THESIS

INCREASING BMEP FOR DOWNSIZING OF INTERNAL COMBUSTION ENGINES THROUGH AN ADVANCED TURBOCHARGING CONCEPT

Submitted by

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In partial fulfillment of the requirements

For the Degree of Master of Science

Colorado State University

Fort Collins, Colorado

Fall 2012

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ABSTRACT

INCREASING BMEP FOR DOWNSIZING OF INTERNAL COMBUSTION ENGINES THROUGH AN ADVANCED TURBOCHARGING CONCEPT

In order to meet more strict national emissions and fuel economy regulations automotive manufacturers are turning to downsized boosted engines. A SuperTurbo^{TM} is a device that delivers the high speed torque of a turbocharger and the low speed torque of a supercharger, with the benefits of turbo-compounding. This technological advantage makes it a perfect candidate for engine downsizing and boosting application.

In order to validate the SuperTurbo^{TM} as viable technology for engine downsizing, a General Motors Ecotec LSJ 2.0l I4 engine was modeled using the industry standard engine simulation software GT-Power. Two additional models of a SuperTurbocharged Ecotec LSJ engine were also generated. One SuperTurbocharged Ecotec engine was tuned to match the performance map of the stock Ecotec LSJ engine and another SuperTurbocharged Ecotec engine was tuned to match the performance map of a larger General Motors Vortec LMG 5.3l V8. Simulation results from the stock Ecotec model were compared to both of the results from the SuperTurbocharged models in order to validate reported efficiency gains through SuperTurbo^{TM} use. Additionally, the models were compared to determine how feasible a SuperTurbo^{TM} is for engine downsizing while maintaining power output.

The simulation results showed improvements in engine brake specific fuel consumption (BSFC) up to 26% at high engine speeds when compared to the GM Vortec LMG engine and BSFC improvements up to 21% at 4500 rpm when compared to the stock Ecotec LSJ engine. At lower to mid-engine speeds both models saw BSFC improvements between 5 and 20%. It was

concluded that downsizing an engine with a SuperTurbo^{TM} was a practical way to improve engine BSFC while maintaining performance.

ACKNOWLEDGMENTS

My mother instilled in me the never-ending desire to question results that I do not agree with and then act to bring about change. When I look at how we as a society function today, the results I find lead me to question how we can do better. I know that I am just one person, but I am not deterred. I am still on my quest to alter results that I don't agree with. I have her to thank for this desire, but my father to thank for the way in which I go about it. Watching him perfect his craft throughout the years has taught me how to do the same with mine. He has done an exceptional job raising me to be the dedicated, fun-loving, knowledge seeker that I am today. I would not be here without his support. Bisous.

Dr. Daniel Olsen has given me the opportunity to expand my knowledge and skills such that someday my quest for change might become a reality. I am eternally grateful for him meeting with me on such short notice in May of 2011 and doing everything he could to find me a research project so that I could attend graduate school at CSU. He could not have found a better position for me and I continuously thank my lucky stars for having him in my life. I hope that I have repaid the favour he did in putting his faith in me with the work I done. My thesis committee, Dr. Allan Kirkpatrick and Dr. Jerry Johnson, also deserve acknowledgement for their support and willingness to embark on this journey with me.

I also must, without a doubt, thank Ed VanDyne of VanDyne SuperTurbo™ for selecting me to research the up and coming SuperTurbo™ technology and prove to the world that it is part of the key to the better result we are all looking for. The entire VanDyne office deserves a thank you for welcoming me into their work community, but expressly: Tom Waldron for giving me the opportunity to continue applying what I have learned and treating me so well; Brian Tuohy for his technical assistance in all things engine related; and the utmost thanks to Jared Brown for educating and helping me with GT-Power whenever I needed it. Finally, previously at VanDyne, Wayne Penfold who serves as the first person I have ever considered a professional mentor, I have to thank for his conviction in me. I value both his mentorship and friendship and look forward to a long and fruitful relationship.

Thank you to my friends Frank Sutley, Bryna Fitzgerald, Alexis Amy, Frazier Malone, Alannah Wheeler, Lacey Bartels, and Johnny Gattoni for their patience with listening to me discuss my thesis and their support, understanding, belief in me, and continued friendship when I disappeared off the face of the Earth to work. Christian L’Orange, thank you for putting up with my antics and willingness to answer any of my thesis or life related questions. Your help and friendship helped carry me through. And of course, Ryan Doolittle, Dave Berube, a very SPECIAL THANKS.

DEDICATION

For DGA 1958-2004

And TLG 1971-2012

"In three words I can sum up everything

I've learned about life: it goes on."

-Robert Frost

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CHAPTER 1: INTRODUCTION

1.1 Motivation for Research

The mantra has been repeated many times over. We've all heard it. It is imperative that as a nation and a globally interconnected world we reduce our dependence on fossil fuels. On one side there are some who argue we will run out of fossil fuels in our children's lifetime, but the more pressing matter is the amount of harmful emissions generated by the combustion of these fossil fuels. Arguably climate change is occurring due in part from the emissions from automobiles and their contribution to the greenhouse effect. The greenhouse effect or warming of the Earth is due to trapped gases such as carbon dioxide, oxides of nitrogen, and hydrocarbons in the Earth's atmosphere. The molecular structures of the gases lead them to trap heat and absorb solar radiation emitted from the Earth's surface [1]. According to the United State Environmental Protection Agency (US EPA) the largest contributor to greenhouse gas emissions is carbon dioxide from fossil fuel combustion [2]. The transportation sector accounted for 27 percent of US greenhouse gas emissions in 2009 [2]. By improving the efficiency of the internal combustion engine by even a few percentage points we can not only drastically reduce our dependence on fossil fuels, but also reduce the amount of greenhouse gases, including carbon dioxide, that are released into the atmosphere each year.

In the United States the National Highway Traffic Safety Administration (NHTSA) administers a Corporate Average Fuel Economy (CAFE) to reduce energy consumption by increasing the fuel economy of cars and light trucks [3]. Docket ID No. NHTSA-2010-0131 has regulated that by 2020 the passenger car fleet of automotive manufacturers must have an average fuel economy (mpg) of 44.7 and carbon dioxide emissions of 113 g CO_2/km. In Europe this regulation is even stricter with a mandate of 95 g CO_2/km [4]. How are original equipment manufacturers (OEMs) expected to reach these targets? It is going to require a combination of innovative automotive technology including downsizing engines.

In 2008 VanDyne SuperTurbo patented a novel idea, the SuperTurbo™, which combines the high speed torque of a turbocharger and the low speed torque of a supercharger, with the benefits of turbo-compounding. It is expected to see gains of 15-20% [5] in efficiency, using brake specific fuel consumption (BSFC) as the gauge for efficiency, because it combines the low-speed performance capabilities of a supercharger with the energy extraction capabilities of turbo-compounding through an added transmission to the turbocharger. The motivation behind this technology is based in the demand for innovative new engine technology. The research performed in this thesis is used to validate the claims that VanDyne SuperTurbo has made in regards to their SuperTurbo™ technology and to verify that the SuperTurbo™ is a viable technology for engine downsizing.

1.2 Literature Review

One of the most cost-effective ways to lower pollutant engine emissions and meet more stringent emissions regulations is through engine downsizing. By downsizing the engine the fuel consumption can be reduced, however, the power output of the engine is reduced. Customers receiving the final automotive product, for the most part, will not accept a less powerful engine. For this reason a method of boosting the power of the engine is sought. The method of forced induction is as old as the invention of the first gasoline powered engine itself [6]. Boosting the engine through forced induction is investigated and the opportunity for new forced induction technology is explored.

1.2.1 Power Boosting

The maximum power produced by an internal combustion engine (ICE) is primarily determined by the amount of fuel that is burned in the cylinder. This, in turn, is limited by the amount of air that is introduced into the cylinder. The air provides the oxidizer to the system which begins combustion. If more air is introduced to the system, more power is produced, hence the power is boosted. A process by which more air is introduced into the intake system is known as forced induction. Air is compressed to a density higher than that of ambient. The maximum volume of air (V_A) that is permissible in the cylinder is equal to the volume of the cylinder (V_{cyl}). In Equation 1 it is apparent that when the density of the cylinder air ($\rho_{A,cyl}$) is increased the mass of air (m_A) is also increased [6].

$$V_A = V_{cyl} \text{ and } m_A = V_{cyl}\rho_{A,cyl} \quad (1)$$

By adding more air more fuel can be added and more work is generated due to the increased temperatures and pressures of combustion. The following equation shows that an increase in heat in the cylinder ($Q_{add,cyl}$) times the indicated efficiency (η_i) results in more indicated work (W_i) generated by the cylinder [6].

$$W_i = Q_{add,cyl}\eta_i \quad (2)$$

As stated before, the chemical energy added to the cylinder is dependent on the amount of fuel that is present in the cylinder. The amount of fuel present in the cylinder is dependent on the amount of air mass in the cylinder since combustion occurs at a fixed air/fuel ratio. Thus, the amount of heat added to the cylinder is dependent on the density of air in the cylinder as seen in Equation 1. This implies that the amount of work done by the cylinder is also dependent on the density of air in the cylinder. Traditionally, work is defined as force times displacement. For a cylinder this is the volumetric displacement of the cylinder times the indicated mean effective pressure ($imep$) [6].

$$W_i = V_{cyl} imep \tag{3}$$

Using the relationship between cylinder volume and mass of air in Equation 1 and by setting Equations 2 and 3 equal to one another reveals the proportional relationship between pressure and air density based on the relationships discussed above [6].

$$imep \sim \rho_{A,cyl} \tag{4}$$

The indicated power (P_i) produced by the engine is related to the work per cycle and engine speed (N) by the number of crank revolutions for each power stroke (n_R) as seen in Equation 5 [7].

$$P_i = \frac{W_i N}{n_R} \tag{5}$$

Substituting Equation 3 into Equation 5, keeping in mind the relationship between pressure and air density from Equation 4, it is apparent that the indicated power of the engine is proportional to the density of air. Finally, the relationship between the density of air and the mass of air from Equation 1 reveals the direct relationship between power and the mass of air in the engine as seen in Equation 6.

$$P_i = \frac{m_A N}{n_R} \tag{6}$$

A form of power boosting known as supercharging utilizes the relationship between indicated power and the mass of air in the cylinder by compressing air before it enters the cylinder by increasing the air's pressure [7]. The three main types of supercharging are mechanical supercharging, turbocharging, and pressure wave supercharging. Mechanical supercharging, henceforth known as supercharging, turbocharging and a method of extracting excess power from the turbocharger, known as turbo-compounding, are further expanded upon in the following sections.

1.2.1.1 Supercharging

Superchargers employ the use of a compressor powered by the engine crankshaft to increase the pressure of the air before it enters the engine cylinder. The compressor typically operates at the same speed as the engine due to its connection to the crankshaft [8]. Three classifications of compressors for automotive application currently exist: sliding vane compressors, rotary compressors, and centrifugal compressors [7]. Sliding vane compressors are not typically used in supercharging, but rather, in air conditioning systems [9]. Centrifugal compressors are normally found in conjunction with turbines for turbocharging application.

The roots blower, found on 90% of passenger cars [10] employing a supercharger, is a common type of rotary compressor. The roots blower is characterized by two to three three-lobe rotors, twisted 60 degrees. Air is brought into one side of the blower by a vacuum created between the two opposite direction rotating rotors as seen in Figure 1.1. As the rotors spin and arrive at the outlet side the air is compressed and forced out by the blades meeting up with one another. The roots blower is used as a standalone compressor for supercharging. The compressor is typically coupled to the crankshaft by a belt through a fixed gear ratio.

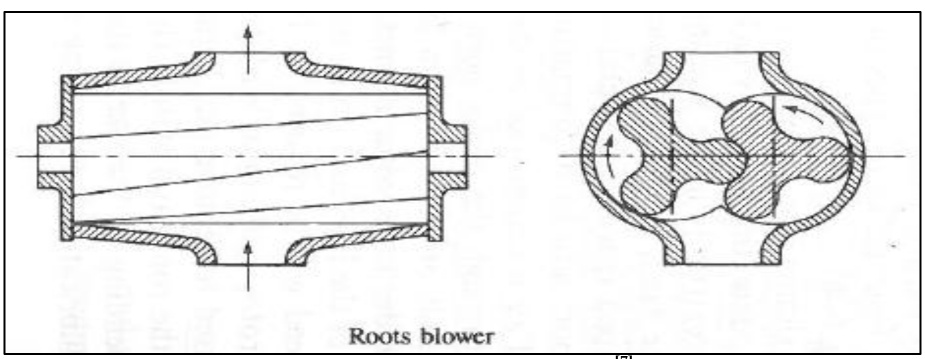

Figure 1.1: Roots type blower [7]

The low speed boost response of a supercharger is exceptional because it is coupled directly to the crankshaft. As boost increases temperatures across the roots blower increase. Process irreversibilities result in additional temperature increase. The relationship between inlet and outlet pressures (P_1, P_2) and temperatures (T_1, T_2) and adiabatic efficiency (η_a) is shown in Equation 7 [11].

$$\eta_a = \frac{\frac{P_2}{P_1}^{k-1/k} - 1}{\frac{T_2}{T_1} - 1} * 100 \tag{7}$$

High compressor outlet temperatures reduce the density of air in the intake manifold and thus, reduce the mass of air in the engine cylinder [12]. High temperatures in the intake manifold also lend to a greater risk of knock occurring because the combustion process begins at higher temperatures [7]. In order to reduce the air temperature before it enters the engine cylinder an intercooler or aftercooler is used.

Although supercharging provides boost quickly and at low engine speeds through its mechanical connection to the crankshaft, this connection is also a drawback of supercharging. The crankshaft is required to power the supercharger generating parasitic losses. It is imperative that the supercharger generates enough power to compensate for its parasitic losses and provide boost to the engine. At higher engine speeds the parasitic losses become more prominent. In order to negate the increasing parasitic losses at higher engine speeds a bypass valve is used. When the engine reaches maximum boost pressure required, the bypass valve will open, allowing the air to circumvent the supercharger.

A study was performed on a three cylinder .79l supercharged engine to validate the effects of supercharging on performance of small gasoline engines. It was found that brake torque was increased, in comparison to the naturally aspirated engine, at medium engine speeds, but was decreased at low and high engine speeds [10]. Figure 1.2 showed the results of the test performed. This test revealed the main advantage of a supercharger was the significant increase in peak torque, at the expense of maximum power, over a naturally aspirated engine. The power of the engine revealed similar results as seen in Figure 1.3. At low speeds engine performance was reduced because of parasitic losses associated with the supercharger. At high speeds the study attributed the reduction in supercharged engine performance to a lower compression ratio than that of the naturally aspirated engine. In another study (Figure 1.4) it was found that supercharging a Chevrolet Chevette decreased the time of acceleration from 0-60 mph from 17.2 seconds to 10.9 seconds [13]. It was apparent that the use of a supercharger on an internal combustion engine increases torque and power output and also improves vehicle performance.

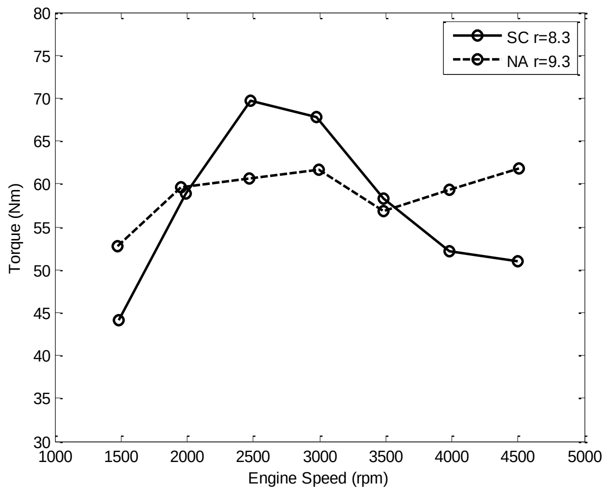

Figure 1.2: Torque comparison of a naturally aspirated engine and supercharged engine [10]

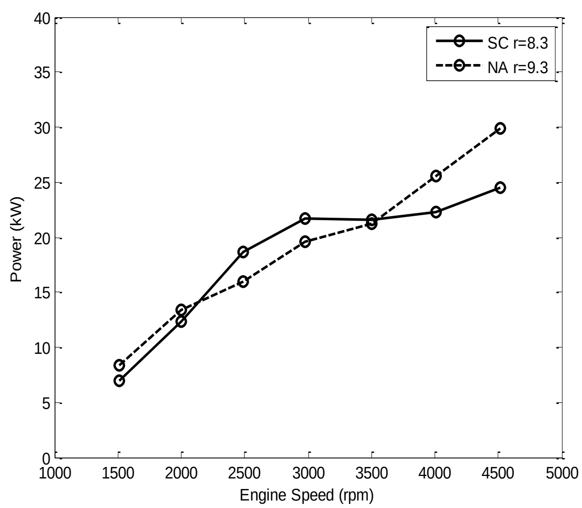

Figure 1.3: Power comparison of a naturally aspirated engine and supercharged engine [10]

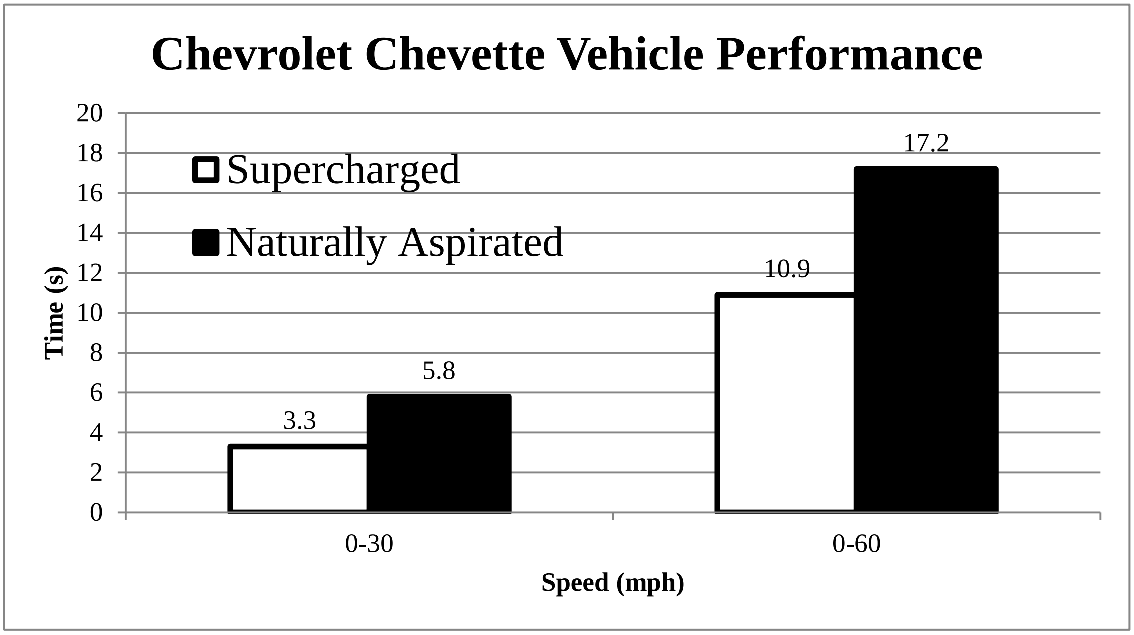

Figure 1.4: Vehicle performance comparisons [13]

1.2.1.2 Turbocharging

Turbocharging, much like supercharging, is used to increase the density of air prior to it entering the cylinder. The compressors used in turbochargers, however, are not driven by the crankshaft of the engine but rather by exhaust gases spinning a turbine on a common shaft. For exhaust gas driven systems it is common to see a centrifugal compressor paired with an axial flow or radial flow turbine. Radial flow turbines can remain compact and deliver high efficiency [12], which makes them most appropriate for packaging in automotive applications.

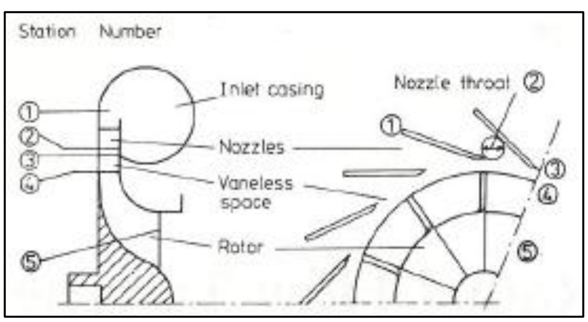

Figure 1.5: Components of a radial flow turbine [12]

The radial flow turbine is typically composed of a scroll, inlet nozzles, and the turbine impeller as seen in Figure 1.5. In an ICE the exhaust is not a continuous stream of air, but rather comes in pulses based off of the firing order of the engine. The turbine, therefore, must be robust enough to accept pulsating flow. The scroll helps to direct the pulsating flow in a more manageable uniform manner to the inlet nozzles where the flow is accelerated into the impeller.

A turbocharger provides boost without taking energy away from the engine using waste energy from the engine exhaust. To generate boost the turbine must overcome its mechanical inertia and accelerate to high rotational speeds. It takes time for the intake and exhaust manifold to fill up with air and for the turbine to accelerate to these high rotational speeds. The time from boost demand to boost delivery is known as turbo lag. Turbo lag can be physically felt by the driver and is most prominent at low engine speeds.

Due to higher pressures in the intake, turbocharged (and supercharged) engines have the propensity for self-ignition, a phenomenon referred to as knock. Knock is detrimental to an engine because of the intense localized and instantaneous explosion that occurs in the cylinder. This causes high pressure waves to propagate throughout the cylinder and can cause physical damage to the piston and cylinder. Knock can be avoided by varying compression ratio, spark retard, valve timing, intake air temperature, and equivalence ratio [7]. Knock in a turbocharged engine is also avoided by use of a wastegate. As engine speed increases the turbine will continue to generate more boost. To help avoid knock boost must be kept constant [7]. When the engine reaches maximum boost pressure required the wastegate will open, allowing the air to pass around the turbine.

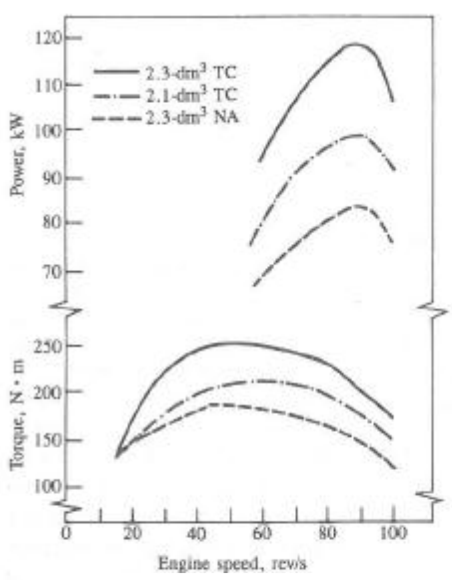

Figure 1.6: Power and torque curves of two turbocharged engines and a naturally aspirated engine [14]

In order to validate the increase in performance of a turbocharged engine compared to a naturally aspirated (NA) engine, Volvo performed tests with their 2.3l engine. The 2.3l engine was equipped with a turbocharger, intercooler, and knock-sensor spark-advance control. Figure 1.6 shows the torque and power curves for the 2.3l naturally aspirated and turbocharged engine. Figure 1.6 also shows curves for a 2.1l turbocharged engine without the intercooler and knock-sensor spark-advance control modifications. As expected the 2.3l turbocharged engine performed better than the 2.3l NA engine with a 36% increase in maximum torque and a 41% increase in maximum power [14]. Although the unmodified 2.1l engine did not perform as well as the turbocharged 2.3l engine it did outperform the naturally aspirated 2.3l engine. This result supports the theory of downsizing engines while retaining power and torque output.

1.2.1.3 Turbo-compounding

The same turbine technology used in turbocharging is utilized for turbo-compounding. In turbo-compounding, however, an additional turbine is mechanically connected to the engine crankshaft, like a supercharger. The turbine, sometimes referred to as a power turbine, is spun by energy from exhaust gas from the turbocharger turbine and supplies additional power to the crankshaft.

1.3 The VanDyne SuperTurbo™

Innovative automotive technology for answering new fuel economy requirements is wanted, needed, and required by today’s OEMs. VanDyne SuperTurbo™ answered this call with the invention of the SuperTurbo™. The SuperTurbo™ is a turbocharger with an integral continuously variable transmission (CVT). The combination of a turbine and a compressor connected to the crankshaft via a high speed planetary gear and a CVT allows the SuperTurbo™ to act as a supercharger, turbocharger, and a turbo-compounder. The SuperTurbo™ utilizes energy from the crankshaft to power the turbine shaft like a supercharger, utilizes waste exhaust heat like a turbocharger, and when extra turbine energy is extracted and given to the crankshaft, it acts like a turbo-compounder. In automotive applications, the SuperTurbo™ can be used to downsize engines while maintaining power output.

Each technology by itself, supercharging and turbocharging, have distinct advantages and disadvantages as explained in the above sections. The nature of the SuperTurbo™ exploits the advantages of these methods of power boosting, while simultaneously eliminating some of their disadvantages. The initial advantages of the SuperTurbo™ were outlined as energy recovery at high speed and high load, quick response of the turbine shaft during transients, and the inclusion of a low cost variable speed hydraulic transmission [15].

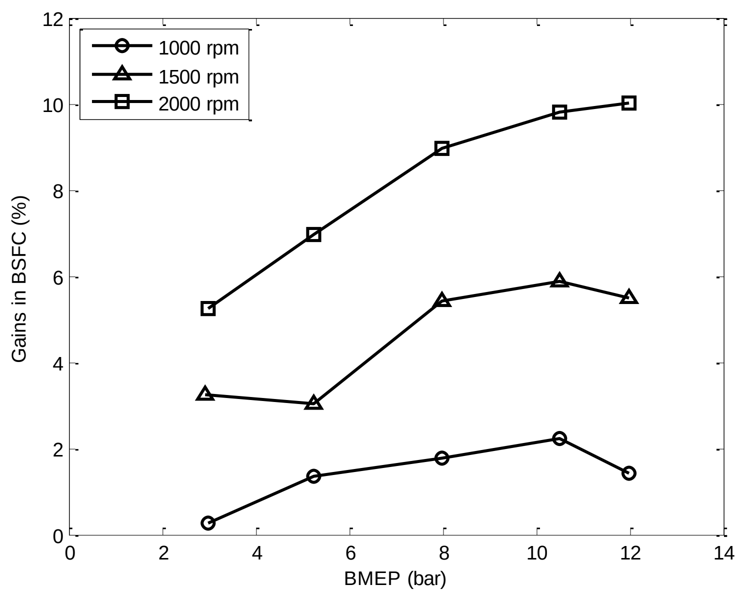

Figure 1.7: Simulated improvement in BSFC with Hyundai natural gas engine [15]

Initial modeling of the first generation SuperTurbo™ was performed on an 11l Hyundai engine with GT-Power [15]. Simulation results shown in Figure 1.7 revealed gains in BSFC for high loads and high speeds at an estimated transmission efficiency of 60%. At high load and high speed the turbine shaft was expected to receive 22kW of power, which would translate to an additional 6% increase in power to the crankshaft. At low speeds benefits were minimal.

In order to validate modeling results the SuperTurbo^{TM} was tested on a Mack E7G engine. The Hyundai engine used in modeling was unavailable for testing so the Mack engine was chosen as a suitable replacement due to its similarities in geometries and performance. The Mack engine was outfitted with a Garrett variable nozzle turbine and the turbine shaft was only modified to incorporate the continuously variable hydraulic transmission. This turbine was not optimized for the Mack engine, but was thought to be sufficient enough.

Engine testing garnered similar results to engine modeling. As seen in Figure 1.8, BSFC was improved by almost 6% at high speed and high load. The reduction in efficiency at other points can be attributed to the miss match between compressor and turbine as well as low transmission efficiencies.

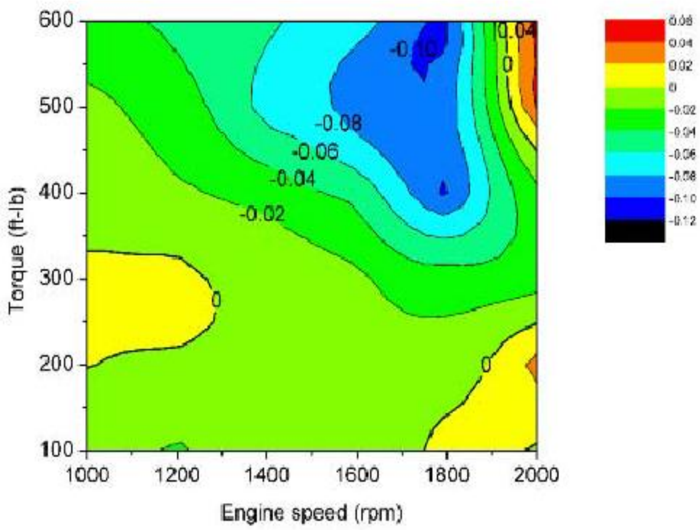

Figure 1.8: Improvement in BSFC for Mack E7G engine with SuperTurbocharger compared to stock turbocharger [15]

A wide open throttle torque curve was also produced from engine testing as seen in Figure 1.9. The SuperTurbocharged engine showed increases in torque at low and high speed over the stock engine. It was predicted that the SuperTurbocharged engine would have exceeded the stock configuration at all engine speeds had the turbine and compressor and transmission been matched properly.

The ability of the SuperTurbo™ to accept load was also of interest. In Figure 1.10 it was shown that the SuperTurbocharged engine could go from 50 ft-lb load to 400 ft-lb load at 1600 rpm in 2.4 seconds compared to the 14 seconds it took the stock engine. Even more impressive is the 1.5 seconds it took the SuperTurbocharged engine to reach 400 lb-ft of load when boost is required. In contrast, the stock model took close to 13 seconds to achieve the same load. The SuperTurbocharged engine can achieve this step faster than the stock engine due to its combined turbocharged and supercharged advantages.

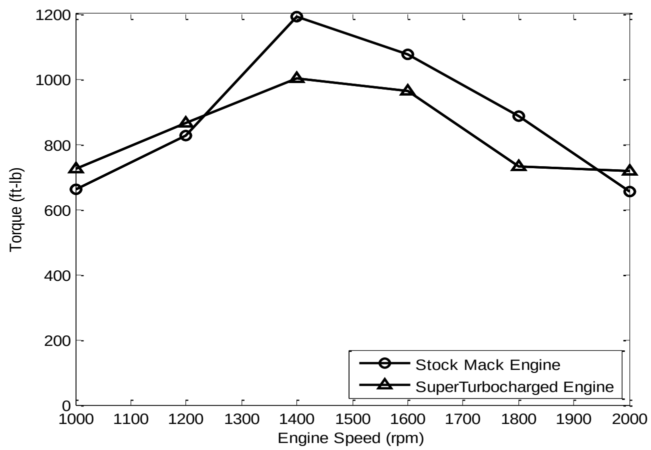

Figure 1.9: Wide open throttle torque curve for Mack E7G with SuperTurbo™ and stock turbocharger [15]

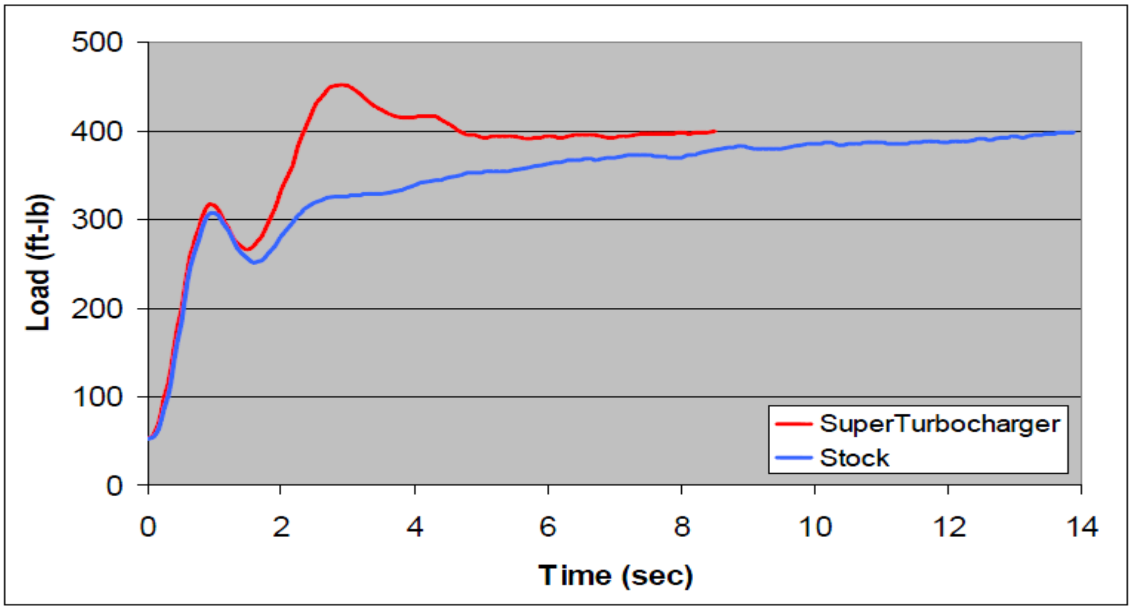

Figure 1.10: Step change response of Mack E7G with SuperTurbo™ and stock turbocharger [15]

From this study the ability of the SuperTurbo™ to improve BSFC, increase torque output, and rapidly accelerate the turbine shaft for boost, was proven. Additionally, the validity of modeling the SuperTurbo™ on GT-Power was confirmed through similar experimental results.

The second generation SuperTurbo™ was upgraded to feature a high speed planetary gear drive and continuously variable transmission [5]. Two studies were performed to validate the claims that a downsized SuperTurbocharged engine could match the torque curves and demands of a naturally aspirated engine, while increasing efficiency and decreasing fuel consumption [5]. The first downsizing study was between a 3.2l V6 naturally aspirated engine and a 2.0l L4 SuperTurbocharged engine. Through modeling and simulation with GT-Power it was estimated that the downsized engine would reduce fuel consumption by 21% and the New European Drive Cycle (NEDC) and EPA drive cycle fuel economy would increase by 17%. It was also shown that the 2.0l SuperTurbocharged engine could not only match, but exceed the torque curve of the naturally aspirated engine at engine speeds of 2000 rpm to 4000 rpm as seen in Figure 1.11. At lower engine speeds the compressor was not able to provide boost due to surge. This fact is trivial because the stall speed of the torque converter is typically 1000rpm. Additionally, the SuperTurbocharged engine took .3 seconds to reach production brake mean effective pressure (BMEP) as seen in Figure 1.12. It was expected that the

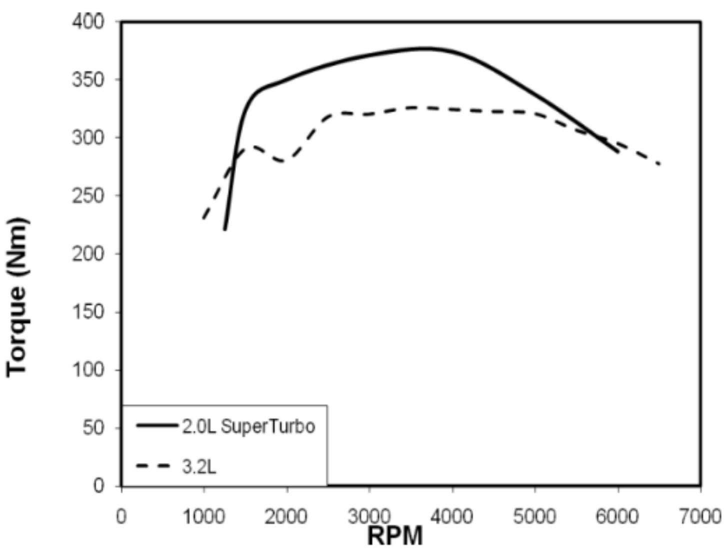

Figure 1.11: Torque curve of 2.0l engine with SuperTurbo™ and 3.2l naturally aspirated engine [5]

traditional turbocharged engine would have taken two to three times longer [5]. At full load, however, the 3.2l naturally aspirated engine had lower BSFC than the SuperTurbocharged engine. This was expected due to the timing retard and enrichment at full load of the SuperTurbocharged engine. Due to the turbo-compounding capabilities of the SuperTurbo™, the difference in BSFC between the two engines was smaller than expected as seen in Figure 1.13.

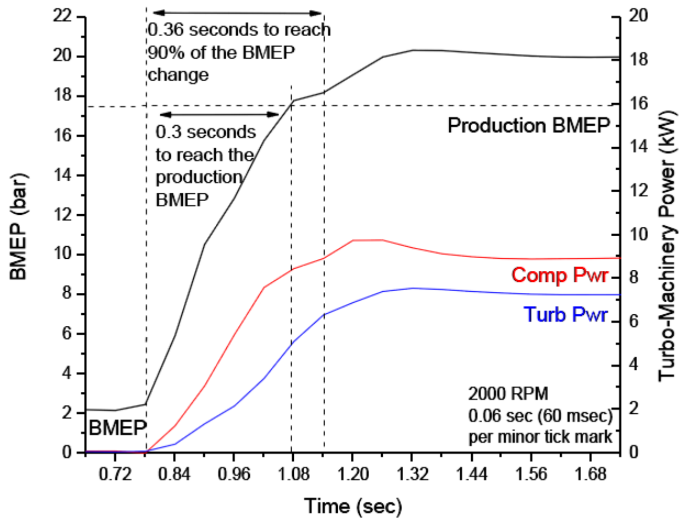

Figure 1.12: SuperTurbo™ transient response time for a pedal snap from 2-bar BMEP to wide open throttle at 2000rpm [5]

The second downsizing study was between a 4.2l V8 naturally aspirated engine and an air bypass equipped 2.0l L4 SuperTurbocharged engine. The air bypass was required in order to provide the engine with enough air to match the 4.2l at peak power [5]. Using the same methods as the first downsizing study it was estimated that the downsized engine would reduce fuel consumption by 36%. It was also shown in Figure 1.14 that the 2.0l SuperTurbocharged engine could again exceed the torque curve of the naturally aspirated engine at engine speeds of 2000 rpm to 4000 rpm. In contrast to the first downsizing study, the SuperTurbocharged engine performed better at full load than the 4.2l engine at most

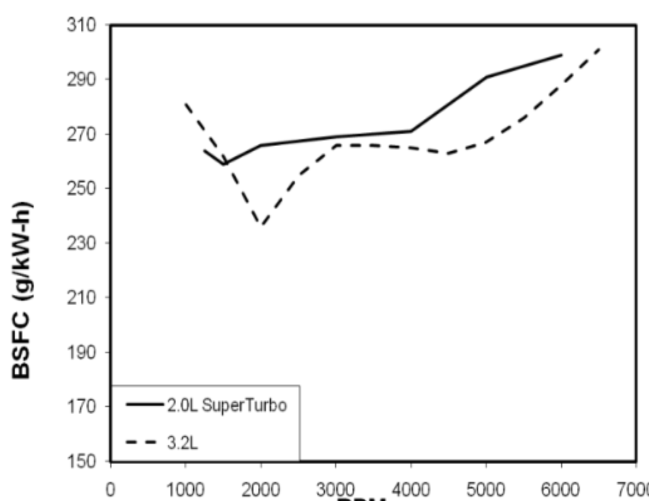

Figure 1.13: Full load BSFC for 2.0l SuperTurbo™ engine and 3.2l naturally aspirated engine [5]

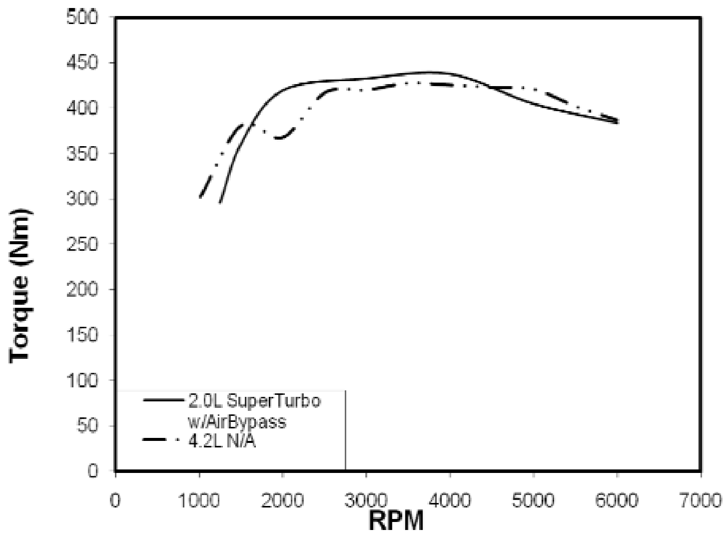

Figure 1.14: Torque curve of 2.0l engine with SuperTurbo™ and 4.2l naturally aspirated engine [5]

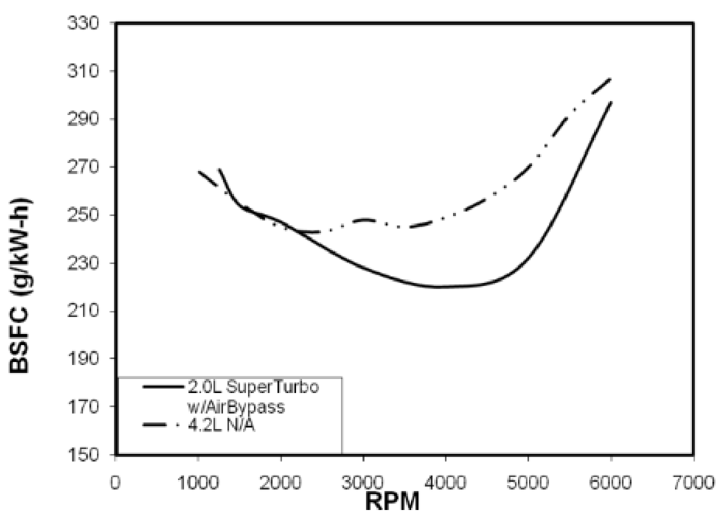

Figure 1.15: Full load BSFC for 2.0l SuperTurbo™ engine and 4.2l naturally aspirated engine [5]

engine speeds as seen in Figure 1.15. At higher speeds spark retard require to combat knock was reduced, increasing efficiency. Additionally, the turbine moved into a more efficient operating range as the engine speed increased.

These two downsizing case studies displayed the ability of a smaller displacement engine equipped with a SuperTurbo™ to compete with a larger naturally aspirated engine in torque output and transient demand while reducing fuel consumption and increasing energy. Although the advantages of a SuperTurbo™ were compelling it must be acknowledged that there will be technical limitations if the turbine was not sized properly or designed in a way that complements the engine it was being placed on.

1.4 GT-Suite Engine Modeling Software

Today, most of industry relies on computer modeling technology to assist in the engineering design process. In the automotive world, Gamma Technologies' GT-Suite is a leading engine simulation software and GT-Power, a part of the GT-Suite, is one of the industry standards for engine simulations [16]. GT-Power uses the one dimensional solution of the fully unsteady, nonlinear Navier-Stokes equations (conservation of continuity, momentum, and energy) to simulate gas flow dynamics throughout the engine. Two different time integration methods, explicit and implicit, are used to generate the primary solution variables for the Navier-Stokes equation. The explicit method is suggested for simulations over small time scales when wave dynamics are important and the implicit method is suggested for non-engine long-duration simulations. The primary solution variables for the explicit method are mass flow, density, and internal energy. The primary solution variables for the implicit method are mass flow, pressure, and total enthalpy. From these three variables any remaining gas properties are calculated. All property quantities are averages across the flow direction because the solutions are solved in one dimension. In order to improve the model's accuracy the entire system is split into smaller parts or discretized. The GT-Power library is equipped for both steady-state and transient simulations.

GT-Power engine models are built by placing library supplied engine components (e.g. pipes, flowsplits, turbines, etc.) and engine connections (e.g. valves, fuel injectors, gears, etc.) onto the graphical user interface known as the GT-ISE. The user is only required to input component geometries and initial conditions due to GT-Power's internal algorithms. For engine performance simulations GT-Power has built in combustion models which are chosen based on how the final simulation model is used. The combustion models are non-predictive, predictive, and semi-predictive. These combustion models are part of what makes GT-Power a powerful engine modeling tool. The non-predictive combustion model uses a predefined function to model combustion, whereas the predictive combustion model requires more input from the user and continuously calculates combustion based on the evolving physical conditions of the engine. The semi-predictive combustion model uses the predefined functions from the non-predictive model based on inputs that are imposed by the user. The combustion models utilized by GT-Power allow for the engine model to be tuned to varying degrees of specificity required by the user for data analysis.

Superchargers and turbochargers are also modeled in GT-Power using turbine and compressor objects from the library. The user is required to input the performance map data of the turbine or compressor typically provided by the manufacturer. Using the mass flow rate, pressure ratio, and efficiency of the turbine or compressor for each speed line, GT-Power extrapolates and interpolates the data and creates an internal performance map.

Another aspect of GT-Power that contributes to its relevance and strength is the ability to integrate controllers. GT-Power has a template for a proportional-integral-derivative (PID) controller. The PID controller controls the input into a system such that the output is a commanded target value [6]. The most important aspect of building a PID controller is choosing the right gains. The correct gains force the controller to output the desired target value as quickly as possible. Calibrating the PID controller with the right gains can be a tedious trial and error process that is still required in GT-Power.

After an engine model is created in GT-Power and simulations are run, the results are analyzed in GT-Suite's post processing application called GT-Post. GT-Post allows the user to plot, view, and manipulate data [16].

Although GT-Power is a powerful modeling tool, if there is no test data available with which to tune the engine after it has been constructed, accuracy of the model decreases.

1.5 Key Engine Performance Parameters

The following normalized key engine performance parameters are discussed in the following chapters in order to understand and analyze engine behaviour. Brake specific fuel consumption (BSFC) is defined as the fuel mass flow rate ($\dot{m}_f$) divided by brake engine power (P_b) [7].

$$BSFC = \frac{\dot{m}_f}{P_b} \tag{8}$$

Indicated specific fuel consumption (ISFC) is defined as the fuel mass flow rate divided by indicated engine power [7].

$$ISFC = \frac{\dot{m}_f}{P_i} \tag{9}$$

Brake mean effective pressure (BMEP) is defined as brake power times the number of crank revolutions for each power stroke divided by displaced volume times engine speed [7].

$$BMEP = \frac{P_b n_R}{V_d N} \tag{10}$$

Thermal engine efficiency is defined as the work per cycle (W_c) divided by the mass of fuel times the heating value of the fuel (Q_{HV}) [7].

$$\eta_t = \frac{W_c}{m_f Q_{HV}} \tag{11}$$

A measure of the engine's ability to pump air is known as its volumetric efficiency. It is defined as the air mass flow rate divided by the density of air times displaced volume and engine speed [7].

$$\eta_v = \frac{2\dot{m}_A}{\rho_A V_d N} \tag{12}$$

1.6 Thesis Overview

In the following chapters the process of modeling a stock and SuperTurbocharged 2.0l General Motors (GM) Ecotec engine on GT-Power is outlined and significant results are discussed. The aim of this research is to show that a SuperTurbocharged small displacement engine has the capability to outperform a large displacement engine while reducing fuel consumption.

CHAPTER 2: STOCK GENERAL MOTORS (GM) ECOTEC 2.0l LSJ ENGINE

2.1 GM Ecotec LSJ Engine

The GM Ecotec LSJ was chosen for research purposes by VanDyne SuperTurbo, Inc. due to its strength as a stock engine, its easy acquisition as a crate engine, and the extensive literature and support from GM Performance Division on upgrades and tuning. Two engines were initially purchased with the intent of testing one for baseline data and the other was to be equipped with the SuperTurbo for testing and data gathering. In the following chapter engine specifications and performance parameters are explained. In order to input accurate engine data into GT-Power for simulation, a GM Ecotec LSJ engine is taken apart and measured; this process is outlined and important measurements acknowledged. The engine model building process and simulation on GT-Power is explained. The engine model is validated when it closely matches the published performance map. Significant results from simulation are discussed.

2.1.1 Engine Specifications

The GM Ecotec LSJ is a 2.0l inline 4-cylinder supercharged engine, henceforth referred to as the Ecotec engine. A high pressure port fuel injection system supplies gasoline to the engine. The head and engine block are lost foam and sand cast aluminum making them lightweight, but also more susceptible to fracture if handled incorrectly. The Ecotec valvetrain utilizes dual overhead camshafts with four valves per cylinder and hydraulic roller finger follower valve lifters. Engine parameters are tabulated below in Table 2.1.

Table 2.1: LSJ Engine parameters

Engine	General Motors Ecotec LSJ
Configuration	I-4 Supercharged
Displacement	1998 cc
Bore	86 mm
Stroke	86 mm
Firing Order	1-3-4-2
Compression Ratio	9.5:1
Throttle Type	Electronic throttle control
Ignition System	Coil-on-plug

The Ecotec engine produces a peak power of 153 kW (205 hp) at 5600 rpm and a peak torque of 271 N-m (200 lb-ft) at 4400 rpm at wide open throttle (WOT) as shown in Figure 2.1. The Ecotec is equipped with a helical roots blower style M62 Eaton supercharger. The supercharger is attached to the integrated air-to-liquid intercooler/intake manifold.

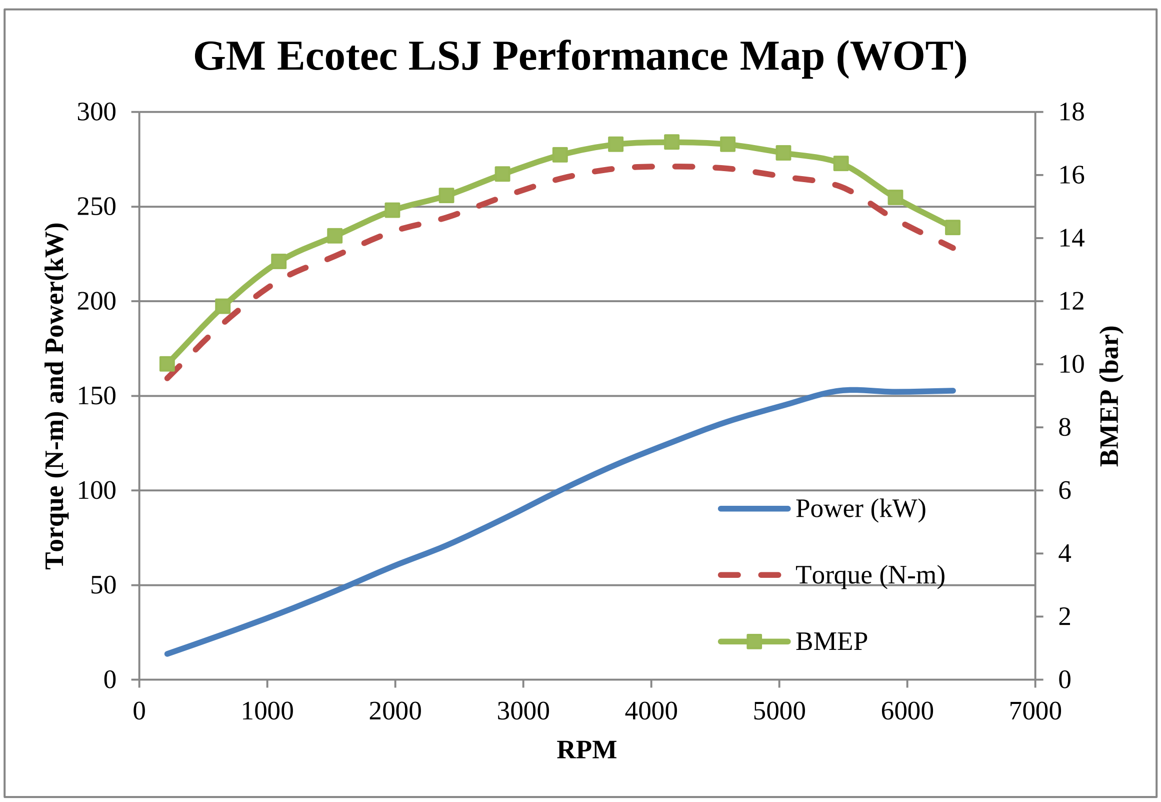

Figure 2.1: Full Throttle GM Ecotec LSJ engine performance

2.1.2 Engine Tear Down Process

GT-Power requires information about the geometry of the engine in order to generate accurate model simulations. The Ecotec engine purchased for SuperTurbo testing was taken apart and measured. Although some Ecotec geometry was available through build books from GM Performance Division, the published measurements were validated.

First, all auxiliary components, hoses, and belts were removed from the engine. After the valvetrain cover was removed the valve lift profile of the Ecotec engine was measured using a degree wheel mounted on the crankshaft and a dial indicator resting on a cam lobe as shown in Figure 2.2.

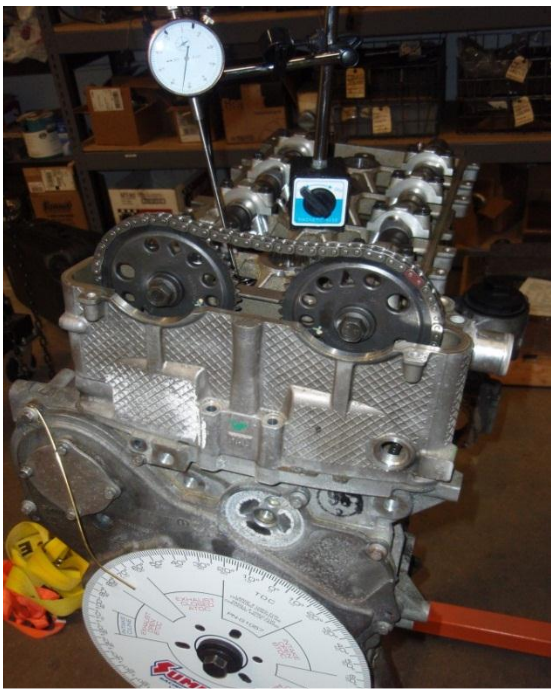

Figure 2.2: Valve lift measurement set-up

Top dead center (TDC) was located and the dial indicator zeroed. At degree increments the lift of the intake and exhaust valve of one cylinder was recorded. This process was repeated at five degree increments on each cam lobe for accuracy. In order to validate the valve lift measurements the dial indicator was moved to another cylinder and the intake and exhaust valve lift was measured at five degree increments. The results from each data set agreed with one another and the valve lift profile for the Ecotec engine is seen in Figure 2.3. A detailed table of values is found in Appendix I. After the valve lift profile was measured the engine was completely taken apart. Measurements of interest of the interior of the engine were recorded and input into GT-Power.

To conclude the engine tear down process the dimensions of pipes and flowsplits of the exhaust, intake/intercooler combination, and supercharger were measured and input into GT-Power. Due to the importance of pipe geometry (volumes, diameters, elbows, etc.) for accurate airflow and GT-Power simulation results this process required attention to detail and time. A table of engine dimensions can be found in Appendix II.

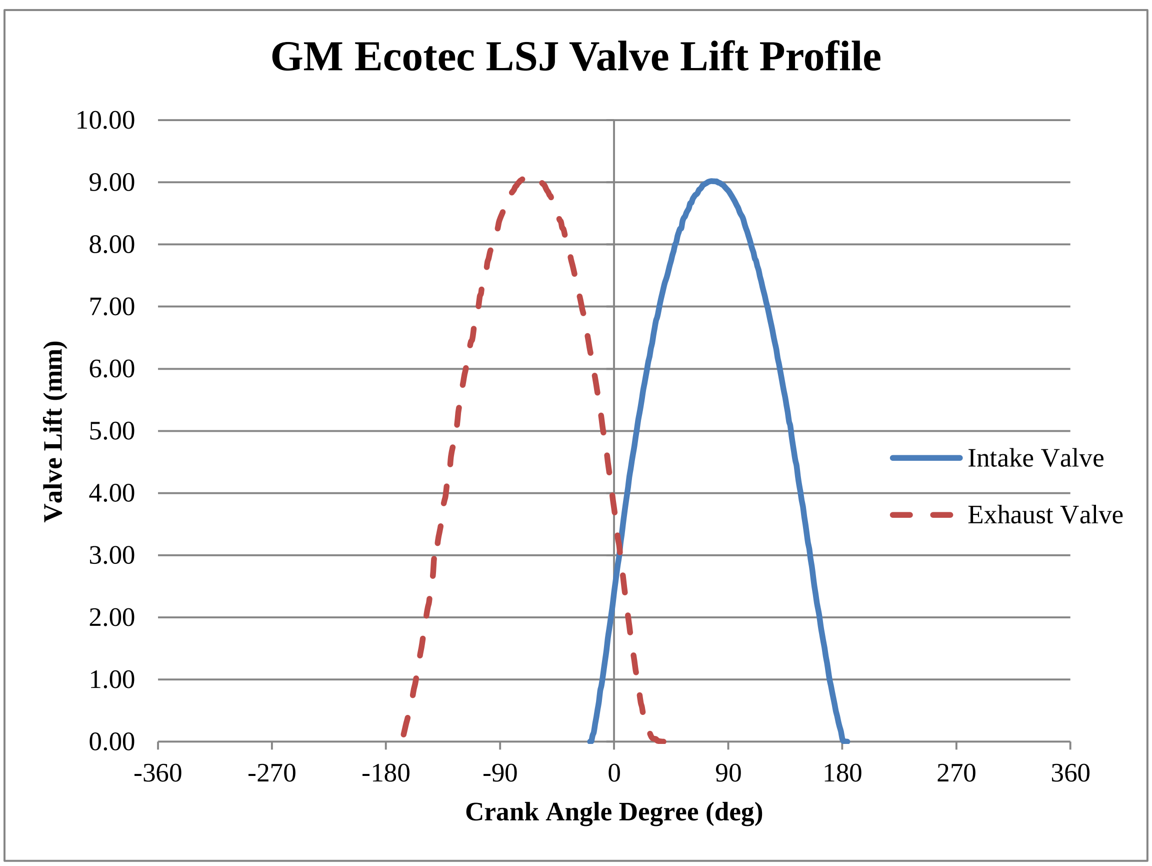

Figure 2.3: GM Ecotec LSJ valve lift profile

2.2 GM Ecotec LSJ Engine Model and Development

GT-Power is used to model the Ecotec LSJ engine. A stock engine model is generated for baseline data. The engine model begins by defining objects from the part library that will be placed on the GT-ISE user interface. When building a new engine model it is customary to begin by defining the inlet environment, moving through the engine from the intake side to the exhaust side, and finishing with the end environment. An example of the object definition window for a pipe part is shown in Figure 2.4. For the Ecotec this process is followed with the addition and

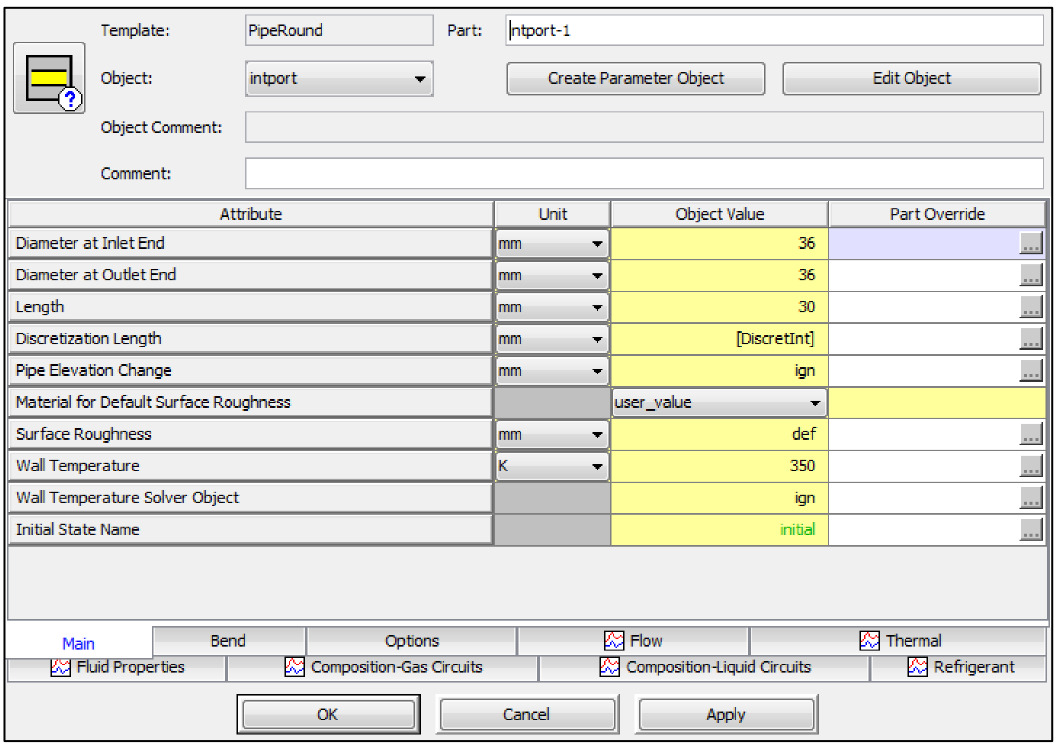

Figure 2.4: GT-Power pipe object definition window

integration of a supercharger and intercooler. After all engine parts have been defined they are placed onto the GT-ISE interface and linked by orifice connections automatically determined by GT-Power.

2.2.1 M62 Eaton Supercharger

General Motors equips the Ecotec LSJ with a M62 Eaton supercharger, a helical roots type blower. A supercharger is modeled in GT-Power by defining a compressor library part. An image of the supercharger map is available for download from Eaton's website. Using a digitizer, inlet volume flow rate, pressure ratio, and efficiency at six different compressor speeds are interpolated. The inlet volume flow rate is converted to inlet mass flow rate so the data can be input into the compressor library file. Figure 2.5 shows the compressor map generated by GT-Post from the input data. The map contours are extrapolated from the data points entered by the user as indicated by the markers on the speed lines. The compressor is connected to the engine crankshaft via a shaft component and a gear connection with a ratio of 1.85. The supercharger is capable of supplying 12 psi of boost according to GM Performance Division [17].

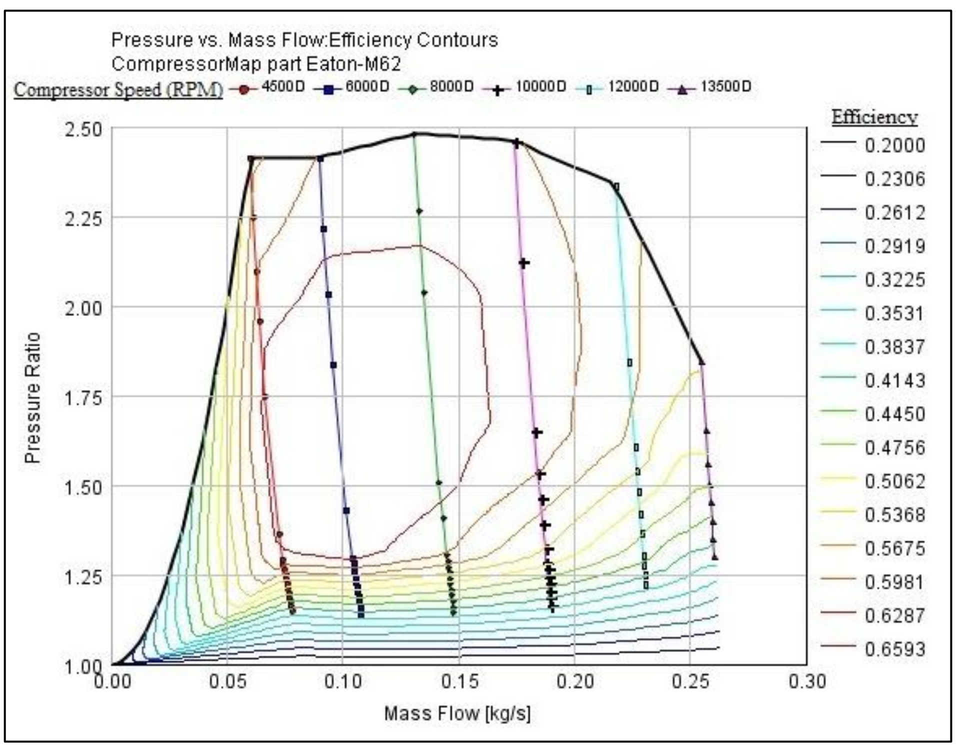

Figure 2.5: Eaton M62 performance map generated by GT-Post

2.2.2 Stock Engine Model Development

Once all engine components were in place and connected on the GT-ISE interface the model was ready to be run. Run parameters were identified in the Run Setup window of GT-Power. For baseline engine data the Ecotec was evaluated at speeds of 200 rpm to 6800 rpm at intervals of 400 rpm. Initially, no blow off valve was included in the model. This resulted in high power and torque, 189 kW (253 hp) at 6800 rpm and 302 N-m (223 lb-ft) at 4000 rpm, respectively. Continuously boosted air from the compressor was fed to the engine, which accounted for the high values of power and torque.

A blow off valve and PID controller were added to the engine model. The final Ecotec engine model is shown in Figure 2.6. The PID controller was set to open the blow off valve at 1.8 bar or 12 psi. After the blow off valve and PID controller were added an engine simulation was run. Again, the power and torque were much higher than desired. The first step to correct this error was to calibrate the PID controller by running simulations with an array of gain values. These simulations had little effect on the performance of the engine. The next step was to look at the parameters of the in-cylinder combustion model.

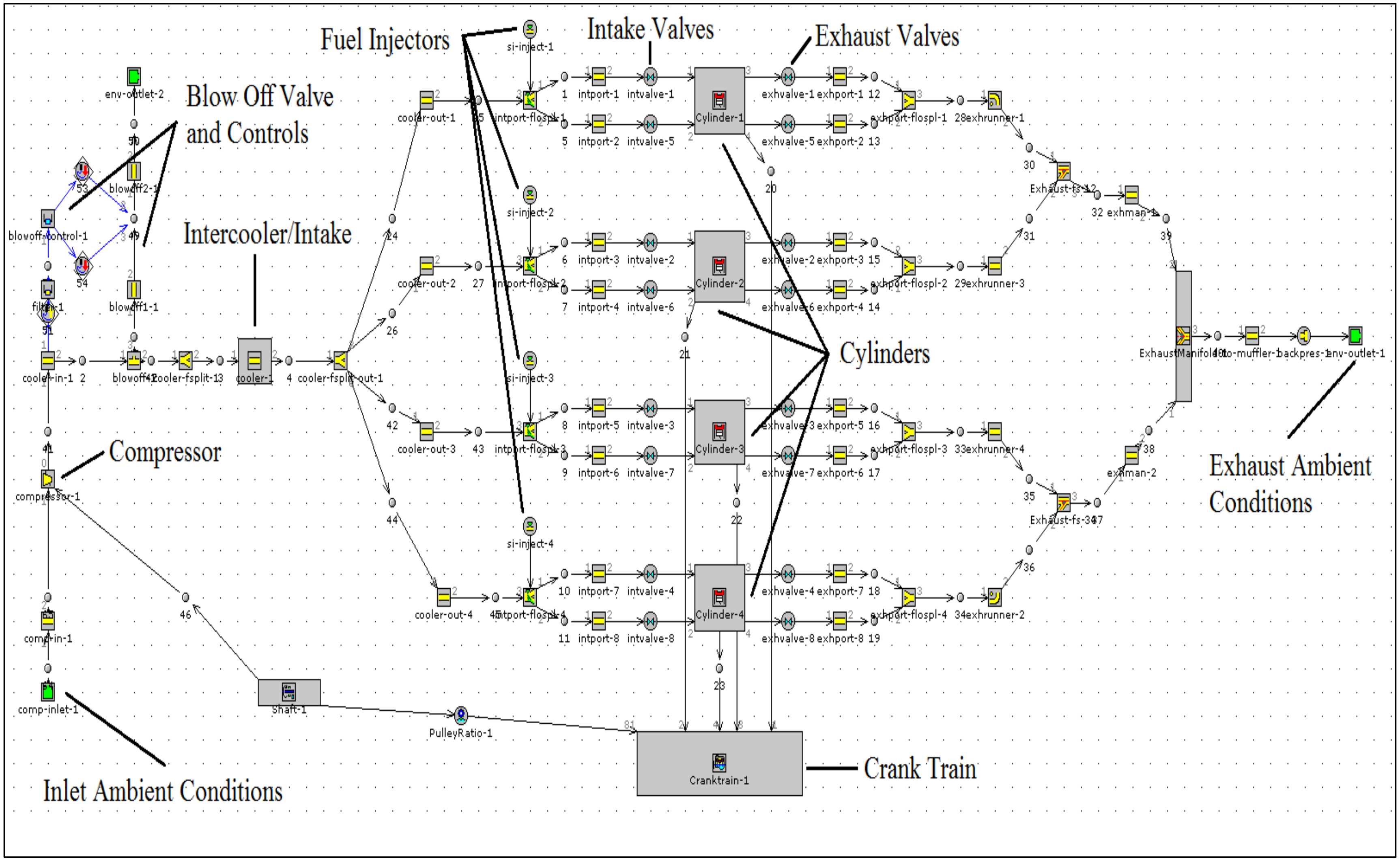

Figure 2.6: Stock Ecotec GT-Power model

By modifying the built in GT-Power combustion models a more accurate burn profile can be determined. An array of typical values defined by GT-Power for burn duration and anchoring angle were run in combination with the array of controller gain values. The anchoring angle was the number of crank angle degrees between TDC and the fifty percent combustion point of the Wiebe combustion model curve. After the simulations were run the results were analyzed using Matlab. Each set of performance values was graphed and compared to the published data. The final simulation results are discussed in the following section and GT-Post generated data tables for select engine speeds are shown in Appendix III.

2.3 Stock Engine Simulation Results

The Ecotec GT-Power engine model is calibrated to match the published performance map. The final simulation results are compared to the only published data readily available for the Ecotec engine in Figure 2.7. The GT-Power simulation results produce a peak power of 159 kW (214 hp) at 6400 rpm and a peak torque of 284 N-m (209 lb-ft) at 4000 rpm. The simulation power and torque results are 4.4% and 4.5% higher than published data, respectively. This is viewed as an acceptable amount of error considering the only data available to tune the engine was the published performance map. Although the engine was taken apart and pipe diameters and lengths measured there is still uncertainty in the measurements. This affected flow through engine components and ultimately, contributed to the final performance of the engine.

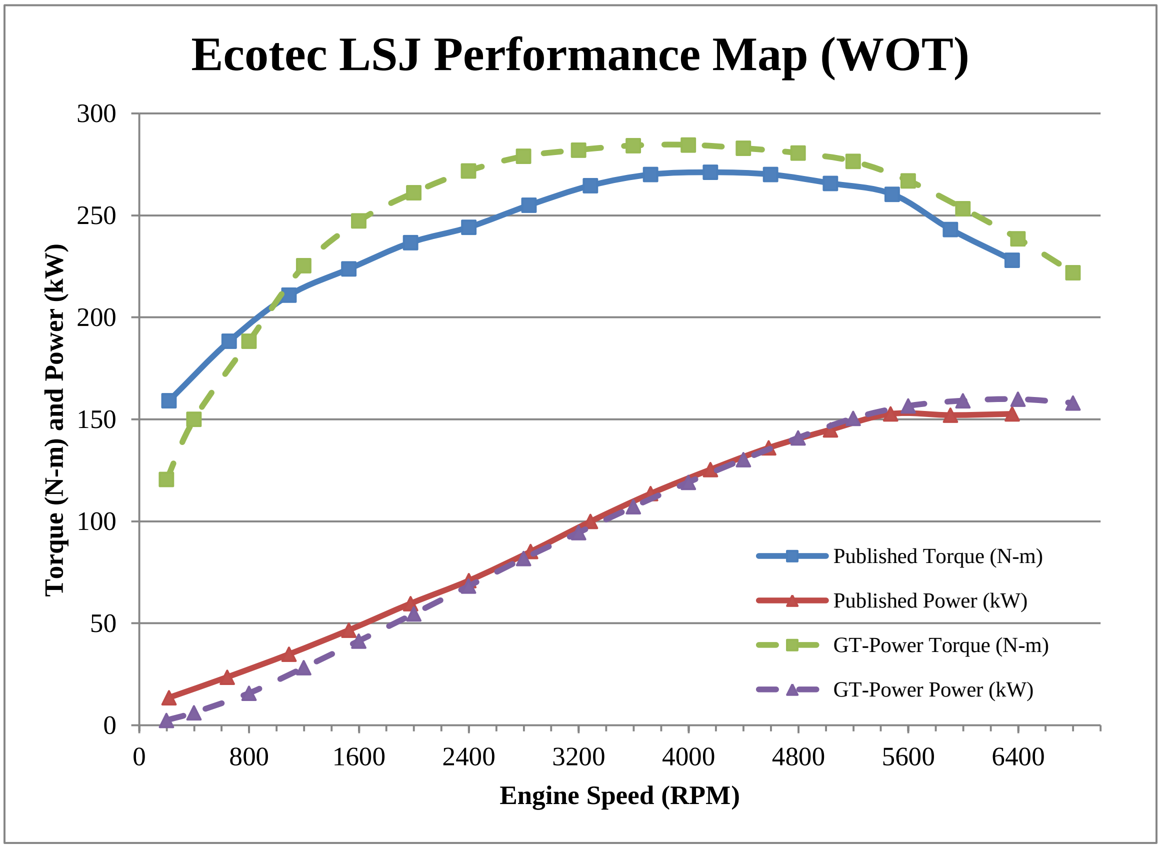

Figure 2.7: Comparison of published WOT performance map to GT-Power simulation generated map

In order to compare the stock engine model to the SuperTurbocharged engine model other plots are generated using GT-Power. It is of interest to look at the performance of the supercharger. In Figure 2.8 the pressure and temperature difference between the inlet and outlet of the supercharger are shown. As expected, the pressure and temperature difference of the compressor increases as engine and compressor speed increase. Between 800 and 1200 rpm the mass flow rate of air through the supercharger doubles resulting in a higher outlet temperature. The efficiency of the supercharger is calculated in GT-Power and is shown in Figure 2.9. As the speed of the engine and compressor increase the work required to spin the compressor increases, also shown in Figure 2.9. Around 3200rpm the compressor requires more work which results in a slight decrease in efficiency. Additionally, due to the geometric nature of the roots type

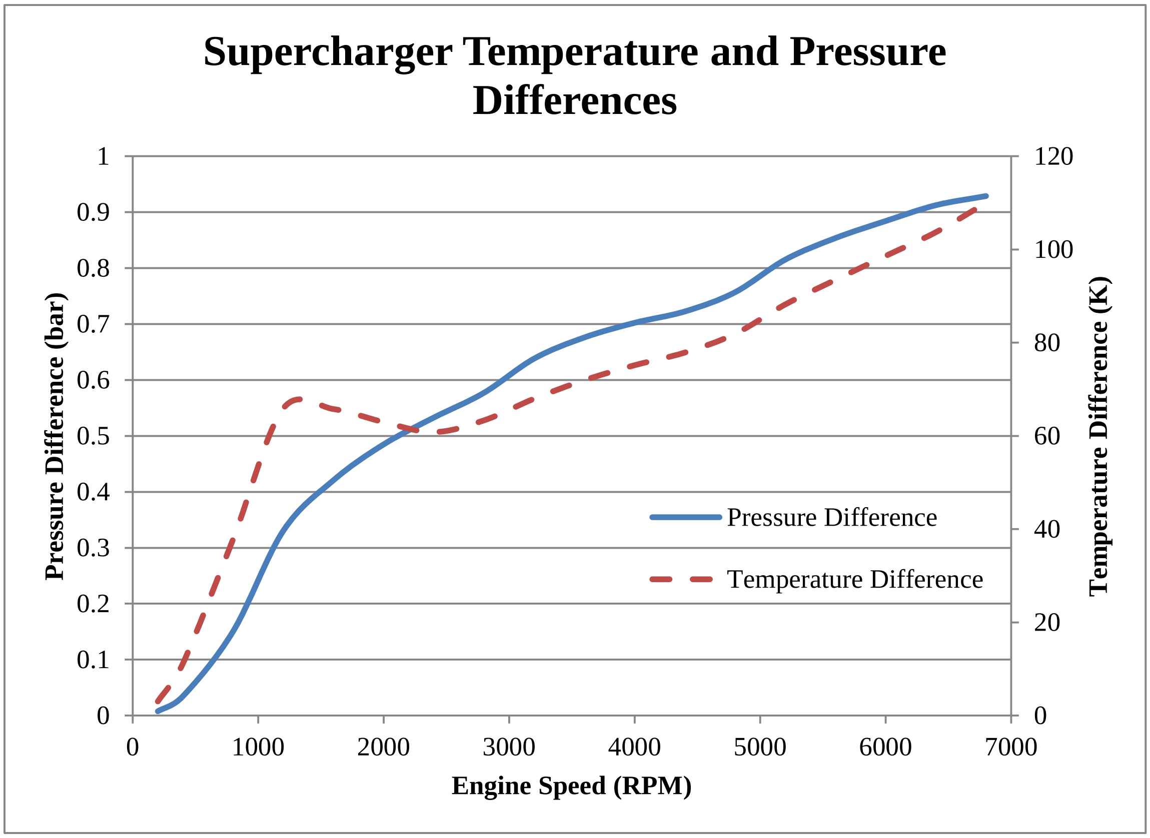

Figure 2.8: Supercharger inlet and outlet pressure and temperature differences

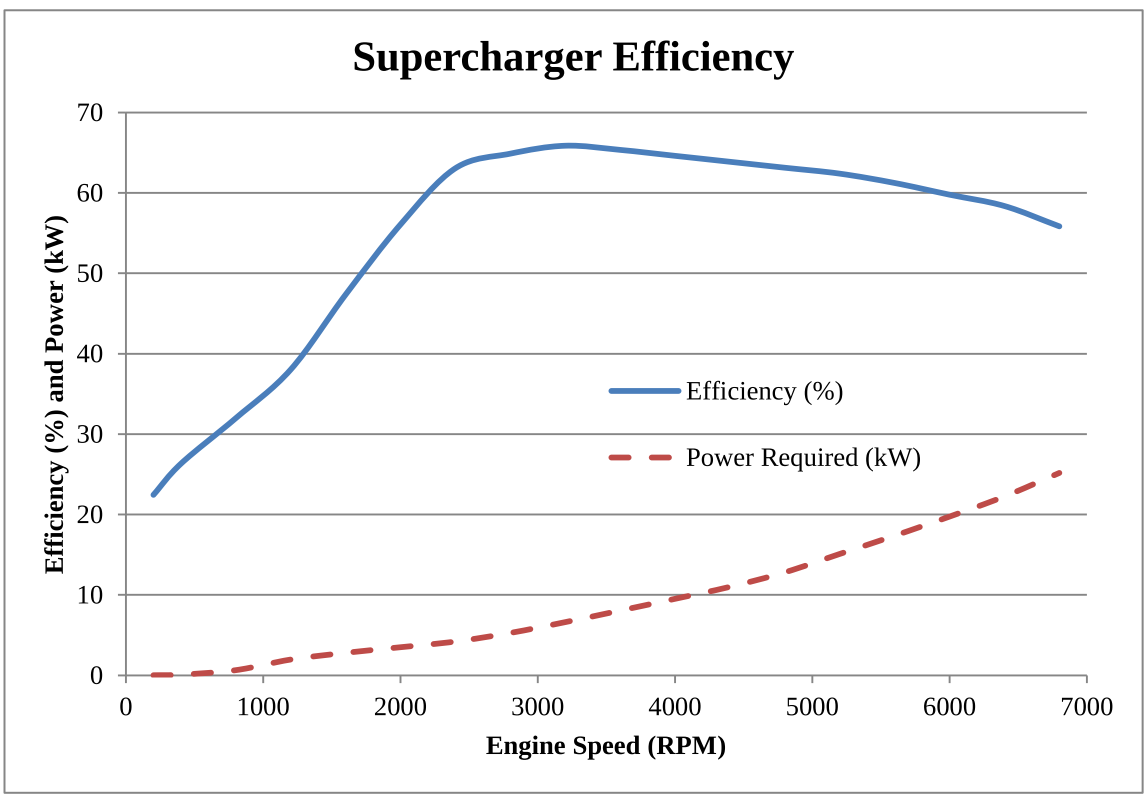

Figure 2.9: Supercharger efficiency and required power at a range of engine speeds

blower inefficiencies can be associated with air leakage around the blades. The efficiency trend line is also indicative of the parasitic losses associated with superchargers as engine speeds increase. The efficiency of the supercharger is comparable to published results of a slightly smaller 1.5l supercharger [11].

The intercooler is an integral component of the Ecotec engine. Figure 2.10 shows the inlet and exit temperature of the intercooler as well as the heat transfer rate to the intercooler walls. As discussed in Chapter 1, the temperature of air entering the intake manifold is critical in increasing the mass of air in the cylinder and reducing knock tendencies. The intercooler substantially reduces the air's temperature as engine speed increased. Engine coolant from the radiator is pumped through the coils of the intercooler. The intercooler on the Ecotec engine has a 1.95l capacity and removes more heat from the coolant as engine speeds increase.

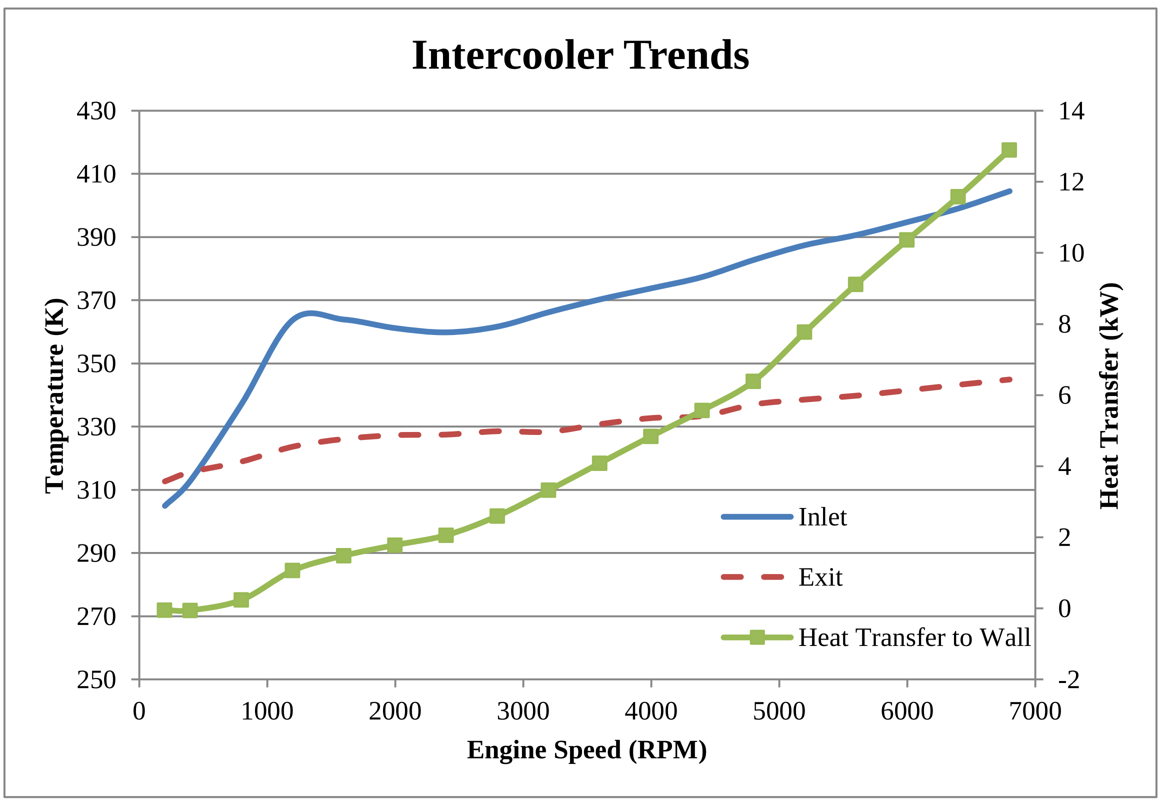

Figure 2.10: Intercooler inlet/exit temperatures and heat transfer rate to walls at a range of engine speeds

A relative assessment of the stock Ecotec engine's performance is of interest for eventual comparison to the SuperTurbocharged engine. Additionally, results from the stock Ecotec engine are used to verify the validity of the GT-Power model simulation. The brake thermal efficiency of the engine is shown in Figure 2.11. Initially, as the power of the engine increases the efficiency of the engine also increases. As more fuel is injected in the cylinder as engine speed increases and the power increase remained fairly linear, the efficiency of the engine decreased. Volumetric efficiency, with intake manifold conditions and ambient pressure used as the reference, of a supercharged engine is expected to be greater than 100% because it is the measure of how well the engine inducts air. At higher engine speeds supercharger speeds increased, allowing more air to flow into the intake. Also shown in Figure 2.11 are losses due to friction. As

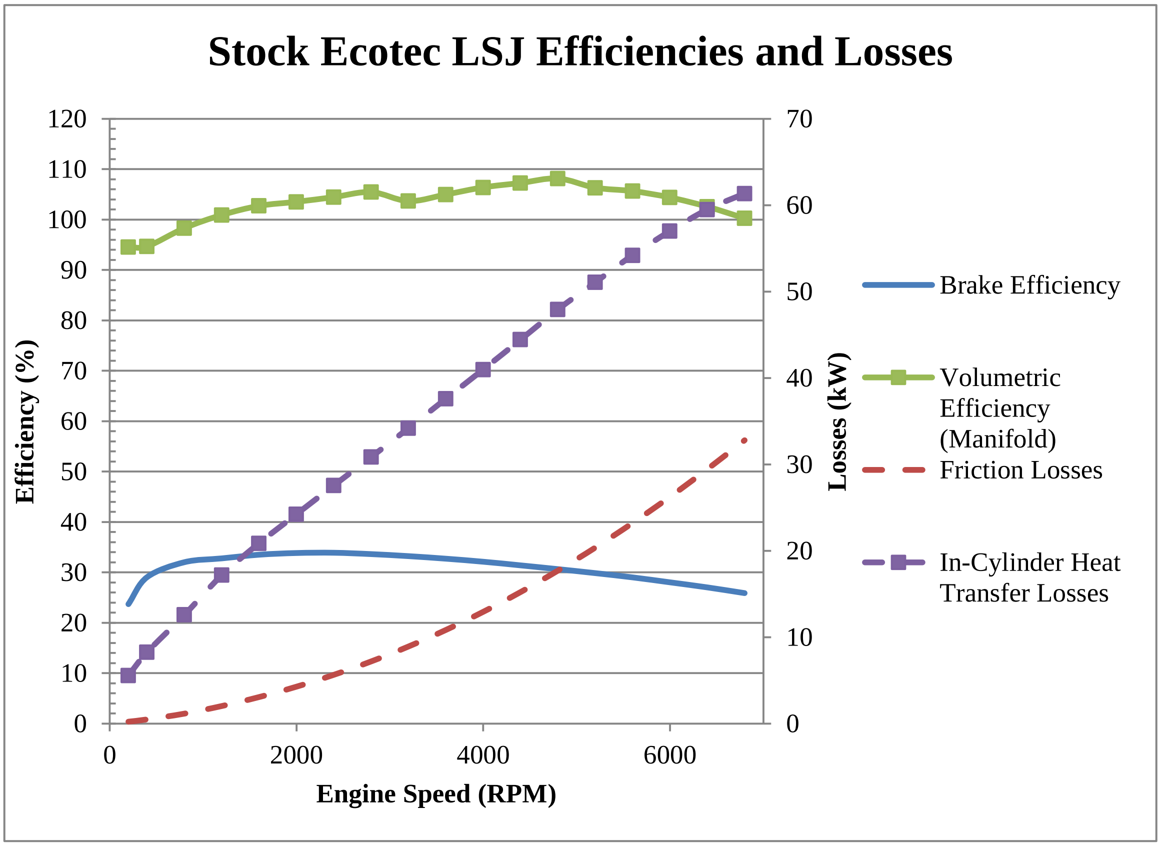

Figure 2.11: Stock Ecotec efficiencies and losses as a function of engine speed

indicated by the trend above, higher engine speeds result in greater friction losses caused by pumping work, rubbing work, and accessory work. In-cylinder heat transfer losses also increase as engine speed increases. The number of compression and expansion cycles increases as engine speed increases. This causes in-cylinder temperatures to increase, thus, increasing heat transfer to the cylinder wall.

Another measure of the Ecotec's efficiency is the BSFC. In Figure 2.12 the BSFC of the Ecotec is shown. As engine speed increases there is less time for heat loss per cycle in the cylinder, thus, fuel consumption decreases. At higher engine speeds friction losses increase, increasing fuel consumption. Again, the BSFC of the stock Ecotec is consistent with accepted BSFC values [10] [17].

The brake mean effective pressure of the Ecotec is an indicator of the engine power density, defined as the brake work per cycle divided by the cylinder volume displaced per cycle. Figure 2.13 shows the BMEP of the Ecotec engine. As torque increases the BMEP of the engine also increases. Likewise, as torque decreases, so did the BMEP.

Although the only data available to tune the engine is the performance map from GM Performance Division [18], the results from GT-Power are consistent with acceptable values for a 2.0l supercharged engine. This stock model will serve as a basis for understanding the effect of SuperTurbocharging the Ecotec engine.

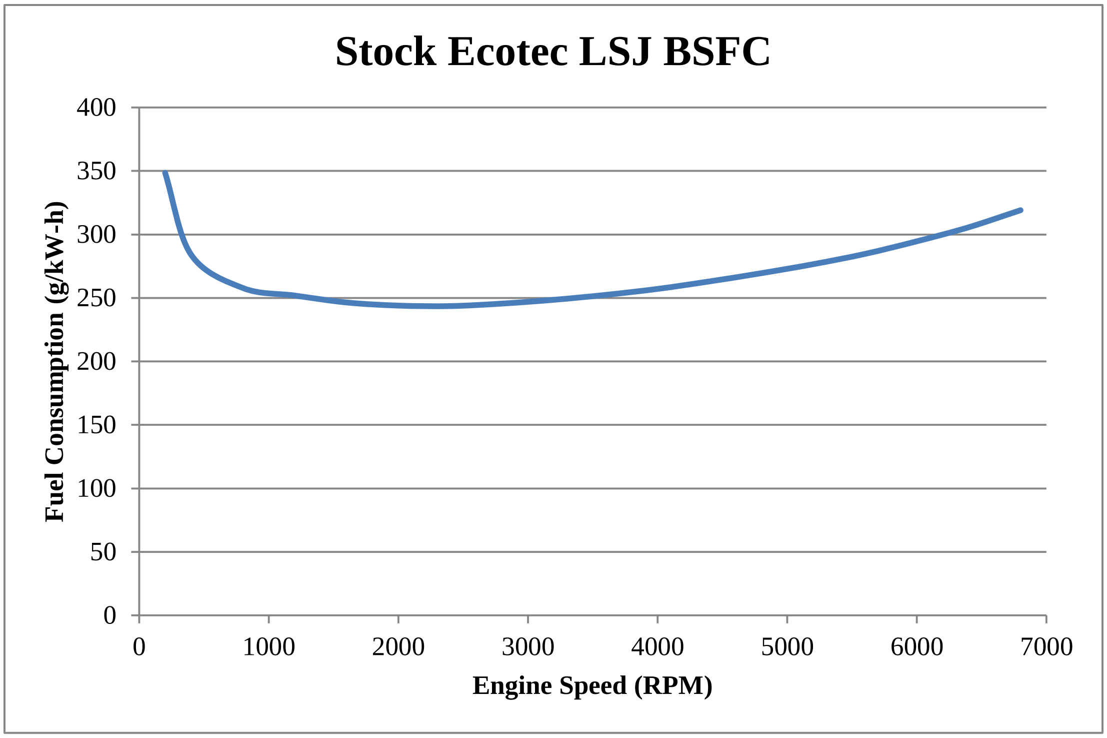

Figure 2.12: Stock Ecotec brake specific fuel consumption as a function of engine speed

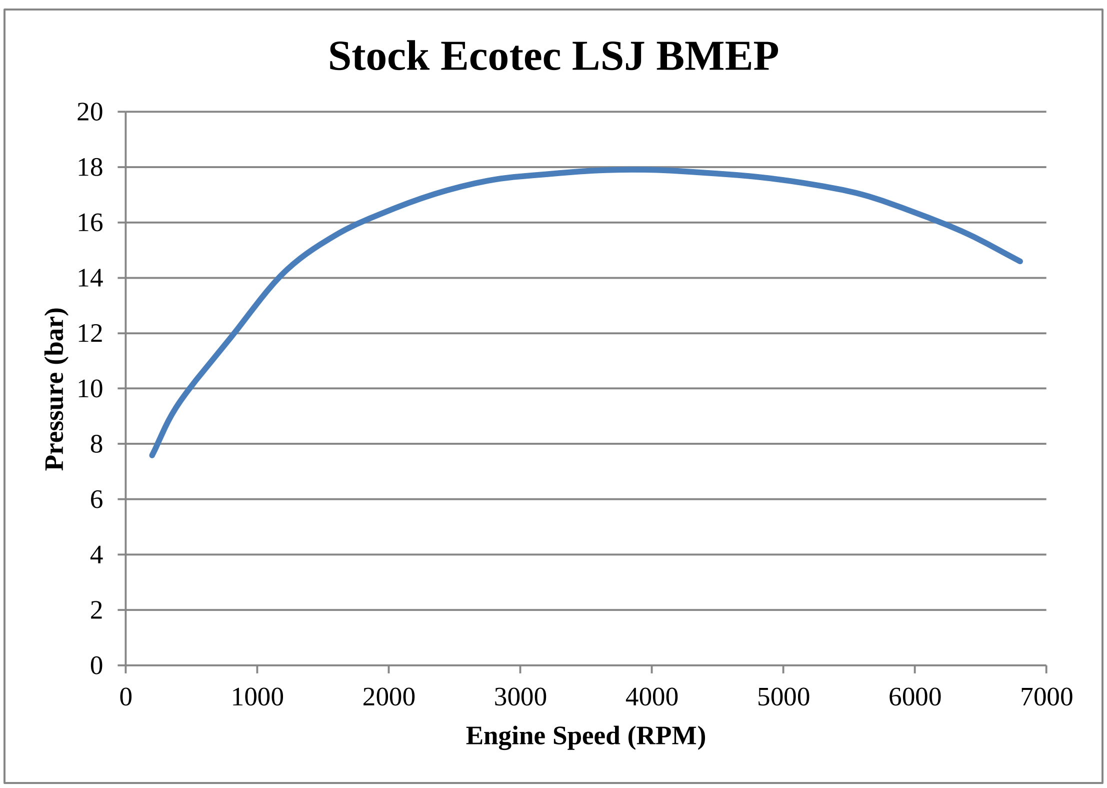

Figure 2.13: Stock Ecotec brake mean effective pressure as a function of engine speed

CHAPTER 3: SUPERTURBOCHARGED GM ECOTEC 2.0L LSJ ENGINE

3.1 SuperTurbocharged GM Ecotec Engine Model and Development

GT-Power is again used to model the SuperTurbocharged Ecotec engine. The SuperTurbocharged engine model is generated to show that the SuperTurbo^{TM} can match and exceed the performance curve of the stock Ecotec engine, while increasing engine efficiency. The SuperTurbocharged Ecotec engine model is built from the stock engine model. The stock model is placed on the GT-ISE user interface and the supercharger and end environment are removed. A throttle, air filter, aftercooler, CVT, engine bypass, and the SuperTurbo^{TM} are integrated into the new model and linked by orifice connections automatically determined by GT-Power. In this chapter the development of the SuperTurbocharged Ecotec engine model and its components are outlined and the simulation process explained. The model is considered complete when the SuperTurbocharging system functions as designed. The project goal is to closely match the performance maps of the stock GT-Power Ecotec LSJ engine model and the engine targeted for downsizing purposes, the GM Vortec LMG.

3.1.1 GM Vortec LMG Engine

The GM Vortec LMG engine is a 5.3l V8 naturally aspirated engine, henceforth referred to as the Vortec engine. It is currently found in a number of Chevrolet and GMC sport utility vehicles and pickup trucks [19]. This engine is ideal for comparison to the Ecotec because of the shared manufacturer as well as the opportunity for downsizing. A technically advanced engine, the Vortec engine is equipped with variable valve timing (VVT), active fuel management, an advanced electronic throttle control, returnless fuel injection, an advanced ignition system, and is E85 flexible [19]. A sequential direct injection fuel system supplies gasoline and E85 to the engine. Engine parameters are tabulated below in Table 3.1.

The Vortec produces a peak power of 230 kW (308 hp) at 5400 rpm and a peak torque of 454 N-m (335 lb-ft) at 4000 rpm at WOT as shown in Figure 3.1.

Table 3.1: LSJ Engine parameters

Engine	General Motors Vortec LMG
Configuration	V8 Naturally Aspirated
Displacement	5328 cc
Bore	96.01 mm
Stroke	92.00 mm
Firing Order	1-8-7-2-6-5-4-3
Compression Ratio	9.9:1
Throttle Type	Electronic throttle control
Ignition System	Coil-near-plug

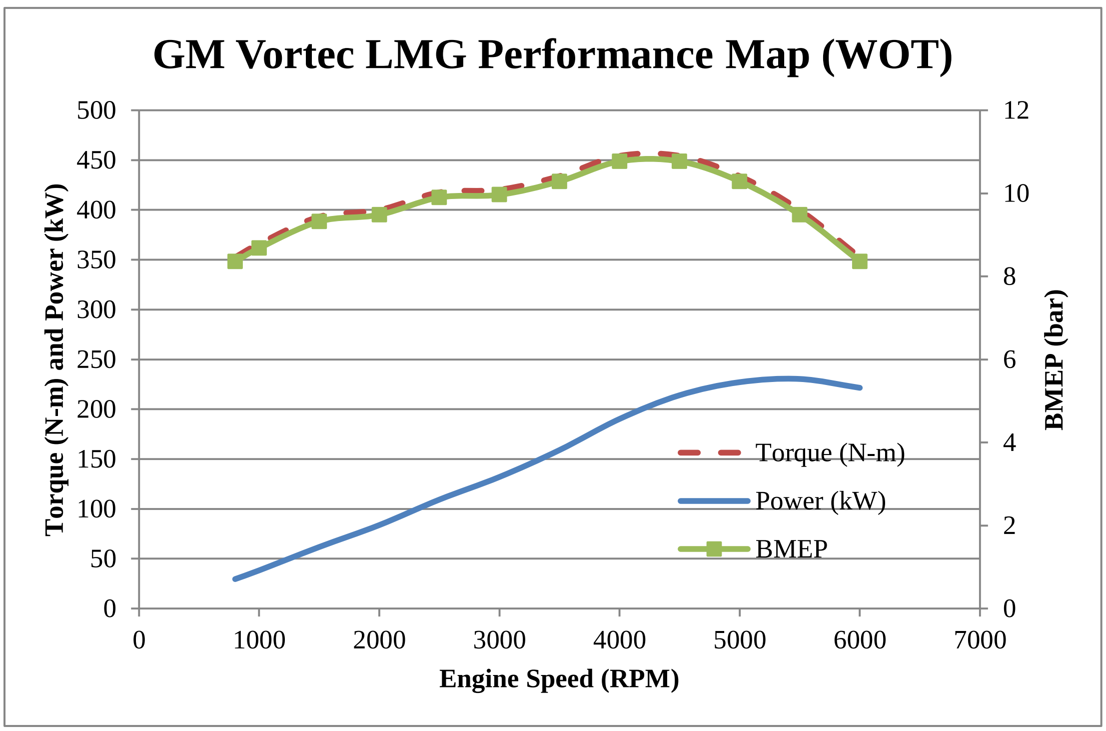

Figure 3.1: Full Throttle GM Vortec LMG engine performance map

3.1.2 SuperTurbo™ Model

A previously constructed GT-Power model of the SuperTurbo™ is provided by VanDyne for the purposes of this research. Figure 3.2 shows this model, which includes a turbine and compressor, a shaft object connecting the compressor and turbine, the expected mechanical losses associated with the SuperTurbo™, the torque imposed on the shaft due to inefficiencies, and a CVT. The speed of the SuperTurbo shaft is sensed using a sensor connection object. A

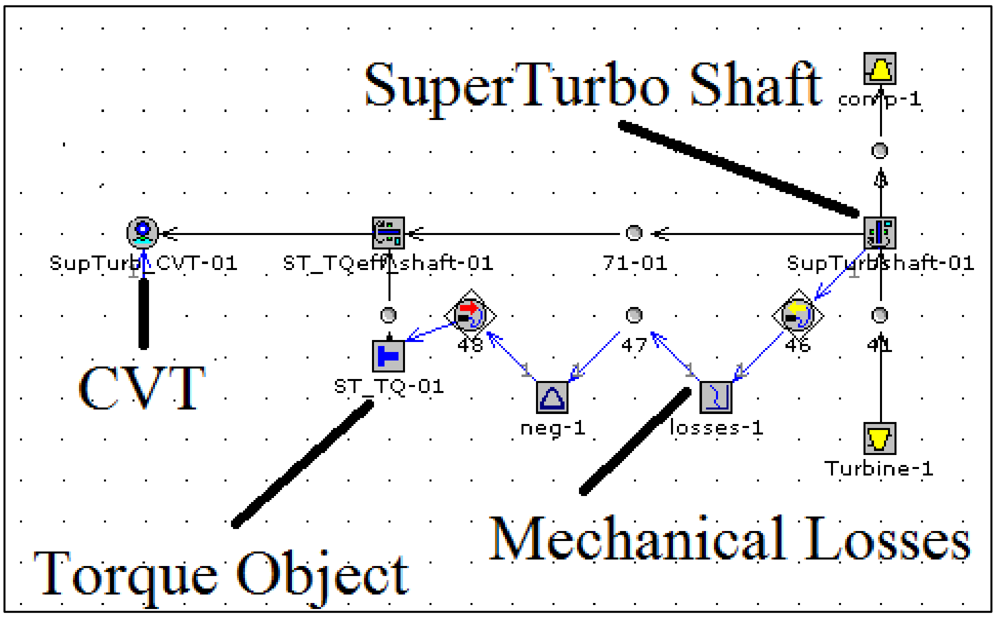

Figure 3.2: GT-Power SuperTurbo™ Model

mechanical loss is associated with the speed of the shaft. This value is then multiplied by a negative number indicating that it is a loss. An actuator connection object relays the final loss value to the torque object. Through a torque connection the appropriate torque due to inefficiencies is imposed on a new SuperTurbo shaft object (labeled ST_TQeff_shaft-01) which is connected to the CVT. The torque delivered to the CVT is estimated by VanDyne to be about 80% of the torque in from the SuperTurbo shaft. The CVT is then connected to the crankshaft (not shown in Figure 3.2).

Turbine and compressor maps are also included in the SuperTurbo™ model. Figure 3.3 shows the compressor map generated by GT-Post from the input data. The map contours are extrapolated from the data points entered by the user as indicated by the markers on the speed lines. Figure 3.4 shows the turbine map generated by GT-Post from the input data. The turbine and compressor map data is provided by VanDyne and are appropriately sized for the 2.0l Ecotec engine.

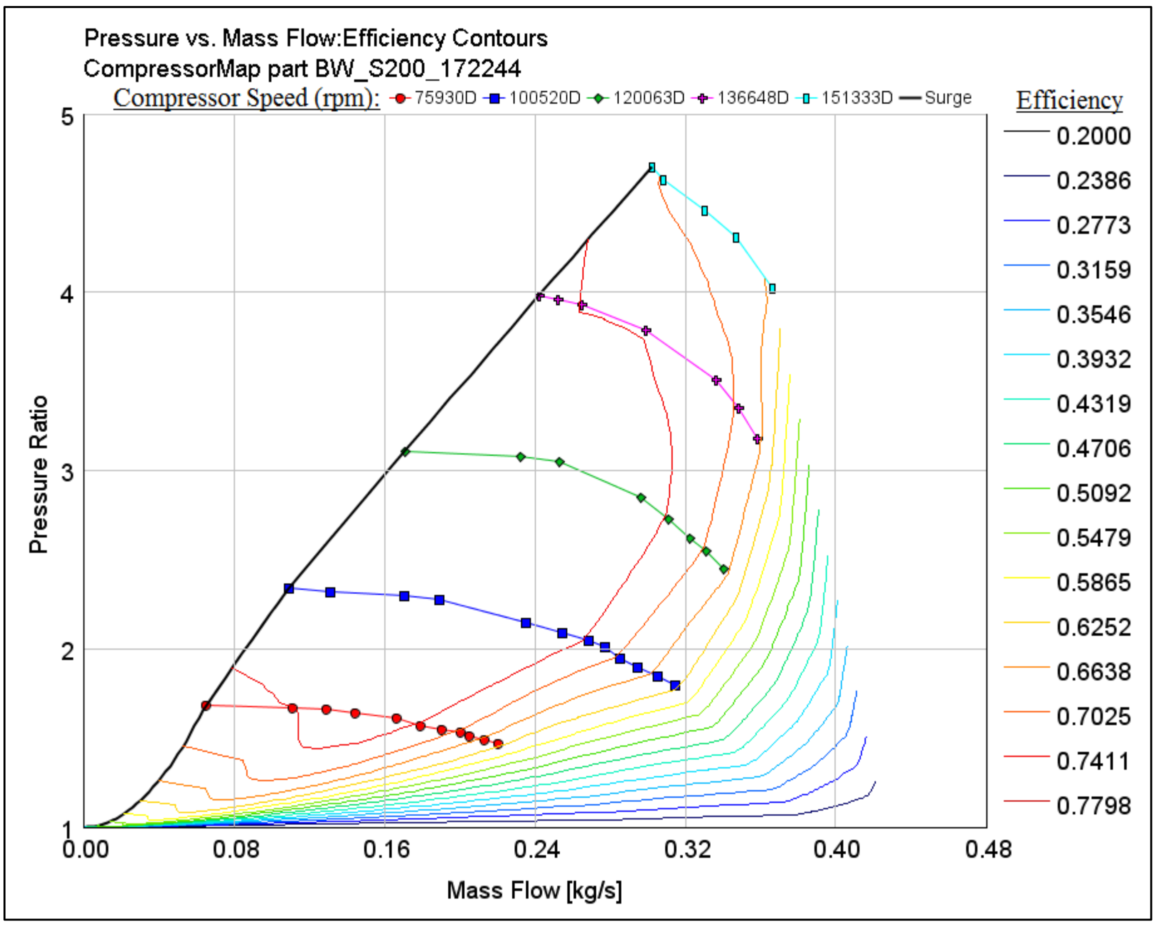

Figure 3.3: SuperTurbo™ compressor performance map generated by GT-Post

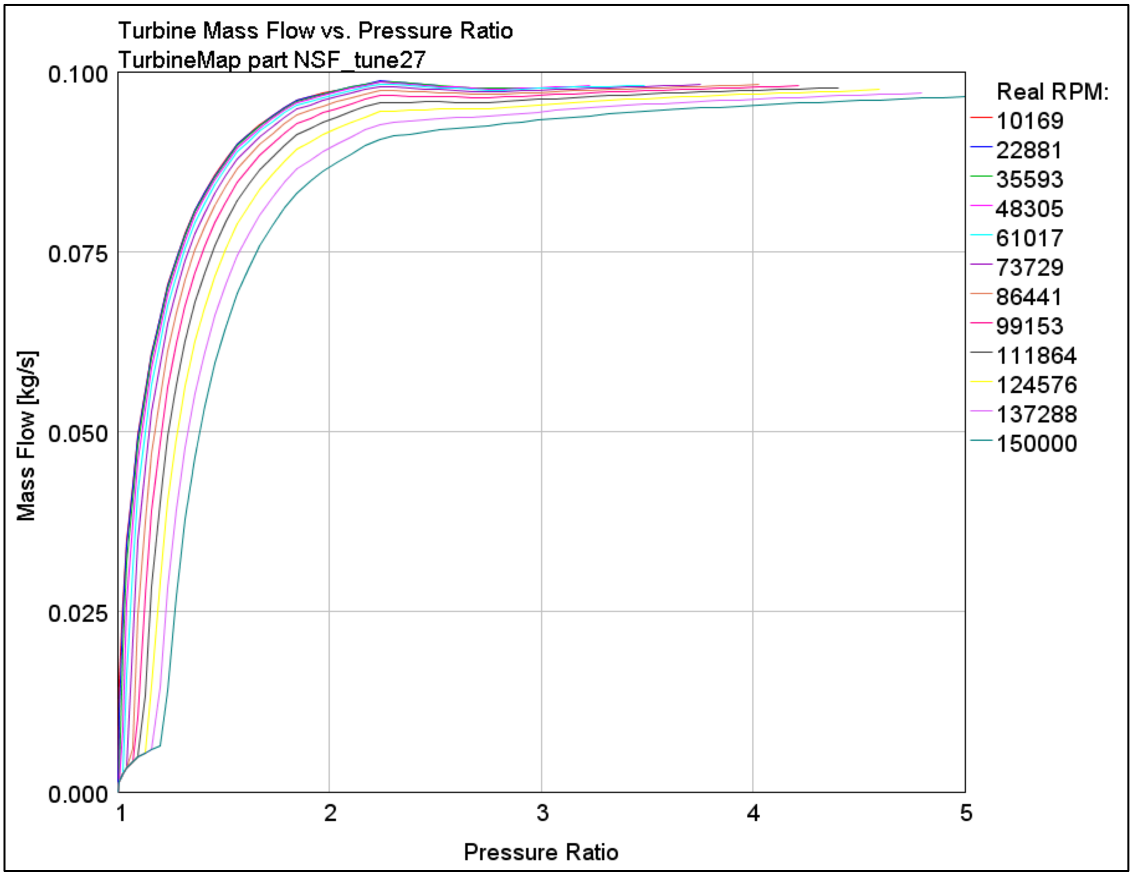

Figure 3.4: SuperTurbo^{TM} turbine performance map generated by GT-Post

3.1.3 SuperTurbocharged Engine Model Development

The stock Ecotec engine served as the basis for the SuperTurbocharged model. In addition to the SuperTurbo^{TM}, a throttle, aftercooler, engine bypass, and air filter were added from a GT-Power model of a 2.0l Volkswagen engine used for previous research at VanDyne SuperTurbo^{TM}, Inc. Additionally, the integral intercooler/intake was removed and replaced by a similarly sized traditional intake manifold. The model was first run at one operating point of 3000 rpm at WOT in order to verify that the new pipe geometry was an acceptable match for research purposes. Flow through the added pipes remained at low Mach numbers and was not restricted.

At increments of 1000 rpm beginning with 1000 rpm and ending with 6000 rpm at WOT, the SuperTurbocharged engine model was run. An error titled 'injection timing overlap' began to appear and caused the simulation to fail at higher engine speeds. When the CVT was added to the SuperTurbocharged model predefined CVT gear ratios were transferred to the new model. A stoichiometric air/fuel ratio was imposed on the fuel injectors. Thus, the fuel injectors were continuously spraying fuel into the engine in order to maintain the stoichiometric air/fuel ratio. This, combined with the predefined CVT ratios, was causing the simulations to fail. To determine an appropriate CVT gear ratio a PID controller was added to the CVT. The controller

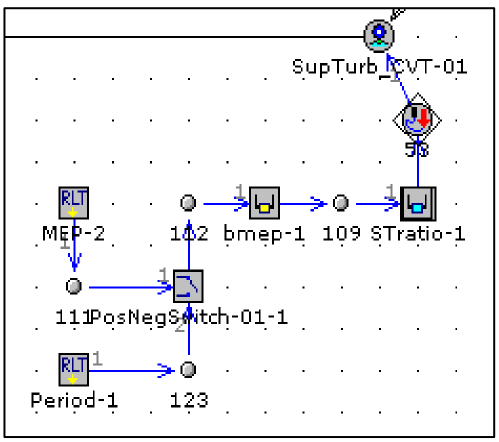

Figure 3.5: CVT controller

adjusts the CVT gear ratio based on a desired BMEP. Figure 3.5 shows the controller schematic. Initially, an attainable BMEP of 17 bar was chosen to get all speed points simulated without failure.

After all speed points were simulated at a desired BMEP output of 17 bar, the BMEP target was changed to reflect the torque and power demands of the stock Ecotec engine and much more powerful Vortec engine.

3.1.3.1 Model Development for GM Vortec LMG Engine Match

In order to match the Vortec performance curve the target BMEP was increased for speed points initially beginning with 1000 rpm and ending with 6000 rpm at 1000 rpm increments, again at WOT. The lower speeds ran without errors. At 6000 rpm, however, the 'injection timing overlap' error caused the simulation to fail. Up to this point the stock fuel injectors remained on the engine. GM Performance Division suggests replacing the stock fuel injectors with performance fuel injectors if the engine will be making more than 240 hp [18]. Using a calculation guideline from GM Performance Division the rate of fuel delivery was effectively doubled for matching the Vortec engine. After this change was made, the desired BMEP for the 6000 rpm speed point was matched. With all speed point simulations converging at the demanded high BMEP values, the thermal and flow data of the engine was looked at for verification. To supplement the data set, additional simulations were run at 800, 1500, 2500, 3500, 4500, and 5500 rpm.

After examining the exhaust manifold and pipes leading to the inlet of the SuperTurbo™ it was determined that the pipe temperatures were too low. Based on results from previous simulations it was expected that the turbine inlet temperature would exceed 1223K, the turbine material failure point [20]. GT-Power has a built-in template called 'WallTempSolver' that helps the user define convective and radiative heat transfer around pipes and flowsplits and thus, better reflect pipe temperatures. The 'WallTempSolver' object was defined and applied to the exhaust configuration. Each speed point was run again and the exhaust pipe temperatures more closely reflected expected conditions.

At 3000 rpm the turbine inlet temperature exceeded 1223K. In order to lower the temperature the engine bypass was opened. As seen in Figure 3.6, opening the engine bypass (the grey valve) allowed intake air to be routed to the turbine for cooling purposes. The engine bypass was opened at 1223K using another PID controller, shown in Figure 3.7. The bypass remained open for all simulations of 3000 rpm and higher.

At 4000 rpm the low pressure difference between the bypass and flowsplit where bypassed air met the air compressed by the SuperTurbo^{TM} resulted in exhaust gas recirculation (EGR), which reduced the turbine inlet temperature. EGR can be an effective tool for cooling

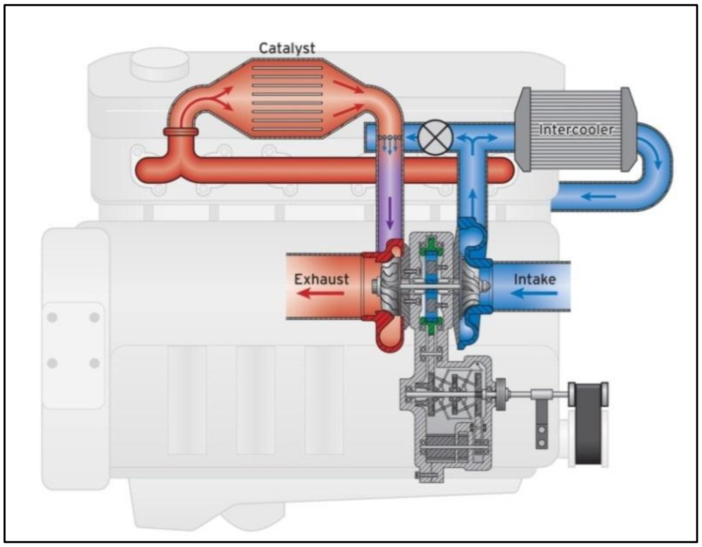

Figure 3.6: SuperTurbo^{TM} air flow schematic

the turbine inlet temperature, but in this case the low pressure difference negated the effect of the bypass and increased fuel consumption. A PID controller managing throttle angle, shown in Figure 3.7, was added to the model in order to maintain a 0.1 bar pressure difference between these two orifices.

At 5000 rpm the turbine inlet temperature exceeded 1223K. Fuel cooling by lowering the air/fuel ratio was introduced to lower the turbine temperature. When extra fuel was added to the system the intake charge was cooled due to fuel evaporation and combustion temperatures decrease because the specific heat of fuel absorbs energy. Multiple simulations were required for each speed point from 5000 to 6000 rpm to pinpoint the appropriate air/fuel ratio for turbine inlet temperature. The final results of throttle closure, engine bypass opening, and equivalence ratio from numerous model simulations are shown in Figure 3.8. The engine bypass was considered 100% open at the speed at which the most air flowed.

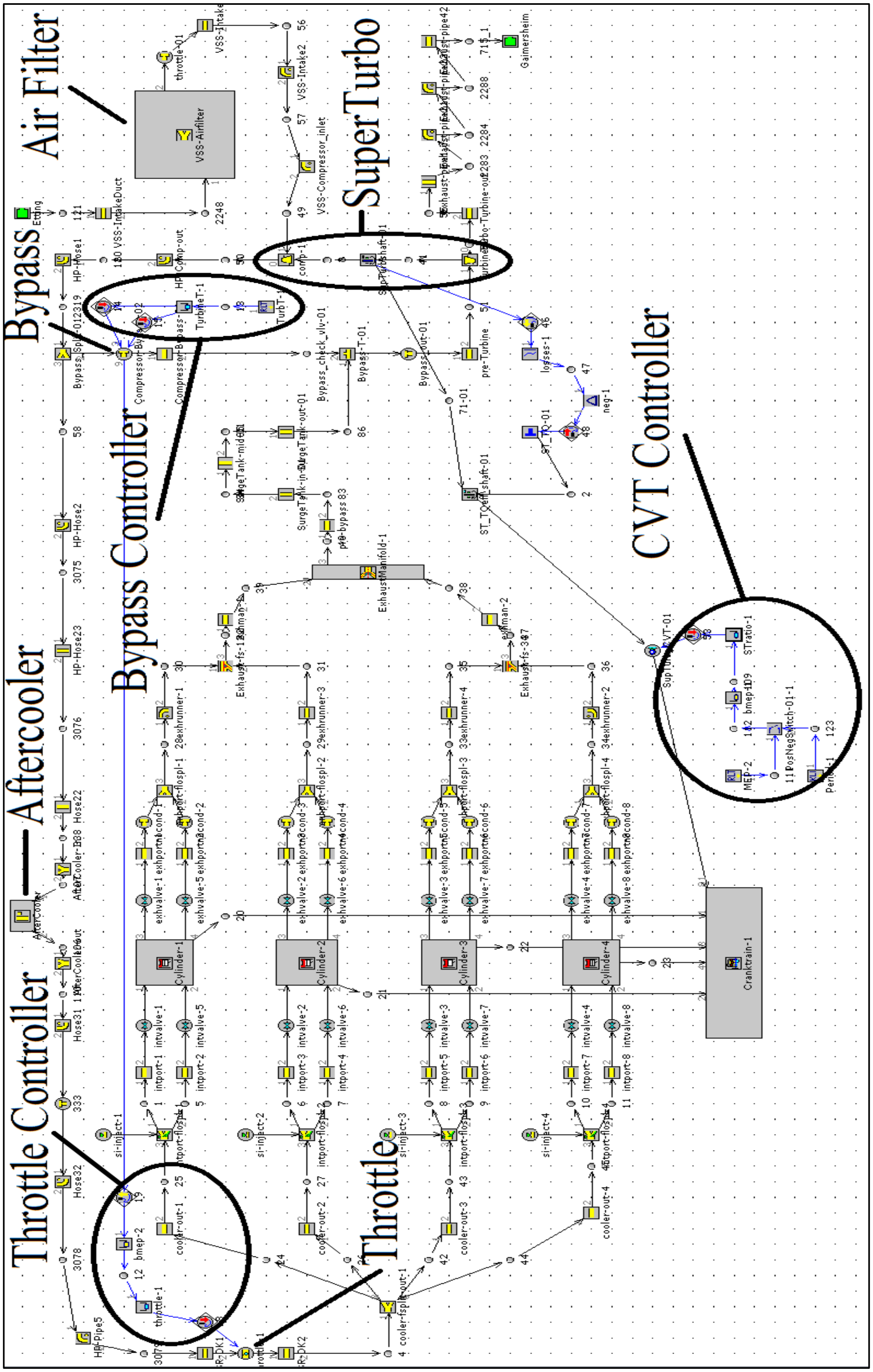

Figure 3.7: SuperTurbocharged Ecotec GT-Power model

The models were considered complete when the turbine inlet temperature was below 1223K, flow velocities and temperatures through pipes were reasonable, and the engine torque and power closely matched that of the Vortec engine.

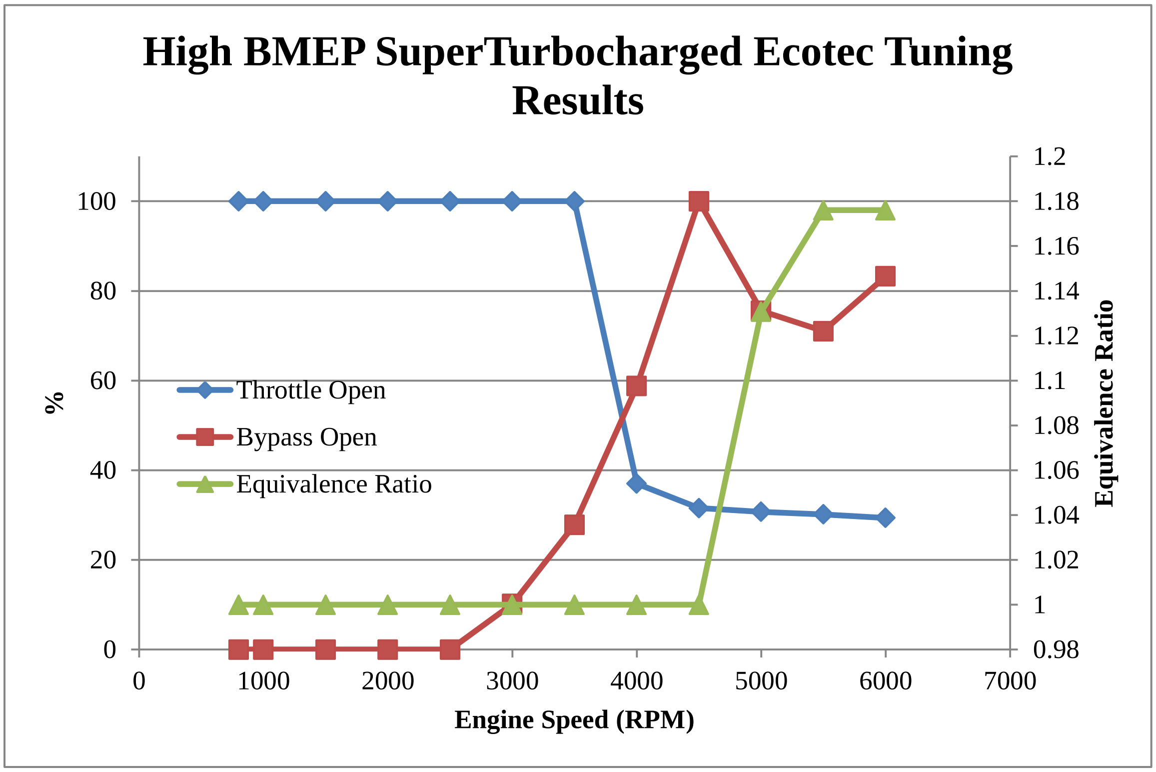

Figure 3.8: Final tuning results for bypass, throttle, and equivalence ratio based on engine speed

3.1.3.2 Model Development for Stock GM Ecotec LSJ Engine Match

In order to match the Ecotec performance curve the target BMEP was increased from the initial model tuning values for speed points 1200, 2000, 3200, 4000, 5200, and 6000 rpm, again at WOT. With all speed point simulations converging at the demanded high BMEP values, the thermal and flow data of the engine was looked at for verification.

Similar controllers used in matching the Vortec engine were utilized for matching the stock Ecotec engine. The speeds at which the controllers were implemented, however, were different. The engine bypass was added at 4000 rpm when the turbine inlet temperature exceeded

1223K. The throttle controller was added at 5200 and 6000 rpm to eliminate EGR effects. Fuel cooling was not required for the Stock Ecotec engine match.

The final results of throttle closure, engine bypass opening, and equivalence ratio from numerous model simulations are shown in Figure 3.9. The engine bypass was considered 100% open at the speed at which the most air flowed.

The models were considered finished when the turbine inlet temperature was below 1223K, flow velocities and temperatures through pipes were reasonable, and the engine torque and power closely matched that of the stock Ecotec engine.

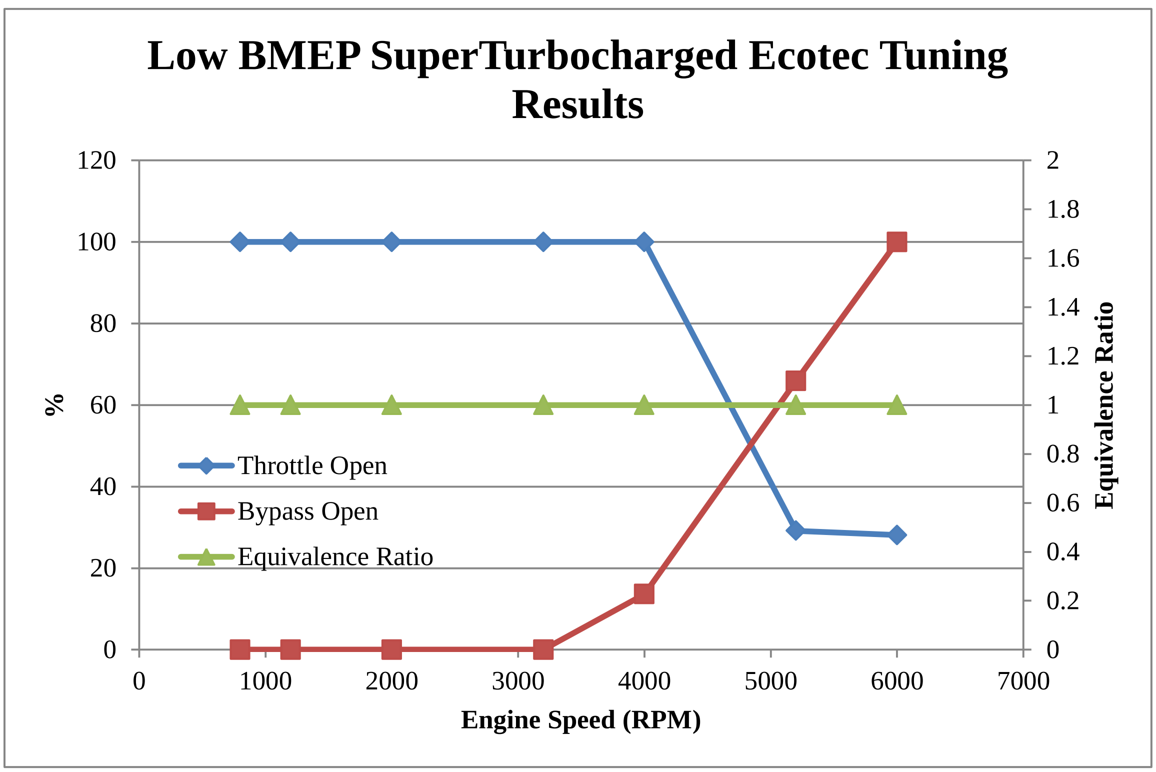

Figure 3.9: Final tuning results for bypass, throttle, and equivalence ratio based on engine speed

3.2 SuperTurbocharged Engine Simulation Results

The SuperTurbocharged Ecotec engine is tuned to match the performance map of the Vortec LMG engine to show the downsizing capabilities and benefits of the SuperTurbo™ and to indicate how a SuperTurbocharged engine would behave on a test bench. Additionally, the SuperTurbocharged Ecotec engine is tuned to match the performance map of the stock Ecotec LSJ engine in order to understand the gains that can be made in efficiency. The final simulation results are discussed in the following sections.

3.2.1 GM Vortec LMG Engine Match

Above, the SuperTurbocharged Ecotec GT-Power model is calibrated to match the published performance map of the GM Vortec LMG engine, henceforth referred to as the high BMEP SuperTurbocharged Ecotec. The final simulations results are compared to the only published data available for the Vortec engine in Figure 3.10. The GT-Power simulations results produce a peak power of 229 kW (307 hp) at 5000 rpm and a peak torque of 453 N-m (334 lb-ft) at 4500 rpm. The simulation power and torque results are equivalent to published data.

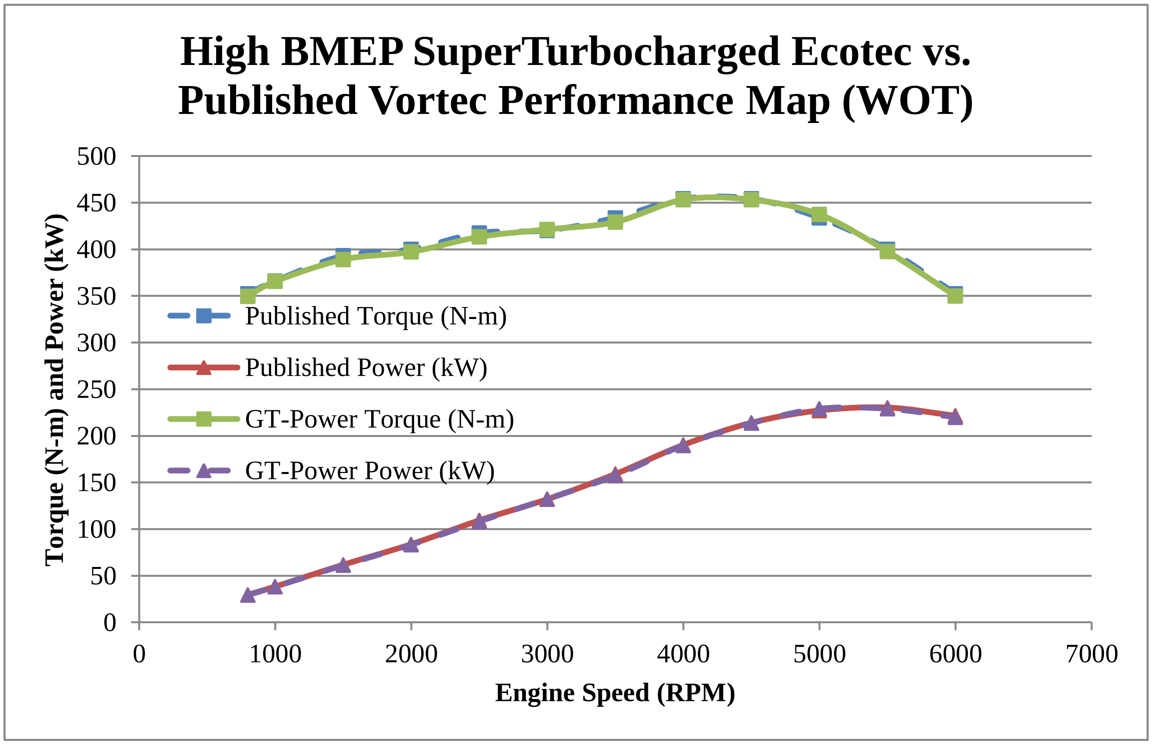

Figure 3.10: Comparison of published WOT performance map to GT-Power SuperTurbocharged simulation generated map

One of the limiting factors in the SuperTurbocharged engine configuration is the turbine inlet temperature. Figure 3.11 shows the turbine inlet temperature as a function of engine speed. As engine speed increases the turbine inlet temperature will also increase. To lower the inlet temperature the engine bypass is opened at 3000 rpm. At 4000 rpm the temperature begins to rise again so the throttle is partly closed. From 5000 rpm and on, the turbine inlet temperature is maintained at 1223K by lowering the air/fuel ratio. Figure 3.12 shows the air/fuel ratio at each engine speed. Although fuel cooling reduces the turbine inlet temperature it increases engine fuel consumption. Figure 3.13 shows the BSFC trend of the engine. The combined effect of fuel cooling, increased friction losses (which are proportional to the square of engine speed), and breathing restrictions from closing the throttle is shown at 5000 rpm when the BSFC begins to drastically increase. Indicated specific fuel consumption (ISFC), defined in GT-Power as the fuel consumption rate divided by net indicated engine power, follows the BSFC trend. At lower

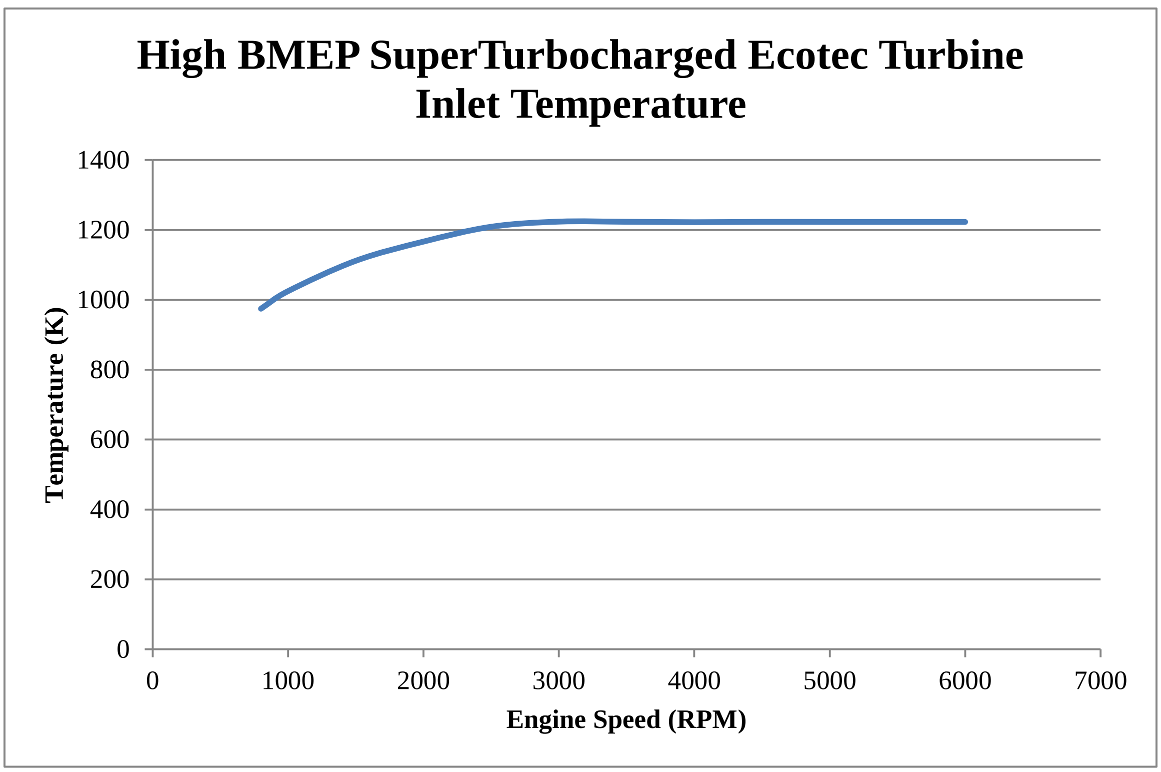

Figure 3.11: Turbine inlet temperature as a function of engine speed

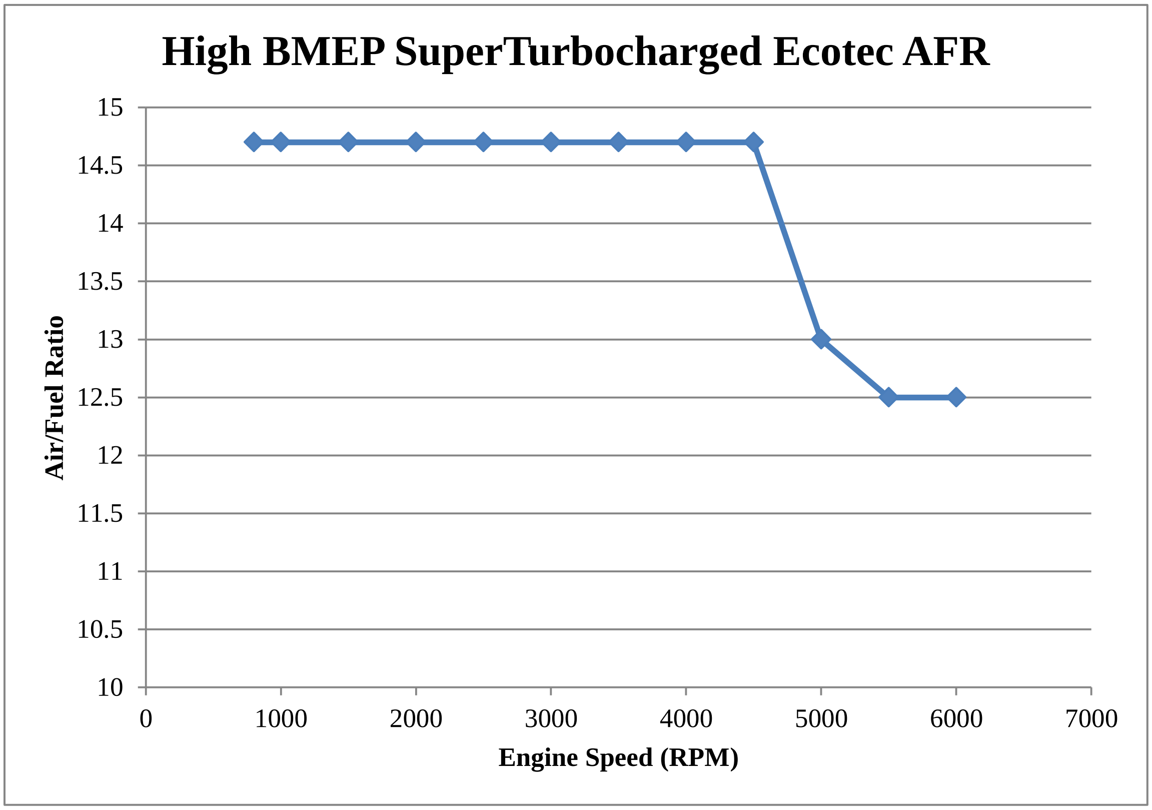

Figure 3.12: Air/Fuel ratio as a function of engine speed

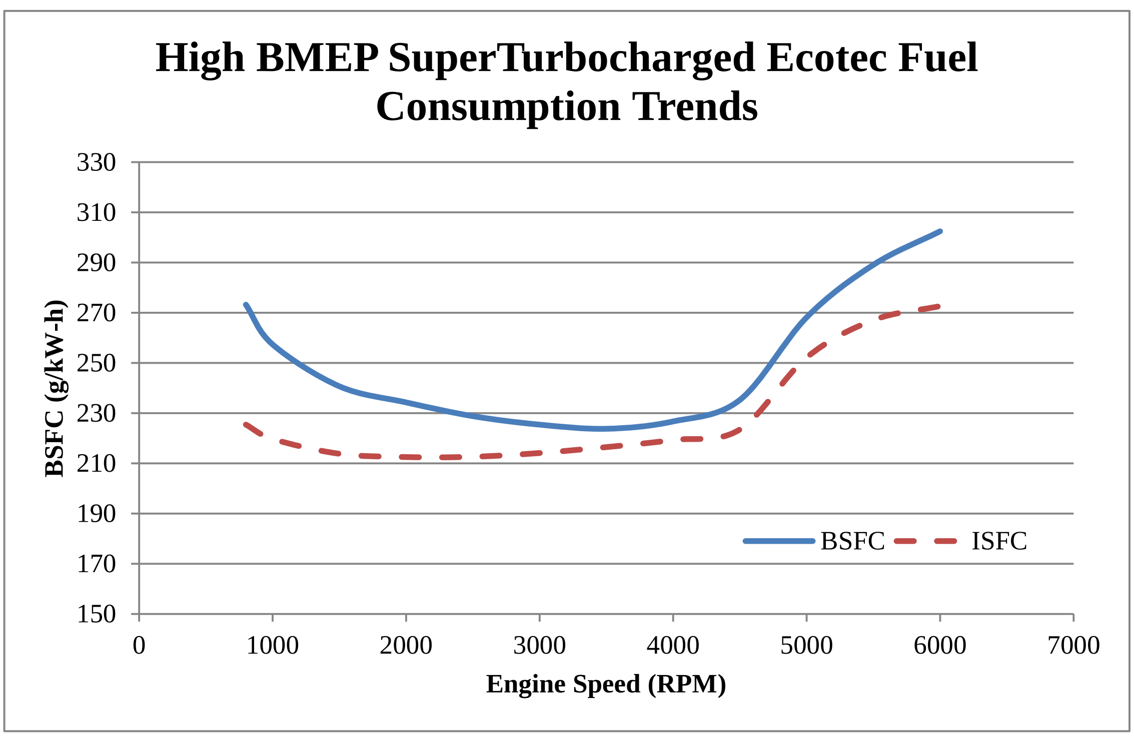

Figure 3.13: Brake and indicated fuel consumption and average peak cylinder pressures as a function of engine speed

speeds the discrepancy between BSFC and ISFC is greater due to the increase in heat transfer and friction losses as a percent of engine power. When the engine bypass is opened at 3000 rpm the ISFC values tend towards BSFC values. At mid-engine speeds the indicated fuel consumption rate increases because there is not enough air to completely burn the fuel.

The BMEP of the SuperTurbocharged engine is shown in Figure 3.14. For research purposes the SuperTurbocharged model is tuned to match a high power output V8 engine, thus the BMEP will be high. The gross indicated mean effective pressure (IMEP) trend, the work of the compression and expansion strokes per cycle, follows the BMEP trend as expected, but at higher values. At high engine speeds the difference between the BMEP and IMEP is greater because the friction work of the system (friction mean effective pressure, FMEP) increases. The

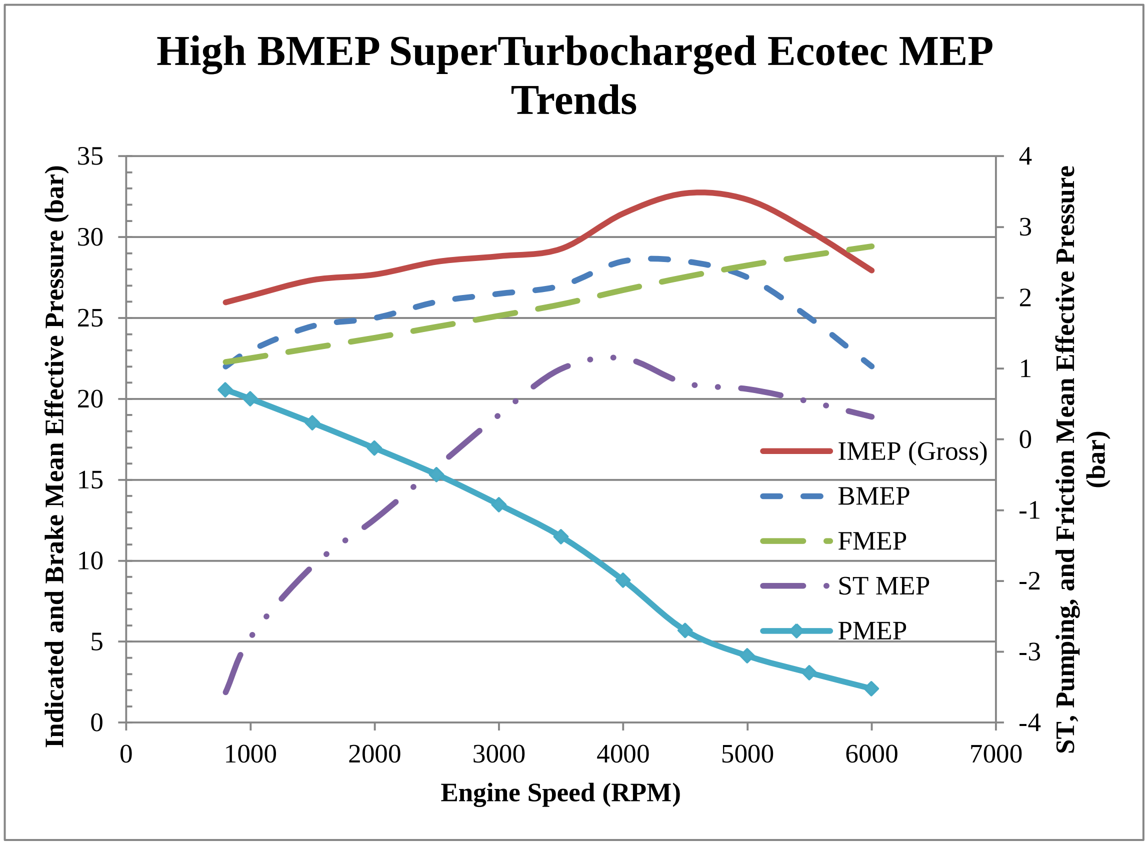

Figure 3.14: Indicated, brake, friction, SuperTurbo™, and pumping mean effective pressures as a function of engine speed

SuperTurbo™ MEP is negative at low speeds because the SuperTurbo™ is operating in supercharging mode, drawing work from the crankshaft. After 3000 rpm the SuperTurbo™ begins turbo-compounding, transferring work back to the crankshaft. In Figure 3.15 the supercharging and turbo-compounding function of the SuperTurbo™ is more clearly shown. When SuperTurbo™ power is negative it operates as a supercharger and when SuperTurbo™ power is positive it operates as a turbocompounder. The losses associated with the SuperTurbo™ increase as engine speed increases based in part from the controller implemented on the SuperTurbo™ shaft. A drag torque is incorporated with the SuperTurbo™ shaft based on SuperTurbo™ speed. As engine speed increases, the SuperTurbo™ shaft speed increases, the drag torque increases, and so do the SuperTurbo™ losses. SuperTurbo™ efficiency is defined as power output divided by total transfer power. Initially, SuperTurbo™ efficiency is

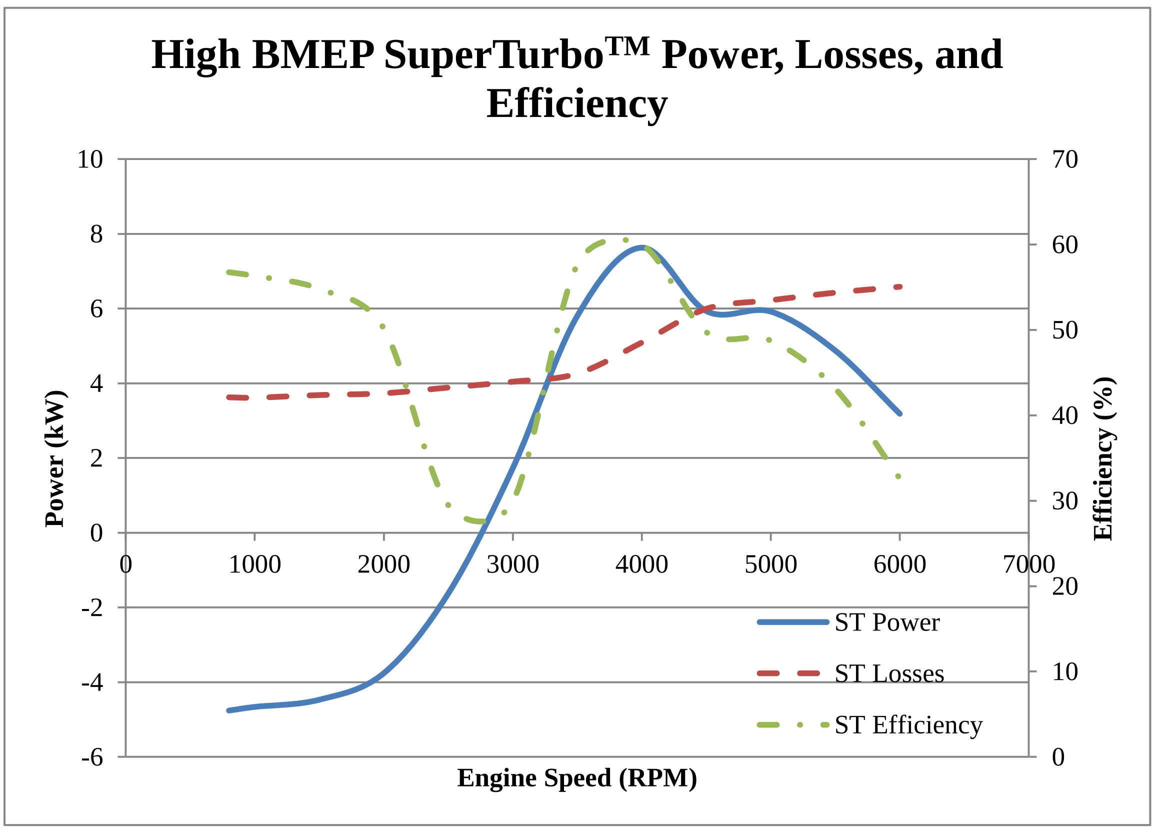

Figure 3.15: SuperTurbo™ power, losses, and efficiency as a function of engine speed

about 56%. As the SuperTurbo™ switches from supercharging to turbo-compounding its efficiency decreases because the SuperTurbo™ losses continue to increase as engine speed increases. Once the SuperTurbo™ is turbo-compounding the amount of work it transfers back to the engine greatly outweighs the losses. Up until 4500 rpm the SuperTurbo™ shaft speed was low enough that the losses increased slowly. At 4500 rpm and above the losses, as defined in the controller, are more profound. This results in a decrease in power and efficiency. Although SuperTurbo™ power decreases it is still able to provide turbo-compounding energy to the engine.

The SuperTurbo™ is intially driven by the engine crankshaft and as a result the efficiency of the compressor is high, around 75%, at low engine speeds. Compressor efficiency increases by a few percentage points when the bypass is opened at 3000 rpm and then decreases by a few percentage points when the throttle is closing at 4000 rpm. With fuel cooling at 5000 rpm the efficiency of the compressor decreases even further to 70%. Figure 3.16 shows the

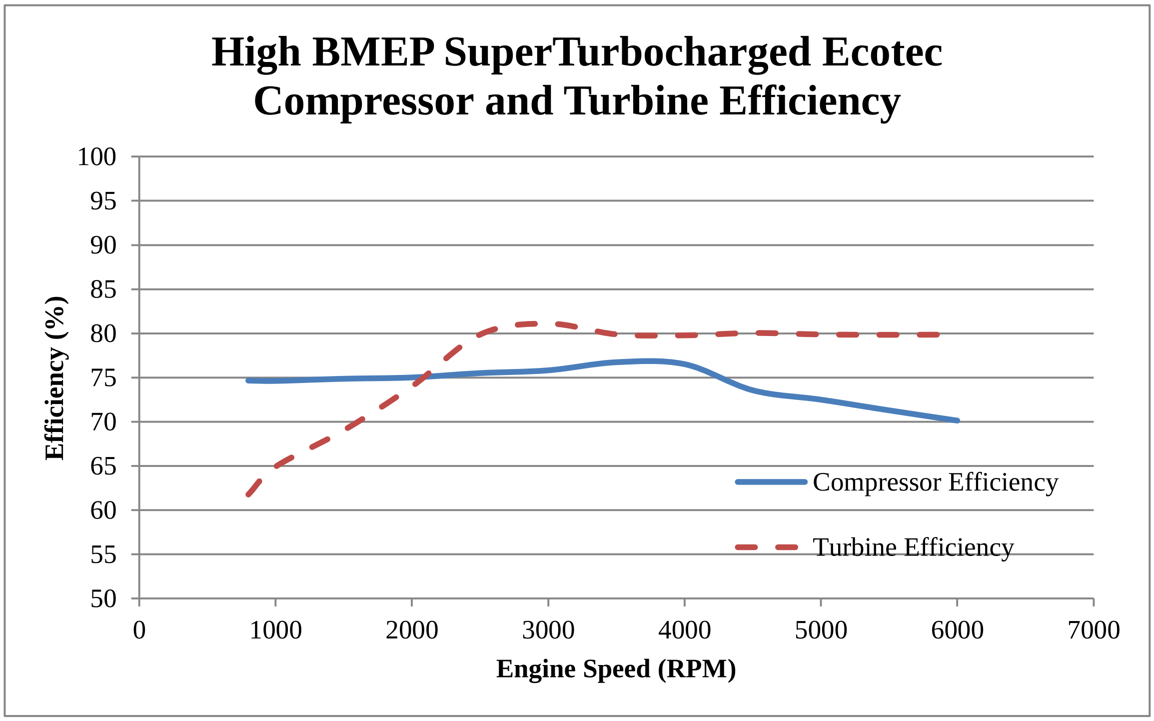

Figure 3.16: SuperTurbo™ compressor and turbine efficiency as a function of engine speed

efficiency of the SuperTurbo™ compressor and turbine. At low engine speeds the turbine, on the other hand, is less efficient than the compressor because less exhaust energy is available to drive the turbine. The reduction in mass flow rate through the turbine results in it operating at an off design point on the turbine map. As engine speed increases the efficiency of the turbine increases and exceeds that of the compressor because more exhaust energy is available to drive the turbine. The increase in mass flow rate through the turbine results in it moving to a more efficient operating point.As the throttle is closed and the amount of air flow diverted away from the turbine decreases the turbine efficiency plateaus. Figure 3.17 shows the mass flow rate of air through the bypass. The engine bypass is opened at 3000 rpm. It is necessary to begin closing the throttle at 4000 rpm in order to maintain a pressure difference across the bypass of 0.1 bar so that EGR does not flow and to continue flowing bypass. Figure 3.17 also shows the turbine speed. Turbine speed trends upwards because engine speed is increasing. The small flat portion of the

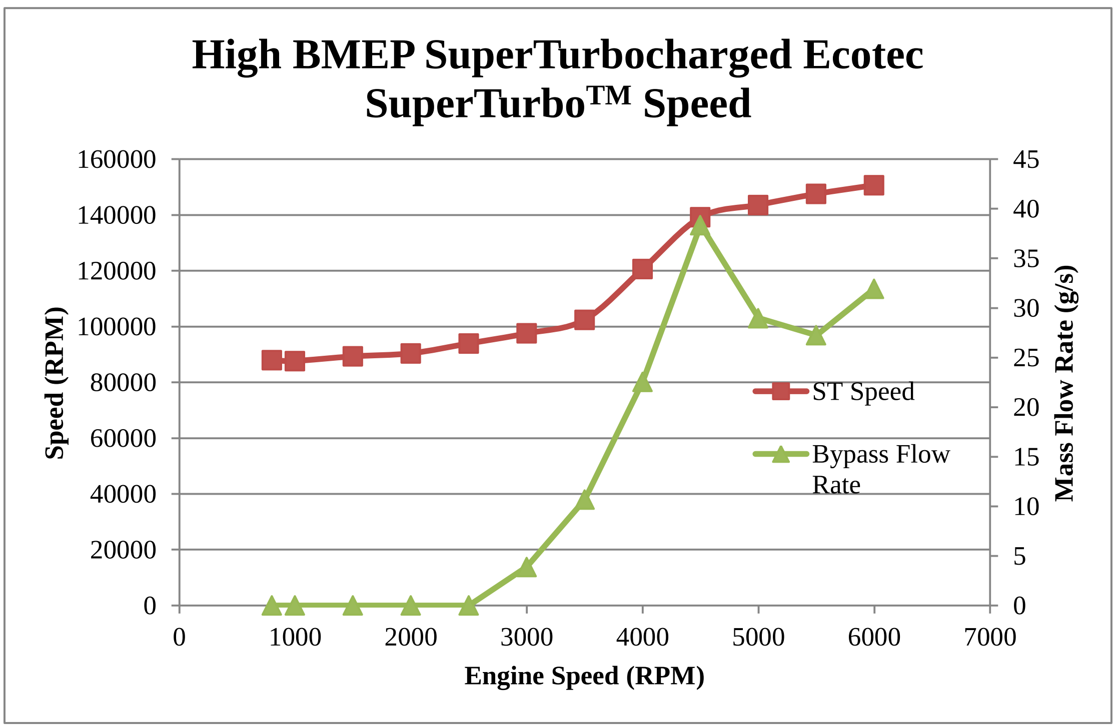

Figure 3.17: SuperTurbo™ speed and bypass flow rate as a function of engine speed

speed curve is due to engaging the bypass. When flow through the bypass is regulated again the speed of the turbine increases.

One of the advantages of a SuperTurbocharged engine is that boost is available at low engine speeds. At 1000 rpm about 2 bar of boost is generated, as illustrated in Figure 3.18, because the compressor is accelerated by the engine crankshaft.When turbo-compounding begins at 3000 rpm boost increases because the turbine is now recovering more waste heat and spinning faster. In addition to the increased turbo-compounding, at 5000 rpm the fuel mixture is enriched. With a mixture rich of stoichiometric the engine can operate at higher speeds without exceeding the turbine inlet temperature, thus producing more boost.

The overall efficiencies and losses of the high BMEP SuperTurbocharged engine are shown in Figure 3.19. As the power of the engine increases, the overall brake efficiency of the engine also increases. When fuel cooling begins at 5000 rpm, the efficiency of the engine

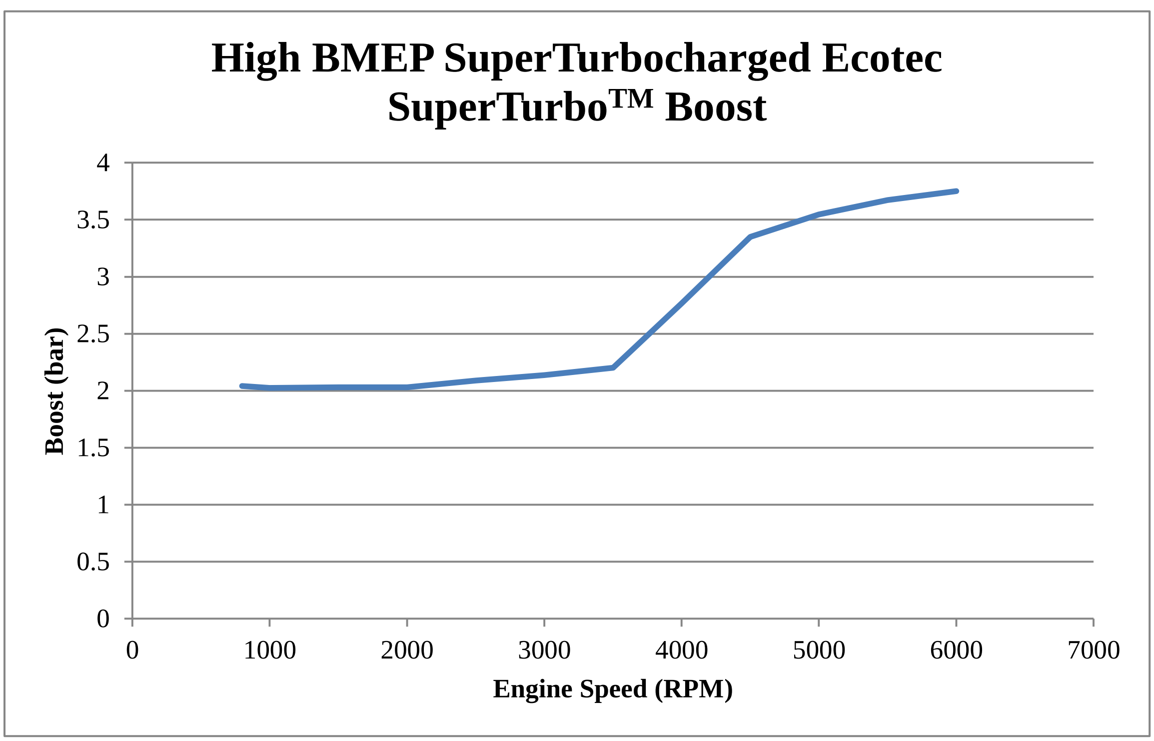

Figure 3.18: SuperTurbo™ boost as a function of engine speed

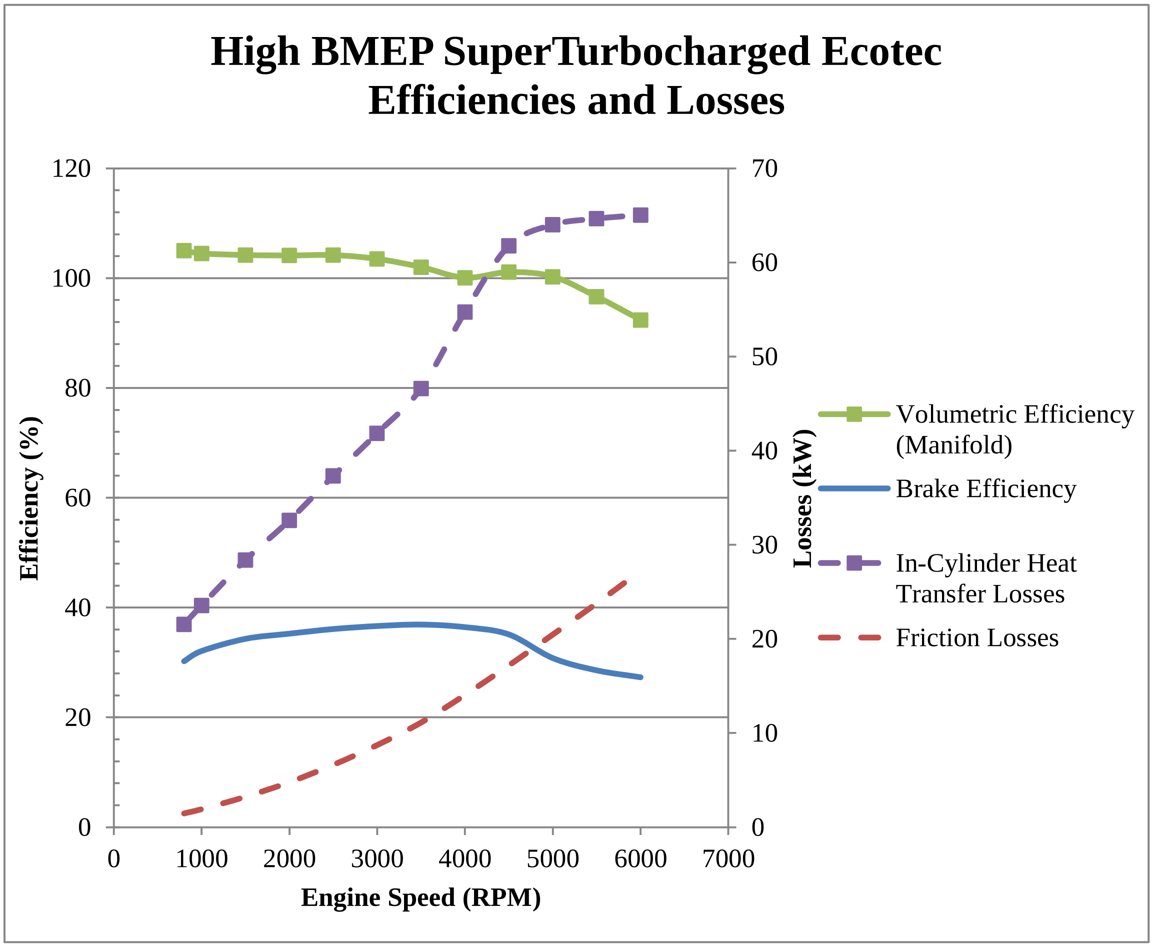

Figure 3.19: Efficiencies and losses as a function of engine speed

decreases because there is not enough air to completely burn all the fuel. A SuperTurbocharged engine has typically seen manifold volumetric efficiency values between 85 and 90% [20]. The port injected nature of the Ecotec engine contributes to the higher than expected SuperTurbocharged manifold volumetric efficiency values. The temperature drop from the beginning of the intake manifold to the intake ports due to fuel spray cooling the air increases air density and volumetric efficiency. When the engine bypass is opened, however, the volumetric efficiency of the engine decreases because more air is routed to the intake manifold. When the throttle is closed more fully a brief increase in volumetric efficiency is due to less air being routed to the intake manifold. Volumetric efficiency decreases after 5000 rpm due to the combination of the throttle closing and restricting airflow, engine speed increasing, and the air/fuel ratio decreasing further. Also shown in Figure 3.19 are the expected increases in losses due to friction and in-cylinder heat transfer as engine speed increases.

The high BMEP SuperTurbocharged Ecotec engine is tuned to match the Vortec LMG engine using the performance map from GM Powertrain. The data gathered from the GT-Power model will be compared in the following chapter to the stock Ecotec engine to understand the effect of using a SuperTurbo^{TM} for engine downsizing.

3.2.2 GM Ecotec LSJ Engine Match

In order to compare the gains in efficiency from SuperTurbocharging an engine, the stock Ecotec performance map is matched with the SuperTurbocharged Ecotec, henceforth referred to as the low BMEP SuperTurbocharged Ecotec. The final low BMEP SuperTurbocharged simulation results are compared to the final stock Ecotec simulation results, both at WOT, in Figure 3.20. The low BMEP SuperTurbocharged Ecotec simulation results match the stock

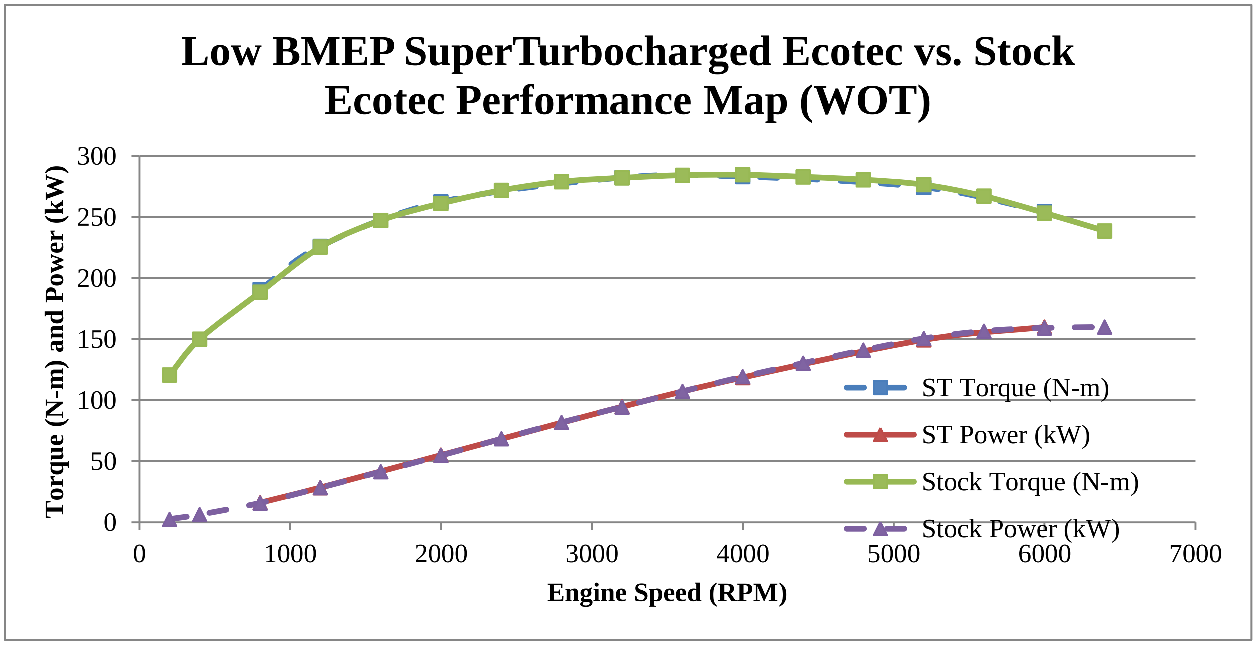

Figure 3.20: GT-Power low BMEP SuperTurbocharged Ecotec vs. GT-Power Stock Ecotec performance map (WOT)

Ecotec simulation results producing a peak power of 159 kW (214 hp) at 6000 rpm and a peak torque of 284 N-m (209 lb-ft) at 4000 rpm.

The purpose of matching the low BMEP SuperTurbocharged Ecotec engine to the stock Ecotec engine is purely for a one-to-one efficiency comparison. In Figure 3.21 the BSFC curve of the low BMEP SuperTurbocharged Ecotec is shown. At high engine speeds BSFC increases due to increased friction losses and throttle closure. In Figure 3.22 the brake thermal efficiency of the engine is shown. Engine efficiency increases as the power of the engine increases, but as more fuel is injected, the efficiency of the engine decreases. When the engine bypass is opened the efficiency of the engine decreases as fuel flow rate and engine power increase.

The low BMEP SuperTurbocharged Ecotec engine is tuned to match the Ecotec LSJ engine using the performance map from the GT-Power stock Ecotec simulation. The data gathered from both GT-Power models will be compared in the following chapter to understand the effect of using a SuperTurbo^{TM} on engine efficiency.

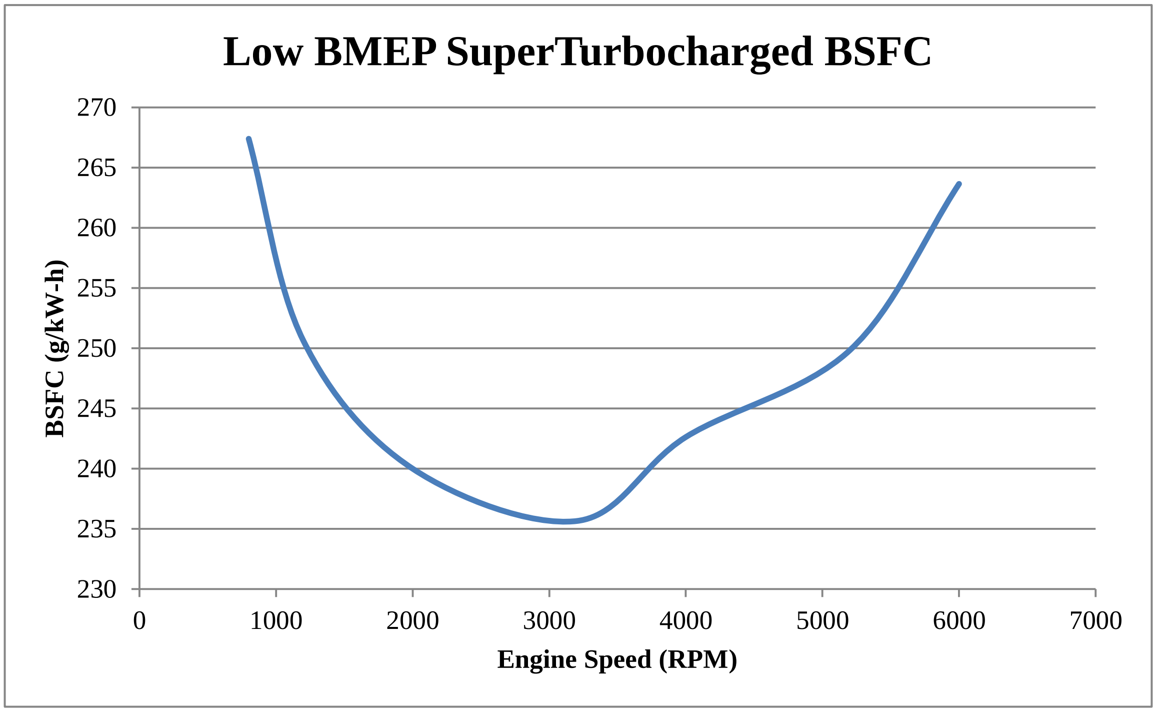

Figure 3.21: Brake specific fuel consumption as a function of engine speed

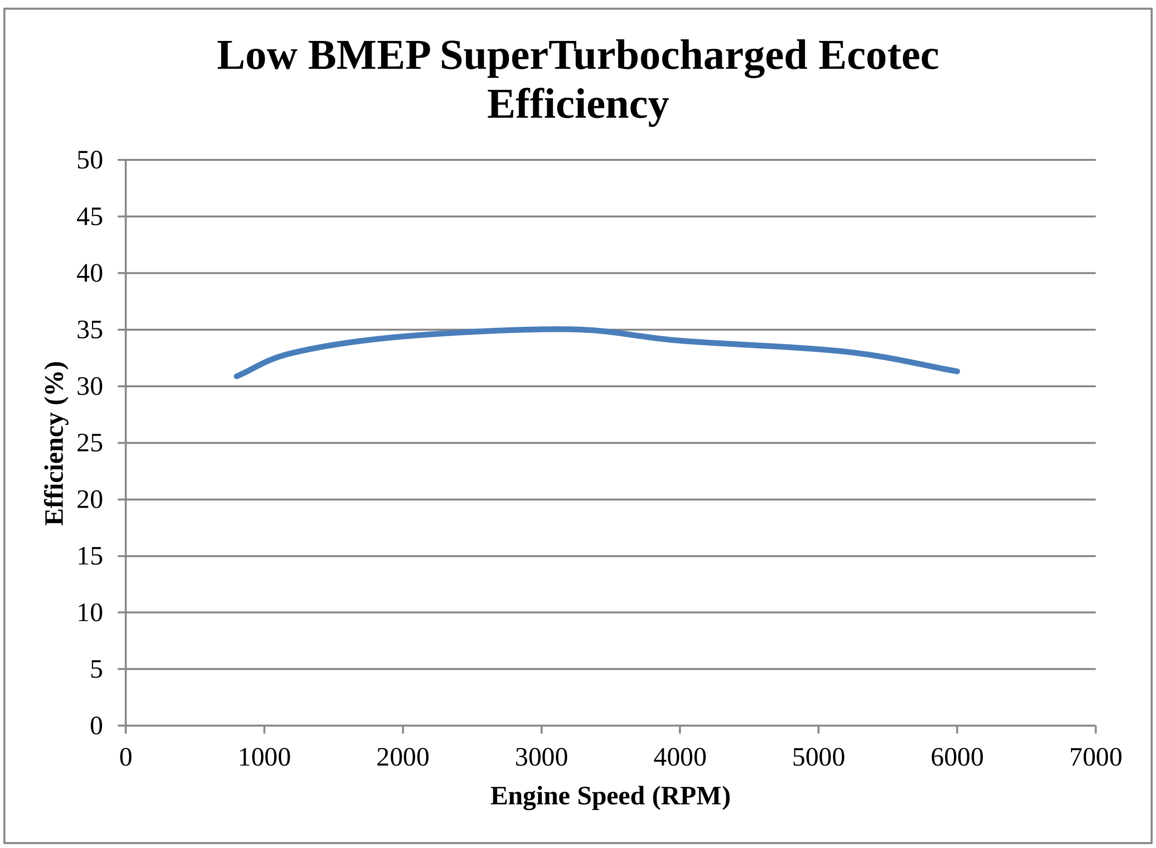

Figure 3.22: Brake efficiency as a function of engine speed

CHAPTER 4: THE EFFECTS OF SUPERTURBOCHARGING

4.1 GT-Power Engine Simulation Comparisons

The demand for boosting technology with the intent of engine downsizing is rising. An integrated supercharger/turbocharger has the opportunity to emerge as a forerunner in the advanced turbocharging market. In order to validate reported performance metrics of SuperTurbo^{TM} technology a stock Ecotec engine is compared to both a high and low BMEP output SuperTurbocharged Ecotec engine. In the previous chapters GT-Power simulation results were shown and discussed in order to validate the engine models that were generated. In the following sections a comparison of engine efficiency and select indicative results are discussed.

4.1.1 High BMEP SuperTurbocharged Ecotec vs. Stock GM Ecotec LSJ

The high BMEP SuperTurbocharged Ecotec engine is compared to the stock Ecotec engine in order to demonstrate the power boosting capabilities and efficiency gains of equipping an engine with a SuperTurbo^{TM} and to show its viability as technology used for engine downsizing.

At low engine speeds the high BMEP SuperTurbocharged engine has slightly worse BSFC values than the stock Ecotec engine, as illustrated in Figure 4.1. At low engine speeds the SuperTurbo^{TM} is operating as a supercharger and using power from the crankshaft in order to spool the compressor. The supercharger on the stock Ecotec engine is also using power from the crankshaft, but less of it at low engine speeds as shown in Figure 4.2. The supercharger on the stock Ecotec engine continues to utilize more crankshaft power as engine speeds increase and contributes to the increase in BSFC through friction losses. Conversely, the high BMEP

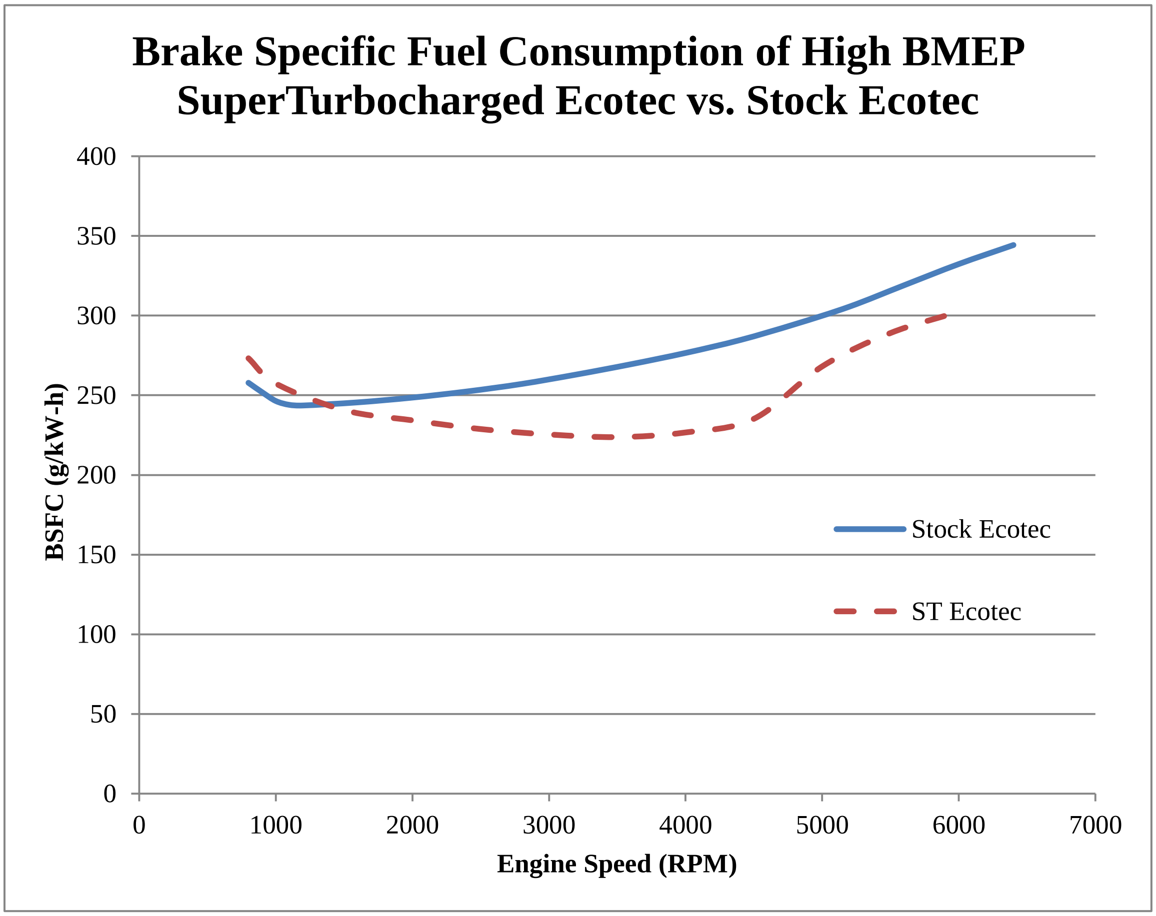

Figure 4.1: Brake specific fuel consumption comparison as a function of engine speed

SuperTurbocharged Ecotec switches into turbo-compounding mode as turbine efficiency and mass flow rate increase, and supplies power to the crankshaft. Figure 4.3 shows the high BMEP SuperTurbocharged Ecotec BSFC improvement over the stock Ecotec engine. When fuel cooling begins at 5000 rpm the BSFC improvement decreases from 21% to 11%, but remains in effect. Due to the fact that the power output of these two engines is different the BSFC improvement is a relative comparison between the two engines.

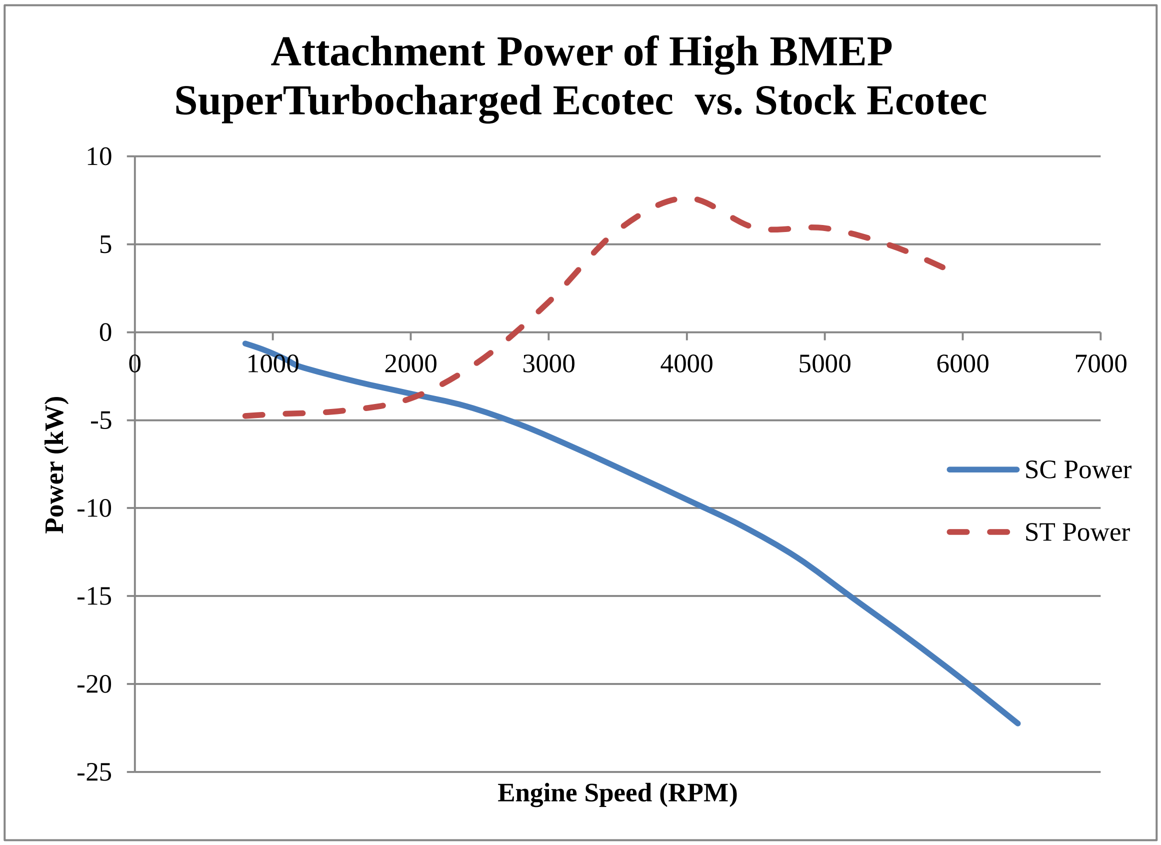

Figure 4.2: SuperTurbo™ and supercharging power comparison as a function of engine speed

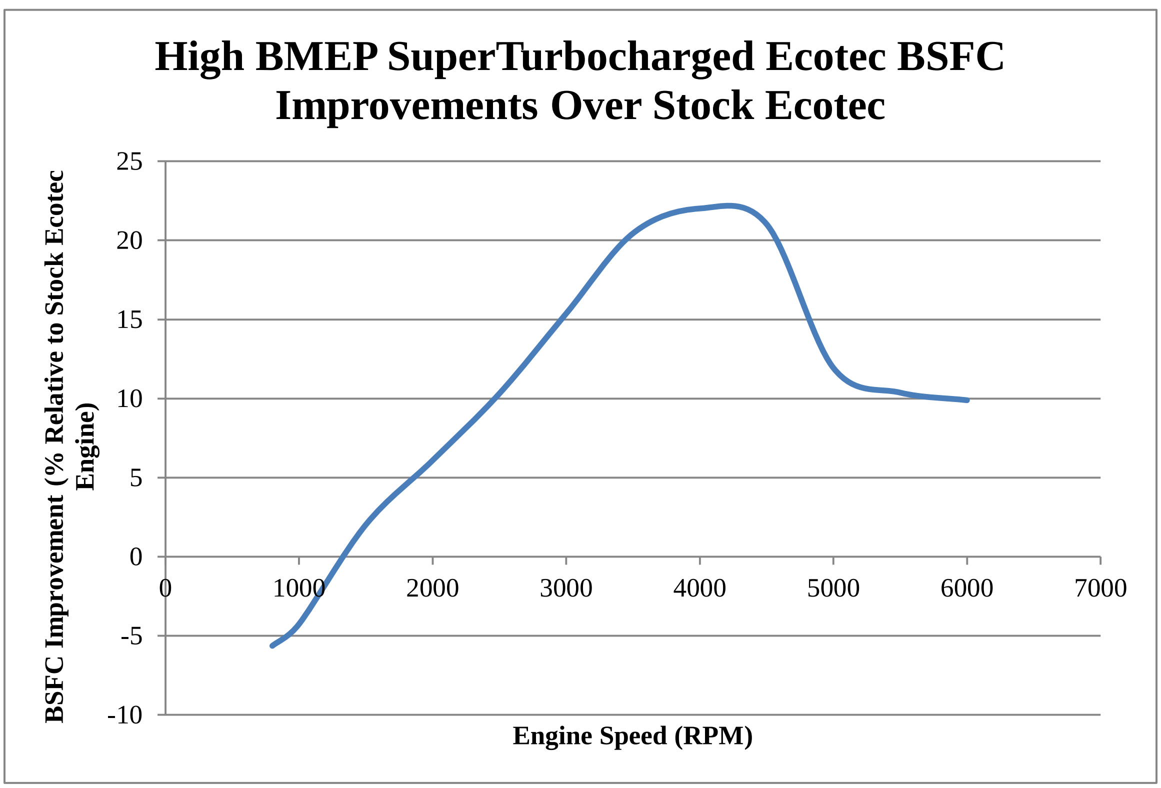

Figure 4.3: Full load BSFC improvements as a function of engine speed

The high BMEP SuperTurbocharged engine is tuned to match the torque and power output of the GM Vortec LMG 5.3l V8 engine. This engine configuration is compared to the stock GM Ecotec LSJ 2.0l I4 in order to show that a SuperTurbocharged small four cylinder engine will not only meet performance curves of a much bigger more powerful engine, but will also increase engine efficiency, in the form of reduced fuel consumption, from the base configuration. Downsizing and boosting an engine with a VanDyne SuperTurbo^{TM} is more than viable, it is practical.

4.1.2 Low BMEP SuperTurbocharged Ecotec vs. Stock GM Ecotec LSJ

The low BMEP SuperTurbocharged Ecotec is compared to the stock Ecotec in order to show the potential gains in efficiency when using a SuperTurbo^{TM}. In this case the brake thermal efficiency of the engines is comparable because both engines have the same rated power output. Figure 4.4 shows the brake thermal efficiency of the stock and low BMEP SuperTurbocharged engines. At low speeds the stock Ecotec more efficiently converts the fuel mass consumed into power because less power is required by the supercharger than the power required by the compressor in the SuperTurbo^{TM}. As engine speed increases the low BMEP SuperTurbocharged engine is more efficient than the stock Ecotec as the power required by SuperTurbo^{TM} decreases eventually giving power back to the engine. A comparison of SuperTurbo^{TM} power and supercharger power requirements is shown in Figure 4.5.

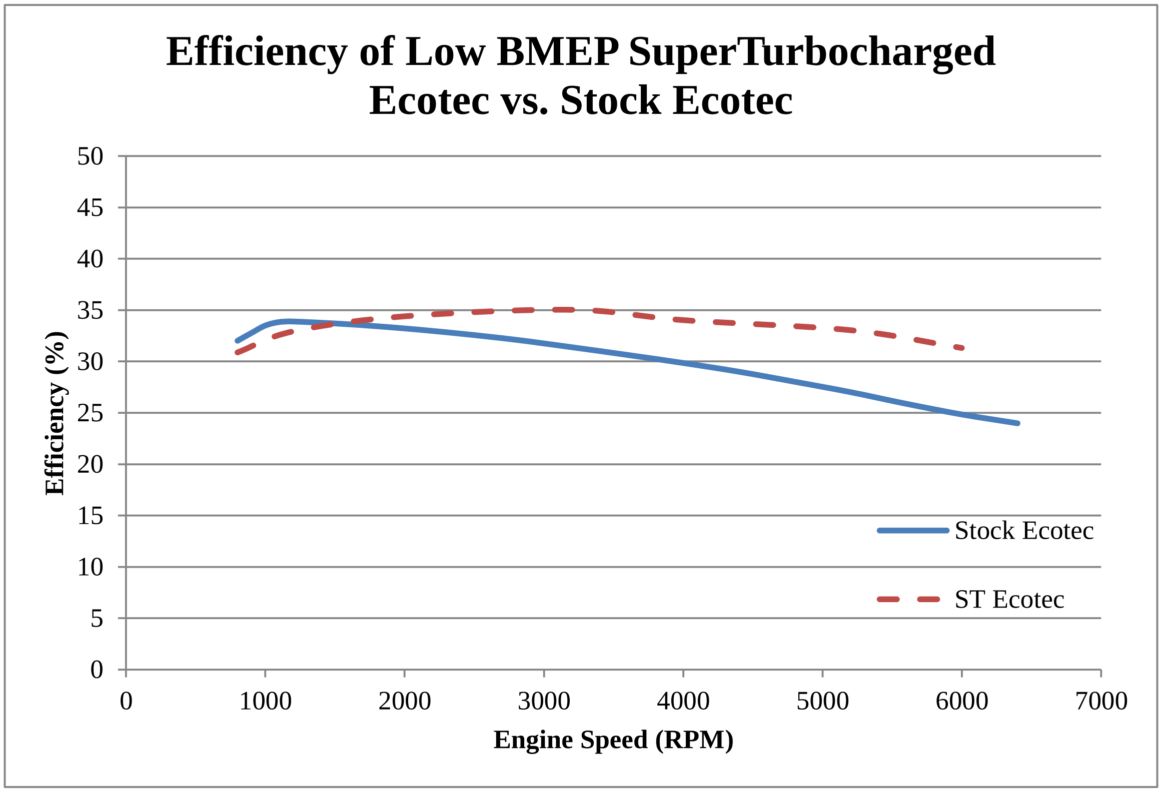

Figure 4.4: Brake thermal efficiency comparison as a function of engine speed

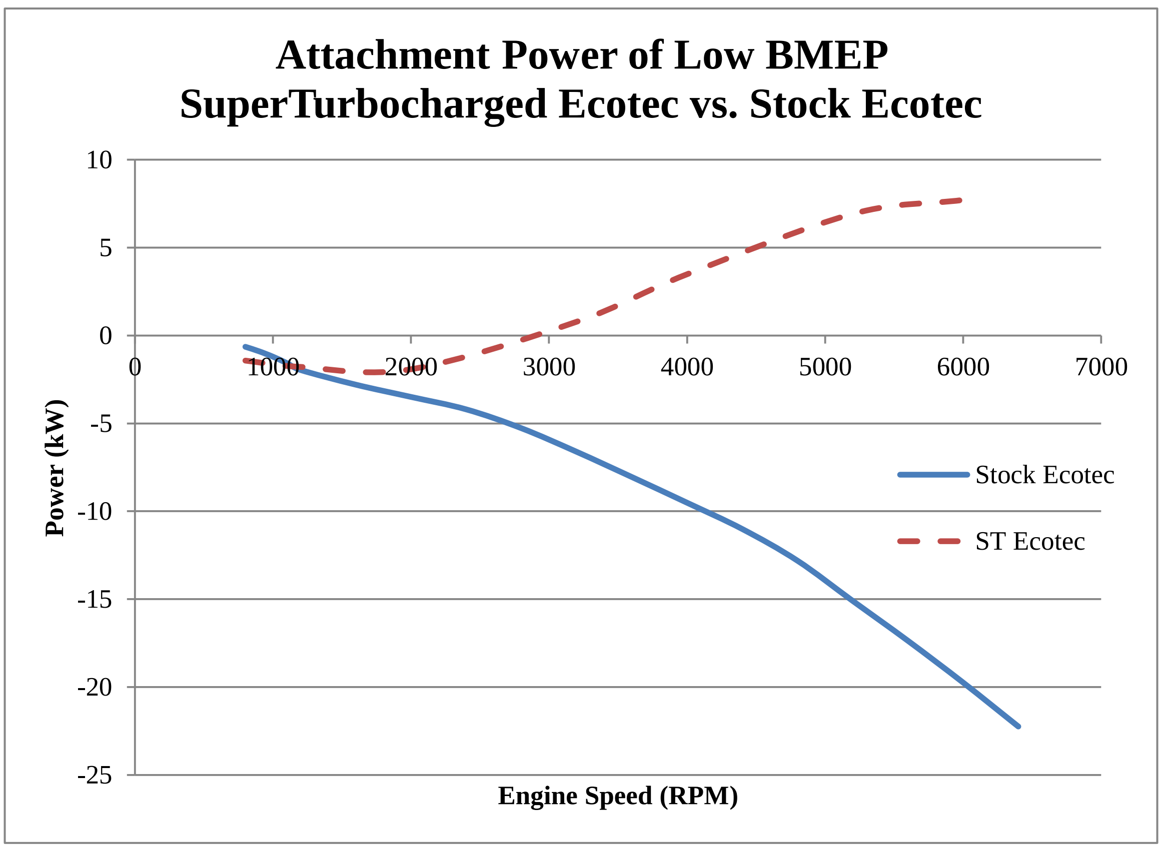

Figure 4.5: : SuperTurbo^{TM} and supercharging power comparison as a function of engine speed

As expected the BSFC of both engines is a reflection of their efficiencies. At low speeds the stock Ecotec has a lower BSFC than the low BMEP SuperTurbocharged Ecotec. As engine speeds increase the low BMEP SuperTurbocharged engine's BSFC is lower than the stock Ecotec's and at 6000 rpm it sees a 26% BSFC improvement over the stock configuration. In Figure 4.6 the BSFC comparison of both engines is shown and in Figure 4.7 the percent BSFC improvement of the low BMEP SuperTurbocharged engine over the stock Ecotec is shown.

The low BMEP SuperTurbocharged engine is tuned to match the torque and power output of the GM Ecotec LSJ 2.0l I4 engine. This engine configuration is compared to the stock GM Ecotec LSJ 2.0l I4 in order to show that a SuperTurbocharged small four cylinder engine

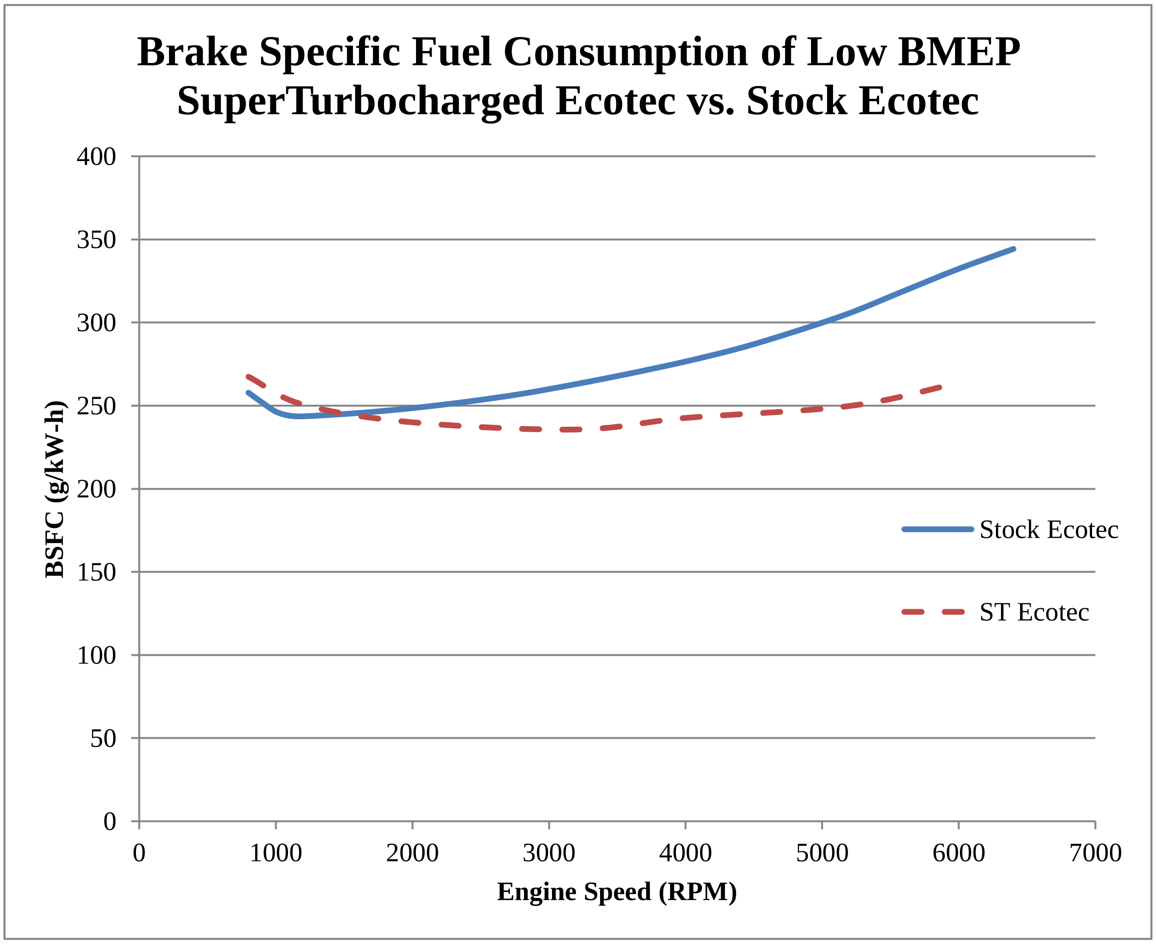

Figure 4.6: Brake specific fuel consumption comparison as a function of engine speed

can meet the performance curves of an identical engine and increase engine efficiency from the base configuration. Efficiency improvements are found boosting even a small engine with a SuperTurbo™ proving again that it more than viable, it is practical.

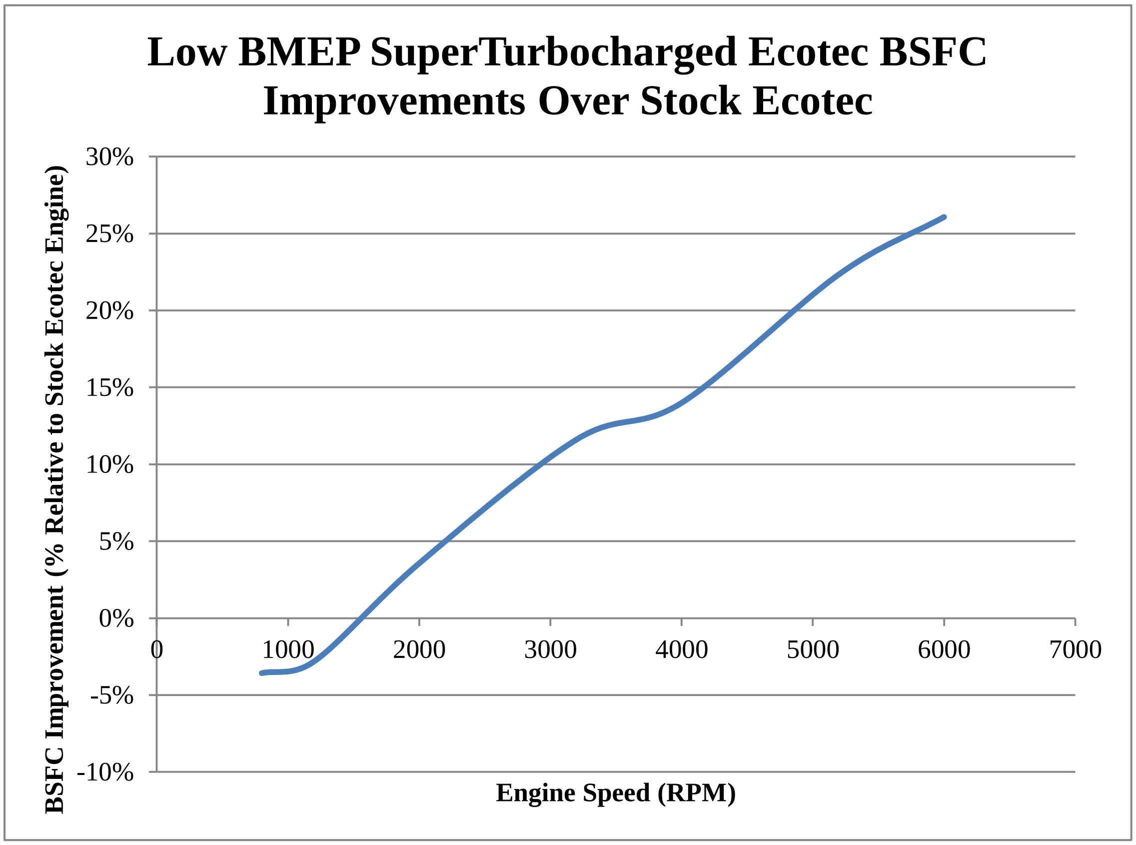

Figure 4.7: Full load BSFC improvements as a function of engine speed

CHAPTER 5: CONCLUSION

5.1 Summary and Conclusions

A GM Ecotec LSJ 2.0l I4 engine and a SuperTurbocharged GM Ecotec LSJ 2.0l I4 engine were modeled using GT-Power. Two configurations of SuperTurbocharged engine models were simulated to validate reported SuperTurbo^{TM} performance, to predict improvements in BSFC over the stock engine configuration, and to show the value of SuperTurbocharging an engine. At low engine speeds the SuperTurbo^{TM} acted as a supercharger taking power from the crankshaft in order to power the compressor to boost the engine. At mid-engine speeds when the amount of power collected by the turbine exceeded the power requirement of the compressor, the SuperTurbo^{TM} began acting as a turbo-compounder, giving power back to the engine.

The claims that were made in regards to the SuperTurbo^{TM} improving engine efficiency up to 20% [5] were validated through the research performed. The high BMEP SuperTurbocharged Ecotec saw BSFC improvements up to 21% at 4500 rpm and the low BMEP SuperTurbocharged Ecotec saw BSFC improvements up to 26% at 6000 rpm. At lower engine speeds the high and low SuperTurbocharged Ecotec models saw BSFC improvements between 5 and 20%.

Additionally, through many simulations and model tuning, it was identified on the high BMEP SuperTurbocharged Ecotec that the engine bypass should begin opening at 3000 rpm, the throttle should begin closing at 4000 rpm, and fuel cooling begun at 5000 rpm. On the low BMEP SuperTurbocharged Ecotec it was identified that the bypass should begin opening at 4000 rpm and the throttle should begin closing at 5200 rpm.

The SuperTurbo^{TM} is an answer to the call for innovative new engine technology and is sustainable and necessary for use in engine downsizing.

5.2 Recommendations for Future Work

At the conclusion of research the following recommendations for future work are made:

- Additional engine data for tuning and validation would improve accuracy of the engine models.
- A finely tuned intake for the SuperTurbocharged Ecotec could improve BSFC values.
- More speed points modeled for the low BMEP SuperTurbocharged Ecotec would give a better idea of when the bypass and throttle controls needed to be engaged.
- With more time it would have been of interest to model pure air cooling versus pure fuel cooling at all engine speeds to see what effect this would have on BSFC.
- An experimental validation of modeling results.

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APPENDIX I

Table of Valve Lift Profile:

Exhaust Valve		Intake Valve	
CAD	Lift (mm)	CAD	Lift (mm)
-168	0	-19	0
-167	0.03556	-18	0.00508
-166	0.12446	-17	0.09906
-165	0.21082	-16	0.15494
-164	0.29972	-15	0.28448
-163	0.37338	-14	0.39624
-162	0.46736	-13	0.52324
-161	0.54356	-12	0.64262
-160	0.62484	-11	0.81534
-159	0.73152	-10	0.90424
-158	0.84836	-9	1.03632
-157	0.92964	-8	1.18618
-156	1.04648	-7	1.32842
-155	1.17856	-6	1.47574
-154	1.27762	-5	1.65862
-153	1.41224	-4	1.79578
-152	1.51638	-3	1.93548
-151	1.651	-2	2.08026
-150	1.78562	-1	2.22758
-149	1.8923	0	2.40538
-148	2.0447	1	2.55778
-147	2.16154	2	2.71272
-146	2.2479	3	2.86004
-145	2.41808	4	2.98704
-144	2.54762	5	3.18516
-143	2.67462	6	3.32994
-142	2.90576	7	3.50266
-141	2.95656	8	3.66014
-140	3.06324	9	3.81254
-139	3.2385	10	3.95224
-138	3.35026	11	4.09448
-137	3.45186	12	4.26212
-136	3.58648	13	4.38404
-135	3.76936	14	4.51866

Exhaust Valve		Intake Valve	
CAD	Lift (mm)	CAD	Lift (mm)
-134	3.87096	15	4.64058
-133	3.95478	16	4.75742
-132	4.13512	17	4.90474
-131	4.2545	18	5.03174
-130	4.26466	19	5.17652
-129	4.54152	20	5.2832
-128	4.67868	21	5.40004
-127	4.7625	22	5.52958
-126	4.82854	23	5.6642
-125	5.04698	24	5.76834
-124	5.0927	25	5.88264
-123	5.2959	26	5.99694
-122	5.4102	27	6.11886
-121	5.49402	28	6.20014
-120	5.67182	29	6.32714
-119	5.79374	30	6.41096
-118	5.91312	31	6.54304
-117	6.00456	32	6.65734
-116	6.1595	33	6.77164
-115	6.24078	34	6.8326
-114	6.33984	35	6.92658
-113	6.43636	36	7.03326
-112	6.46684	37	7.12724
-111	6.604	38	7.2136
-110	6.7691	39	7.29996
-109	6.86308	40	7.38378
-108	6.90626	41	7.4422
-107	7.00532	42	7.50824
-106	7.16534	43	7.59206
-105	7.2136	44	7.67334
-104	7.3787	45	7.74446
-103	7.45998	46	7.83082
-102	7.50316	47	7.89686
-101	7.56158	48	7.99084
-100	7.71398	49	8.03402

Exhaust Valve		Intake Valve	
CAD	Lift (mm)	CAD	Lift (mm)
-99	7.77748	50	8.13308
-98	7.874	51	8.19658
-97	7.9375	52	8.25246
-96	8.02386	53	8.26008
-95	8.08228	54	8.37438
-94	8.14578	55	8.42772
-93	8.21436	56	8.45312
-92	8.24738	57	8.509
-91	8.35152	58	8.5471
-90	8.41502	59	8.5852
-89	8.46582	60	8.6614
-88	8.51408	61	8.67156
-87	8.56996	62	8.73252
-86	8.59536	63	8.76554
-85	8.66648	64	8.79602
-84	8.67156	65	8.80872
-83	8.7503	66	8.83412
-82	8.82396	67	8.87984
-81	8.82904	68	8.89508
-80	8.85444	69	8.92048
-79	8.88238	70	8.9535
-78	8.9281	71	8.9662
-77	8.94842	72	8.9789
-76	8.98144	73	8.98906
-75	9.00176	74	9.0043
-74	9.02716	75	9.01192
-73	9.03732	76	9.017
-72	9.05764	77	9.01954
-71	9.07288	78	9.017
-70	9.08304	79	9.017
-69	9.09574	80	9.01446
-68	9.09828	81	9.01446
-64	9.08558	82	8.99668
-63	9.0805	83	8.9916
-62	9.07796	84	8.98144
-61	9.05764	85	8.9662
-60	9.04748	86	8.95604
-59	9.0297	87	8.93318

Exhaust Valve		Intake Valve	
CAD	Lift (mm)	CAD	Lift (mm)
-58	9.00684	88	8.91032
-57	8.9916	89	8.88746
-56	8.97128	90	8.86714
-55	8.9535	91	8.8392
-54	8.91032	92	8.80618
-53	8.86968	93	8.77316
-52	8.84174	94	8.7376
-51	8.79602	95	8.70204
-50	8.77316	96	8.6614
-49	8.70966	97	8.62076
-48	8.65378	98	8.58266
-47	8.62076	99	8.52424
-46	8.57758	100	8.4836
-45	8.51154	101	8.45058
-44	8.45058	102	8.39978
-43	8.3947	103	8.32358
-42	8.36676	104	8.26008
-41	8.27024	105	8.20674
-40	8.24738	106	8.13816
-39	8.16356	107	8.07466
-38	8.06196	108	7.99846
-37	7.98576	109	7.92734
-36	7.91464	110	7.86892
-35	7.85622	111	7.77494
-34	7.75716	112	7.73684
-33	7.67842	113	7.65048
-32	7.5946	114	7.58952
-31	7.50062	115	7.49046
-30	7.39394	116	7.41426
-29	7.3279	117	7.32282
-28	7.22884	118	7.24154
-27	7.14502	119	7.1628
-26	7.0485	120	7.06882
-25	6.94436	121	6.99262
-24	6.86816	122	6.89864
-23	6.73608	123	6.79958
-22	6.63702	124	6.70814
-21	6.53288	125	6.60908

Exhaust Valve		Intake Valve	
CAD	**Lift (mm)**	**CAD**	**Lift (mm)**
-20	6.4135	126	6.49986
-19	6.29412	127	6.40334
-18	6.19506	128	6.3119
-17	6.09346	129	6.17474
-16	5.96646	130	6.08584
-15	5.85216	131	5.97154
-14	5.7277	132	5.86232
-13	5.59816	133	5.74548
-12	5.48132	134	5.63626
-11	5.34416	135	5.5372
-10	5.20446	136	5.41274
-9	5.04444	137	5.29844
-8	4.92252	138	5.15366
-7	4.78028	139	5.08254
-6	4.67106	140	4.92252
-5	4.50596	141	4.78282
-4	4.3561	142	4.65328
-3	4.19608	143	4.52628
-2	4.06146	144	4.43738
-1	3.89636	145	4.26974
0	3.75158	146	4.13258
1	3.5941	147	4.02082
2	3.42646	148	3.88112
3	3.2639	149	3.78206
4	3.15468	150	3.62204
5	2.96418	151	3.4925
6	2.8067	152	3.34264
7	2.65684	153	3.19786
8	2.48158	154	3.10134
9	2.32156	155	2.94386
10	2.17678	156	2.8194
11	2.01168	157	2.66192
12	1.86436	158	2.5019
13	1.69926	159	2.3749
14	1.57226	160	2.23012
15	1.42748	161	2.12598
16	1.29794	162	2.01168
17	1.14554	163	1.85928
18	1.04394	164	1.7399
19	0.90678	165	1.62052
20	0.77216	166	1.51384
21	0.62992	167	1.37414
22	0.55118	168	1.26746
23	0.42418	169	1.1303
24	0.30988	170	0.99822
25	0.26416	171	0.90678
26	0.23876	172	0.8001
27	0.19304	173	0.6985
28	0.14478	174	0.59944
29	0.09398	175	0.48768
30	0.06096	176	0.41148
31	0.04826	177	0.31242
33	0.04064	178	0.23368
34	0.01524	179	0.16256
35	0.01016	180	0.0508
36	0.00508	181	0.00762
37	0.00254	184	0
38	0		

APPENDIX II

Table of Engine Dimensions:

Part Name	Diameter (mm)	Length (mm)	Volume (mm^3)	Ratio
DiscretInt	--	34.4	--	--
DiscretExh	--	47.3	--	--
comp-in-1	60	100	--	--
cooler-in-1	119.3	23.12	--	--
blowoff-1	119.3	100	--	--
blowoff1-1	30	50	--	--
blowoff2-1	25	50	--	--
cooler-1	30.2	179.6	--	--
cooler-out-1	37.48	34.4	--	--
cooler-out-2	37.48	34.4	--	--
cooler-out-3	37.48	34.4	--	--
cooler-out-4	37.48	34.4	--	--
intport-flospl-1	60	75.46	--	--
intport-flospl-2	60	75.46	--	--
intport-flospl-3	60	75.46	--	--
intport-flospl-4	60	75.46	--	--
intport-1	36	30	--	--
intport-2	36	30	--	--
intport-3	36	30	--	--
intport-4	36	30	--	--
intport-5	36	30	--	--
intport-6	36	30	--	--
intport-7	36	30	--	--
intport-8	36	30	--	--
intvalve-1	35.17	--	--	--
intvalve-2	35.17	--	--	--
intvalve-3	35.17	--	--	--
intvalve-4	35.17	--	--	--
intvalve-5	35.17	--	--	--
intvalve-6	35.17	--	--	--
intvalve-7	35.17	--	--	--
intvalve-8	35.17	--	--	--
Bore	--	86	--	--
Stroke	--	86	--	--
Connecting Rod Length	--	145	--	--

Part Name	Diameter (mm)	Length (mm)	Volume (mm^3)	Ratio
TDC Clearance Height	--	0.03	--	--
exhvalve-1	30.09	--	--	--
exhvalve-2	30.09	--	--	--
exhvalve-3	30.09	--	--	--
exhvalve-4	30.09	--	--	--
exhvalve-5	30.09	--	--	--
exhvalve-6	30.09	--	--	--
exhvalve-7	30.09	--	--	--
exhvalve-8	30.09	--	--	--
exhport-1	31	42.74	--	--
exhport-2	31	42.74	--	--
exhport-3	31	42.74	--	--
exhport-4	31	42.74	--	--
exhport-5	31	42.74	--	--
exhport-6	31	42.74	--	--
exhport-7	31	42.74	--	--
exhport-8	31	42.74	--	--
exhport-flospl-1	--	--	13710	--
exhport-flospl-2	--	--	13710	--
exhport-flospl-3	--	--	13710	--
exhport-flospl-4	--	--	13710	--
exhrunner-1	32.5	70	--	--
exhrunner-2	32.5	70	--	--
exhrunner-3	32.5	70	--	--
exhrunner-4	32.5	70	--	--
Exhaust-fs-12	60	47.3	--	--
Exhaust-fs-34	60	47.3	--	--
exhman-1	60/40	65	--	--
exhman-2	60/41	66	--	--
ExhaustManifold-1	56.75	114.3		--
to-muffler-1	56.75	180		--
PulleyRatio-1				1.85

APPENDIX III

GT-Power Data Tables for Select Cases:

Stock Ecotec LSJ Engine:
1600 rpm:

Engine and Cylinder

Engine Geometry (Cyl # 1)

Bore [mm]	86.0
Stroke [mm]	86.0
Connecting Rod Length [mm]	145.0
Piston Pin Offset [mm]	0.00
Displacement/Cylinder [liter]	0.500
Total Displacement [liter]	1.998
Number of Cylinders	4
Compression Ratio	9.50
Bore/Stroke	1.000
IVC [CA]	-161
EVO [CA]	177
IVO [CA]	356
EVC [CA]	383

Engine and Cylinder

Engine Performance Predictions (SI)

Brake Power [kW]	41.4
Brake Power [HP]	55.6
Brake Torque [N-m]	247.3
IMEP [bar]	17.76
FMEP [bar]	1.15
PMEP [bar]	0.08
Air Flow Rate [kg/hr]	150.1
BSAC [g/kW-h]	3623
Fuel Flow Rate [kg/hr]	10.2
BSFC [g/kW-h]	246.4
Volumetric Efficiency [%]	135.1
Volumetric Efficiency (M) [%]	102.7
Trapping Ratio	0.996
A/F Ratio	14.70
Brake Efficiency [%]	33.2

Compressor/Turbine

Compressor/Turbine/Pump/Fan

	compressor-1
Type of Device	Compressor
Speed [RPM]	2960
Pressure Ratio (static)	1.42
Pressure Ratio	1.42
Mass Flow Rate [kg/s]	0.04
Power [kW]	2.8
Efficiency [%]	47.4
Inlet Pressure [bar]	1.00
Outlet Pressure [bar]	1.42
Inlet Temperature [K]	299
Outlet Temperature [K]	365
Map PR Exceeded/Stalled ?	NO
PR less than 1.0 ?	NO
Map RPM Exceeded ?	NO
Pressure Rise [bar]	0.42

Engine and Cylinder

Key Cylinder Predictions

Cylinder #	1	2	3	4
Part Name	Cylinder-1	Cylinder-2	Cylinder-3	Cylinder-4
Volumetric Efficiency [%]	135.6	134.6	134.4	135.6
Volumetric Efficiency (m) [%]	103.2	102.4	102.2	103.1
Trapping Ratio	0.994	0.997	0.998	0.995
Burned Residuals Mass (SOC) [%]	1.9	2.1	2.1	1.9
EGR [%]	0.0	0.0	0.0	0.0
F/A Ratio (trapped)	0.068	0.069	0.068	0.068
Lambda, Effective	1.018	1.009	1.011	1.017
IMEP [bar]	17.74	17.78	17.74	17.76
PMEP [bar]	0.08	0.08	0.08	0.08
ISFC [g/kW-h]	216.0	215.9	215.7	216.0
Indicated Efficiency [%]	37.9	37.9	38.0	37.9
Fuel Mass [mg]	53.2	53.3	53.1	53.2
Maximum Pressure [bar]	64.03	64.04	63.96	64.07
CA at Max. Pressure [deg]	19.4	19.4	19.3	19.3
dPmx/DCA [bar/deg]	1.722	1.723	1.719	1.723
Maximum Temperature [K]	2439	2443	2442	2440
Intake Pressure [bar]	1.417	1.417	1.417	1.417
Intake Temperature [K]	309	309	309	309
Exhaust Pressure [bar]	1.081	1.078	1.083	1.088
Exhaust Temperature [K]	1234	1246	1242	1234
Heat.Tr. (frac. of F.E) [%]	16.7	16.8	16.8	16.7
Swirl at TDC	0.000	0.000	0.000	0.000
Swirl at BDC	0.000	0.000	0.000	0.000
NOx in ppm	312.96	229.80	248.52	303.91
Indicated Specific NO2 [g/kW-h]	0.00	0.00	0.00	0.00
Soot Concentration @ STP [g/m^3]	0.00	0.00	0.00	0.00
Indicated Specific Soot [g/kW-h]	0.00	0.00	0.00	0.00
HC in ppm	1.64	1.73	1.69	1.72
Indicated Specific HC [g/kW-h]	0.02	0.02	0.02	0.02
CO in ppm	30.59	49.03	43.29	32.19
Indicated Specific CO [g/kW-h]	0.10	0.16	0.14	0.11
CO2 in ppm	132177.00	133282.00	133067.00	132323.00
Indicated Specific CO2 [g/kW-h]	679.98	681.85	681.32	680.20
Knocking zones				

3200rpm:

Engine and Cylinder

Engine Geometry (Cyl # 1)

Bore [mm]	86.0
Stroke [mm]	86.0
Connecting Rod Length [mm]	145.0
Piston Pin Offset [mm]	0.00
Displacement/Cylinder [liter]	0.500
Total Displacement [liter]	1.998
Number of Cylinders	4
Compression Ratio	9.50
Bore/Stroke	1.000
IVC [CA]	-161
EVO [CA]	177
IVO [CA]	356
EVC [CA]	383

Engine and Cylinder

Engine Performance Predictions (SI)

Brake Power [kW]	94.5
Brake Power [HP]	126.8
Brake Torque [N-m]	282.1
IMEP [bar]	20.66
FMEP [bar]	1.67
PMEP [bar]	-0.43
Air Flow Rate [kg/hr]	345.4
BSAC [g/kW-h]	3654
Fuel Flow Rate [kg/hr]	23.5
BSFC [g/kW-h]	248.6
Volumetric Efficiency [%]	155.4
Volumetric Efficiency (M) [%]	103.7
Trapping Ratio	0.998
A/F Ratio	14.70
Brake Efficiency [%]	33.0

Compressor/Turbine

Compressor/Turbine/Pump/Fan

	compressor-1
Type of Device	Compressor
Speed [RPM]	5920
Pressure Ratio (static)	1.64
Pressure Ratio	1.64
Mass Flow Rate [kg/s]	0.10
Power [kW]	6.6
Efficiency [%]	65.9
Inlet Pressure [bar]	0.99
Outlet Pressure [bar]	1.63
Inlet Temperature [K]	299
Outlet Temperature [K]	367
Map PR Exceeded/Stalled ?	NO
PR less than 1.0 ?	NO
Map RPM Exceeded ?	NO
Pressure Rise [bar]	0.64

Engine and Cylinder

Key Cylinder Predictions

Cylinder #	1	2	3	4
Part Name	Cylinder-1	Cylinder-2	Cylinder-3	Cylinder-4
Volumetric Efficiency [%]	155.5	155.3	155.3	155.5
Volumetric Efficiency (m) [%]	103.7	103.6	103.6	103.8
Trapping Ratio	0.998	0.998	0.998	0.998
Burned Residuals Mass (SOC) [%]	1.9	1.9	1.9	1.9
EGR [%]	0.0	0.0	0.0	0.0
F/A Ratio (trapped)	0.068	0.068	0.068	0.068
Lambda, Effective	1.013	1.017	1.010	1.016
IMEP [bar]	20.67	20.62	20.71	20.63
PMEP [bar]	-0.43	-0.41	-0.42	-0.44
ISFC [g/kW-h]	213.6	213.1	213.7	213.5
Indicated Efficiency [%]	38.3	38.4	38.3	38.4
Fuel Mass [mg]	61.3	61.0	61.4	61.1
Maximum Pressure [bar]	74.78	74.62	74.80	74.75
CA at Max. Pressure [deg]	19.5	19.6	19.6	19.5
dPmx/DCA [bar/deg]	2.011	2.004	2.011	2.006
Maximum Temperature [K]	2490	2487	2492	2488
Intake Pressure [bar]	1.620	1.620	1.620	1.619
Intake Temperature [K]	310	310	310	310
Exhaust Pressure [bar]	1.259	1.248	1.275	1.287
Exhaust Temperature [K]	1338	1341	1346	1335

Heat Tr. (frac. of F.E) [%]	11.9	11.9	11.9	11.9
Swirl at TDC	0.000	0.000	0.000	0.000
Swirl at BDC	0.000	0.000	0.000	0.000
NOx in ppm	392.46	432.12	338.53	423.22
Indicated Specific NO2 [g/kW-h]	0.00	0.00	0.00	0.00
Soot Concentration @ STP [g/m^3]	0.00	0.00	0.00	0.00
Indicated Specific Soot [g/kW-h]	0.00	0.00	0.00	0.00
HC in ppm	1.65	1.74	1.75	1.72
Indicated Specific HC [g/kW-h]	0.02	0.02	0.02	0.02
CO in ppm	109.39	92.78	136.07	95.93
Indicated Specific CO [g/kW-h]	0.35	0.30	0.44	0.31
CO2 in ppm	132700.00	132301.00	133139.00	132395.00
Indicated Specific CO2 [g/kW-h]	674.68	673.37	674.95	674.32
Knocking zones				

4800rpm:

Engine and Cylinder

Engine Geometry (Cyl # 1)

Bore [mm]	86.0
Stroke [mm]	86.0
Connecting Rod Length [mm]	145.0
Piston Pin Offset [mm]	0.00
Displacement/Cylinder [liter]	0.500
Total Displacement [liter]	1.998
Number of Cylinders	4
Compression Ratio	9.50
Bore/Stroke	1.000
IVC [CA]	-161
EVO [CA]	177
IVO [CA]	356
EVC [CA]	383

Engine and Cylinder

Engine Performance Predictions (SI)

Brake Power [kW]	141.0
Brake Power [HP]	189.1
Brake Torque [N-m]	280.6
IMEP [bar]	21.46
FMEP [bar]	2.21
PMEP [bar]	-1.52
Air Flow Rate [kg/hr]	558.8
BSAC [g/kW-h]	3962
Fuel Flow Rate [kg/hr]	38.0
BSFC [g/kW-h]	269.5
Volumetric Efficiency [%]	167.6
Volumetric Efficiency (M) [%]	108.2
Trapping Ratio	0.999
A/F Ratio	14.70
Brake Efficiency [%]	30.4

Compressor/Turbine

Compressor/Turbine/Pump/Fan

	compressor-1
Type of Device	Compressor
Speed [RPM]	8880
Pressure Ratio (static)	1.77
Pressure Ratio	1.75
Mass Flow Rate [kg/s]	0.16
Power [kW]	12.8
Efficiency [%]	63.1
Inlet Pressure [bar]	0.98
Outlet Pressure [bar]	1.74
Inlet Temperature [K]	298
Outlet Temperature [K]	380
Map PR Exceeded/Stalled ?	NO
PR less than 1.0 ?	NO
Map RPM Exceeded ?	NO
Pressure Rise [bar]	0.76

Engine and Cylinder

Key Cylinder Predictions

Cylinder #	1	2	3	4
Part Name	Cylinder-1	Cylinder-2	Cylinder-3	Cylinder-4
Volumetric Efficiency [%]	168.0	167.7	167.4	167.2
Volumetric Efficiency (m) [%]	108.4	108.3	108.0	107.9
Trapping Ratio	0.999	0.999	0.999	0.999
Burned Residuals Mass (SOC) [%]	1.6	1.6	1.7	1.7
EGR [%]	0.0	0.0	0.0	0.0
F/A Ratio (trapped)	0.068	0.068	0.068	0.068
Lambda, Effective	1.015	1.015	1.010	1.016
IMEP [bar]	21.47	21.48	21.53	21.37
PMEP [bar]	-1.55	-1.49	-1.49	-1.54
ISFC [g/kW-h]	221.8	221.2	221.5	221.7
Indicated Efficiency [%]	36.9	37.0	37.0	36.9
Fuel Mass [mg]	66.1	66.0	66.2	65.7
Maximum Pressure [bar]	81.50	81.40	81.45	81.19
CA at Max. Pressure [deg]	19.3	19.5	19.4	19.4
dPmx/DCA [bar/deg]	2.165	2.162	2.165	2.155
Maximum Temperature [K]	2518	2517	2520	2516
Intake Pressure [bar]	1.707	1.707	1.707	1.706
Intake Temperature [K]	314	315	314	314
Exhaust Pressure [bar]	1.555	1.538	1.574	1.592
Exhaust Temperature [K]	1399	1398	1400	1395
Heat.Tr. (frac. of F.E) [%]	10.3	10.3	10.3	10.3
Swirl at TDC	0.000	0.000	0.000	0.000
Swirl at BDC	0.000	0.000	0.000	0.000
NOx in ppm	484.67	491.28	400.81	492.48
Indicated Specific NO2 [g/kW-h]	0.00	0.00	0.00	0.00
Soot Concentration @ STP [g/m^3]	0.00	0.00	0.00	0.00
Indicated Specific Soot [g/kW-h]	0.00	0.00	0.00	0.00
HC in ppm	1.69	1.80	1.69	1.73
Indicated Specific HC [g/kW-h]	0.02	0.02	0.02	0.02
CO in ppm	162.41	158.42	212.93	155.70
Indicated Specific CO [g/kW-h]	0.55	0.53	0.71	0.52
CO2 in ppm	132464.00	132406.00	133048.00	132385.00
Indicated Specific CO2 [g/kW-h]	701.27	699.49	700.24	701.03
Knocking zones				

6000rpm:

Engine and Cylinder

Engine Geometry (Cyl # 1)

Bore [mm]	86.0
Stroke [mm]	86.0
Connecting Rod Length [mm]	145.0
Piston Pin Offset [mm]	0.00
Displacement/Cylinder [liter]	0.500
Total Displacement [liter]	1.998
Number of Cylinders	4
Compression Ratio	9.50
Bore/Stroke	1.000
IVC [CA]	-161
EVO [CA]	177
IVO [CA]	356
EVC [CA]	383

Engine and Cylinder

Engine Performance Predictions (SI)

Brake Power [kW]	163.4
Brake Power [HP]	219.2
Brake Torque [N-m]	260.1
IMEP [bar]	20.96
FMEP [bar]	2.63
PMEP [bar]	-2.41
Air Flow Rate [kg/hr]	708.2
BSAC [g/kW-h]	4333
Fuel Flow Rate [kg/hr]	48.2
BSFC [g/kW-h]	294.6
Volumetric Efficiency [%]	169.9
Volumetric Efficiency (M) [%]	104.4
Trapping Ratio	0.999
A/F Ratio	14.71
Brake Efficiency [%]	27.8

Compressor/Turbine

Compressor/Turbine/Pump/Fan

	compressor-1
Type of Device	Compressor
Speed [RPM]	11100
Pressure Ratio (static)	1.92
Pressure Ratio	1.87
Mass Flow Rate [kg/s]	0.20
Power [kW]	19.7
Efficiency [%]	59.8
Inlet Pressure [bar]	0.96
Outlet Pressure [bar]	1.85
Inlet Temperature [K]	297
Outlet Temperature [K]	396
Map PR Exceeded/Stalled ?	NO
PR less than 1.0 ?	NO
Map RPM Exceeded ?	NO
Pressure Rise [bar]	0.88

Engine and Cylinder

Key Cylinder Predictions

Cylinder #	1	2	3	4
Part Name	Cylinder-1	Cylinder-2	Cylinder-3	Cylinder-4
Volumetric Efficiency [%]	170.0	169.8	170.2	169.6
Volumetric Efficiency (m) [%]	104.4	104.3	104.6	104.2
Trapping Ratio	1.000	0.999	1.000	0.999
Burned Residuals Mass (SOC) [%]	1.2	1.2	1.1	1.1
EGR [%]	0.0	0.0	0.0	0.0
F/A Ratio (trapped)	0.068	0.067	0.068	0.069
Lambda, Effective	1.015	1.025	1.016	1.001
IMEP [bar]	20.94	20.83	21.02	21.05
PMEP [bar]	-2.44	-2.36	-2.38	-2.46
ISFC [g/kW-h]	230.1	228.7	229.4	231.5
Indicated Efficiency [%]	35.6	35.8	35.7	35.4
Fuel Mass [mg]	66.9	66.1	66.9	67.6
Maximum Pressure [bar]	82.56	82.18	82.60	82.60
CA at Max. Pressure [deg]	19.3	19.4	19.5	19.7
dPmx/DCA [bar/deg]	2.191	2.174	2.193	2.201
Maximum Temperature [K]	2531	2523	2531	2540
Intake Pressure [bar]	1.806	1.806	1.806	1.806
Intake Temperature [K]	317	317	317	316
Exhaust Pressure [bar]	1.702	1.686	1.745	1.761
Exhaust Temperature [K]	1444	1433	1441	1456
Heat.Tr. (frac. of F.E) [%]	9.7	9.7	9.7	9.7
Swirl at TDC	0.000	0.000	0.000	0.000
Swirl at BDC	0.000	0.000	0.000	0.000
NOx in ppm	523.27	649.14	537.21	219.11
Indicated Specific NO2 [g/kW-h]	0.00	0.00	0.00	0.00
Soot Concentration @ STP [g/m^3]	0.00	0.00	0.00	0.00
Indicated Specific Soot [g/kW-h]	0.00	0.00	0.00	0.00
HC in ppm	1.69	1.76	1.84	1.83
Indicated Specific HC [g/kW-h]	0.02	0.02	0.03	0.03
CO in ppm	202.20	133.26	196.04	618.75
Indicated Specific CO [g/kW-h]	0.71	0.47	0.68	2.15
CO2 in ppm	132415.00	131217.00	132316.00	133698.00
Indicated Specific CO2 [g/kW-h]	727.54	723.65	725.44	729.59
Knocking zones				

High BMEP Ecotec Engine:
1500 rpm:

Engine and Cylinder

Engine Geometry (Cyl # 1)

Bore [mm]	86.0
Stroke [mm]	86.0
Connecting Rod Length [mm]	145.0
Piston Pin Offset [mm]	0.00
Displacement/Cylinder [liter]	0.500
Total Displacement [liter]	1.998
Number of Cylinders	4
Compression Ratio	9.50
Bore/Stroke	1.000
IVC [CA]	-161
EVO [CA]	177
IVO [CA]	356
EVC [CA]	383

Engine and Cylinder

Engine Performance Predictions (SI)

Brake Power [kW]	61.2
Brake Power [HP]	82.1
Brake Torque [N-m]	389.6
IMEP [bar]	27.58
FMEP [bar]	1.29
PMEP [bar]	0.23
Air Flow Rate [kg/hr]	216.5
BSAC [g/kW-h]	3538
Fuel Flow Rate [kg/hr]	14.7
BSFC [g/kW-h]	240.7
Volumetric Efficiency [%]	207.8
Volumetric Efficiency (M) [%]	104.2
Trapping Ratio	0.991
A/F Ratio	14.70
Brake Efficiency [%]	34.0

Compressor/Turbine

Compressor/Turbine/Pump/Fan

	comp-1	Turbine-1
Type of Device	Compressor	Turbine
Speed [RPM]	89328	89328
Pressure Ratio (static)	2.05	1.41
Pressure Ratio	2.05	1.37
Mass Flow Rate [kg/s]	0.06	0.06
Power [kW]	5.5	4.7
Efficiency [%]	74.9	69.0
Inlet Pressure [bar]	0.99	1.47
Outlet Pressure [bar]	2.03	1.04
Inlet Temperature [K]	300	1112
Outlet Temperature [K]	390	1044
Map PR Exceeded/Stalled ?	YES(1.05286)	NO
PR less than 1.0 ?	NO	NO
Map RPM Exceeded ?	NO	NO
Pressure Rise [bar]	1.04	-0.43

Engine and Cylinder

Key Cylinder Predictions

Cylinder #	1	2	3	4
Part Name	Cylinder-1	Cylinder-2	Cylinder-3	Cylinder-4
Volumetric Efficiency [%]	208.1	207.4	207.5	208.1
Volumetric Efficiency (m) [%]	104.4	104.0	104.1	104.4
Trapping Ratio	0.991	0.992	0.992	0.991
Burned Residuals Mass (SOC) [%]	1.2	1.3	1.3	1.2
EGR [%]	0.0	0.0	0.0	0.0
F/A Ratio (trapped)	0.068	0.069	0.069	0.069
Lambda, Effective	1.020	1.013	1.008	1.017
IMEP [bar]	27.49	27.60	27.69	27.55
PMEP [bar]	0.23	0.23	0.23	0.23
ISFC [g/kW-h]	213.6	213.7	214.0	213.8
Indicated Efficiency [%]	38.3	38.3	38.3	38.3
Fuel Mass [mg]	81.5	81.8	82.2	81.7
Maximum Pressure [bar]	97.47	97.62	97.79	97.54
CA at Max. Pressure [deg]	19.5	19.6	19.6	19.6
dPmx/DCA [bar/deg]	2.698	2.705	2.712	2.702
Maximum Temperature [K]	2444	2448	2451	2446
Intake Pressure [bar]	2.020	2.020	2.020	2.020
Intake Temperature [K]	293	293	293	293
Exhaust Pressure [bar]	1.372	1.367	1.370	1.375
Exhaust Temperature [K]	1246	1255	1259	1248

Heat.Tr. (frac. of F.E) [%]	15.8	15.8	15.8	15.8
Swirl at TDC	0.000	0.000	0.000	0.000
Swirl at BDC	0.000	0.000	0.000	0.000
NOx in ppm	328.36	266.80	218.49	305.51
Indicated Specific NO2 [g/kW-h]	0.00	0.00	0.00	0.00
Soot Concentration @ STP [g/m^3]	0.00	0.00	0.00	0.00
Indicated Specific Soot [g/kW-h]	0.00	0.00	0.00	0.00
HC in ppm	1.72	1.68	1.71	1.72
Indicated Specific HC [g/kW-h]	0.02	0.02	0.02	0.02
CO in ppm	23.16	32.99	44.20	26.57
Indicated Specific CO [g/kW-h]	0.07	0.11	0.14	0.09
CO2 in ppm	131938.00	132877.00	133419.00	132330.00
Indicated Specific CO2 [g/kW-h]	669.70	671.19	672.17	670.34
Knocking zones				

3000 rpm:

Engine and Cylinder

Engine Geometry (Cyl # 1)

Bore [mm]	86.0
Stroke [mm]	86.0
Connecting Rod Length [mm]	145.0
Piston Pin Offset [mm]	0.00
Displacement/Cylinder [liter]	0.500
Total Displacement [liter]	1.998
Number of Cylinders	4
Compression Ratio	9.50
Bore/Stroke	1.000
IVC [CA]	-161
EVO [CA]	177
IVO [CA]	356
EVC [CA]	383

Engine and Cylinder

Engine Performance Predictions (SI)

Brake Power [kW]	132.4
Brake Power [HP]	177.5
Brake Torque [N-m]	421.4
IMEP [bar]	27.90
FMEP [bar]	1.75
PMEP [bar]	-0.92
Air Flow Rate [kg/hr]	438.5
BSAC [g/kW-h]	3312
Fuel Flow Rate [kg/hr]	29.8
BSFC [g/kW-h]	225.4
Volumetric Efficiency [%]	210.4
Volumetric Efficiency (M) [%]	103.5
Trapping Ratio	0.998
A/F Ratio	14.70
Brake Efficiency [%]	36.3

Compressor/Turbine

Compressor/Turbine/Pump/Fan

	comp-1	Turbine-1
Type of Device	Compressor	Turbine
Speed [RPM]	97568	97568
Pressure Ratio (static)	2.23	1.81
Pressure Ratio	2.23	1.69
Mass Flow Rate [kg/s]	0.13	0.13
Power [kW]	12.9	18.7
Efficiency [%]	75.8	81.1
Inlet Pressure [bar]	0.96	1.86
Outlet Pressure [bar]	2.14	1.03
Inlet Temperature [K]	299	1224
Outlet Temperature [K]	399	1097
Map PR Exceeded/Stalled ?	NO	NO
PR less than 1.0 ?	NO	NO
Map RPM Exceeded ?	NO	NO
Pressure Rise [bar]	1.18	-0.83

Engine and Cylinder

Key Cylinder Predictions

Cylinder #	1	2	3	4
Part Name	Cylinder-1	Cylinder-2	Cylinder-3	Cylinder-4
Volumetric Efficiency [%]	210.9	209.8	209.9	210.9
Volumetric Efficiency (m) [%]	103.8	103.2	103.3	103.8
Trapping Ratio	0.998	0.999	0.999	0.998
Burned Residuals Mass (SOC) [%]	2.0	2.1	2.1	2.0
EGR [%]	0.0	0.0	0.0	0.0
F/A Ratio (trapped)	0.068	0.068	0.068	0.068
Lambda, Effective	1.014	1.010	1.008	1.021
IMEP [bar]	27.94	27.90	27.94	27.81
PMEP [bar]	-0.93	-0.91	-0.92	-0.93
ISFC [g/kW-h]	214.2	214.1	214.3	213.8
Indicated Efficiency [%]	38.2	38.3	38.2	38.3
Fuel Mass [mg]	83.1	82.9	83.1	82.5
Maximum Pressure [bar]	101.33	101.11	101.21	101.12
CA at Max. Pressure [deg]	19.6	19.6	19.6	19.5
dPmx/DCA [bar/deg]	2.788	2.785	2.782	2.777
Maximum Temperature [K]	2484	2485	2486	2479
Intake Pressure [bar]	2.095	2.095	2.095	2.094
Intake Temperature [K]	294	294	294	295
Exhaust Pressure [bar]	2.005	1.992	2.002	2.017
Exhaust Temperature [K]	1348	1350	1350	1341

Heat.Tr. (frac. of F.E) [%]	11.5	11.5	11.5	11.5
Swirl at TDC	0.000	0.000	0.000	0.000
Swirl at BDC	0.000	0.000	0.000	0.000
NOx in ppm	380.14	337.02	304.11	456.17
Indicated Specific NO2 [g/kW-h]	0.00	0.00	0.00	0.00
Soot Concentration @ STP [g/m^3]	0.00	0.00	0.00	0.00
Indicated Specific Soot [g/kW-h]	0.00	0.00	0.00	0.00
HC in ppm	1.71	1.69	1.77	1.66
Indicated Specific HC [g/kW-h]	0.02	0.02	0.02	0.02
CO in ppm	82.83	97.03	112.58	60.06
Indicated Specific CO [g/kW-h]	0.27	0.31	0.36	0.20
CO2 in ppm	132702.00	133068.00	133317.00	131838.00
Indicated Specific CO2 [g/kW-h]	676.90	677.08	677.64	675.64
Knocking zones				

4500 rpm:

Engine and Cylinder

Engine Geometry (Cyl # 1)

Bore [mm]	86.0
Stroke [mm]	86.0
Connecting Rod Length [mm]	145.0
Piston Pin Offset [mm]	0.00
Displacement/Cylinder [liter]	0.500
Total Displacement [liter]	1.998
Number of Cylinders	4
Compression Ratio	9.50
Bore/Stroke	1.000
IVC [CA]	-161
EVO [CA]	177
IVO [CA]	356
EVC [CA]	383

Engine and Cylinder

Engine Performance Predictions (SI)

Brake Power [kW]	213.6
Brake Power [HP]	286.5
Brake Torque [N-m]	453.3
IMEP [bar]	30.01
FMEP [bar]	2.29
PMEP [bar]	-2.70
Air Flow Rate [kg/hr]	736.3
BSAC [g/kW-h]	3447
Fuel Flow Rate [kg/hr]	50.2
BSFC [g/kW-h]	235.2
Volumetric Efficiency [%]	235.5
Volumetric Efficiency (M) [%]	101.1
Trapping Ratio	1.000
A/F Ratio	14.65
Brake Efficiency [%]	34.8

Compressor/Turbine

Compressor/Turbine/Pump/Fan

	comp-1	Turbine-1
Type of Device	Compressor	Turbine
Speed [RPM]	139178	139178
Pressure Ratio (static)	4.12	3.22
Pressure Ratio	3.88	2.49
Mass Flow Rate [kg/s]	0.24	0.26
Power [kW]	47.6	59.5
Efficiency [%]	73.6	80.0
Inlet Pressure [bar]	0.81	3.29
Outlet Pressure [bar]	3.35	1.02
Inlet Temperature [K]	295	1223
Outlet Temperature [K]	488	982
Map PR Exceeded/Stalled ?	YES(1.02592)	NO
PR less than 1.0 ?	NO	NO
Map RPM Exceeded ?	NO	NO
Pressure Rise [bar]	2.54	-2.27

Engine and Cylinder

Key Cylinder Predictions

Cylinder #	1	2	3	4
Part Name	Cylinder-1	Cylinder-2	Cylinder-3	Cylinder-4
Volumetric Efficiency [%]	235.9	235.1	235.2	236.1
Volumetric Efficiency (m) [%]	101.2	100.9	100.9	101.3
Trapping Ratio	1.000	1.000	1.000	1.000
Burned Residuals Mass (SOC) [%]	3.4	3.5	3.5	3.4
EGR [%]	0.3	0.3	0.3	0.3
F/A Ratio (trapped)	0.068	0.068	0.068	0.068
Lambda, Effective	1.014	1.009	1.010	1.010
IMEP [bar]	29.98	30.01	29.99	30.05
PMEP [bar]	-2.72	-2.67	-2.67	-2.73
ISFC [g/kW-h]	223.4	223.5	223.3	223.7
Indicated Efficiency [%]	36.7	36.7	36.7	36.6
Fuel Mass [mg]	92.9	93.1	92.9	93.3
Maximum Pressure [bar]	116.75	116.64	116.62	116.92
CA at Max. Pressure [deg]	19.4	19.3	19.3	19.4
dPmx/DCA [bar/deg]	3.106	3.103	3.102	3.113
Maximum Temperature [K]	2502	2505	2504	2505
Intake Pressure [bar]	2.502	2.502	2.502	2.501
Intake Temperature [K]	307	307	307	307
Exhaust Pressure [bar]	3.519	3.496	3.508	3.535
Exhaust Temperature [K]	1414	1420	1418	1417
Heat.Tr. (frac. of F.E) [%]	10.1	10.1	10.1	10.1
Swirl at TDC	0.000	0.000	0.000	0.000
Swirl at BDC	0.000	0.000	0.000	0.000
NOx in ppm	428.73	349.92	380.75	383.54
Indicated Specific NO2 [g/kW-h]	0.00	0.00	0.00	0.00
Soot Concentration @ STP [g/m^3]	0.00	0.00	0.00	0.00
Indicated Specific Soot [g/kW-h]	0.00	0.00	0.00	0.00
HC in ppm	1.63	1.64	1.81	1.79
Indicated Specific HC [g/kW-h]	0.02	0.02	0.02	0.02
CO in ppm	113.42	150.81	134.04	135.25
Indicated Specific CO [g/kW-h]	0.38	0.51	0.45	0.46
CO2 in ppm	132677.00	133242.00	133038.00	133029.00
Indicated Specific CO2 [g/kW-h]	706.93	706.94	706.61	707.84
Knocking zones				

6000 rpm:

Engine and Cylinder

Engine Geometry (Cyl # 1)

Bore [mm]	86.0
Stroke [mm]	86.0
Connecting Rod Length [mm]	145.0
Piston Pin Offset [mm]	0.00
Displacement/Cylinder [liter]	0.500
Total Displacement [liter]	1.998
Number of Cylinders	4
Compression Ratio	9.50
Bore/Stroke	1.000
IVC [CA]	-161
EVO [CA]	177
IVO [CA]	356
EVC [CA]	383

Engine and Cylinder

Engine Performance Predictions (SI)

Brake Power [kW]	219.9
Brake Power [HP]	294.9
Brake Torque [N-m]	350.0
IMEP [bar]	24.42
FMEP [bar]	2.73
PMEP [bar]	-3.52
Air Flow Rate [kg/hr]	830.8
BSAC [g/kW-h]	3778
Fuel Flow Rate [kg/hr]	66.5
BSFC [g/kW-h]	302.5
Volumetric Efficiency [%]	199.3
Volumetric Efficiency (M) [%]	92.4
Trapping Ratio	1.000
A/F Ratio	12.49
Brake Efficiency [%]	27.1

Compressor/Turbine

Compressor/Turbine/Pump/Fan

	comp-1	Turbine-1
Type of Device	Compressor	Turbine
Speed [RPM]	150712	150712
Pressure Ratio (static)	4.82	3.55
Pressure Ratio	4.44	2.62
Mass Flow Rate [kg/s]	0.26	0.28
Power [kW]	60.6	70.3
Efficiency [%]	70.1	79.9
Inlet Pressure [bar]	0.78	3.62
Outlet Pressure [bar]	3.75	1.02
Inlet Temperature [K]	293	1223
Outlet Temperature [K]	522	959
Map PR Exceeded/Stalled ?	YES(1.01609)	NO
PR less than 1.0 ?	NO	NO
Map RPM Exceeded ?	NO	NO
Pressure Rise [bar]	2.97	-2.60

Engine and Cylinder

Key Cylinder Predictions

Cylinder #	1	2	3	4
Part Name	Cylinder-1	Cylinder-2	Cylinder-3	Cylinder-4
Volumetric Efficiency [%]	199.4	199.7	199.6	198.6
Volumetric Efficiency (m) [%]	92.5	92.6	92.5	92.1
Trapping Ratio	1.000	1.000	1.000	1.000
Burned Residuals Mass (SOC) [%]	4.6	4.6	4.5	4.6
EGR [%]	0.1	0.1	0.1	0.1
F/A Ratio (trapped)	0.080	0.080	0.080	0.081
Lambda, Effective	0.850	0.847	0.851	0.836
IMEP [bar]	24.40	24.50	24.51	24.25
PMEP [bar]	-3.57	-3.49	-3.49	-3.55
ISFC [g/kW-h]	272.1	271.8	270.6	276.1
Indicated Efficiency [%]	30.1	30.1	30.3	29.7
Fuel Mass [mg]	92.1	92.4	92.0	92.9
Maximum Pressure [bar]	102.73	102.82	102.79	102.26
CA at Max. Pressure [deg]	19.2	19.6	19.1	19.1
dPmx/DCA [bar/deg]	2.734	2.738	2.737	2.726
Maximum Temperature [K]	2468	2466	2470	2456
Intake Pressure [bar]	2.304	2.304	2.304	2.301
Intake Temperature [K]	318	317	317	318
Exhaust Pressure [bar]	3.909	3.885	3.894	3.919
Exhaust Temperature [K]	1371	1369	1371	1363

Heat.Tr. (frac. of F.E) [%]	8.1	8.0	8.1	7.9
Swirl at TDC	0.000	0.000	0.000	0.000
Swirl at BDC	0.000	0.000	0.000	0.000
NOx in ppm	0.22	0.21	0.23	0.17
Indicated Specific NO2 [g/kW-h]	0.00	0.00	0.00	0.00
Soot Concentration @ STP [g/m^3]	0.00	0.00	0.00	0.00
Indicated Specific Soot [g/kW-h]	0.00	0.00	0.00	0.00
HC in ppm	2.05	1.82	1.83	2.08
Indicated Specific HC [g/kW-h]	0.03	0.03	0.03	0.03
CO in ppm	43799.60	44445.80	43316.10	47516.10
Indicated Specific CO [g/kW-h]	160.71	162.67	158.29	175.29
CO2 in ppm	105667.00	105265.00	105971.00	103358.00
Indicated Specific CO2 [g/kW-h]	609.17	605.34	608.47	599.08
Knocking zones				

Low BMEP Ecotec Engine:
1200 rpm:

Engine and Cylinder

Engine Geometry (Cyl # 1)

Bore [mm]	86.0
Stroke [mm]	86.0
Connecting Rod Length [mm]	145.0
Piston Pin Offset [mm]	0.00
Displacement/Cylinder [liter]	0.500
Total Displacement [liter]	1.998
Number of Cylinders	4
Compression Ratio	9.50
Bore/Stroke	1.000
IVC [CA]	-161
EVO [CA]	177
IVO [CA]	356
EVC [CA]	383

Engine and Cylinder

Engine Performance Predictions (SI)

Brake Power [kW]	28.4
Brake Power [HP]	38.1
Brake Torque [N-m]	226.1
IMEP [bar]	16.13
FMEP [bar]	1.01
PMEP [bar]	0.01
Air Flow Rate [kg/hr]	104.7
BSAC [g/kW-h]	3684
Fuel Flow Rate [kg/hr]	7.1
BSFC [g/kW-h]	250.6
Volumetric Efficiency [%]	125.6
Volumetric Efficiency (M) [%]	99.8
Trapping Ratio	0.995
A/F Ratio	14.70
Brake Efficiency [%]	32.7

Compressor/Turbine

Compressor/Turbine/Pump/Fan

	comp-1	Turbine-1
Type of Device	Compressor	Turbine
Speed [RPM]	47299	47299
Pressure Ratio (static)	1.26	1.19
Pressure Ratio	1.26	1.18
Mass Flow Rate [kg/s]	0.03	0.03
Power [kW]	0.9	1.1
Efficiency [%]	66.5	68.1
Inlet Pressure [bar]	1.00	1.21
Outlet Pressure [bar]	1.26	1.02
Inlet Temperature [K]	300	1011
Outlet Temperature [K]	331	976
Map PR Exceeded/Stalled ?	YES(1.05973)	NO
PR less than 1.0 ?	NO	YES(-0.408908E-02)
Map RPM Exceeded ?	NO	NO
Pressure Rise [bar]	0.26	-0.19

Engine and Cylinder

Key Cylinder Predictions

Cylinder #	1	2	3	4
Part Name	Cylinder-1	Cylinder-2	Cylinder-3	Cylinder-4
Volumetric Efficiency [%]	126.2	125.0	124.9	126.2
Volumetric Efficiency (m) [%]	100.3	99.3	99.2	100.3
Trapping Ratio	0.993	0.996	0.996	0.994
Burned Residuals Mass (SOC) [%]	2.1	2.3	2.4	2.1
EGR [%]	0.0	0.0	0.0	0.0
F/A Ratio (trapped)	0.068	0.069	0.068	0.069
Lambda, Effective	1.017	1.010	1.023	1.007
IMEP [bar]	16.16	16.12	15.96	16.27
PMEP [bar]	0.01	0.01	0.01	0.00
ISFC [g/kW-h]	221.3	220.9	220.0	221.8
Indicated Efficiency [%]	37.0	37.1	37.2	36.9
Fuel Mass [mg]	49.6	49.4	48.7	50.1
Maximum Pressure [bar]	58.84	58.68	58.39	59.03
CA at Max. Pressure [deg]	19.3	19.3	19.4	19.4
dPmx/DCA [bar/deg]	1.606	1.600	1.587	1.615
Maximum Temperature [K]	2400	2402	2393	2406
Intake Pressure [bar]	1.257	1.257	1.257	1.257
Intake Temperature [K]	291	291	291	291
Exhaust Pressure [bar]	1.115	1.113	1.113	1.116
Exhaust Temperature [K]	1206	1216	1205	1216
Heat.Tr. (frac. of F.E) [%]	19.4	19.5	19.5	19.4
Swirl at TDC	0.000	0.000	0.000	0.000
Swirl at BDC	0.000	0.000	0.000	0.000
NOx in ppm	247.13	194.29	291.63	164.22
Indicated Specific NO2 [g/kW-h]	0.00	0.00	0.00	0.00
Soot Concentration @ STP [g/m^3]	0.00	0.00	0.00	0.00
Indicated Specific Soot [g/kW-h]	0.00	0.00	0.00	0.00
HC in ppm	1.70	1.66	1.62	1.71
Indicated Specific HC [g/kW-h]	0.02	0.02	0.02	0.02
CO in ppm	18.43	23.58	15.62	27.86
Indicated Specific CO [g/kW-h]	0.06	0.08	0.05	0.09
CO2 in ppm	132375.00	133161.00	131583.00	133522.00
Indicated Specific CO2 [g/kW-h]	695.51	696.73	694.06	697.61
Knocking zones				

3200 rpm:

Engine and Cylinder

Engine Geometry (Cyl # 1)

Bore [mm]	86.0
Stroke [mm]	86.0
Connecting Rod Length [mm]	145.0
Piston Pin Offset [mm]	0.00
Displacement/Cylinder [liter]	0.500
Total Displacement [liter]	1.998
Number of Cylinders	4
Compression Ratio	9.50
Bore/Stroke	1.000
IVC [CA]	-161
EVO [CA]	177
IVO [CA]	356
EVC [CA]	383

Engine and Cylinder

Engine Performance Predictions (SI)

Brake Power [kW]	94.6
Brake Power [HP]	126.9
Brake Torque [N-m]	282.4
IMEP [bar]	19.26
FMEP [bar]	1.65
PMEP [bar]	-0.85
Air Flow Rate [kg/hr]	327.8
BSAC [g/kW-h]	3464
Fuel Flow Rate [kg/hr]	22.3
BSFC [g/kW-h]	235.7
Volumetric Efficiency [%]	147.4
Volumetric Efficiency (M) [%]	101.0
Trapping Ratio	1.000
A/F Ratio	14.70
Brake Efficiency [%]	34.8

Compressor/Turbine

Compressor/Turbine/Pump/Fan

	comp-1	Turbine-1
Type of Device	Compressor	Turbine
Speed [RPM]	69198	69198
Pressure Ratio (static)	1.54	1.47
Pressure Ratio	1.55	1.42
Mass Flow Rate [kg/s]	0.09	0.10
Power [kW]	5.1	8.7
Efficiency [%]	72.6	76.8
Inlet Pressure [bar]	0.98	1.51
Outlet Pressure [bar]	1.51	1.02
Inlet Temperature [K]	300	1217
Outlet Temperature [K]	354	1137
Map PR Exceeded/Stalled ?	NO	NO
PR less than 1.0 ?	NO	NO
Map RPM Exceeded ?	NO	NO
Pressure Rise [bar]	0.53	-0.49

Engine and Cylinder

Key Cylinder Predictions

Cylinder #	1	2	3	4
Part Name	Cylinder-1	Cylinder-2	Cylinder-3	Cylinder-4
Volumetric Efficiency [%]	148.1	146.9	146.8	148.0
Volumetric Efficiency (m) [%]	101.5	100.7	100.6	101.5
Trapping Ratio	0.999	1.000	1.000	0.999
Burned Residuals Mass (SOC) [%]	2.4	2.7	2.7	2.4
EGR [%]	0.0	0.0	0.0	0.0
F/A Ratio (trapped)	0.068	0.068	0.068	0.068
Lambda, Effective	1.018	1.010	1.008	1.019
IMEP [bar]	19.28	19.25	19.27	19.26
PMEP [bar]	-0.86	-0.84	-0.85	-0.86
ISFC [g/kW-h]	217.0	217.3	217.6	217.0
Indicated Efficiency [%]	37.7	37.7	37.6	37.7
Fuel Mass [mg]	58.1	58.0	58.2	58.0
Maximum Pressure [bar]	70.74	70.54	70.58	70.73
CA at Max. Pressure [deg]	19.7	19.7	19.6	19.5
dPmx/DCA [bar/deg]	1.927	1.926	1.919	1.934
Maximum Temperature [K]	2467	2470	2471	2466
Intake Pressure [bar]	1.477	1.477	1.477	1.476
Intake Temperature [K]	290	290	290	290
Exhaust Pressure [bar]	1.594	1.585	1.592	1.603
Exhaust Temperature [K]	1344	1348	1348	1342

Heat.Tr. (frac. of F.E) [%]	11.9	12.0	12.0	11.9
Swirl at TDC	0.000	0.000	0.000	0.000
Swirl at BDC	0.000	0.000	0.000	0.000
NOx in ppm	419.00	326.18	281.85	429.06
Indicated Specific NO2 [g/kW-h]	0.00	0.00	0.00	0.00
Soot Concentration @ STP [g/m^3]	0.00	0.00	0.00	0.00
Indicated Specific Soot [g/kW-h]	0.00	0.00	0.00	0.00
HC in ppm	1.70	1.66	1.77	1.67
Indicated Specific HC [g/kW-h]	0.02	0.02	0.02	0.02
CO in ppm	72.92	106.13	129.46	69.74
Indicated Specific CO [g/kW-h]	0.24	0.35	0.43	0.23
CO2 in ppm	132150.00	133073.00	133403.00	132024.00
Indicated Specific CO2 [g/kW-h]	686.56	687.76	688.45	686.58
Knocking zones				

5200 rpm:

Engine and Cylinder

Engine Geometry (Cyl # 1)

Bore [mm]	86.0
Stroke [mm]	86.0
Connecting Rod Length [mm]	145.0
Piston Pin Offset [mm]	0.00
Displacement/Cylinder [liter]	0.500
Total Displacement [liter]	1.998
Number of Cylinders	4
Compression Ratio	9.50
Bore/Stroke	1.000
IVC [CA]	-161
EVO [CA]	177
IVO [CA]	356
EVC [CA]	383

Engine and Cylinder

Engine Performance Predictions (SI)

Brake Power [kW]	149.4
Brake Power [HP]	200.4
Brake Torque [N-m]	274.4
IMEP [bar]	18.77
FMEP [bar]	2.31
PMEP [bar]	-2.16
Air Flow Rate [kg/hr]	548.7
BSAC [g/kW-h]	3672
Fuel Flow Rate [kg/hr]	37.3
BSFC [g/kW-h]	249.8
Volumetric Efficiency [%]	151.9
Volumetric Efficiency (M) [%]	96.1
Trapping Ratio	1.000
A/F Ratio	14.70
Brake Efficiency [%]	32.8

Compressor/Turbine

Compressor/Turbine/Pump/Fan

	comp-1	Turbine-1
Type of Device	Compressor	Turbine
Speed [RPM]	111235	111235
Pressure Ratio (static)	2.73	2.33
Pressure Ratio	2.69	2.04
Mass Flow Rate [kg/s]	0.18	0.19
Power [kW]	22.6	34.2
Efficiency [%]	76.8	79.8
Inlet Pressure [bar]	0.91	2.36
Outlet Pressure [bar]	2.47	1.01
Inlet Temperature [K]	298	1223
Outlet Temperature [K]	424	1046
Map PR Exceeded/Stalled ?	YES(1.00801)	NO
PR less than 1.0 ?	NO	NO
Map RPM Exceeded ?	NO	NO
Pressure Rise [bar]	1.57	-1.35

Engine and Cylinder

Key Cylinder Predictions

Cylinder #	1	2	3	4
Part Name	Cylinder-1	Cylinder-2	Cylinder-3	Cylinder-4
Volumetric Efficiency [%]	151.9	152.0	152.1	151.5
Volumetric Efficiency (m) [%]	96.1	96.2	96.3	95.9
Trapping Ratio	1.000	1.000	1.000	1.000
Burned Residuals Mass (SOC) [%]	3.8	3.8	3.7	3.8
EGR [%]	0.0	0.0	0.0	0.0
F/A Ratio (trapped)	0.068	0.068	0.068	0.068
Lambda, Effective	1.013	1.011	1.017	1.015
IMEP [bar]	18.76	18.85	18.78	18.69
PMEP [bar]	-2.18	-2.15	-2.14	-2.18
ISFC [g/kW-h]	230.0	229.7	229.1	229.9
Indicated Efficiency [%]	35.6	35.7	35.7	35.6
Fuel Mass [mg]	59.9	60.1	59.7	59.6
Maximum Pressure [bar]	74.61	74.73	74.60	74.41
CA at Max. Pressure [deg]	19.5	19.3	19.3	19.5
dPmx/DCA [bar/deg]	1.966	1.970	1.964	1.960
Maximum Temperature [K]	2488	2490	2486	2487
Intake Pressure [bar]	1.625	1.625	1.625	1.624
Intake Temperature [K]	303	303	303	303
Exhaust Pressure [bar]	2.547	2.536	2.542	2.555
Exhaust Temperature [K]	1429	1428	1421	1428
Heat.Tr. (frac. of F.E) [%]	10.4	10.4	10.4	10.4
Swirl at TDC	0.000	0.000	0.000	0.000
Swirl at BDC	0.000	0.000	0.000	0.000
NOx in ppm	419.48	383.77	471.75	439.78
Indicated Specific NO2 [g/kW-h]	0.00	0.00	0.00	0.00
Soot Concentration @ STP [g/m^3]	0.00	0.00	0.00	0.00
Indicated Specific Soot [g/kW-h]	0.00	0.00	0.00	0.00
HC in ppm	1.67	1.70	1.70	1.77
Indicated Specific HC [g/kW-h]	0.02	0.02	0.02	0.02
CO in ppm	139.80	161.53	115.75	129.86
Indicated Specific CO [g/kW-h]	0.49	0.56	0.40	0.45
CO2 in ppm	132703.00	132984.00	132230.00	132528.00
Indicated Specific CO2 [g/kW-h]	727.63	726.55	725.12	727.58
Knocking zones				

6000 rpm:

Engine and Cylinder

Engine Geometry (Cyl # 1)

Bore [mm]	86.0
Stroke [mm]	86.0
Connecting Rod Length [mm]	145.0
Piston Pin Offset [mm]	0.00
Displacement/Cylinder [liter]	0.500
Total Displacement [liter]	1.998
Number of Cylinders	4
Compression Ratio	9.50
Bore/Stroke	1.000
IVC [CA]	-161
EVO [CA]	177
IVO [CA]	356
EVC [CA]	383

Engine and Cylinder

Engine Performance Predictions (SI)

Brake Power [kW]	159.9
Brake Power [HP]	214.5
Brake Torque [N-m]	254.5
IMEP [bar]	17.82
FMEP [bar]	2.58
PMEP [bar]	-2.69
Air Flow Rate [kg/hr]	619.7
BSAC [g/kW-h]	3875
Fuel Flow Rate [kg/hr]	42.2
BSFC [g/kW-h]	263.7
Volumetric Efficiency [%]	148.7
Volumetric Efficiency (M) [%]	90.4
Trapping Ratio	1.000
A/F Ratio	14.70
Brake Efficiency [%]	31.1

Compressor/Turbine

Compressor/Turbine/Pump/Fan

	comp-1	Turbine-1
Type of Device	Compressor	Turbine
Speed [RPM]	124125	124125
Pressure Ratio (static)	3.32	2.72
Pressure Ratio	3.21	2.25
Mass Flow Rate [kg/s]	0.21	0.22
Power [kW]	32.7	45.6
Efficiency [%]	76.2	79.8
Inlet Pressure [bar]	0.87	2.75
Outlet Pressure [bar]	2.87	1.01
Inlet Temperature [K]	297	1223
Outlet Temperature [K]	452	1015
Map PR Exceeded/Stalled ?	YES(1.00492)	NO
PR less than 1.0 ?	NO	NO
Map RPM Exceeded ?	NO	NO
Pressure Rise [bar]	2.01	-1.74

Engine and Cylinder

Key Cylinder Predictions

Cylinder #	1	2	3	4
Part Name	Cylinder-1	Cylinder-2	Cylinder-3	Cylinder-4
Volumetric Efficiency [%]	148.8	148.9	149.0	148.0
Volumetric Efficiency (m) [%]	90.4	90.5	90.5	90.0
Trapping Ratio	1.000	1.000	1.000	1.000
Burned Residuals Mass (SOC) [%]	4.5	4.5	4.5	4.5
EGR [%]	0.0	0.0	0.0	0.0
F/A Ratio (trapped)	0.068	0.068	0.068	0.069
Lambda, Effective	1.017	1.014	1.020	1.004
IMEP [bar]	17.77	17.88	17.81	17.81
PMEP [bar]	-2.71	-2.66	-2.65	-2.72
ISFC [g/kW-h]	236.9	236.4	236.0	238.1
Indicated Efficiency [%]	34.6	34.6	34.7	34.4
Fuel Mass [mg]	58.4	58.7	58.3	58.8
Maximum Pressure [bar]	73.90	74.02	73.90	73.76
CA at Max. Pressure [deg]	19.1	19.1	19.2	19.2
dPmx/DCA [bar/deg]	1.912	1.917	1.912	1.914
Maximum Temperature [K]	2489	2491	2488	2497
Intake Pressure [bar]	1.702	1.702	1.702	1.700
Intake Temperature [K]	313	313	313	313
Exhaust Pressure [bar]	2.965	2.949	2.954	2.974
Exhaust Temperature [K]	1449	1451	1445	1462
Heat.Tr. (frac. of F.E) [%]	10.3	10.2	10.2	10.3
Swirl at TDC	0.000	0.000	0.000	0.000
Swirl at BDC	0.000	0.000	0.000	0.000
NOx in ppm	487.95	444.80	513.11	274.85
Indicated Specific NO2 [g/kW-h]	0.00	0.00	0.00	0.00
Soot Concentration @ STP [g/m^3]	0.00	0.00	0.00	0.00
Indicated Specific Soot [g/kW-h]	0.00	0.00	0.00	0.00
HC in ppm	1.62	1.75	1.81	1.76
Indicated Specific HC [g/kW-h]	0.02	0.02	0.03	0.02
CO in ppm	126.47	148.31	115.32	287.29
Indicated Specific CO [g/kW-h]	0.46	0.53	0.42	1.03
CO2 in ppm	132197.00	132590.00	131937.00	133610.00
Indicated Specific CO2 [g/kW-h]	749.75	748.02	746.87	752.49
Knocking zones				

LIST OF ABBREVIATIONS

AFR	–	Air Fuel Ratio
BMEP	–	Brake Mean Effective Pressure
BSFC	–	Brake Specific Fuel Consumption
CAFE	–	Corporate Average Fuel Economy
CVT	–	Continuously Variable Transmission
EGR	–	Exhaust Gas Recirculation
FMEP	–	Friction Mean Effective Pressure
GM	–	General Motors
GT-ISE	–	Gamma Technologies-Integrated Simulation Environment
ICE	–	Internal Combustion Engine
IMEP	–	Indicated Mean Effective Pressure
ISFC	–	Indicated Specific Fuel Consumption
NEDC	–	New European Drive Cycle
NHTSA	–	National Highway Traffic Safety Administration
OEM	–	Original Equipment Manufacturer
PID	–	Proportional-Integral-Derivative
PMEP	–	Pumping Mean Effective Pressure
ST	–	SuperTurbo™
TDC	–	Top Dead Center
US EPA	–	United States Environmental Protection Agency
VVT	–	Variable Valve Timing
WOT	–	Wide Open Throttle