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SAE TURBOCHARGER DEVELOPMENT

SIBEUDU CHIWETALU EMENIKE AND OCHUBA NNAMDI
Department Of Mechanical Engineering, Federal Polytechnic Oko

ABSTRACT

The goal of this project was to increase the output of that engine to 60 horsepower and 35 ft-lb through the use of a turbocharger. The addition of a turbocharger to this engine required the design of multiple subsystems such as the intake, exhaust, oiling, fuel, and boost control. Ricardo WAVE engine simulation software was used to optimize designs without having to spend time, money, and resources on actual dynamometer testing of all possible configurations. The simulation's output was determined to be an accurate representation of the actual engine's output based on comparison to results obtained from the naturally aspirated engine. The final design produced a simulated power curve with peaks of 63 horsepower and 45 ft-lb of torque at 8 psi of boost. Two turbochargers were available to select from Garrett: the GT12-41 and the GT15V. The GT12- 41 is the smallest turbocharger Garrett currently has available and the GT15V features variable vanes. The GT15V was selected based on matching the compressor map from each to the engine's predicted operating range as well as quicker boost response offered by the variable vane design. To take full advantage of the turbocharger's potential for power, the static compression ratio of the engine was lowered from 12.5:1 to 11:1 and E-85 was selected as the fuel. A new piston, connecting rod, valve springs, head studs, head gasket, clutch springs, pressure plate, and modified crankshaft were installed to withstand the increased power output. These components were selected for the engine to safely produce 85 horsepower, allowing room for future Cal Poly FSAE teams to further increase the engine's output. During testing it was discovered that the variable vanes on the GT15V are not able to limit boost levels below 15 psi. Oil leakage past the compressor seal also proved to be problematic, with a significant volume of oil being sucked into the intake and burned by the engine. Testing also revealed that the engine's factory oil pump cannot provide enough pressure to feed the turbocharger when the engine and turbocharger are

plumbed in parallel. While engine output was not measured across an RPM range, one data point was obtained which proves that this engine is capable of producing and surviving the desired power: 55 hp and 40 ft-lb at 7200 RPM and 15 psi of boost. Re-running the WAVE simulation with 15 psi of boost instead of 8 psi predicts 58 hp and 42 ft-lb at 7200 RPM. These figures are realistically obtainable with more time spent tuning and lend further credibility to the simulation's accuracy, further suggesting that this system is capable of reproducing the predicted power. We believe that switching to the GT12-41 is the most effective way to regulate boost pressure without adding weight. This should be done in conjunction with continued refinement of critical subsystems in order for the turbocharged engine to become a reliable source of power for FSAE. 13 1.0 Introduction Jackie Stewart, a three time Formula 1 World Drivers' Champion, once said "It is not always possible to be the best, but it is always possible to improve your own performance." SLO Racing's challenge was to implement a turbocharger system onto Cal Poly's Formula SAE Team car to greatly improve upon the vehicle's performance. Our senior project team, SLO Racing, consists of Matt Roberts, Eric Griess, and Kevin McCutcheon who are all Mechanical Engineering students at Cal Poly, San Luis Obispo. Our goal was to successfully design and install a complete turbocharger system that would meet all SAE competition regulations for the 2013 Formula SAE car. Stakeholders of this project include the current and future Cal Poly Formula SAE Teams, supervisor John Fabijanic, aspiring engineers who are motivated by the project, and Cal Poly's College of Engineering. This report outlines the details of the project, including a background to cover the basics of internal combustion and forced induction, requirements of the project, subsystem design development, manufacturing of parts, and testing the turbocharger system. 2.0 Background The internal combustion engine is a man-made marvel that is the driving force behind Formula SAE cars.

INTRODUCTION

Stringent SAE regulation of these engines pushes undergraduate engineers from all over the world to design the strongest and fastest engines they can within competition specifications. Some of these specifications include a 4-stroke cycle, displacement restriction of 610cc, an intake air restrictor, and limited fuel choice. In order to successfully design within these parameters, it is necessary to understand how each ones affects the desired performance of the engine. 2.1 Combustion Basics For combustion, the only necessary ingredients are fuel and an oxidizer (air in our case). With gasoline, a complete combustion is achieved when the air to fuel ratio (AFR) is stoichiometric, or approximately 14.7:1. Keep in mind that this is a mass ratio, meaning that for every 1 unit mass of fuel, 14.7 units mass of air are needed for complete combustion. Complete combustion is an ideal case, however, and doesn't necessarily produce the most power. Increasing the fuel slightly (~10%) so the AFR is nearly 13:1 has experimentally produced more power than the stoichiometric AFR. 2.2 Engine Basics The 4-stroke engine specification determines how often this combustion takes place. These 4 strokes consist of the following: 1. Intake stroke – The piston moves from top dead center (TDC) down to bottom dead center (BDC) inside the cylinder while the exhaust valve is closed and the intake valve is open. This creates a temporary low pressure area and the air from the surroundings rushes in to equalize the pressure. While this intake air enters the cylinder, fuel vapor is sprayed into the air (port injection) to enter the combustion chamber as an air/fuel mixture. 14 2. Compression stroke – The intake valve closes and the piston moves upwards in the cylinder, compressing the air/fuel mixture. The amplitude of this compression is the compression ratio. This ratio is defined as: Compression Ratio= Free volume in cylinder when piston is at BDC (VBDC) Free volume in cylinder when piston is at TDC (VTDC) 3. Power stroke – Just before the piston reaches TDC, a spark ignites the compressed air-fuel mixture to combust the fuel. The volume of the products of this chemical reaction is much greater than the reactants, so the combustion creates a very high pressure area that does work on the piston, moving it downwards. 4. Exhaust stroke – When the piston nearly reaches BDC, the exhaust valve opens and allows the pressure to equalize through the exhaust. Then the piston travels back upwards and expels the remaining products. At the top of this stroke the exhaust valve closes and the intake valve opens, restarting the cycle. Figure 1: Four Stroke Cycle From www.britannica.com The important thing to note from the 4 stroke engine is that power is only produced for 1 out of the 4 strokes. Displacement has a large effect of how much power can be produced in that one stroke, because a larger displacement allows more air/fuel mixture into the cylinder while the intake valve is open. Combusting more air/fuel mixture creates a higher pressure, and consequently more work. 15 2.3 Forced Induction There are ways to work around displacement limitations. If more air/fuel mixture is forced in during the intake cycle, higher power output numbers can be achieved. The process of creating a high pressure area outside of the intake valve so more mixture can be forced in during the intake stroke is called forced induction. The two main methods of forced induction are turbocharging and supercharging. Both methods use compressors, creating more pressure inside the intake manifold, but the main difference is how they are driven. A supercharger is mechanically driven by a belt connected to the crankshaft; while a turbocharger uses exhaust gases to power a turbine, which shares a shaft with the compressor. Figure 2: Cutaway of Turbocharger (From www.hipermath.com) Figure 3: Cutaway of Supercharger (From www.hipermath.com) 16 2.4 Air Restrictor The power produced by an engine is the product of the torque (work) created by the engine and the angular speed at which the crankshaft is rotating. However, the faster an engine is rotating, the more air it needs for combustion. This is where the air restrictor specification plays a large role. To prevent teams from creating immense amounts of power by spinning the engine extremely fast, there is a small restrictor that the air must pass through (20mm for gasoline and 19mm for E-85). At higher speeds, the restrictor can't allow enough air flow for the fuel to fully combust and therefore "chokes" the engine. The most common way that teams have approached this restriction in the past was by designing a converging-diverging nozzle that optimizes flow and minimizes losses. However, the restrictor still plays one of the largest roles in power limitation. 2.5 Fuel Choice Fuel choice plays a large role in the magnitude of the compression ratio that is possible, size of the restrictor, how much forced induction is possible, and choice of hardware. Fuel has such a large effect based mainly on its octane rating. Octane is a hydrocarbon (C_8H_{18} series) that is obtained in the refinement of petroleum [2] and is part of the gasoline fuel mixture. A higher octane rating indicates a higher concentration of octane in the gasoline, and increases the temperature of combustion for the fuel. Since temperature rise of the mixture is proportional to the amount it's compressed due to the ideal gas law, higher octane fuels are used with engines with higher compression ratios to prevent pre-ignition. Pre-ignition is a phenomenon in which the air/fuel mixture is compressed but reaches its temperature of combustion before the spark initiates combustion, resulting in the combustion of fuel much earlier than desired. This creates a force against the engine's natural movement which can cause catastrophic damage to the engine and should be avoided at all costs

METHODOLOGY

The Formula SAE organization also expands the choice of fuel to include E-85. This is a mixture comprised of 85% ethanol and 15% gasoline. Ethanol (C_2H_5OH) is a volatile alcohol that is mainly made by fermenting and distilling starch crops such as corn [3]. This type of fuel provides many benefits to engine operation including: Ethanol is an alcohol, and it therefore draws much more energy from surrounding air as it is• injected into the air stream, meaning that the air/fuel mixture going into the engine is much cooler and denser than it would be using gasoline. Denser air allows for more mass of air into the cylinder, which also means more fuel can be burned creating more power. Running at cooler temperatures is also easier on engine components and increases the lifetime of the engine. Ethanol has an estimated equivalent octane rating of 105, and has higher resistance to predetonation or knocking than gasoline. This compares favorably to the 91, 93, and sometimes• 98 octane gasoline provided at the competition. Therefore the use of ethanol allows for higher compression ratios which allow forced induction to be implemented with less risk of knocking problems. 17 Figure 4: Equivalent Octanes of Various Fuels [9] However, some disadvantages of E-85 compared to gasoline include: ● E-85 has a lower energy density than gasoline, meaning gasoline has a higher energy output per mass. When E-85 is used, more fuel is needed to create the same amount of energy. ● The ethanol in E-85 is very volatile and reacts poorly with many materials, including cork, some rubbers and plastics, and raw aluminum. Components in the fuel system need to be changed to accommodate the volatility of E-85 and the larger volumetric flow rate necessary to compensate for lower energy density. ● Ethanol draws water much more easily than gasoline, so it must be carefully stored in either stainless steel or certain plastic containers. 2.6 FSAE Engine History at Cal Poly Figure 5: FSAE Car, Yamaha R6, WR450 From www.yamaha-motor.com 18 Until 5 years ago, Cal Poly Formula SAE implemented naturally aspirated inline 4 cylinder Yamaha R6 (600cc) engines to power their cars. Some benefits included higher power output and greater reliability. However, these engines were especially heavy, so the team switched to a naturally aspirated single cylinder Yamaha WR450 (450cc) engine. Although this engine had a much lower power output and smaller displacement, it saved almost 70 pounds on the total weight of the car, therefore improving the car's power to weight ratio. 2.7 Ways to Increase Power of the Single Cylinder Engine The largest considerations for the engine are reliability and the expected increase in power. Reliability is important because the engine has historically been the least reliable part of the car and needs to run in order to finish the competition. Increasing the power is the entire point of this process, so naturally it is weighted very heavily. Low weight is important but the power to weight ratio is more important. Lastly, feasibility must be taken into account when considering possible options; if it cannot be successfully implemented then there is no point in pursuing it. Table 1, below, shows a decision matrix of our selection choice. Table 1: Decision Matrix for Increasing Power Power Increase Methods GOALS (Weight) Forced Induction Intake Exhaust Cam Profile High Compression Variable Valve Timing Direct

Injection Head Porting Good Reliability 5 4 4 4 3 3 2 2 5 Power Increase 5 5 1 1 1 1 2 2 1 Low Weight 3 3 5 5 5 5 4 4 5 Low Cost 1 2 3 3 4 4 1 1 2 Feasibility 5 4 1 1 2 3 1 1 3 Total: 76 48 48 49 54 38 38 62 A former senior project team, Speed Systems, previously implemented intake design, exhaust design, cam profile, and high compression ratios to increase power. At the time, those options were the best, but since they have already been optimized there is very little room for further improvement. 19 Variable valve timing and direct injection are two new technologies found on many modern engines that give more power and reduced fuel consumption. However, the gains from these features would be small and would not justify the resources spent on them. Head porting is the re-shaping of the intake and exhaust ports to allow for more flow, which in turn allows for more power. The issue is that this would only provide a small power increase because the intake restrictor limits the amount of air getting to the head, so air flow through the head is not the limiting factor. This leaves forced induction as the best option because it allows for the greatest increase in power while still balancing the other criteria. 2.8 Which Engine is Right for the Car? Increasing the power of the single cylinder is great, but if it is not the best fit for the entire car then it should not be used. Table 2 below, uses past information from the 4 cylinder and single cylinder performance characteristics and compares them to the projected performance of a turbocharged single cylinder. Table 2 shows that the turbocharged single cylinder engine is the best choice for the Formula SAE car. Table 2: Engine Choice Decision Matrix Engine Choice (Weight) 4 cylinder Single Cylinder Turbocharged Single Cylinder Good Reliability 5 5 4 4 Power 4 5 1 4 Low Weight 5 1 5 4 Good Fuel Mileage 1 1 5 3 Uniqueness 3 1 3 5 Low Cost 2 5 4 3 Feasibility 5 2 5 5 Drivability (torque curve) 4 4 3 5 Total: 90 108 125 20 2.9 Engine Conclusion The tight interweaving of variables such as fuel choice, compression ratio, induction method, engine type, weight, and flow restriction create design challenges that FSAE teams all over the world strive to perfect, and how teams overcome these obstacles bring out the engineering talent that each competing school has to offer. For the 2013 Formula SAE competition, Cal Poly FSAE has determined that a turbocharged single cylinder engine is the best option to power the car. 3.0 Requirements and Specifications 3.1 Goals of the project The main objective of this project was to design and implement a functional turbocharging system to a single cylinder engine to produce more power than the previous engine design. This included installing a turbocharger, designing and fabricating an intake and exhaust to accommodate the turbocharger, installing internal engine parts that could handle the increased power output, designing a fuel system that could supply the increased demand of

E-85, designing an oiling system to supply the turbocharger, and tuning an Engine Control Unit (ECU) based on optimized fuel delivery and ignition timing maps. Below is a list of requirements that SLO Racing created to define the objectives of the project: ● 60 Horsepower: A well designed single cylinder turbocharged engine can achieve around 70 peak horsepower. However, since this was the first year implementing such a system, our goal was a more conservative 60 horsepower. We did not target peak horsepower because engine components become more prone to failure, but future teams can optimize power as they learn more about the system and ways to overcome obstacles that arise from forced induction. ● 35 lb-ft of torque: The torque from the engine should peak in the lower rpm range and stay there throughout the power band. We aimed for a target of 35 lb-ft of torque. This allows for fewer shifts which will reduce lap times and also allows for more time on the throttle and concentration on steering and braking. ● Intake design: The intake has an air restrictor that must be placed after the throttle body and before the turbocharger, in accordance with SAE rules. The restrictor is a convergingdiverging nozzle that is 19mm at the throat, which is the requirement for E-85 fuel. One of the most significant design issues caused by the single cylinder engine is the fact that it only draws in air for ¼ of the time, resulting in a pulsing effect. The restrictor causes the engine to starve for air with each intake stroke; therefore we added an intake plenum to store a positive charge of air in between intake strokes. ● Exhaust design: The turbocharger relies completely on exhaust gas to turn the turbine inside of it. The fact that there is only one exhaust pulse per two revolutions of the engine requires a very efficient exhaust design to keep the turbine rotating above its threshold rotational speed to compress the air. If the turbocharger is rotating below its threshold speed, the intake air is not compressed and there is no forced induction. ● Boost control system: The design of the turbocharger is such that it produces boost in proportion to the rotational speed of the compressor wheel. In order to prevent the 21 turbocharger from supplying too much pressure to the engine, we implemented a boost control method that limits boost to a safe level. On the Garrett GT15V (discussed later), this is accomplished with the use of variable geometry vanes in the turbine which limit the effectiveness of the turbine in converting exhaust energy into rotational speed. We designed a mechanical control system, rather than electrical, to regulate the intake boost pressure. ● Lubrication: Due to the high rpm at which the turbine operates, the turbocharger must have sufficient oil to lubricate the internal components and keep it cool. We used the oil already in the engine and designed a system that was directly integrated into to existing oil circuit to supply the turbocharger. ● Intercooling effects: Compressing air also increases the temperature of the air. When the air going into the engine is too hot, pre-ignition or detonation can occur which lowers the efficiency of the engine and can cause serious damage. To prevent this, an intercooler can be installed after the compressor of the turbocharger. However, we decided that this was not needed since we chose to use E-85 fuel with its cooling properties. ● Weigh less than 20 lbs: The entire system cannot increase the weight of the naturally aspirated engine system by more than 20 lbs. Increasing the power of the engine is not beneficial if the method used to do so will increase the weight of the car to the point that the power to weight ratio is not increased. The power to weight ratio is the best way to measure the success of the project. ● Engine temp. under 200°F: The engine must kept under 200°F in order to ensure that it does not overheat. If it were to become too hot, power output would decrease and the risk of engine damage would significantly increase. ● Engine durability: Heavy duty components were installed in order to withstand the increased power output. Research has shown that the most common parts to fail on the WR450 engine are the clutch, connecting rod, piston, and head gasket. To decrease the risk of severely damaging our engine, we replaced all the components mentioned above. ● Cost under $1000: Formula SAE is always running on a tight budget and therefore costs must be kept to a minimum where possible. An outline of these objectives is listed below in Table 3. Table 3. Technical Specifications to Outline the Project Specification Requirement Target Tolerance Risk* Compliance** Power 60 hp -5, +20 M A,T Torque 35 lb-ft -5, +10 M A,T Exhaust 45 cm behind rear axle, 60cm above ground, 110dB Max L T,I,S Boost Control See below H T,S Cooling 200°F Max L T,I,S 22 Weight 20 lbs. Max H A,I,S Life 50 hours Min M T,I,S Cost $1000 Max H A,I *Symbols: H (high), M (medium), L (low) ** A (analysis), T (testing), I (inspection), S (similar design) 3.2 Risks and Verification Methods 3.2.1 POWER To measure the success of the turbocharger system, we used Formula SAE's dynamometer and Dynomax software to obtain accurate power and torque output values. Intake and exhaust design, as well as fuel and ignition tuning, played a large role in power and torque output. 3.2.2 TORQUE We aimed for a flat torque curve in the usable range of engine speeds with a decrease close to redline in order to minimize shifting, maximize tractive effort, and have linear power delivery. If the power delivery is not linear, the car can become unstable in corners where it is important to provide the tires with gradual power. A flat torque curve also minimizes the number of shifts needed to complete a lap and therefore reduces the risk for driver error. 3.2.3 EXHAUST For competition, the exhaust must meet noise and height requirements to be in accordance with SAE regulations otherwise the FSAE team is penalized. The placement of the exhaust will be determined by the FSAE team when they determine how the turbocharger system will be packaged into the car. The turbocharger partially muffles the exhaust noise, but a muffle is still necessary to meet noise regulations. 3.2.4 BOOST PRESSURECONTROL Boost pressure on the GT15V is controlled by the variable nozzle turbine (VNT) design, discussed later. It is important to have a control system that keeps the vanes open as much as possible in order to minimize back pressure and maximize overall efficiency, yet will close the vanes proportional to the demand for power. Finally, the boost control must override the pedal position and open the vanes the required amount in order to not exceed the desired maximum boost. Secondary design goals include preventing the vanes from sticking and maintaining, as closely as possible, the “stock” feel of the accelerator pedal. 3.2.5 COOLING At steady state, the coolant of an engine is usually about 2-3 degrees cooler than the engine block itself. Coolant temperatures above 200°F drastically increase the probability of engine failure, predetonation, or component damage. To verify this specification, we used a temperature sensor at the top of the radiator tank, since that represents the temperature of the coolant when it leaves the engine. 23 3.2.6 WEIGHT For the 2013 Formula SAE car, one of the main goals for the team is decreasing the weight of the car. Since FSAE is our sponsor, we decided to align our goals with those of the team, so we aimed to have the turbocharger system weight under 20 pounds. To determine the overall weight of the turbocharger system, we weighed each component individually. 3.2.7 LIFE At FSAE competitions, about half of the teams do not finish all events due to issues with their cars. This proves how important it is for the car to be reliable, which is why reliability was set as one of our goals. We aimed to have 50 hours of run time without an engine rebuild. To verify this we documented how much time the engine was run during testing. 3.2.8 COST Formula SAE is funded by the ME department at Cal Poly, sponsorships, and donations. However, lack of funding usually results in a very tight budget for the car. As our sponsors, FSAE had to allocate some of their already menial budget to fund our project. Therefore, our goal was to keep the cost of our project under $1000 to Cal Poly FSAE. Otherwise, we risk spending money that was budgeted for other parts of the car, which might decrease system reliability. 3.2.9 QUALITY FUNCTION DEPLOYMENT Additional requirements are located in the Quality Function Deployment (QFD) graph in Appendix A. QFD is a design technique where measurable objectives are weighted against the customer’s desires in order to decide which objectives are the most important to focus on. The most important requirements in the QFD are to meet the FSAE rules; otherwise the car will not be able to compete. 4.0 Design Development 4.1 Simulation – Ricardo WAVE In order to determine the optimum design for the intake and exhaust components we used a program called Ricardo WAVE. From Ricardo's website: "WAVE is the market-leading ISO approved 1D engine & gas dynamics simulation software package from Ricardo Software. It is used worldwide in industry sectors including passenger car, motorcycle, truck, locomotive, motor sport, marine and power generation. WAVE enables performance simulations to be carried out based on virtually any intake, combustion and exhaust system configuration, and includes a drivetrain model to allow complete vehicle simulation." [8] We did not use the drivetrain model in our simulation. The advantage to using a simulation program like WAVE is that many design iterations of a component can be performed without physically building and testing them. WAVE saved us a significant amount of time, money, and materials by optimizing the system design before dynamometer testing. 24 WAVE is an extremely powerful tool capable of producing results so accurate that major manufacturers all over the world use it to design engines before they ever build one. This accuracy is solely dependent on the accuracy of the computer model in relation to the actual engine. Each geometry must be properly measured and input into WAVE or the result will be irrelevant. We measured many parameters of the WR450 engine and used data given from Garrett to construct a reasonably accurate model. Greater accuracy could be obtained through the use of actual flow bench data from the cylinder heads instead of using default values within WAVE and through more time fine tuning the tube wall heat transfer and friction coefficients. The model used is shown in Figure 6. Figure 6: Ricardo WAVE model of WR450 Engine Camshaft profiles, turbocharger properties, and other values used in the simulation are in Appendix J. Camshaft profiles were measured using a dial indicator and a degree wheel. One point to note is that both simulations used the camshaft profiles as shown, but the turbocharged engine has the exhaust camshaft timing advanced by 22.5 degrees in order to reduce the amount of overlap. This equates to rotating the camshaft gear 1 tooth counterclockwise in relation to the camshaft chain on the real engine. Camshaft overlap is when both the intake and exhaust valves are open at the same time at the end of the exhaust stroke. While this is beneficial to a naturally aspirated engine due to the scavenging effects and longer power stroke, it is undesirable on a turbocharged engine because the exhaust pressure is greater than the intake pressure, which prevents fresh charge from entering the cylinder and can even cause reversion. It is a common modification on WR450 engines to retard the exhaust camshaft timing by one tooth in order to realize these benefits, and this is what was done on the 25 naturally aspirated engine for

FSAE. Since the engine is now turbocharged it is more beneficial to return the exhaust camshaft to its original timing so as to minimize the amount of overlap. Since an internal combustion engine is just that, combustion events cannot be directly observed. We do not know the exact patterns for how the fuel burns during each cycle, how much of the work produced is lost to friction, or how much heat transfer occurs within the cylinder. Fortunately, WAVE has built-in models for approximating these events. The Weibe combustion model, the ChenFlynn friction model, and the Woschini heat transfer model provide valuable approximations for events that are extremely difficult to measure. The values used in the Weibe, Chen-Flynn, and Woschini models are also shown in Appendix J. When a model is constructed to simulate results, it is extremely important to verify that the model is accurate before it can be used for design decisions. Since there the turbocharged engine is not built yet, the only option is to validate the model using data from the naturally aspirated (NA) engine. Figure 7 shows the results from the simulation with the results measured on the engine dyno for the 2012 naturally aspirated engine. Figure 7: Ricardo WAVE simulation validation The results from the validation show that the model accurately predicts the performance of the engine. Some ranges are slightly different, especially the lower RPM range, but the results are plenty close enough for the model to be used to base design decisions. 4.2 Turbocharger Selection 26 Since the decision had already been made that turbocharging the car would be the most valuable, our goal was to determine the best turbocharger for our system. With numerous manufacturers and multiple types of turbochargers, this seemed like it would be a major part of this project. However, our task was made much simpler after the discovery of Honeywell's FSAE Sponsorship Program. We found that Honeywell would provide a turbocharger free of charge to any FSAE team that wanted to implement forced induction onto their vehicle. All we had to do was to provide supporting calculations to show that the turbocharger would in fact increase our performance. After contacting Honeywell, they provided us with drawings and specifications on the two different turbochargers that they were willing to provide, one being the GT12-41 and the other one being the GT15V. The main difference between the two, other than a slight difference in size, is that the GT15V has a Variable Nozzle Turbine or VNT. 4.2.1 TURBO BASICS To understand the benefits of the VNT, one must first understand the aspect ratio, which is the cross-sectional area over the radius of the turbocharger. The aspect ratio is also known as the A/R ratio. To understand this concept, it is best to examine a fixed geometry turbocharger or FGT. With a FGT, the cross-sectional area and the radius used to determine the aspect ratio are products of the turbocharger geometry. This results in a fixed aspect ratio that is constant for a given turbocharger. The aspect ratio remains constant for a given FGT because as the radius increases so does the crosssectional area resulting in a constant ratio of the two values. Figure 8 shows a FGT with a constant aspect ratio. Figure 8: Fixed Geometry Turbocharger with Constant A/R Ratio

CONCLUSION

The turbocharger system that we built around the WR450 engine proved to be capable of producing large increases in power output relative to the naturally aspirated engine. Even though full torque and power curves were not obtained from testing, the engine still produced power comparable with projections. With this, we are confident in the validity of the WAVE simulation model and therefore the ability of this system to match projected power output. The GT15V compressor proved to be a good match for the engine, but the vanes in the turbine could not regulate the boost at the desired levels. Since an external wastegate is necessary for it to operate at the correct level, we recommend that the Formula SAE team switch to a GT12-41 turbocharger for continued refinement. The GT12-41 offers an integrated wastegate built into the turbine housing to manage boost. This would greatly simplify the control system in relation to adding an external wastegate to the GT15V, which would require control systems for both the vanes and the wastegate. Additionally, the GT12-41 would be several pounds lighter, partially because the unit itself weighs 2 pounds less and partially because it would not require the added weight of an external wastegate. A potential downside with switching to the GT12-41 is the possibility for longer time for the turbocharger to spool up and build boost. Variable vanes are designed to make the turbine react as quickly as possible instead of dumping potential energy past the turbine through a wastegate. Theoretically this sounds like the perfect scenario for an engine, but the reality is that the GT12-41 is so small anyway that it will still spool up very quickly even without variable vanes. The GT15V was set up so that its vanes would be fully open at 4 psi of boost. This means that at every operating point above 4 psi of boost the vanes were at a constant position and no longer acting like a variable vane turbine. Boost response was still very quick in spite of this fact so we feel that switching to the GT12- 41 will not cause any significant increase in turbo lag. The largest unresolved problems with this system revolved around the oiling system. The first was the insufficient oil pressure feeding the turbocharger. Further research has shown that there is an oil bypass valve located in the right outer engine case cover which can be shimmed to produce more oil pressure. Additionally, a high output oil pump from a 2007-2009 YFZ450 is a direct bolt on replacement for the WR450 oil pump and is capable of supplying much more oil. The Yamaha part number for this oil pump is 5D3-13300-00-00. The next issue was oil leaking past the compressor seal. Large volumes of oil would be sucked into the intake tract and burned by the engine regardless of what we tried. This issue needs to be investigated further as it presents a potentially serious problem if so much oil is burned that none is left to lubricate the engine. Potential solutions are outlined in reference [13] but their compliance with FSAE rules must first be determined. 98 Further testing time is required to refine crucial turbocharger subsystems before the turbocharged engine can become a reliable powerplant for the Formula car. This engine is capable of serving as the solid base for future iterations of turbocharger development at Cal

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