
Oil Pressure	Not having enough oil pressure in the cam phaser	The mechanism will not rotate	8	The pump not being powerful enough	6	Engineering and fluid analysis on oil pressure	5	240	Attach the mechanism to the vehicle's oil supply to increase the pressure
Cam Phaser Sealing	The mechanism not sealing and oil leaking out of the cam phaser and solenoid	The mechanism will not rotate	10	Too much space between the inner and outer rotor	10	Test the cam phaser first to show if the mechanism is sealing	3	300	Use a more precise manufacturing process to limit the space between parts

Figure 26: FMEA table

Verification

Before the manufacturing process even began, we used GT-Power simulations to find the ideal valve timings for the phaser, and confirmed that variable valve timing would give us the torque increases we were looking for. After successfully manufacturing the cam phaser, we were able to verify that the system would be capable of varying timing by 16 degrees. This was done simply by using a sharpie to mark the system at its minimum timing, and rotating to its maximum timing, and confirming the timing change with a protractor. All of the machining was completed using the 4th axis mill and CNC lathe at the wilson center. Given a completed assembly, it was fairly simple to validate the mass requirement, by simply weighing all of the different components. The total weight came out to 2.2 pounds, however this is only for one cam phaser assembly, two would be necessary for varying both the intake and exhaust camshafts. Thus, the total weight of our system would be 4.4 pounds. This comes in under our weight target of 5.5 pounds, but is slightly higher than the CAD predicted 3 pounds. This is likely due to the weight of the oil lines, as well as the slightly different method of attaching the oil lines to the phaser and solenoid. Due to the risk involved in running the phaser on an actual running engine, we used a 12 volt oil pump to attempt to validate the rest of our requirements, this setup can be seen in figure 26 (p. 32) below. When using the oil pump to pump oil into our phaser, we discovered various leakage issues with our current design. These issues are addressed further in the Discussion and Recommendations section, as well as our recommendations on how to address the packaging issues. However, these issues were unable to be resolved by the end of the semester, and therefore we were unable to verify our packaging requirements, as well as the requirement to have the phaser continuously vary valve timing.

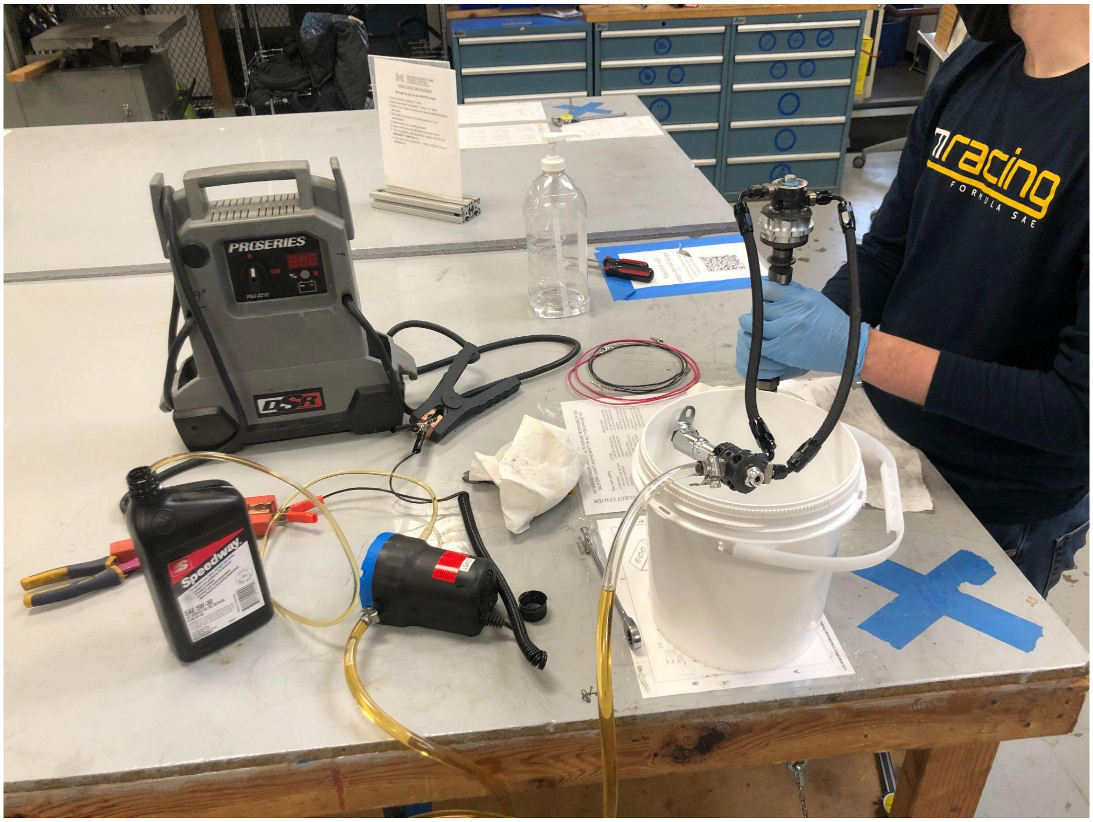


Figure 27: Cam Phaser Verification Setup.

Discussion and Recommendations

Lessons Learned

Creating a VVT mechanism to retrofit to an existing engine system involves complex problems in fluid mechanics, structures, size and weight constraints, and machining. While solving these issues our team learned a great deal about internal combustion engine design, especially regarding the valvetrains of these systems. The key lessons learned throughout this process were regarding the limitations of small engine packaging, the complexity of powertrain controls, and understanding oil sealing.

The CBR600RR engine MRacing uses is very small compared to standard automotive engines. At 600CC of displacement, most components are less than half the size of a 2,000CC small car engine. The camshafts and phasers are no exception to this and created a large challenge for our team. Not only was it difficult to design phasers small enough to fit axially within the engine head with the proper sized gears, but it was also very hard to design the oil passageways and connections in a way that was small enough but also manufacturable. One thing we learned is that typical automotive setups of this nature take oil supply from passages within the camshaft and are fed oil through journal bearings. Having something like this would eliminate the need for the protruding shaft in our design and the clunky shaft collars and bearings used to feed oil into the system from the outside. It would also eliminate the oil lines which would save weight. Designing an entire camshaft and possibly engine head for the purpose of VVT would be a much larger project, but would also open avenues for advanced exhaust and turbocharger design.

Powertrain controls were not the main focus of our project project, but through it we learned a lot about their importance and necessity in implementing a system like this in our engine. To do this project properly and in its entirety we would need to spend much more time focusing on the function of the ECU within this system and fine tuning it to our specifications. I truly believe that we did not have the time or resources to explore this aspect during one semester, but nevertheless it would be something that we do a great deal of work on during the validation process of this project.

The final major lesson learned is regarding oil sealing. This aspect of the design was admittedly made second to other aspects such as manufacturability and passageway logic. Sealing in an engine is obviously very important as leaking oil is an environmental hazard, makes a mess, will eventually cause damage to your engine, and in our case ruins functionality of a pressurized system. Focusing on the design of gaskets or an extremely high tolerance ground surface may have increased the chances of smooth operation as compared to the liquid gasket we used. This would also be an important thing to do prior to using our VVT during competition as oil leaks are ground for disqualification.

Next Steps

There are several steps that must be taken to improve the design to meet the system requirements. The two biggest areas of concern during validation was the oil supply and oil seals. These two issues really work hand in hand as addressing one will help improve the other. If steps are taken to sufficiently address these two areas, we believe that a functional variable valve timing solution could be reached.

The first step in addressing these two areas of concern would be performing a higher fidelity oil analysis. The oil analysis performed for our design relied on many assumptions that did not fully describe the test environment. Additionally, many of the oil flowing orifices on the cam phaser were sized using the pre-existing oil passage oils on the engine head as examples. The best way to analyze the oil supply to the cam phaser would likely be a computational fluid dynamics (CFD) analysis. Using the existing cam phaser design as a baseline, you could simulate the oil flow paths. This would allow a better understanding of the pressure distributions along the oil passages in the inner rotor. Perhaps there were blockages that built up pressure and compounded the sealing issues. Performing a CFD analysis would help identify these issues and allow them to be properly addressed.

The next step, and one that could likely be performed in parallel, would be a redesign of the oil supply hardware and fittings. One of the most difficult parts of the design was figuring how to supply oil to the phaser. However, we believe these concerns can be addressed with proper research and design effort. The first step involved with this would be obtaining or designing some sort of relative motion fitting. We investigated some off the shelf relative motion fittings, but they could not meet the speed requirements. Perhaps there are other fittings that could address this concern or a novel solution could be developed. The second step with this would be supplying oil from the solenoid to the phaser itself. You must purchase or design new fittings to place on the solenoid as our implementation was non-optimal.

The last step in addressing these concerns and likely the most significant in development time would be how to adequately seal the phaser. As previously mentioned, our design was able to supply the chambers in the phaser. However, the seals were not adequate enough to withstand the pressure needed to turn the inner rotor. The first step in doing this would be performing some more research. Since a standard o-ring would not work well under relative motion, you must find a solution that can hold a pressure seal while still allowing for relative motion. After doing this and finding a more adequate solution, we would suggest developing a sealing test bench to help quickly iterate on the design without going through the laborious manufacturing process. A simple sealing test bench that can roughly replicate the different interfaces and pressures seen during operation could greatly help in building confidence in a design prior to fully manufacturing it.

On top of the improvements to the existing design, there are two more big action items that are necessary for engine testing. The first item is designing an enclosure for the engine head to address the interference issues. Although this could be mitigated with a redesign, the current design clashes with the side of the engine head. As a result, you must design a closeout that can be welded on to the side of the engine head to provide more clearance for the system during operation. The second outstanding item is addressing the control aspect of the VVT solenoid. This can be addressed by either removing the paywall on the Bosch ECU or designing a simple PWM controller to modulate the solenoid.

Engineering Standards

Since our project is to be used in the Formula SAE competition, our team followed the SAE rules and guidelines along with the fundamentals and common practices from industry and machine shops. According to FSAE, exposed high speed final drivetrain equipment such as sprockets, gears, pulleys must be fitted with scatter shields intended to contain drivetrain parts in case of failure. Hence, one of the initial aspects of our design was to determine the size of the whole mechanism so its dimensions would be within the constraints of the scatter shield and the engine head.

Our concept exploration and selection stages heavily relied on industry standards for various VVT systems available in the industry as creating our own design for continuously varying the valve timing was outside the scope of this project. The material selection process was also influenced by industry standards which helped determine what material would be the most feasible to use.
Our team also strictly adhered to the Wilson Center's safety standards and protocols such as wearing safety glasses when working with any equipment, and monitoring material feed speeds to protect the tool. Due to the ongoing pandemic, our team also adhered to the COVID-19 safety protocol which consisted of weekly COVID-19 tests and completing the ResponsiBLUE screening check prior to entering the lab.

Engineering Inclusivity

Stakeholder Interaction - Our stakeholders (MRacing) gave us a lot of freedom for our design process with the only constraints being cost and durability which have been specified in our requirements and specifications. This gave us a lot of room during the concept generation and selection phases. However, aware of the importance of actively engaging stakeholders, our team shares our progress with MRacing on a weekly basis to rule out any issues or concerns. After going through the Engineering Inclusivity learning block, we realized that we could have made our design process more inclusive. Previously, two of our team members who are also currently on the MRacing team, would meet with our stakeholders during their regular weekly MRacing meetings to discuss our progress. However, to make our design more inclusive, we realized that having the entire team present during stakeholder meetings would have been a much more effective and inclusive method of communication.

Social Identities within the team - Our team consists of two MRacing members, one previous MRacing member and two members with no MRacing experience or background at all. Having this diversity really helped shape our team dynamic as throughout our design process all of our concepts and suggestions were from different perspectives. This helped our team take a diverse path to finding our design solution. For example, having a team that only consisted of MRacing team members, would have led to having suggestions and ideas not very different from each other which could have constrained our design process within a MRacing bubble. At the same time, a team that consisted of no MRacing members, would lack any experience of working with MRacing and also lack a lot of in-depth knowledge about the car and engine (such as, ECU compatibility, Engine capacity and speed range limits etc.) which would have made the design process a lot of more harder, tedious and exclusive. Although there is not a specific example of how our team with mixed MRacing experience impacted the outcome differently than a team with only MRacing members would have, the majority of the decisions (such as, concept selection, material selection etc) were taken unanimously by the team with everyone voicing their opinions on these decisions. However, one decision that we think was driven by the MRacing team members was determining the intricate details of the inner rotor. This is because the part was manufactured using a Haas CNC VF2 vertical mill with 4-axis attachment which the MRacing team members have been working on for the past 3 years. Hence, due to their knowledge of what exactly the machine can or can not do, this decision was taken by them. One way that we think we could approach this differently in the future is to make sure that even the non-MRacing team members familiarize themselves with the working of the CNC mill so that they can also have a better understanding of what the machine is capable of doing and hence they can too be involved in decisions regarding the intricate details of such manufacturing parts.

Environmental Context Assessment

In order to “meet the needs of the present without compromising the ability of future generations,” our team needs to consider the environmental, social, and economic factors our mechanism will have on society. Our team was able to determine how sustainable our mechanism is by asking two questions that need to be answered favorably to be considered sustainable.

The first question is “Does the system make significant progress towards an unmet and important environmental or social challenge?” The answer to this question is, Yes. Implementing variable valve timing directly contributes to lowering vehicle emissions. EGR (Exhaust Gas Recirculation) is a technique to reduce emissions and improve fuel efficiency. Through VVT, exhaust gas recirculation is done when the vehicle is running at low or medium speeds. Since the exhaust valves do not close until the intake valves have been open for a while, some of the exhaust gas is recirculated back into the cylinder at the same time as the new fuel and air is injected. When the fuel and air mixture is replaced by exhaust gases, less fuel is needed. The exhaust gas contains mostly non-combustible gas, such as CO2, so the engine runs properly at the leaner fuel and air mixture without failing to combust. On average, implementation of VVT systems reduces fuel consumption by 6% and maintains the combustion temperature below 2500 ^{o} F, which reduces NO_x emissions by 40% [18]. Over a 10 year span, variable valve timing can save the vehicle owner between $120 to $1,680 and carbon dioxide emissions by 280 to 3,860 kg [19]. This is equivalent to three quarters of an olympic sized swimming pool of Carbon Dioxide. Variable valve timing is able to meet both unmet environmental and economic challenges.

The next question we need to answer is “Is there potential for the system to lead to undesirable consequences in its lifecycle that overshadow the environmental/social benefits?” A VVT mechanism does have the potential to have undesirable consequences during its life cycle. A lack of regular oil change can drastically affect the efficiency and life of the VVT system. In such cases the VVT solenoid can malfunction, compromising the entire system, which may result in intake and exhaust valves opening and closing at the wrong time. This causes the fuel economy to drastically reduce and overshadow the environmental benefits. We also need to consider the environmental, life cycle assessment of the mechanism. The mechanism is relatively small and will require a very small amount of energy to completely manufacture and assemble. During its use cycle, it will use the oil that is currently being cycled through the engine. At the end of the VVT’s life cycle, it will need to be recycled. We are currently estimating that the mechanism will require 0.25 lbs of steel and 2.75 pounds of aluminum. It currently takes 95% less energy to recycle aluminum and steel than it does to make it from raw materials [20]. While the VVT does have environmental and economic challenges like the energy and cost to manufacture, assemble, and recycle, we plan that the money and emissions saved from the VVT will outweigh the negatives.

Social Context Assessment

Our team followed the Social Context Assessment learning block guidelines to evaluate and assess the social impact of our project. The three main points have been addressed below:

Is the system likely to be adopted and self sustaining in the market?: Although our project was made with the intention of being used only in the MRacing car, VVT systems in general have already been adopted and are self sustaining in the market. Most of the components used can be recycled while the toxic materials have to be properly neutralized. VVT systems are very engine specific as different factors such as size, type of VVT system (cam phaser, free valve etc.), and cost heavily rely on the type of engine in use. Hence, as our prototype was made using the available resources and making modifications to the already existing drivetrain, it is difficult to analyze if our particular product can be mass produced and be self sustaining in the market.

Is the system so likely to succeed economically that planetary or social systems will be worse off?: Variable Valve Timing mechanisms, most common being the cam phaser type, are present in almost every internal combustion engine car made in recent years. Although our team's main intention behind implementing the VVT mechanism was to increase the performance of the engine, VVT systems are also used to create more fuel-efficient cars. This has helped bring down the pollution caused by cars all over the world and at the same time has not significantly increased the price of cars making them still affordable to the general public. Considering these factors, it is very unlikely that planetary or social systems will be worse off due to the economic success of our product.

Is the sustainable technology resilient to disruptions in business as usual?: The cam phaser type VVT mechanism that has been adopted by our team in our design has seen some strong competition from the newer inventions and methods to regulate valve timing such as the free valve systems consisting of pneumatic valve actuation and electric valve actuation. Despite these strong competitors, cam-phaser type is still the most dominantly used form of VVT mechanism thanks to its lower cost and easy maintenance. However, this technology is not perfectly resilient. With the recent growing trend in EV cars and the billions of dollars spent by automakers to focus their production on electric cars, over the course of the next few years, internal combustion car engines, and hence VVT mechanisms, are likely to lose their throne to the less polluting and greener alternative which disposes the need for varying the valve time.

Ethical Decision Making

Engineering ethics was one of the most important design aspects our team needed to consider during our 450 design project. Our team completed this project by following the three fundamental principles of ASME's Engineering Code of Ethics.

The first fundamental principle is "Engineers shall use their knowledge and skill for the enhancement of human welfare." Our project aimed to make the MRacing engine more efficient and produce better results during their competitions. Although our mechanism was specifically designed for a project team, the work we did can be directly applied to vehicles used for every-day transportation. A variable valve timing mechanism can make your car more efficient, get better gas mileage, and produce more power. This can save the user money on gas, as well as contribute less in global pollution.

The second fundamental principle is "Engineers shall be honest and impartial, and serve with fidelity the public, their employers and clients." All the data that we documented within this report and previous reports is accurate and truthful. We reported all the successes and failures of our mechanism and did not alter data in order to meet our initial requirements and specifications. An important part of our project this semester was to provide the groundwork for a VVT mechanism for potential future MRacing members that may want to continue on our work. If we were to provide incorrect information, this would hurt any future design projects.

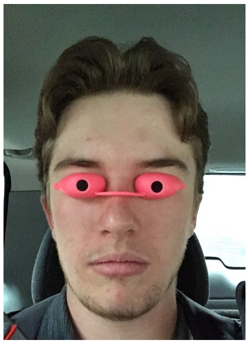
The third fundamental principle is “Engineers shall strive to increase the competence and prestige of the engineering profession.” Throughout this entire class and project, all of our team members learned more about the entire field of engineering. Members that were not previously on MRacing learned about how variable valve timing worked and how we could use it to increase the performance of the competition vehicle. Current MRacing members learned how to use MRacing techniques to test and verify the design. Every team member became more knowledgeable about researching a problem, creating possible solutions, choosing a final design, and manufacturing and testing that design. While this project helped our team learn about VVT and become better engineers, we also hope it can help others learn about our project. We focused on documenting both the successes and failures during our project with hopes that others can build on the successes and eliminate the failures.

The biggest ethical decision we approached during our project was the following: What should we do with the final outcomes of our project? Because we were not able to achieve the exact movements we hoped to from our mechanism, we were not able to equip the current engine with VVT. It is crucial in engineering that you do not release a product or idea that is unsuccessful and does not meet requirements and specifications. Instead, our team focussed on providing all our information so other MRacing members can utilize the information and progress.

Conclusion

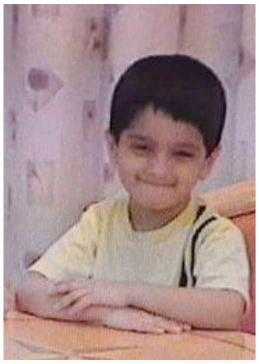
Our team has completed the development of an initial variable valve timing solution for MRacing’s Honda CBR600RR engine. Our solution did not meet all of MRacing’s requirements for the valve timing system, but it served as an adequate proof of concept and baseline to aid future development. We started development by performing research into valve timing in order to ground ourselves in our future development. We then constructed a comprehensive set of engineering specifications for packaging, weight, controllability, reliability, and functionality based upon the requirements of the MRacing team. The resulting specifications were then used to inform the concept selection as we explored the variable valve timing solution space. A hydraulic cam phaser was selected to best address the requirements of the variable valve timing system. A cam phaser solution was then designed and modeled to work with the CBR600RR engine. Preliminary validation was then conducted using CAD and hand calculations. The cam phaser was then machined and assembled to verify the system requirements. The system was not fully functional but showed promise with future development. Future steps are proposed to mitigate the issues that arose during our initial development.

About The Authors



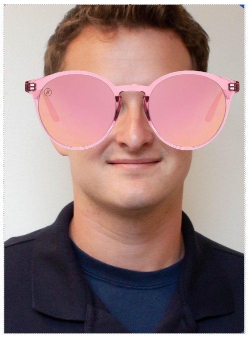
Jared Dirksen (formally known as “Gary”) is a senior from Portage, Michigan. Jared is the team captain at MRacing where his primary responsibilities include being the butt of the joke and wasting precious money. This Summer Jared plans to intern at Tesla in California where duties will be mining BTC and frequently checking Twitter. While not doing MRacing, Jared enjoys playing table tennis, watching cartoons, and gambling on the NYSE.

Jacob Thayer is a senior in Mechanical Engineering from Woodhaven, Michigan. He is the chassis director for the MRacing team. After graduation, he will be working as a body in white design engineer at Tesla where he looks to render his ME 450 project obsolete. In his free time, he enjoys watching sports, formatting, and buying silver children’s sunglasses at dollar stores in suburban Canada.



Malay Arya is a senior in Mechanical Engineering. Originally from Delhi, India, he spent his entire childhood in the Middle East (Qatar and Oman) before coming to Ann Arbor for his undergrad. He is not a member of the MRacing team but ‘claims’ to be a car enthusiast and the fastest in town at go-karting. In his free time he likes playing the guitar but most importantly he looks for jobs because he is currently jobless.

Chad Peterson is a senior in Mechanical Engineering from Houghton Lake, Michigan. After graduation, he will be moving to Hawaii to work as a project engineer for a Civil Engineering firm. He is a member of Students for Clean Energy and StartUM. In his free time, he enjoys small town, northern Michigan hobbies like fishing, snowboarding, and trying to get his 89 bronco to start.



Blake Schoof is a senior in Mechanical Engineering from Chelsea, Michigan. He is not a current member of MRacing. Enjoys running, mountain biking and taking dogecoin to the moon. His current summer plans include testing autonomous vehicles for the American Center for Mobility and golfing.

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Heather Cooper	*ME450 Section Instructor*
A. Harvey Bell IV	*MDP Professor; MRacing Faculty Advisor*
Luca Ranzani	*Undergraduate Student, ME Major; MRacing CNC Mill Operator*
Caleb Velzen	*Undergraduate Student, AE Major; MRacing Router Operator*

Citations

[1] John B. Heywood. Internal Combustion Engine Fundamentals, Second Edition. FLOW THROUGH VALVES AND PORTS, Chapter (McGraw-Hill Education: New York, Chicago, San Francisco, Athens, London, Madrid, Mexico City, Milan, New Delhi, Singapore, Sydney, Toronto, 2018).

[2]Kitchen, K. (2016, October 19). Spooling up - tuning dohc variable valve timing for boost. Retrieved February 08, 2021, from https://www.enginelabs.com/news/spooling-up-tuning-dohc-variable-valve-timing-for-boost/

[3] The facets of variable valve timing. (2017, November 9). In Autodata. Retrieved from https://www.autodata-group.com/baltics/news/industry/facets-variable-valve-timing/

[4] Hong, H, Parvate-Patil, G B, and Gordon, B. Review and analysis of variable valve timing strategies - eight ways to approach. United Kingdom: N. p., 2004. Web.

[5] Ghazal, O. H., & Dado, M. S. (2013). Gear drive mechanism for continuous variable valve timing of ic engines. Gear Drive Mechanism for Continuous Variable Valve Timing of IC Engines, 05(03), 245-250. doi:10.4236/eng.2013.53035. Retrieved from https://www.tomorrowstechnician.com/variable-valve-timing-import-vehicles/

[6] Carley, L., Becker, M., Lutz, J., & Staff, T. (2016, August 02). Variable valve timing on import vehicles. Retrieved February 03, 2021, from https://www.tomorrowstechnician.com/variable-valve-timing-import-vehicles/

[7] E. Sher, T. Bar-Kohany, Optimization of variable valve timing for maximizing performance of an unthrottled SI engine—a theoretical study, Energy, Volume 27, Issue 8, 2002, ISSN 0360-5442, https://doi.org/10.1016/S0360-5442(02)00022-1.

[8] M. (n.d.). Variable valve timing (vvt). Retrieved February 28, 2021, from https://www.autobytel.com/car-ownership/variable-valve-timing-vvt-104258/

[9] Freevalve | Camless Engine Technology for Sustainable Engines. (2021, February 2). Freevalve. https://www.freevalve.com/

[10]Colwell, K. C. (2015, August 7). Timing Changes: How Honda’s VTEC Variable-Timing System Works. Car and Driver. https://www.caranddriver.com/news/a15353612/timing-changes-how-hondas-vtec-variable-timing-system-works/

[11]Variable Valve Timing (VVT). (2020). Variable Valve Timing (VVT). https://www.austincc.edu/wkibbe/vvt.htm

[12] Nice, K. (2000, December 13). How camshafts work. Retrieved from https://auto.howstuffworks.com/camshaft.htm#pt2

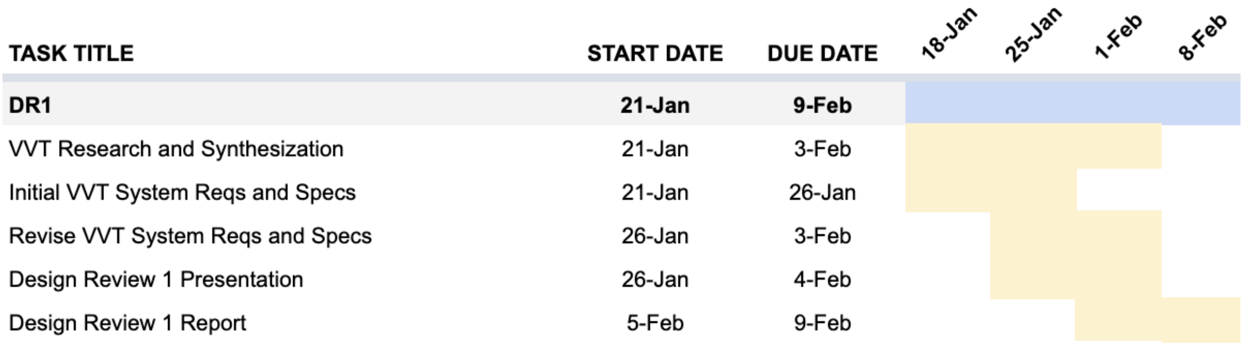
[13] Galt, S. (2006, February 08). Ferrari VVT. Retrieved February 28, 2021, from https://www.physicsforums.com/threads/ferrari-vvt.109476/

[14] = Austin, M. (2020, August 12). Cam-torque actuated variable valve timing system. Retrieved from https://www.caranddriver.com/features/a15127388/cam-torque-actuated-variable-valve-timing-system-feature/

[15] Carley, L. (2019, August 21). Variable valve timing. Retrieved February 23, 2021, from https://www.aa1car.com/library/variable_valve_timing.htm
[16] Lee, S., Baek, SW. A study on the improvement of the cam phase control performance of an electric continuous variable valve timing system using a cycloid reducer and BLDC motor. Microsyst Technol 26, 59–70 (2020). https://doi.org/10.1007/s00542-019-04411-5
[17] https://commons.wikimedia.org/wiki/File:Engine_movingparts.jpg
[18] Chaichan, M. T., Saleh, A. M., & Khudhur, S. H. (august 2015). The Effect of Variable Valve Timing on SIE Performance and Emissions. International Journal of Scientific and Engineering Research.
[19] *Variable valve timing*. (2018, September 4). Government of Canada. https://www.nrcan.gc.ca/energy/efficiency/energy-efficiency-transportation-and-alternative-fuels/choosing-right-vehicle/tips-buying-fuel-efficient-vehicle/factors-affect-fuel-efficiency/variable-valve-timing/21018
[20] “Recycle ▸ The Facts: Aluminum.” *RCU*, 2020, utahrecycles.org/get-the-facts/the-facts-aluminum/#:%7E:text=Recycling%20aluminum%20takes%2095%25%20less,as%20little%20as%2060%20days.

Appendix A

Various figures showing our project plan as it developed through the design reports.



TASK TITLE	START DATE	DUE DATE	18-Jan	25-Jan	1-Feb	8-Feb
DR1	**21-Jan**	**9-Feb**	🟦	🟦	🟦	🟦
VVT Research and Synthesization	21-Jan	3-Feb	🟨	🟨	🟨	
Initial VVT System Reqs and Specs	21-Jan	26-Jan	🟨	🟨		
Revise VVT System Reqs and Specs	26-Jan	3-Feb		🟨	🟨	
Design Review 1 Presentation	26-Jan	4-Feb		🟨	🟨	
Design Review 1 Report	5-Feb	9-Feb			🟨	🟨

Figure: The above figure contains the Gantt chart used to outline the project plan prior to the design review 1 report. The Gantt chart lists different tasks and the timeline for each task.

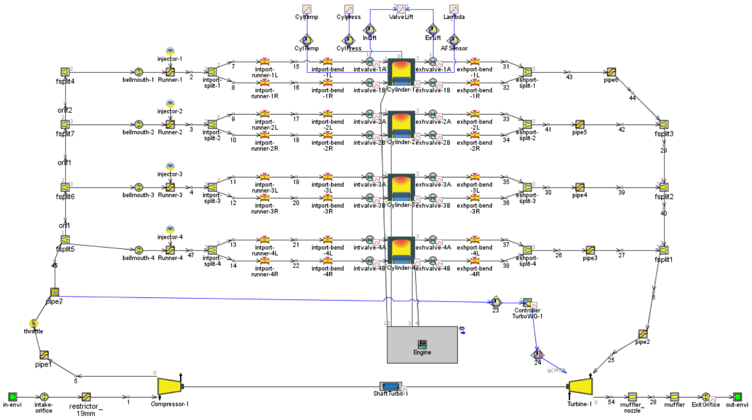
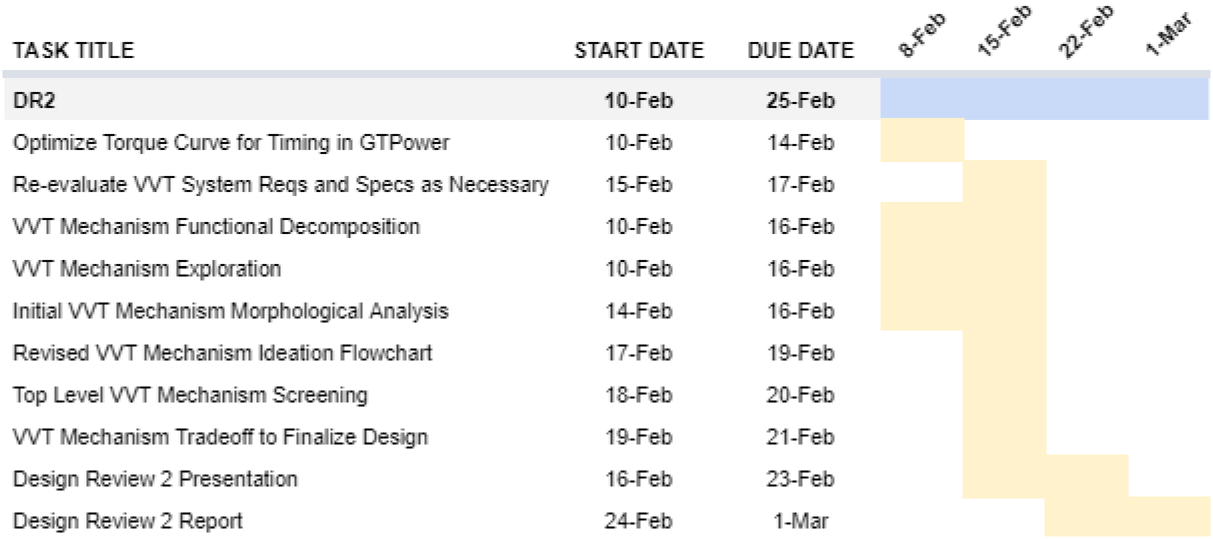
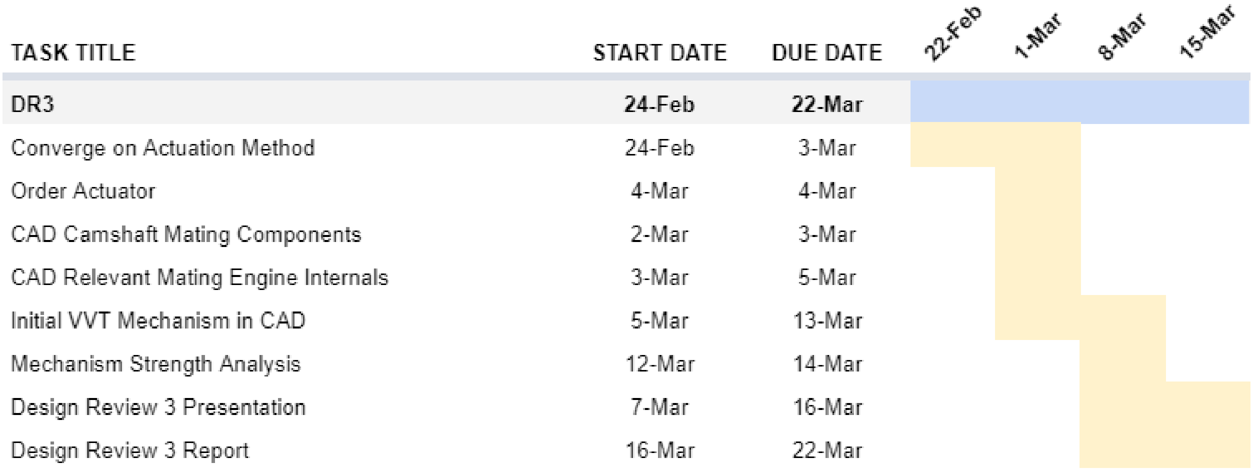


Figure: CBR600RR GT Power engine model.



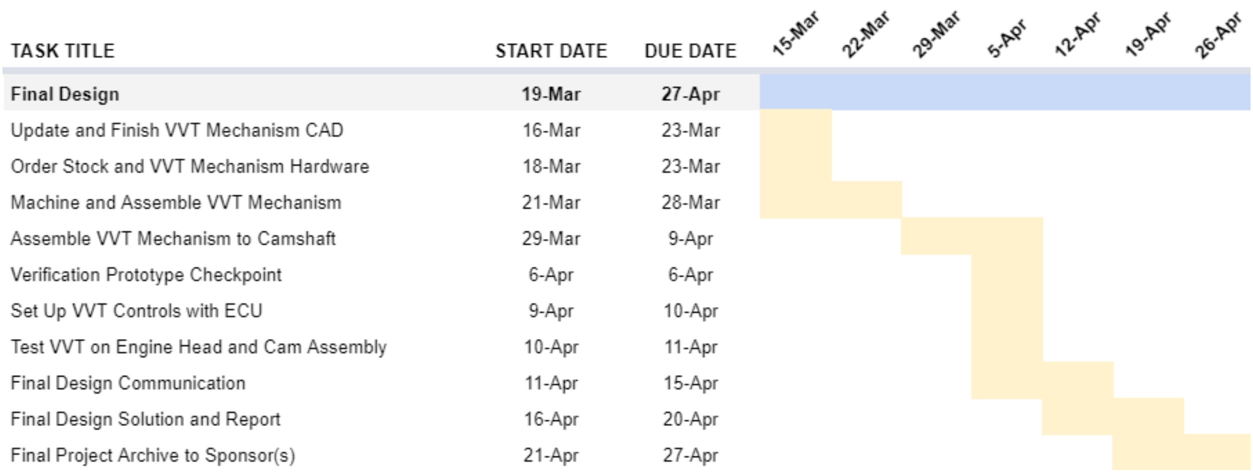
TASK TITLE	START DATE	DUE DATE	8-Feb	15-Feb	22-Feb	1-Mar
DR2	**10-Feb**	**25-Feb**	🟦	🟦	🟦	🟦
Optimize Torque Curve for Timing in GTPower	10-Feb	14-Feb	🟨			
Re-evaluate VVT System Reqs and Specs as Necessary	15-Feb	17-Feb		🟨		
VVT Mechanism Functional Decomposition	10-Feb	16-Feb	🟨	🟨		
VVT Mechanism Exploration	10-Feb	16-Feb	🟨	🟨		
Initial VVT Mechanism Morphological Analysis	14-Feb	16-Feb	🟨	🟨		
Revised VVT Mechanism Ideation Flowchart	17-Feb	19-Feb		🟨		
Top Level VVT Mechanism Screening	18-Feb	20-Feb		🟨		
VVT Mechanism Tradeoff to Finalize Design	19-Feb	21-Feb		🟨		
Design Review 2 Presentation	16-Feb	23-Feb		🟨	🟨	
Design Review 2 Report	24-Feb	1-Mar			🟨	🟨

Figure: The above figure contains the Gantt chart used to outline the project plan prior to the design review 2 report. The Gantt chart lists different tasks and the timeline for each task.



TASK TITLE	START DATE	DUE DATE	22-Feb	1-Mar	8-Mar	15-Mar
DR3	**24-Feb**	**22-Mar**	🟦	🟦	🟦	🟦
Converge on Actuation Method	24-Feb	3-Mar	🟨	🟨		
Order Actuator	4-Mar	4-Mar		🟨		
CAD Camshaft Mating Components	2-Mar	3-Mar		🟨		
CAD Relevant Mating Engine Internals	3-Mar	5-Mar		🟨		
Initial VVT Mechanism in CAD	5-Mar	13-Mar		🟨	🟨	
Mechanism Strength Analysis	12-Mar	14-Mar			🟨	
Design Review 3 Presentation	7-Mar	16-Mar			🟨	🟨
Design Review 3 Report	16-Mar	22-Mar			🟨	🟨

Figure: The above figure contains the Gantt chart used to outline the project plan prior to the design review 3 report. The Gantt chart lists different tasks and the timeline for each task.



TASK TITLE	START DATE	DUE DATE	15-Mar	22-Mar	29-Mar	5-Apr	12-Apr	19-Apr	26-Apr
Final Design	**19-Mar**	**27-Apr**	▨	▨	▨	▨	▨	▨	▨
Update and Finish VVT Mechanism CAD	16-Mar	23-Mar	▨						
Order Stock and VVT Mechanism Hardware	18-Mar	23-Mar	▨						
Machine and Assemble VVT Mechanism	21-Mar	28-Mar	▨	▨					
Assemble VVT Mechanism to Camshaft	29-Mar	9-Apr			▨	▨			
Verification Prototype Checkpoint	6-Apr	6-Apr				▨			
Set Up VVT Controls with ECU	9-Apr	10-Apr				▨			
Test VVT on Engine Head and Cam Assembly	10-Apr	11-Apr				▨			
Final Design Communication	11-Apr	15-Apr				▨	▨		
Final Design Solution and Report	16-Apr	20-Apr					▨	▨	
Final Project Archive to Sponsor(s)	21-Apr	27-Apr						▨	▨

Figure: The above figure contains the Gantt chart used to outline the project plan for the Final Design portion of our project. The Gantt chart lists different tasks and the timeline for each task.

Appendix B

Verification Plan after manufacturing.

Table Final specification verification plan

Specification	Verification Strategy
Optimize valve timing at step sizes of 200 RPM	GT-Power simulation
≥ 3.5% increase in torque across engine speed range on average	GT-Power simulation
System varies timing by ≤ 16 degrees from nominal orientation	CAD analysis, physical testing
≥ 0.1 in. clearance to all existing powertrain components	Under review
Must attach to CBR600RR engine without any required machined to the engine head	Under review
Must vary valve timing with continuous camshaft phase angle adjustment	CAD analysis, physical testing
All machining done with: CNC 4-axis mill, CNC lathe	Creating toolpaths using CAM, physically machining the part
≤ 5.5 lbs. added mass	CAD analysis, physical testing
Can operate ≥ 1,700,000 revolutions at an average engine speed of 8200 RPM	Hand calculations, physical testing outside scope of ME450

Table Preliminary mass analysis from CAD

Component	Unit Mass [lb]	Quantity	Total Mass [lb]
Coupling Plate	0.12	2	0.24
Outer Rotor	0.50	2	0.99
Inner Rotor	0.08	2	0.16
Chamber Seals	0.0004	12	0.005
Retaining Plate	0.03	2	0.06
Oil Supply Bearing	0.04	4	0.16
Oil Passage Closeout	0.001	2	0.001
Retention Clip	0.001	8	0.01
Solenoid Fitting	0.14	2	0.27
Phaser Fitting	0.13	2	0.26
Solenoid	0.40	2	0.80
Dowel Pins	0.002	4	0.01
Total			**3.0**

Appendix C

Figures showing existing continuously variable valve timing options in industry.

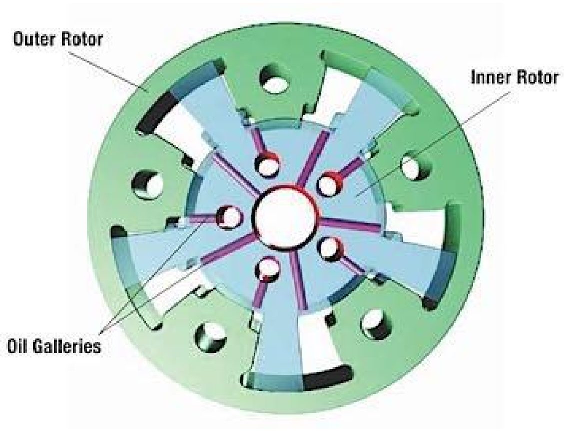


Figure: Existing Cam Phaser[5]

Figure: Koenigsegg Freevalve[6]

Appendix D
Various figures showing the different concepts developed.

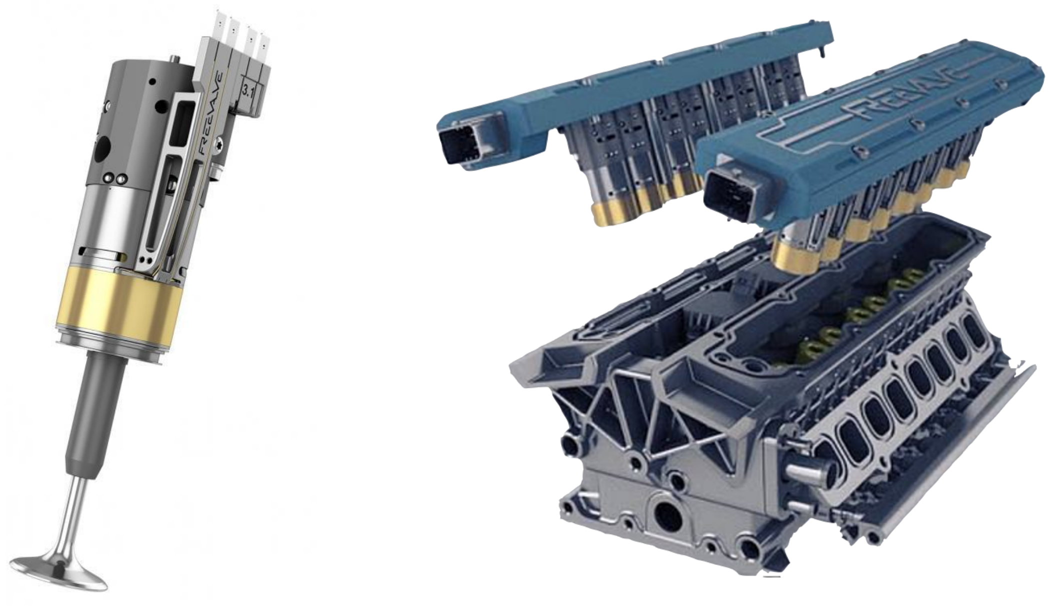


Figure: Koenigsegg free valve engine[9].

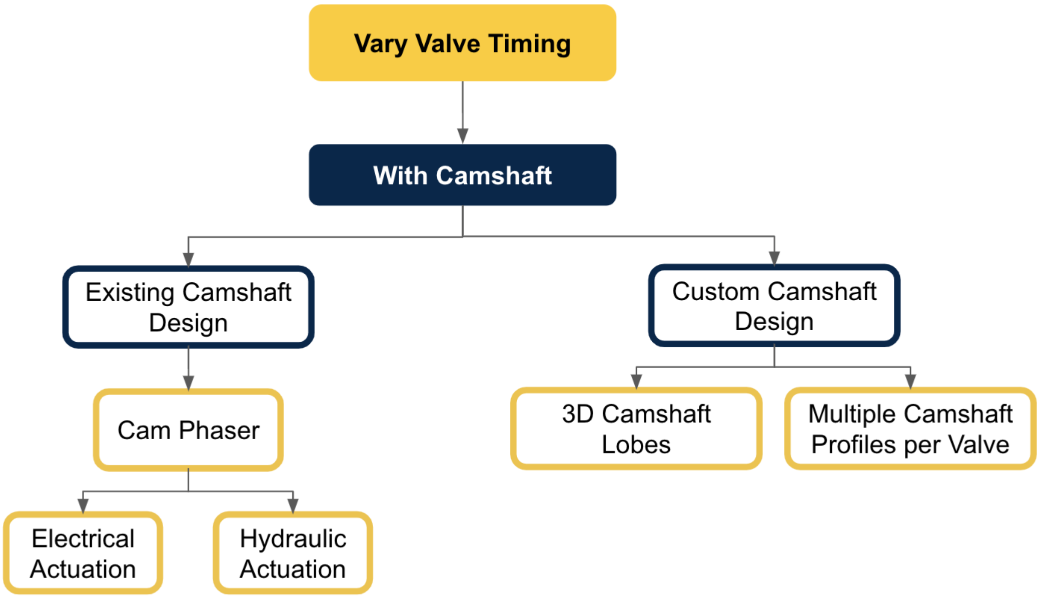


Figure: Updated ideation flowchart that only includes the designs requiring a camshaft

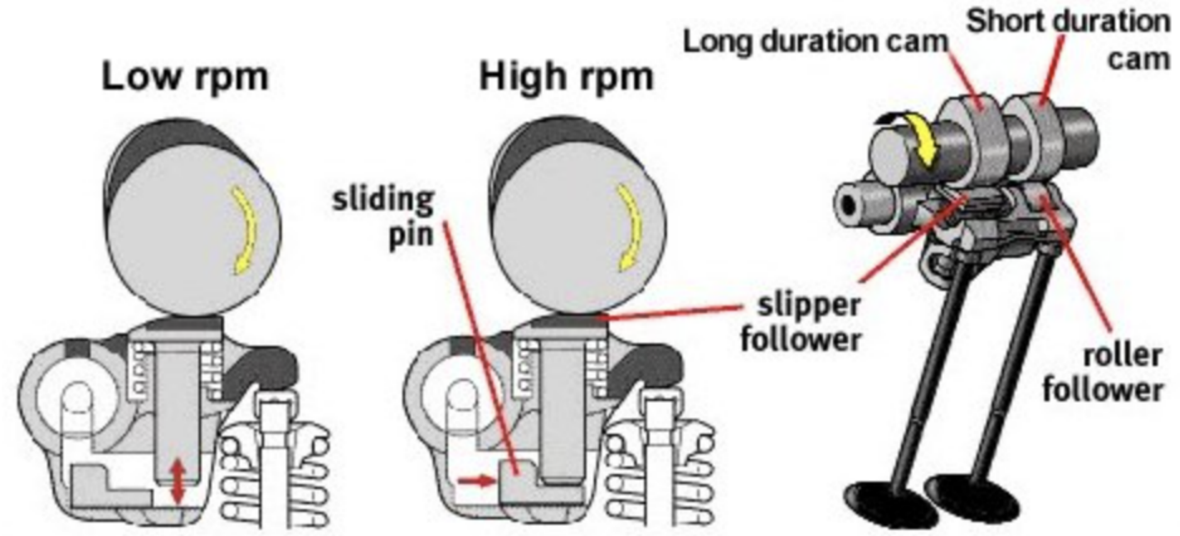


Figure: The variable valve timing mechanism in Toyota's VVTL-i. The different cam lobe sizes vary valve lift[11]

Figure: The cam phaser mechanism on a dual overhead engine[15]

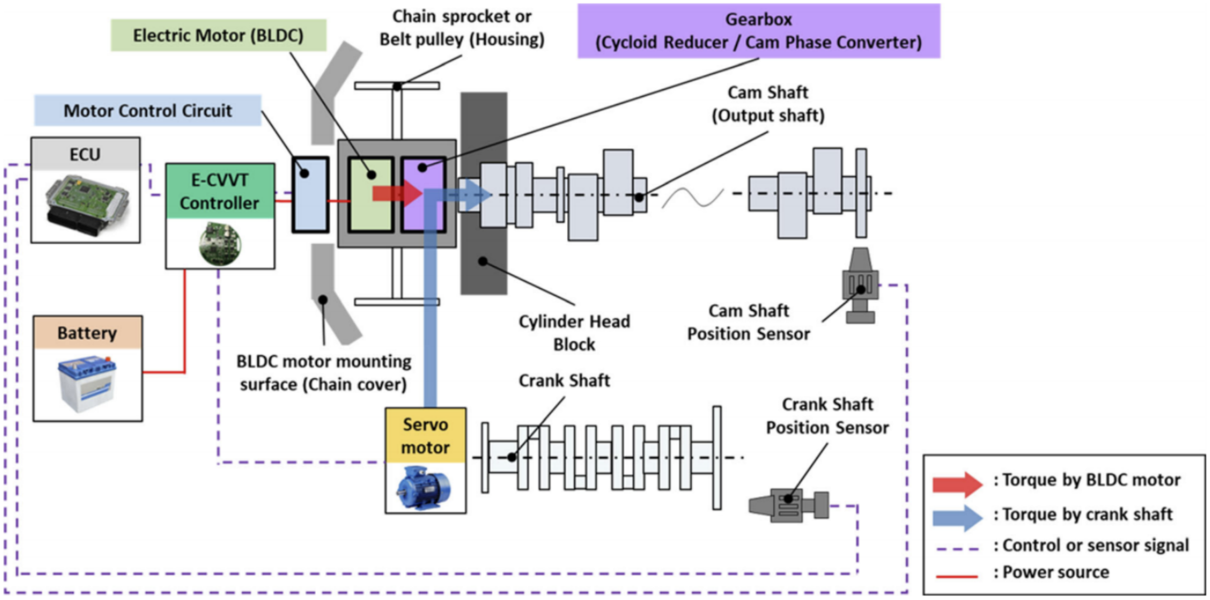


Figure: Configuration of an E-CVVT system[16]..

Appendix E
Figures showing various methods used during concept generation.

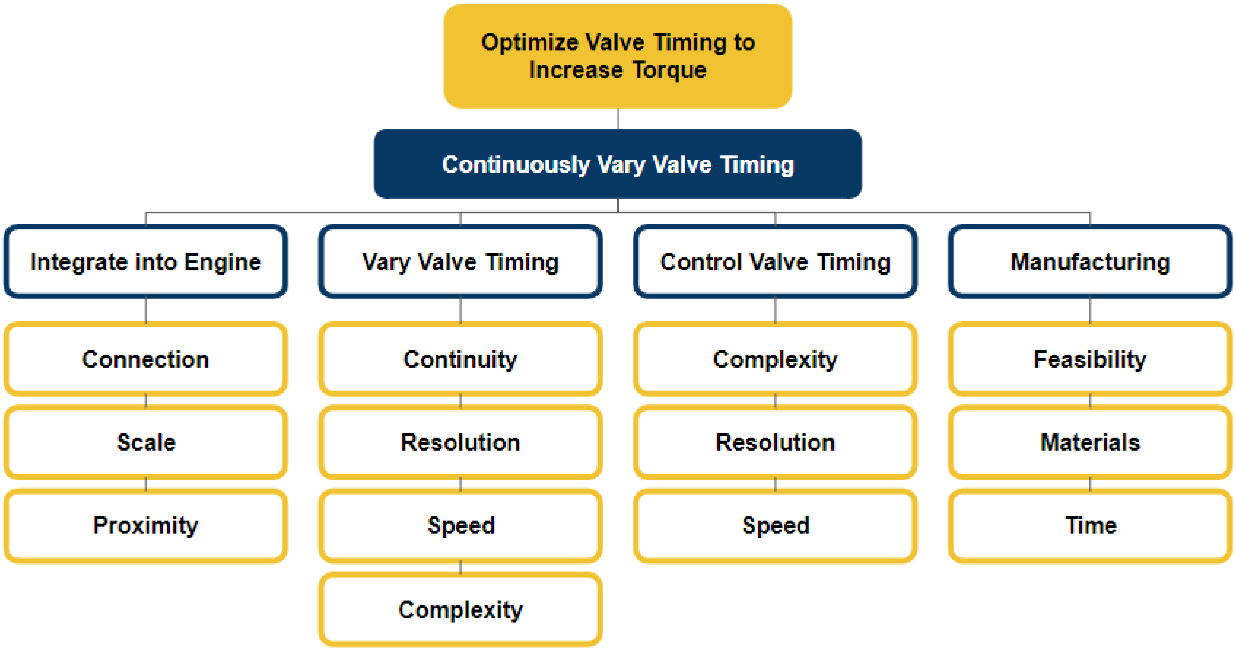


Figure: Functional decomposition tree for optimizing valve timing. The primary function and secondary function and shown in yellow and blue, respectively. The sub-functions and considerations are outlined in blue and yellow, respectively.

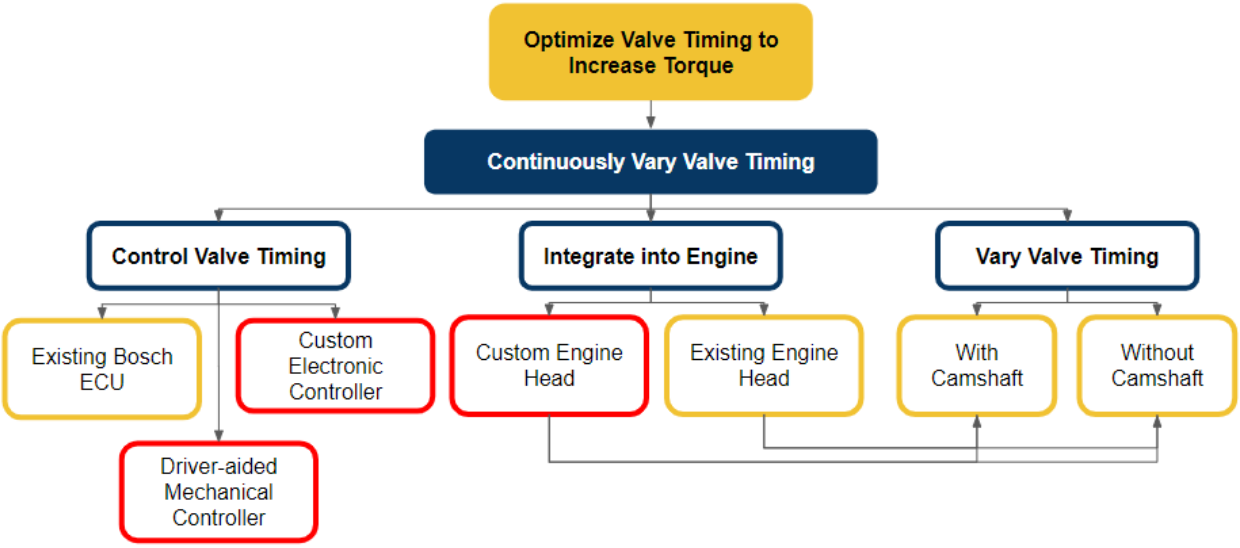


Figure: High level design ideation flowchart. Top three levels of decision developed from functional decomposition. The in scope and out of scope solutions are outlined in yellow and red, respectively.

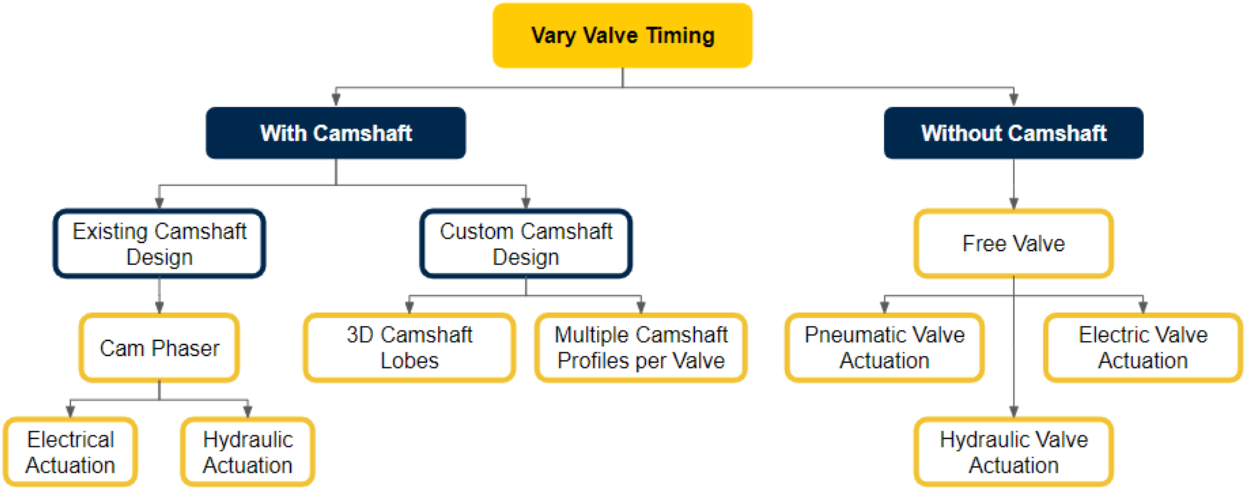


Figure: Low level design ideation flowchart. The major and minor subcategories and shown in solid blue and outlined blue, respectively. The mechanism solutions are outlined in yellow.

Appendix F

Various figures showing our GT-Power simulation setup and results

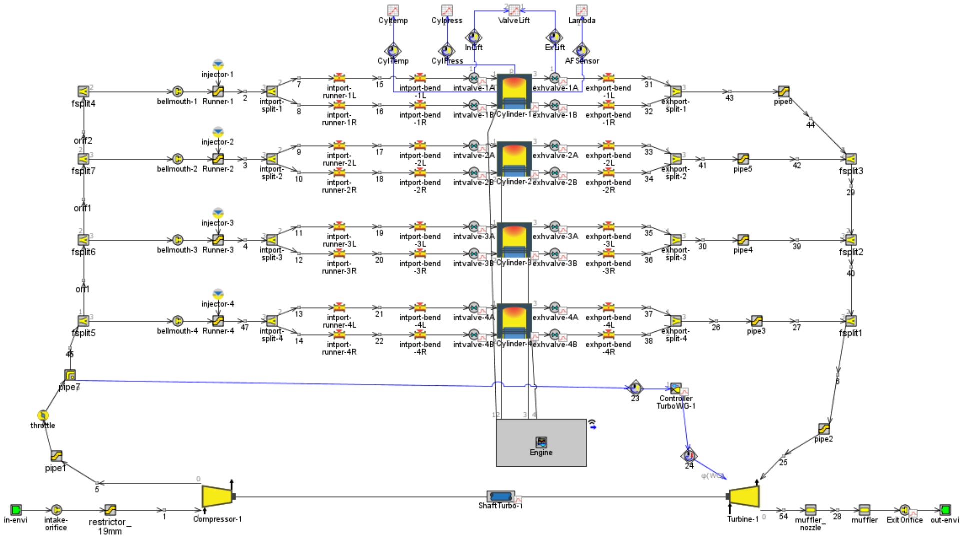
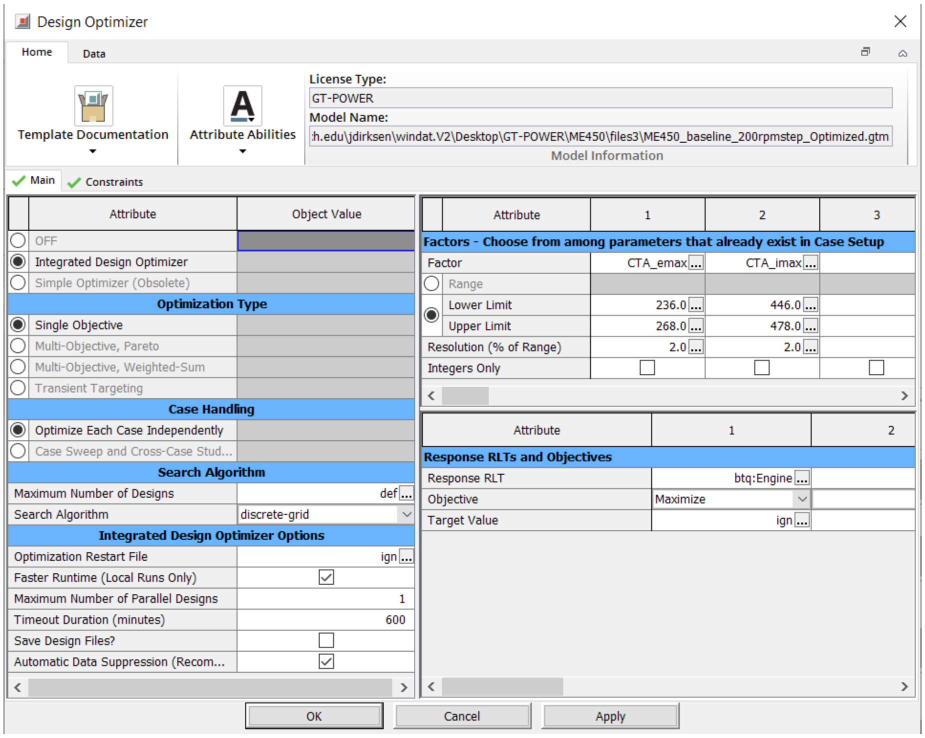


Figure: MRacing's GT-Power model with all relevant components to simulate engine performance and valve timing


Design Optimizer

Home | Data

Template Documentation | Attribute Abilities

License Type: GT-POWER

Model Name: h.edu\jdirksen\windat.V2\Desktop\GT-POWER\ME450\files3\ME450_baseline_200rpmstep_Optimized.gtm

Model Information

Main | Constraints

Attribute	Object Value
○ OFF	
● Integrated Design Optimizer	
○ Simple Optimizer (Obsolete)	
Optimization Type	
● Single Objective	
○ Multi-Objective, Pareto	
○ Multi-Objective, Weighted-Sum	
○ Transient Targeting	
Case Handling	
● Optimize Each Case Independently	
○ Case Sweep and Cross-Case Stud...	
Search Algorithm	
Maximum Number of Designs	def
Search Algorithm	discrete-grid
Integrated Design Optimizer Options	
Optimization Restart File	ign
Faster Runtime (Local Runs Only)	☑
Maximum Number of Parallel Designs	1
Timeout Duration (minutes)	600
Save Design Files?	☐
Automatic Data Suppression (Recom...	☑

Attribute	1	2	3
Factors - Choose from among parameters that already exist in Case Setup			
Factor	CTA_emax	CTA_imax	
○ Range			
● Lower Limit	236.0	446.0	
● Upper Limit	268.0	478.0	
Resolution (% of Range)	2.0	2.0	
Integers Only	☐	☐	☐

Attribute	1	2
Response RLTs and Objectives		
Response RLT	btq:Engine	
Objective	Maximize	
Target Value	ign	

OK | Cancel | Apply

Figure: GT-Power inputs to optimize exhaust and intake valve timing. CTA_emax and CTA_imax are the variables controlling exhaust and intake timing, respectively.

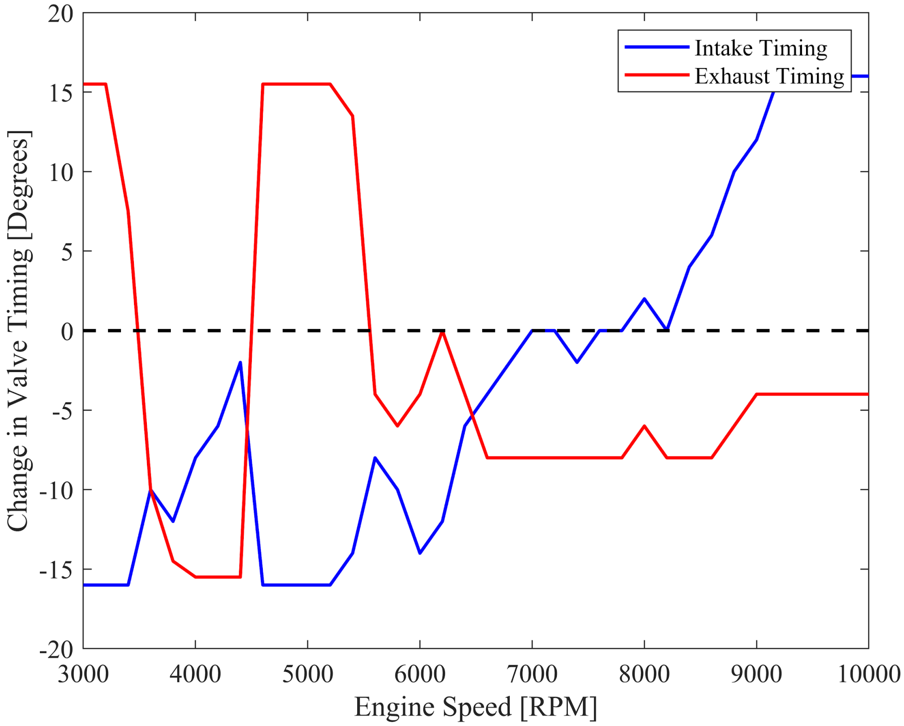
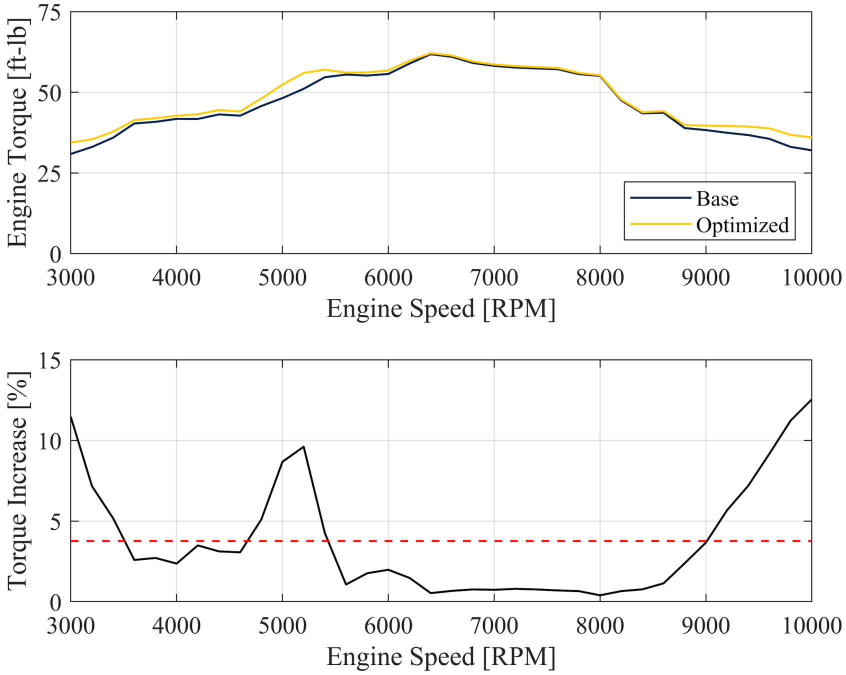


Figure: GT-Power's suggested change of valve timing compared to nominal in order to maximize torque.

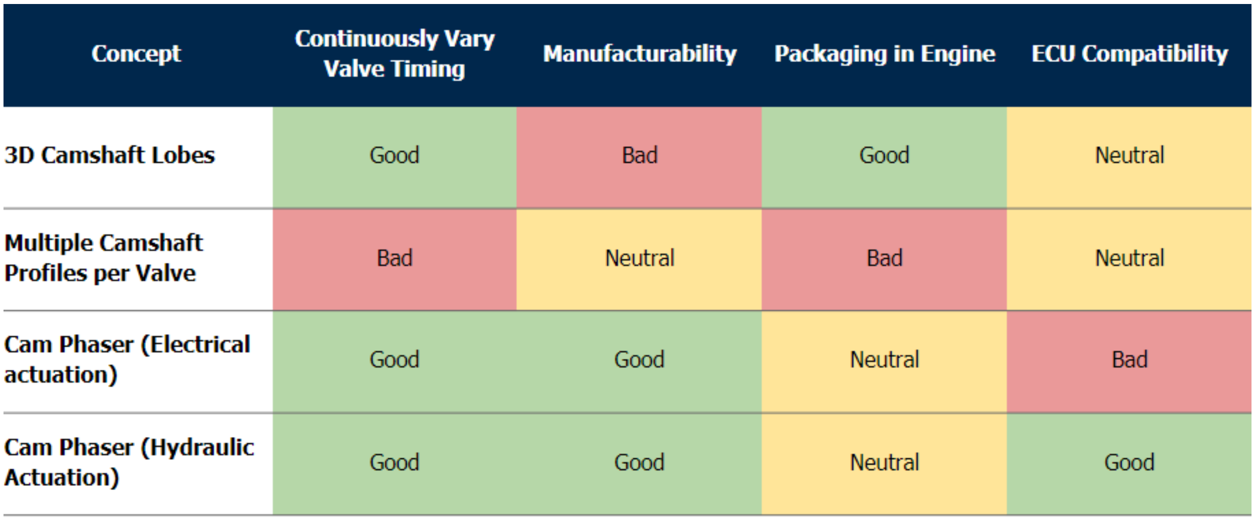


Figures: Simulated increase in torque due to optimized valve timing.

Appendix G

Concept Selection Aids.

Table : Concept Selection Table



Concept	Continuously Vary Valve Timing	Manufacturability	Packaging in Engine	ECU Compatibility
3D Camshaft Lobes	Good	Bad	Good	Neutral
Multiple Camshaft Profiles per Valve	Bad	Neutral	Bad	Neutral
Cam Phaser (Electrical actuation)	Good	Good	Neutral	Bad
Cam Phaser (Hydraulic Actuation)	Good	Good	Neutral	Good

Figure : Duralast TS1013 oil valve solenoid.