A report on

Design and Simulation of a turbo charged system for a FSAE car

Submitted in partial fulfillment for the
award of the degree of
Bachelor of Technology in Mechanical Engineering
By

Mr. Jay Saini
(Reg No. M1610008, Seat No. BTM708)
Mr. Allister Sequeira
(Reg No. M1610010, Seat No. BTM710)

Supervisor:
Dr. Santosh B Rane
Associate Professor,
Mechanical Engineering Department,
Sardar Patel College of Engineering

(Mechanical Engineering Department)
Bharatiya Vidya Bhavan's
SARDAR PATEL COLLEGE OF ENGINEERING
(Government Aided Autonomous Institute)
MUNSHI NAGAR, ANDHERI (W),
MUMBAI, INDIA.
Year: 2019-2020

Design and Simulation of a turbo charged system for a FSAE car

by

Jay Saini & Allister Sequeira

Submitted in partial fulfilment for the
award of the degree of
Bachelor of Technology in Mechanical Engineering

Abstract

The Formula Student Car is designed by keeping various performance factors in mind, and engine output power being one of them is the most widely recognized. New boundaries are being constantly discovered to increase the output power of the engine. In the formula student world, there is a constant urge of being the best in the pack which encourages teams to develop and modify the engine system of the racecar for maximum power extraction. Considering all the new developed methods, all come out to be heavy on the pocket and have more complex components involved.

Thus sticking to the traditional forced induction system is what we vouch for and try to introduce in our FSAE racecar. This report explains the criteria for choosing forced induction as the preferred choice for an FSAE racecar and also the design considerations required. The engine modifications required to incorporate into the system and make it reliable are explained. Also, this report suggests optimal engine system geometry by doing flow simulation for the same. An engine model is made to analyze the power output and dynamic operating characteristics of the engine which include the Air-Fuel ratio (AFR), Coolant temperatures and engine temperature.

The report commences with selecting an appropriate type of turbo charger suited for the engine, followed by the design parameters of the same. On finalizing the type, a desired spec turbo is selected for the use and incorporated in the model. Changes in the engine system layout are done accordingly in terms of the intake and exhaust system of the racecar. Along with this, an optimum geometry is finalized by the CFD analysis of the whole engine model. Lastly, showing the results which are obtained for justifying our design. Thus, this report studies all possible ways of engine performance advancement and narrows down to the selection of a turbo charged system, along with the calculations and simulations for optimizing the same.

Acknowledgement

Even though we have taken great efforts in this project, our success would not have been possible without the kind support and help of many individuals and organizations. We would like to extend our gratitude to all of them.

We are highly indebted to Dr. Santosh Rane for his guidance and constant supervision while completing this project. Also, we appreciate the help offered by our Principal; Dr. P.H. Sawant, in facilitating space and other facilities in our college. We would like to thank Dr. Nilesh Raykar (HOD, Mechanical Engineering) and all other teaching and supporting staff of Mechanical Engineering Department, SPCE for their kind co-operation and encouragement.

We also appreciate the guidance given by all concerned faculty for helping out in the progress of the project and designing of specific components.

Table of Contents

List of Tables and Figures

1 Introduction

Forced induction is a method used since the late 19^{th} century where more air is been forced inside the combustion chamber to improve the volumetric efficiency of the engine and also increase the power output from the vehicle. Since then, various advanced techniques have been developed to increase the engine power but still nowadays forced induction is the most reliable and preferred choice of all automotive manufactures for engine development.

1.1 Problem Statement

"To design and simulate a turbo charged system for an FSAE car" which involves engine modeling and simulation for the desired results. These results will be compared to the desired ones and a final iteration of geometry along with the turbo charger is finalized. In an FSAE car, there are various competition enforced constraints which don't allow maximum flexibility in the engine design and also the air restrictor vouches for the need of more power during dynamic running. Along with these constraints, financial aspect plays an important role in the racecar development. Thus keeping these points in mind, we decide to use a forced induction engine for having an upper hand with peak performance delivered.

1.2 FSAE

Formula SAE is a student design competition that was started in 1978 by the Society of Automotive Engineers. The completion focuses on the design of a small, formula-style race car, which is evaluated for its potential as a production item. Each student team must design, fabricate, and test a race car, based on a set of rules (see 'Appendix 1: Applicable 2019 FSAE Rules' to view the rules that apply to this project). The vehicle is then tested by several judges in various categories, in order for its quality to be determined. The categories include design, cost & manufacturing analysis, presentation, acceleration, skid-pad performance, autocross performance, fuel economy, and endurance.

1.3 Forced Induction

This involves sending in compressed air into the intake manifold. Thus the compressor is driven by two most widely known methods to introduce this air boost. The two methods are by using Turbochargers and Superchargers. Both have their own pros and cons, here we'll be selecting turbochargers as our choice of forced induction that will be backed by the study explained further in the report

1.4 Turbochargers

These consist of a turbine-compressor pair which helps in providing turbo boost. The turbine which will drive the compressor is driven by exhaust gases produced during the combustion of the engine. Turbo chargers are usually accounted with a turbo lag term which refers to the delayed power response in the dynamic engine operating conditions. This was the case with earlier developed turbocharger which comes under the section of a single turbo setup. More research and development in the field of turbochargers has been carried out in the 20th century and now we are provided with various types of turbo chargers. The current designs eliminate most of the issues faced by traditional single turbo. We'll be learning each one in detail and selecting the best type for our FSAE car

2 Content and Literature Review

2.1 Internal Combustion Engines

An internal combustion engine is a piece of machinery that converts chemical energy into mechanical energy via a combustion process. Fuel is burned in a sealed chamber and the temperatures and pressures from the chemical reaction force a piston downwards in a linear motion, which is converted to rotational motion via a crankshaft. The produced power is then transmitted to the wheels of the vehicle via the drivetrain. This conversion of air and fuel into a radial force is a simple process, which involves complex variables and methods.

2.1.1 Basic Components

Despite the variety of available internal combustion engines, the one most commonly used in car and motorcycle applications is the 4 stroke, single-cylinder -or- inline 4-cylinder engine. This engine employs 4 cylinders, arranged in a row. The largest assemblies in the engine are the cylinder head and block. These two separate assemblies contain many of the components required for power to be produced.

The Cylinder Head:

The cylinder head contains the camshafts, the valves, and all other associated hardware, such as springs and retainers. In order to maximize performance, designing the shape and size of the inlets and outlets of the head is a critical process. The selection of the camshaft to accompany the properties of these inlets and outlets is also important.

Nowadays, most cylinder heads contain camshafts that are built into the head. Engines with such a configuration are referred to as overhead cam engines. This design has historically been higher revving and higher flowing than the older, cam-in-block, “overhead valve (OHV)” engines. The KTM DUKE 390, which is the engine used in the project, is a dual overhead cam (DOHC) engine. This engine configuration is optimal for the high RPM, high flowing requirements of a motorcycle engine.

The Engine Block:

All of the thermodynamic work is performed in the engine block. The engine block is the assembly that contains the pistons, the connecting rods, the crankshaft, and all other associated bearings and hardware. The piston fits inside the cylinder walls and is connected to the crankshaft by the connecting rod. Combustion occurs on the face of the piston and the increased pressure forces it to linearly push down on the connecting rod. The connecting rod then transfers the linear motion into the crankshaft which then converts that energy into rotational motion.

The Piston:

The piston is the component that attaches to the connecting rod. This cylindrically shaped object is typically made of an aluminum alloy, which often contains elements such as copper, magnesium, and silicone, to name a few. Pistons can be cast or forged. The amount of silicon in a piston determines if it is termed hypereutectic, eutectic, or hypoeutectic. Most performance vehicles use hypereutectic (containing at least 16-18% silicon) as this results in a lower rate of thermal expansion. The necessity to control the thermal expansion originates from the heat ranges that the piston is exposed to. The vehicle needs to be able to start when temperatures are below 0oF and it also needs to be able to withstand very high combustion temperatures. The most common type of piston is the eutectic piston, which contains about 12.5% silicon. A forged piston is typically stronger than a cast piston, as well as being more ductile. With this being said, forged pistons are more capable of withstanding detonation and they can generally be used in higher horsepower applications. The equation used to find the maximum force that a piston experiences is the one seen below in 'Eq. 1'

$$\textit{Max force on a piston} = (\textit{Max Combustion Pressure} - \textit{Crankcase Pressure}) * \left(\frac{Piston\ Diameter}{4}\right)^2 * \pi \qquad [Eq.1]$$

The Connecting Rod:

The forces from the pressures due to combustion are transmitted to the crankshaft from the piston by the connecting rod. The connecting rod is typically made of a stronger material, since weaker materials such as aluminum would most likely fail. Forged connecting rods are recommended for forced induction applications as they can take more stresses than other, more basic types. The connecting rod is a fairly simple component that connects the piston on the "small end" by a wristpin and also connects to the crankshaft on the "big end" by the use of a cap. Oiled journal bearings are used in between the crankshaft and the rod in order to minimize friction. Compromising the proper functionality of these bearing usually results in complete engine failure.

The Crankshaft:

The crankshaft transmits the linear motion from the piston into the rotational motion required to eventually rotate the wheels of the vehicle. The crankshaft mounts to the block, from below, by a set of caps. Journal bearings are used here as well, in order to reduce frictional losses. The camshafts, which control the opening and closing of the valves, as well as other critical accessories, such as the oil pump, are all indirectly connected to the crankshaft through the timing belt or timing chain.

2.1.2 Theory of Operation

In a dual overhead cam, single-cylinder engine, which employs the Otto cycle (typical gasoline cycle), operation is fairly straightforward. A charge of air enters the cylinder through the open intake valve. The intake valve opens due to the displacement caused by the lobe on the camshaft. The charge enters the cylinder due to a combination of the vacuum created by the moving piston, as well as the higher pressure (boost) associated with the presence of a forced induction system. In addition, to a lesser extent, the low pressure behind the exhaust leaving through the exhaust valve during valve overlap can also increase the amount of charge flowing into the cylinder.

After the air/fuel mixture enters the engine, the piston continues to lower until it has reached bottom dead center (BDC). The intake valve then begins to close as the piston rises in the cylinder. This is called the compression stroke. The air/fuel mixture continues to increase in pressure until the position has been reached, in which the spark plug is fired. This ignition point is decided upon by the ECU and is based on multiple factors. At this point, the air/fuel mixture begins to combust, which produces very high temperatures and pressures. As a result, the generated force pushes down on the piston and continues to do so until the piston has reached bottom dead center. This is known as the power stroke. At approximately the point where the piston reaches BDC, the exhaust valve opens. The piston then rises and pushes the high temperature combustion products out of the cylinder. This is known as the exhaust stroke. When the combustion products leave the cylinder, they enter the exhaust manifold. If the engine is equipped with a turbocharger, the exhaust then enters the turbine housing radially and spins the turbine wheel of the turbocharger. The exhaust then leaves the turbine axially and continues to flow through the exhaust system until it reaches the ambient air outside of the vehicle.

The performance of an engine can be viewed in terms of its volumetric efficiency, which is discussed later on in this paper. The volumetric efficiency of an engine is simply the ratio of the actual mass of air inside the cylinder at a given instance, compared to the theoretical amount of mass, which can be held inside the cylinder. The goal of an engine designer is to maximize the volumetric efficiency of the engine for the typical RPM range, in which the vehicle operates.

2.1.3 Otto cycle (4-stroke)

The 4-stroke engine specification determines how often this combustion takes place. These 4 strokes consist of the following:

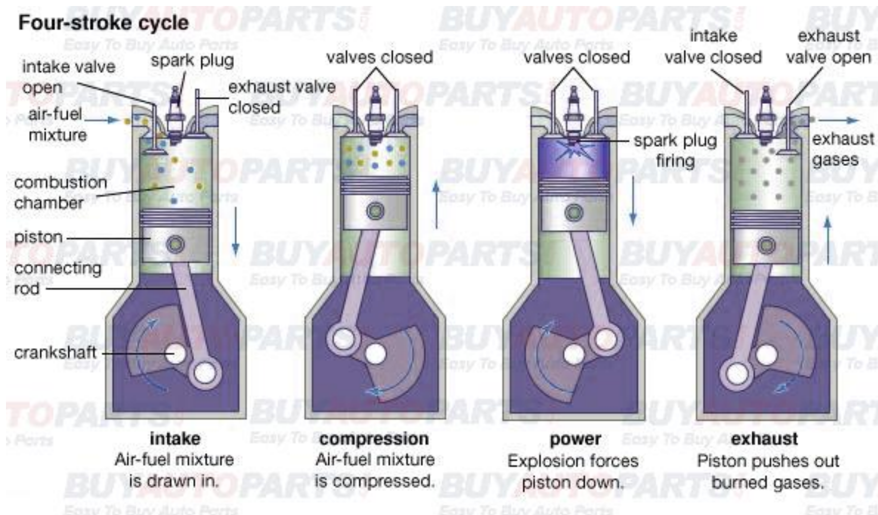


Figure 1 - 4 stroke cycle

- **Intake stroke** – The piston moves from top dead center (TDC) down to bottom dead center (BDC) inside the cylinder while the exhaust valve is closed and the intake valve is open. This creates a temporary low pressure area and the air from the surroundings rushes in to equalize the pressure. While this intake air enters the cylinder, fuel vapor is sprayed into the air (port injection) to enter the combustion chamber as an air/fuel mixture.
- **Compression stroke** – The intake valve closes and the piston moves upwards in the cylinder, compressing the air/fuel mixture. The amplitude of this compression is the compression ratio. This ratio is defined as:

  $$\text{Compression Ratio} = \frac{\text{Free volume in cylinder when piston is at BDC (VBDC)}}{\text{Free volume in cylinder when piston is at TDC (VTDC)}}$$

- **Power stroke** – Just before the piston reaches TDC, a spark ignites the compressed air-fuel mixture to combust the fuel. The volume of the products of this chemical reaction is much greater than the reactants, so the combustion creates a very high pressure area that does work on the piston, moving it downwards.

- **Exhaust stroke** – When the piston nearly reaches BDC, the exhaust valve opens and allows the pressure to equalize through the exhaust. Then the piston travels back upwards and expels the remaining products. At the top of this stroke the exhaust valve closes and the intake valve opens, restarting the cycle.

2.2 Methods to improve engine power output – Major Advantage

From the traditionally ways of forced induction to the newly developed engine component materials and designing strategies, there are a number of ways in which we can increase the power which is being obtained from the engine. These are all heavy on the pocket, but yield out maximum power as output hence accounting for a major, i.e. significantly change the engine characteristic. All these types are discussed further and explained

Forced induction:
Forced induction is the process of delivering compressed air to the intake of an internal combustion engine. A forced induction engine uses a gas compressor to increase the pressure, temperature and density of the air. An engine without forced induction is considered a naturally aspirated engine. Forced induction is used in the automotive and aviation industry to increase engine power and efficiency. A forced induction engine is essentially two compressors in series. The compression stroke of the engine is the main compression that every engine has. An additional compressor feeding into the intake of the engine causes forced induction of air. A compressor feeding pressure into another greatly increases the total compression ratio of the entire system. This intake pressure is called boost. This particularly helps aviation engines, as they need to operate at higher altitudes with lower air densities. High compression on a naturally aspirated engine can reach the detonation threshold fairly easily. However, a forced induction engine can have a higher total compression without detonation because the air charge can be cooled after the first stage of compression, using an intercooler.

Intake tuning:
The intake system on a four-stroke car engine has one main goal, to get as much air-fuel mixture into the cylinder as possible. One way to help the intake is by tuning the lengths of the pipes. When the intake valve is open on the engine, air is being sucked into the engine, so the air in the intake runner is moving rapidly toward the cylinder. When the intake valve closes suddenly, this air slams to a stop and stacks up on itself, forming an area of high pressure. This high-pressure wave makes its way up the intake runner away from the cylinder. When it reaches the end of the intake runner, where the runner connects to the intake manifold, the pressure wave bounces back down the intake runner. If the intake runner is just the right length, that pressure wave will arrive back at the intake valve just as it opens for the next cycle. This extra pressure helps cram more air-fuel mix into the cylinder -- effectively acting like a turbocharger.
Due to the pulsing nature of the air flow in the intake manifold, pressure waves exist that travel along the length of the intake runner / port. When the pressure waves are timed such that the maximum point of the pressure wave occurs at the intake valve as it is closing, and the piston is acting to force the intake charge back out of the cylinder, additional charge can be rammed in the cylinder. This phenomenon is known as the *Ram Effect* and generally increases with engine speed due to the increasing inertia of the air. When these pressure waves are timed to increase

the volumetric efficiency of the engine at the certain engine speed and load then the intake manifold is tuned.

Exhaust tuning:

In an internal combustion engine, the geometry of the exhaust system can be optimized ("tuned") to maximize the power output of the engine. Tuned exhausts are designed so that reflected the pressure waves arrive at the exhaust port at a particular time in the combustion cycle. The same principles in terms of the pulsing nature of the system and the generation of pressure waves which apply to intake manifold also apply to the exhaust manifold. However, for the exhaust manifold it is desirable to have the lowest possible pressure at the exhaust valve when the exhaust valve is closing to aid in the extraction of combustants from the cylinder. When the pressure waves are timed to optimize this scenario then the exhaust manifold is tuned.

Cam profile change:

The camshaft is your engine's "mechanical computer". It controls the opening and closing of the valves which is critical to how your engine will operate. Change the camshaft and your engine can become a high MPG highway cruiser, and high torque high climber, a high revving circle track engine with a broad power band, or a "peaky" drag racing motor. The most important part of your camshaft are the lobes. As the camshaft rotates, the lobes open and close the valves via the follower which "rides" on these lobes.

While the intake valve is open, the piston starts its intake stroke by sucking the air fuel mixture into the cylinder by the piston moving down. The mixture is moving at a very fast rate while this is happening. The faster the engine is spinning the longer the intake valve should stay open. This is controlled by valve lift which is directly related to the cam lobe profile.

Then at some point the intake valve closes and the piston starts moving back up the cylinder. This compresses the air fuel mixture where it is ignited and the explosion forces the piston back down. When the piston gets close to the bottom of the cylinder the exhaust valve opens to let the waste gases out while the piston is moving back up the cylinder. Then it starts all over again.

Now, any camshaft will perform perfectly at a certain engine speed. But at other speeds the engine will perform at a lower level. Therefore, a fixed camshaft will always be a compromise. This is why engine makers have worked on ways to vary the cam profile as the engine RPMs change using Variable Valve Timing.

Engine cylinder heat porting:

Cylinder head porting refers to the process of modifying the intake and exhaust ports of an internal combustion engine to improve the quality and quantity of the air flow. Cylinder heads, as manufactured, are usually suboptimal due to design and manufacturing constraints. Porting the heads provides the finely detailed attention required to bring the engine to the highest level of efficiency. More than any other single factor, the porting process is responsible for the high power output of modern engines.

This process can be applied to a standard racing engine to optimize its power output as well as to a production engine to turn it into a racing engine, to enhance its power output for daily use or to alter its power output characteristics to suit a particular application.
Daily human experience with air gives the impression that air is light and nearly non-existent as we move slowly through it. However, an engine running at high speed experiences a totally different substance. In that context, air can be thought of as thick, sticky, elastic, gooey and heavy (see viscosity). Pumping it is a major problem for engines running at speed, so head porting helps to alleviate this.

Changing to a higher compression ratio:
Higher compression ratios produce more power, up to a point. The more you compress the air/fuel mixture, however, the more likely it is to spontaneously burst into flame (before the spark plug ignites it). Higher-octane gasolines prevent this sort of early combustion. That is why high-performance cars generally need high-octane gasoline because their engines are using higher compression ratios to get more power

2.3 Methods to improve engine power output – Minor Advantage

These changes account for a little power boost from the engine. These are cheaper alternatives and can be used in harmony with the major types of changes to be done which are mentioned above. Here are the list of changes that can be done in the engine system to get an additional amount of boost which is minor by cost effective as it is a cheaper alternative

Cool the incoming air:
Compressing air raises its temperature. However, you would like to have the coolest air possible in the cylinder because the hotter the air is, the less it will expand when combustion takes place. Therefore, many turbocharged and supercharged cars have an intercooler. An intercooler is a special radiator through which the compressed air passes to cool it off before it enters the cylinder.

Let air come in more easily:
As a piston moves down in the intake stroke, air resistance can rob power from the engine. Air resistance can be lessened dramatically by putting two intake valves in each cylinder. Some newer cars are also using polished intake manifolds to eliminate air resistance there. Bigger air filters can also improve air flow.

Let exhaust exit more easily:
If air resistance makes it hard for exhaust to exit a cylinder, it robs the engine of power. Air resistance can be lessened by adding a second exhaust valve to each cylinder. A car with two intake and two exhaust valves has four valves per cylinder, which improves performance. When you hear a car ad tell you the car has four cylinders and 16 valves, what the ad is saying is that the engine has four valves per cylinder.
If the exhaust pipe is too small or the muffler has a lot of air resistance, this can cause back-pressure, which has the same effect. High-performance exhaust systems use headers, big tail pipes and free-flowing mufflers to eliminate back-pressure in the exhaust system. When you hear that a car has "dual exhaust," the goal is to improve the flow of exhaust by having two exhaust pipes instead of one.

Make everything lighter:
Lightweight parts help the engine perform better. Each time a piston changes direction, it uses up energy to stop the travel in one direction and start it in another. The lighter the piston, the less energy it takes. This results in better fuel efficiency as well as better performance.

Inject the fuel:
Fuel injection allows very precise metering of fuel to each cylinder. This improves performance and fuel economy.

Install a performance chipset:
There's an automatic system that controls all the activities in latest car models. For example, the onboard computer system can control the anti-lock brakes, the ratio of gas combustion, timing, etc. There are aftermarket performance ships that can hack into the system and override the factory settings. Replace your factory chip with a new one and use it to boost engine power.

Larger diameter Throttle Body:
In combination with your fuel injection system, the throttle body regulates the air flow that goes into your engine. This system is an important part of your vehicle because, as with all combustion, air is required for your engine to fire properly.
Installing a large-diameter throttle body with bigger flaps allows more air to flow into the engine. Doing this increases several aspects of performance, one being—you guessed it—an increase in horsepower. And it's no subtle shift. You'll feel faster acceleration and a surge in engine power of up to 25hp.To squeeze some more juice out of your engine, you can install a throttle body spacer which looks like a small circular metal ring. It creates just a bit more space for air to enter into the manifold, enhancing your fuel economy and giving you even more torque.

2.4 Forced Induction

Two commonly used forced-induction compressors are turbochargers and superchargers. A turbocharger is a centripetal compressor driven by the flow of exhaust gases. Superchargers use various different types of compressors but are all powered directly by the rotation of the engine, usually through a belt drive. The compressor can be centrifugal or a Roots-type for positive displacement[clarification needed] compression. An example of an internal compressor is a screw-type supercharger or a piston compressor.

Turbocharging:
The starting point for many turbo systems is figuring out a way to mount the turbocharger to the engine. Exhaust manifolds accomplish this task. In addition to attaching the turbocharger to the engine, an exhaust manifold also feeds exhaust gas into the turbine housing of the turbocharger. There are two types of exhaust manifolds, cast or tubular. Cast exhaust manifolds are generally known for their durability while tubular manifolds are known for their increased turbo response due to their influence on exhaust gas velocity. The trade-offs are increased weight with cast and increased cost with tubular.
With the exhaust manifold directing exhaust gas from the ports of the cylinder head to the turbocharger, we can follow the path that the gasses take to understand how the turbo generates more power. Turbochargers have two distinct sections connected by one common shaft. On one side, a turbine section uses the energy of the exhaust gas flow to spin the shaft. On the other side, a compressor wheel within the compressor housing funnels in and compresses ambient air before directing the pressurized air charge toward the engine's throttle body.

Intercooler for the Magnus built EVO XSince pressure and temperature are directly related, compressed air undergoes an increase in temperature. To maximize efficiency and performance, the incoming air charge needs to be cooled. This is where an intercooling solution comes into play. In most applications, an air-to-air intercooler is used. In this type of intercooling, the charge air moves across a core that dissipates heat across the fins of the intercooler. Typically, the intercooler is mounted at the front of the vehicle. By virtue of the vehicle's forward movement, air passes through the fins, which leads to subsequent convectional cooling.
Intercooling piping makes the connection between the turbo, intercooler and engine. In general, a high-quality system will feature aluminum mandrel-bent piping that keeps the length of the pipes to a minimum, minimizes the number of bends and selects a diameter that's well matched for the engine and its intended usage. Fitment is the key to quality intercooling piping.

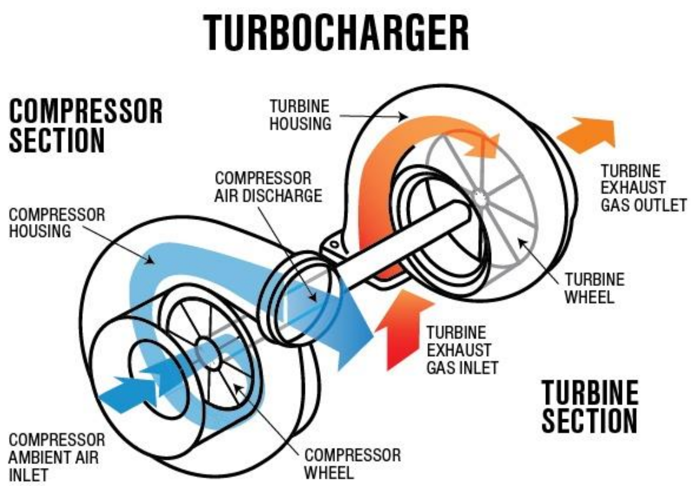


Figure 2 - Turbochager

Supercharging:
Like turbochargers, superchargers pressurize the air intake and force it into the engine. Unlike turbochargers, superchargers don't use the exhaust gas but instead achieve their rotational power by adding a belt driven by the engine's crankshaft.
Supercharger systems include a number of components beginning with the supercharger itself, mounting brackets or mounting intake manifold, pulleys and belts. There are two main categories of superchargers: positive-displacement or centrifugal.
Positive-displacement superchargers are often integrated into a new intake manifold. These types of superchargers are known for reaching peak boost pressure almost immediately after the accelerator is depressed. With near instantaneous response, positive-displacement superchargers deliver great low-end and mid-range torque.
While boost response from positive-displacement superchargers is superior to centrifugal superchargers, centrifugal units are typically more efficient and draw less crankshaft horsepower to produce the same peak boost pressure. Centrifugal superchargers build boost pressure as the

engine revs through its RPM range. This is beneficial for cars with limited traction since the boost curve is linear.

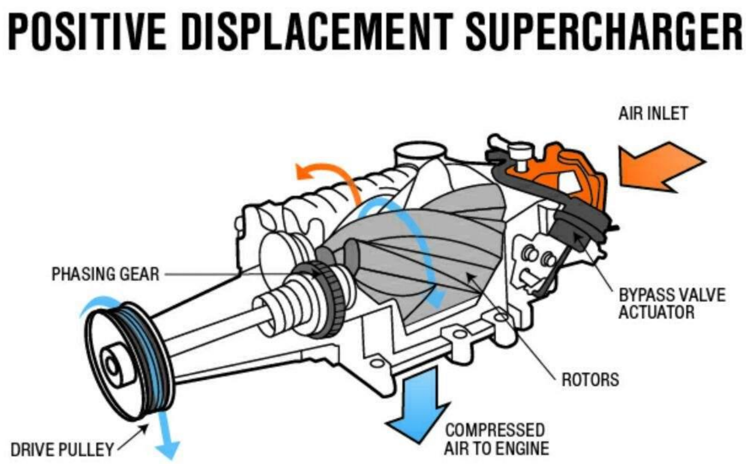


Figure 3 - Supercharger

2.5 Turbo chargers

A turbocharger, or turbo, is a gas compressor. It is used to force air into an internal combustion engine. A turbocharger is a form of forced induction. It increases the amount of air entering the engine to create more power. A turbocharger has the compressor powered by a turbine. The turbine is driven by the exhaust gas from the engine. It does not use a direct mechanical drive. This helps to improve the performance of the turbocharger.

A turbocharger is a small fan pump that spins around a shaft. The pump is driven by the pressure of the exhaust gas. A turbocharger consists of a turbine and a compressor. They are both mounted on the same shaft. The turbine is a heat engine. It converts exhaust heat and pressure to rotation. This rotation is used to turn the compressor. The compressor takes in the draws in the outside air. It squeezes or compresses the air. It then sends the air to the engine. Because the air pressure has been increased, more air and fuel may be put into the cylinders. This is sometimes called boost pressure. With more fuel to burn, the engine can create more power. This increases the horsepower of the engine.

2.5.1 Working Principle

The basic idea is that the exhaust drives the turbine (the red fan), which is directly connected to (and powers) the compressor (the blue fan), which rams air into the engine. For simplicity, we're showing only one cylinder. Here then, in summary, is how the whole thing works:

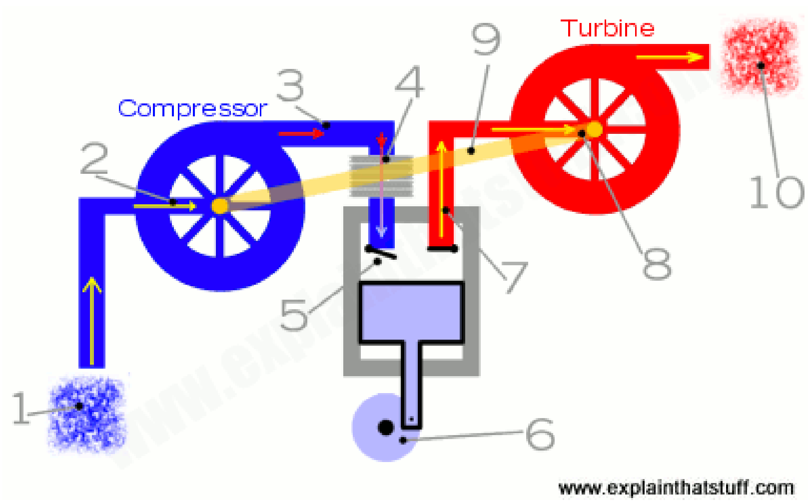


Figure 4 - Turbocharger Working Principle (a)

- Cool air enters the engine's air intake and heads toward the compressor.
- The compressor fan helps to suck air in.
- The compressor squeezes and heats up the incoming air and blows it out again.
- Hot, compressed air from the compressor passes through the heat exchanger, which cools it down.
- Cooled, compressed air enters the cylinder's air intake. The extra oxygen helps to burn fuel in the cylinder at a faster rate.
- Since the cylinder burns more fuel, it produces energy more quickly and can send more power to the wheels via the piston, shafts, and gears.
- Waste gas from the cylinder exits through the exhaust outlet.
- The hot exhaust gases blowing past the turbine fan make it rotate at high speed.
- The spinning turbine is mounted on the same shaft as the compressor (shown here as a pale orange line). So, as the turbine spins, the compressor spins too.
- The exhaust gas leaves the car, wasting less energy than it would otherwise.

In practice, the components could be connected something like this. The turbine (red, right) takes in exhaust air through its intake, driving the compressor (blue, left) that takes in clean outside air and pumps it into the engine. This particular design features an electric cooling system (green) in between the turbine and compressor.

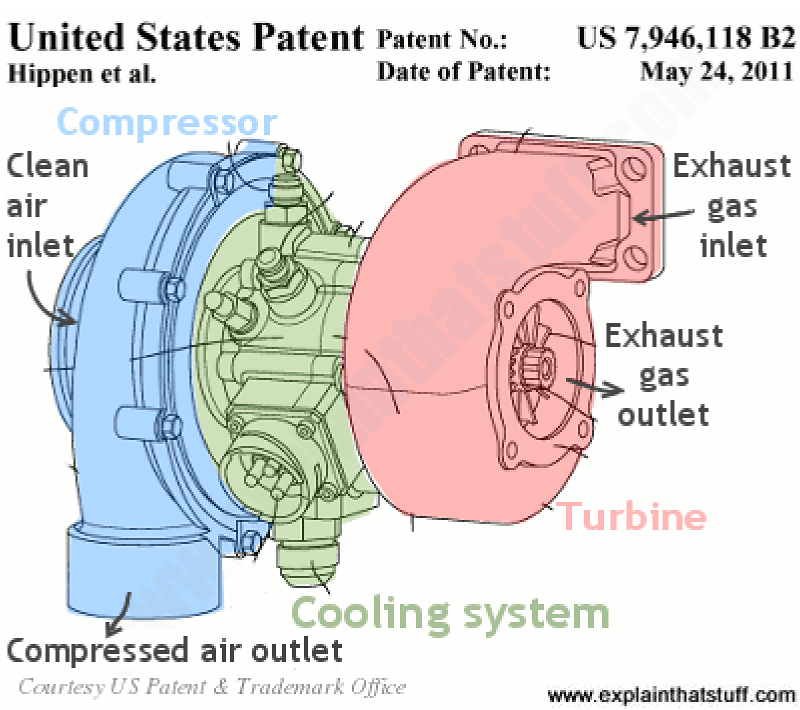


Figure 5 - Turbocharger Working Principle (b)

2.5.2 Types of Turbo chargers

There are 6 different types of turbo chargers which are widely recognized in the automobile industry. Below you'll find the description of each type along with its advantaged and disadvantages over others. Following are the types of turbo chargers:

Single-Turbo:

Single turbochargers are what most people think of as turbos. By differing the size of the elements within the turbo, completely different torque characteristics can be achieved. Large turbos provide higher levels of top end power, whilst smaller turbos can spool faster and provide better low-end power. They are a cost-effective way of increasing engine power and efficiency, and as such have become increasingly popular, allowing smaller engines to increase efficiency by producing the same power as larger naturally-aspirated engines, but with a lower weight. They do however tend to work best within a narrow RPM range, and drivers will often experience 'turbo-lag' until the turbo starts to operate within its peak rev band.

Advantages

- Cost effective way of increasing an engine's power and efficiency.
- Simple, generally the easiest of the turbocharging options to install.
- Allows for using smaller engines to produce the same power as larger naturally-aspirated engines, which can often remove weight.

Disadvantages

- Single turbos tend to have a fairly narrow effective RPM range. This makes sizing an issue, as you'll have to choose between good low-end torque or better high-end power.
- Turbo response may not be as quick as alternative turbo setups.

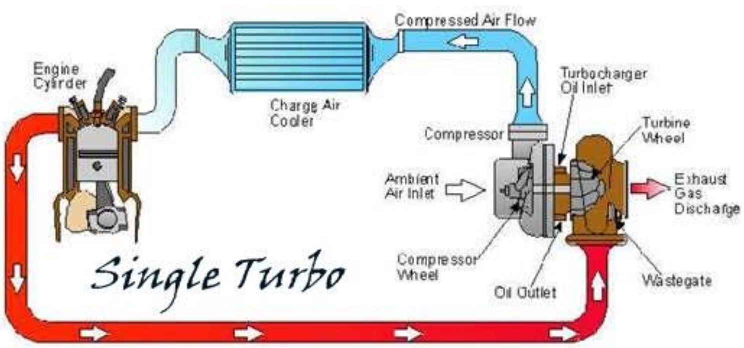


Figure 6 - Single Turbo

Twin-Turbo:

As the name implies twin-turbos mean adding a second turbocharger to an engine. In the case of V6 or V8 engines, this can be done by assigning a single turbo to work with each cylinder bank. Alternatively, one smaller turbo could be used at low RPMs with a larger turbo for higher RPMs. This second configuration (known as twin sequential turbocharging) allows for a wider operating RPM range, and provides better torque at low revs (reducing turbo lag), but also gives power at high RPMs. Unsurprisingly, having two turbos, significantly increases the complexity and associated costs.

Advantages

- For parallel twin turbos on ‘V’ shaped engines, the benefits (and drawbacks) are very similar to single turbo setups.
- For sequential turbos or using one turbo at low RPM and both at high RPM, this allows for a much wider, flatter torque curve. Better low-end torque, but the power won’t taper at high RPM like with a small single turbo.

Disadvantages

- Cost and complexity, as you’ve nearly double the turbo components.
- There are lighter, more efficient ways of achieving similar results (as discussed below).

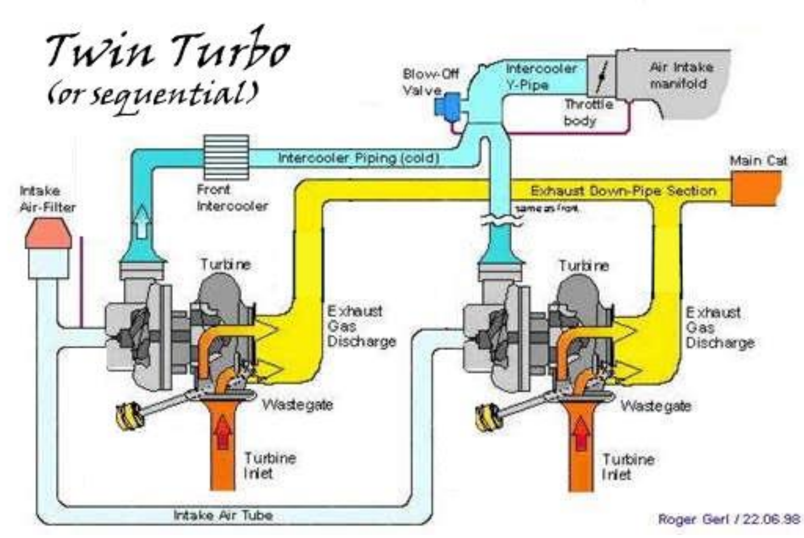


Figure 7 - Twin Turbo

Twin-Scroll Turbo:
Twin-scroll turbochargers require a divided-inlet turbine housing and exhaust manifold that pairs the correct engine cylinders with each scroll. independently. For example, in a four-cylinder engine (with a firing order 1-3-4-2), cylinders 1 and 4 might feed to one scroll of the turbo, while cylinders 2 and 3 feed to a separate scroll. This layout provides more efficient delivery of exhaust gas energy to the turbo, and results and helps provide denser, purer air into each cylinder. More energy is sent to the exhaust turbine, meaning more power. Again, there is a cost penalty for addressing the complexity of a system requiring complicated turbine housings, exhaust manifolds and turbos.

Advantages
- More energy is sent to the exhaust turbine, meaning more power.
- A wider RPM range of effective boost is possible based on the different scroll designs.
- More valve overlap is possible without hampering exhaust scavenging, meaning more tuning flexibility.

Disadvantages
- Requires a specific engine layout and exhaust design (eg: I4 and V8 where 2 cylinders can be fed to each scroll of the turbo, at even intervals).
- Cost and complexity versus traditional single turbos.

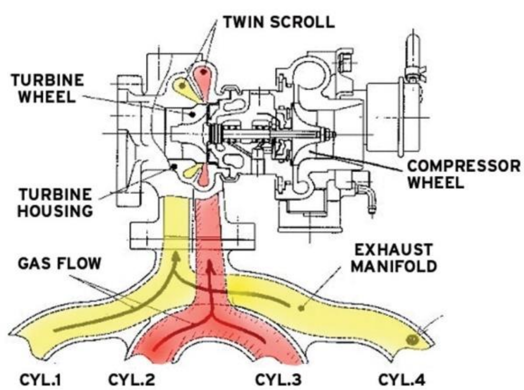


Figure 8 - Twin Scroll Turbo

Variable Geometry Turbocharger (VGT):
Typically, VGTs include a ring of aerodynamically-shaped vanes in the turbine housing at the turbine inlet. In turbos for passenger cars and light commercial vehicles, these vanes rotate to vary the gas swirl angle and the cross-sectional area. These internal vanes alter the turbos area-to-radius (A/R) ratio to match the engines RPM, and so give peak performance. At low RPM, a low A/R ratio allows the turbo to quickly spool up by increasing exhaust gas velocity and. At higher revs the A/R ratio increases, ther4eby allowing increased airflow. This results in a low boost threshold reducing turbo lag, and provides a wide and smooth torque band.

Whilst VGTs are more typically used in diesel engines where exhaust gases are lower temperature, until now VGTs have been limited in petrol engine applications due to their cost and the requirement for components to be made from exotic materials. The high temperature of the exhaust gases means that the vanes must be made from exotic heat-resistant materials to prevent damage. This has restricted their use to applications within luxury, high performance engines.

<u>Advantages</u>

- Wide, flat torque curve. Effective turbocharging at a very wide RPM range.
- Requires just a single turbo, simplifying a sequential turbo setup into something more compact.

<u>Disadvantages</u>

- Typically only used in diesel applications where exhaust gases are lower so the vanes will not be damaged by heat.
- For gasoline applications, cost typically keeps them out as exotic metals have to be used in order to maintain reliability. The tech has been used on the Porsche 997, though very few VGT gasoline engines exist as a result of the cost associated.

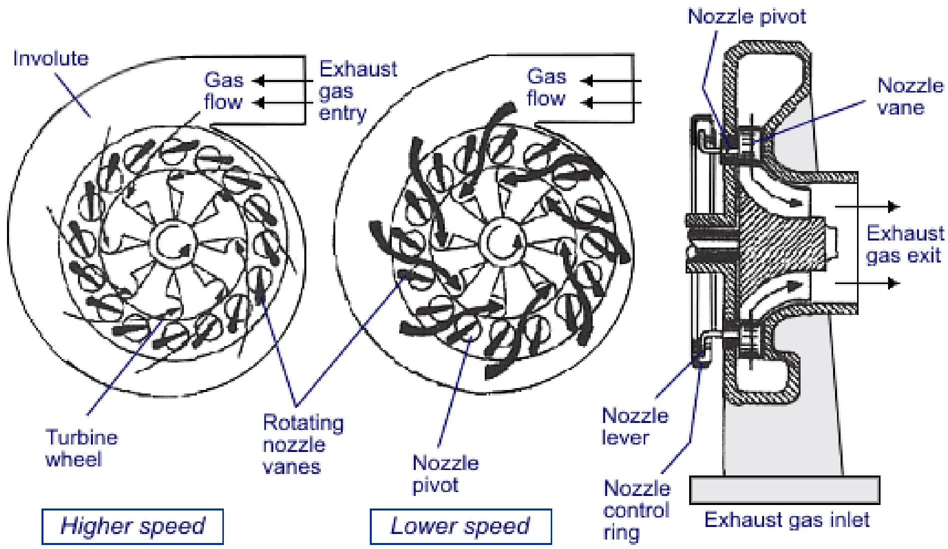


Figure 9 - Variable Geometry Turbo (VGT)

Variable Twin-Scroll Turbocharger (VTS):

As the name suggests a VTS turbocharger combines the advantages of a twin-scroll turbo and a variable geometry turbo. It does this by the use of a valve which can redirect the exhaust airflow to just a single scroll, or by varying the amount the valve opens can allow for the exhaust gases to split to both scrolls. The VTS turbocharger design provides a cheaper and more robust alternative to VGT turbos, meaning it is a viable option for petrol engine applications.

Advantages

- Significantly cheaper (in theory) than VGTs, thus making an acceptable case for gasoline turbocharging.
- Allows for a wide, flat torque curve.
- More robust in design versus a VGT, depending on the material selection.

Disadvantages

- Cost and complexity versus using a single turbo or traditional twin-scroll.
- The technology has been played with before (eg: quick spool valve) but doesn't seem to catch on in the production world. There are likely additional challenges with the technology.

Electric Turbochargers:

An electric turbocharger is used to eliminate turbo lag and assist a normal turbocharger at lower engine speeds where a conventional turbo is not most efficient. This is achieved by adding an electric motor that spins up the turbo's compressor from start and through the lower revs, until the power from the exhaust volume is high enough to work the turbocharger. This approach makes turbo lag a thing of the past, and significantly increases the RPM band within which the turbo will efficiently operate. So far, so good. It appears that electronic turbos are the answer to all the negative characteristics of conventional turbochargers, however there are some disadvantages. Most are around cost and complexity, as the electric motor must be accommodated and powered, plus also cooled to prevent reliability issues.

Advantages

- By directly connecting an electric motor to the compressor wheel, turbo lag and insufficient exhaust gases can be virtually eliminated by spinning the compressor with electric power when needed.
- By connecting an electric motor to the exhaust turbine, wasted energy can be recovered (as is done in Formula 1).
- A very wide effective RPM range with even torque throughout.

Disadvantages

- Cost and complexity, as you now must account for the electric motor and ensure it remains cool to prevent reliability issues. That goes for the added controllers as well.
- Packaging and weight become an issue, especially with the addition of a battery on board, which will be necessary to supply sufficient power to the turbo when needed.
- VGTs or twin-scrolls can offer very similar benefits (though not at quite the same level) for a significantly lower cost.

2.5.3 Main components of a turbo charger

At the most basic level, a turbocharger consists of just three major components: the turbine, the compressor, and the bearing system that supports the turbine shaft, connecting the turbine and compressor wheels together. Understanding how all three parts work together is crucial, and even a basic understanding of the component’s relationships to one another will make selecting a turbo for your project much easier.

The Turbine:

The turbine wheel is responsible for converting heat and pressure into rotational force. To understand how this process occurs, we would need to delve into some of the basic laws of thermodynamics, but within the scope of this article, understand that high pressure (from the exhaust manifold) will always seek low pressure and, within this process, the turbine wheel converts kinetic energy into rotation. As the turbine wheel rotates, it spins the turbine shaft, which in turn spins the compressor wheel. Often overlooked, turbine wheel selection is critical to a properly built turbocharger system, as having too small of a turbine wheel will induce excessive backpressure and can choke the engine, making it lose power. On the other hand, selecting too large of a turbine will result in increased lag and can make it difficult to achieve specific target boost numbers.

Of course, the turbine wheel doesn’t act alone. It is part of the turbine housing, which is that giant, sometimes rusty looking piece of iron or steel you always see bolted to an exhaust manifold or merge collector on a turbo car. Because of the tremendous heat involved in collecting and moving pressurized exhaust gasses, the turbine housing is constructed from thick iron or steel and always consists of a turbine foot (the flange which connects to the exhaust manifold piping), an outlet connection (the large opening that connects to the downpipe), and a volute, which is the path the hot exhaust travels to get across the turbine wheel, from the turbine foot to the outlet. When someone calls a turbo a "T4 turbo," they are talking about this flange. Exhaust enters from the flange, rotates around the wheel inside the volute, and exits across the outlet connection, into a piece of exhaust that enthusiasts call the downpipe.

The Compressor:

Like the turbine, the compressor section is made up of two primary components: the compressor wheel and the compressor cover. The compressor’s job is to, quite literally, compress fresh air and funnel it towards the throttle body. Since it is connected directly to the turbine wheel via the turbine shaft, the compressor wheel rotates at the same RPM as the turbine wheel and, as the engine and turbine wheel accelerate, so does the compressor wheel. This process creates pressure in the intake tract, which we call "boost" and is the reason anyone would install a turbocharger in the first place. Again, to fully understand this process, we would need to explain several laws of thermodynamics, including the ideal gas law, but for our purpose, understand that a compressor wheel’s job is to gather fresh air and compress it--simple as that. As the wheel spins, it takes

ambient air, rotates it 90 degrees along the blade of the wheel, and forces it into the compressor cover, where it is collected and then forced into the intake tube.
Compressor wheels are one of the most commonly talked about parts of a turbocharger. Even if you haven't ever seen a turbo before, you have probably heard someone say "it's an 88mm turbo" or "I can't believe they outlawed the 116." What we are talking about is the compressor wheel diameter, measured at the tip or, more accurately, measured at the tip of the inducer. The compressor wheel and cover are also the most photogenic parts of a turbocharger since they are made of shiny aluminum, and, consequently, people enjoy taking pictures of them with dollar bills, Coke cans, or various other items, to show how large the compressor wheel actually is. Now, all fun aside, it is important to understand the compressor is the money maker in this system and it is the one part of the turbocharger that does all of the pumping, so it is important to size it correctly for your application.

Center Housing / Rotating Assembly (CHRA):

The CHRA may not get a lot of ink time, but it is one of the most critical parts of any turbocharger assembly. Practically, the CHRA serves as the mounting point for both housings and must be made of substantial material to handle the heat and stress of the turbine. Of course, holding the housings together is child's play compared to the real job of the CHRA, which is to support and lubricate the turbocharger's bearings. With turbine shaft speeds in excess of 100,000 rpm, the bearing's job is much, much more difficult than that of a traditional camshaft bearing, and as such turbo manufacturers have spent a lot of time and money building serious bearings to handle these jobs. If you have ever heard of someone "rebuilding a turbo," they are most likely talking about replacing the bearings, which can start to wear based on a variety of factors including oil condition, axial loads, or shaft movement. Traditionally, a CHRA will house two bronze full-floater bearings and a separate bronze thrust bearing. Today, many quality manufacturers offer upgraded bearing systems, including the Turbonetics ceramic ball-bearing unit, which eliminates the traditional thrust bearing allowing the turbo to withstand "up to 50 times the thrust load capacity, compared to a conventional unit." Many other manufacturers have also upgraded to ball bearings systems, including Garrett, to help reduce drag and increase a turbocharger's life.

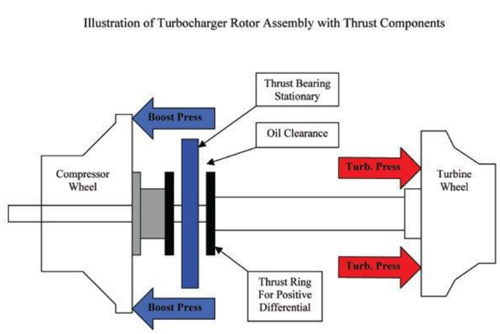


Figure 10 - Three Main Components of a Turbo

2.5.4 Additional technologies for a turbocharged engine

Intercooling

When the pressure of the engine's intake air is increased, its temperature also increases. This occurrence can be explained through Gay-Lussac's law, stating that the pressure of a given amount of gas held at constant volume is directly proportional to the Kelvin temperature. With more pressure being added to the engine through the turbocharger, overall temperatures of the engine will also rise. In addition, heat soak from the hot exhaust gases spinning the turbine will also heat the intake air. The warmer the intake air, the less dense, and the less oxygen available for the combustion event, which reduces volumetric efficiency. Not only does excessive intake-air temperature reduce efficiency, it also leads to engine knock, or detonation, which is destructive to engines.

To compensate for the increase in temperature, turbocharger units often make use of an intercooler between successive stages of boost to cool down the intake air. A charge air cooler is an air cooler between the boost stage(s) and the appliance that consumes the boosted air.

Water injection:

An alternative to intercooling is injecting water into the intake air to reduce the temperature. This method has been used in automotive and aircraft applications.

Water injection was used historically to increase the power output of military aviation engines for short durations, such as dogfights or takeoff. However it has also been used in motor sports and notably in drag racing. In Otto cycle engines, the cooling effects of water injection also enables greater compression ratios by reducing engine knocking (detonation). Alternately, this reduction in engine knocking in Otto cycle engines means that some applications gain significant performance when water injection is used in conjunction with a supercharger, turbocharger, or modifications such as aggressive ignition timing.

Depending on the engine, improvements in power and fuel efficiency can also be obtained solely by injecting water. Water injection may also be used to reduce NOx or carbon monoxide emissions.

Water injection is also used in some turbine engines and in some turboshaft engines, normally when a momentary high-thrust setting is needed to increase power and fuel efficiency.

Methanol Injection:

Methanol/water injection has been around since the 1920s but was not utilized until World War II. Adding the mixture to intake of the turbocharged engines decreased operating temperatures and increased horse power. Turbocharged engines today run high boost and high engine temperatures to match. When injecting the mixture into the intake stream, the air is cooled as the liquids evaporate. Inside the combustion chamber it slows the flame, acting similar to higher octane fuel. Methanol/water mixture allows for higher compression because of the less detonation-prone and, thus, safer combustion inside the engine.

Fuel-air mixture ratio:
In addition to the use of intercoolers, it is common practice to add extra fuel to the intake air (known as "running an engine rich") for the sole purpose of cooling. The amount of extra fuel varies, but typically reduces the air-fuel ratio to between 11 and 13, instead of the stoichiometric 14.7 (in petrol engines). The extra fuel is not burned (as there is insufficient oxygen to complete the chemical reaction), instead it undergoes a phase change from atomized (liquid) to gas. This phase change absorbs heat, and the added mass of the extra fuel reduces the average thermal energy of the charge and exhaust gas. Even when a catalytic converter is used, the practice of running an engine rich increases exhaust emissions.

Wastegate:
A wastegate regulates the exhaust gas flow that enters the exhaust-side driving turbine and therefore the air intake into the manifold and the degree of boosting. It can be controlled by a boost pressure assisted, generally vacuum hose attachment point diaphragm (for vacuum and positive pressure to return commonly oil contaminated waste to the emissions system) to force the spring-loaded diaphragm to stay closed until the overboost point is sensed by the ecu or a solenoid operated by the engine's electronic control unit or a boost controller, but most production vehicles use a single vacuum hose attachment point spring-loaded diaphragm that can alone be pushed open, thus limiting overboost ability due to exhaust gas pressure forcing open the wastegate.

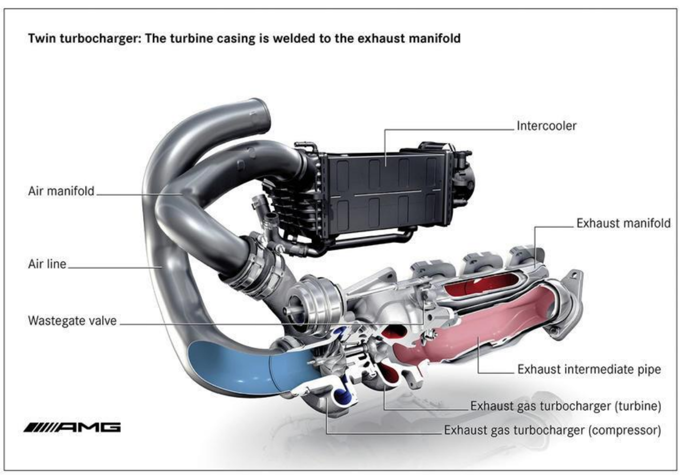


Figure 11 - AMG Turbo Prototype

Anti-surge/dump/blow off valves:
A recirculating type anti-surge valve
Turbocharged engines operating at wide open throttle and high rpm require a large volume of air to flow between the turbocharger and the inlet of the engine. When the throttle is closed, compressed air flows to the throttle valve without an exit (i.e., the air has nowhere to go).

In this situation, the surge can raise the pressure of the air to a level that can cause damage. This is because if the pressure rises high enough, a compressor stall occurs—stored pressurized air decompresses backward across the impeller and out the inlet. The reverse flow back across the turbocharger makes the turbine shaft reduce in speed more quickly than it would naturally, possibly damaging the turbocharger.
To prevent this from happening, a valve is fitted between the turbocharger and inlet, which vents off the excess air pressure. These are known as an anti-surge, diverter, bypass, turbo-relief valve, blow-off valve (BOV), or dump valve. It is a pressure relief valve, and is normally operated by the vacuum from the intake manifold.

Free float:
A free floating turbocharger is used in the 100-litre engine of this Caterpillar mining vehicle.
A free floating turbocharger is the simplest type of turbocharger. This configuration has no wastegate and cannot control its own boost levels. They are typically designed to attain maximum boost at full throttle. Free floating turbochargers produce more horsepower because they have less backpressure, but are not driveable in performance applications without an external wastegate.

2.6 Academic Knowledge basic requirements

Computational Fluid Dynamics (CFD):
For all the intake and air flow simulation purpose, we will need to know what are the flow parameters and also the extend to which there is inseparable flow into the intake system. Also to determine minimum losses in the whole system, we need to design the system geometry according to the flow results.

Thermal and Heat Systems (THS):
As the driving force is in the hands of the exhaust gas, the temperature and velocity at which they are released play an important role for the turbo selection. Also the the compressed gases will have a greater temperature that the temperature of the sucked in ambient air, which means that it needs to be cooled down before it enters the engine. Also the whole air flow depends on the thermodynamic properties of air at the inlet and outlet.

Heat and Mass Transfer (HMT):
The work of cooling down the temperature of the compressed gas is done by an inter-cooler which uses the heat transfer principles as it is a basic heat exchanger.

Internal combustion Engines (ICE):
We must know how an engine works and the basic principles on which it operates and produces the output power. Also what would be the affect on the internal engine parameters after incorporating a turbocharger.

Computer Aided Designing (CAD):
The whole geometry will be designed using CAD software and the dimensions of the same will be decided by the doing Finite element Analysis (FAE) of the designed part

Engine modeling:
This will be an additional experience as the output power curves, gearing torque and shifting points can be obtained by specifying the whole engine system and the parameters on which it is functioning.

3 Methodology

3.1 Initial steps

In a Formula Student Competition, there is an Engine Capacity restriction of 710cc. This means that the maximum power is already capped with the engine limit. Further, they also include an intake restrictor which is 19mm in diameter into the intake system from which the air should pass through before entering the engine.
The 19mm restrictor is used to even out the performance of each engine and get it to an equitable range. The basic fundamental of this intake restrictor is to reduce 50% of the engine power. Thus the engine is already running down on power in the competition due to the restrictor. Considering a single cylinder engine, its performance is so hampered that it may not able to compete with the multiple cylinder engine which also happen to have a higher engine capacity.

We have 3 options to choose from:

1. Switch to a higher capacity engine with single cylinder
2. Switch to a higher capacity multicylinder engine
3. Find a way to recover the lost power

The first two options are not financially feasible and the second one also happens to make the system more bulky and the compact packaging a nightmare for the car designing, thus the option that we choose is to recover this lost engine power, i.e the third one, by some means so that even having a lower capacity engine would not hold back us to unleash the peak performance out of the car.

3.2 Engineering decision

These are the decisions being made on the basis of the background study of turbochargers and also the type which is going to be suited for our design. This starts with the selection of a type of method to increase the output power of the engine and then progressing further by taking more in depth study of each component associated with the design. Now we’ll see all the aspects of designing which are taken into consideration with proper engineering practices.

3.2.1 Type of Engine Performance boost method

After the decision of recovering the engine power, we listed down all the possible ways in which we could do so and compared the same based on 5 parameters

Parameters	Forced induction	Intake tuning	Exhaust tuning	Cam profile	Head porting	High compression
Reliability (5)	**4**	4	4	3	5	3
Power increase (5)	**5**	2	2	2	2	2
Feasibility (5)	**4**	3	3	2	2	2
Weight (3)	**3**	5	5	5	4	4
Low cost (2)	**2**	4	4	3	2	2
Total	**78**	68	68	56	65	55

Table 1- Methods for Increasing Engine Power

From last years performance of the car, the results of the dynamic events were comparable to the top runners, hence we knew that the intake and exhaust have been nearly perfect and required a few teaks to get to its peak performance outcome.
The table above also clearly shows that the option of going on with a forced induction system for the intake would be the most beneficial option at the moment according to the 5 parameters that were used for the comparison.
Thus reviewing the past performance and tweaking the new intake and exhaust design accordingly, we choose **forced induction** as the preferred option

3.2.2 Type of Forced Induction system

We were now supposed to decide which system to go with for forced induction. The 2 fairly popular systems in the industry are:

1. Turbocharger
2. Supercharger

A turbocharger is a centripetal compressor driven by the flow of exhaust gasses, whereas a supercharger uses various different types of compressors but are all powered directly by the rotation of the engine, usually through a belt drive.

Why choose a turbocharger over a supercharger for our system:

1. **More Efficient**

As the supercharger will be directly coupled with the engine crankshaft, it has a tendency to suck into the generated power, thus proving turbocharger as a better option as it utilizes the exhaust gas's energy to run the turbine coupled with a compressor

2. **More Reliable**

Since this doesn't involve and internal engine connection, it is more reliable and a better working system than the supercharger.

3. **Higher Power to Size ratio**

The power which the turbo charger produces is almost of the same range as that of the supercharger but at the same time it weighs only 80% of that of the supercharger. Hence, the Power to Size ratio of the whole system is higher

4. **Better Fuel Economy**

Since the engine power is not eaten up in this system, it theoretically consumes less fuel that the other one.

5. **Easy troubleshooting**

No direct engine components involved hence easy to diagnose an issue

6. **More Cost Effective**

Both the systems cost almost the same, but better reliability and easy troubleshooting makes this cost effective

Drawbacks of the turbo charged system:

Not every component is amply perfect. Thus there are some shortcomings in the turbocharged system as well. Below we have discussed each issue with the turbo charger.

1. **Turbo lag**

Since the turbo boost generated is not directly from the engine, but is from the exhaust gasses, there is a considerable lag in the turbo boost to be available for the intake stroke. Hence a fraction of delay is experienced by the driver when operating the throttle pedal and flooring it suddenly.

2. **Negligible Low RPM boost generation**

Since the exhaust gasses at a lower range of rpm do not posses the energy required to run the turbine at its max potential, there is negligible boost produced at the lower rpm and it may be consider ineffective when the engine works on load condition.

3. **Specific RPM range for a boost**

The turbocharged system will not provide a uniform boost all over the RPM range and hence as at lower engine RPM the boost is insignificant, the boost produced will be for a particular RPM range which mostly houses the maximum torque range and maximum power range into it. Hence a full boost isn't available as it is the case for supercharged system.

4. **Extra lubrication**

The turbo operates at very high RPM and has a tendency to get very hot. Thus a provision for lubricating the whole system comes into play. The lubrication is mostly provided by the engine crankcase and only external bypass is required

The first problem can be eliminated by deciding a simple connection system between the exhaust port and the intake port, whereas the second and third problems are related to the type of turbocharger we choose. Thus considering carefully each and every type, we can choose a perfect type of turbo for our system. The last issue is the most common and the easiest way to idea with it is by integrating the engine lubrication bypass.
<u>We deice to go with a **turbo charger** for our system</u>

3.2.3 Desired Output Power for our system

The current engine being used in our car is a KTM Duke 390 engine (2016 model), which is well-known for its punchy power output as well as the quick boost provided when the throttle is engaged. Thus, this engine is made for racing and not for cruising, which gives an upper hand to us while tuning the same.

Engine Specifications:

No. of cylinders – 1 **Capacity** – 373.3 cc

Bore – 89mm **Stroke** – 60mm **Compression ratio** – 12.88:1

Max power output – 44 bhp @ 9500 RPM **Max torque output** – 35 Nm @ 7250 RPM

Now, these are the fundamental stock parameters on which the engine operates. By tuning it further, we can improve the same to a much better desired value. But as per our FSAE car and competition rules, the restrictor does the work what is suggested by its name i.e restricting the air flow in the engine. Hence the output parameters of our engine as of now after the competition Formula Bharat 2019 are:

Max power output – 35.3 bhp @ 6200 RPM

Max torque output – 31.5 Nm @ 6800 RPM

Here we can clearly see that the range of the power delivered has dropped due to the use of a restrictor. Our main aim over here is that the lost power to the restrictor must be gained along with a significant boost which the engine is capable of. According to aftermarket turbo performance characteristics and also industrial applications, we can assume that on an average the turbo-charger can provide a minimum of 20-40% boost on the current operating conditions, if implemented properly. Also there are cases where the output can almost reach 1.5 times of the initial value. Considering these values and also the nature of the engine being used, we have decided to aim for a 50hp max power output from the single cylinder engine. This can be further improved by taking a more aggressive approach but over here we want to first test the reliability of the engine and are considering a moderate value.

Thus, desired power output – **50hp.**

3.2.4 Turbocharger selection

Now we need to choose the type of turbocharger we need to use in our system. There are _ types of turbocharges available in the market and now, we'll be looking at each one individually to choose the best one that suits our needs.

Types:

- Single turbo
- Sequential turbo
- Twin-scroll turbo
- Variable geometry turbo
- Variable twin-scroll turbo
- Electric turbo

Now, based on these types, we had to choose the best turbo that would be best fitted for our purpose. We have compared all in terms of specific parameters and have finalized on a type

Comparison Chart (5-best, 1-worst)

Turbo type / **Parameter**	**Single turbo**	**Sequential turbo**	**Twin-scroll turbo**	**Variable geometry turbo**	**Variable twin-scroll turbo**	**Electric turbo**
Turbo boost (range)	2	3	4	4	5	5
Turbo boost (value)	2	3	4	5	5	5
Weight	5	3	4	4	3	4
Practicality	4	3	3	5	3	4
Cost	5	4	3	3	2	3
Total	18	17	18	**21**	18	**21**

Table 2 - Comparison of Turbos

As per the table comparison, the turbo which are suited for our needs were:

- Variable geometry turbo
- Electric turbo

Considering in depth now some more features of these types, we would be finalizing the desired turbo

Parameter	**Weightage(1-5)**	**Variable geometry turbo**	**Electric turbo**
Turbo lag	5	5	4
Reliability	5	4	3
Ease of troubleshooting	4	5	3
Future development consideration	3	3	5
Compactness	3	4	3
Availability	3	4	2
Flexibility in designing	2	3	4
Total	-	**104**	85

Table 3 - Variable Geometry Turbo vs Electric Turbo

It is clear that as per the priorities of the team in designing, the Variable geometry type turbo charger will be the optimum choice. It checks all the priority boxes and is also more widely used than the newer technology of an electric turbo.

Thus, we have finalized to go with a **Variable Geometry Turbo** for are project.

3.2.5 Turbo Specification

This is carried out by simulation of an engine model on GT Power and getting the values in th e post processor GT Suit. We made and engine model replicating our FSAE car and simulated it for various engine parameters that will be used in the calculation process.

- **Actual Air Flow required**

The first thing to do was to decide on a horsepower target, which for us is 50 hp. Then knowing the Air/Fuel Ratio (8.5:1) and estimating Brake Specific Fuel Consumption (0.72 lb/hp*hr.) we calculated actual airflow, Wa, using the equation:

$$\text{Wa} = \text{HP}*\frac{A}{F}*\frac{BSFC}{60}$$

$$= 50*\frac{8.5}{1}*\frac{0.72}{60}$$

$$= 5.1 \text{ lb/min} = 0.03855 \text{ kg/sec}$$

- **Manifold Pressure Required**

We needed to calculate the required manifold pressure, MAPreq, which is the pressure of the air after it has left the compressor of the turbocharger and just before it enters the engine, to meet the horsepower target. For this we used the gas constant (R=639.6 in/°R), intake manifold 30 temperature (Tm=100°F), Volumetric Efficiency (VE=0.9), engine speed in rpm (N=9500), and engine displacement in cubic inches (Vd=373.2 cc = 22.774 in^3) and calculated the manifold pressure using the equation:

$$\text{MAPreq} = \frac{Wa*R*(460+Tm)}{VE*{}^{N}/_{2}*Vd}$$

$$= \frac{5.1*639.6*(460+100)}{0.9*{}^{9500}/_{2}*22.774}$$

$$= 18.7625 \text{ psi} = 126.5431 \text{ kPa}$$

The intake configuration as per the latest FS rules is as shown below:

Air filter – Restrictor – Compressor - Throttle body – Intercooler - Manifold.

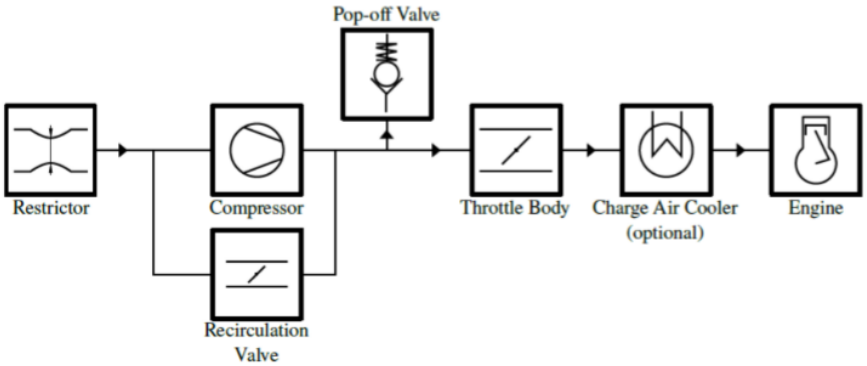


Figure 12 - FS intake configuration

Ambient pressure, P_{atm} = 14.68 psi … (Coimbatore, India)

Pressure drop due to air filter, ΔP_{intake} = 0.5 psi

Pressure drop due to restrictor, Ƞr = 15%

Therefore, Compressor intake pressure, P1c = (P_{atm} - ΔP_{intake}) * Ƞr

= (14.68 - 0.5) * 0.85

= 12.053 psi

Pressure drop due to throttle body and intercooler = 2.5 psi

Therefore, Compressor discharge pressure, P2c = MAPreq + ΔP_{loss}

= 18.763 + 2.5

= 21.263 psi

Compressor Pressure Ratio, $\boldsymbol{\pi_c} = \frac{P2c}{P1c} = \frac{21.263}{12.053} = 1.764$

Engine speed at maximum torque = 6600 rpm

Actual airflow at maximum torque, $\boldsymbol{(Wa)_t} = \frac{MAPreq * VE * {}^{N}/_{2} * Vd}{R * (460 + Tm)}$

$$= \frac{18.763 * 0.9 * \frac{6600}{2} * 22.774}{639.6 * (460 + 100)}$$

= 3.543 lb/min

Compressor MAP calculations for desired HP targets:

Horsepower Target (hp)	**48**	**50**	**52**	**54**	**56**	**58**	**60**
MAPreq (psi)	18.012	18.763	19.513	20.204	21.015	21.765	22.516
Compressor Pressure Ratio (π_c)	1.702	1.764	1.826	1.884	1.951	2.013	2.075
Wa (lb./min)	4.896	5.1	5.304	5.508	5.712	5.916	6.12
$(Wa)_t$ (lb./min)	3.401	3.543	3.685	3.815	3.968	4.11	4.252

Table 4 - Turbo spec for power range (48-60hp)

Here, we have listed the operating characteristics of the system when the desired output power is varied from 48-60hp. Our current system is being designed for an output power of 50hp, but in future it can be upgraded to produce a power upto 60hp as per these calculated specifications.

4 Engineering Decisions

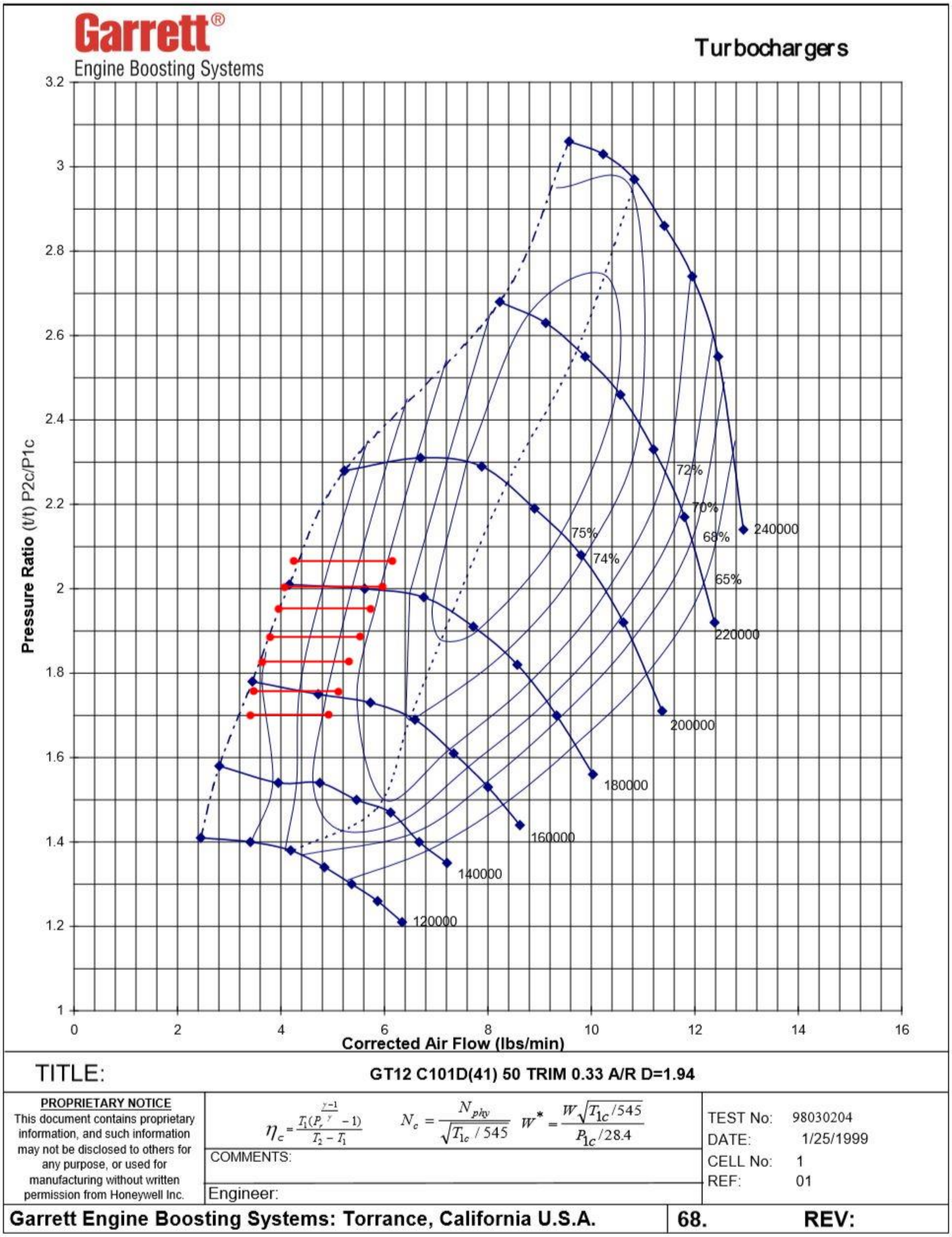
4.1 Turbocharger Selection

Garrett's Collegiate Design Series sponsorship is available to colleges and universities that compete in any of the Formula SAE or Formula Student events globally as well as some other college competitions while supplies last. Teams sponsored by Garrett will receive one turbocharger to be used in their competition

Current offerings:

- GT12 C101D
- GT14 C101D

The turbo charts provided from Garrett are given below. According to these charts the decision of the final turbo charger were taken.



$$\eta_c = \frac{T_1(P_r^{\frac{\gamma-1}{\gamma}} - 1)}{T_2 - T_1} \qquad N_c = \frac{N_{phy}}{\sqrt{T_{1c}/545}} \qquad W^* = \frac{W\sqrt{T_{1c}/545}}{P_{1c}/28.4}$$

Figure 13 - Compressor Map of GT12 C101D

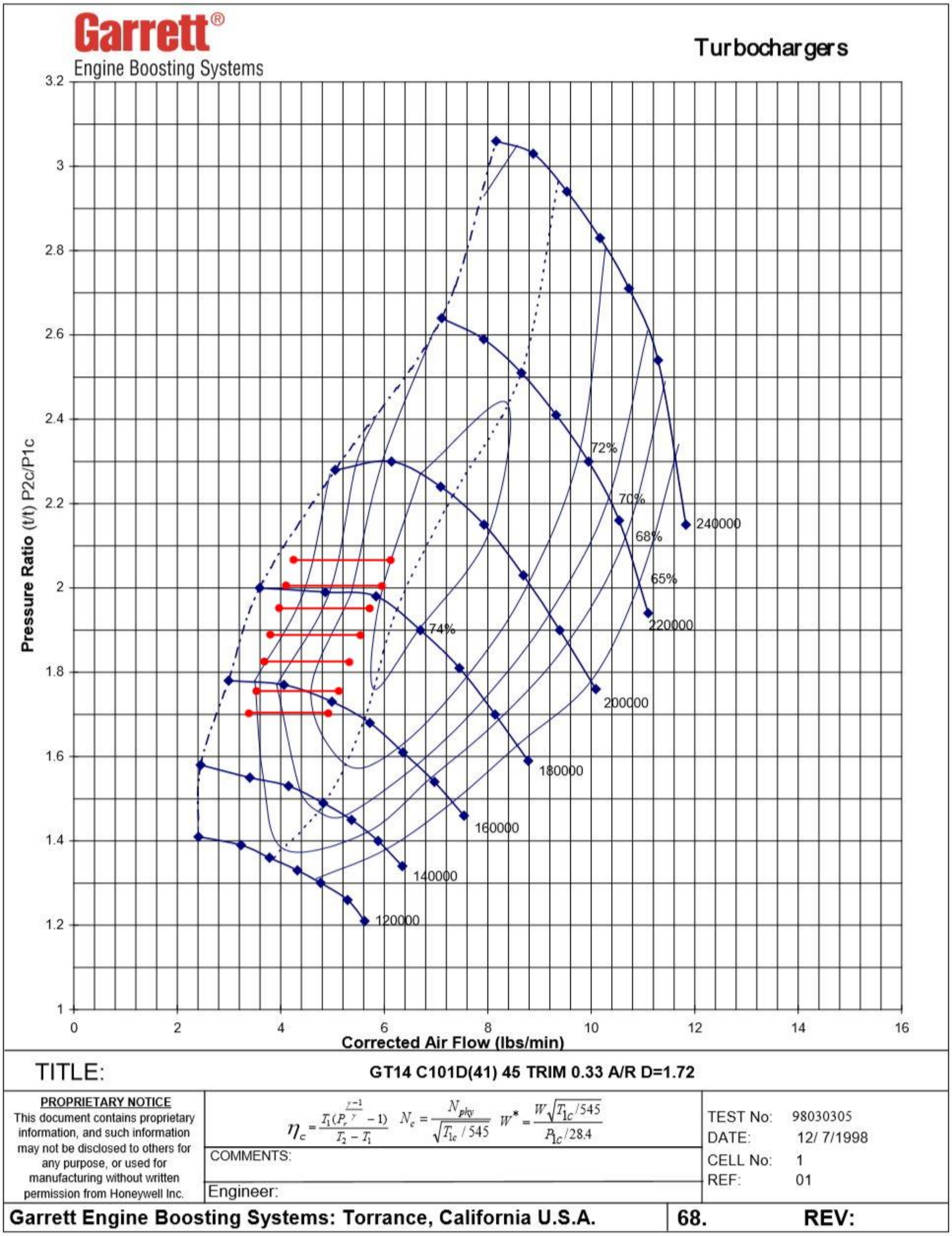


Figure 14 - Compressor Map of GT14 C101D

On plotting the points of the compression ratios and mass flow rates onto the compressor maps of the two turbochargers, we found that the operating range of the system was closer to the higher efficiency islands in case of GT14 turbo for the targeted range of 48 hp to 60 hp. **Hence, the GT14 turbocharger was selected.**

4.2 Boost control

To successfully integrate a turbocharger into an engine system you must accurately control the air flow into the engine. If the turbocharger is providing more airflow than the engine can accept, then extreme pressure can build in the intake manifold and cylinder that will most certainly damage the engine and possibly the turbocharger. There are several ways to control this pressure, commonly known as boost pressure, so that it does not reach damaging levels. However, because we have chosen the Variable Nozzle Turbine (VNT) turbocharger, the responsibility of controlling the boost pressure lays solely on the correct controlling of the vane position. The four types of control systems that are used to accomplish this are: hydraulic, pneumatic, electrical, and mechanical. Most often a combination of two of these types is used to create the control system for the vanes.

Hydraulic control is certainly the least used method of vane control and is usually only used in aerospace applications. This method requires a separate pump to provide the needed pressure of the working fluid, usually engine oil, to control the vane position.

Pneumatic control is the most common control method in the automotive industry. A separate pump may be used, but is not always necessary, to provide positive or negative pressure depending on the type of actuator that is used. Either a vacuum actuator or a positive pressure actuator can be used and the air pressure can be taken from the intake or exhaust manifold so that a secondary pump is not needed.

Electrical control is very common in the automotive industry, mainly in high performance or race applications. Most electrical control systems are integrated into a pneumatic or hydraulic system to produce quick response and additional benefits like enhanced boost settings and tuning. Mechanical control is the simplest way to control the vane position. This method takes advantage of the fact that the vane position is directly proportional to the throttle position. A linkage system with a spring is utilized to tie the throttle to the vane actuator.

Based on our understanding of these systems, we have chosen to use an electric control for the boost variation of our turbocharger. This is simple considering the mechanical linkage and the desired variation that can be obtained by the absolute pressure values given out by the MAP sensor to the ECU.

4.3 Intercooler selection

Most turbocharger systems that run more than 5-6psig of manifold pressure will typically require an intercooler. Despite the ill effects of the restrictor, positive pressure will still be attainable by the turbocharger. However, the turbocharger is most likely not running at its optimal efficiency range. When the compressor is operating in an inefficient location on the compressor map, high compressor discharge temperatures occur. Without an intercooler, high discharge temperatures (typically greater than 140°F) can lead to detonation, which can be harmful to the engine. Therefore, it was necessary to determine the expected compressor outlet temperature, so that the use of an intercooler could be justified. After all, intercoolers represent yet another restriction in the system and they also increase the weight of the vehicle, as well as the cost of the build. Equation below was used to find the aforementioned compressor outlet temperature:

$$T2 = T1 * \left(\frac{P2}{P1}\right)^{\left(\frac{\gamma-1}{\gamma*\eta}\right)}$$

With a low pressure ratio of 1.764:1, and compressor efficiency of 70% (assumed low as a safety factor), the outlet temperature was determined to be 315°F:

$T2 = 311 * 1.764^{\left(\frac{1.4-1}{1.4*0.7}\right)} = 392.1\ K = 246.1°F$ (118.94°C)

Another basic analysis for the sizing of the intercooler would be to calculate the heat flow rate of the air charge, using Equation below:

$$Heat\ Flow\ Rate\ (W) = Specific\ Heat\left(\frac{J}{kg * K}\right) * MAF\left(\frac{kg}{s}\right) * IAT(K)$$

$$Heat\ Flow\ Rate\ (W) = 1000 * 0.386 * 392.1 = 15135\ W = 15.135\ kW$$

Under the modeled conditions, which are likely to occur at some point in operation, engine damage is highly plausible if an intercooler is not used. In order to reduce the risk of harming the engine, as well as to maximize performance, the team decided to look out for fuel cooling options available to aid the intake charge cooling and helping to eliminate the intercooler.

4.4 Fuel System

One of the first decisions our team needed to make was which fuel to use to power the turbocharged engine. We needed to make the fuel type selection first because it would dramatically affect the calculations that would need to be done in order to correctly size a turbocharger for the engine. It would also affect the decision of what components we were going to need to buy to complete the turbocharging system. For example, the fuel injector that is currently on the car cannot be used with ethanol fuel. Many factors came into play in this decision, and they are all shown in the decision matrix in Table on the following page.

Criteria	**Weight**	**Fuel Type**	
		E-85	**91 Octane**
Availability (testing)	2	2	5
Availability (consumption)	5	5	5
Cost	4	3	4
Power output	5	5	2
Weight	5	5	1
Fuel Efficiency	3	3	3
Compatibility	4	4	5
Tuning Friendly	4	4	1
Uniqueness	4	4	1
TOTAL		**148**	103

Table 5 - Comparison of E-85 with 91 OCTANE

The largest factors weighing in on the fuel selection were the availability of the fuel at competition, the potential for safe power output, tuning ability, and the weight the fuel type would contribute to the car. Since the competition organizers provide the fuel and teams cannot bring their own fuel to run, selection is limited to what the organizers provide. Historically the higher octane race gas has been in short supply at competitions. Cal Poly has run into problems in the past with tuning an engine for race gas and then being stuck with pump gas at competition, causing reliability issues. E-85 has always been provided and is another high performance alternative to pump gas. Since reliability is one of the major design considerations we must tune for the fuel that we know the car will be running at the competition. The following paragraphs outline the fuel decision process in depth.

In order to begin the decision process, it was crucial that relevant properties of each fuel be fully understood.

Fuel Type / Characteristics	Ethanol	Gasoline	E-85 Perfect Mix (85% Ethanol,15% Gasoline)
Density (kg/m^3)	770	700	759.5
Latent Heat of Vaporization (MJ/kg)	0.84	0.35	0.77
Stoichiometric AFR	9	14.7	9.9
Ideal AFR	8	13.23	8.5

Table 6 - Properties of E-85

Density plays a role in determining how much volume of fuel is going to be required. For example, if we need equal mass amounts of gasoline and E-85 is going to take up more space on the car.

Lower Heating Value represents the amount of energy released from the complete combustion of one unit mass of fuel. Notice that E-85 has a lower value – implying that for a given amount of power output, 1.5 times the mass of fuel must be combusted (ideally).

Latent Heat of Vaporization is the amount of heat that the fuel takes from its surroundings in a constant temperature phase change from liquid to vapor.

The Stoichiometric AFR, as aforementioned, is the ratio of mass of air to fuel needed for a complete combustion of the fuel.

The Ideal AFR is the air to fuel ratio recommended for peak power output.

Another property that plays a large role in hardware choice is corrosiveness. Although E-85 itself isn’t much more corrosive than gasoline, its chemical properties cause it to attract water. This in turn accelerates oxidation in fuel lines, pumps, tanks, etc. Although this isn’t a large issue during engine operation because the fuel is constantly moving through the system, it can potentially damage components if left sitting for an extended period of time.

Cooling effects of E-85

Another property we must take into consideration is the latent heat of vaporization of each fuel. In order to analyze this, a simple thermodynamic model was created with hot air entering the control volume (intake runner), liquid fuel sprayed into the duct, then the combined fuel and air exiting the control volume (into the engine). Assuming that the intake runner is perfectly insulated and all the energy from the intake charge is used to vaporize the fuel, the temperature drop of the intake was calculated.

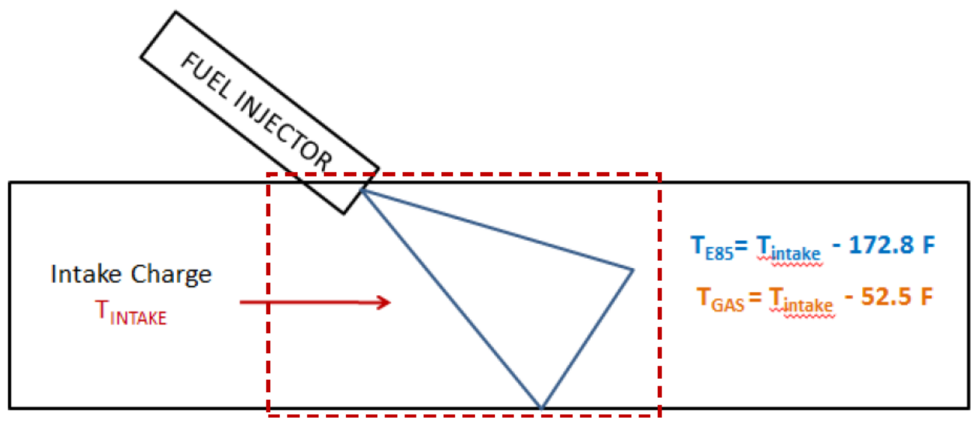


Figure 15 - Intake charge temperature variation

The figure above shows that the temperature of the intake charge after the fuel spray drops 172.8 °F with E-85, and 52.5 °F. Note that this temperature drop is independent of initial temperature of the intake charge. Some general temperatures we expect to see from the compressor outlet are around 200-300°F, so cooling the intake charge is extremely important.

A cooler intake charge is vital because it decreases chance of pre-detonation and knocking, and allows a denser mixture into the engine (more mass of air and fuel) allowing for more power output. Although it is possible to cool the intake charge with gasoline, it would be necessary to implement an intercooler. This would increase both packaging issues and system weight by around 5 kg.

Now, as per the calculated outlet temperature from the compressor (T2 = 264.1°F). After the fuel E-85 is sprayed, it cools down the charge by 172.8°F. Thus effective intake charge temperature is:

$$T2 = 264.1 - 172.8 = 91.3°F\ (32.94°C)$$

Potential Power

An important aspect of fuel selection is what operating point it allows the engine to run at. Operating point refers to maximum allowable compression ratio and boost pressure before pre-detonation occurs. To study this relationship, the following figure is introduced on the following page.

Finding an operating point with a balance of high compression ratio and high boost pressures is desirable. The high compression ratio lets the engine produce as much of its own power as possible without the need for high boost pressures, increases efficiency and improves low-end torque. However, we also want the power increase associated with increasing boost pressure. The three red, dotted lines represent the different octanes of gasoline available at the FSAE competition. Notice that at a given compression ratio, E-85 always has a higher boost pressure limit. Furthermore, the properties of E-85 give us a larger margin of error while tuning around the upper limit.

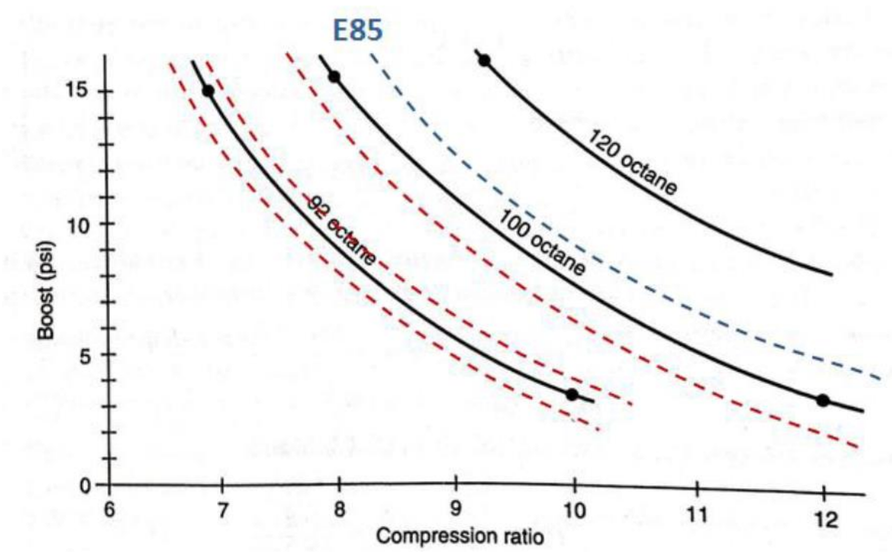


Figure 16 - Boost vs CR for different fuels

4.5 Lubrication System

For the oiling system of the turbocharger, oil has to be teed off from a suitable location of the engine where there is adequate pressure for the oil to flow through the turbocharger bearings. The oil must be below the maximum temperature specified by Honeywell.

According to "Maximum Boost," a good rule of thumb is to have a minimum oil pressure of 5 psi (0.34 bars) at 0.1 gal/min at idle and 25 psi (1.72 bars) at 0.5 gal/min at maximum load going into the turbo. The GT14, however, requires a pressure of 0.6 bar at idle, 1.7 bar at peak torque, and 5 bars at the rated speed. Oil temperature is usually one of the biggest issues that would cause turbocharger failure as coking occurs due to insufficient flow. This usually happens when the engine is shut off immediately after a very long, hot run and oil flow is stopped. When this oil flow stops the turbine and compressor are still spinning at a very fast rate heating up the oil hot enough for it to coke and destroying the turbocharger. To possibly prevent oil coking in the turbocharger Honeywell specifies that the oil entering the turbocharger be less than 130 °C (266 °F). If it is found out that the oil temperature is above this, then an oil cooler must be added to the system.

Contaminants and metal shavings from engine wear can also cause catastrophic failure to the turbocharger. The average engine usually has an adequate enough oil filtration system. However, turbocharger specifications will specify the oil filter size. If the OEM filtration system is not to the turbochargers specification an in-line oil filter to the turbocharger can be added. In the case of the GT14, it requires an oil filter of 15 microns.

To be sure the pressure and filtration requirements are met, the best place to T off the oil is the after the oil pump and filter. Most street vehicles use a spin-on oil filter where a sandwich plate can be added with no modifications to the engine block that even includes ports for pressure gauges and temperature sensors. However, the KTM390 uses a cartridge filter, so this option does not apply to us.

A solution to this would be to tee off the oil from the oil delivery pipe that goes from the oil filter to the top of the engine block. This part should have enough pressure for flow and it is also an external interchangeable part that would be a cheap fix in-case a mistake is made during the modification process. To ensure that the oiling system works without any leaks and problems the correct hoses and fitting should be used. These include 1in fittings and steel braided hoses.

Once the oil has been teed off it has to go into the turbocharger at an angle that allows the outlet to be within 20° of vertical with the vehicle on level ground. This will ensure that gravity can drain the oil from the turbocharger sufficiently to keep the oil circulating. After the oil has gone through the turbocharger it will have to be either drained back to the sump or crank case. In this case, oil will be drained back to the case

1. Suction Pump
2. Force Pump
3. Oil Filter
4. Oil Pressure Regulator Valve
5. Oil Jet for Piston Cooling
6. Oil Spray Tube
7. Oil Jet for Cam Follower Lubrication

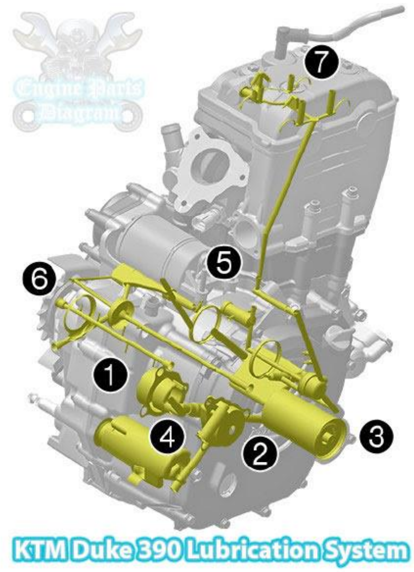


Figure 17 - Lubrication system of KTM Duke 390

Another failure in the oiling system can happen when the oil returning enters below the oil level in the case. This can cause oil to back up into the turbocharger, heat up, and coke up the bearings. If it is not possible to return the oil above the engine oil level, a scavenging pump will be required to ensure that the oil will not back up into the turbocharger. The turbocharger should also not be mounted below the pump. It is extremely important that the scavenging pump is capable of out flowing the oil leaving the turbo. To ensure that a scavenging pump will not be required, the turbocharger will be located well above the oil level in the engine case.

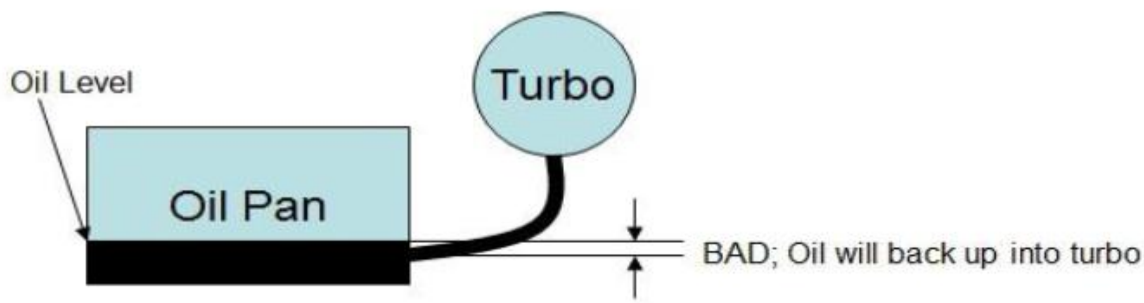


Figure 18 - Lubrication System (1) – SL Racing

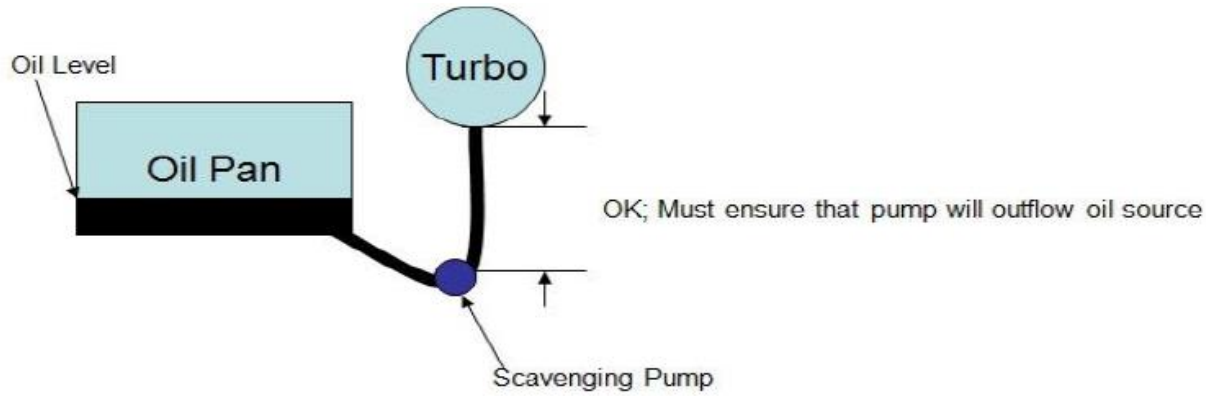


Figure 19 -Lubrication System (2) – SL Racing

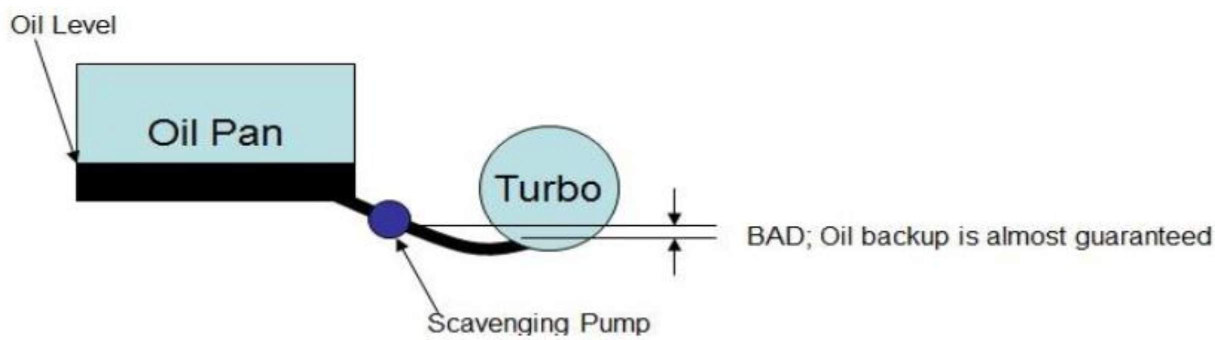


Figure 20 - Lubrication System (3) – SL Racing

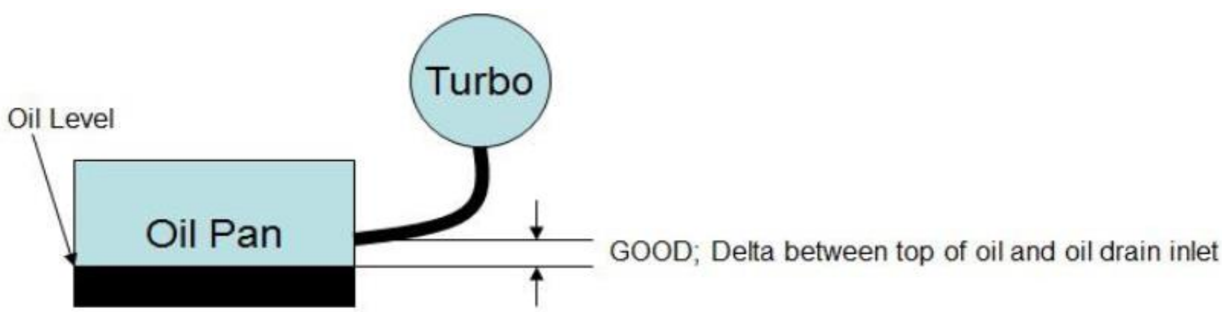


Figure 21 - Lubrication System (4) – SL Racing

Due to the regulations on the order of intake components, there will be some issues concerning the compressor oil seals. The problem arises due to the throttle being placed ahead of the compressor. This creates a significant vacuum under certain conditions such as idle and quickly letting off the throttle. In turn, oil can be drawn from the center section of the turbocharger, past the compressor seals, and into the intake tract. This oil burning causes the buildup of deposits in the combustion chamber and can even cause oil starvation in the crank case if enough is burned. To prevent this, Honeywell has suggested a style of positive crankcase ventilation to keep the pressures in the compressor and oil return line equalized. With this setup, the entire crank case is under vacuum so that the oil is sucked into the drain line instead of the intake. In order to comply with FSAE rules, the crankcase vent line must first be routed to a catch can and the connection to the intake must be located ahead of the restrictor as shown.

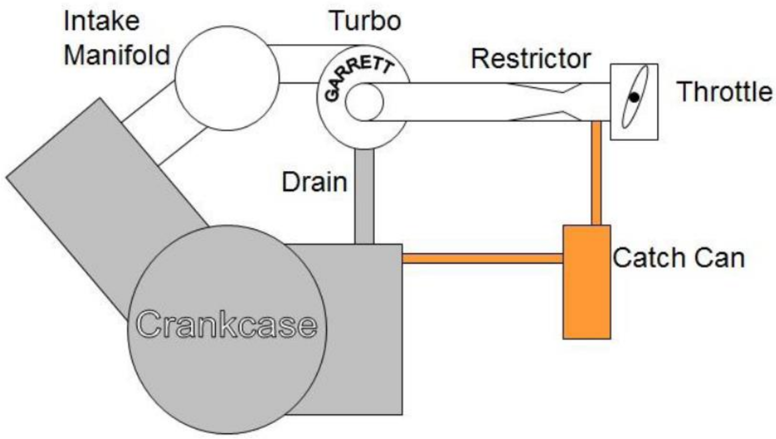


Figure 22 - Modified Lubrication system – SL Racing

4.6 Engine Preparation

The compression ratio is an important parameter of the engine that will affect the power delivery characteristics, fuel choice, boost level, and efficiency.

The static compression ratio (static CR) of an engine is defined as:

$$SCR = \frac{V_{bdc}}{V_{tdc}}$$

Where V_{bdc} is the volume in the cylinder when the piston is at bottom dead center and V_{tdc} is the volume in the cylinder at top dead center. This is the compression ratio most often discussed and listed in engine specifications. The higher the compression ratio, the more work can be extracted from the fluid. The dynamic compression ratio (dynamic CR) is the effective compression ratio that the engine sees while running. While the static CR is defined simply by the geometry of the engine, the dynamic CR is influenced by multiple factors such as the engine geometry, cam timing, intake pressure, connecting rod length, and volumetric efficiency.

The dynamic compression ratio (DCR) of an engine is defined as:

$$DCR = \frac{V_{ivc}}{V_{tdc}} * \left(\frac{P_{boost} + P_{atm}}{P_{atm}}\right) * VE$$

Where V_{ivc} is the volume in the cylinder when the intake valve closes, P_{boost} is the boost pressure above atmospheric, P_{atm} is atmospheric pressure, and VE is the naturally aspirated volumetric efficiency of the engine. Due to different volumetric efficiencies at different engine operating speeds, only the maximum value is used to calculate the dynamic compression ratio. It is the dynamic CR that determines how much the fluid is actually compressed during engine operating and therefore the minimum octane rating necessary to avoid predetonation. This is why some engines require 100+ octane with an 11:1 compression ratio while others are perfectly fine on 91 octane with a 13:1 compression ratio. E-85 has an equivalent octane rating of 105, and with an expected operating temperature of around 180°F, the maximum dynamic CR is slightly above 10.5

When it comes to turbocharged engines, the effective compression ratio depends largely on boost pressure. As the Dynamic CR approaches the maximum value, the fuel and ignition tuning have almost no room for error. We want this system to have some margin for error because it is the very first iteration, but we also want to leave room for future FSAE teams to be able to expand. The results for the calculated effective compression ratio over a range of static ratios and boost pressures are shown in table below. Calculations for the dynamic CR are shown below. The reason that the lowest static CR was not selected even though it is safe at all boost levels on the chart is because lower compression ratios will not give good off-boost performance. The total power output from the engine can be split into two categories: power from the base engine and power added by the turbocharger. With a lower static CR the power from the base engine is reduced and the turbocharger is relied upon more heavily to produce the desired power. Since the engine must be spinning at a certain speed for the turbocharger to produce boost, lowering the static CR reduces performance below this threshold. This system will be running 6.75 psi of boost, and based on the criteria a compression ratio of 12.88:1 which is default is considered to be safe.

Boost (psi)	6	6.75	7.5	8.25	9	9.75	10.5
Power (hp)	48	50	52	54	56	58	60
Static CR	Dynamic CR						
10	7.22	7.48	7.74	8	8.26	8.51	8.84
10.5	7.54	7.815	8.09	8.365	8.64	8.91	9.23
11	7.87	8.155	8.44	8.725	9.01	9.29	9.57
11.5	8.2	8.4975	8.795	9.0925	9.39	9.68	9.99
12	8.52	8.83	9.14	9.45	9.76	10.07	10.41
12.5	8.85	9.17	9.49	9.81	10.13	10.42	10.69
13	9.03	9.37	9.71	10.05	10.39	10.61	10.98
13.5	9.28	9.63	9.98	10.33	10.68	10.92	11.32
		DCR<9.5	9.5<DCR<10.5		DCR>10.5		
			KTM Duke 390				
Boost (psi)	6	6.75	7.5	8.25	9	9.75	10.5
Power (hp)	48	50	52	54	56	58	60
Static CR	Dynamic CR						
12.88	8.94	9.27	9.6	9.93	10.26	10.515	10.835

Table 7 - Dynamic CR and Boost available

5 Modifications Required

Following are the list of modifications to be done in the existing system to incorporate the designed turbocharged system effectively.

5.1 Engine Modification

Whenever an engine's output is raised significantly above its stock power level, the chance of component failure greatly increases. Some stock parts are strong enough to withstand the increased stress but there are always weak links in the system. Due to limited time, money, and resources, we relied on the experience of professional motorcycle engine builders to determine what components need to be upgraded instead of waiting for our engines to destroy themselves. These professionals have spent years testing hundreds of engines at all power levels from completely stock to absolutely crazy so they know exactly what is going to break and at what point it is going to break. Based on their recommendations for the KTM Duke 390 engine we selected the following components to be upgraded since the engine was used for 3 years and was also tuned during its usage period:

- Piston
- Connecting Rod
- Crankshaft
- Lubrication Oil
- Valve Springs
- Cylinder Head Gasket
- Clutch Plate

5.1.1 Piston

The stock piston suffices the need as it is able to withstand a higher pressure of the system. As per the talks with the KTM personnel, The replacement of a new piston will ensure better reliability once the turbo charged system is driven and also the piston will endure the higher intake pressure. Thus, there was no part upgrade in the piston department, only a new OEM piston head was purchased. Also now the 2018 spec KTM parts are available which are more reliable and have more refined manufacturing processes involved. Thus the old 2013 piston head was replaced by a new KTM duke 390 2019 spec piston head.

5.1.2 Connecting Rod

Unlike the piston head, here we had to opt for a connecting rod which would be able to withstand impacts of higher loads. The KTM 450 engine of a dirt bike has a higher strength material used in its connecting rod. The connecting rod is responsible for transmitting the force generated by the combustion process to the crankshaft and for controlling the motion of the piston. These two forces, the first in compression and the second in alternating compression and tension, are caused by two distinct engine parameters. When the torque level is increased, the force acting through the connecting rod is increased as well. The second force depends entirely on the mass of the piston, the mass of the connecting rod, and the speed of the engine. It is the combination of everything from increased power to more mass that drives the need for a stronger connecting rod, even though the maximum engine speed will be reduced from stock.

Thus the selected new connecting rod was borrowed from the dirt bike engine category of KTM, 450cc engine, which had the same stroke and a more strength when compared to the existing component

5.1.3 Crankshaft

As the connecting rod of this system was different from the OEM design, engine balancing is considered. Here the connecting rod of the system is 200gms heavier and also has a different mass distribution around its area. Here the selection of KTM 450 crankshaft is not possible as the system is not compact, and also using the same will be only possible if the engine casing is self-manufactured. Hence, we went back to KTM for their advice regarding the issue of engine balancing. They offered to help us by providing a custom manufactured crankshaft which would be compact as well as reliable, but the time of availability was unsure. The other option was to go with a 2019 spec crankshaft from the 390 model and sacrifice on reliability by around 10% due to the extent of balancing it would offer. As per the testing schedule of the FSAE car, the OEM crankshaft would last for one competition and then further will require servicing. Considering the time of production and also the testing time in hand, we decided to go with an OEM KTM 390 2019 spec crankshaft.

5.1.4 Lubrication Oil

The lubrication oil rated for the KTM Duke 390 bike is MOTUL 7100 4T 20w50, a semi-synthetic oil. During our FSAE season and testing, we prefer to use a 100% synthetic oil as it is better in terms of retaining its viscosity and also thermal heat reduction. The lubrication oil that we use is MOTUL 300V 15w50 which is a high performance lubrication oil used in dirt bikes and super bikes. When using a turbocharged system, the temperature of the system increases, but due to the usage of a 100% synthetic oil instead of a semi-synthetic oil provides better lubrication and wear resistance of transmission.

Hence, the earlier switch to MOTUL 300V 15w50 oil suffices the need of the turbocharged system and does not require an upgrade in the lubrication oil department.

5.1.5 Valve Springs

Now that the bottom end had been appropriately strengthened, the next step was to look at the cylinder head. When an engine is turbocharged, both the intake and exhaust pressures are raised to well above atmospheric conditions. This means that the pressure, and therefore the force, acting on the back side of the valves has increased as well. The purpose of valve springs is to close the valves after they have been opened and to hold them closed until the next time the camshaft pushes them open again. Since the forces of the intake and exhaust pressures are acting in the direction that would push the valves open, the effective spring rate, and therefore the force, closing or holding the valves closed has been reduced. At 6.75 psi of intake boost (about 10.5 psi for the exhaust) this equates to a reduction of 3.9 pounds (18% of seat pressure) for each intake valve and 6.4 pounds (29% of seat pressure) for each exhaust valve. This increases the risk of "valve float," where the valve does not stay in contact with the camshaft, and corresponding valve to piston contact. The solution to this problem was to install stiffer springs from a local manufacturer who had helped in manufacturing suspension springs for the FB2020 competition. The dual rate springs hold the valves closed with 25% more force than the stock KTM springs (33lbs vs. 26lbs) and have a 38% higher spring constant (89 lb/in. vs. 63 lb/in.) KTM installed titanium valves on the Duke 390 in order to reduce the reciprocating mass and allow the engine to rev higher, but stainless steel is better at conducting heat away from the cylinder and will typically last longer before wearing out. It was decided that stainless steel valves would not offer any performance benefits at this time so they were not installed.

5.1.6 Cylinder Head + Gasket

Higher power levels, especially when achieved by forced induction, produce much higher cylinder pressures. These higher cylinder pressures place more force on all of the sealing surfaces around the cylinder. When everything is sealed properly all of the force goes into driving the piston down and producing power. However if there is one weak point, all of the pressure will try to escape from there. This is why it is so important to install a high quality head gasket between the cylinder and the cylinder head. A multi-layer steel (MLS) head gasket from KTM was installed in place of the stock gasket.

Along those same lines, the higher cylinder pressures produce a greater force acting downward on the piston. Newton's first law states that every action has an equal and opposite reaction, and in this case that reaction is trying to separate the cylinder head from the rest of the engine. The KTM Duke 390 comes with 4 long bolts holding the cylinder head in place. These bolts are adequate for stock power levels but they cannot withstand much more. They are designed to be torqued to their yield point, so tightening them beyond factory specifications will not produce any extra clamping force.

Thus the OEM KTM head was replaced by the 2019 spec head along with multi-layer steel (MLS) head gaskets from KTM to ensure durability in high operating pressures.

5.1.7 Clutch Plate

The transmission gears are capable of holding up to the increased power level, but the clutch needed to be strengthened to handle the torque without slipping. The clutch itself consists of 15 plates; 8 are mechanically connected to the crankshaft and 7 are connected to the transmission. Engine torque is transferred to the transmission through friction contact between these plates and the friction is directly proportional to the force clamping the plates together. The stock KTM 390 clutch can transfer a maximum of 40 N-m of torque before slipping. The most effective way to increase the torque capacity of the clutch is to install stiffer clutch springs to increase the force clamping the clutch plates together or using an aftermarket slipper clutch. As per the specification of OEM KTM 390 clutch, Rekluse manufactures slipper clutches for KTM Duke 390, and the same was used for our project.

5.2 Intake Modification

5.2.1 Design

The idea was to incorporate the new turbocharged intake system into the previous car. The intake geometry of last car is shown below, here we had to ensure that the new turbo will be connected in such a way that the intake routing and components remain the same, only a connection from the turbo compressor will be made to the air filter section and the throttle body. Since we had eliminated the intercooler, the charge air must be cooled even before the plenum since it is an SLS manufactured part. To ensure the charge air to be cooled through natural air flow, we have decided the routing of the system which enables cooling through air flow when the car moves, and the connection pipe is made up of Al 6061, which is light in weight and also helps in thermal heat transfer to cool the charge. Also the core intake geometry which involves the plenum and runner is unchanged as they were found to be reliable and also produce a considerable power range even with a restrictor. Below you can see the new layout and previous layout of the whole system.

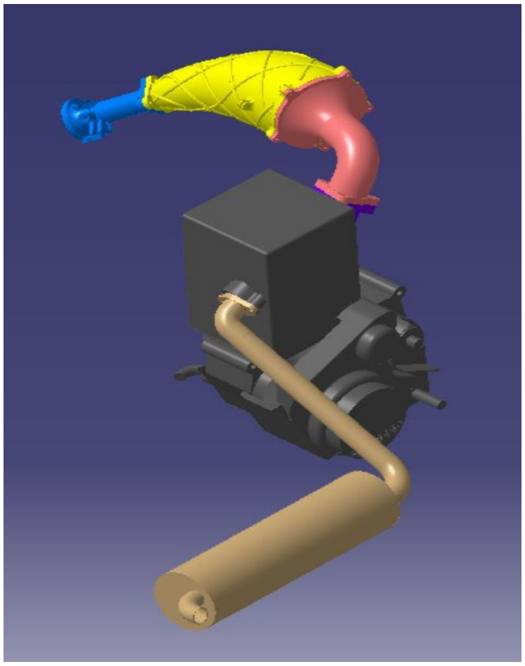


Figure 23 - Last year layout

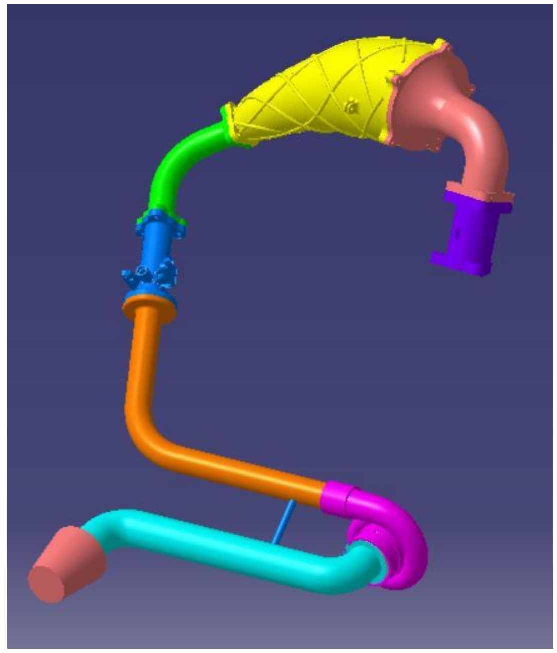


Figure 24 - Turbocharged Intake layout

Here, one can see the parts as follows:

Part Name	Color	Material
Air filter	Pink	Foam
Air filter connector	Light Blue	Al 6061
Turbocharger compressor	Magenta	Cast iron
Intake pipe connector	Orange + Green	Al 6061
Throttle body	Dark Blue	ABS plastic
Plenum	Yellow	ABS plastic
Runner	Pink	ABS plastic
Intake port	Purple	Al 6082

Table 8 - Turbocharged intake system

The Al 6061 pipes acts as a thermal stability part to ensure that the air is cooled and does not harm the SLS parts further down the line.

5.2.2 Simulation – CFD

Now, to check the flow characteristics of the intake system, CFD simulation was carried out on SimScale. The CFD setup is explained below:

Setup:

Type: Incompressible flow analysis

Turbulence model: k – ω SST

Initial k (turb. kinetic energy): 0.06 m^2/s^2

Initial ω (specific dissipation rate): 30.4 1/s

Pressure inlet: 146603.224 Pa (total pressure)

Pressure outlet: 0 Pa (fixed value)

Mesh fineness: Coarse

Mesh refinement: 0.0025m

Solver U, P, k, ω: Smooth solver

Results:

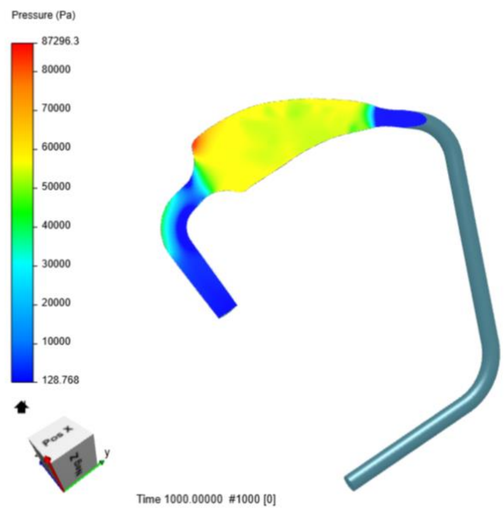


Figure 25 - Intake pressure slice

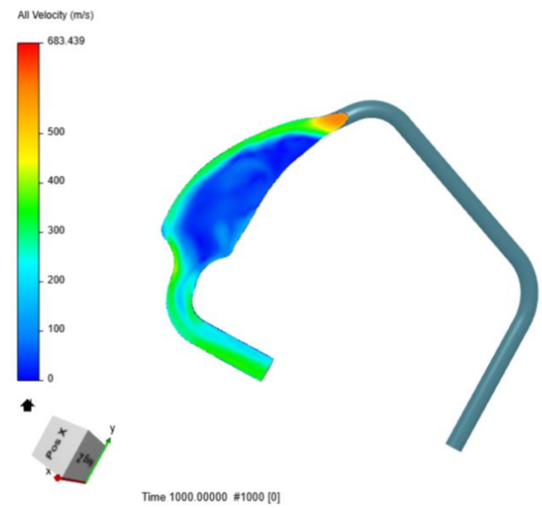


Figure 26 - Intake velocity slice

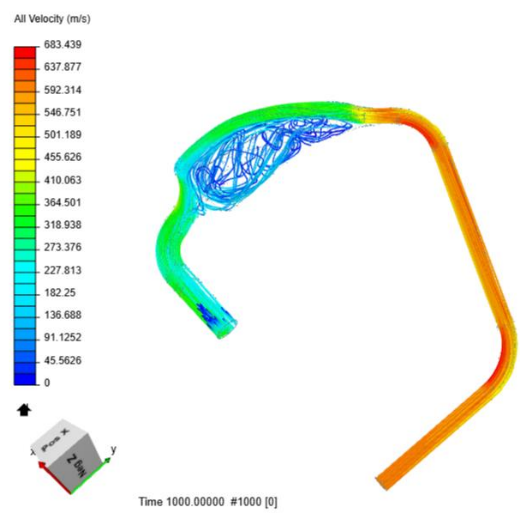


Figure 27 - Intake velocity particle trace

Inference:

From the pressure slice, we come to know that there is no stagnation or negative pressure being generated in the system and also the flow is of almost stable when it comes to the pressure distribution across the plenum. This means that the work of the plenum to act as a storage compartment for the air when it is needed is being properly executed as there is very less pressure variation in the value of pressure.

From the velocity slice, we get to understand the variation in the intake velocity of charge that is received by the engine. Here we can clearly see that the design of the plenum is perfect when compared to its storage property and the velocity is increased in the runner section which helps in improving the mass flow rate and hence improving the volumetric efficiency of the complete system.

Lastly the particle trace of velocity shows that there is very less disruption in the flow and the visible turbulence is seen in the plenum region for accounting the air storage capability. This ensures that even during sudden acceleration, the air stored is readily available to provide boost to the engine and thus improving the volumetric characteristics.

Hence, as per the preliminary results, the design of intake is capable of providing adequate air flow during acceleration and also has less disruption in flow which avoids large amount of turbulence.

5.3 Exhaust Modification

5.3.1 Design

To start with the exhaust system, the muffler design was kept similar to last year as it produced significant amount of flow to go through without disruption. Also the engine was already tuned for maximum power output for the dedicated system, hence we decided to stay with the earlier muffler design. The only setup change was to connect the exhaust port outlet to drive the turbo section and then the turbo outlet to the manifold. The material used for the exhaust outlet was the same as the exhaust manifold material, i.e. SS 316. Stainless Steel 316 pipe provides better corrosion resistance at high temperatures and also better thermal conductivity. Hence this was used for the complete exhaust setup. Below are the images of the previous exhaust setup and the new exhaust setup for the turbocharged system.

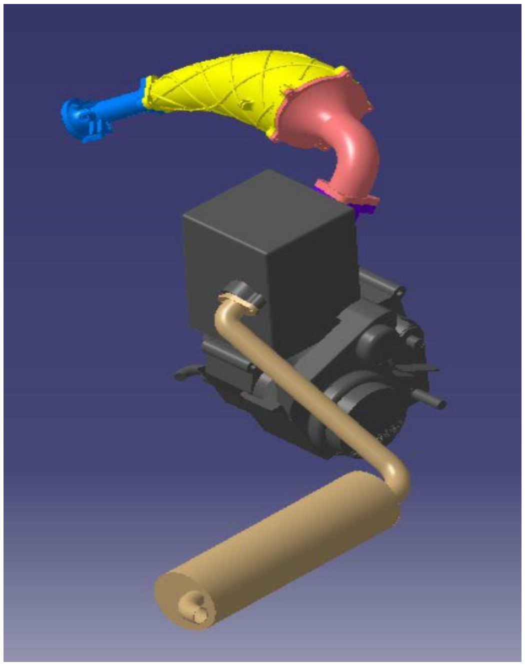


Figure 28 - Last year layout

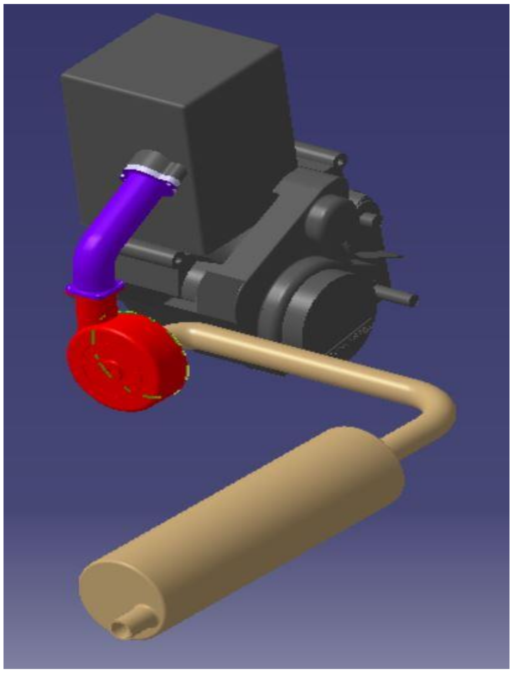


Figure 29 - Turbocharged Exhaust layout

Here one can see the parts as follows:

Part Name	**Color**	**Material**
Exhaust port pipe	Purple	SS 316
Turbocharger turbo	Red	Cast iron
Exhaust manifold	Brown	SS 316
Muffler	Brown	SS 304 casing + baffles

Table 9 - Turbocharged exhaust system

This setup was reliable and consists of very minute changed indicating the same power output stability is ensured.

5.3.2 Simulation – CFD

Now, to check the flow characteristics of the exhaust system, CFD simulation was carried out on SimScale. The CFD setup is explained below:

Setup:

Type: Incompressible flow analysis
Turbulence model: k – ω SST
Initial k (turb. kinetic energy): 0.12 m^2/s^2
Initial ω (specific dissipation rate): 148.5 1/s
Velocity inlet: 27.14 m/s (fixed value)

Pressure outlet: 0 Pa (fixed value)
Mesh fineness: Coarse
Mesh refinement: 0.0025m
Solver U, P, k, ω: Smooth solver

Results:

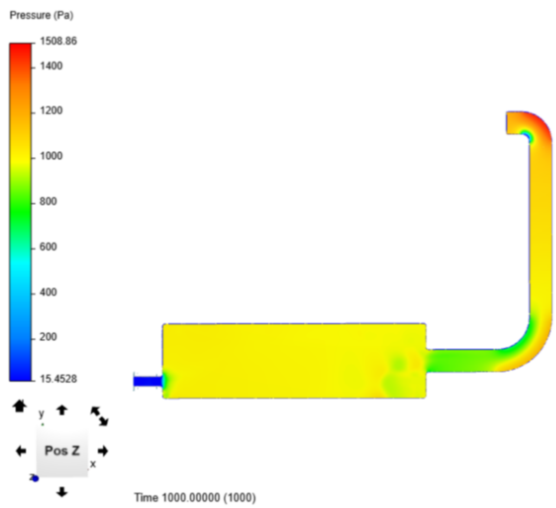


Figure 30 - Exhaust pressure slice

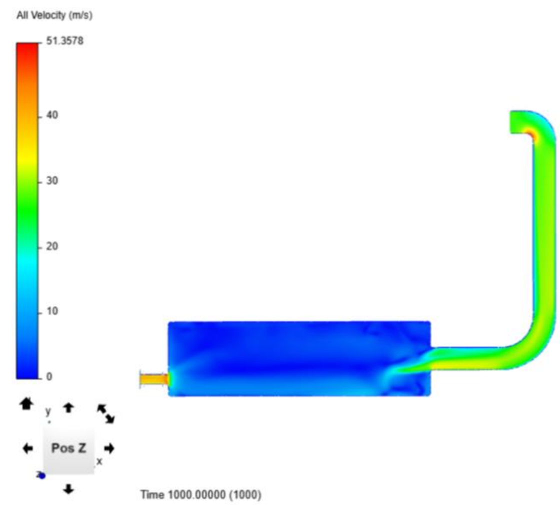


Figure 31 - Exhaust velocity slice

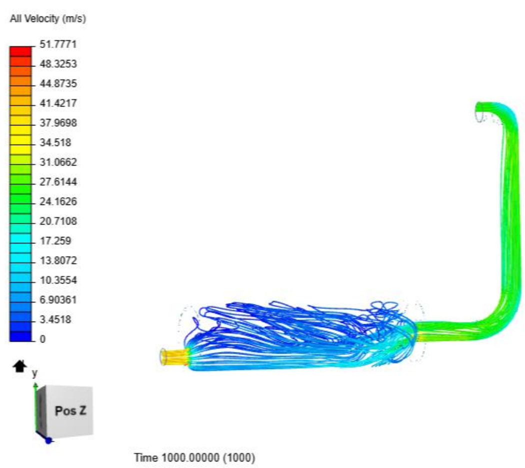


Figure 32 - Exhaust velocity particle trace

Inference:

The pressure and velocity slices show the distribution of the same, as per the visual appearance there is no back flow being created in the system which ensures proper delivery of gases to the atmosphere. This indicated that there is no accumulation of gasses in the muffler system.

According to the velocity particle trace, there is randomness in the muffler region. But according to the actual design, we have baffles in the system which helps in reduction of randomness and also the exhaust noise. Thus this result will be improved with the presence of baffles.

Hence, according to these preliminary results, the exhaust system behaves the same as the previous car and is capable of delivering high power-band values and performance. The presence of baffles adds to the performance level and there is no back flow observed in the exhaust system.

5.4 Fuel tank Modification

For our fuel choice, we implemented E-85 to take advantage of the benefits outlined above. After the fuel was chosen, the main goals of the fuel system were to provide adequate fuel pressure, filter the fuel properly, and prevent corrosion.

To provide adequate fuel pressure, we chose the same KTM fuel pump. We didn't change the injector, which was an RC Engineering SH4-750 injector. The main changes we made from our initial design included plumbing details, filters, and fuel tank. Our previous fuel tank was full of gasoline, made of stainless steel, and dirty. FSAE was also interested in replacing the tank, so we purchased a new fuel tank made of polyethylene for excellent corrosion resistance.

After looking into the E-85 community, and with personal recommendations from Matt Bezkrovny, the best fuel filtering setup was a 100 micron filter before the fuel pump, and 10 micron afterwards. To plumb the lines, we were initially going to use United Rubber Pro-Flo Nylon braided hose, but research indicated that ethanol dried and cracked nitrile rubber lines to the point where the fuel would bleed through the walls of the hose. For that reason, we decided to use Aeroquip's Teflon stainless steel braided hose (PTFE hose), and their hose ends.

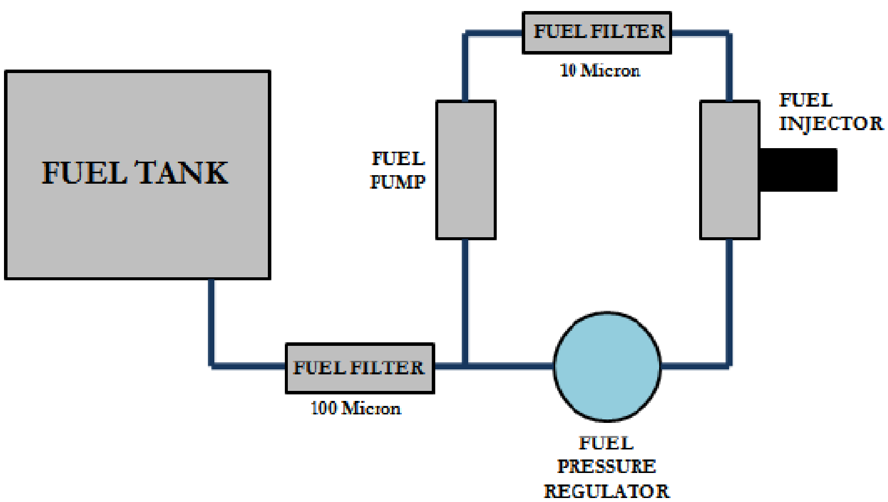


Figure 33 - Fuel system schematic

5.5 Lubrication System Modification

The oiling system proved, by far, to be the most difficult sub-system to successfully integrate with the turbocharger. The original goals of the oiling system included:

- Provide adequate oil pressure to the turbocharger
- Provide adequate oil return system from the turbocharger
- Maintain safe oil temperatures
- Filter oil adequately
- Minimize oil burned through the engine

In our attempt to address these issues, we went through multiple iterations and found that the most adequate system was one where we ran an oiling system in parallel with the engine. The oil supply was teed off of the oil pump, fed to the turbocharger, and drained to a scavenge pumping system which returned the oil to the oil sump. We also implemented an oil cooler before the engine supply to keep temperatures lower.

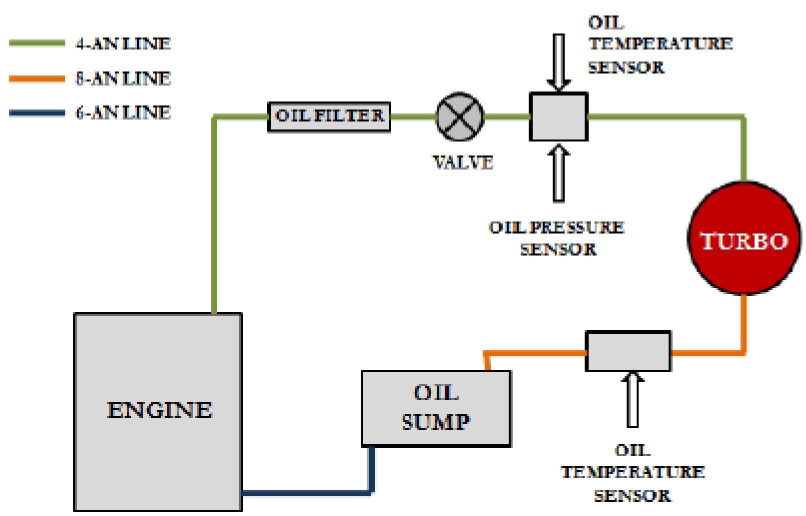


Figure 34 - Lubrication system schematic

6 Model Layout

6.1 Naturally aspirated system (Previous year vehicle-FB19)

The intake manifold along with the plenum and restrictor were routed along the right-hand side of the vehicle in accordance with the envelope defined in the rules, where in these components were required to be within its limits. The exhaust manifold was routed such that the muffler came within the left side pods. Keeping in mind the flow characteristics of the air, the intake and exhaust manifold was routed for most efficient flow of air, given all the dimensional and spacial constraints

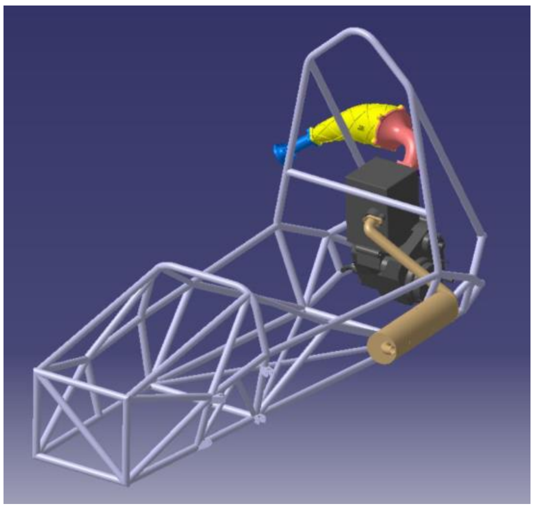


Figure 35 - FB19 vehicle (1)

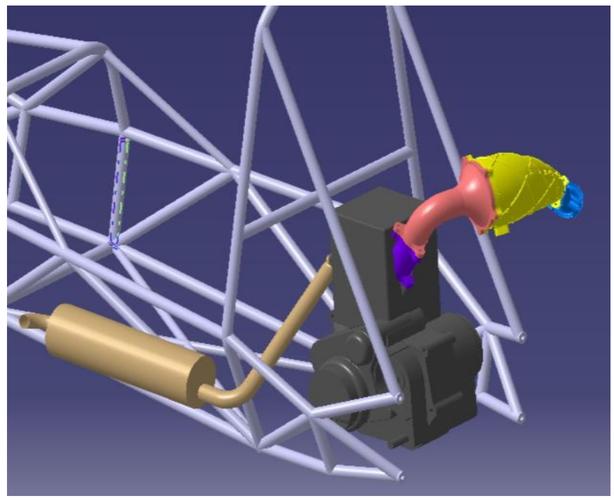


Figure 36 - FB19 vehicle (2)

6.2 Location of turbocharger

We tried keep the turbine of the turbocharger as close to the exhaust in order to reduce the thermal and kinetic energy loss of the exhaust gases due to longer routing and piping. The turbocharger was placed just behind the seat and as low as possible in order to lower the centre of gravity of the vehicle. At this position a streamlined elbow attached the exhaust of the engine to the inlet of the turbine.

The compressor shaft being coupled to the turbine doesn't allow for axial adjustments of the compressor, but can be rotated. Hence, it is positioned such that the exit of the compressor points straight towards the right-hand side of the vehicle opposite to the exhaust. This makes it feasible for attachment to the previously existing intake plenum.

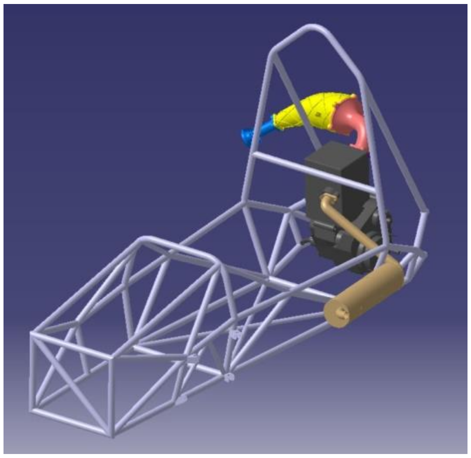


Figure 37 - FB19 vehicle layout (1)

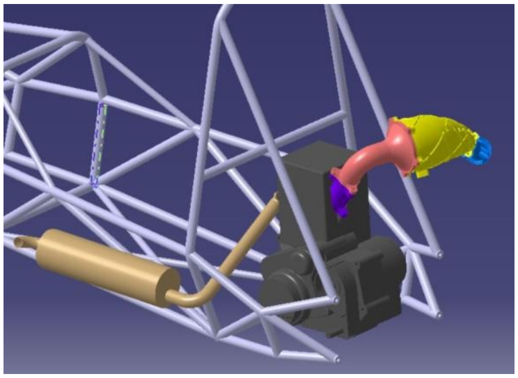


Figure 38 - FB19 vehicle layout (2)

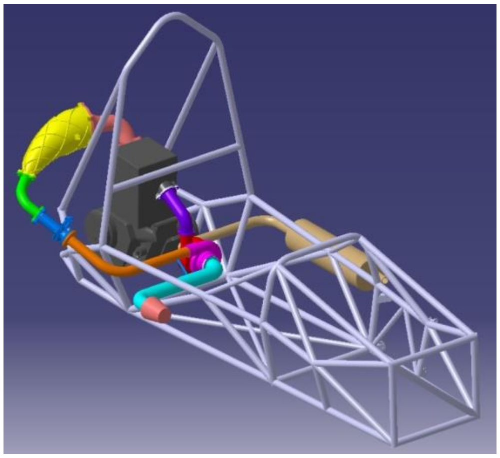


Figure 39 - Turbocharged vehicle layout (1)

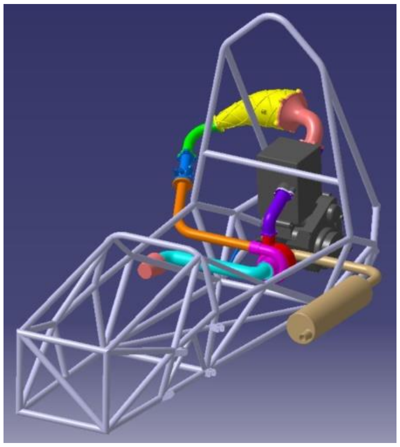


Figure 40 - Turbocharged vehicle layout (2)

6.3 Final model

Below is the final layout which explains the complete airflow in the turbocharged system.

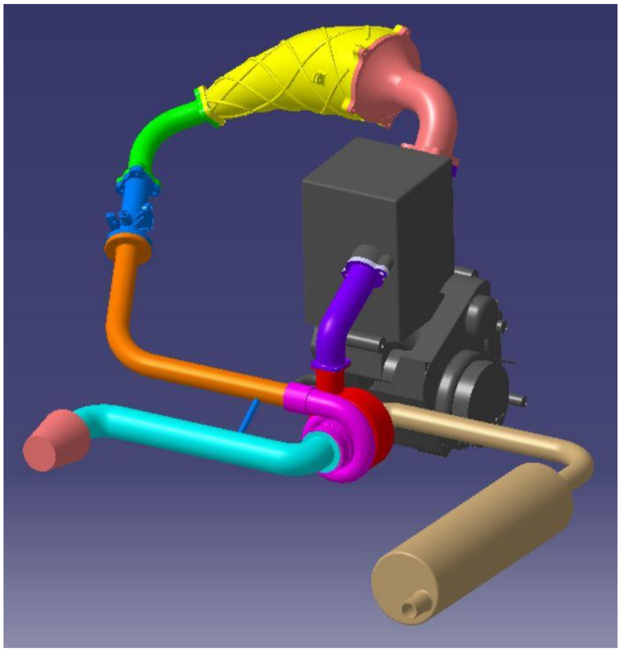


Figure 41 - Turbocharged engine model layout

The air enters the through the air filter and followed by the restrictor (not shown) enters the inlet of the compressor (pink) of the turbo through the compressor inlet pipe (light blue). The compressed air from the compressor is pushed to the intake manifold through the intake routing pipes (orange and green), intake plenum (yellow) and runner (pink), while the flow rate being controlled by the throttle body (dark blue). The exhaust gases leaving the engine pass through an elbow (purple) to the inlet of the turbine (red). The gases then exit the turbine into the exhaust muffler(brown) and into the atmosphere.

The entire system was to be incorporated in an already compact existing system. This helped to keep the weight to minimum and reduce turbo lag.

7 Project Simulated Results

7.1 Powerband Analysis

A powerband of an engine is its primary operating range. The minimum and maximum engine speeds are typically determined by engine geometry such as bore/stroke ratio and overall configuration. The powerband is designed around the intended use of the vehicle. A vehicle can be used for towing, commuting, racing, etc. Each design scenario will have different parameters, which will be altered. The powerband of an engine can be tweaked through changing the maximum engine speed (redline), through cam selection, through intake and exhaust manifold design, and through turbocharger sizing. A city transportation bus will have different requirements than a motorcycle designed for track use.

The basic laws of motion govern the motion of a vehicle. The acceleration is proportional to the force and inversely proportional to the mass. For a racecar, the acceleration should be optimized by increasing the force as much as reasonably possible and reducing unnecessary mass. Equation below shows the interaction between force, mass, and acceleration:

$$Force = Mass * Acceleration$$

The two primary ways to characterize and engine's performance are the power and torque that they produce. These two characteristics are linked by engine speed, as seen below:

$$Power(watts) = Torque\ (N * m) * Engine\ Speed\ ({}^{radians}/_{sec})$$

In order to increase the power of a vehicle, there needs to be an increase in the torque and/or engine speed. Power plays a crucial role in the dynamics of a vehicle. The power output required to sustain a certain force (mainly drag) at a certain velocity is:

$$Power = Force * Velocity$$

The force from an engine is calculated from the engine torque after drivetrain losses, multiplied by the various gear ratios for that selected gear and divided by the wheel radius. This can be seen below:

$$Force\ from\ engine = \frac{Engine\ torque * Gear\ ratio}{Wheel\ Radius}$$

The power of an engine can be estimated by the heat of combustion of the fuel, the fuel mass flow rate, and the energy conversion efficiency. This relationship is shown below:

$$Power\ Output = Conversion\ Efficiency * Heat\ of\ combustion * Fuel\ Mass\ flow\ rate$$

The conversion efficiency is the product of the various efficiencies affecting the process of converting chemical energy to mechanical energy. This can include anything from combustion efficiency, thermal efficiencies (heat losses to cylinder walls, exhaust to atmosphere, etc.), and mechanical efficiencies (spark timing, compression ratio, etc.). This conversion efficiency value is typically between 25% and 35%, depending on various factors. Several ways to improve this percentage are increasing the compression ratio (mechanical), optimizing ignition timing (mechanical), and optimizing the combustion process through better fuel injection techniques.

The next variable in the equation is the heat of combustion for the given fuel. This is a chemical value, which cannot be modified without mixing fuels. A table containing the heat of combustion values of common fuels is shown below in the table:

Fuel	**kJ/g**	**BTU/lb**
Hydrogen	141.9	61000
Gasoline	47	20000
Diesel	45	19300
Ethanol	29.8	12000
E-85	**32.4**	**13200**
Natural Gas	54	23000

Table 10 - Fuel properties (heat of combustion)

The final, and most alterable variable in the equation for power is the fuel mass flow rate. This rate is dependent on the air mass flow rate, combined with the air/fuel ratio. The AFR is dependent on the engine loading requirements, factored onto the stoichiometric values for the combustion reaction. The air mass flow rate is dependent on the volumetric flow rate of the engine, the volumetric efficiency, and the charge of the density. The density of the charge is dependent on the pressure and temperature. The use of a turbocharger increases the density of the charge and therefore the air mass flow rate. This consequently increases the fuel mass flow rate, which results in a higher amount of power output at the same engine speed, for a given displacement.

Vehicle Propulsion Dynamics

With the data available from the dynamometer testing, as well as the gear ratios and tire diameter, an accurately estimated acceleration analysis can be performed. The propulsive force from a vehicle is provided by the engine through the torque multiplications of the drivetrain. This relationship is show below:

$$Propulsive\ Force = \frac{Engine\ Torque * Gear\ Ratio * Primary\ Ratio * FDR}{Wheel\ Radius}$$

Below are the gear ratios for the KTM Duke 390 gear set. From the equation above, the momentary propulsive force can be increased by increasing the engine torque, having a numerically higher transmission and final drive ratio, or a smaller wheel radius.

Gear	Ratio
1	2.6667
2	1.8571
3	1.4211
4	1.1428
5	0.9565
6	0.84
Primary	2.6667
Final Drive	3.2857

Table 11 - Gearing system of KTM Duke 390

The road speed value is determined by the wheel radius, the gear ratios, and the engine speed:

$$Road\ Speed = \frac{Engine\ RPM}{Gear\ Ratio * FDR} * Tire\ Diameter$$

As a continuation to the powerband and acceleration analysis, the data was further used in predicting the times that it would take to accelerate from a stop to maximum speed. This process can be seen below:

$$Final\ Velocity = Initial\ Velocity + Acceleration * \Delta t$$

The initial velocity is the value that was generated at the previous time step. The acceleration is chosen either from test data (1st gear) or from the acceleration chart (every following gear). The distance from the starting line is derived from the following equation:

$$Final\ Distance = Initial\ Distance + Velocity * \Delta t + \frac{1}{2} * Acceleration * (\Delta t)^2$$

7.2 Optimum Lap Simulation

The following are the graphs obtained from simulating both, the naturally aspirated system and turbocharged system in our FSAE car.

7.2.1 Naturally Aspirated Engine System:

The following are the data graphs obtained from vehicle simulation of a naturally aspirated engine system.

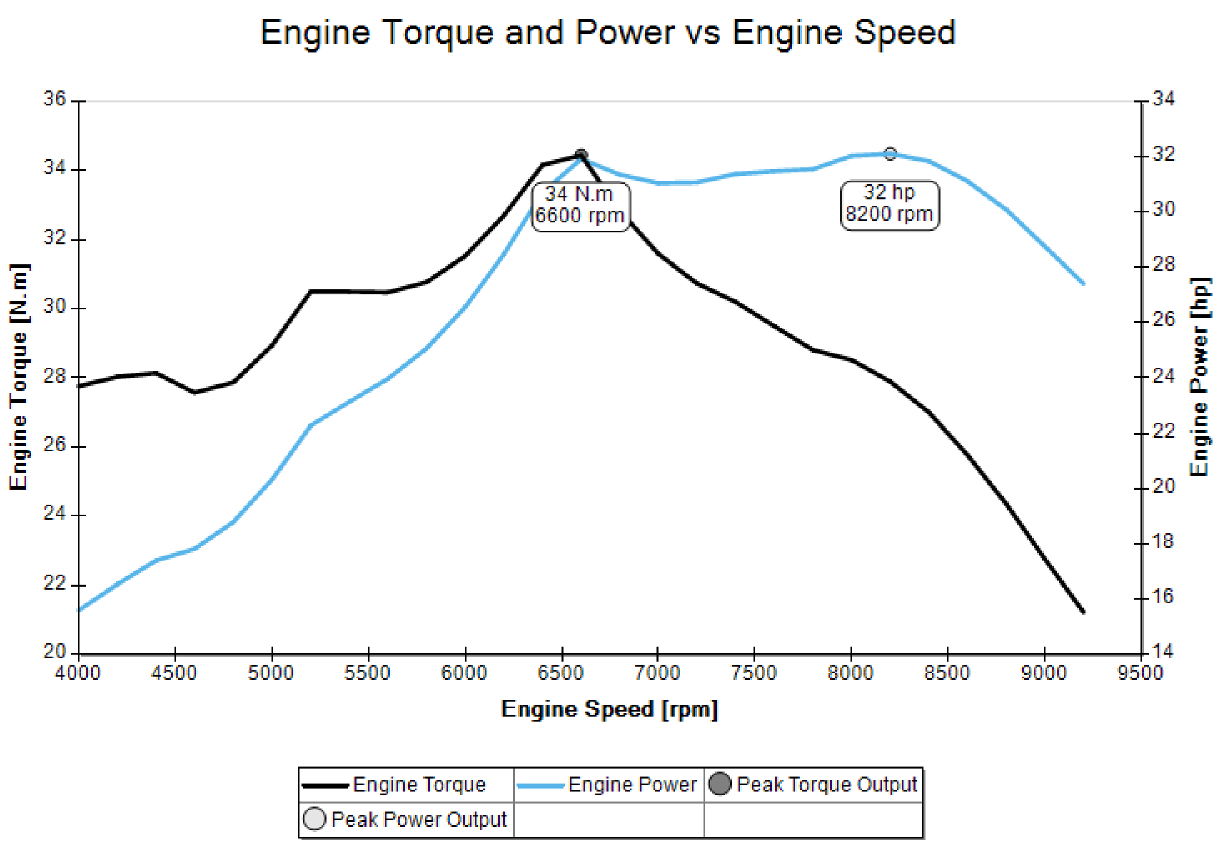


Figure 42 - Engine Torque & Power vs RPM - Naturally Aspirated

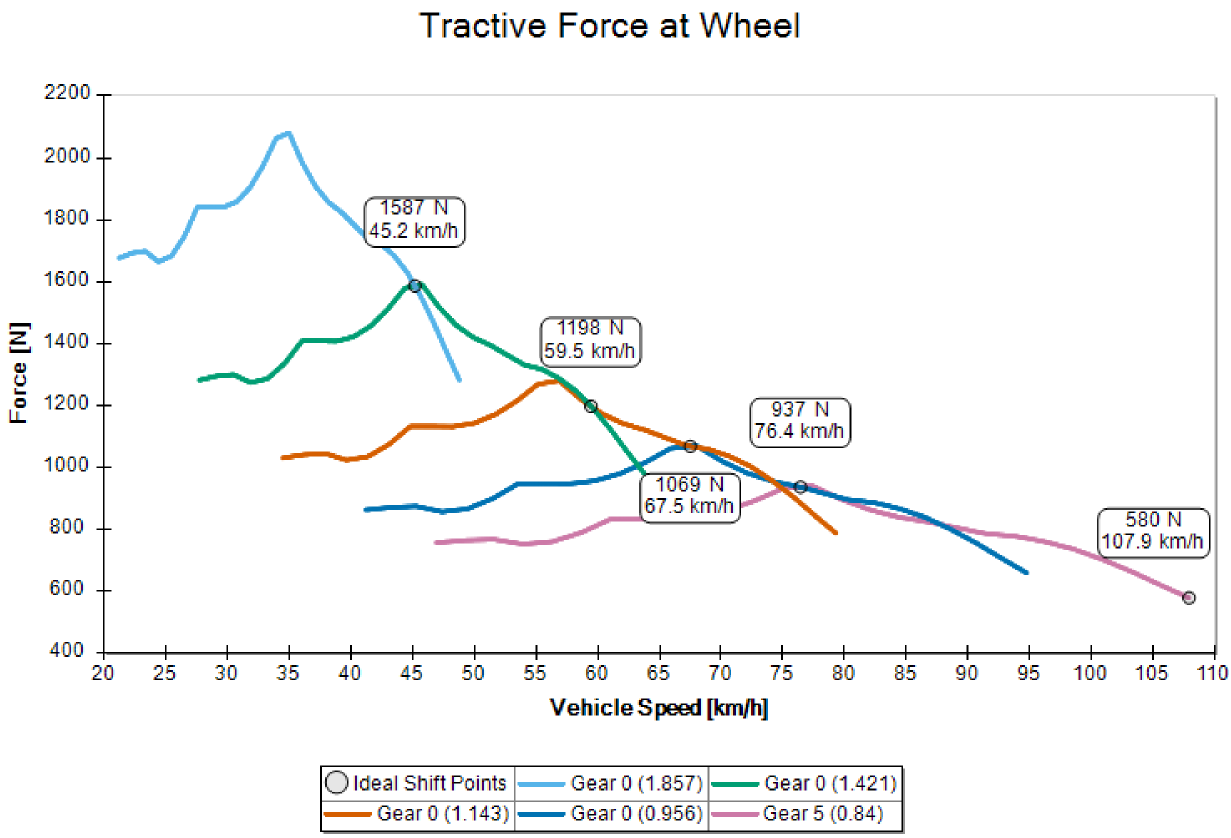


Figure 43 - Traction Model - Naturally Aspirated

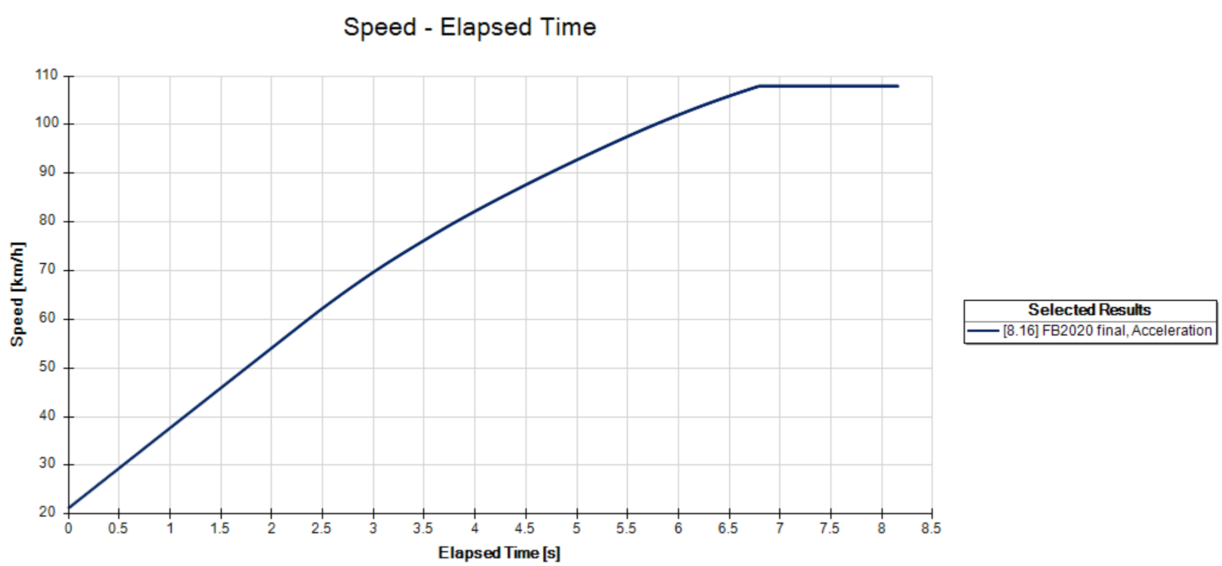


Figure 44 - Speed vs Time - Naturally Aspirated

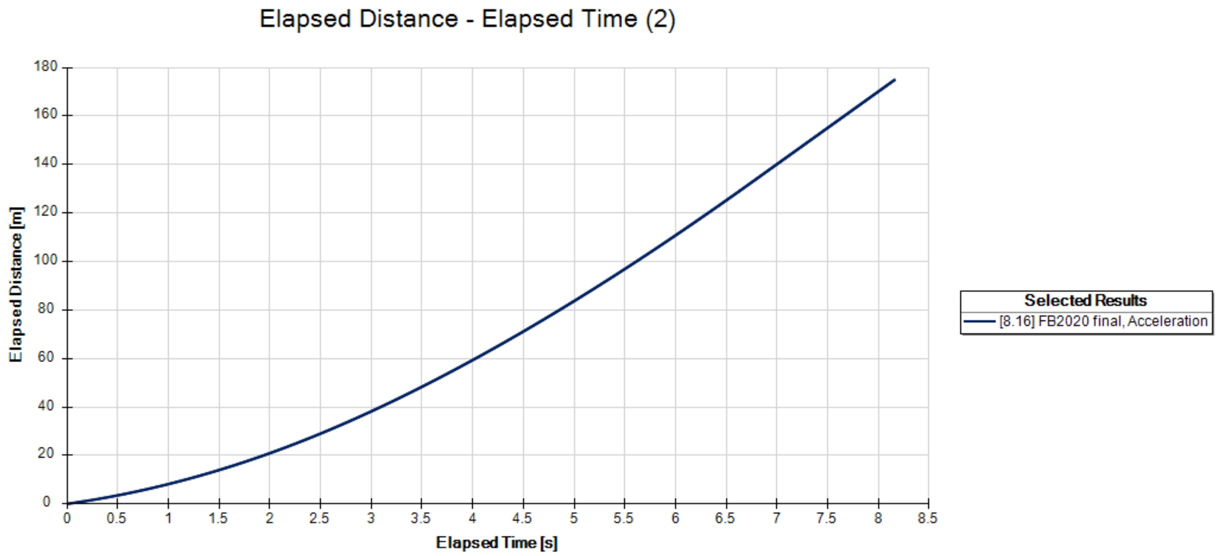


Figure 45 - Distance vs Time - Naturally Aspirated

Vehicle Report

FB2020 final

Sunday, April 26, 2020

Vehicle Configuration

Parameter	Value
Total Mass	244 kg
Max Torque	34.45 N.m @ 6600 rpm
Type of Fuel	Gasoline
Type of Transmission	Sequential Gearbox
Max Power	32.12 hp @ 8200 rpm
Power Mass Ratio	0.13 hp/kg
Downforce @ 100 km/h	72.68 N
Drag @ 100 km/h	119.02 N

Performance Metrics

Metric	Value
Top Speed	107.91 km/h
Time for 0 to 100 km/h	5.77 s
Time for 100 to 0 km/h	2.83 s
Lateral Acceleration - Skidpad 50 m	10.73 m/s^2

Figure 46 - Optimum Lap Report - Naturally Aspirated

7.2.2 Turbocharged Engine System:

The following are the data graphs obtained from vehicle simulation of a turbocharged engine system.

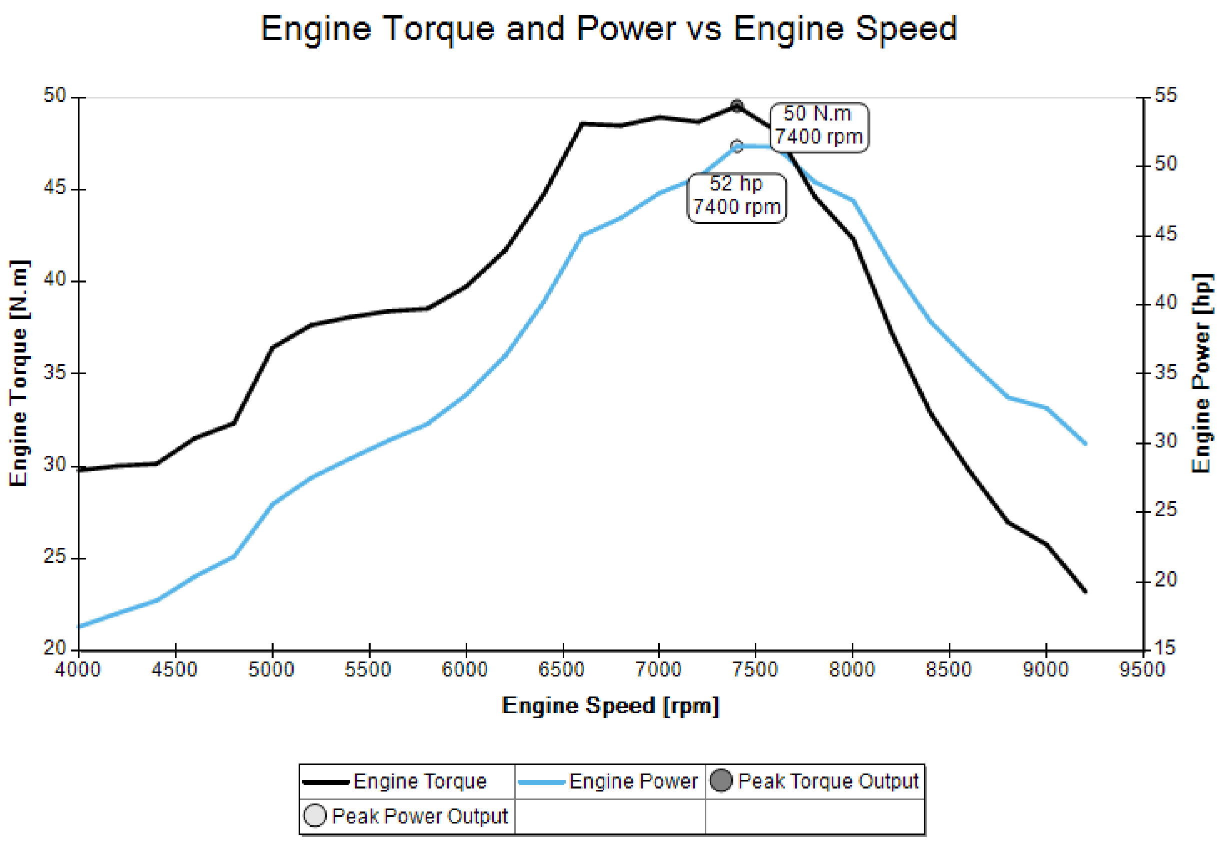


Figure 47 - Engine Torque & Power vs RPM - Turbocharged

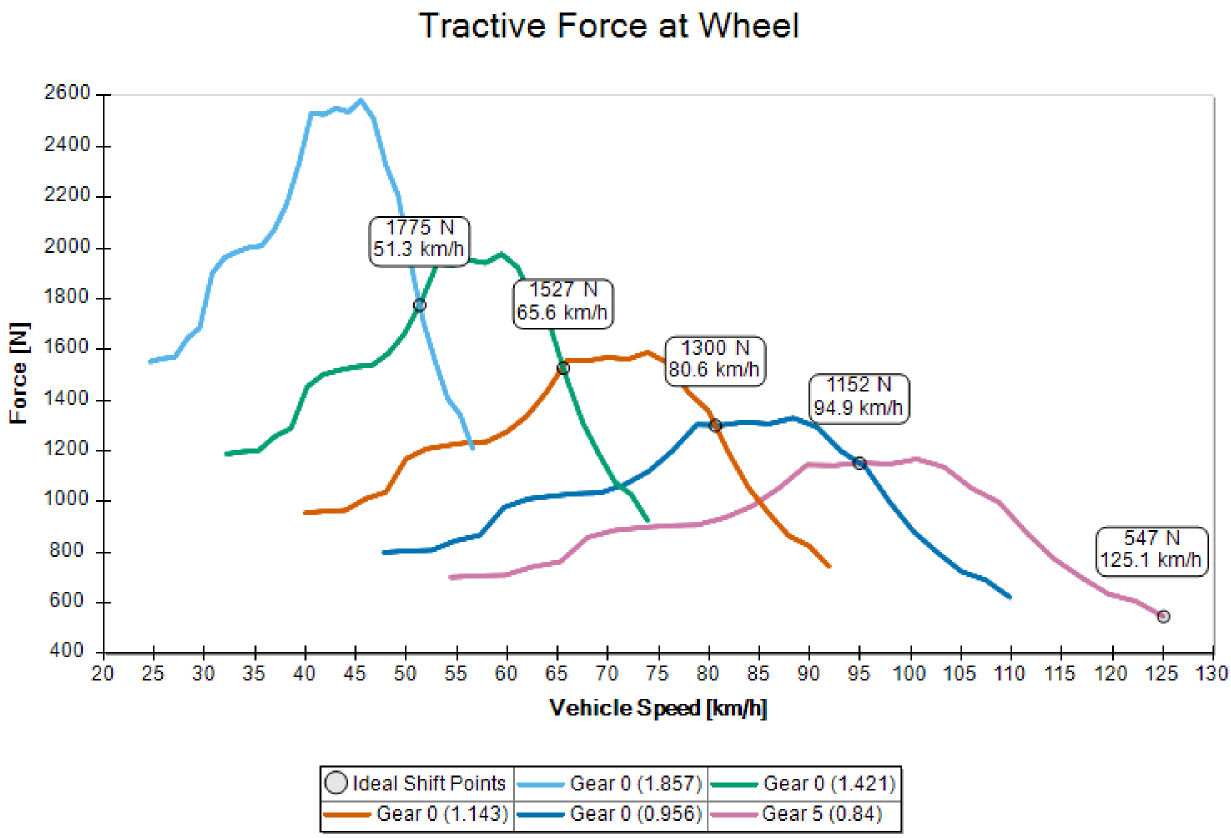


Figure 48 - Traction Model – Turbocharged

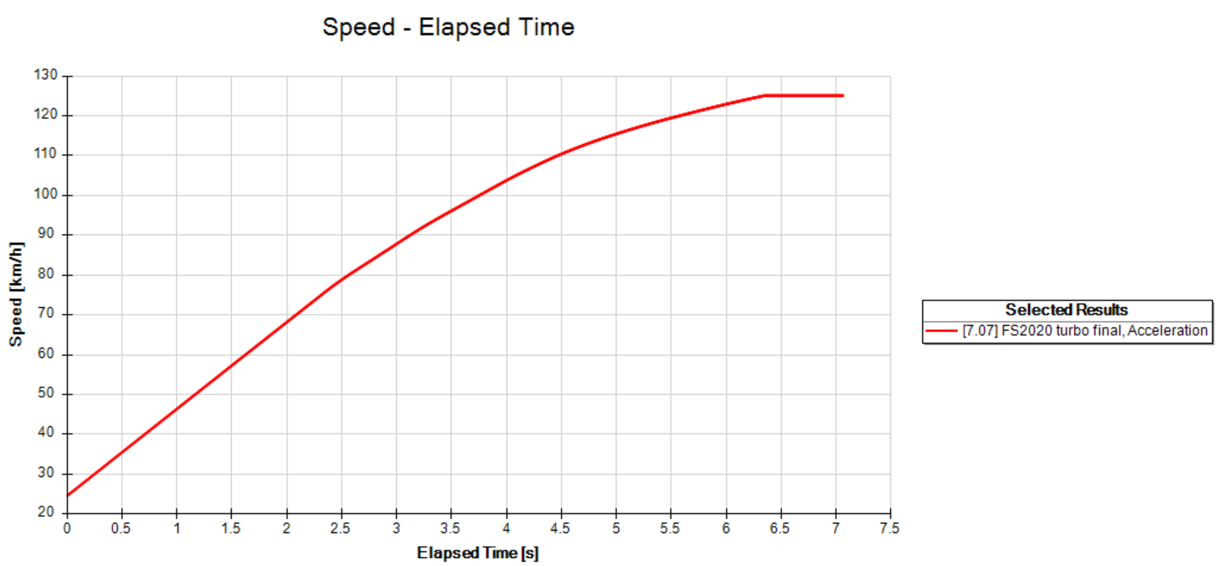


Figure 49 - Speed vs Time - Turbocharged

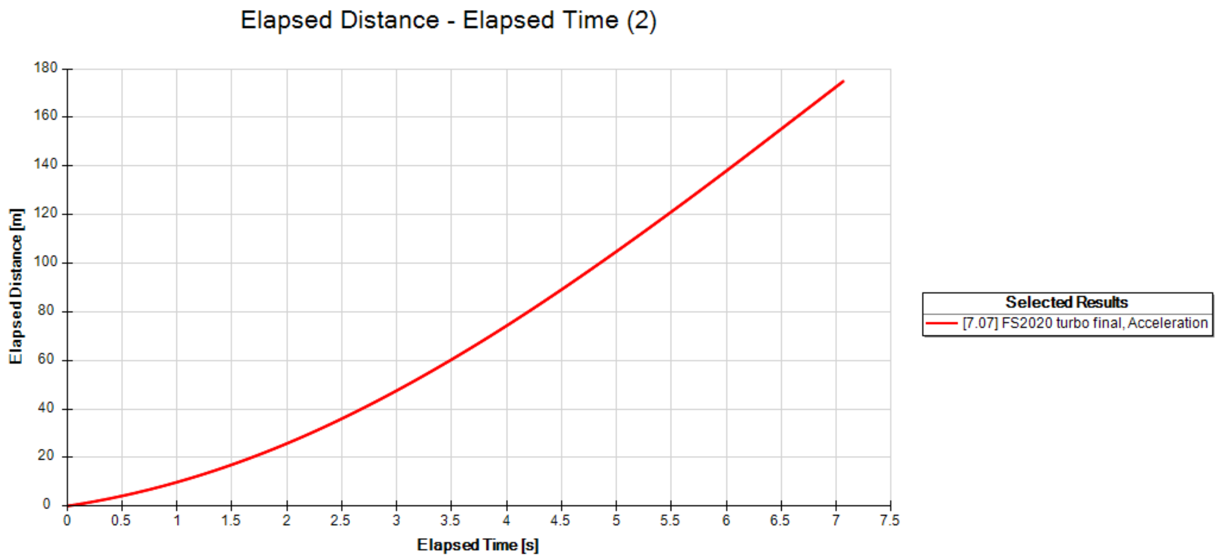


Figure 50 - Distance vs Time – Turbocharged

Vehicle Report

FS2020 turbo final

Sunday, April 26, 2020

Vehicle Configuration

Parameter	Value
Total Mass	244 kg
Max Torque	49.56 N.m @ 7400 rpm
Type of Fuel	Gasoline
Type of Transmission	Sequential Gearbox
Max Power	51.5 hp @ 7400 rpm
Power Mass Ratio	0.21 hp/kg
Downforce @ 100 km/h	72.68 N
Drag @ 100 km/h	119.02 N

Performance Metrics

Metric	Value
Top Speed	125.07 km/h
Time for 0 to 100 km/h	3.75 s
Time for 100 to 0 km/h	2.24 s
Lateral Acceleration - Skidpad 50 m	14.18 m/s^2

Figure 51 - Optimum Lap Report - Turbocharged

7.2.3 Combined Graphs:

The following graphs are the combined graphs of naturally aspirated and turbocharged engine systems. There is consistently an increased distance travelled and vehicle speed attained in the same amount of time for the turbocharged vs naturally aspirated counterpart. These results would be exacerbated if the turbocharged setup was further optimized, which is certainly possible.

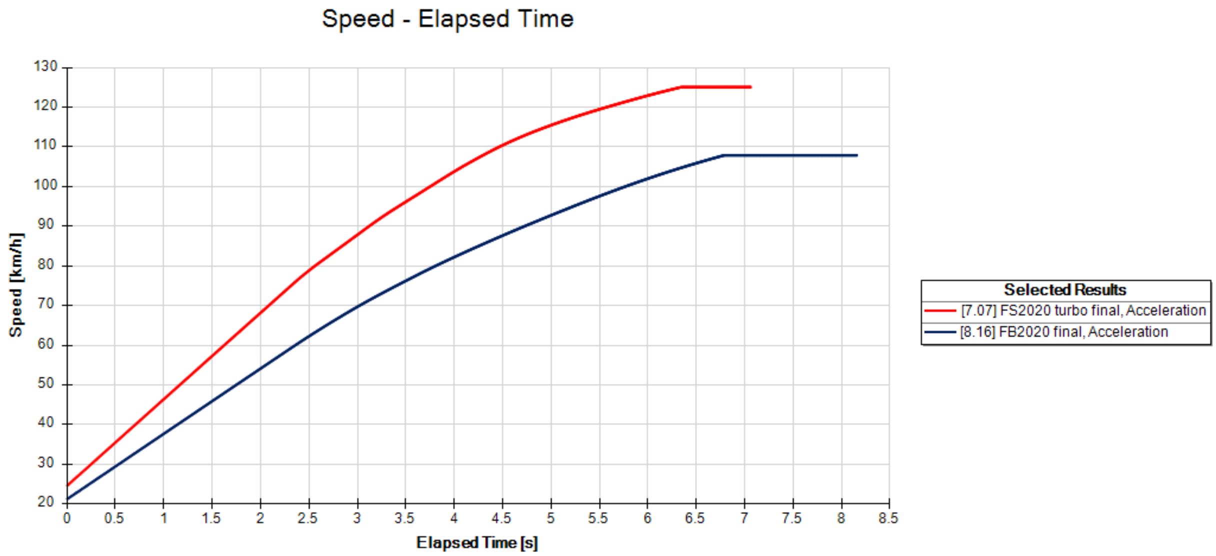


Figure 52 - Speed vs Time - Combined

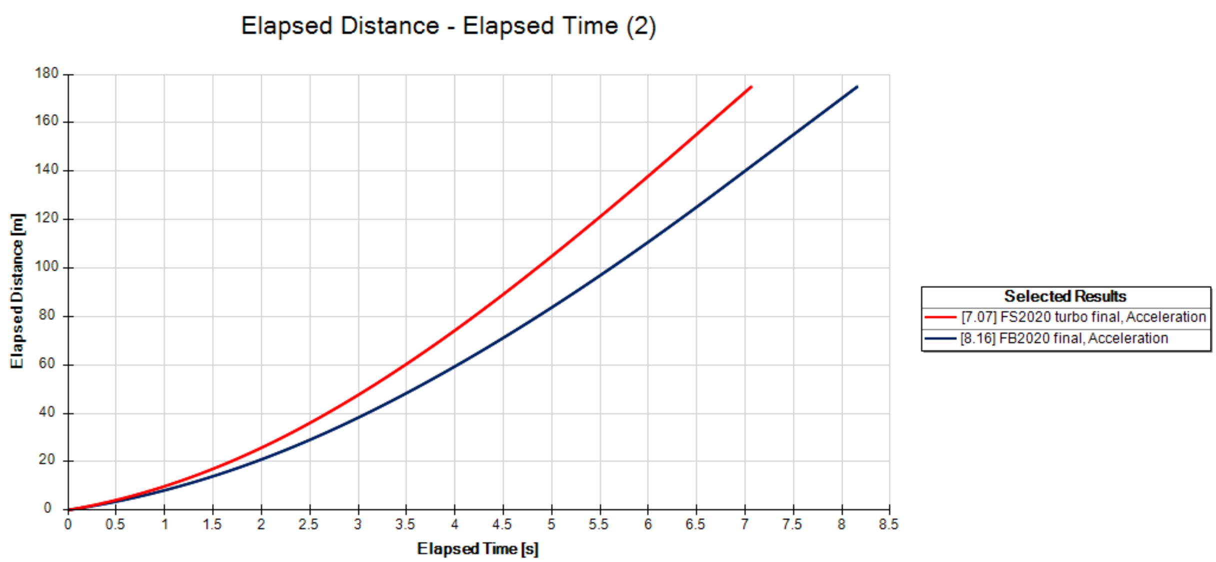


Figure 53 - Distance vs Time – Combined

As a final note, perhaps the greatest benefit of turbocharging an FSAE car is the ability to keep the vehicle in a higher gear for longer. This is due to the larger and wider powerband provided by the turbocharger.

The greater area under the torque curve, as seen below, is noted by the diagonal black lines. This extra area results in greater acceleration. Due to the wider powerband, the driver can retain higher gear throughout a turn instead of having to rapidly downshifting and up-shifting back after the corner. Shifting is time lost will be minimized in order to maximize performance.

Vehicle wear is also lowered if shifting is avoided due to less stress experienced from shifts and potential driver error.

Also a wider powerband benefits the output performance of the FSAE vehicle as it aids in higher accelration throughout a single gear which not only helps in reducing the gear shifts but also helps in constant fuel consumption and less heat generation during the dynamic condition. Thus this signifies the benefits turbocharging to increase longetivity of performance and also engine life during running condition.

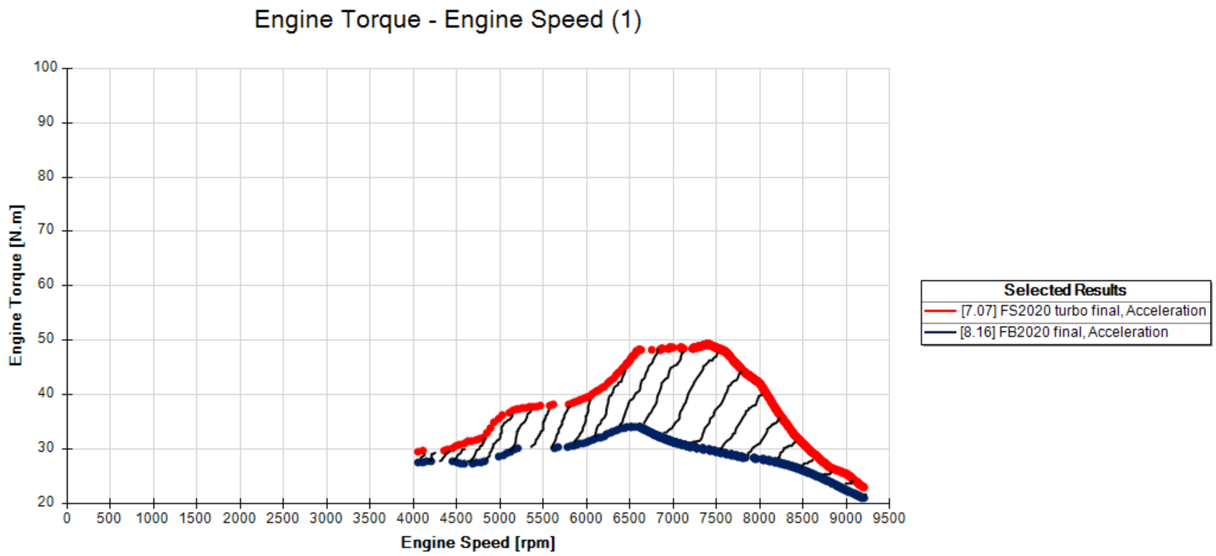


Figure 54 - Torque gained under the turbocharged curve

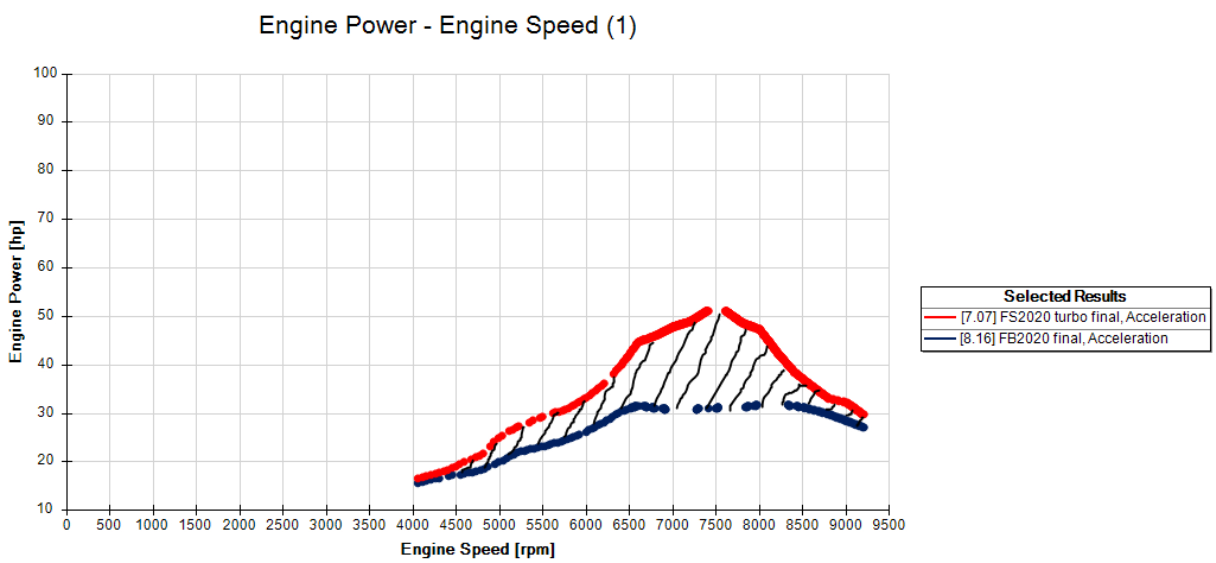


Figure 55 - Power gained under the turbocharged curve

8 Predicted cost of Project

The idea of this project is implementing a turbocharged system in previous FSAE car and thus only the required changes will be done on the system to make sure that economic factor is considered during this course. The following table shows the estimated cost of all the changes that will be done in the system.

System Name	**Part Name**	**Process**	**Part Number #**	**QTY**	**Cost**
Engine	Crankshaft, Piston	Crankshaft assemby comp	93830018100	-	10,499
		GEAR BALANCER DRIVE	90230055000	1	
		CONICAL WASHER 28,35X38X1,75	90230069000	1	
		NUT FOR DRIVE WHEEL AGW	90130018008	1	
		ROTOR SCREW CPL.	90239005050	1	
		PRIMARY GEAR 30T	90232023030	1	
		SPROCKET CRANKSHAFT	90236014000	1	
		WASHER PLAIN	90236015000	1	
		SPECIAL WASHER	90236015001	1	
		NUT M16X1,5	90230029000	1	
		WOODRUFF KEY 4X5X13	J888040050	1	
		CON ROD CPL.	90230015100	1	
		PARALLEL PIN	90630015002	2	
		CON ROD SCREW	90230015013	2	
		CONROD BEARING SHELL	90230015010	1	
		PISTON CPL.	90230007200	1	

		PISTON RINGS CPL.	90230030010	1	
		RING SNAP	90230074000	2	
		PISTON PIN	90230033000	1	
		PLAIN WASHER 28,2X39X1,5	90230068000	1	
		Parallel pin	90134013000	1	
		Woodruff key 4X4X12	J888040150	1	
	Cylinder Head	Head Cylinder with Camholder	93836020033	-	15,999
		Valve mechanism cover cmpl.	93336052100	1	
		Gasket rubber	93836053000	1	
		GASKET SPARK PLUG SHAFT	90236054000	1	
		SPARK PLUG SHAFT	90236074000	1	
		Gasket Cylinder Head	93830036000	1	
		HH-COLLAR SCREW M6X35 WS8	J025060356	4	
		HH COLLAR SCREW M6X45	J025060453	2	
		CHAIN GUIDE TOP	90236018000	1	
		OIL JET	90130064000	4	
		VALVE GUIDE	90236025000	4	
		PIN DOWEL 8X6,4X14MM	90130024000	2	
		intake funnel	J912061026	2	
		WASHER 7X11X2	J125070003	2	
		bolt soket-M10X1.25XL143.75XSTEP	J912101433	4	

		WASHER 11,2X18X2	J125110003	4	
		STUD M8	90136020001	2	
		FLANGED NUT M8 H7,5 WS12	90136038000	2	
		O-RING	90138091001	1	
		OIL PRESSURE SENSOR	90138091000	1	
		PIPE COOLANT	90235019000	1	
		TEMPERATURE SENSOR	90135047000	1	
		O-RING	90135047001	1	
		VALVE COVER SCREW	90136052020	4	
		DECOUPLING ELEMENT	90136052010	4	
		PLUG	90236024000	1	
		HH COLLAR SCREW M6X40	J025060401	2	
		O-RING 29,8X1,9	J770029819	2	
	Crankshaft	BALANCER SHAFT	90230057100	-	5,999
		DEEP GR. BALL BEAR.6304 HN3 C3	J625063041	2	
		DRIVE WHEEL BALANCER SHAFT	90130055000	1	
		CLUTCH HUB DRIVE WHEEL BAL.SHA	90130055001	1	
		Washer 8,2X26X3	90130057150	1	
		SPACER SHIM	90130055006	1	
		DOME NUT WAPU-WHEEL	90135058000	1	
		Special screw	90130055103	1	
		STOPPER BALANCER	90230079000	1	

		SHAFT BEARING			
		FLANGED BOLT 6X12	90130078001	1	
	Valve Springs	-	-	2	1,500
	Clutch Plate	Rekluse Radius X Centrifugal Force	28532900000	1	24,999
				Total	**58,996**
Lubrication	Oil	MOTUL Engine oil	300V 15w50	2	2,040
	Sump	Sump Plate	-	1	1,200
		Connectors	-	5	1,000
	Pumps	Service kit and pump Accessories	90238015010	-	3,999
		OIL PUMP CPL.	90238010044	1	
		GEAR OIL PUMP	90238001000	1	
		OIL FILTER	90138015000	1	
		SHAFT OIL PUMP	90238002000	1	
				Total	**8,239**
Intake	Port - Flange	Raw Material – Al 6061 pipe: 32x2.5mm, l = 950mm	-	-	1050
		Turning, boring – Manual Lathe	-	-	200
		CNC bending – 5axis	-	-	450
		Hard Anodizing	-	-	450
		Connections & Mounting	-	-	600
				Total	**2,750**
Exhaust	Port -Flange	Raw Material – SS 316 pipe: 34x2mm, l = 400mm	-	-	800

		Facing – Manual Lathe	-	-	150
		CNC Machining – 3axis	-	-	350
		Heat Treatment- 40HRC	-	-	250
		Connections & Mounting	-	-	400
				Total	**1,950**
Fuel	Pump	KTM Fuel Pump	93007088000	1	6,500
	Filter	100 micron filter	-	1	1,050
	Connectors	United Rubber Pro – Flo Nylon hose	-	2	1,500
		Connectors	-	4	400
				Total	**9,450**

Table 12 - Project cost (1)

Now, as per these subsystem costs, we have determined the overall cost required to get the desired power:

System Name	Cost (INR)
Engine	58,996
Lubrication	8,239
Intake	2,750
Exhaust	1,950
Fuel	9,450
Total	**81,385 (85,000 approx.)**

Table 13 - Project Cost (2)

Thus, the overall extra cost of getting a power output is INR 85,000.

Considering a switch to a new engine with higher power would cost about INR 2,50,000. Thus we have achieved that level of performance in almost one-third (33.33%) of that.

Below is the illustration of each system cost in terms of charts:

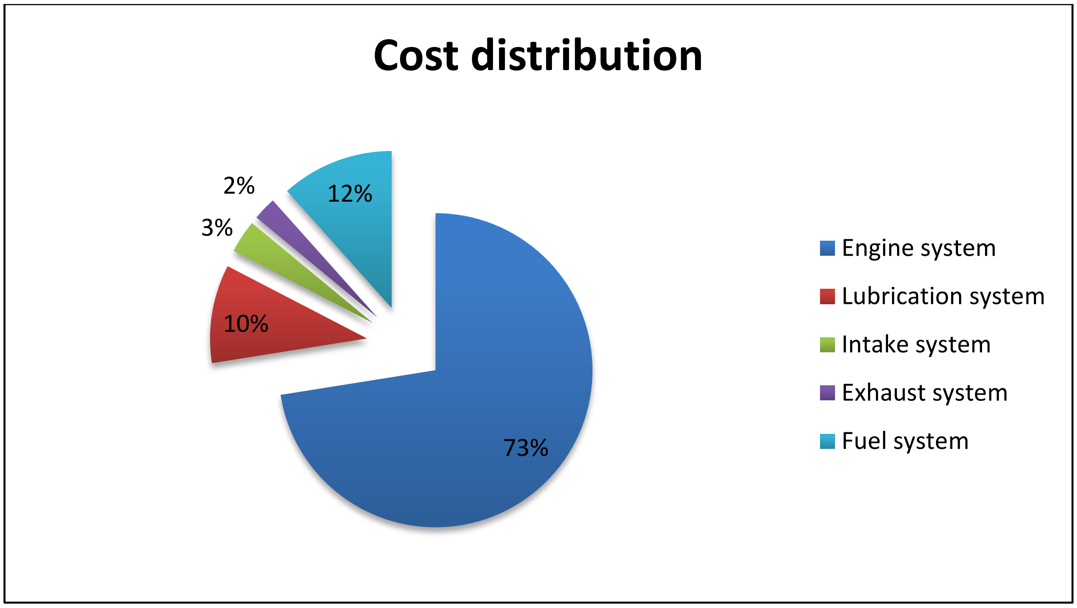


Figure 56 - Cost Distribution Chart

9 Project Summary

To summarize, the project was to add a turbocharger and all other supporting components onto an old FSAE race car, which was used in competition FB2020. We had to analyze the system, select a turbocharger, design the turbo-system around the turbocharger selection, select and configure an engine management system, and finally tune the engine management system, so that the maximum, safe amount of horsepower and torque could be extracted from the setup. In this process, custom parts had to be designed and manufactured, so that the turbocharger system could be adapted to the naturally aspirated vehicle. Also, automotive theory had to be explored to find solutions to critical problems, which could threaten the success of the project, as well as the lifespan of the system.

The turbocharger system that we built around the KTM Duke 390 engine proved to be capable of producing large increases in power output relative to the naturally aspirated engine. Simulations on GT Power, to obtain the torque and power graphs of the engine were done successfully. This was followed by vehicle modeling on Optimum Lap, this was done to get the predicted performance graphs regarding time, speed, distance and the performance gains during the dynamic running condition of the engine.

The turbocharged system produced power and torque gains of roughly 35-40% throughout the RPM range. The cost of the parts associated with the project was rather low due to several sponsorships and the weight gains were not comparable to the performance gains associated with this project. Therefore, if this specific system is reused in the future and the race car is designed with the consideration of operating with a turbocharger, we believe that adding a turbocharger would produce a result similar or better to the one obtained in this project, which can be considered very successful.

Thus the goal of producing 50hp of power was successfully achieved in this project. The overall cost of the project is around INR 80,000. This is almost one-third (of INR 2,50,000) of the cost of a new engine for comparable power.

10 Future Recommendation

Since this was the last season of the team with a combustion FSAE car, we don't think that the team would continue to build on the foundation of this turbocharged system. The team is considering a shift to electrical FSAE car and that is the leap for catching up with the progressing automobile industry.

Still, if the team wants to improve on this system, there are a few areas to work upon for getting a more performance Combustion FSAE car.

- **Engine system designing**

This time we have considered the use of an old intake and exhaust system of the previously designed FSAE car. We have done this to ensure that the overall cost of the project is reduced, and also there are less variables in the designing system. But now, the team can take into account the turbocharger and build the complete engine system around it.

The Intake system can be modified to produce a larger boost in the system. The plenum volume can be optimized even further if the flow geometry of the intake system is modified. The location of the fuel injector and the intake port attachment can be altered to give a more reliable firing response of the injector and perfect air-fuel mixture to be transferred in the combustion chamber during the power stroke. Also a new geometry of the intake can help in better throttle response from the engine during acceleration.

The exhaust system can be designed on a more reactive principle that would help in making the system lighter. Scavenging principle can be more effectively used to help in removing the combustion byproducts to ensure a higher volumetric efficiency of the system.

- **More power output (around 60hp)**

The design considered during this project was to produce a power output of 50hp, but as per the calculations for further improvement, we can go upto 60hp to attain maximum performance. This can be considered by altering the compressor setup of the turbocharged system and also enabling a different sot for the boost control.

By selecting the power output as 60hp the team might face the difficulties to run the system without an intercooler, but when designing a new intake system this problem can be tackled. Also if the system is subjected to more force, the reliability of some vital engine components will be questioned. These must be looked into during the designing phase.

- **Dynamometer testing**

Here we don't have enough testing facilities available and hence the performance of the system is judged upon the simulated results solely. If the team can get a dynamometer testing setup it would be beneficial to measure the actual performance gains and also validate the design by comparing the simulated results to the actual ones.

The team can also consider manufacturing a simple rope-drum dynamometer in the workshop if the testing facilities remain unavailable. This can also be helpful for future validation purpose.

- **Advanced Engine Tuning**

This deals with dynamic tuning of the system on a vehicle dyno setup. The current tuning system deals with changing the values and then testing the vehicle to get data out of it. If the dynamic tuning method id attempted then the actual performance output can be varied according to the input parameters as Fuel injector open time and also the point of Spark ignition.

In terms of tuning, using a knock sensor would be beneficial to determine the limit of advancement in spark ignition. This will help in achieving peak performance of the engine. The engine will run at a less reliability percentage but that will always be a secondary aspect to be considered if this engine is reused.

Thus, these are the parameters that can be looked into for getting more power out of the turbocharged system. But considering a switch to Electric FSAE car, the team can focus on the future and nonetheless the purpose of this project was to transform an existing naturally aspirated system into a turbocharged one to attain maximum performance possible and switch from combustion class to electrical class.

11 References

[1] “Formula SAE Turbocharger Engine Development” by SLO Racing .PDF

[2] “2010_WPI_Turbo_FSAE” by Brian Beach Stoyan Hristov Patrick Napier. PDF

[3] "HowStuffWorks "How Car Engines Work"" HowStuffWorks "Learn How Everything Works!"Web.

<http://www.howstuffworks.com/engine.htm>.

[4] “Turbo Selection- Gas.’ Garrett by Honeywell 2018: 8-11. Pdf.

[5] KTM. “2014 DUKE 390 Service Manual.” .PDF

[6] “Compression Ratio Tech.” Popular Hot Rodding.Web.

<http://www.popularhotrodding.com/tech/0311_phr_compression_ratio_tech/>.