MRacing Formula SAE

Improving Fuel Efficiency

Team 005
ME 450 Section 003
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University of Michigan

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Sponsor: MRacing

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Executive Summary

Founded in 1986, the University of Michigan's MRacing Formula SAE team has continually pushed the boundaries of vehicle design. Competing in the Formula SAE collegiate motorsport racing series, students are put to the test of using technical innovation and advanced engineering analysis to design and build formula-style race cars. With over 30 years of experience, MRacing is the 1st ranked team in the United States and the 5th ranked team in the world. Using prior knowledge and experience this team has successfully designed and built new cars annually, looking to test and improve new innovations onto the track. Despite the many achievements this team has had they are now looking to improve in their worst performance areas. In the 2019 Michigan International Speedway (MIS) competition, MRacing scored 18th in fuel efficiency. For our ME450 course project, we will complete the task of improving the vehicle's fuel efficiency for the summer 2021 competition.

During the competition fuel efficiency is calculated from fuel usage and is weighted by lap times from the endurance event. We decided to maintain the current engine and fuel system to framework specific areas of improvement for the vehicle’s fuel efficiency. Through stakeholder meetings with Harvey Bell, and competition insight from our MRacing members, we came up with several requirements to define the scope of our project. We specified a target score in fuel efficiency that we hoped to achieve to demonstrate improvement. The engine improvements must maintain 2019’s lap time and conform to SAE and event rules. We found it critical to implement reliability for the most optimal performance.

For the scope of our project we explored four possible solutions to improve fuel efficiency: higher compression pistons, leaner fuel calibration, variable cam timing, and direct injection engine. We did extensive research on existing conceptual solutions as fundamental engine principles have been explored and we are looking to improve a current design. We found leaner fuel calibrations to be best implemented as solutions due to COVID-19 restrictions and our team's time constraint.

Our design process was to be split into four segments: analysis, dynamometer (dyno) testing, mock endurance and competition. Using GT-Power and design of experiment we created possible solution simulations to analyze engine torque, power and fuel consumption from the data acquired at MIS 2019. After we had determined our favored solutions we were going to test them on the dyno to gather real world results measuring engine characteristics and reliability. However due to sooner than anticipated shop closings we were unable to complete the dyno testing. Per the State of Michigan's epidemic order we had to cease work in the wilson center on 11/18/2020. We hope next semester our work can be completed.

As such our recommendations to MRacing are to complete testing and validation of the calibrations we found to give the greatest improvement to efficiency.

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Project Report

Problem Description and Background

Every year the Society of Automotive Engineers (SAE) puts on the Formula SAE series. Formula SAE is a collegiate competition where students design, build, and race a small open-wheeled race-car against other college teams. Competitors are scored in two categories, static events and dynamic events. Static events are where industry professionals judge the quality of the car and the team through a series of reports and presentations. Dynamic events are where the car races a series of time trials against other teams. The five dynamic events at Formula SAE competitions are Acceleration, Endurance, Autocross, Efficiency, and Skidpad.

MRacing is the University of Michigan's Formula SAE team. MRacing typically performs very highly in the Acceleration, Endurance, and Autocross events, but poorly in the efficiency and skidpad events. **Table 1**, below, shows our dynamic event scores from our last competition at the Michigan International Speedway.

Table 1: MRacing Dynamic Event Score at MIS 2019 [1]

Event	Raw Score	Placement
Acceleration	100/100	1st
Endurance	237.8/275	3rd
Autocross	91.4/125	9th
Efficiency	63.5/100	18th
Skidpad	36.9/75	33rd

Another MRacing group has decided to work on improving the Skidpad score, while we focus on Efficiency. In the Efficiency event teams are judged on CO_2 produced during a 22km Endurance race. CO_2 produced is used as a metric over fuel consumed to account for the different fuel types allowed in competition. The amount of CO_2 produced is weighted by a team's lap time and compared against other teams to calculate an efficiency factor via **Equation 1** below.

$$\text{Efficiency Factor} = \frac{\text{Tmin} / \text{LapTotal}_{\text{Tmin}}}{\text{Tyours} / \text{Lap yours}} \times \frac{CO_2\,\text{min} / \text{LapTotal}_{CO_2\,\text{min}}}{CO_2\,\text{your} / \text{Lap yours}} \qquad (1)\ [2]$$

In **Equation 1**, Tmin is the lowest Endurance time of the fastest team, Tyours is the Endurance time of the team being scored, CO_2 min is the smallest mass of CO_2 used by any competitor, CO_2 your is the mass of CO_2 used by the team being scored, Laptotal Tmin and Laptotal CO_2 min are the number of laps completed by the teams which set Tmin and CO_2min respectively, and Lap yours is the number of laps driven by the team being scored [2]. This efficiency factor is then converted into a score ranging from 0-100 by **Equation 2**:

$$\text{Efficiency Score} = 100 \times \frac{(\text{Efficiency Factor min} / \text{Efficiency Factor your}) - 1}{(\text{Efficiency Factor min} / \text{Efficiency Factor max}) - 1} \qquad (2)\ [2]$$

The efficiency factor can be improved in two ways. The first is to decrease lap times during the Endurance event, while the other is to reduce the amount of CO_2 produced by reducing the amount of fuel consumed. Since MRacing's lap times are already very competitive, we believe the best way to improve our efficiency score is to reduce our fuel consumed during Endurance.

General Powertrain Specifications

To allow the reader to familiarize themselves with the powertrain of the MRacing vehicle, **Table 2** is presented below, containing general powertrain specifications. Notably these include that the engine is from a Honda CBR600RR sportbike and is modified to be turbocharged and operate on E85 Gasoline. Additional modifications are also made to conform to the Formula SAE rules.

Table 2: General engine specifications of the MRacing vehicle.

Specification	Quantity
Manufacturer/Year	Honda/2007-2012
Engine Geometry	Inline 4 Cylinder
Displacement	599cc
Maximum Torque/Power @ MIS 2019	54.0 ft-lbs @ 7000 RPM/78 HP @ 8500 RPM
Fuel Volume Used & Efficiency Factor @ MIS 2019	6.316 L/0.560
Engine Block & Cylinder Head Material	Cast Aluminum
Bore/Stroke	67mm/42.5mm
Cylinder Head Design	DOHC (Dual-Overhead Cam), 16 Valve
Compression Ratio	12.2:1
Turbocharger	BorgWarner KP35
Fuel System	Port Electronic Fuel Injection
Fuel Type	E85

The most important specification to the efficiency and overall performance of our car are the maximum torque/power, compression ratio, the turbocharger (more specifically the amount of turbocharging we are able to achieve), and the fuel type.

Requirements and Specifications

The requirements and their associated specifications are shown below in **Table 3**. The justifications for these requirements are discussed in detail following.

Table 3: Requirements and specification for improving fuel efficiency in the MRacing Formula SAE car. These requirements were developed based on the current global events, the rules set out by FSAE, and the team's goals for next year's competition. Priority 1 requirements must be met while priority 2 requirements have some flexibility.

Priority	Requirement	Engineering Specification	Justification
1	Improve Efficiency score	Score ≥ 75 points out of 100 possible in the efficiency event. Achieve this while only considering powertrain improvements.	Scored 63.5 out of 100 points and placed 18th at MIS in 2019. Top 10 teams scored ≥ 75 points or greater. Project scope limited to powertrain.
1	Maintain lap times	Maintain or improve previous endurance event total time of 22:07 [1]	Placed 3rd in the endurance event at MIS in 2019. Lap times are used to score the endurance event and to weight the efficiency score.
1	Conform to all SAE and event rules	Must be able to pass pre and post event technical inspections. [2]	SAE has extensive rules that limit the types of engines and their implementations. [2, IC.1.1, IC.2.4, IC.5.1]
1	Maintain reliability	Powertrain must be able to complete all competition events including finishing the 22 km endurance event without suffering a reduction in performance.	The powertrain should not require any maintenance over the course of the competition. Lap times will suffer greatly if the powertrain operates at less than peak performance during the endurance event. If the powertrain fails during the endurance event no point will be scored.
2	Stay within budget	New engine components cost ≤ $800.	MRacing team defined the budget.
2	Maintain driveability	Maintain current usable RPM range, peak power should be produced (78 HP) between 8000 and 9000 RPM	The drivers ability to confidently drive the car is an important factor to the team's performance. Making sure the driver does not have to drastically change how they drive the car will help them drive with confidence Changes to the power delivery will be the most noticeable to the driver if the usable RPM range is changed.

Improve Efficiency score

This requirement is the primary goal of the project. The team wants to improve on their performance in the efficiency event. We placed 18th with a score of 63.5 out of 100 at the Michigan International Speedway (MIS) competition in 2019. Our goal for the 2021 competition at MIS is to score 75 points in efficiency. This goal was determined from a study conducted on the past 5 years competition results at MIS. The top 10 teams in efficiency at MIS 2019 scored greater than 75 points. The overall points goal was determined to place us in the top 3 overall based on this study. The extra points needed to be earned to achieve top 3 were then dispersed among the various events we felt we could perform better in and the efficiency score of 75 was decided. The scope of this project is limited to powertrain improvements only. While there are other means of improving efficiency, reducing drag and weight, the current global health crisis has limited the team's ability to make improvements in other areas. The current global health crisis has meant that MRacing needed to change its strategy and development plans for this year's car. Due to current restrictions the team has had reduced time and access to resources such as the Wilson Student Team Project Center and outside sponsor work. Because of this MRacing has chosen to use the car that was built for the 2020 season. This means that the chassis, powertrain and basic structure of the car must remain the same. This project aims to improve the fuel efficiency of the car using only modifications to the existing powertrain.

Maintain lap times

This requirement is important because it ensures that modifications made to the powertrain to improve the efficiency score do not hurt the car's performance in other events worth more points. The team placed 3rd in the endurance event at MIS in 2019. Maintaining a high finish in this event is important to both the overall team score, and to the efficiency event because the efficiency score is weighted by the lap times from the endurance event.

Conform to all SAE and event rules

The car must be able to legally compete for any improvements made to be validated. This requirement makes sure that any modifications made to the powertrain will still conform to the rules laid out by SAE. Specific rules of note are IC.1.1, IC.2.4, and IC.5.1. Rule IC.1.1 restricts the size and type of engine the team is allowed to use to four stroke piston engines with a displacement of no more than 710 CC. Rule IC.2.4 mandates that all airflow to the engine must pass through a circular restrictor plate. Rule IC.5.1 limits the fuels teams are allowed to use to gasoline and E85. These rules mean that we cannot switch the car over to a different cycle engine or use higher performance fuels to improve our efficiency.

Maintain reliability

Any modifications made to the powertrain to improve its efficiency should in no way compromise its ability to complete all the dynamic events at a competition. The powertrain will need to remain reliable enough after modification that it does not have to operate at reduced performance in order to complete the endurance event. Failure to complete the endurance event would result in a DNF and a noncompetitive score.

Stay within budget

This requirement was defined by the MRacing management. The budget is to be used for purchasing of new engine components that may be used to help us reach our goal. The number is based on the team's initial estimates for the price of components that had been considered as a part of a potential solution prior to the initiation of this project. This requirement is priority 2 because the MRacing budget is flexible and our initial budget is only based on an estimation.

Maintain Drivability

This requirement is inherently qualitative because it depends on the driver's feel for the car. This requirement was quantified by the usable RPM range of the engine. This is the change that the driver would most likely feel if any changes to the powertrain were made. Minimizing the amount of changes to where peak power is produced and thus how much the driver must adapt will help the drivers maintain their confidence in the car and therefore drive faster. While ensuring that the driver is confident in the car is important this requirement was made priority 2 because the drivers will be able to adapt to the changes we make.

Concept Exploration

With our problem defined and our design requirements established, we began exploring the design space. Firstly we needed to be able to generate solution ideas. Due to the high technicality of our project, we started with taking a closer look at the thermodynamics involved in how our engine produces usable power. With this understanding we were better equipped to come up with potential solutions.

The Otto Cycle

In order to generate meaningful solutions, we must first understand the thermodynamic cycle our engine operates on. Our engine operates on the Otto cycle, also known as the four stroke cycle. The Formula SAE rules dictate that all combustion teams must use a piston engine that operates on this cycle. As its name suggests, the four stroke cycle has four distinct parts of the cycle called strokes. Each stroke consists of a piston in a cylinder traveling from the top of its stroke to the bottom, or vice versa. The working fluid is allowed to enter and leave the system through intake and exhaust valves. The names of each stroke in order, starting with the intake stroke, are intake, compression, expansion and exhaust. A visual representation of each stroke can be found below in **Figure 1**. During the intake stroke, the intake valve(s) is opened and a mixture of air and fuel (for port fuel injected engines) are drawn into the cylinder as the piston moves downward. The intake valve then closes and the mixture is then compressed during the compression stroke. A spark plug fires around the top of the compression stroke to ignite the air and fuel mixture and the piston is driven downward while the working fluid expands. This is the expansion stroke. Finally, at the bottom of the expansion stroke, the exhaust valve(s) opens and the working fluid is allowed to leave the system as the piston travels upward and the cycle starts again.

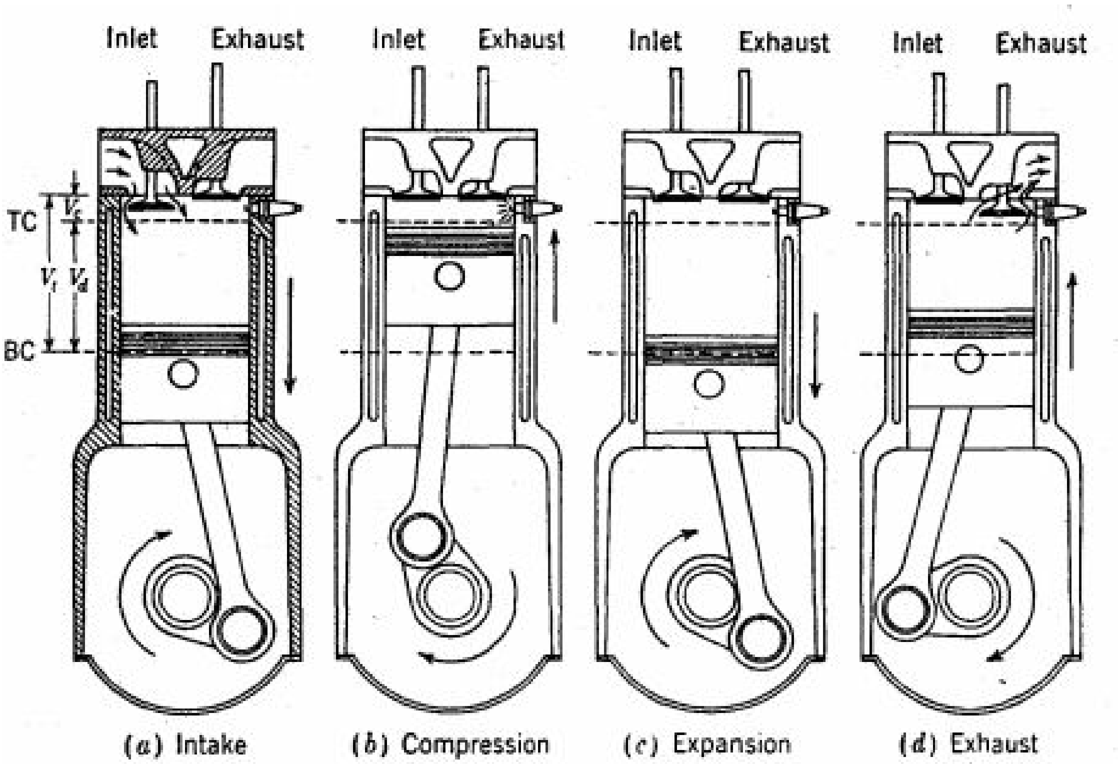


Figure 1: Each stroke of a four stroke cycle as a section view of a single piston in a cylinder. Intake and exhaust valves allow the working fluid to enter and exit the system. [3]

Otto Cycle Thermodynamics

Important characteristics of an internal combustion engine can be visualized on a pressure vs. volume (PV) plot of a cycle. From these plots, work quantities can be calculated from thermodynamic cycles, or “loops”. For a four stroke engine, there are two of these loops. The first loop is called the power loop and it consists of the compression and expansion strokes. The second loop is called the pumping loop and it consists of the intake and exhaust strokes. The pumping loop represents the work that the piston must do on the air in order to move it in and out of the system. The power loop represents the gross work production of the engine. A PV plot generated from our engine is shown below in **Figure 2**. Net work is calculated by subtracting the pumping loop from the power loop. A PV plot for any given cycle of an internal combustion engine does not paint the full picture of all the sources for energy loss, but it does provide a good basis for conceptual understanding of why we are pursuing certain solutions. For example, a PV plot does not capture the energy loss due to friction and the mechanical components that deliver power all the way to the wheels of a vehicle.

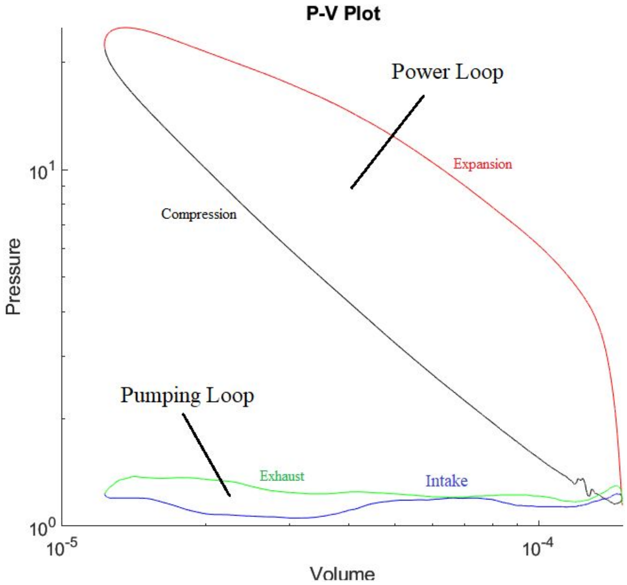


Figure 2: A pressure [bar] vs. volume [m^3] plot of our Honda CBR600RR engine on a log-log scale. Pressure is in units of bar and volume is in cubic meters. Each stroke, as well as the two work loops, are colored and labeled.

Functional Decomposition

After learning about the important thermodynamics and functions of our engine we started our concept development with a functional decomposition of the subsystems and variables we can change to improve the fuel efficiency of our engine. A visualization of our decomposition is shown below in **Figure 3**.

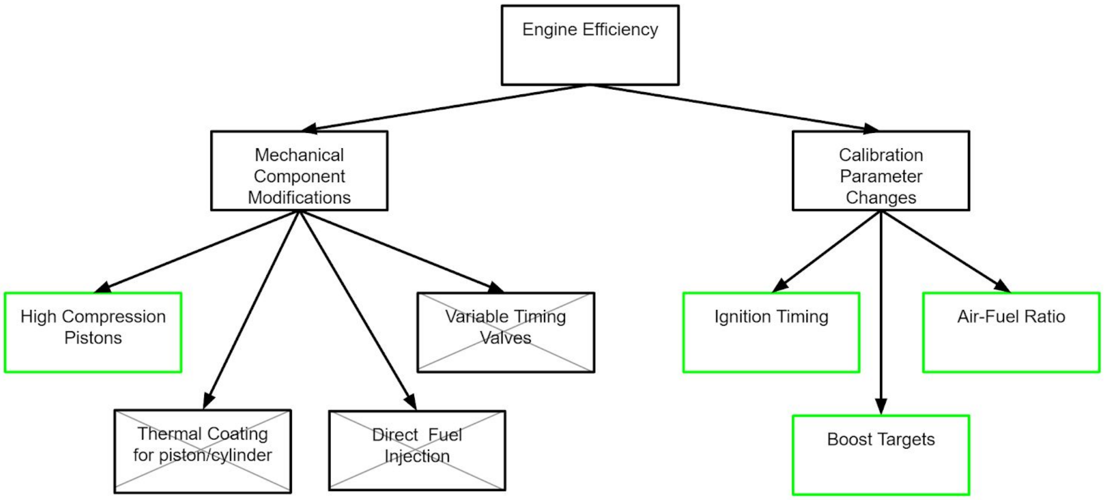


Figure 3: Functional Decomposition of the way we can improve our engine's efficiency. Green boxes are concepts we will be further pursuing. Crossed out boxes are concepts that we will not be considering because of their high complexity and our time limitations.

We started by splitting the possibilities into two categories, mechanical component modifications, and calibration parameter changes. Calibration parameters are the parameters the engine control unit uses to operate the engine. They can be changed relatively easily and can dramatically impact the performance of the engine. The parameters we are considering working with are ignition timing, boost targets, and the air-fuel ratio. The mechanical component modifications that could help us improve our efficiency are Higher Compression pistons, thermal coatings for the piston and/or cylinder, direct fuel injection, and variable valve timing. For this project we are only going to consider using high compression pistons because the amount of time and work needed to implement the other solutions is outside the scope of this project.

Boost Targets

Intake manifold pressure (boost) is an important factor in internal combustion engine calibration. Higher intake manifold pressure reduces the work that is required from the piston to pull air into the cylinder. If intake pressure is high enough, the pumping loop can actually add to the gross work of the engine. This is due to a turbocharger that recovers energy that would otherwise be wasted in the exhaust by driving a turbine. Intake manifold pressure also has an enormous impact on torque/horsepower production and fuel consumption. Because the air charge is pressurized before entering the cylinder, it has a higher density which means that more fuel must be added as well to maintain the same air/fuel ratio. What is less intuitive, is the effect boost pressure has on brake specific fuel consumption, which is why it is an important factor to consider for our project.

For our testing we are changing the maximum boost target for the engine, meaning the turbocharger will be used to produce as much boost as it can till it reaches the target. Once it reaches that target the wastegate will limit the turbocharger such that it does not produce any higher pressures.

Ignition Timing

Ignition timing is when the spark plug fires in relation to the position of the cycle. Because the combustion process is not instantaneous, the firing event must be started early. This is why the spark plug normally fires before the piston reaches top-dead-center (TDC) of the compression stroke. Ignition timing has a large impact on torque production. There is an optimal time to fire the spark plug which results in the most torque possible at that operating condition. This is called max brake torque (MBT) ignition timing. It is not uncommon for engines to be limited on close they can get to MBT ignition timing because of what's called knock. Simply put, knock is an auto-ignition of the fuel/air charge in the cylinder after the spark plug has fired. Knock can cause catastrophic engine failure, and must be managed properly. Other engine calibration factors have a great effect on how prone an engine is to knock. But, due to its high sensitivity to torque and horsepower production, ignition timing should also be as close to MBT as possible for our application. For all these reasons, ignition timing is an extremely important factor to consider for our project.

Air-Fuel Ratio

Fuel consumption can be reduced simply by injecting less fuel per cycle, or in other words, by using a leaner air-fuel ratio. This can be done very easily by changing the fuel calibration.

Using a leaner fuel calibration would also increase an engine's likelihood of knock because of its effect on in-cylinder temperatures. Rich mixtures (air-fuel ratios below the stoichiometric ratio) are typically used at wide open throttle (WOT) because of the cooling effect it has on the combustion process. We have also run into engine performance issues in the past when testing leaner air-fuel ratios (AFR's) such as excessive misfiring. We believe this to be due to in-cylinder local AFR differences; aka a non-homogenous mixture. The CBR600RR was designed to use a homogenous mixture in the combustion chambers. This problem can be improved upon by redesigning intake ports, piston crowns and/or by using direct injection; but developing these designs require complex in-cylinder CFD models and/or heavy modification to the engine.

For our testing we will manipulate the air-fuel ratio (AFR)through the lambda parameter in our engine. Lambda is the air-fuel equivalence ratio, that is the ratio of the current AFR to the stoichiometric AFR. This is shown in **Equation 3** below.

$$\lambda = \frac{AFR}{AFR_{stoich}} \qquad (3)[3]$$

The stoichiometric AFR is the AFR needed to create a balanced chemical reaction. The exact proportion of fuel and air are present so no fuel or air is left unburned. Lambda values of 1 are at the stoichiometric and greater than 1 are said to be lean, meaning there is excess air. Values less than 1 are rich meaning there is excess fuel.

Higher Compression Pistons

Higher compression pistons will increase the compression ratio of each cylinder in the engine. This improves the fuel conversion efficiency as shown by **Equation 4**:

$$\eta_{f,i} = 1 - \frac{1}{r_c^{\gamma-1}} \qquad (4)[3]$$

Where $\eta_{f,i}$ is the indicated fuel conversion efficiency, r_c is the compression ratio and γ is the ratio of constant specific heat at a constant pressure to the specific heat at a constant volume. The indicated fuel conversion efficiency is a measure of how much of the fuel in a given cycle is converted into usable power.

Some challenges involved with higher compression pistons are increasing the engines likelihood to knock or spontaneously ignite the fuel-air charge in the cylinder. Testing new pistons would also involve a rebuild of our dyno test engine.

Solution Development and Verification

The majority of the work of this project was the analysis of determining which combination of the proposed concepts would lead to the most points at the MIS competition. The GT-Power simulation program was used to determine torque, horsepower and fuel consumption for each solution. This data was then input into a fuel consumption model and a lap time simulation, both developed by MRacing, to predict the points change that the simulated solution would provide at competition. The Taguchi Method was used for the design of this experiment to greatly reduce the number of simulations we would have to run from 81 to 9, saving both labor and computational resources.

Gauging Results

In order to evaluate concept ideas in regards to efficiency we must compare them all with the same measurement. The main measurement we will be using to gauge our efficiency gains is the Brake Specific Fuel Consumption (BSFC). The BSFC is calculated by dividing the fuel mass flow rate by the brake power. This is shown in **Equation 5** below.

$$BSFC = \frac{\dot{m}}{P_b} * (3.6 * 10^6) \tag*{(5)[3]}$$

In **Equation 5**, $\dot{m}$ is the fuel mass flow rate into the engine, in grams/second, and P_b is the brake power, in watts, produced by the engine. Brake power is the power produced by the engine measured at the engine’s output, which means it includes all internal energy losses. The coefficient used to convert the value to the desired unit of grams/kilowatt-hour.

The BSFC allows us to assess the efficiency of our engine rather than just the fuel usage. Lower values for the BSFC are what we are looking for. The BSFC can be lowered by increasing the amount of power produced by a given amount of fuel or reducing the amount of fuel needed to produce a given amount of power.

GT-Power Model Simulations

The primary method we will be using to initially test out concepts is GT-Power Simulations. GT-Power is an industry-standard, 1 dimensional engine simulation software developed by Gamma Technologies. GT-Power will be used to model different possible solutions and compare them based on torque, horsepower, and fuel consumption outputs. MRacing currently has a GT-Power model that it has developed over multiple seasons. This model will be used to assess concepts and collect data on theoretical engine performance in a relatively short period of time. A screenshot of the team’s model is shown below in **Figure 4**.

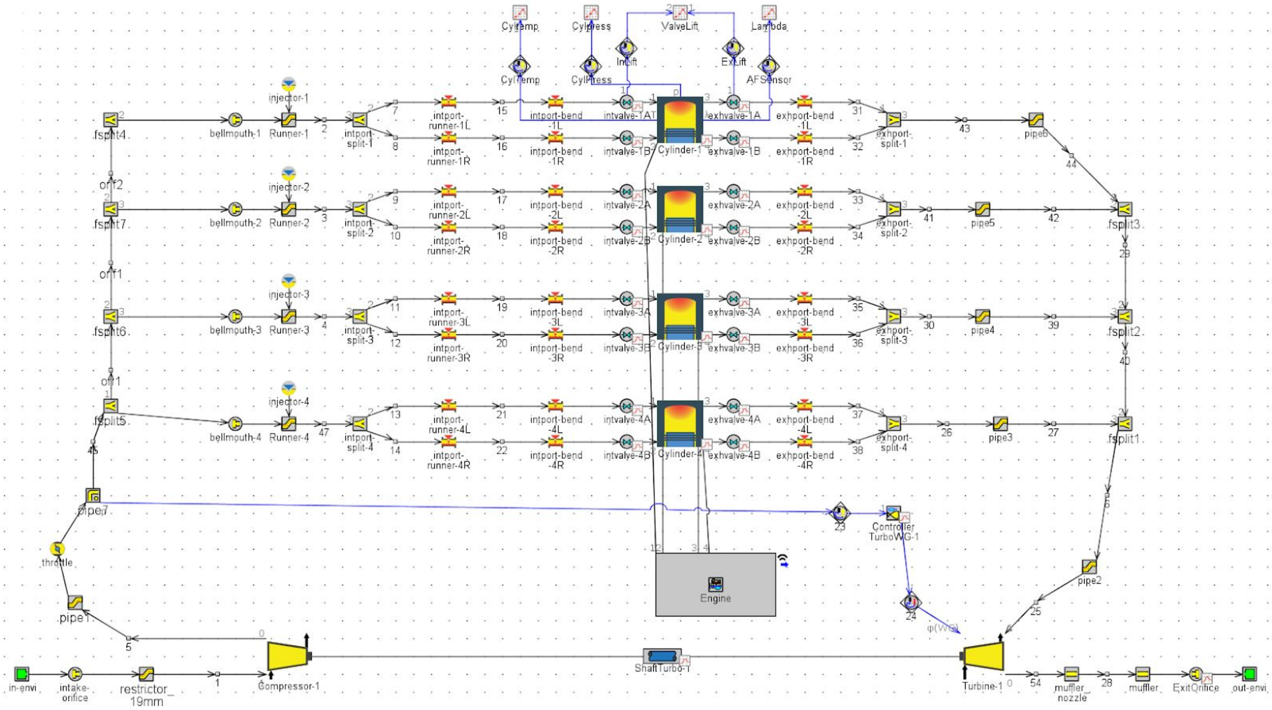


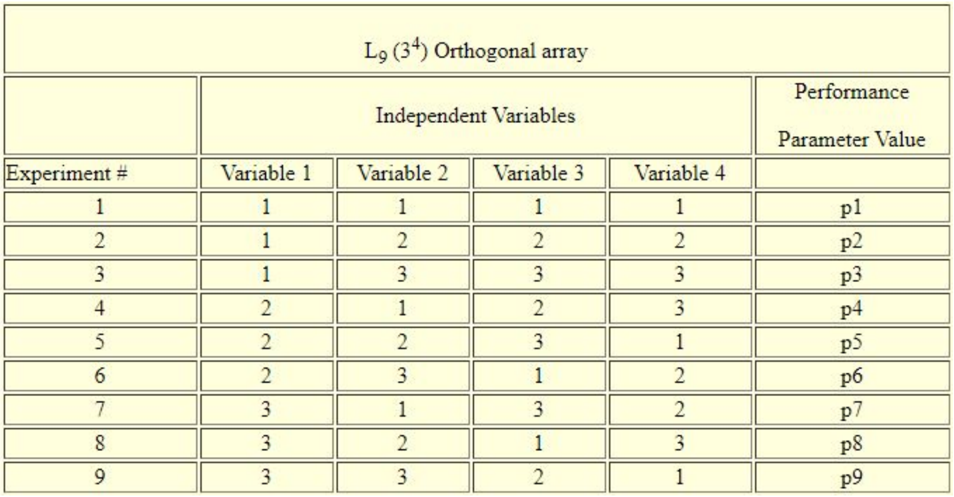
Figure 4: Team developed GT-Power model of the current powertrain. The model is built around an engine block with 4 pistons connected. The intake and exhaust components are modeled individually for each cylinder and the turbocharger is modeled as its two components, the turbine and compressor.

GT-Power is a very robust tool for running engine simulations, but due to the system's complexity there are a few limitations. GT-power assumes all engine components are in pristine condition not accounting for carbon build up, faulty spark plugs and fuel system failure. These key components can lead to engine misfire causing serious performance problems for the engine. This software runs a 1-D simulation using only one direction and time, meaning that the flow will always be uniform in the cross sections. In many parts of a real engine the flow field is three dimensional, so this tells us that the model is unable to account for knock. Knock prediction models can be made through a more in depth analysis using Wiebes function and the creation of a 0-D model in conjunction with our 1-D model. For the purpose of our project we did not find this to be necessary as we are using respective knocking boundaries determined from past years to validate our new operating conditions. Moving past solution development, GT-Powers limitations will be put to the test during our validation stage of dynamometer testing.

Design of Experiments: Taguchi Method

From the functional decomposition it was determined that four parameters would be tested to assess ways to improve the BSFC. These parameters are the ignition timing, the boost targets, the air-fuel ratio (lambda), and the compression ratio. For each of these parameters we selected to test three different levels: low, medium and high. If all combinations of these parameters and levels were tested 81 (3^4) different simulations would need to be performed.

Design of experiments is a way to plan and conduct experiments in order to gain an understanding of the factors that affect a selected parameter. In this case we are trying to understand how ignition timing, boost targets, air-fuel ratio, and compression ratio affect the efficiency of our engine measured by its BSFC. One method within design of experiments is the Taguchi method. The Taguchi method utilizes orthogonal arrays to help generalize the trends and sensitivity of our parameters [4]. Employing a L9 orthogonal array and the Taguchi method the number of simulations we would need to perform to understand the trends of our parameters is reduced from 81 to 9. An example of this type of array is shown below in **Figure 5.**



L_9 (3^4) Orthogonal array

	Independent Variables				Performance Parameter Value
Experiment #	Variable 1	Variable 2	Variable 3	Variable 4	
1	1	1	1	1	p1
2	1	2	2	2	p2
3	1	3	3	3	p3
4	2	1	2	3	p4
5	2	2	3	1	p5
6	2	3	1	2	p6
7	3	1	3	2	p7
8	3	2	1	3	p8
9	3	3	2	1	p9

Figure 5: Example L9 Array using the Taguchi method. Each variable has three different levels and these levels are varied for each experiment. The performance parameter is used to compare the results of each experiment [4].

When populating our L9 Array, as seen in **Table 4** on page 17, the performance parameter was the BSFC. For the compression ratio our low value was 12.2:1, which is the stock compression ratio. With the medium and high being 13:1 and 13.5:1 respectively, these are targets for the compression ratio we could achieve with upgraded pistons. For the air fuel ratio our parameter is Lambda. We selected our low to be 0.85. 0.93 was selected for the mid range value, this was the AFR we ran at MIS 2019. 1.05 was selected as the high value. 1.05 is actually beyond the leanest we have run the engine in previous testing but it was selected for the sake of observing the trends in GT-power. The boost targets were 1100, 1450, and 1800 millibar absolute pressure for low, mid and high respectively. For ignition timing we chose to delay the timing from the current timing. The current timing is the most advanced the engine has run at (advanced timing is desirable for engine performance, but can have some side effects). For the low we selected to delay the timing by 6 crank angle degrees for each operating condition. Mid was chosen to be 3 degrees delay, and for high the timing was left untouched.

Brake Specific Fuel Consumption Weighting

Brake specific fuel consumption (BSFC) changes depending on the operating condition of the engine, so in order to compare results from each run, a weighted average was used. Data collected from the 2019 Michigan International Speedway endurance event was used to determine the percentage of time spent at wide-open-throttle (WOT). These percentages can be seen in **Figure 6**. So, the BSFC value that will be reported later in this report will all be weighted by this standard. An example showing how brake specific fuel consumption changes at different operating conditions is shown in **Figure 7** from the first run of the Taguchi Method.

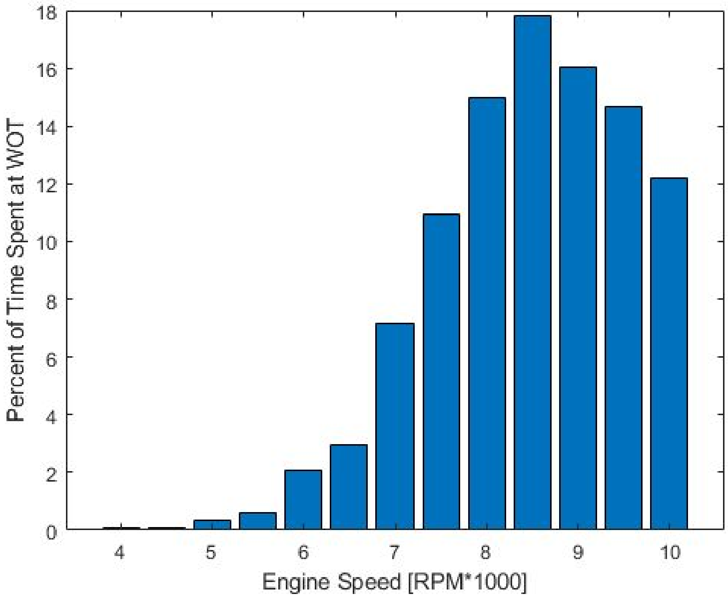


Figure 6: Percentage of time spent at wide-open-throttle (WOT) per engine speed during the 2019 Michigan International Speedway endurance event.

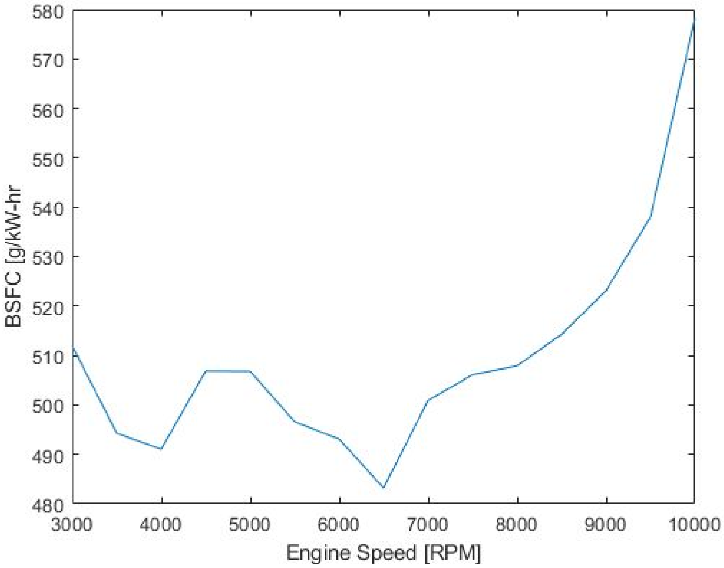


Figure 7: Taguchi method run one brake specific fuel consumption (BSFC) per engine speed, as an example of how BSFC changes based on engine operating conditions.

Taguchi Method Results

Once each combination of parameters was decided for the Taguchi Method of analysis, each of the 9 runs were performed in GT-Power. The resulting weighted average BSFC from each of these runs can be seen below in **Figure 8**. These results are also in tabulated form below in **Table 4**.

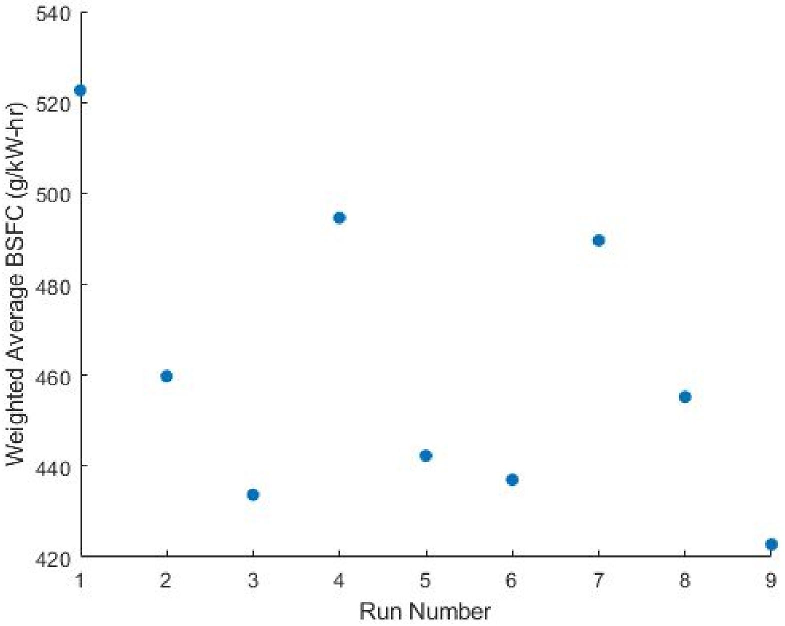


Figure 8: Weighted average BSFC for each combination of parameters tested during the Taguchi Method design of experiments. Runs three, six and nine have the three lowest BSFC which correspond to the leanest lambda tested of 1.05. Also, the three highest BSFC runs correspond to the richest lambda tested of 0.85.

Table 4: Each run of the Taguchi Method design of experiments showing how each parameter was varied for each run. The weighted average BSFC for each run is also reported here.

#	Compression Ratio	Lambda	Boost (mbar)	Ignition timing (degrees)	Weighted AverageBSFC (g/kw-hr)
1	12.2:1	0.85	1100	-6	522.6263
2	12.2:1	0.93	1450	-3	459.8051
3	12.2:1	1.05	1800	0	433.7397
4	13:1	0.85	1450	0	494.6092
5	13:1	0.93	1800	-6	442.3504
6	13:1	1.05	1100	-3	437.0383
7	13.5:1	0.85	1800	-3	489.629
8	13.5:1	0.93	1100	0	455.2514
9	13.5:1	1.05	1450	-6	422.8582

Based on these results, it is reasonable to conclude that the air-fuel-ratio, or lambda target, has the greatest effect on BSFC. Each of the three runs that have the lowest weighted average BSFC correspond to each run that was done at the leanest lambda of 1.05. Conversely, the highest weighted average BSFC values correspond to each of the richest runs, which had lambda values of 0.85. It is also worth noting that each of the runs that resulted in the lowest BSFC were at three different compression ratios. This confirms our suspicions that further increasing the compression ratio will have an incremental impact on BSFC, since the current compression ratio is already relatively high.

Lambda Sweep

Our next step was to perform a lambda sweep in GT-Power. Based on the results from the Taguchi Method experiments, lambda was determined to be the most sensitive parameter to BSFC. First, a course sweep was done from 0.93 to 1.1. This was done to determine the general trend of BSFC based on the lambda target. A fine sweep was then performed around the area where the minimum occurs to determine the lowest BSFC to 0.01 accuracy. The results of this experiment can be seen in **Figure 9**. The lowest BSFC corresponds to a lambda value of 1.02. This knowledge will be heavily considered as we move forward with our project.

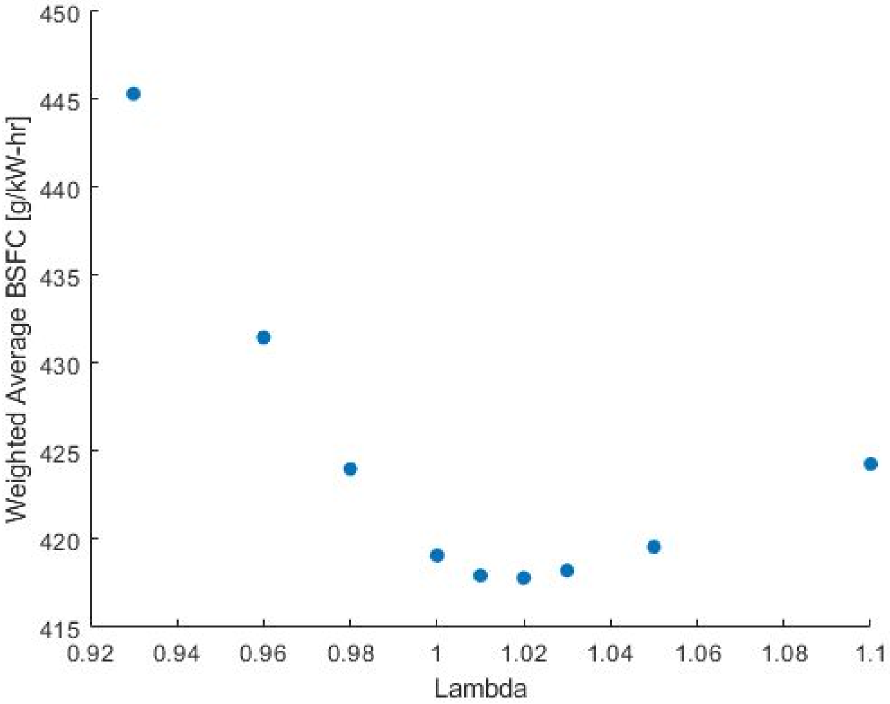


Figure 9: Weighted average BSFC vs. a wide range of lambda values. It was found that a lambda of 1.02 resulted in the lowest BSFC holding all other parameters constant with the baseline calibration that was used at MIS 2019.

Compression Ratio

A compression ratio sweep was performed before the Taguchi Method design of experiments was developed. This was due to the fact that changing compression ratios would require a rebuild of our dyno engine. The results of this sweep can be seen in **Figure 10**. The compression ratio that MRacing currently uses is already relatively high, at 12.2:1. Increasing it further would improve BSFC, but because it is already relatively high for a spark-ignition (SI) engine, concerns for knock or engine misfire are significant. The already high compression ratio also means that increasing it further would only result in incremental improvements to performance parameters such as BSFC.

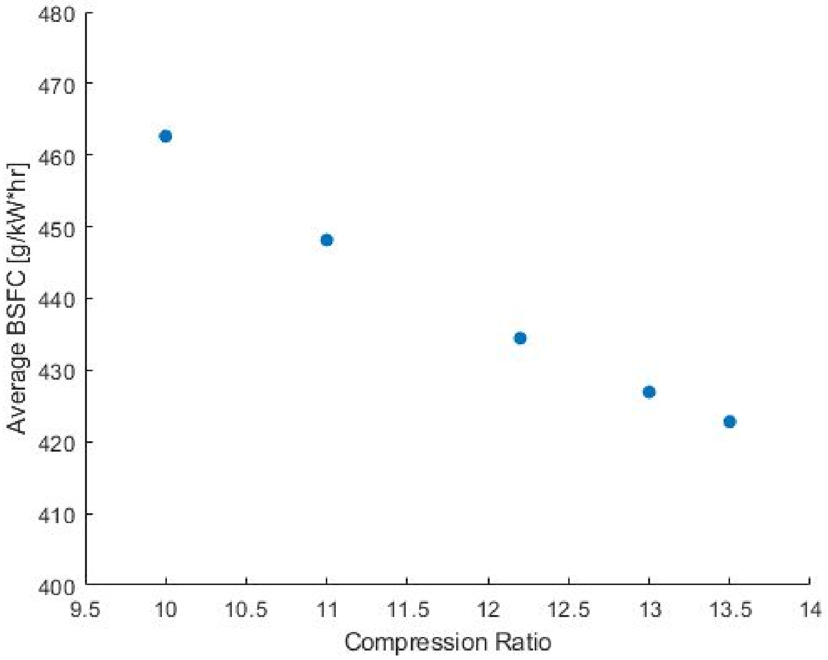


Figure 10: Average BSFC vs. compression ratio, showing the improved results of increasing compression ratio. The current compression ratio is 12.2:1, for reference.

Effects on Torque and Horsepower Output

Once the Taguchi Method design of experiments was completed and the three lowest BSFC runs were identified, the torque and horsepower curves were compared. It is important that we consider these parameters due to our lap time design requirement. As you can see in **Figure 11**, runs six and nine have horsepower curves with sharp peaks and relatively short power bands, as well as a lower peak horsepower. Run three has a higher peak horsepower and a much less dramatic peak, which results in a wider, more usable power band. This is most likely due to the high intake manifold pressure that was used in run three. It is reasonable to then assume that horsepower output is most sensitive to boost pressure. As we move forward with our analysis, horsepower curves will be utilized to determine the overall effect on lap times, which play a significant role in our projected performance at competition.

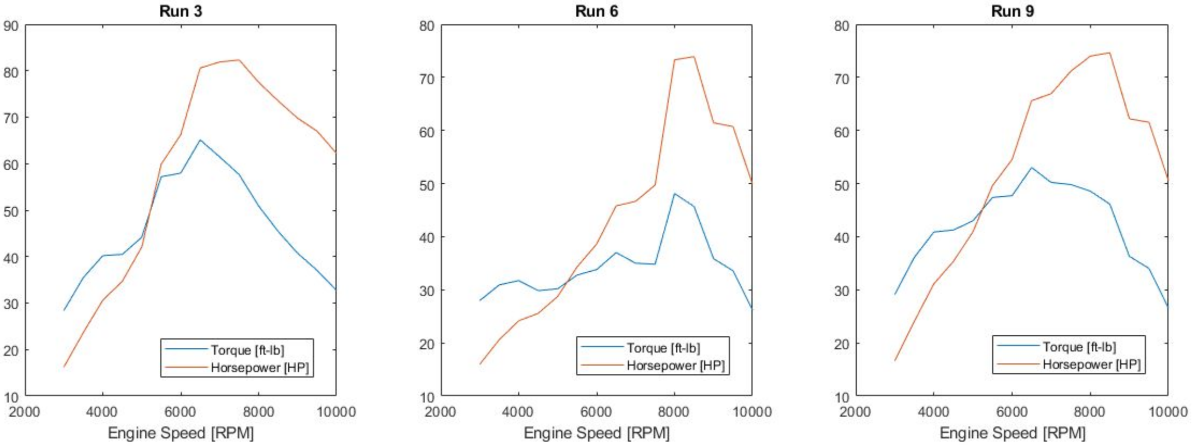


Figure 11: Three examples of torque and horsepower output for the three runs of the Taguchi Method design of experiments that resulted in the lowest BSFC; runs three, six and nine.

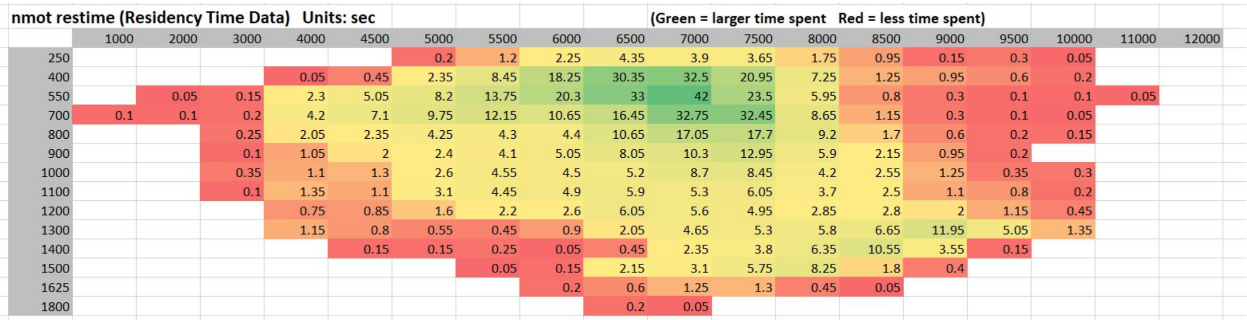
Final Concept Selection

Based on the results of our simulations, we decided to compare two different final calibrations at 1.02 lambda and 12.2:1 compression ratio. One calibration was set with a high max intake manifold pressure target of 2000 mbar absolute and more retarded ignition timing, and the other was set with a low intake manifold target of 1450 mbar and advanced timing. These two calibrations were chosen due to the low BSFC of a 1.02 lambda target. Intake manifold pressure and ignition timing are two different ways of controlling in-cylinder pressures, and thus both extremes are compared to determine which would theoretically result in the most points earned at competition. Both of these calibrations were simulated in GT-Power to obtain horsepower and torque curves and BSFC figures. Both horsepower curves were suitable for on-car use, so the projected points earned at competition were calculated using a fuel consumption model and a full-vehicle horsepower sensitivity study. This process will be explained in detail in the sections that follow.

Fuel Consumption Modeling

In addition to GT-Power fuel consumption predictions, MRacing has also developed its own fuel consumption model to predict fuel consumed during the Endurance event specifically, correlated to data from MIS 2019. From this model, we can directly compare how many points each simulated solution will earn us at competition.

The model is a collection of *MATLAB* scripts built with data collected on the car during the Endurance event at MIS 2019. The time spent at each engine operating condition was calculated from this data. An example of this can be seen in **Figure 12**. The air mass flow through the engine is then estimated for each of these operating points using intake manifold pressure targets, engine displacement and intake air temperature and thus a total air mass can be calculated. Once air mass is known for each operating condition, a fuel mass quantity can be calculated from targeted air/fuel ratios. Changes in time spent at each operating condition for each proposed solution can be accounted for by the change in horsepower. A full vehicle simulation was used to determine the sensitivity of horsepower on lap time. Thus, an accurate assumption can be made on the changes in lap time for each solution. The change in event time is then weighted by the time spent at wide-open-throttle (WOT) at each engine speed during the 2019 MIS endurance event. These times are then added or subtracted from residency times before they're used to calculate fuel quantity.



nmot restime (Residency Time Data) Units: sec (Green = larger time spent Red = less time spent)

	1000	2000	3000	4000	4500	5000	5500	6000	6500	7000	7500	8000	8500	9000	9500	10000	11000	12000
250						0.2	1.2	2.25	4.35	3.9	3.65	1.75	0.95	0.15	0.3	0.05		
400				0.05	0.45	2.35	8.45	18.25	30.35	32.5	20.95	7.25	1.25	0.95	0.6	0.2		
550		0.05	0.15	2.3	5.05	8.2	13.75	20.3	33	42	23.5	5.95	0.8	0.3	0.1	0.1	0.05	
700	0.1	0.1	0.2	4.2	7.1	9.75	12.15	10.65	16.45	32.75	32.45	8.65	1.15	0.3	0.1	0.05		
800			0.25	2.05	2.35	4.25	4.3	4.4	10.65	17.05	17.7	9.2	1.7	0.6	0.2	0.15		
900			0.1	1.05	2	2.4	4.1	5.05	8.05	10.3	12.95	5.9	2.15	0.95	0.2			
1000			0.35	1.1	1.3	2.6	4.55	4.5	5.2	8.7	8.45	4.2	2.55	1.25	0.35	0.3		
1100			0.1	1.35	1.1	3.1	4.45	4.9	5.9	5.3	6.05	3.7	2.5	1.1	0.8	0.2		
1200				0.75	0.85	1.6	2.2	2.6	6.05	5.6	4.95	2.85	2.8	2	1.15	0.45		
1300				1.15	0.8	0.55	0.45	0.9	2.05	4.65	5.3	5.8	6.65	11.95	5.05	1.35		
1400					0.15	0.15	0.25	0.05	0.45	2.35	3.8	6.35	10.55	3.55	0.15			
1500							0.05	0.15	2.15	3.1	5.75	8.25	1.8	0.4				
1625								0.2	0.6	1.25	1.3	0.45	0.05					
1800									0.2	0.05								

Figure 12: Residency times spent at each operating condition organized by engine speed and intake manifold pressure from the 2019 Michigan International Speedway endurance event.

Sensitivity Analysis

A full vehicle sensitivity analysis was performed to determine the effects of various vehicle parameters on event times and points. This study was performed using *VI-Car Real Time* software from *VI-Grade*. Using the results from this simulation, an estimate of changes in lap time due to changes in horsepower can be made. This is how changes in lap time were accounted for when estimating fuel consumption for new calibrations. A more in depth explanation of how this was done can be found in the fuel consumption model section above.

Points Analysis

The results from the GT-Power and fuel consumption modeling can be seen below in **Table 5**. Horsepower production seems to be more sensitive to intake manifold pressure, so the calibration with a higher maximum pressure target results in faster lap times. The lower boost calibration resulted in less fuel consumption, but when you consider the combination of both events, the high boost target calibration wins. The high maximum boost target calibration results in 322.0 points between the endurance and fuel efficiency events, up from our score of 301.3 at MIS in 2019. The lower boost target calibration resulted in 315.1 points, which would still be an improvement, but when considering both events, it is still more rewarding to have faster lap times.

Table 5: A summary of the two final calibrations compared to the baseline calibration used at MIS 2019. The calibration with a higher maximum intake manifold pressure target results in the most points between both the endurance and efficiency events.

	Average HP	Endurance Event Time (s)	Fuel Used (L)	Endurance Points	Efficiency Factor	Efficiency Points	Total Points
Baseline - MIS 2019	42.62	1329.128	6.316	237.8	0.560	63.5	301.3
2000 mbar - Low Timing	61.02	1303.832	5.991	252.7	0.602	69.3	322.0
1450 mbar - High Timing	52.63	1316.961	5.865	244.9	0.609	70.2	315.1

Failure Modes and Effects Analysis (FMEA)

Our FMEA can be seen in Appendix F. The highest risk failure mode we identified was engine knock caused by advanced timing and a lean air-fuel ratio. This failure mode can lead to serious engine damage including bent rods, melted pistons, or even a completely blown engine. This can not only get expensive to replace broken engine parts, but if a severe failure occurs on the car, it can seriously damage many adjacent systems, and even pose a risk to the driver. This failure mode has a moderate likelihood because our selected calibration is lean with a lambda target of 1.02, whereas in the past MRacing has experienced knock around a lambda of 1.05.

The best way to manage this risk is by continuing to monitor for it and prepare an alternative if it is found our solution produces too much knock. We will monitor for the risk by testing our solution on our engine dyno, and using our knock detection equipment to see if a knock event occurs and how severe the event is. Unfortunately the engine dyno can only test steady-state conditions, and if transience is to be taken into account, the solution will have to be tested for knock on the car as well.

Verification

From the results of our analyses we were able to complete verification for most of our requirements, though there are some that we were unable to verify due to COVID-19 restrictions. Notably, we were able to determine that, based on simulation results, we could not meet our first requirement of scoring 75 points in the efficiency event, as the highest efficiency score our models predicted was 70.2 points. However, we were able to achieve our second requirement of maintaining lap times, and even managed to reduce lap times by 2%. The reduction in lap times from the increased horsepower of our new solution makes up for the lack of points gained in efficiency, and brings our total points gained to 20.7, greater than the 11.5 points we were hoping to gain from the efficiency event alone.

We were also able to verify that our solution conforms to all FSAE rules and regulations. While the ultimate decision of whether our car can compete is up to the discretion of the technical inspectors, we have thoroughly read the rulebook and believe our solution does not violate any rules. Since we did not purchase any engine components, we also stayed within our budget requirements. The torque and horsepower curves output by GT-Power also allowed us to confirm that we met our drivability requirement by maintaining our usable RPM range and producing peak power between 8000-9000 RPM.

Unfortunately, due to the Wilson Center closing earlier than expected we were not able to test on our engine dyno and confirm our reliability requirement. This requirement cannot be verified by simulations and requires physical testing, both on the dyno and on-track to confirm. We will continue our work when our shop space reopens for the Winter semester. A more in-depth explanation of the verification process will be done in the discussion and recommendations section below.

Discussion and Recommendations

Our recommendations for how to continue will be detailed in this section. As stated above, we were unable to complete the testing and verification portion of the project. Engine dynamometer and on-car testing must be completed prior to using our recommended calibration at competition. How we recommend this testing be carried out is explained in detail below. That being said, we recommend that the team use a calibration that most closely resembles the highest points earning calibration from the points analysis section above. We recognize that the simulated calibration may not be feasible, so this calibration should be adjusted throughout the validation process. An attempt should be made to develop a calibration at, or close to, 1.02 lambda, at the maximum feasible intake manifold pressure considering knock and engine component strength, and the most advanced ignition timing feasible at that intake manifold pressure. At these operating conditions, it is likely that ignition will be knock limited for most, if not all engine speeds. Higher compression pistons are not recommended at this time, due to the incremental improvement that they would provide and the added complication to fitting them to every engine.

Engine Dynamometer Testing

From the results of our analyses, we planned to physically test the recommended calibration on MRacing's engine dyno. With dyno testing we would have been able to physically measure torque, horsepower, and fuel consumption, as well as engine reliability. This phase of the project was supposed to last until November 20th when MRacing would lose access to its dyno for the rest of the semester. Unfortunately due to circumstances outside of our control we lost access to the dyno on November 18th. Because of this unexpected shift in schedule and unforeseen problems with the dyno we were unable to complete any dyno testing. The engine dyno will be the first step in testing whether the recommended calibration is feasible and if any adjustments will be required.

Mock Endurance Event

Changes tested on our dyno will then be added to the physical car itself where we will be able to test them in as close to a competition environment as possible. The car will undergo a mock Endurance event in which lap times and fuel consumed will be measured and our mock Efficiency event score will be calculated. This will be the most intense test of our powertrain's reliability, and will determine if we satisfy our reliability requirement. This testing will be done in the spring, once the weather gets warm enough to test our car again. Expected completion is early March 2021.

Competition

Finally we will bring our car to competition in the summer of 2021 and test it officially at the Efficiency event there. At competition we will get our new Endurance and Efficiency scores, which will ultimately determine if we satisfied requirements 1 and 2.

Conclusion

This report contains an in-depth overview of our fuel efficiency project. Requirements and specifications serve as a design process framework for identifying engine characteristics and functionalities required to achieve our success with our solution. Our concept generation requires extensive research as each potential solution presents its own individual challenges and setbacks. Using GT-Power for computational analysis, we were able to learn how various key parameters and engine components affected the vehicle's powertrain and system. This engine simulation software served as a proof of concept to verify that we have a working, viable, effective solution prior to implementation.Through dynamometer testing and a mock endurance event the actual engine and vehicle will be put to the test prior to competing. Per the State of Michigan's epidemic order we had to cease work in the wilson center on 11/18/2020. Dynamometer testing could not have been completed with this sudden change and has impacted our team's ability to validate our proof of concept. Though we weren't able to complete testing, we determined that a calibration at, or close to, 1.02 lambda, and at the maximum feasible intake manifold pressure would allow us to achieve our goal of improving MRacings fuel efficiency. We hope next semester that testing can resume and be finished so we can implement our findings to the 2021 vehicle. All prototyping and testing is in preparation for achieving success at 2021 Formula SAE competitions.

Authors

Tom Eggleston: Tom has enjoyed burning corn and tires for three years on MRacing. He is looking forward to finally graduating with his Bachelor's after 30 years on planet Earth. He is also looking forward to helping lead the team to a 1st place overall finish at MIS this Summer. Hopefully, he will find a job despite complications due to COVID-19. Go fast, go blue!!

Teddy Gartland: Teddy has been on the team for three years and during that time has forgotten more about cars than he'll ever know. His diet largely consists of Mtn Dew Baja Blast and frozen taquitos. As a part of MRacing he occasionally makes excel spreadsheets and tries to figure out how to make every last piece of the car out of carbon fiber (piston heads are next on his list).

Miguel Escobar: Miguel is a hotrod enthusiast graduating in the fall. With a focus in mechanical engineering he joined MRacing to learn more about combustion engines and contribute to the team's success. After graduation Miguel looks to gain industry experience before returning to school to receive his MBA.

Ryan Jenkins, is a senior in Mechanical engineering with a passion for engines. He joined the MRacing members this fall to help in any way he could. Outside of class he is a part of the Michigan Men's Rowing team. After he graduates in the spring Ryan hopes to return to the University of Michigan in the fall to begin working towards his Master's degree.

Acknowledgements

We would like to thank our instructor, Heather Cooper, and our project advisor Harvey Bell for their input and encouragement throughout the semester. They helped us through the unforeseen challenges and unknown territories of our project. Their availability and willingness to make time for meeting during these challenging times helped us put together a project we can all be proud of.

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Appendix

Appendix A: Engineering Standards

In this project we chose to incorporate one specific engineering standard into our solution. Since our car is not a production car and does not need to be street legal, the only mandatory "standard" we had to follow was the FSAE 2021 rules [2]. This document sets safety requirements for our car that are quite strict, eliminating the need to use any typical standards for passenger cars used in industry. That we race on a closed course far away from other competition vehicles and are extremely light compared to production cars further reduces the need to use typical industry standards for visibility, comfort, noise, and emissions. We therefore felt confident that our solution could be safe and ethical by focusing on satisfying the FSAE rules.

Appendix B: Engineering Inclusivity

Our team worked closely with our stakeholder and sponsor, MRacing, throughout the semester. Since two of our team members are active members of MRacing, one of whom is the Powertrain lead and the other is the Technical Director, our design process directly involved the stakeholders in all aspects. Tom Eggleston is the Powertrain lead for MRacing and he had a clear vision for what he wanted to accomplish with this project. While we could have included more members of the MRacing powertrain team, working with the division lead directly reduced the amount of indecisiveness.

Appendix C: Environmental Context Assessment

Following the first two necessary conditions presented in the environmental context assessment, our solution has proven to be sustainable. Aiming to improve fuel efficiency, our key goal was to reduce the CO_2 produced during the 22km endurance event. Although our solution is focused to help MRacing, this improvement will create a significant difference in their future work from testing to competing. This significant change will greatly help with the paris climate agreement in reducing greenhouse gas emission mitigation. As we are only adjusting system parameters we anticipate our solution to have no environmental repercussions.

Appendix D: Social Context Assessment

This solution was developed specifically for a Honda CBR600RR engine running on MRacing's current powertrain system. It is unlikely that even other Formula SAE teams would be able to see the same benefits as our team when switching to our developed solution. These potential benefits get even smaller when extending the scope to the world of passenger cars.

Established automotive companies are continually striving for ways to reduce fuel consumption, for both economic and regulatory reasons. It is believed that their engine calibrations are already optimized to provide high power while minimizing fuel consumed. It is therefore unlikely, barring a new breakthrough in engine technology, that there would be significant gains to be made in the larger society by tuning manufacturers' calibrations for production cars.

For these reasons, we do not see our solution being adopted and self-sustaining in the wider market. Nor will it significantly affect existing planetary and social systems or be affected by disruptions in the status quo. For the most part, this solution is autonomous to the current societal climate and exists primarily for use by MRacing.

Appendix E: Ethical Decision Making

As engineers we were constantly facing challenges, conflicts and dilemmas during our design process. Having two members from our group that were a part of MRacing we had a greater sense of responsibility to the stakeholder and ourselves. Working around two major dilemmas, COVID-19 restrictions and time. We had to be realistic as to what could feasibly be done while maintaining personal integrity. Having an abundance of knowledge we could easily identify a single solution and stick to that method to achieve success. As Engineers from the University of Michigan we knew we couldn't fall behind the standard of outstanding so we chose to perform a utilitarianism test. This allowed us to determine all the foreseeable benefits and harms that would result from whichever course of action we chose. Also using a publicity test, we found as professional individuals we wanted to demonstrate as much knowledge and expertise that really exemplifies the engineers we strive to be.

Appendix F: Failure Modes and Effects Analysis

Table 6: Failure Modes and Effects Analysis

Item	Function	Failure Mode	Potential Effects	Root Cause	S	O	D	RPN	Recommended Action
Fuel Consumption model	Predict Fuel Consumed	More fuel consumed than predicted	Reduction in points at competition	Fuel consumption model not accurate	3	4	7	84	Test fuel consumed during mock endurance
Lap time sensitivity analysis	Predict Lap Times	Lap times are slower than predicted	Reduction in points at competition	Lap time sensitivity analysis not accurate	5	3	7	105	Validate sensitivity analysis
New Calibration	Produce power	Misfire	Reduction in power	AFR too lean / timing too advanced	3	5	5	75	Test new calibration on dyno
	Maintain good engine condition	Knock	Damage to piston and cylinder wall	AFR too lean / timing too advanced	6	5	5	150	Test new calibration on dyno
	Pass Technical Inspection	Fail Technical Inspection	Not allowed to compete with our solution	Solution not complaint with Formula SAE rules	8	2	4	64	Mock technical inspection before competition