Automation Lab Report - Energy Converters for Sustainable Transportation (MVKN51)

Group E - Engine Optimizers
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1 Task 2

The aim of Task 2 is to experiment with engine parameters to obtain trend curves for peak power, efficiency and emissions, which will further be explained and analyzed. Evaluated parameters include: ignition timing, fuel mixture and compression ratio.

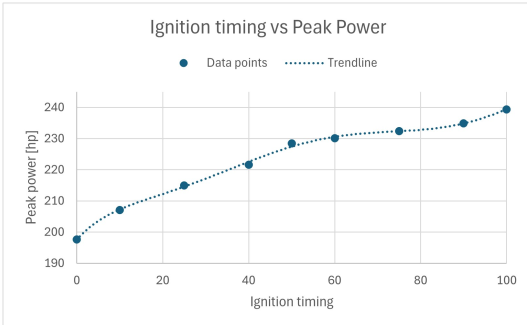
1.1 Method

The method starts with a basic engine from Task 1. Further, the three parameters are increased as well as decreased from the start values, and results are documented in order to obtain a trend curve, generated in Excel. Warnings were also noted. Only one parameter was altered at a time, except in 'Subtask 2.1'.

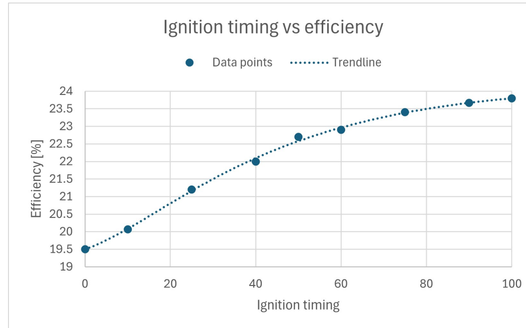
1.2 Results and discussion

The results are presented in figures 1, 2 and 3. The values marked as triangles show warning from the program. The results will be presented together with discussions in the order: ignition timing, fuel mixture and compression ratio.

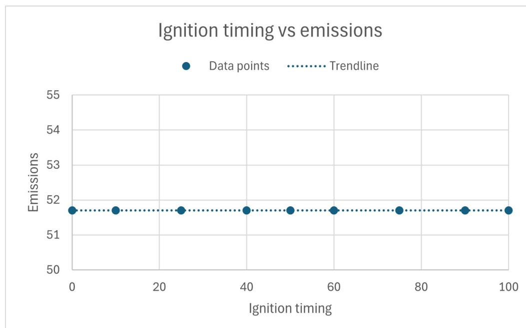
Ignition timing refers to when the spark is introduced in the SI-engine, with regards to the piston's position relative to TDC. Due to delay from spark ignition until combustion commences, the spark must be introduced before the piston reaches TDC. Generally speaking, earlier firing is called advanced timing while later is called retarded timing. The recorded effects of ignition timing on peak power, efficiency and emissions can be seen in figure 1a, 1b and 1c respectively.



(a) Change in peak power[hp] when ignition timing is varied.



(b) Change in efficiency [%] when ignition timing is varied.

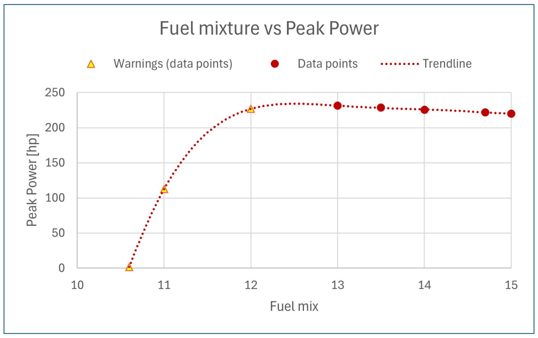


(c) Change in emissions when ignition timing is varied.

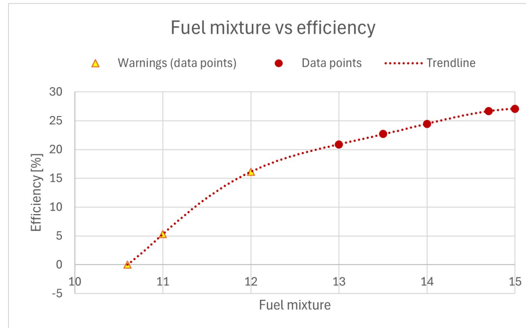
Figure 1: Effect of ignition timing on peak power, efficiency and emissions. Low values for ignition timing represents retarded ignition timing while high values represent advanced.

According to figures 1a and 1b, both peak power and efficiency increase with advanced ignition timing, for the range observed in the figures. When the spark is introduced earlier combustion will occur closer to maximum pressure, allowing for more power extraction. However, if the spark is introduced too early (with advanced timing) combustion begins before the piston reaches TDC and the gas expansion will push against the compression stoke, creating negative work which results in energy loss. When the burning air/fuel mixture is compressed by the piston it can also auto ignite and cause knocking or engine damage. However, according to the results in figure 1, it was not a problem during the simulation scenario. Changing ignition timing did not affect the emissions, which stayed constant at a value of 51.7, according to figure 1c. In theory advanced ignition timing allows for higher temperatures in the combustion chamber, which increase thermal NO_x emissions. Since the emission parameter in the program merges various emissions such as carbon monoxide, particulate matter, hydrocarbons etc. the overall emissions are not significantly effected by altering the ignition timing.

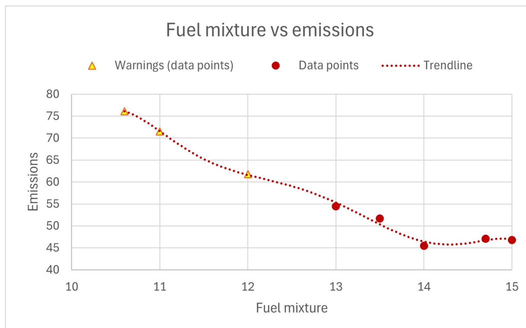
Fuel mixture refers to the average air-to-fuel ratio (AFR) used in the engine. The stoichiometric AFR assumes ideal combustion and provides exactly enough air to burn the fuel. AFR_{ST} is 14.7:1 for the fuel, 'Premium 95 RON', used in this simulation. Lean mixture means that combustion took place in an excess of air, while rich mixture means air deficit. The results are compiled in figure 2.



(a) Change in peak power[hp] when fuel mixture is varied.



(b) Change in efficiency [%] when fuel mixture is varied.

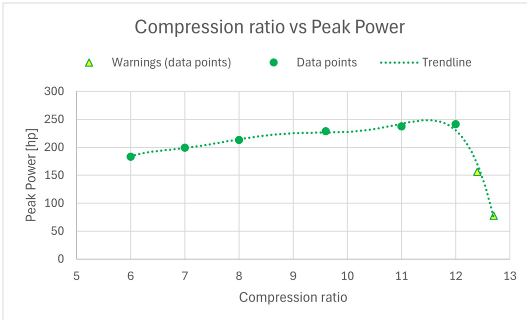


(c) Change in emissions when fuel mixture is varied.

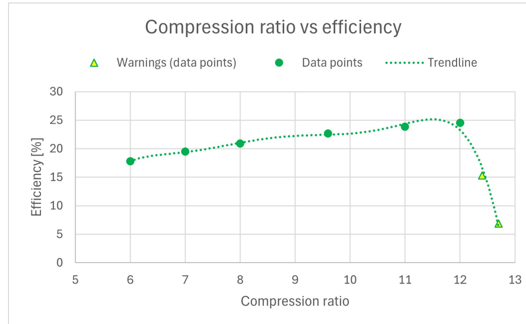
Figure 2: Effect of fuel mixture on peak power, efficiency and emissions. Low values of fuel mixture represent a rich mixture while high values represent lean.

Figure 2 displays some warnings when the fuel mixture is too rich (low values on x-axis), indicating relatively low amount of air in comparison to fuel. The maximum peak power in figure 2a is displayed between a ratio of 12-13:1, which is when the mixture is rich but not rich enough to induce knocking. More fuel provides more available energy to the engine which can be converted to torque, related to power. However, the maximal efficiency and power does not occur at the same fuel mixture. According to figure 2b, max efficiency is instead obtained when the fuel mixture is leaner since it allows for complete combustion, hence, more useful work can be extracted. It also provides lower combustion temperatures, which decreases the heat loss though the combustion chamber walls. Emissions (figure 2c) show a clear trend of decreasing as the fuel mixture becomes less rich, with a minimum around 14:1, which is close to stoichiometric conditions but slightly on the richer side. More oxygen in relation to fuel allows for more complete combustion which decreases formation of carbon monoxide and particulate matter. Also, it leaves less unburned hydrocarbons. Lower combustion temperatures can reduce emissions such as thermal NO_x, which is the most prominent type of NO_x.

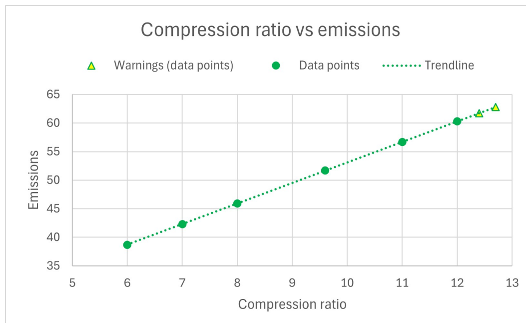
Compression ratio refers to how much the fuel/air mixture can be compressed during the compression stroke. A higher ratio indicates more compression. Efficiency in a SI engine is limited by the limitation in compression ratio. The fuel and air mixture is somewhat volatile, and can only be compressed to some extent before it auto ignites, inducing knocking. This limit for compression ratio is higher in CI-engines, since only air is compressed and fuel injected later. Air is less volatile than gasoline, allowing for more compression before auto ignition. The simulated results can be seen in figure 3.



(a) Change in peak power[hp] when compression ratio is varied.



(b) Change in efficiency [%] when compression ratio is varied.



(c) Change in emissions when compression ratio is varied.

Figure 3: Effect of compression ratio on peak power, efficiency and emissions.

Peak power and efficiency display a similar trend, according to figures 3a and 3b. They increase with higher compression ratio, until a compression ratio of 12.4 where warnings appears. It seems reasonable that too high ratios result in auto ignition, due to high pressure and temperature of the air/fuel mixture. The emissions (figure 3c) linearly increase with compression ratio. More compression causes higher temperature of the air/fuel mixture, resulting in higher combustion temperatures. As previously discussed, resulting in more emissions such as thermal NO_x.

1.3 Subtask 2.1:

When the compression ratio of the basic engine is set to 11.2 and the ignition timing is advanced, knocking is induced. This did not occur with the same compression ratio when using neutral ignition timing of 50, as in Task 2. As previously mentioned, a high compression ratio results in higher pressure and temperature of the air/fuel mixture. Advanced ignition timing introduces the spark earlier, allowing combustion to occur before the piston reaches top dead center (TDC). If this occurs, the combustion pressure will rapidly increase as the piston continues to compress the mixture, leading to a rapid temperature rise. This can result in auto-ignition (knocking).

2 Task 3

The aim of this task is to optimize the engine to get the maximum peak power output without exceeding the emission value of 52 by altering the parameters such as ignition timing, compression ratio and fuel mixture.

2.1 Method

The method used for this task includes adjusting the parameters such as ignition timing, compression ratio and fuel mixture to match those of the basic engine configured in Task 1 as shown in Table 1. Thereafter, each of these parameters was altered based on its relationship to peak power output and emission values to achieve the maximum peak power output while keeping emissions below 52 and avoiding knocks.

2.2 Results and Discussion

Parameter values such as ignition timing, compression ratio and fuel mixture, as well as peak power, efficiency and emissions from the baseline scenario can be seen in table 1.

Table 1: Base Scenario

Ignition Timing	Compression Ratio	Fuel Mixture	Power[hp]	Efficiency[%]	Emissions
50	9.6:1	13.5	228.5 @6500rpm	22.73 @3200rpm	51.7

From Task 2, it was observed that an increase in the ignition timing yielded higher peak power output and greater efficiency without impacting the emission levels. Thus, our initial goal was to increase the ignition timing to the maximum possible value while avoiding knock formation and keeping emissions below 52.

Following this we decided to increase the compression ratio, as from Task 2, it was noted that an increase in the compression ratio resulted in higher engine efficiency and maximum peak power output. However, a drawback to this approach was that too high a compression ratio resulted in knock warnings and slightly higher emission values. The formation of knock was mainly due to the end gas auto ignition caused by the increased temperature in the combustion chamber resulting from the higher compression ratio. This increase in temperature also enhanced the NOx formation, leading to a slightly higher emission values. Therefore, we decided to adjust the compression ratio to a level that avoided knock while keeping the emission values below the desired value of 52.

Our next goal was to adjust the fuel mixture to a slightly richer mixture while keeping the emission values below 52. By doing so, the peak power output increased due to the enhanced fuel supply to the combustion chamber. Additionally, the emission levels decreased because of the lower combustion temperatures (as NOx formation is generally associated with higher temperature). It was also noted that making the mixture too lean caused knock warnings to occur. This was due to pre-ignitions or incomplete ignitions from insufficient fuel in the fuel mixture.

The optimized engine we configured had a maximum peak power output of 242.3 hp at 6500 rpm, with an ignition timing of 100, a compression ratio of 10.5:1 and a fuel mixture of 14.1. The emissions were below 52, and the engine efficiency obtained was 26.91% at 3500 rpm. The results are shown in Table 2.

Table 2: Optimized Scenario

Ignition Timing	**Compression Ratio**	**Fuel Mixture**	**Power[hp]**	**Efficiency[%]**	**Emissions**
100	10.5:1	14.1	242.3 @6500rpm	26.91 @3500rpm	52

3 Task 4

The aim of this task is to visually explain explain the working principle of a turbocharger that has been added to the previous engine model.

3.1 Method

The method used for this task includes explaining the working principle of the turbocharger (intake and exhaust) by using screenshots of the engine from different angles where the air and exhaust flow are visually shown with arrows (blue for intake and red for exhaust). A written explanation has also been included.

3.2 Results and discussion

As it can be seen in Figures 4 and 5, the air is firstly taken through the air inlet and driven to the compressor where it becomes more dense, thus more oxygen can be inserted into the engine. The air then goes through an air cooler in order to dissipate some of the heat generated during its compression and is taken through the intake valves into the combustion chamber. After combustion, the exhaust air is sucked into the turbine, whose rotation makes the compressor spin, and then exits through the exhaust system into the atmosphere.

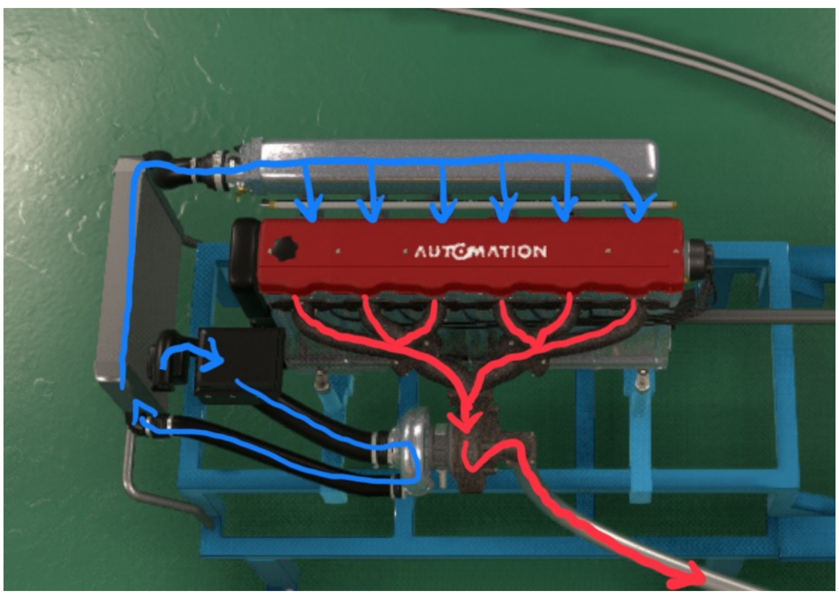


Figure 4: Intake (blue) and exhaust (red) flow of a turbocharger.

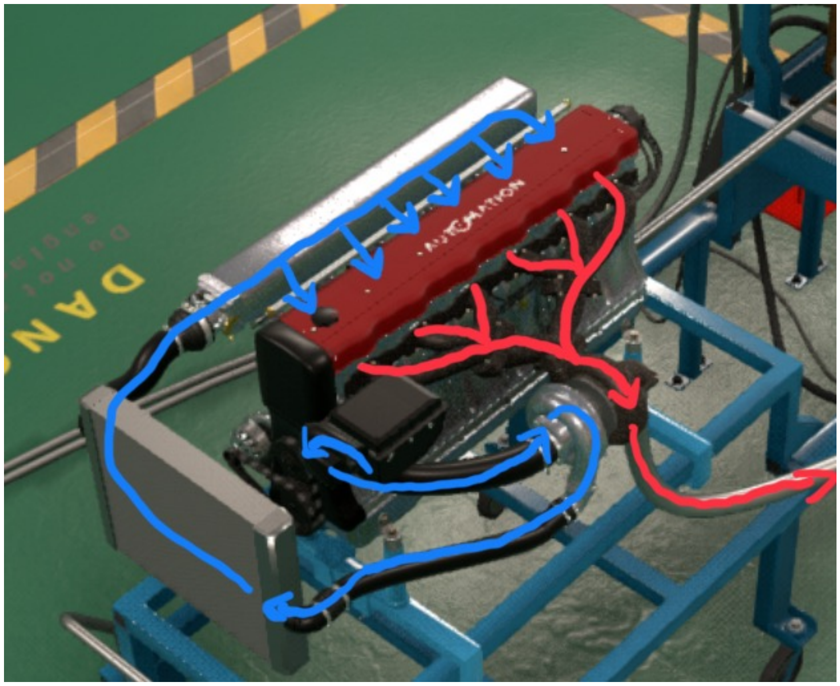


Figure 5: Intake (blue) and exhaust (red) flow of a turbocharger.

4 Task 5

The aim of this task is to downsize the engine from 6-cylinder to 4-cylinder while achieving the same emissions and power levels as in the previous task by adapting the parameters to this new type of engine. This new engine configuration includes a turbocharger that allows to compensate the lack of engine power from the downsizing.

4.1 Method

The method used for this task includes creating a turbocharged 4-cylinder engine on the software in order to test how the new engine works with the optimizing parameters from the previous task. If the aimed behaviour of the engine is not met, the parameters will be tweaked in order to avoid engine malfunctioning and knocking.

4.2 Results and discussion

Table 3: Base Scenario (Optimized 6-Cylinder)

Ignition Timing	**Compression Ratio**	**Fuel Mixture**	**Power[hp]**	**Efficiency[%]**	**Emissions**
100	10.5:1	14.1	242.3 @6500rpm	26.91 @3500rpm	52

Table 4: Downsized Scenario (4-Cylinder Turbocharged)

Ignition Timing	**Compression Ratio**	**Fuel Mixture**	**Power[hp]**	**Efficiency[%]**	**Emissions**
50	8.5:1	12.7	246.7 @6500rpm	26.32 @3500rpm	51.7

In order to do an engine downsizing, the engine has been changed from a 6-cylinder to a 4-cylinder and a turbocharger has been added with the objective of having at least the same amount of power from the 6-cylinder engine. The optimized parameters from task 3 are meant to be maintained for this task.

However, if the same optimized parameters are used, severe knocking happens during combustion. When downsizing an engine, a turbocharger is added to compensate for the power reduction from the previous 6-cylinder engine, which produces higher temperature and pressures inside the combustion chamber as more air is led inside it. Turbocharger helps to burn more amount of fuel as more air can enter the combustion chamber. This increase of temperature is a reason for knocking appearance. Thus, to achieve the desired power increase within the emissions boundaries (52 or less), new optimizing parameters need to be found.

As seen in Tables 3 and 4, compression ratio has been reduced from 10.5:1 to 8.5:1 because higher compression ratios increase temperature and pressure, which can possibly lead to knocking. At the previous compression ratio knocking was appearing, so it had to be lowered slightly.

To compensate for that decrease in the compression ratio, a richer fuel mixture from 14.1 to 12.7 has been added. As the emissions and power were a bit below the desired increase in power, a richer AFR was favorable to avoid knocking as the temperature and pressure are reduced when less air is allowed in the mixture, while getting more power as more quantity of fuel is burned during each cycle, always keeping in mind the increase in emissions when the mixture gets more and more rich. Ignition timing has not been touched between both configurations because it did not really affect that much the behavior of the engine emission-wise, whereas maintaining a higher value provided more power. As these parameters were tweaked, in Figures 6 and 7 can be seen that a slightly higher power of 246.7 hp and a 26.32% of efficiency has been achieved, compared to 242.3 hp and 26.91% in Task 3 (table 2) before downsizing. This while maintaining emissions below the limit of 52, specifically at 51.7.

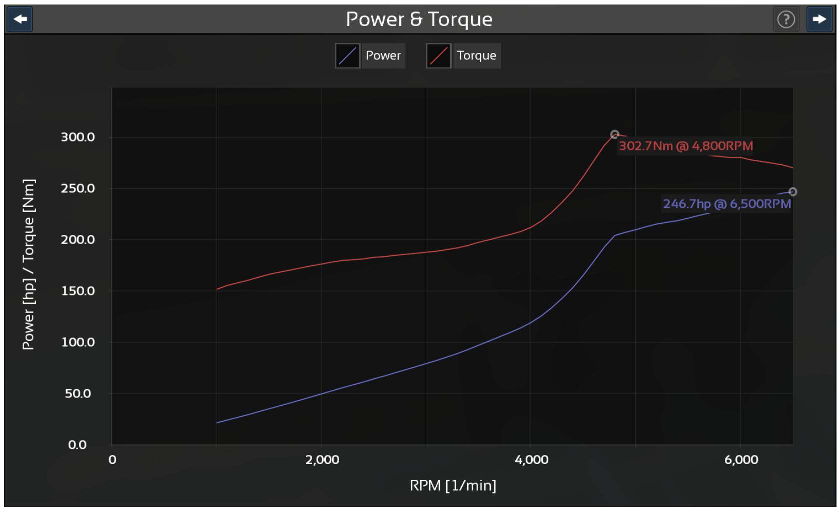


Figure 6: Variation of power and torque depending on RPM.

Figure 7: Variation of power and efficiency depending on RPM.

Observing figures 6 and 7, it can be already seen a considerably different behaviour of the engine from the 6-cylinder configuration. The power curve shows a steep and sudden increase at slightly above 4000 RPM, where the turbo reaches its optimal boost pressure due to turbolag. This is due to the turbo's need of having a certain inertia as the torque demand increases in order for the rotor to keep up with the speed for the required amount of gas exchange. At low RPM the turbocharger is not so effective due to the lack of sufficient exhaust gas in order to spin the rotor. When the optimal boost pressure point is reached, the power rises up quickly until 4800 RPM, where it recovers its initial rhythm of increase due to possible reasons such as having reached intake and exhaust maximum capacity or due to mechanical and temperature limits to avoid damage in the turbocharger.

Torque also suffers a sudden increase at 4000 RPM due to the turbo's reaching the optimal boost pressure. After reaching the peak torque value at 4800 RPM, torque curve slightly starts to decrease due to a possible decrease in volumetric efficiency, where the cylinder does not have sufficient time to fill up with air and fuel at high RPMs. To compensate for this drop in torque, the engine increases its RPM to keep getting higher values of power.

Taking a look at the efficiency curve it can be seen that the efficiency climbs up slowly until it gets to the turbo boost region, where it suddenly increases until a peak at 4500 RPM and then decreases at a faster pace. This peak in efficiency is due to the boost provided by the turbocharger as more quantity of air enters the engine, gaining more power at the same rate of consumption. Afterwards, the decrease might be caused due to the increase in RPM in order to keep up with the power needs. Also, the drop in efficiency could be caused by the cooling system of the engine having reached its maximum point as temperatures increase after the sudden turbo boost, which does not allow to dissipate the required amount of heat correctly.

5 Task 6

The aim of the task was to design a Formula 1 V10 engine with power, torque, high RPM, low compression ratio, lightweight, durability and performance longevity.

5.1 Method

The method which was adopted in this task is to select and adjust the Engine parameters to increase the power, torques and efficiency of the V10 engine. Each parameter was tweaked to maximize the engine performance simultaneously balancing the reliability across various racing conditions. The fuel economy, emission and noise pollution were not considered.

5.2 Results and discussion

Parameter	Value	Reason
Power	1289.5 hp @ 8600 RPM	Achieved through lightweight construction, twin-turbocharging, and over-squared engine design, ensuring maximum power at high RPMs.
Torque	1084.7 Nm @ 8400 RPM	High torque is ensured by variable valve timing and direct fuel injection, providing strong acceleration and sustained performance across the RPM range.
Peak Efficiency	22.11% @ 5600 RPM	Efficiency is optimized with direct injection and turbocharging, allowing the engine to perform effectively at high speeds while preventing excessive fuel consumption.

Table 5: Power, Torque, and Efficiency of the Formula 1 V10 Engine

Material selection:
Generally, a Formula 1 car attains an average RPM of 11500 to 12000. As a result, dissipating the heat from the engine is a crucial factor to improve the engine performance and to maintain an optimal temperature. Therefore, the material used for the construction of block plays an important factor. Aluminum alloy (AlSi) is the material that was chosen as engine block material due to its good thermal conductivity, thermal stability, and strength-to- weight ratio. Additionally, Si in the alloys provides wear resistance as the engine block houses moving parts and ensuring the durability of the components. The materials for most of the engine components are selected based on reducing the reciprocating mass. The material chosen for crankshaft and connecting rods are billet steel and lightweight titanium, respectively. The engine is built with lightweight forged pistons. Reducing the reciprocating mass aids in reducing the inertia, thus allowing these parts to move with less resistance, allowing high RPM, and reducing stress on the rotational body.

Geometry:
Engine dimensions are crucial in determining the engine performance. The idea behind choosing the specific stroke length and bore distance is to design an over squared engine. Over squared engines help to generate high horsepower at higher rpm, better engine breathing, and importantly, reduce the mechanical stress in the piston, connecting rod, and crankshaft as the stroke length is shorter, which ultimately enhances the performance of the car.

Valve train and Timing Mechanism:
The valve train of the engine is designed with a combination of Dual Overhead Camshaft (DOHC), Variable Valve Timing (VVT), and Variable Valve Lift (VVL). The combination is so pivotal in achieving

high maximum power, torque, and efficiency. The F1 cars are particularly designed with high reliability, and this setup plays an important role in achieving this. The combination enhances reliability by reducing the mechanical stress of the engine components with the help of precise valve control and optimized flow of air throughout the engine, thereby preventing issues like Valve float at high RPMs, which contributes to the overall durability and longevity of the engine components for a wide range of Formula 1 conditions. Variable valve timing performs the crucial role in increasing the torque at lower speeds by dynamically changing the valve timing, due to which the valve is opened for a bit longer, which results in a higher intake of air that helps in acceleration in the cornering. Similarly, VVT advances the intake valve timing and increases the valve overlap, which in turn results in more complete combustion. As a consequence, maximum power can be produced. VVL is set to 100, prioritizing the peak power at high RPMs

Turbocharging System

The engine that has been designed is a turbocharged engine. The compression ratio and the Twin Turbocharger setup complement each other. The idea of having compression ratio of 7.0:1 is specifically chosen to work in harmony with the high boost twin turbocharger. The setup helps the engine to run at optimal temperature and pressure, thereby preventing knocking and producing high power. The Size of the compressor and turbine is precisely chosen to make the setup ideal for high power output at high RPMs. The Intercooler is rated with 2090 hp which should be quite sufficient for Formula 1 engines. The Area to Radius ratio (AR) directly influences the boost response and power delivery of the turbocharger. A higher AR ratio such as 1.40, helps Formula 1 cars, as most of them perform at higher rpm, which means more exhaust gas will be produced. Higher the AR ratio, higher will be the cross-sectional area. Allowing more gasses to flow through to turn the turbine wheel, and as a result of the high AR ratio, spool up is delayed at lower RPMs. The reason behind choosing the ball bearing is to compensate for this delay by reducing the rotational friction.

Exhaust System:

Most of the exhaust components complement the high AR ratio. Short- cast headers were preferred because they reduce the distance travelled by the exhaust gasses, which in turn raises the throttle response. The combination of a dual exhaust system and a large exhaust diameter (203 mm) aids in raising up the flow of exhaust, essential for managing the high volume of gasses in high AR ratio setup. Exhaust system with no mufflers and catalytic converters assists in reducing the backpressure, ensuring the turbo reaches optimal boost, and delivering the required power output at high RPMs.

Fuel Injection System:

The V10 Formula 1 engine is equipped with a Direct injection fuel system. This allows for precise control over the air fuel mixture, which ultimately enhances the combustion efficiency. The direct injection fuel system injects the fuel at an ideal time which helps to maximize the combustion process. The setup of the direct injection system and per cylinder configuration helps to produce maximum power and efficiency by providing optimal fuel delivery. The 100 RON is selected to prevent detonation under high boost conditions. The F1 engines are intended to perform at high RPMs for extended periods, so race intake setup is opted to prioritize airflow over fuel economy. A Slightly higher fuel mixture is set at 12.3, allowing more aggressive ignition timing, high performance, and reducing the risk of knocking.

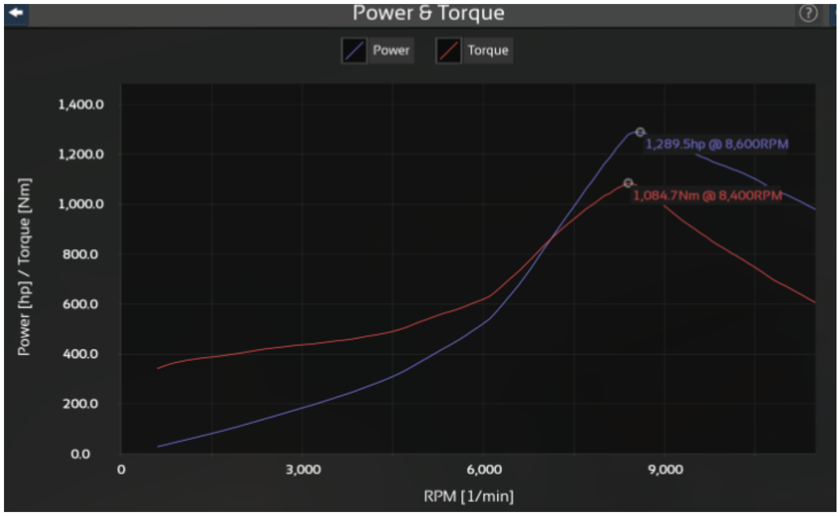


Figure 8: Power and Torque

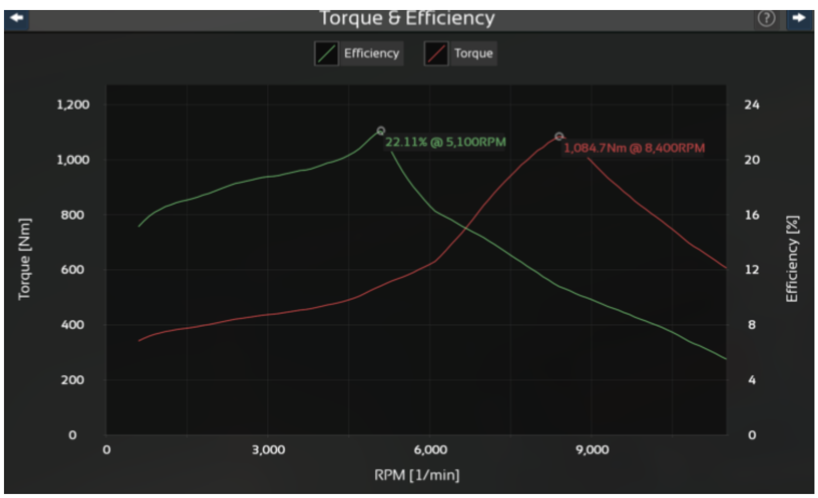


Figure 9: Torque and efficiency

In conclusion, the Formula 1 V10 engine is meticulously designed to produce high power output and torque. From the graph, it can be seen that the engine produces a formidable 1289.8 hp at 8600 RPM and 1084.7 Nm of torque at 8400 RPM, with a peak efficiency of 22.11 percentage at 5600 RPM. These results portray that the engine is highly reliable and has exceptional performance in high stress racing conditions.