Multidisciplinary Senior Design Conference
Kate Gleason College of Engineering
Rochester Institute of Technology
Rochester, New York 14623

Project Number: P12221

DEVELOPMENT OF A LIGHTWEIGHT, FUEL EFFICIENT ENGINE PACKAGE FOR FORMULA SAE COMPETITION

Brittany Borella
Mechanical Engineering

Stanley Fofano
Electrical Engineering

Taylor Hattori
Mechanical Engineering

Chris Jones
Mechanical Engineering

John Scanlon
Mechanical Engineering

Evan See
Mechanical Engineering

ABSTRACT

The primary objective of the design team was to create an engine model in GT-Suite and supplemental CFD analysis to include in the a new engine package for the RIT Formula SAE team, while providing extensive documentation and backing for engineering decisions. Additionally, engine testing on a DC Dynamometer and engine maps were required to ensure high power and optimum fuel efficiency. Furthermore, the design of a cooling system adequate for the varied conditions seen in competitions is outlined. During the course of the project, the design and testing procedures were well documented to provide support for design judging and future use of similar data. A theoretical model for the engine package was created and verified against empirical data, showing a strong correlation. The final tested design provided functionality requested by customer, however additional performance modifications that had been verified through the theoretical modeling were recommended to supply the horsepower metric requested by customer. The final product serves as a well-developed system that will be integrated into the RIT Formula SAE vehicle.

NOMENCLATURE

Air/Fuel Ratio – Mass ratio of air to fuel in the combustion chamber of an internal combustion engine
CAD – Computer Aided Design
CFRP – Carbon-fiber-reinforced polymer
CFRP Monocoque – Chassis made of CFRP in which external skin is the supporting structure which carries the major stresses
CFD – Computational Fluid Dynamics
DAQ – Data Acquisition System
DC Dynamometer – Setup used for measuring torque used by team to test, tune, and quantify modifications to the engine
Encoder – Device used to translate rotation of the engine to signals read by the DAQ
Formula SAE – Student design competition organized by SAE International to develop a small Formula-style race car
GT-Suite – Software used by team to create a virtual engine platform, and provide theoretical models for system
Honda CRF250R – Alternative engine used by team to preliminarily model valve flow
Intake Plenum – Chamber at the intake of the engine meant to hold the intake gasses at a positive pressure
Maximum Brake Torque (MBT) – Optimal ignition timing (minimum advance) to achieve maximum torque
Mean Effective Pressure (MEP) – Capacity to do work not dependent on displacement by the engine
P-V Diagrams – Pressure-Volume diagrams used to describe the thermal cycle of the engine
ProE – CAD Software package utilized by customer

RIT Engine Test Facility
Solidworks – Additional CAD Software package utilized by customer and team
Yamaha YZF-R6R (R6) – Engine package previously used by the customer
Yamaha WR450F – Current engine used by customer and team
Yamaha YFZ450R – ATV engine used by team to source appropriate radiator
WOT – Wide open throttle

INTRODUCTION

Fuel economy scoring in Formula SAE has become increasingly more competitive in recent years. The event, which measures fuel consumption over a 13.67 mile (22 km) distance, was previously worth only 50/1000 points. It has grown to be worth 100/1000 total event points, and is weighted based on the overall time required for a vehicle to complete the 13.67 mile (22 km) race. The RIT Formula SAE team has been able to rely on its impressive speed to consistently place in the top 5 of every competition it finishes. However, due to the more stringent fuel consumption rules many teams have developed lightweight, single cylinder cars which can both match the lap times of the more powerful four cylinder teams, and use approximately 60% of the fuel over the 13.67 mile run [1].

	Detroit	Germany
Design	**25**	**60**
Cost	**20**	**0**
Sales	**7**	**7**
Acceleration	**6**	**0**
Skidpad	**8**	**6**
Autocross	**25**	**18**
Endurance	**N/A**	**86**
Fuel	**40**	**42**

Table 1 - Summary of Points Lost during 2011 FSAE Competitions

Table 1 displays the points lost for each event in the two competitions participated in by the 2011 Formula FSAE team. As highlighted in orange, the majority of points lost are related to fuel economy and design documentation.

In order to stay competitive, RIT must develop its own lightweight, fuel efficient car to compete in the 2012 Formula SAE season. This new prototype will feature a full CFRP monocoque chassis, an aggressive aerodynamics package, and a highly modified engine package. Key to these goals is the development of the aforementioned engine package providing weight reduction, increased fuel efficiency, and required power. This development requires measurements of existing engine parameters, engine simulation, internal component design and modification, 3D CFD simulation, engine sensor specification and wiring, engine testing, data analysis of testing data, and engine calibration for both maximum power and optimized fuel consumption. The design team was tasked with creating an engine model in GT-Suite and supplemental CFD analysis to develop the engine package. Additionally, engine testing on an engine dynamometer and engine maps are required to ensure high power and optimum fuel efficiency. Engine parameters measured on the dynamometer must also be correlated with the analysis of empirical data and the theoretical model in order to provide a solid foundation for design reporting within the competition.

Table 2 below displays a summary of the most important customer needs as identified by the design team.

Customer Need #	Rank	Description
		Engine
CN1	1	Reduce fuel consumption compared to the previous engine package
CN2	1	The engine must provide sufficient power output and acceleration
		Control System
CN11	2	Provide accurate fuel delivery and measurement
		Cooling System
CN14	1	Allow operation in high ambient temperatures under race conditions
		Documentation and Testing
CN17	1	Documented theoretical test plan and anticipated results
CN18	1	Must provide a CFD analysis of the intake manifold, restrictor, and throttle
CN19	2	Must provide an accurate model of the engine in GT-suite

Table 2 - Summarized Customer Needs

PROCESS

A variety of methods for meeting the customer needs were evaluated, and compared against the customer constraints. The primary constraint was that the package must comply with all Formula SAE rules, including, but not limited to, the use of provided race fuel, spark ignition, and a four stroke engine. To allow for the selection of key systems without a bias, the options were compared using morphological charts.

The primary decision to be evaluated was the style of engine to base the new engine package on. Various displacements ranging from 250 CC (15.26 in^3) to 609 CC (37.16 in^3) were considered, in both naturally aspirated and forced induction layouts. While forced induction typically benefits horsepower per unit volume, its added complexity and weight can offset some of its benefits. Additionally, any air used in the forced inductions system is required to travel through the 20 mm (0.787 in) restrictor which greatly reduces the advantages of forced induction. Furthermore, as the weight and fuel efficiency of the new engine package was of top concern for the customer, engine packages below 550 CC (33.56 in^3) were favored for their lower mass and lower fuel consumption. Table 3 summarizes the morphological chart, and highlights three key engine packages. Firstly, the forced induction 550 CC (33.56 in^3) V-Twin which performed the worst in this analysis. Its increased complexity, lower reliability, and higher weight were highly detrimental to the customer's need.

			Engine Selection									
		Weight	NA 250 Single	FI 250 Single	NA 450 Single	FI 450 Single	NA 550 V-Twin	FI 550 V-Twin	NA 500 I2	FI 500 I2	NA 600 I4	FI 600 I4
Requirements	Fuel Efficient	5	1	1	1	0	0	-1	0	-1	0	-1
	Reliable	5	0	-1	1	0	-1	-1	1	0	0	0
	Light	5	1	1	1	1	1	0	-1	-1	-1	-1
	Practical	5	-1	0	1	0	0	-1	1	1	1	0
	Driveable	4	1	0	1	0	1	0	1	0	1	0
	Powerful	3	-1	0	0	1	1	1	-1	0	1	1
	Serviceable	3	1	0	1	0	1	0	1	0	1	0
	Complexity	3	1	-1	1	-1	0	-1	0	-1	0	-1
	Ease of calibration	3	1	-1	1	-1	1	-1	1	-1	1	-1
	Inexpensive	2	1	-1	0	-1	0	-1	1	0	1	0
	Attractive Sound	1	-1	0	0	0	1	1	0	0	1	1
	Totals:		**16**	**-3**	**33**	**0**	**14**	**-19**	**14**	**-11**	**16**	**-12**

Table 3 - Engine Selection Matrix; Naturally Aspirated (NA) Forced Induction (FI)

Secondly, the 600 CC (37.16 in^3) Inline 4 cylinder is highlighted as previously being used by the customer. While scoring relatively high, its higher weight and average fuel economy pull down its score. Finally, the 450 CC (27.46 in^3) single cylinder engine is highlighted as the selected system, due to its combination of low weight, minimal fuel usage, and reliability.

Additionally, the fuel used was considered using morphological charts. Three fuels were considered due to FSAE rule restrictions; 93 Octane, 100 Octane, and E-85. Through the analysis, they each received scores of 8, 11, and 9 out of 21 respectively. While 100 Octane was favored in this decision, all options proved viable.

A similar process was followed to evaluate components of the cooling system, such as the addition of an oil cooler, number of radiators, and use of a surge tank. Based on the decisions about each component, more detailed research was applied to each concept to verify the correct design path.

SYSTEM DESIGN

Engine Model

For preliminary analysis and design of the theoretical engine model in GT-Power, several assumptions needed to be established. The primary assumption was a simplified tubular geometry used for initial induction and exhaust models combined with CRF250R valve flow data scaled to approximate the WR450F. Additionally, the initial intake and exhaust valve lift was estimated from the Yamaha YZ400F to provide approximate values. These assumptions are later relaxed after accurate flow data for WR450F is obtained. For initial values of Air/Fuel Ratio, a value of 0.86 Lambda is assumed. The Wiebe combustion model parameters were estimated until cylinder pressure data could be obtained. Surface roughness values and wall heat transfer properties for steel exhaust sections were estimated. Finally, constant operating temperature and component temperatures were assumed, which was correlated with dynamometer data and iterated to provide an accurate model. In Figure 1- Schematic of Inlet & Exhaust

Valves below, a portion of the initial engine model is shown as it appears in GT-Power.

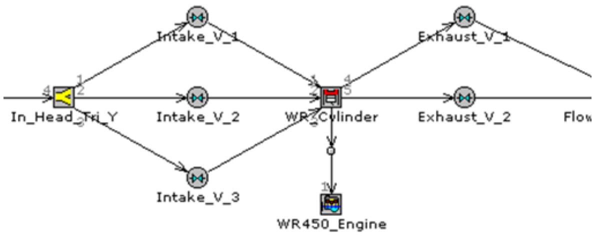

Figure 1- Schematic of Inlet & Exhaust Valves

In order to create a finalized engine model, several parameters were needed to iterate and validate the preliminary model. These included the finalized intake, throttle, and restrictor geometry, as well as P-V diagrams from dynamometer testing to validate Wiebe model assumptions. These parameters were gathered throughout the project in order to create the finalized engine model discussed in the results section.

Cooling System

The design of the cooling system occurred as a parallel process between theoretical design and reviewing empirical data from previous systems. An initial system schematic was designed to incorporate a radiator with a separate surge tank, water pump, and thermostat. The primary focus of the initial analysis centered on the sizing of the radiator. As a rule of thumb, it has been suggested that a 1.1 in^2 radiator surface area is needed per horsepower produced. Thus, it follows that approximately 66 in^2 will be needed at the desired horsepower rating. Based on the packing size and approximate required size, the radiator from a YFZ450R Yamaha ATV was selected for the initial design. This provides 86.25 in^2 of surface area, significantly more than the empirical estimation required.

Previously obtained data from the customer was analyzed to monitor average coolant temperature at the inlets and outlets of the radiator. Based on the rate of rise in temperature of the coolant, the heat rejection was calculated and scaled to the expected horsepower value of the new engine package. Using Equation (1), the required airflow (cfm_r) can be calculated and compared to the vehicle speed required to create the necessary airflow.

$$cfm_r = \frac{Q}{\Delta T} \qquad \textbf{(1)}$$

In order to verify the radiator is receiving adequate airflow at low speeds, two methods were used. Firstly, the airflow was calculated based on the predicted power of the new engine package, which resulted in a minimum airflow of 450 CFM. Second, the airflow was calculated based on the data supplied by the customer and average vehicle speed, which resulted in a minimum airflow of 500 CFM.

As an initial point of reference, the SPAL Axial Fan previously used by the customer was analyzed. With an 11" diameter, the fan provides 755.0 CFM of airflow [2]. While providing more than adequate airflow, the fan is larger than would package easily behind the radiator. A maximum of 7" diameter was allowable to fit the radiator, thus a Yamaha R6 fan was selected with a 5.5" diameter and estimated 500 CFM of airflow.

Additionally, a thermostat was selected to allow bypass of the radiator for faster engine warm-up. Placed at the outlet of the engine, a thermostat allows water to circulate through the block, but doesn't allow this water to circulate through the radiator until it has reached proper operating temperature. This temperature melts the "wax motor", which forces the thermostat piston to open and allows the water to flow through. If the engine's temperature is lowered too much, the piston closes until it has reached proper operating temperature once again

VERIFICATION

The DC dynamometer is a key component of the testing, characterization, and verification. Three main tasks will be performed using this equipment: Load Simulation, Power Characterization, and Fuel/Spark Mapping. The system primarily focuses around torque measurements and feedback from the DC motor. With the addition of thermocouples throughout the coolant system, the temperature rise through the engine is monitored, as well as the operating temperature. Through the use of wideband lambda, cylinder pressure, and crank angle, additional metrics can be monitored to create live P-V diagrams and calculate brake specific fuel consumption (BSFC).

Additional basic engine diagnostics are monitored through the use of a Motec M400 engine control module. Using the supplied software, the Motec ECM allows the creation of custom fuel maps for each event, and enables fuel/spark mapping; as well as provides built-in data acquisition.

Figure 2 - DC Dyno

The Dyno is controlled by the ECU shown in Figure 3 - DC Dyno ECU. A primary concern was that the ECU did not provide a high enough data acquisition rate to cope with the engine's high speed and pressure. Therefore, a new PCI card, the NI-PCI-6024E, was installed in the ECU. This provides 16 analog inputs, as well as digital inputs, at a rate of up to 200 kS/s [3]. This PCI card is solely dedicated to handle the fast input data, such as encoder data.

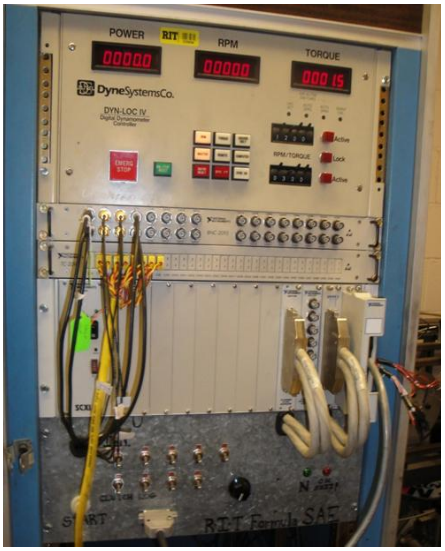

Figure 3 - DC Dyno ECU

To measure cylinder pressure the team used a transducer (112B10) and in-line charge converter from PCB Piezotronics. The transducer is connected to the spark plug so that it can measure the pressure applied by the piston inside the cylinder at any given time. The PCB pressure transducer had to be connected in series to a charge amplifier so that a reasonable measurement could be performed. The crystals in the transducer are very sensitive and their charge output had to be amplified for improved signal to noise ratio. Figure 4 shows a block diagram of the pressure measurement system:

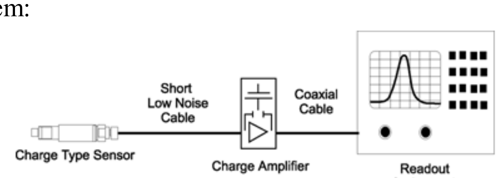

Figure 4 - Pressure Transducer Wiring [4]

The charge amplifier used was a Kistler type 5010B. The amplifier has a serial port to allow for a communication channel with a processing unit. However, the team decided it was unnecessary to use an extraneous connection and decided to use the amplifier as a stand-alone instrument. The amplifier has both voltage and charge inputs. The charge input was used in the design, and the voltage input was used for calibration and proof of concept. As can be observed in the next figure, the amplifier is composed of an operational amplifier in conjunction with parallel capacitors and resistors:

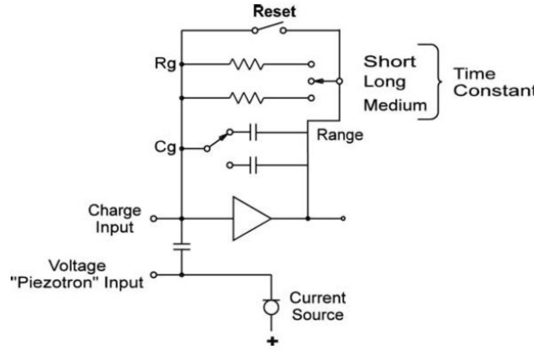

Figure 5 - Simplified Charge Amplifier Circuit [5], [6]

The charge amplifier was tested before being connected to the pressure sensor. A function generator was used to input a 2V sine wave into the amplifier. The amplifier was then set up according to the manual specifications. After experimenting with the amplifier's configuration, the group was able demonstrate proper function by measuring a 5V sine wave in LabVIEW.

An absolute, rotary, magnetic encoder was considered to measure crank angle and determine the position of the piston at any given time. It works by sensing the changes in magnetic field as the magnet above it rotates. The encoder outputs position in several ways including incremental, analogue sinusoidal, and linear voltage. The team must develop a casing for the encoder so that it can accurately measure the crankshaft angle.

Initially, the team pursued using a magnetic encoder. However, this type of encoder turned out to be impractical for the application because it was very sensitive to movement. An appropriate mounting of the magnetic encoder on the engine was not feasible.

After the magnetic encoder proved unreliable, the team pursued an absolute encoder. It was concluded that absolute encoders were unrealistic for budgetary constraints. The absolute encoder was desired because, in general, it has a better performance than an incremental encoder. Nevertheless, the group attempted to use an already available incremental encoder such as the one in Figure 6:

Figure 6 - Incremental Encoder [7]

RESULTS

CFD

In order to supplement the system design, DC Dyno data, and theoretical model, CFD models of specific components as well as the full vehicle were used.

The initial area focused on was the intake restrictor, which has a 20 mm inlet diameter (19 mm for E85) [1]. It creates choked flow conditions, limiting total mass airflow to engine. This is required by competition rules to keep engine power at a safe level for competition. The main design goal is to minimize the loss coefficient through restrictor geometry to allow maximum airflow into engine, which was approached using a supersonic converging – diverging nozzle geometry. An expanding out diverging section allowed for proper shock development in order to minimize the loss coefficient. The diffuser angle was kept low enough to avoid potential flow separation, while the overall length had to remain small enough to reduce viscous losses due to surface friction and boundary layer growth. This was then verified using a 2-Dimensional Axis-Symmetric analysis allowing for fast solving time with refined mesh in areas of shock development.

A second area of focus was the intake manifold, including the intake runner length and the intake plenum. The intake plenum acts as an air reservoir for the engine to draw air from during the intake stroke. The primary purpose is to damp out pressure pulses from the intake stroke to create steady flow conditions at the restrictor. Additionally, the intake runners provide the path through which the engine pulls air from the plenum into the combustion chamber during the intake stroke. Their length was decided by the harmonic frequency at various engine operating speeds, which can be used to create a resonant "tuning point". These were analyzed using a transient pressure boundary condition used to simulate pressure pulses within the manifold from an intake stroke. A piecewise-linear approximation was used for initial analysis and trouble-shooting.

In order to support the development of the cooling system, the radiator shroud structure was analyzed to ensure uniform airflow distribution across the radiator face and verify proper mass airflow through the radiator. The radiator was modeled as a material resistance with heat addition and flow re-direction to properly simulate airflow through the core. Finally, a full car simulation was utilized to verify that the shroud is receiving adequate airflow.

Engine Model/DC Dyno

The engine was mated to the RIT DC Dynamometer to obtain initial performance data and provide a baseline for the project progress. Upon successfully testing the engine on the DC Dyno, an initial fuel map was created using conservative ignition timing for safe, yet reliable running. Using MoTeC M400 Engine Tuning Software, ignition timing was incrementally advanced to more aggressive values. During this preliminary tuning, a primary concern was the potential for knock, a key consideration in fuel choice. During the ignition timing tuning, knock was not noticed using 93-octane fuel, thus the engine could be run at MBT. As knock was not seen with 93-octane fuel, 100-octane fuel was considered unnecessary and would provide minimal benefits. After ignition tuning, peak torque was increased by 1 lb-ft to 29 lb-ft and peak horsepower increased to approximately 42 hp, as seen in Figure 7.

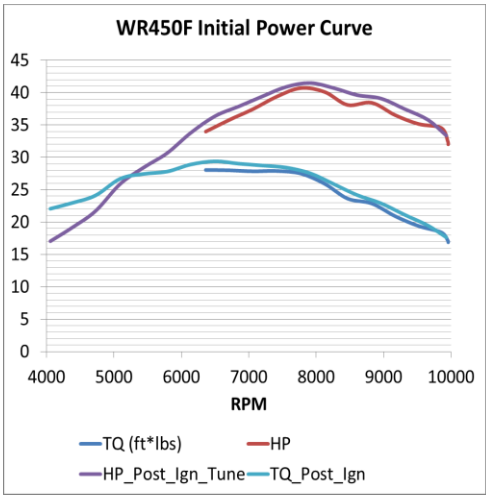

Figure 7 – Initial Power Curve from DC Dyno

After the initial spark tuning, the team investigated the effect of intake runner length on engine performance metrics. The runner lengths were varied in 2" increments from 6" to 10". This initial range of lengths was calculated using induction wave ram charging theory. While the shorter lengths slightly improved peak power, they also reduced low end torque, which agrees with common theory on runner length sizing.

After completing the investigation into intake runner length, the team focused on correlating the DC Dyno data with the theoretical GT-Power model. The initial model was created using general measurements taken from the test engine/intake/exhaust, as described in the system design. The accurate cam profiles and valve flow were integrated into the GT-Power model after being measured at Mercury Marine. While further measurements were ultimately needed to reduce inconsistencies between the theoretical model and physical components, these measurements provided an adequately accurate "second pass" model. In order for the model to be complete two major assumptions were made. Firstly, the fuel burn rate was assumed based on reasonable values, as the team did not have accurate experimental values. Secondly, the friction MEP (FMEP) had to be quantified. This is critical due to the fact that frictional losses need to be accurately measured for theoretical model in order to gain a realistic estimation of output.

In order to obtain FMEP, losses had to be measured using a special DC Dyno procedure concurrently with a specialized GT-Power model. The engine can be driven by the DC Dyno without fuel, essentially turning it into a large air pump. By using a simplified exhaust and intake runner, a simplified system can be tested that still includes pumping losses of the engine. This can yield the empirical PMEP of the engine. Concurrently, the team created a GT-Power model which accurately estimates theoretical PMEP. Thus by subtracting PMEP from the combined FMEP+PMEP data (typical Dyno run), an estimation of FMEP can be obtained. The curve that results should be quadratic in nature according to the Chen-Flynn Engine Friction Model (see Equation 2). The specific coefficient values are unimportant to this model, because friction is derived empirically. This estimation of FMEP was then input into the final engine model.

$$FMEP = FMEP_{Const} + A \times P_{Cyl,max} + B \times c_{p,m} + C \times c_{p,m}^2 \quad (2)$$

This finalized GT-Power model was then compared to results from the DC Dyno. A comparison of the empirical DC Dyno data and the theoretical values from GT-Power is shown in Figure 8. While predicting the DC Dyno values fairly well, the theoretical model does show slight inconsistencies. These can be accounted for through a variety of factors. Primarily, induction leaks in the intake plenum are likely at fault for the greatest error. Additionally, in the final model the cylinder head geometry is still largely approximated. In order to further improve the model, supplementary data from combustion analysis should be added, as well as, cylinder pressure measurement. Finally, to increase the model's accuracy post processing is necessary to determine mass fraction burn rate and 50% timing.

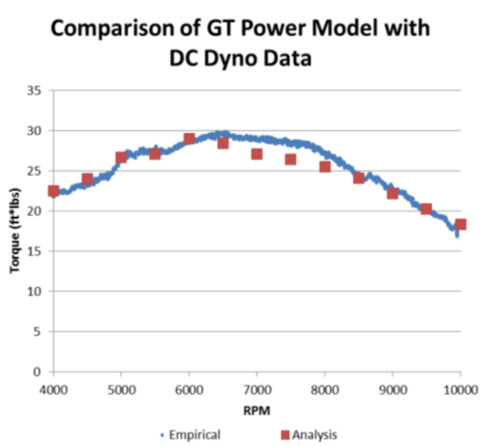

Figure 8 – Comparison of GT-Power and DC Dyno

Upon completion of a functional comprehensive theoretical model, the team evaluated the performance of the engine package to the established metrics. Improvements in performance are required to meet customer metric of at least 50 HP output. The DC Dyno data showed a 42 peak HP, leaving an 8 HP required improvement.

As an initial potential performance modification, a high compression piston was evaluated for an increase in horsepower. Based on the GT-Power model, the increase in compression ratio from 12.3 to 13.75 provided up to 4% improvement in power. Based on this data, the decision was made to purchase a piston from Cosworth for future DC Dyno evaluation.

In order to obtain the additional required power, several aftermarket camshafts were evaluated that are readily available for the WR450F engine. General data was acquired from Hot Cams detailing various different aftermarket cam profiles. Camshafts suggested by Hot Cams engineers proved to have the greatest positive effect on engine performance. In order to model these modifications in GT-Power, the team scaled the stock intake cam profile using a quartic function. An Excel macro was used to meet specific duration and max lift parameters provided by Hot Cams, since the exact information is proprietary. Using the GT-Power model, it was found that the modified cam shafts could provide up to 33% increase in power, as shown in Figure 9. This increase allowed the team to reach its required metric for horsepower.

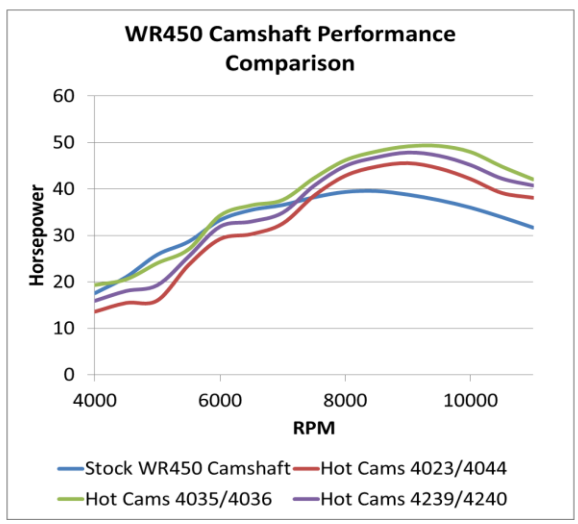

Figure 9 – Comparison of Aftermarket Cams

Two additional investigations were competed at the request of the customer to allow for better understanding of the characteristics of the engine package. The first study examined the effects of intake plenum volume. Cases were created in GT-Power to vary plenum volume over a large range. These were then simulated at 1000 RPM increments under WOT. Peak performance was achieved at an unrealistic volume of 9500 cc (2.5 gal). This is unrealistic as it would be much too large to package, as well as throttle response would suffer greatly with such a large plenum. 3500 cc (0.9 gal) was considered satisfactory, but packaging will still be extremely difficult. The throttle response will need to be evaluated in-car through subjective testing. In addition, geometric variations of the plenum were tested which verified that volume had the most significant effect on performance.

Additionally, the customer requested a second investigation into the air flow at idle. This parameter is necessary for customer's throttle design. Based on a desired idle of 3000 RPM which was determined from dynamometer testing, the plenum pressure and restrictor mass flow were estimated.

CONCLUSIONS

A lightweight, fuel efficient engine package was developed, which fits within the rules of Formula SAE competitions. The design and testing procedures were well documented to provide support for design judging and future use of similar data. A theoretical model for the engine package was created and verified against empirical data, showing a strong correlation. The final tested design provided functionality requested by customer, however was below the horsepower metric requested by customer. Additional performance modifications were researched and verified through the use of proven theoretical models, however were not implemented during the scope of this project due to time constraints. The final product serves as a well-developed system that will be integrated into the RIT Formula SAE vehicle.

RECOMMENDATIONS

Beyond the scope of this project, several areas have been identified as key opportunities as extensions of this work. Firstly, the use of GT-Power can be extended beyond the full theoretical engine model to allow for combustion analysis post-processing, design of experiments, component-wise optimization, valvetrain design, further cooling system analysis, and advanced data analysis. Further work on completing a GUI for live cylinder pressure measurement would complement the DC Dyno work and GT-Power modeling. Finally, the work of characterizing the engine for brake specific fuel consumption would improve understanding of potential fuel consumption reductions.

REFERENCES

[1] "Formula SAE® Rules & Important Documents - Collegiate Design Competitions - SAE Student Central." [Online]. Available: http://students.sae.org/competitions/formulaseries/rules/. [Accessed: 24-Feb-2012].

[2] "AUTOMOTIVE | SPAL." [Online]. Available: http://www.spalautomotive.com/. [Accessed: 24-Feb-2012].

[3] "NI PCI-6024E - 200 kS/s, 12-Bit, 16-Analog-Input Multifunction DAQ - National Instruments." [Online]. Available: http://sine.ni.com/nips/cds/view/p/lang/en/nid/10968. [Accessed: 24-Feb-2012].

[4] "PCB Piezotronics, Inc. - Tech Support." [Online]. Available: http://www.pcb.com/techsupport/tech_pres.php. [Accessed: 24-Feb-2012].

[5] "Kistler - Willkommen bei Kistler Schweiz (www.kistler.com)." [Online]. Available: http://www.kistler.com/ch_de-ch/KistlerCountryHome_KCH. [Accessed: 24-Feb-2012].

[6] "000-387a-07.09.pdf." .

[7] "ELCO." [Online]. Available: http://www.elco-holding.com/productlist.asp?bigclass=0&smallclass=46. [Accessed: 24-Feb-2012].

ACKNOWLEDGMENTS

The authors would like to acknowledge the support of the RIT Formula SAE team, as well as the sponsorship of Yamaha Motor Corporation, Mobil 1, Gamma Technologies, Autodesk, Bosch, and Delphi Automotive LLP. The authors would also like to thank Phillip Vars and Dr. Alan Nye for their assistance and input.