Multi-Disciplinary Senior Design Conference
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Rochester, New York 14623

Project Number: P10227

RIT FORMULA SAE RACING VARIABLE INTAKE

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ABSTRACT

The primary goal of the Formula SAE Variable Intake senior design project was to design, manufacture and integrate a successful upgrade to the engine package that would allow for gains in engine power while maintaining simplistic manufacturing and maintenance with high reliability. The RIT Formula SAE Racing Team is world renown for high standards of engineering excellence and the addition of a variable intake system to the engine package is viewed as an upgrade that will keep the car ahead of the design curve.

The senior team was divided into five titles: project manager, design engineer, test engineer, integration engineer and programming engineer. The quarter began with initial testing for a comparative analysis in order to understand where areas of improvement were needed regarding the plenum design and positioning of the runners. The team went into the design phase where upgrades were made to the overall intake system along with the initial stages of programming of the engine's control system. This led into the manufacturing and assembly of the plenum and runners. The results of testing the final design will be described in detail in this paper.

NOMENCLATURE

SAE – Society of Automatic Engineers
CFD – Computational Fluid Dynamics
FEA – Finite Element Analysis

INTRODUCTION

The Rochester Institute of Technology Formula SAE Racing Team was formed 18 years ago with the hope of beginning a legacy to cultivate design, test and manufacturing engineers in the automotive industry. Over the span of the 18 year history, RIT FSAE has made lasting impressions on many international race tracks. In recent years, other teams around the world have caught onto the superior design capabilities that RIT has brought to competition and began to step up in their own design advancements. In order to keep the design of car ahead of the curve, advancements will be necessary.

To make advancements to the engine package, the FSAE senior design team will redesign, manufacture and integrate a two position variable intake system. This engine package was targeted for improvement because fuel efficiency and technical superiority has become much more prevalent in competition scoring as each competition passes. This senior design project will allow for increased fuel efficiency, design advancements and a greener methodology to produce more engine power.

Our project deliverables consist of increased volumetric efficiency of the engine, increased fuel economy, improved power/torque, better drivability, high reliability, manufacturability and serviceability. This system would be implemented using a pneumatic control system that will vary the runner length based a specific RPM range.

METHODOLOGY

Comparative Analysis for Previous Static Intake Designs

The intent of the variable runner length system is not to increase max torque or power, but rather to broaden the torque and power curves. However, peak power gains may be found with the design of a less restrictive and more evenly flowing intake.

CFD analysis has been employed on the last two competition intakes using the CFDesign fluids analysis software. The fluids problem that exists within the intake system is quite complex. A steady state flow does not exist, as the intake valves open and close. To simplify the analysis, the volumetric flow rate of air that a 600cc engine consumes at 10,000 rpm is applied to the inlet of the intake. The four exits are set as "unknown" conditions. This simplified analysis will solve much faster than a time dependent solution, but can only be used as a comparative analysis. Intake designs can be compared for overall pressure drop and equitable division of flow across the 4 runners. The Solid works model of last year's design can be seen in Figure 1.

Figure 1. F17 Static Intake Design

Based on CFD analysis, the results show that the F17 intake did not have a favorable distribution of air, as cylinder #1 is shown to receive 17% of the total ingested air, where cylinder #4 receives 30%. Cylinder #3 and #4 both received approximately 26%. A CFD screen shot of the results are shown in Figure 2.

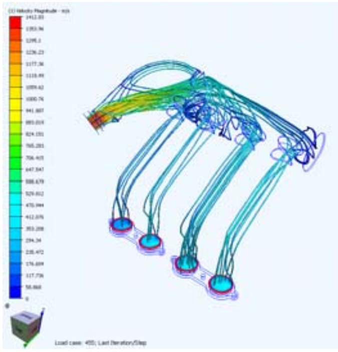

Figure 2. Air Flow Path Results from CFD Analysis

CFD will be used to compare our design iterations and to select an optimized geometry.

Preliminary Variable Intake Analysis

Both the Helmholtz resonance and Induction Wave Ram Cylinder Charging Theories can be used to approximate where a torque peak should occur for any given intake geometry. A theoretical optimal runner length versus RPM curve can also be generated for a given engine. Below are the equations for both Induction Wave Ram Cylinder Charging and Helmholtz Resonance (Heisler p. 258), as well as the ideal intake runner length versus engine speed curves for a 600cc, 4 cylinder engine, with a 1.43 inch runner diameter, shown in Figure 2.

Induction Wave Ram Cylinder Charging:

$$L = \frac{\Theta \times c}{0.0012 \times N}$$

Helmholtz Resonator: $L = \dfrac{A}{V\left(\dfrac{2\pi \times n}{c}\right)^2}$

where $n = \dfrac{1}{N \times 60}$

L = Length of runner

Θ = Crankshaft angular displacement (85° is optimal)

c = Local speed of sound (m/s)

N = Engine Speed (RPM)

A = Cross section area of runner (m^2)

V = Resonating volume (m^3)

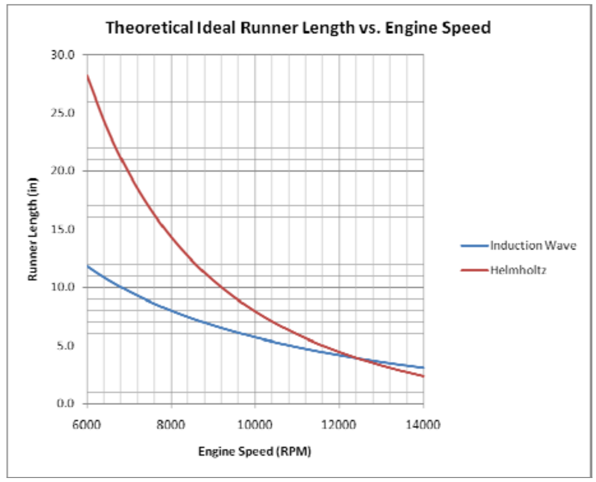

Figure 3. Theoretical Runner Length V. Engine Speed

Since both of these theories are acting at the same time within the intake, perhaps with constructive or destructive effects on each other, it is best to use empirical data to set design parameters. The theoretically derived graphs, as well as historic dynamometer data sets were used to select a range of runner lengths from 6 inches to 12 inches to dynamically test.

Preliminary Testing

Empirical testing of various intake manifold variables was required to reinforce analytical calculations. The variables tested were plenum volume, runner length and the gap size needed to affect an overall change in runner length.

Preliminary Testing of Plenum Volume

Plenum volume was tested in three sizes, 1200, 1800 and 2200 cubic centimeters. Plenum volume has a direct effect on maximum horsepower and throttle response. A small volume offers the best throttle response but does not have sufficient air to provide maximum horsepower. The 1800 cc plenum offers a compromise with negligible horsepower loss and decent throttle response. Driver feedback was key to this testing and complaints were made about the throttle response of the 2200 cc size. Given this information 1800cc's was chosen both for its favorable power and throttle response as well as its ease of packaging. This was set as a design goal to be upheld with the new variable system.

Preliminary Testing of Runner Lengths

Dynamometer testing of static runner lengths was needed before a final variable range could be chosen. All current dyno testing was performed on the DC dynamometer located in the Mechanical Engineering machine shop. This system provides repeatable torque measurements at the entire range of the engine's operating conditions. The system is also a great asset in tuning the engine controller's fuel map when intake changes are made, allowing for rpm points to be held consistently at varying loads.

Based off older engine testing and preliminary analysis a range of 6 to 12 inches was chosen to be tested in 1 inch increments. A test intake was constructed utilizing a previous design as basis. It was adapted to allow for sliding runners that could be adjusted manually between tests. This system allowed for the length to be quickly reset to any of the desired lengths if additional variables needed to be accounted for. As each length change was made the engine was retuned to ensure that it was running at the desired air fuel ratio. The data, shown in Figure 4, exemplifies the results for 8 to 12 inch lengths.

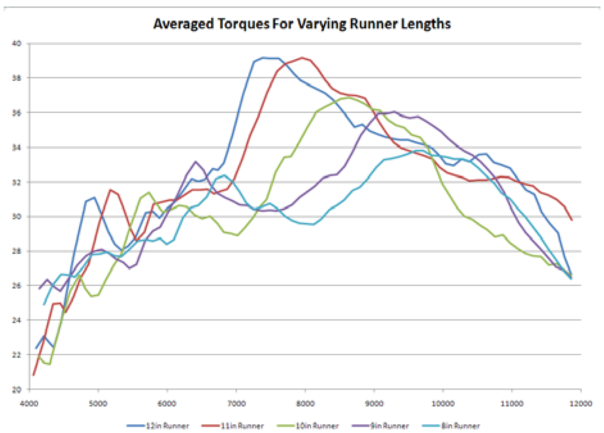

Figure 4. Average Torques for Varying Runners Lengths

Lengths below 8 inches never produced an adequate torque peak and were eliminated from any further testing. The 11 and 12 inch curves produce the same peak torque with about a 700 rpm difference in this peaks location. This information allowed the team to decide on a final long length of 11.5 inches. Nine inches was chosen for the short length because even though it made less torque than the 10 inch runner the gains from the area under the curve were greater.

Preliminary Testing of Gap Width

The variable intake system works by creating an air gap between the fixed and movable portions of the runners to affect a change in length. For packaging reasons the team wished to investigate if this gap could be reduced under an inch. A second prototype intake was constructed to test a two runner length system and to see if the air gap could be reduced to 0.5 inches. The results, shown in Figure 5, prove that there are not any differences larger than the error in the testing system, proving that the system can be effective with a 0.5 inch gap.

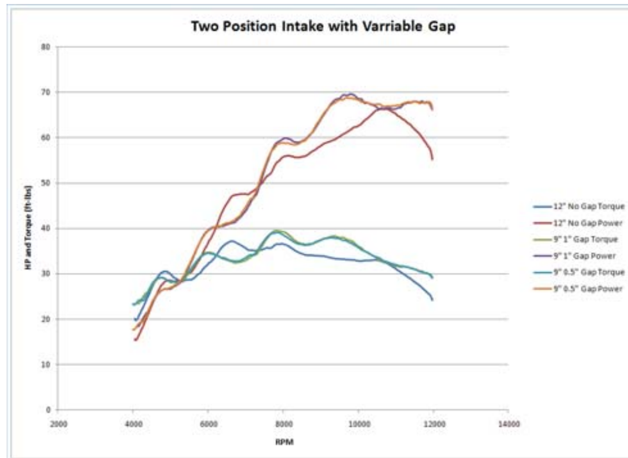

Figure 5. Resulting Horsepower and Torque of Test Two Position Intake with Varying Gap Width

Preliminary Electrical Design

Two preliminary design concepts were proposed knowing the availability of space and power capacity on the car. The first idea utilized an electrical solenoid for actuation. This design was the most reliable, and would allow for the quickest actuation times. Only a single component would be needed for actuation, thereby reducing complexity and weight. The second design was an electro-pneumatic system, which would take advantage of the compressed air currently on the car. This design would use a valve to actuate an air cylinder. This form of actuation would have comparable transition times, but could generate a greater force. Through mechanical analysis it was found the actuation would need to generate 10 pounds of force. It was determined that in order to generate this force using an electric solenoid, the system would become too large and heavy.

Finalized Design

Mechanical Design

The long and short lengths were selected via empirical testing and therefore, the development of the design could be finalized. In an effort to better distribute the incoming airflow, the four runners were arranged into a quad pattern rather than the prior single row design. The initial design showed a notably better distribution, with a disparity of 8%, shown in Figure 6. However, it was seen that the entering flow passed by the runner openings and impinged on the back of the plenum, causing much circulation within the intake.

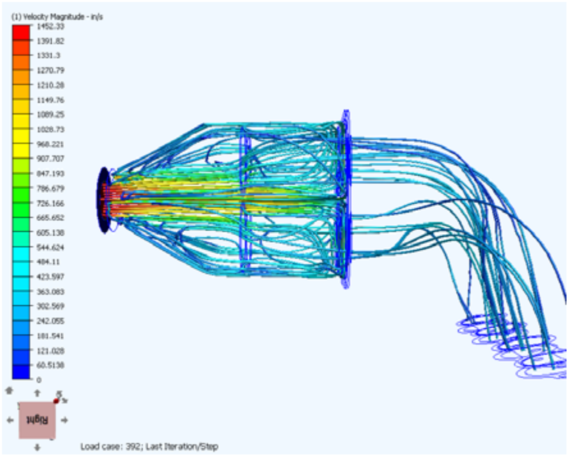

Figure 6. First Phase on Finalized Design

A flow diverter was then added ahead of the runner openings, with the intention of directing the flow into the runners and reducing circulation. The diverter was quite successful, and reduced the disparity in flow distribution to 4% while in long mode, shown in Figure 7.

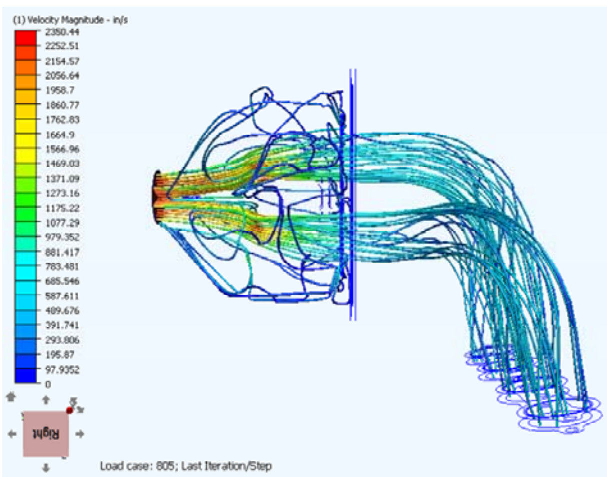

Figure 7. Finalized Design in Long Mode

Analysis in the short mode shows a flow distribution disparity of 6%, shown in Figure 8. This increase is likely due to the circulation induced by the gap created between the static and dynamic runners.

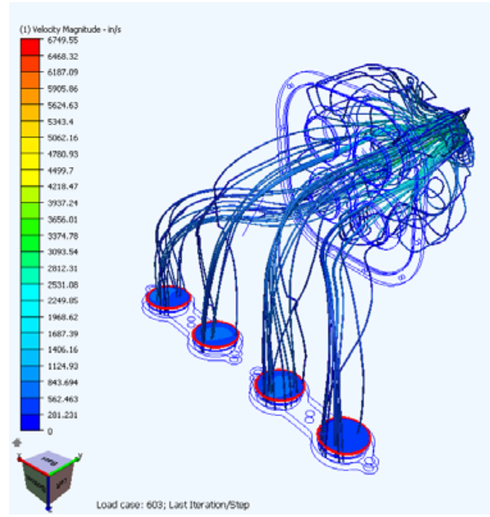

Figure 8. Finalized Design in Short Mode

The plenum base and intake splitter geometries underwent a static structural analysis in ANSYS Workbench, shown in Figure 9. Material properties of 6061 aluminum was used for the base and ABS Plus properties for the splitter. Both components were analyzed in a condition of a 3G bump, which is the most demanding condition that the remainder of the vehicle is designed to withstand. Both the base and splitter were found to have a factor of safety of approximately 5 in yield.

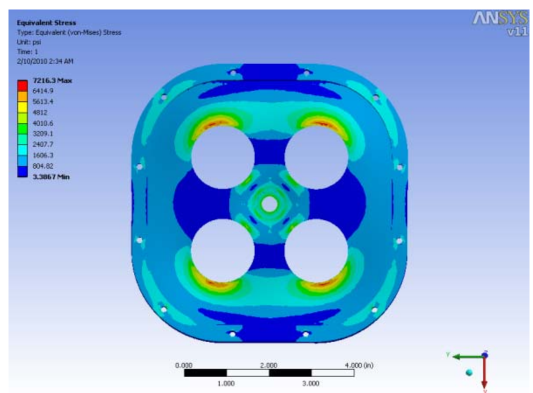

Figure 9. Static Analysis of Plenum Base

Electrical Design

The electrical design began by analyzing the specifications of the system provided by the customer. The important specifications included total current draw, actuation speed, and system weight. The system was also required to operate using the available DC voltage supplies of 12, 8 or 5 Volts. In order to determine a maximum specification for current draw, an in depth analysis of the formula cars existing electrical system was performed.

It was determined that the car charging system provides 30 A of current at normal operating conditions, while the maximum current draw was measured to be 26 A. These measurements are shown in Table 1. This allotted for a maximum current draw of 4 A, so it was concluded that 1 A of current draw would be an ideal specification. The ideal actuation speed was determined by the time it takes for a shift to be completed. This value is approximately 100 ms. The intake system was designed to actuate within this window of time. In order to meet the systems total weight requirement, it was important to specify small and lightweight components in the actuation system.

Component	Max Limits (A)	Duty Cycle	Average (A)
Motec and Sensors	2.5	1	2.5
MW Power	6	1	6
Dash	2	1	2
Brake Light	0.5	0.2	0.1
Fuel Pump	5.4	1	5.4
Fan	7.4	1	7.4
Shift Solenoids	0.5	0.2	0.1
TCMX	1	1	1
Wheel Speed Sensors	0.8	1	0.8
Intake Actuation System	**0.5**	**0.5**	**0.25**
Totals	26.6	7.9	25.55

Table 1. Current Analysis

Based on the design requirements of the intake system, the electro-pneumatic system was chosen to actuate the variable runners. A block diagram of the final electrical design is shown in Figure 10.

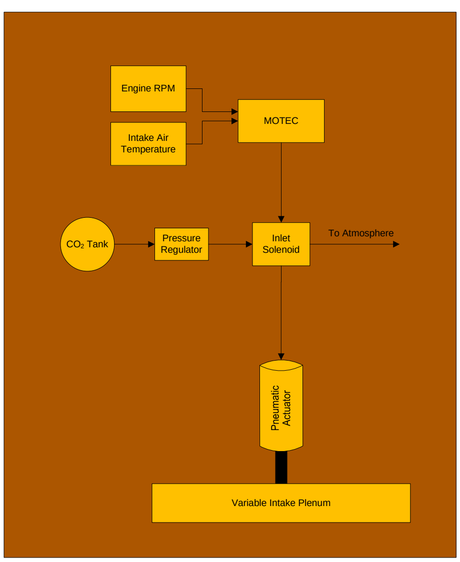

Figure 10. Electro-Pneumatic Actuation Block Diagram

The actuation system is controlled by the cars ECU, a Motec M400. The ECU monitors the state of the engine through sensors measuring air temperature and pressure, engine speed, and throttle position. The outputs of the ECU can be configured through many functions available through the software. The most suitable function was the auxiliary output table, which could be custom programmed to control the output at any given state of the engine. Figure 11 shows a screen capture of the output configuration.

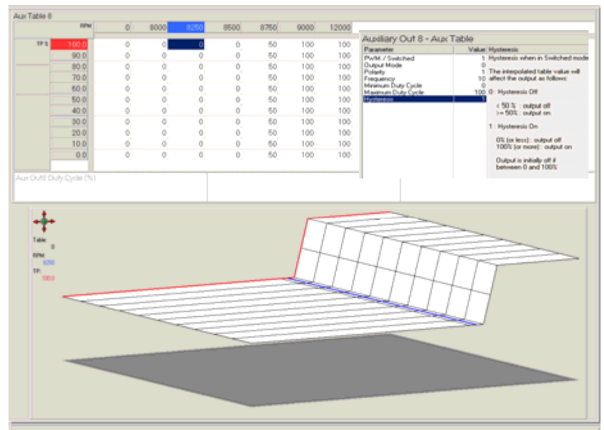

Figure 11. Motec Output Configuration

Each cell of the table represents a different Throttle Position and RPM combination. It was decided from dynamometer testing that the optimum actuation time would be at 9000 RPM. At this point the table value of 100 tells the ECU to actuate the air solenoid. One concern from the customer was fluctuations in engine speed around 9000 RPM that would trigger the system to actuate multiple times. In order to overcome this hardship, a hysteresis function was developed in Motec. This function allows for a buffer around the transition point. With the completion of function, the ECU will have accurate control over the solenoid valve.

The solenoid valve is used to direct compressed carbon dioxide to the Bimba air cylinder providing actuation of the system. The compressed air system currently provided by the car operates at 120 PSI. This pressure is much higher than required for actuation of the intake, so a pressure regulator was designed to reduce this pressure to 30 PSI. A lower operating pressure results in less air usage per actuation. The air cylinder is single acting with an integrated return spring. When the solenoid is fired the cylinder is charged with air, extending the shaft. If the solenoid is then disengaged, the shaft returns venting the air to atmosphere through the solenoid.

Performance Testing

Dynamometer Testing

In order to prove our product to the customer it was necessary to quantify its performance. True improvement from the system can only be determined from race performance; however testing with a dynamometer is a useful way to quantify engine components.

After the final design was manufactured and assembled, the variable intake was tuned and run on the same engine that was used for all the previous tests. By designing the system overall airflow distribution, flow was improved compared to older intake systems. These improvements should result in increased power even without gains from the variable runner lengths. This was tested first on the dynamometer with the system set in the 12 inch length. Compared to a previous intake design torque and horsepower were improved along the entire curve with peaks of 3 ft-lbs and 5 hp improvement.

The engine controller was then programmed to shorten the runner length at 9000 RPM and return to the long length at 8000 RPM. The results show additional substantial gains in torque as the curve was flattened out, shown in Figure 12. The horsepower curve was also improved and peak power delivery was extended from 12,000 to 12,300 RPM.

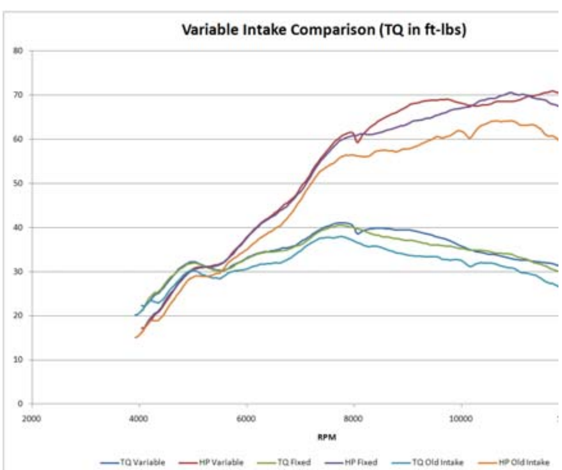

Figure 12. Comparison of Variable to Static Intake Horsepower and Torque

While power and torque output ultimately determine a better intake design, it is important to analyze other aspects of the engine. Exhaust gas temperatures (EGT), cylinder pressures, and brake specific fuel consumption were all examined to verify a well performing product. Figure 13 shows the testing setup created for analysis.

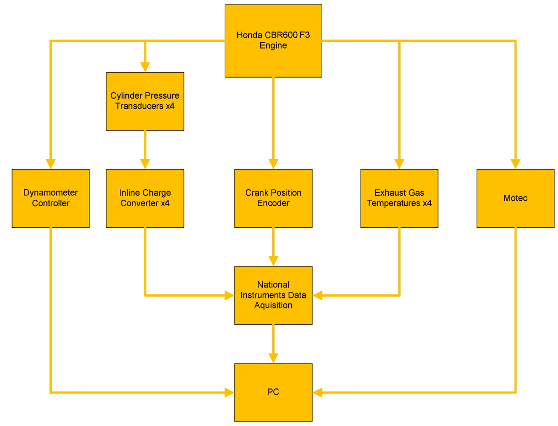

Figure 13. Dynamometer Electrical Test Diagram

Exhaust Gas Temperature's were measured from each individual cylinder through the use of J type thermocouples. By comparing these values to one another, it is possible to determine how evenly distributed the air flow is. Ideally the intake will direct the same amount of air to each cylinder, resulting in equal temperatures. If the distribution is off, it is possible to tune each cylinder independently through the ECU. The pressure in each cylinder helps quantify the amount of air used by each cylinder. The pressure is measured through in-cylinder pressure transducers. An inline charge converter is needed to condition the signal for proper data acquisition. A better intake design would provide more air to the engine, thereby increasing pressures in each cylinder.

The Exhaust Gas Temperature of the current engine are shown in Figure 14. It can be seen that cylinders 1 and 4 follow the same temperature path at higher temperature while cylinders 2 and 3 follow the same path at lower temperatures. This trend in temperature directly correlates to the intake runner design where cylinders 1 and 4 have identical geometries and cylinders 2 and 3 have identical geometries. Again, exhaust gas temperature for all cylinders are most ideal if all cylinders run at identical temperatures.

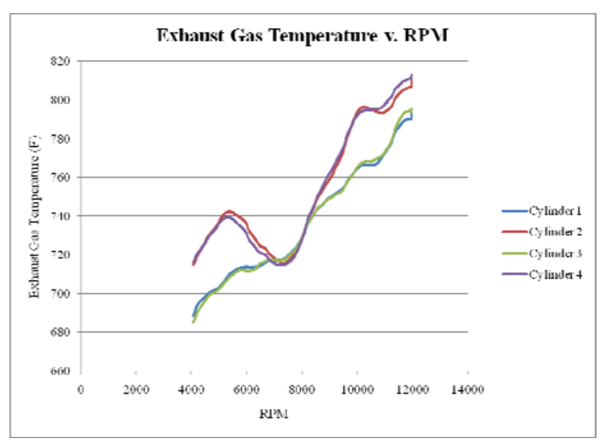

Figure 14. Exhaust Gas Temperatures for Current Engine

On Car Testing

With the intake system checked over and functioning correctly on the dynamometer, it was installed on the Formula SAE race car. The focus of the on car testing was based on driver feedback. The system was swapped with an older static intake for driving comparisons. The end goal of the testing was to understand the effects the two position intake had on the car regarding engine performance and if there were any unexpected jolts while driving due to the actuation of the dynamics runners.

Thus far, driver feedback was very positive. The testing drivers stated that the system did not have any negative impact on car control and the power band was now much more useful allowing for improved drivability.

TESTING RESULTS

After all dynamometer and on car testing was completed, the required specifications were compiled, shown in Table 2. It can be seen in the percent difference column, the two position variable intake system was a large improvement to the previous engine package. Although many of the specifications for the new intake package indicate that the intake requires more time to service, manufacture and assemble, the highest ranked specifications, including performance and fuel efficiency, outweigh the added production time.

In addition, weight is also a large concern on a performance vehicle such as this. The baseline non-variable intake weighed 1.5 lbs. As implemented the new system weighs 2.2 lbs. This 0.7 lb increase will be justified by the performance increase provided.

As shown in Table 2, the performance of the engine has increased significantly. The peak horsepower increased by approximately 10% and the peak torque increased by approximately 7%. In addition, the fuel consumption, measured in kg/km, decreased by 17% which will greatly contribute to better ranking in the fuel economy dynamic event at FSAE competitions.

CONCLUSIONS

The final two position intake system successfully met the desired goals of the Formula SAE Racing Team. These goals consisted of making advancements to the previous engine package via a redesign of the entire intake system, to manufacture all of the components in house and to integrate the two position variable intake system into the race car. In addition, the intake system has allowed for better fuel efficiency and broader horsepower and torque curves.

Source	Specification	Unit of Measure	Variable Intake Values	Previous Static Intake Values	Percent Difference
Fuel Efficiency	Overall fuel consumption	Kg/lap	0.091	0.109	-17%
Performance	HP output	HP	70.8	64.2	10%
	Torque Output	ft-lbs	40.5	37.8	7%
Drivability	Noticeability of length of change while driving	Scale of 1 to 5*	1	-	NA
	Time to change length	ms	16	-	NA
Weight	The overall weight of the system compared to previous models	lbs	2.2	1.5	47%
Maintenance	Hours between services	hr	50	100	-50%
Manufacturability	Hours to manufacture	hr	15	11	36%
Serviceability	Hours to program Motec code	hr	1.25	1	25%
	Hours to assemble	hr	1	0.3	233%
Cost	Total cost	$	240	200	20%

Figure 2. A Comparison of the Specifications of the Two Position Intake Package to the Previous Static Intake

RECOMMENDATIONS

The goal of the senior design project is to not only increase the performance of the current engine, but to set the stage for future improvements that would eventually lead to higher quality testing and design. Therefore, it is recommended that a future senior design team takes the next step in the design and development stage to an infinitely variable intake package. This should yield broader horsepower and torque curves than the newly designed two position intake system.

REFERENCES

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ACKNOWLEDGMENTS

The team would like to express its sincerest gratitude to those who have made invaluable contributions to this project. Many thanks to our advisor Dr. Alan Nye for his support and guidance. Additionally, the team would like to express thanks to the consultants who provided additional guidance and assistance, as well as consultative advice when necessary. These consultants include Mr. Chris DeMinco, Fernando Fiore, Robert Hammond, John Scanlon and Taylor Hattori.