Spring 2017

The Design and Testing of a High Performance Formula SAE Powertrain

Ryan T. Harty
The University of Akron, rth23@zips.uakron.edu

Recommended Citation

Harty, Ryan T., "The Design and Testing of a High Performance Formula SAE Powertrain" (2017). *Honors Research Projects*. 494.
http://ideaexchange.uakron.edu/honors_research_projects/494

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Ryan Harty

April 28th, 2017

Abstract

Every year the Society of Automotive Engineers (SAE) tasks collegiate students with designing, constructing, testing, and competing with an open wheel formula style racecar. This vehicle has to meet stringent technical requirements that are provided in a rule book published by SAE. The Formula SAE (FSAE) rule book is a very comprehensive set of requirements that are centered on safety of the driver of the vehicle and the safety of the track workers. The students are required to read and understand the rulebook in order to use sound engineering practices to build not only a high performing vehicle but a safe one. There are several aspects of the competition series to test the students understanding and knowledge of their vehicle. There are not only dynamic events that test the dynamic performance of the vehicle, but static events that test the knowledge and understanding of the students.

The Zips Racing team at the University of Akron has been competing in the FSAE competition series since 1990. The team is on its 27th vehicle design since inception and has recently switched its powertrain from a 600cc Inline 4 engine to a 450cc single cylinder engine. This report will detail why and how the switch in powertrains was accomplished. The design of the powertrain package will include a detailed analysis as to the selection of the base engine to be used, general conceptual design (Normally Aspirated or Forced Induction), and then particular component design to fit the overall conceptual design. The next section that will be evaluated will be the construction of the particular powertrain components. This is where material selection and manufacturing processes will be evaluated for each part. Once the powertrain is designed and then constructed, it is important to ensure it is tested to verify the package meets the design requirements that were previously chosen. When the powertrain is finished being tested, it is then essential to implement the package into the entire vehicle design. This is where component packaging will be determined. While these sections have been separated into distinct categories, there are a very close tie between each of them. One cannot exist without the other and many times one is found repeating the process to improve on a previous iteration. Overall, the Zips Racing team's powertrain package has proven to be a very high performance system that will deliver an overall win this year.

Introduction

The powertrain of a FSAE vehicle is one of the three most important systems that contribute to the forces that accelerate the vehicle. This leads it to be a large area or research and development for teams across the world. There are several optimal solutions that will achieve the same performance and efficiency goals, but the concept that was chosen by the Zips Racing team will be discussed. Many different aspects of the system need to be considered when choosing the base concept, those including performance, efficiency, reliability, cost, and manufacturability. A good compromise between all of the above aspects of the design will lead to a successful powertrain. These goals can be reached by a good decision making process, simulation techniques, build quality, and testing.

The rule book that is provided by SAE for the collegiate racing series limits the engine that can be used to a 710cc or less 4-stroke piston engine. Inside of this restriction the only other design parameters are that all combustion air needs to be passed through a 19mm restrictor plate and that only air and the fuel provided are to be burned in the combustion chamber of the engine. Beyond that all engine designs are open. This means that a team may choose to design their own cylinder block and head and machine the entire system, or a team may choose to select an existing engine as a base to then expand on. The decision of which route to pursue is based on the performance, efficiency, reliability, cost, and manufacturing goals of that particular team. The Zips Racing Team at the University of Akron has evaluated many different options for the bas of the powertrain and has ultimately chosen the 2008 Yamaha WR450. This engine is produced by the Yamaha motor corporation and is intended for use in an off-road motorcycle. Below in Table 1 & 2, the decision matrix for which this engine platform was selected can be seen. A detailed list for all engine platform options can be found in the appendix.

Engine Selection Decision Matrix

Weight	Category	1	2	3	4	5	6
35%	***Weight***	4	5	2	4	4	3
25%	***Performance***	4	2	5	4	3	4
15%	***Life Span***	3	2	5	2	3	2
10%	***Safety***	3	3	5	2	3	2
10%	***Cost***	3	3	3	2	3	2
10%	***Manufacturability***	3	3	2	3	3	2
	Totals	16	13	20	13	15	12
	Weighted Totals	3.75	3.45	3.7	3.4	3.5	2.95

Table 1: Engine Platform Selection Matrix

Key	Engine Model	Year Range	# of Cylinders / Type	Stock Displacement (cc)	Stock Compression Ratio	Bore (mm)	Stroke (mm)	Ratio	Fuel Injected (y/n)	Transmission	Oiling	Weight (lbs)
1	Yamaha WR 450	2008	Single	449	12.3:1	95	63.4	1.498	n	5 Speed Wide	Dry Sump	73
2	Yamaha WR 250	2008	Single	250	12.5:1	77	53.6	1.437	n	5 Speed	Dry Sump	68
3	Yamaha YZF R6	2007	Inline 4	599	12.8:1	67	42.5	1.576	y	6 speed	Wet Sump	112
4	KTM 450 SX-F	2015	Single	449	12.6:1	95	63.4	1.631	y	5 Speed	Dry Sump	75
5	Honda CRF 450X	2010	Single	449	12.0:1	96	62	1.548	n	5 speed Wide	Dry Sump	72
6	Aprilia SXV 4.5	2009	77 Degree V-Twin	449	12.5:1	76	49.5	1.535	y	5 Speed	Dry Sump	85

Table 2: Engine Platform Selection Key

The Yamaha WR450 was selected because of it compromise between all of the selection criteria. Since there is no minimum weight in FSAE, weight is the most important factor when making design decisions. Because of this it is given the highest weight in the decision matrix. The performance of the powertrain is the next most important aspect in the selection of an engine platform. The performance of the engine will dictate the maximum amount of tractive force that can be created to accelerate the car. The following selection criteria revolve around the cost and manufacturability of the engine platform. The combination of these selection criteria lead to the decision that the 2008 Yamaha WR450 is the best engine platform for the Zips Racing Team.

This engine platform will then be analyzed and a simulation model of the engine will be created using AVL Boost 1D to predict the performance characteristics of this engine. This will allow many design iterations to happen in a small amount of time, thus maximizing potential gains. After the simulation portion is complete and the performance goals have been met, the engine will be built to the specification that was determined via the simulation. Upon completion, the engine will then be installed on an engine dynamometer to retrieve actual performance data to validate the simulation model. At this point, the engine will be calibrated using a Motec M150 Engine Control Module (ECM) to ensure that the correct air to fuel ratio (AFR) and minimum best ignition timing (MBT) are being achieved. Following the calibration of the engine on the engine dynamometer, the engine will be installed into the FSAE vehicle for in vehicle testing. There will be final calibration changes made in the vehicle to account for vehicle acceleration and to ensure that the calibration also meets the efficiency requirements. The powertrain system will then remain in the vehicle for the remainder of the racing season to allow for testing of other on vehicle components.

Design

With the selection of the 2008 Yamaha WR450 engine, performance targets can be set and evaluated for the selected platform. In general, the goal of any high performance powertrain should be to maximize the mean power of the engine over the entire operating range. This will give the vehicle the highest acceleration over the entire lap, thus reducing lap time. The operating range determined for the WR450 was chosen to be 7000 RPM to 11000 RPM. This was chosen based on engine platform limitations as well as historical data that was collected on track. With a proposed operating range, the performance needed can be determined. Using data collected from the previous competitions, it is reasonable to expect a peak power output of 60hp form a normally aspirated 450cc single cylinder. The power goal was set at 65hp. This would give the engine a power to weight ratio of one pound per one horsepower (better power to weight than many professional racing engines). It was also determined that the engine will be normally aspirated instead or forced induction to reduce failure points, weight, and complexity. To achieve this power goal AVL Boost

1D simulation software was employed to predict the performance of the engine package. A sample of this model can be seen below in figure 1.

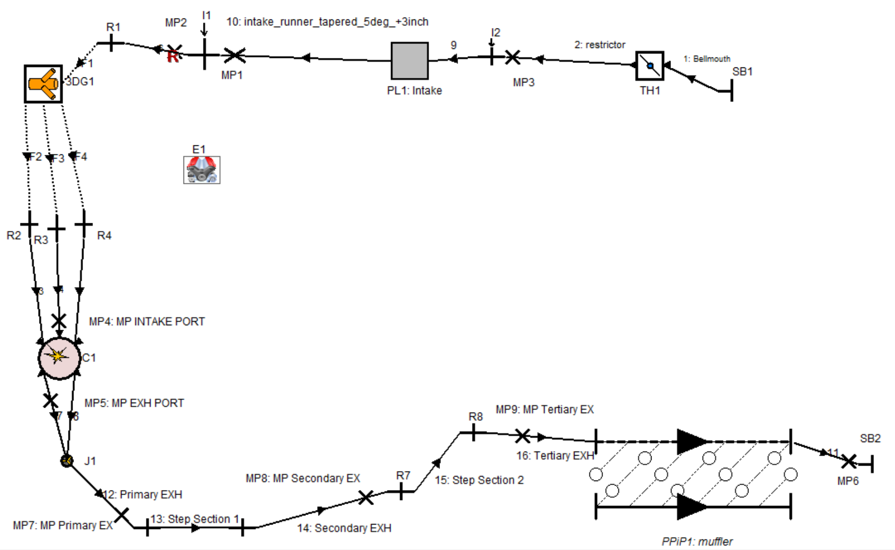


Figure 1: AVL Boost 1D Simulation Model

Using this simulation model the performance of the engine package can be predicted. This allows for quick and easy changes to the engine design. Many different configurations of the engine can be tested to determine if they are worth pursuing before investing in the design. This will ultimately same time and money, both of which are scares in FSAE. All aspects of the engine design will we evaluated to reach the performance target. These include the air induction system, fuel system, internal engine modifications, exhaust system, and power transmission system.

Air Induction System:

The air induction system on an engine is involved with taking ambient air and metering it to provide the proper air mass to the engine for a given torque request from the driver. This achieved by using some sort of throttling device. The throttling device can be as simple as a cable operated slide valve or as complex as an electronically closed loop controlled barrel valve. The chosen design for the Zips Racing team was a mechanically cable actuated barrel valve throttle body. A representation of the throttle can be seen below in figure 2 &3.

Figure 2: Cable Actuated Barrel Throttle Valve

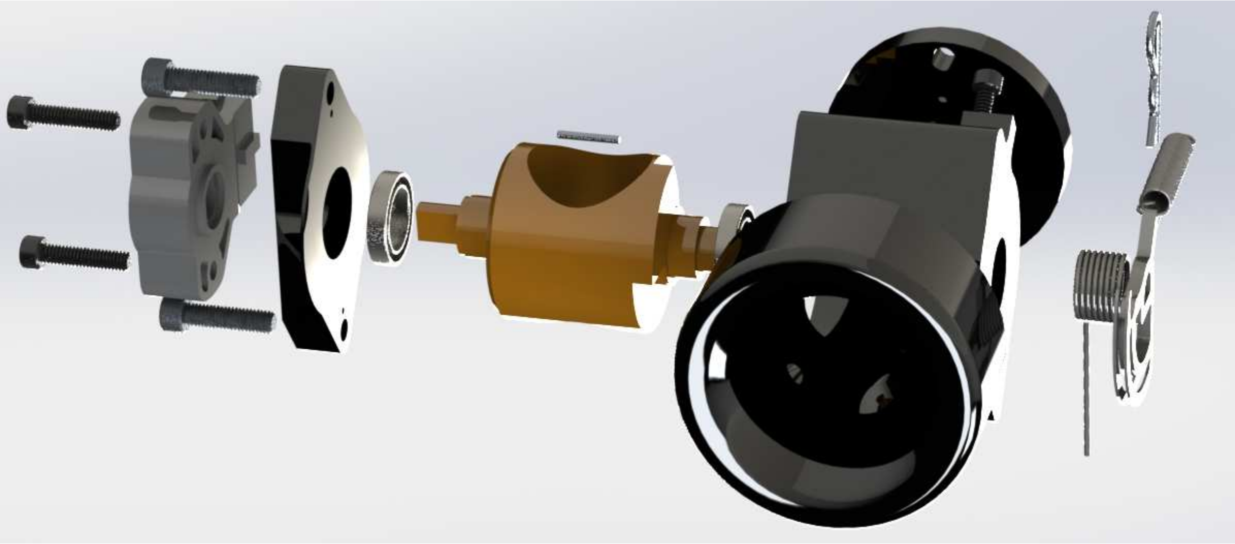


Figure 3: Exploded View of Throttle Valve

This method of actuation was chosen because of its simplicity and ease of service. The barrel throttle valve was chosen because of the more linear relationship between the throttle angle and air flow rate as compared to the throttle blade style. This relationship can be seen in Figure 4.

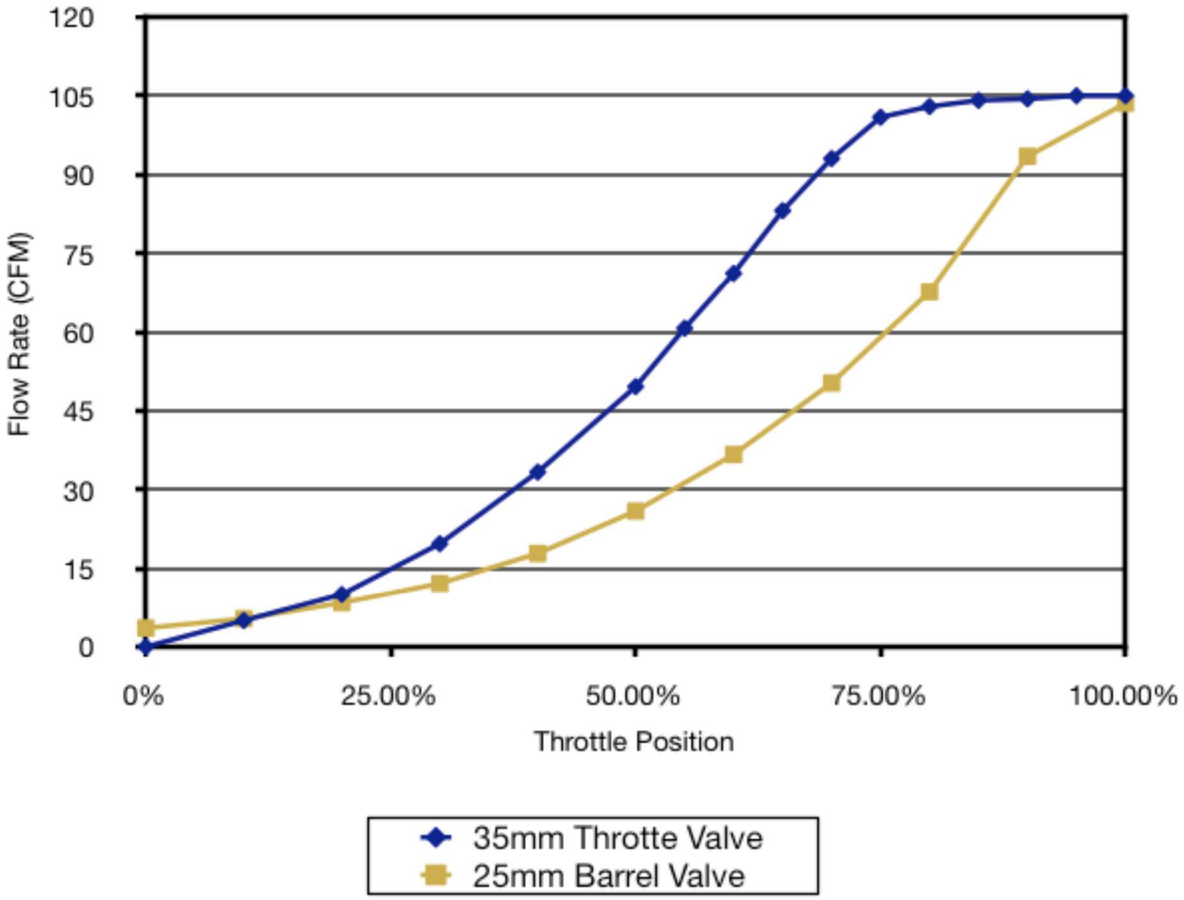


Figure 4: Throttle Position vs. Flow Rate

Per the FSAE rules, there needs to be an intake restrictor after the throttle valve. This is to limit the overall engine power that can be produced. The intake restrictor was integrated into the throttle housing and multiple different configurations of restrictor design were considered to limit the losses across the restrictor. A converging/diverging nozzle was chosen to reduce the pressure loss across the restrictor plate. A simulation was set up to investigate the optimal angles of the nozzle and the pressure differential across the restrictor was used as the defining goal. The goal was to minimize pressure loss across the restrictor. An example of the flow simulation can be seen below in Figure 5.

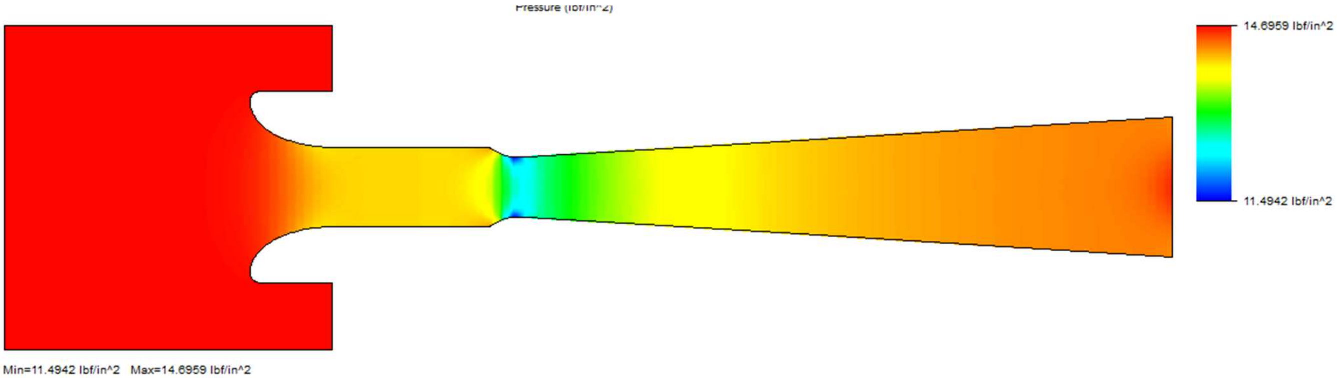


Figure 5: Pressure Cut Plot of Throttle Body Restrictor Geometry Study

After finalizing the throttle valve and restrictor geometry, the next component to be designed is the intake manifold. The AVL Boost model of the engine was used to determine the optimal plenum volume and intake runner geometry. These two parameters were iterated using AVL's built in optimization software to maximize power over the entire operating range. An example of this optimization can be seen in the figure below.

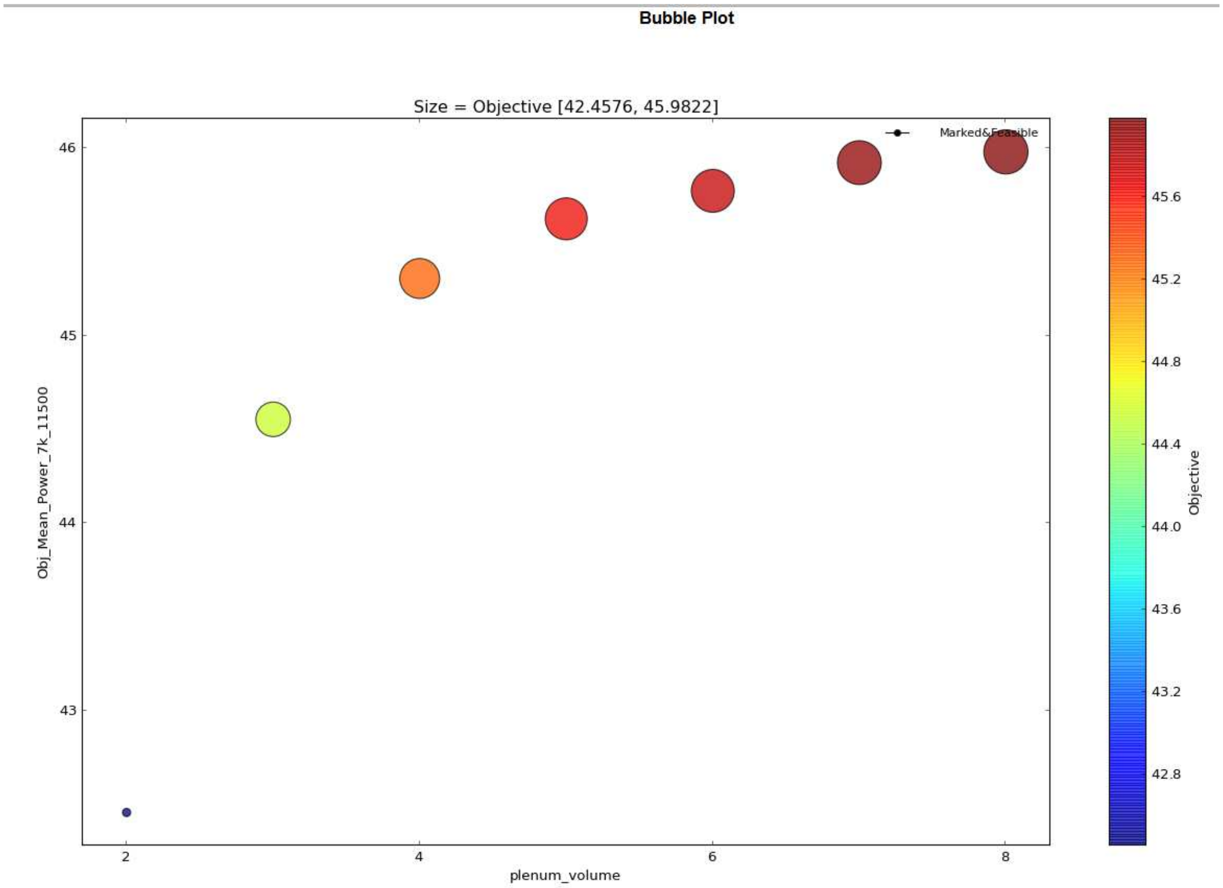


Figure 6: AVL Boost 1D Optimization Output

Once the optimal volume and runner length are determined using the 1D engine model, the intake manifold geometry can then be determined to package it on the vehicle. The method for manufacturing was chosen to be Stereolithography (SLA) 3D-Printed ABS. The SLA 3d printing process was chosen to reduce costs due to the complex geometry that is required to package the intake system on the vehicle. This also allows for integration of mounting for the engine, fuel injectors, various sensors, and the throttle body with very little restriction. As the intake manifold is being modeled and fit to the vehicle the design is constantly being check with a CFD flow simulation to ensure that the performance of the intake is not be hindered by the packaging constraints of the vehicle. This CFD simulation also allows for the fuel injectors to be placed in appropriate locations since a visual representation of the flow stream lines can be seen to ensure that the fuel is being injected into the airflow in the right direction. This can be seen in the figure below.

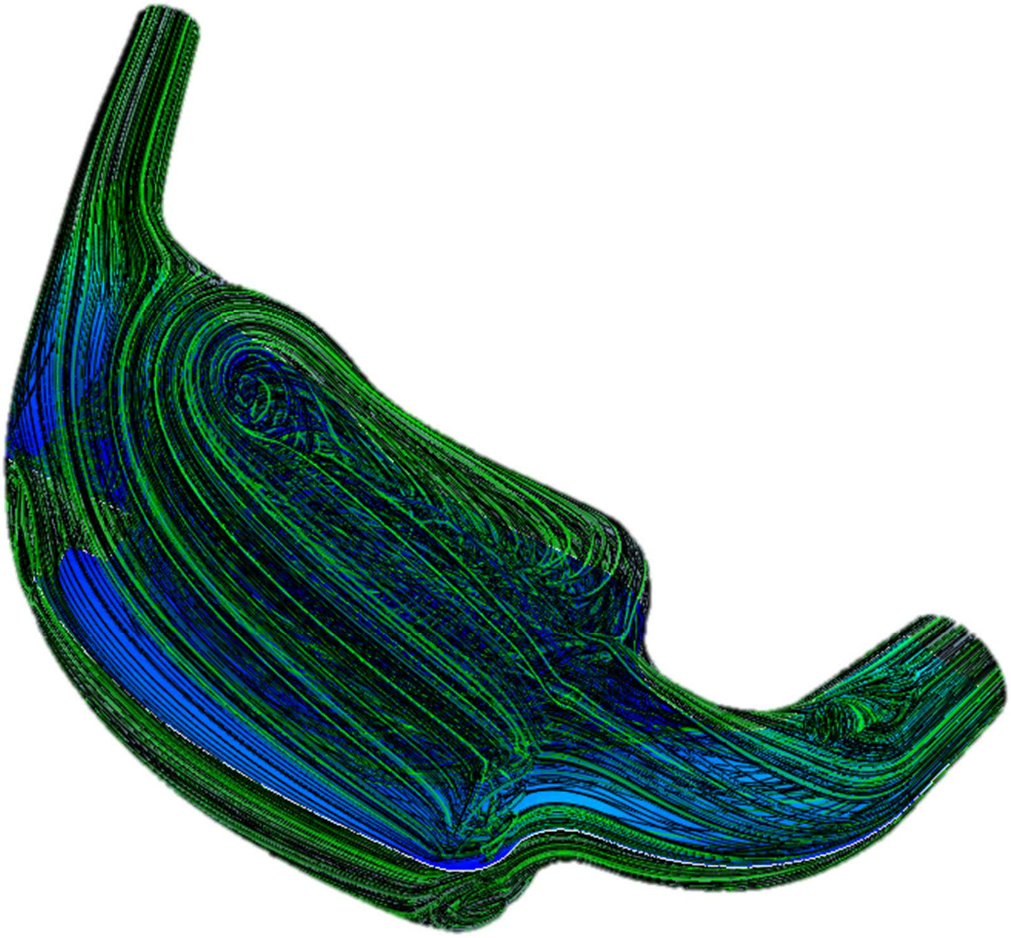


Figure 7: Intake Manifold Flow Simulation

After the intake manifold is adequately packaged on the car and all of the associated components have been added to the intake, the final assembly of the intake manifold can be produced. This allows for mounting to be manufactured and a bill of materials to be created and ordered. The final intake assembly model can be seen below in Figure 8.

Figure 8: Final Assembly of Intake Manifold

This design process has led to an overall high performance and reliable intake manifold design. There is still room for improvement in the CFD simulation technique. The software is complex and powerful which could lead to more performance if the flow paths can be optimized. Another area of improvement can using carbon-fiber reinforced polymer (CFRP) construction to build the intake manifold. This area has been investigated and a prototype has been built using this manufacturing process, however it is cumbersome and requires too many man hours to produce. If the manufacturing process can be improved then the CFRP construction can be used.

Internal Engine Components:

Once the intake manifold has been designed, the next components along the path of the engine are the internal engine components. The components that will be focused on will be the piston, camshaft profiles, and transmission. The camshaft profiles are responsible for controlling the combustion air charge and its timing of entering and leaving the combustion chamber. The intake camshaft is responsible for controlling the intake air charge and fuel that is going to be used to produce power. The camshaft operates the intake poppet valve(s) to allow the fresh air intake charge into the cylinder. This event happens very rapidly and needs to be controlled very accurately. If the intake valve is opened too soon it can contact the piston and if it is opened too late it can allow the piston to push air back out of the cylinder. The intake cam profile is determined by clearance limitations and air flow requirements. With the natural reciprocating motion of the piston engine pressure waves are created and reflected in the intake runner. These pressure waves can be used to increase the amount of air that is forced into the cylinder. If the clearance limitations allow, the intake cam profile can allow the valve to be opened long enough for the high pressure wave to be reflected back at the intake valve and allow the cylinder to be filled more. This intake resonance theory is how the Zips Racing team determines runner length and intake cam timing. The cam profiles are an input to the AVL Boost 1D model and can be iterated on based on the same highest mean power output objective. After this optimization the cam profile is determined and can be seen in the figure below.

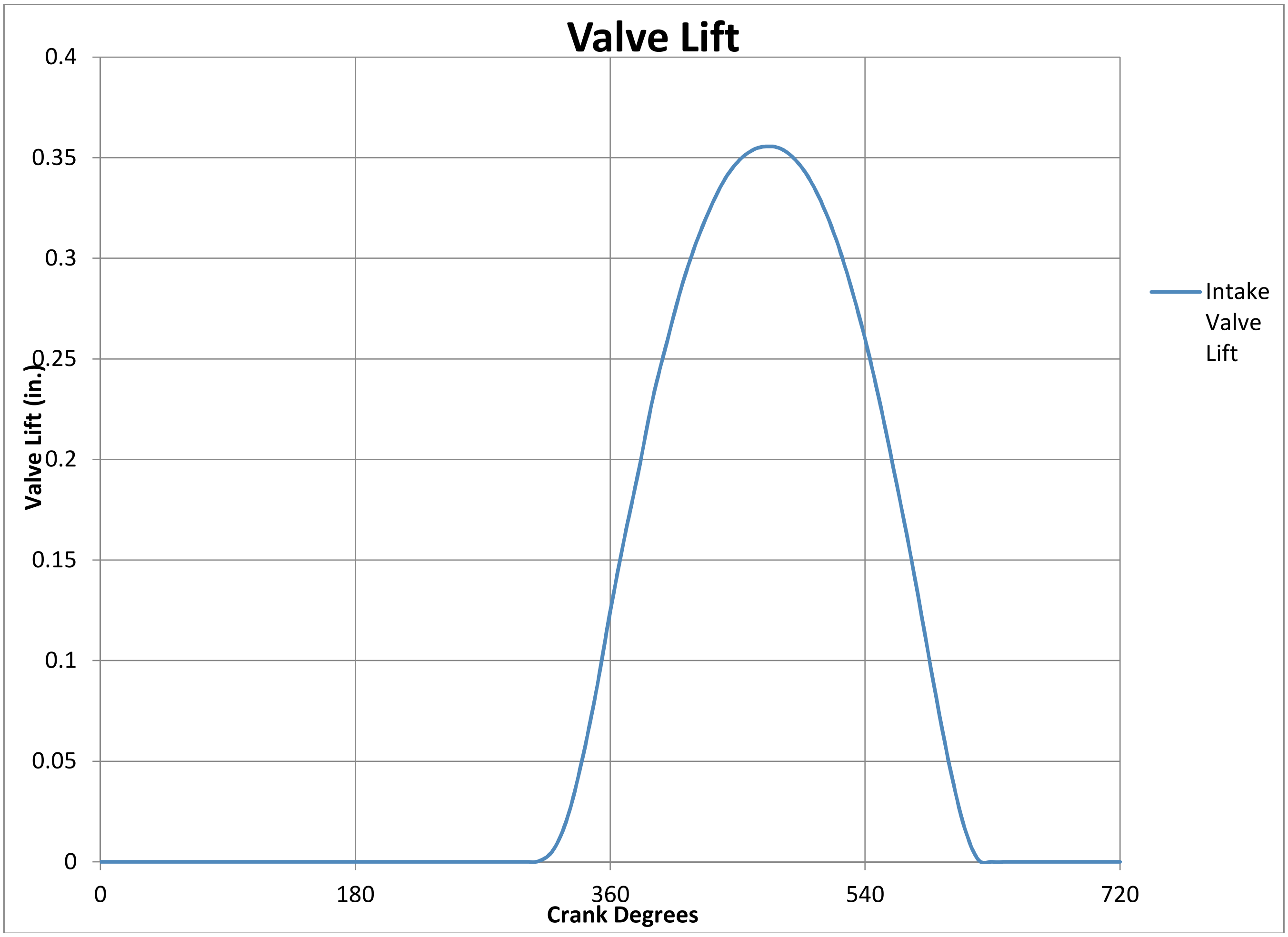


Figure 9: Intake Camshaft Profile

After the intake cam profile has been iterated on the exhaust cam profile can be determined. The exhaust cam shaft is responsible for controlling the flow and timing of the combustion gases from the combustion chamber to the exhaust system. Again the profile and duration of the valve event is limited by the clearance in the engine and the overall piston motion. If the valve is opened to early the power produced is limited since gasses are able to escape the cylinder while the piston is still capable of producing power and if the valve is closed too late it may contact the piston. Along with the intake valve the exhaust valve profile is optimized using the AVL Boost 1D engine simulation software. The optimal exhaust camshaft profile can be seen below.

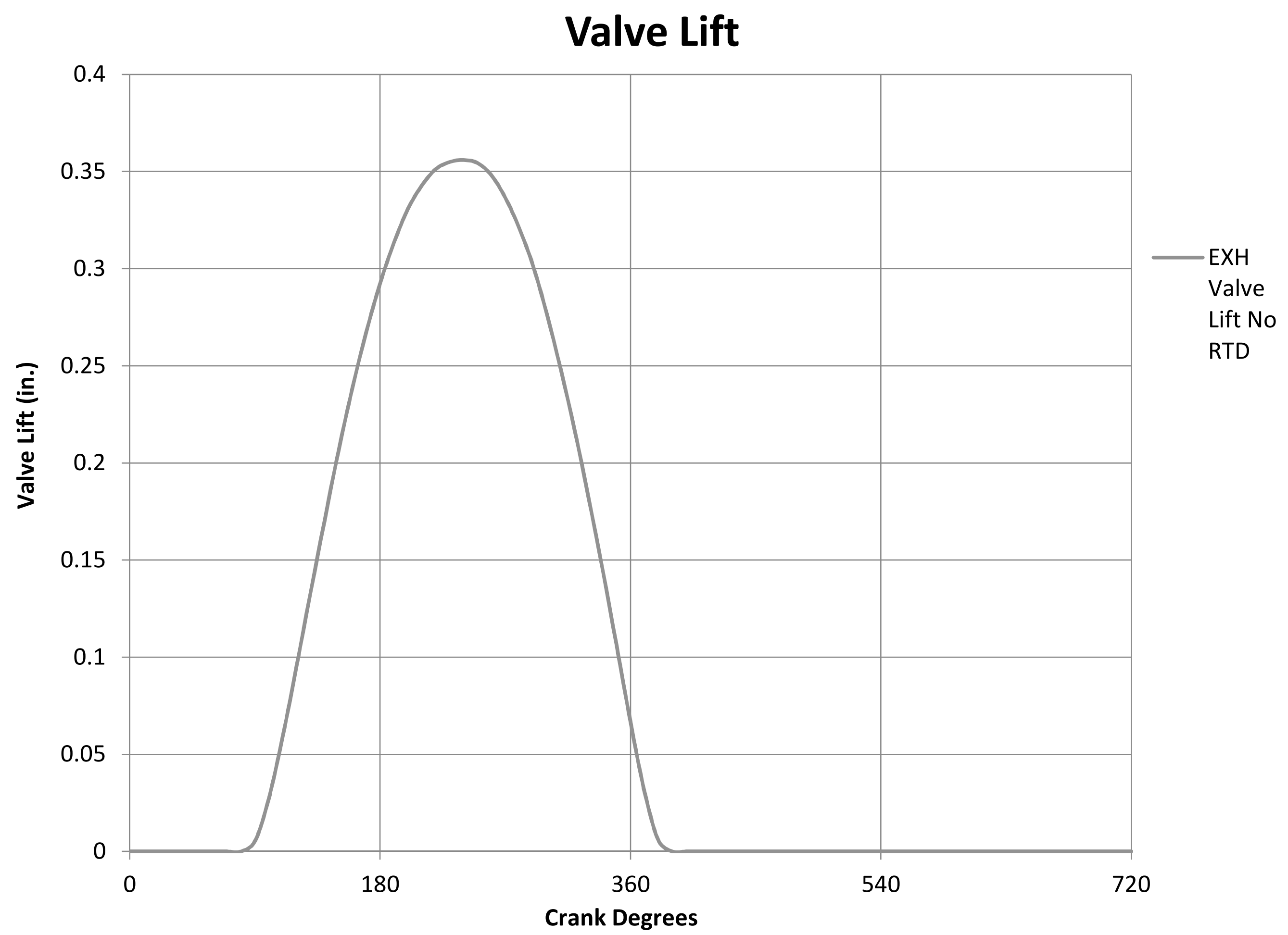


Figure 11: Exhaust Camshaft Profile

Once the camshaft profiles have been determined the piston can be designed. The piston is the main component that converts the gas pressure from combustion to useful mechanical power. The goal of the piston should be to have the highest compression ratio that is allowed by clearances and fuel limitations (namely knock resistance). The compression ratio of an engine be defined using the equation below:

$$CR = \frac{Displacement\ Volume}{Clearence\ Volume}$$

The compression ratio is mainly controlled by the clearance volume that is available in the engine. If this clearance volume can be decreased the compression ratio is increased. The design for the piston for the Zips racing team came with a collaboration between a highly renowned piston supplier and the team. This allowed for the performance goals to be achieved and for the piston to feature a level of craftsmanship that would be unattainable otherwise. The engine was very closely measured and modeled to determine where material could be added and taken away to raise the compression ratio to above 16:1. This compression ratio was a compromise between the increased thermal efficiency gained and knock propensity given the fuel provided. This decision was also largely based on an optimization using the AVL software and engineering principles to determine what a good compromise would be. The thermal efficiency can be defined by the equation below:

$$Thermal\ Efficiecy = \frac{\text{Actual Engine Power Output}}{Theoretical\ Fuel\ Energy\ Power\ Output}$$

With the designs stated above the power output of the engine is increased by 58%. This requires that the components that are responsible for transferring that power to the wheels are capable. The transmission in the WR450 is included in the engine and due to cost and complexity concerns is not replaced. However, it is required to transfer the power of the engine reliably. To achieve this the transmission components are cryogenically treated to increase their toughness as well as REM finished. REM finished is a superfinishing process that removes surface roughness. This allows the transmission to run cooler, thus decreasing thermal loading because of the reduction in friction. Overall these two processes increase the strength and reliability of the transmission. [1]

Exhaust:

The exhaust system on the FSAE vehicle is the next component chronologically in the path along the engine. This system is responsible for directing the hot exhaust gasses away from the engine and driver. It is also responsible for suppressing the sound energy produced by the internal combustion engine. Like the intake and cam profiles, the exhaust system can also be tuned to increase the performance of the engine. When the exhaust valve opens there is a large increase in pressure. As this high pressure wave travels down the exhaust pipe, it is eventually reflected back at the valve. The goal of the exhaust system is to time this pressure wave so that it arrives at the valve when the valve is closed. This will result with a low pressure when the valve is open and thus aid in the emptying of the cylinder. This theory can be applied using the AVL software to iterate the exhaust runner length and diameter. This resulted in a two stepped exhaust header design that starts at 1.625in diameter then transitions to 1.75in then to 2.00in. This design gives a combination of many different exhaust runner diameters to give the broadest overall power. Figure 12 below is a rendering of the final exhaust header design. [2]

Figure 12: Exhaust Header Design

After the exhaust header has been finalized the next step is to meet the sound requirement set forth by the rules committee. Per the FSAE rules the engine needs to meet a sound emission requirement of 103dbC at idle and 110dBC at 7000rpm. This is to ensure that engines are not too loud for bystanders and track workers. The design process for the silencers that are used on the Zips Racing vehicle start with an expansion chamber that is then followed by a typical absorptive silencer. The expansion chamber is a simple devise that works to attenuate the sound energy by giving the exhaust gasses a chance to expand and cool. It also attenuates some of the energy by reflecting the exhaust pulse back at the next pulse to cancel it out. The volume of the expansion chamber is the most important design parameter which is governed by the length and diameter of the chamber. This type of silencer is referred to as a reactive silencer and has a cut off frequency. A cut off frequency is the frequency at which the silencer starts to become effective. It can be seen in the equation below how the cut off frequency will be effected by the length and diameter of the chamber.

$$f_c = \left(\frac{cS}{\pi L (S_1 - S)} \right)$$

Where c is the local speed of sound, S is the area of inlet and outlet piping to the chamber, and Sl is the area of the chamber itself. This equation can be used to preliminarily size the expansion chamber. Once the expansion chamber has been sized to match the cutoff frequency required, the absorptive silencer can be designed. Since the absorptive silencer is a bit trickier to design a simple calculation will not suffice and a simulation must be used. AVL Boost has a linear acoustics package that allows the user to set up and execute simulations to determine the transmission loss of a particular exhaust system. A model was created using the exhaust manifold that was described earlier and the expansion chamber. Once this model was created the design parameters of the absorptive silencer can be optimized. These are namely length, diameter, perforation density, and perforation size. The results of these sound simulations can be seen in the figure below. [3]

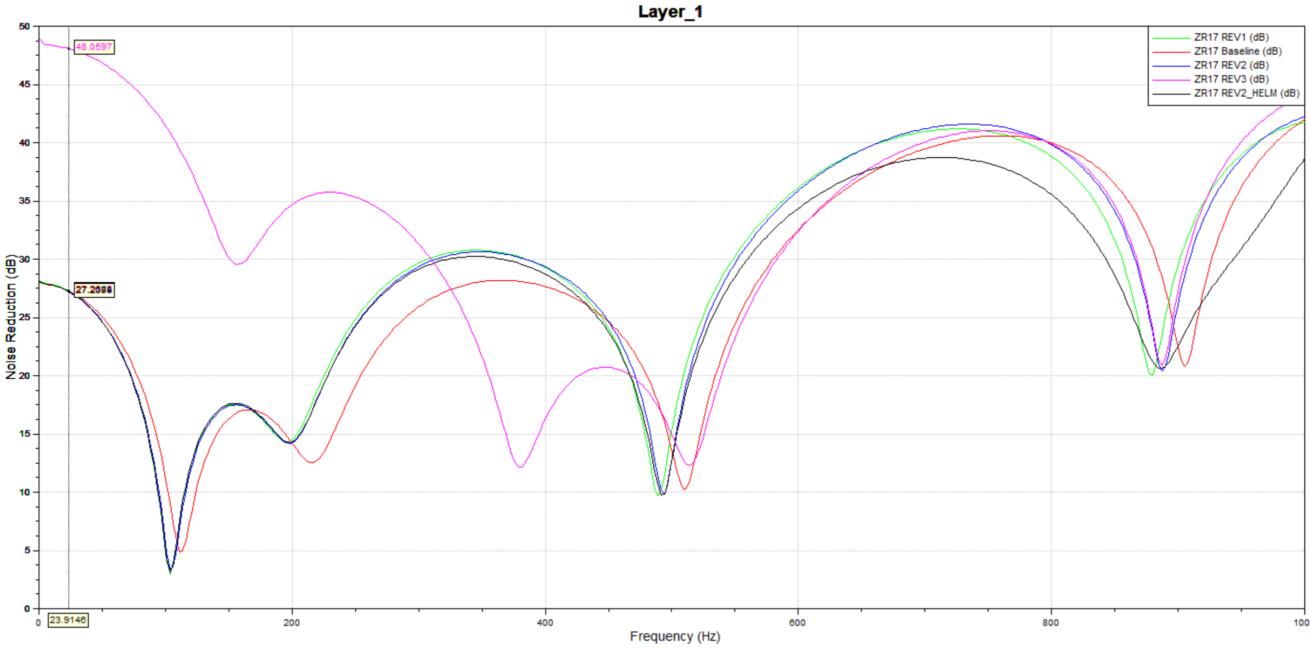


Figure 12: Sound Simulation Results

It can be seen in the simulation results that the total silencer system employed on the FSAE vehicle reduces the sound output of the engine by roughly 49dB over the unsilenced exhaust header. This gives the car a passing sound reading.

Cooling:

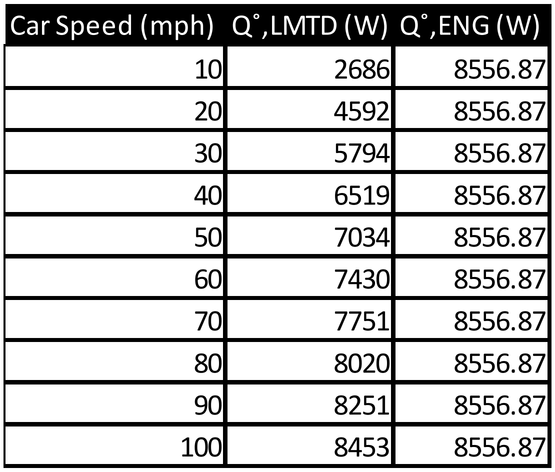
The internal combustion engine does not convert all of the fuel energy to useful work during the combustion process. Some of the energy is lost in light and sound, heat of combustion, and frictional losses that produce heat in the engine. Since there is a significant amount of heat created inside the engine, there needs to be a way to expel this energy to prevent premature failure of the engine components. This is achieved by using a water cooled system that passes water around the cylinder and cylinder head of the engine to control the temperature of those components. This heated water is then pumped outside the engine to some sort of air to water heat exchanger. This heat exchanger is placed in the natural airflow of the vehicle and relies on the vehicle speed to pass air over its cooling fines to remove heat from the water. The size of the heat exchanger depends on how much heat is necessary to remove from the engine. This can be achieved through some simple heat transfer calculations and testing iteration.

One way to determine the maximum heat transfer rate the cooling system needs to reject can be found using data collected from the engine dynamometer. The water flow rate, and temperatures coming into and leaving the engine can be measured and using the follow equation the heat rejection rate of the engine at full power can be determined.

$$\dot{Q} = \dot{\mathrm{m}} * \boldsymbol{c_{p,water}} * (T_H - T_L)$$

The maximum heat rejected from the 2008 WR450 was determined to be 8.5 kW. This will be the base line target when sizing a radiator. It is important to note that the heat rejection rate of the heat exchanger will vary with vehicle speed. This leads to the fact the heat exchanger will be operating in a very transient sate and will need to remove heat at various speeds. To achieve this a calculation was performed in Excel to determine 3 different heat exchanger configurations heat rejection capabilities as a function of track speed. This calculation was performed using heat transfer calculations from the water to the wall, through the wall, then from the wall to the air. [4]

The first configuration that was investigated was a single core single pass radiator from an YZF450 ATV. This configuration was considered because of its low cost and easy availability. Below is a table and graph of the heat rejected as a function of vehicle speed.



Car Speed (mph)	Q˚,LMTD (W)	Q˚,ENG (W)
10	2686	8556.87
20	4592	8556.87
30	5794	8556.87
40	6519	8556.87
50	7034	8556.87
60	7430	8556.87
70	7751	8556.87
80	8020	8556.87
90	8251	8556.87
100	8453	8556.87

Table 3: YZF450 Radiator Heat Transfer

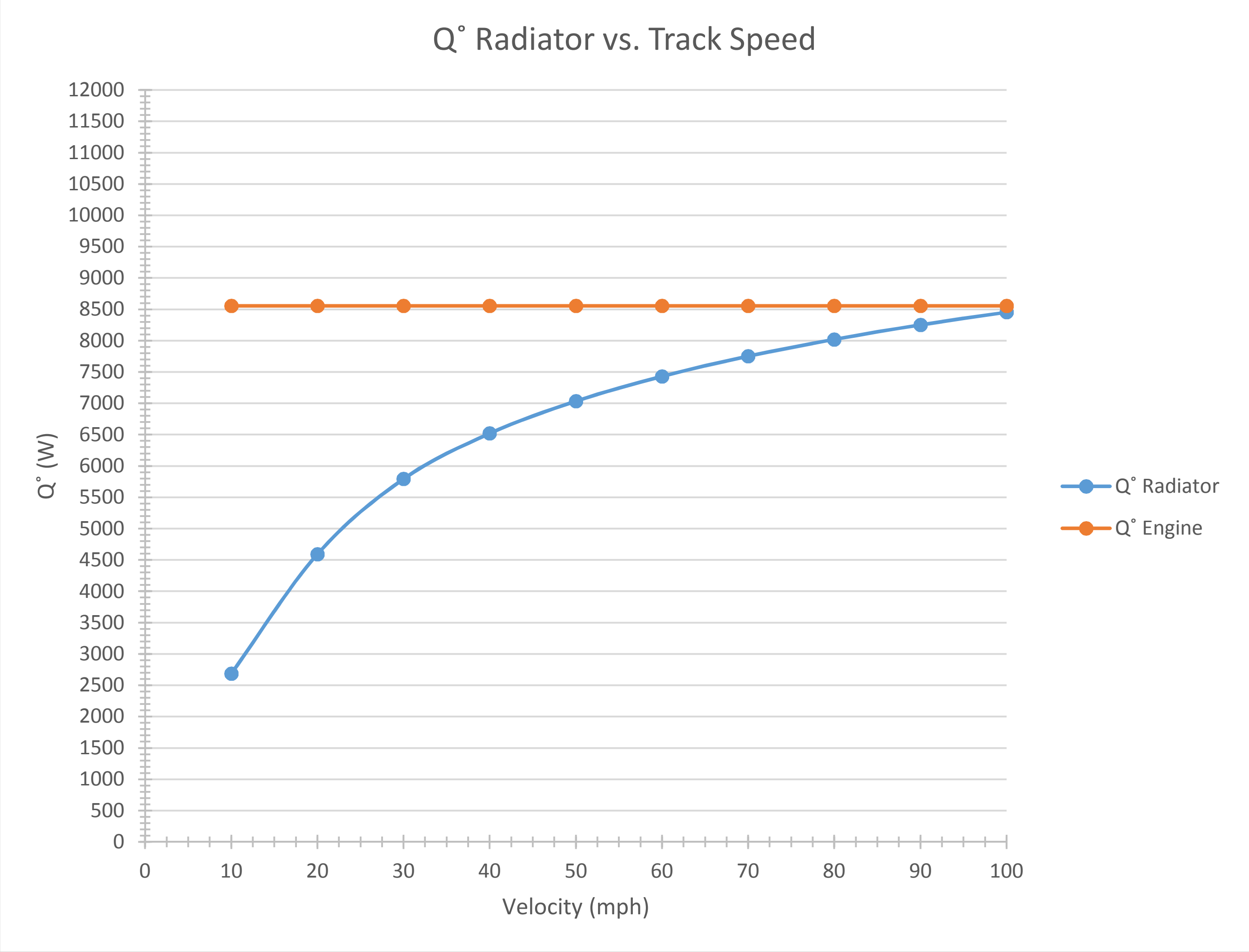


Figure 13: YZF450 Heat Transfer vs Vehicle Speed

As it can be seen in the figure above, the selected heat exchanger can never remove enough heat from the cooling water within the FSAE vehicle's operating range. This lead to the exploration of another option. The second option that was considered was a dual radiator design where two smaller radiators were mounted to the side of the car. These radiators were taken from a motorcycle with a larger engine than the WR450 and thus should have the cooling capacity required. Below is the data table from the dual radiator configuration.

Car Speed (mph	Q˚,LMTD (W)	Q˚,ENG (W)
10	3376	8556.87
20	7087	8556.87
30	8533	8556.87
40	9433	8556.87
50	10081	8556.87
60	10584	8556.87
70	10994	8556.87
80	11338	8556.87
90	11635	8556.87
100	11894	8556.87

Table 4: Dual Side Radiator Heat Transfer

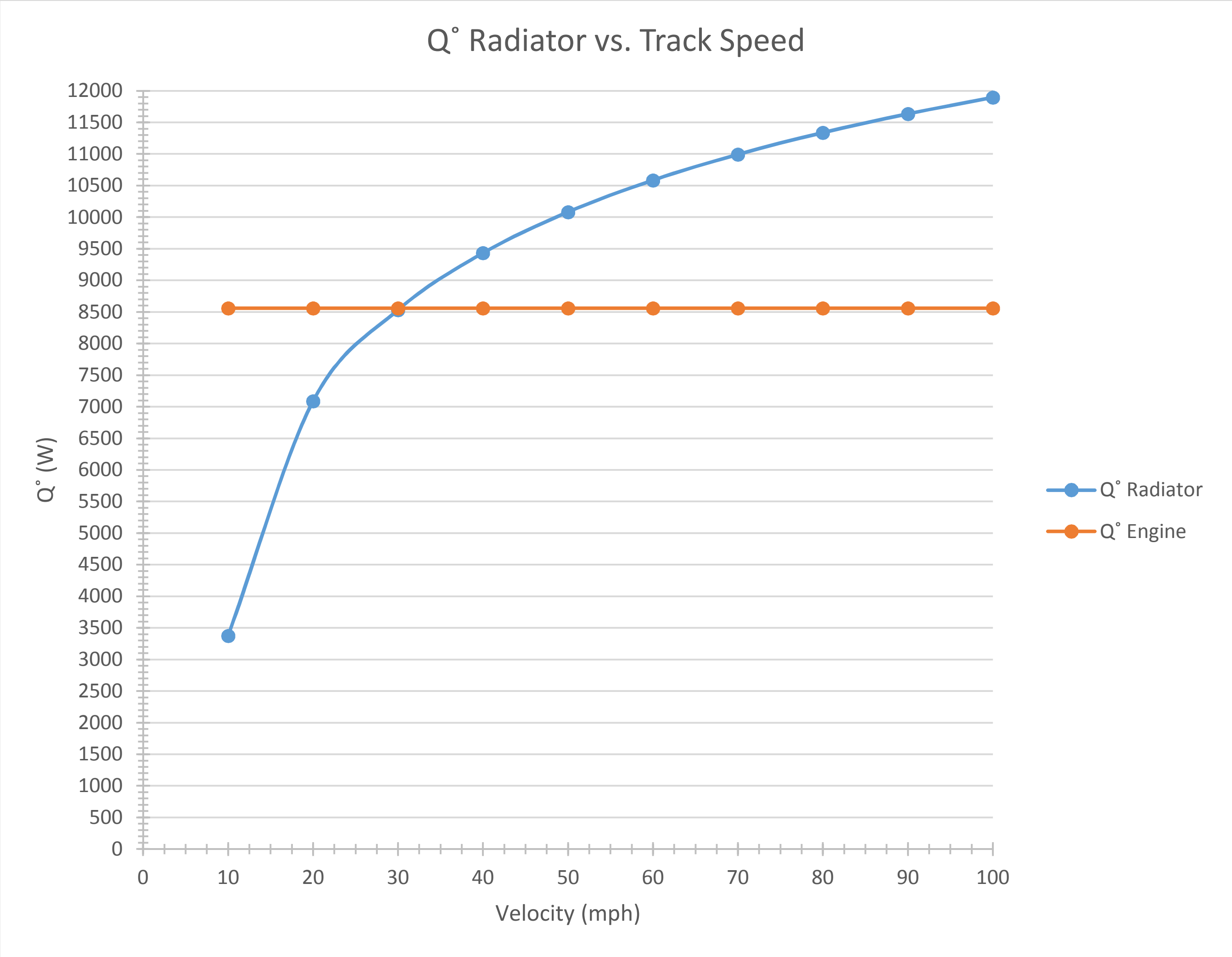


Figure 14: Dual Radiator Heat Transfer vs. Vehicle Track Speed

As it can be seen the dual radiator option will remove enough heat from the cooling water to ensure the engine is operating within its limits. At a track speed of 30 miles per hour the radiator will be able to cool the engine adequately. Below 30 mile per hour the radiator will require a cooling fan to pull air through the radiator at the slower track speeds. This configuration will offer adequate cooling capacity at a very minimal increase in weight.

Testing

After ensuring the powertrain meets the goals set forth for the design, it is important to validate all of the calculations and simulations that were performed. This is accomplished by building many of the components that were designed and physically testing them on the engine dynamometer. The engine will be built to the specifications determined and then tested to ensure that the simulation is predicating the proper power output. This step is extremely important and requires a very keen attention to detail. The engine requires a break in cycle to thermally cycle all of the new components and break them in. After this break in period the engine is ready to be tested at full load and have data recorded. The test bench being used is a Super Flow 901 engine dynamometer that is provided by the University and then outfitted with a custom data and control system to accurately measure all the important parameters. Below is the horsepower and torque curve produced by the 2017 spec engine.

MoTeC i2 Pro 1.0.21.0030 [Dyno Room Project 2-11-15]

[1:48.000] No Lap, 11:55:24 AM, 3/4/2017, , Dyno Room, AutoX Validation, Fuel Timing Fuck Up [20170304-0006702.ld]

0 Samples, Zoom Linked, Gated by RPM ROC

Time 0:56.320 [s] Distance 0 [m]

Figure 15: 2017 Spec Engine Raw Power and Torque Output

As it can be seen the power output is the blue curve and the torque curve is the yellow. The engine produces a peak power output of 68hp at 10,100rpm. This by far exceeds the expectations that were set forth at the beginning of the design season.

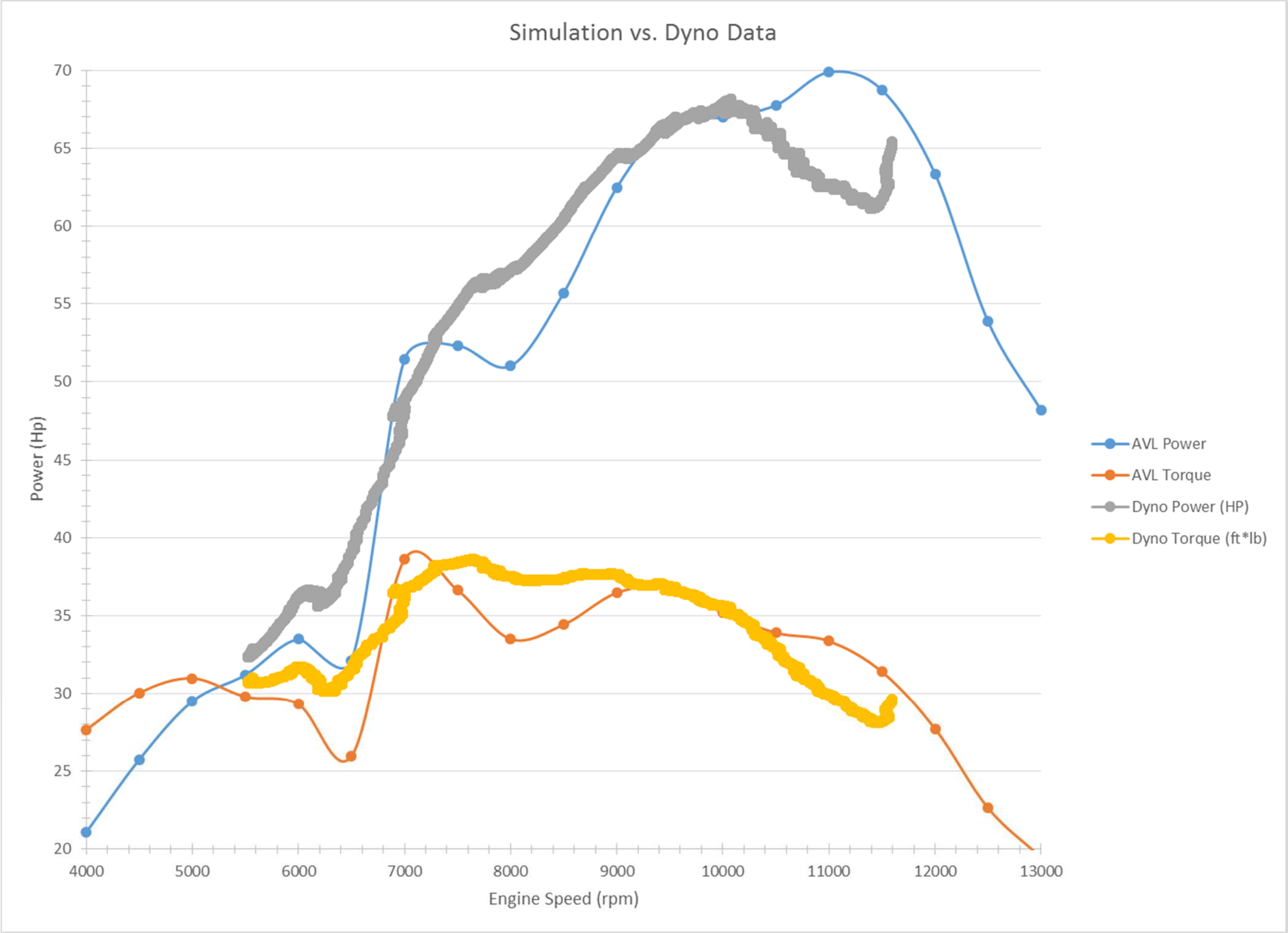


Figure 16: Simulation vs. Dyno Data Comparison

It can be seen in the above figure that the overall prediction of the power output is very close to that of the actual engine power output. The trend of peaks and troughs are in the same locations. The area of interest is the upper engine speed area where the two graph tend to deviate. It is hard to say for certain what causes this deviation, but the data points towards a restriction in airflow above 10500 rpm. The simulation uses flow coefficients to determine the performance of the intake and exhaust components. Currently these flow coefficients are set to one. In reality these flow coefficients are less than one and the simulation accuracy can be improved by finding the exact flow coefficients of these components. This can be accomplished by using a flow bench to determine the flow through a system and then comparing that to the theoretical flow capable of the device. This will ultimately lead to a more accurate simulation and better prediction of actual engine performance.

Conclusion

With the careful engine platform selection, it was shown that the 2008 WR450 was the best choice for the Zips Racing team in the 2017 racing season. This engine platform was then carefully evaluated to determine where the performance of the system might be able to be increased. The air intake assembly was evaluated using CFD flow simulation coupled with AVL's Boost 1D simulation software to determine the optimal intake geometries. The next components that were evaluated were the internal engine components. Again with AVL's software these components were iterated on the find the optimal geometries to increase the air flow into and out of the cylinder. This then played into the optimization of the exhaust runner length and diameters to ensure that the exhaust was tuned to offer the optimal pressure wave reflection. The exhaust was the simulated to ensure that the sound output of the engine would not exceed the sound limitations set forth by the FSAE rules. The next step in the design process was to ensure that the waste heat that the engine produced could be adequately rejected to the air to ensure the engine operated at a temperature that was with in specification. This was done by developing a calculation to easy compare different heat exchanger configurations and plot the heat rejection as a function of the vehicle speed.

With the design portion being completed, the next logical step is to build what has been designed and subject the design to testing. The engine was built to the specifications determined, and then tested on an engine dynamometer. The engine dyno confirmed that the overall power output of the 2017 spec engine was 68hp and exceeded the expectations set forth in the beginning of the year. During this testing the design has been proven to be tough and robust and will bring an overall win at the FSAE competitions this year!

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