



NAZARBAYEV
UNIVERSITY

School of Engineering and Digital Sciences

Bachelor of Engineering in
Mechanical and Aerospace Engineering

**SELECTION AND DESIGN OF A
TURBOCHARGER SYSTEM FOR A CAR
ENGINE**

by

Raimbek Zhumake
Alibek Kairbekov
Diaz Shortanbay
Alisher Atrauov

Principal Supervisor: Associate Professor Amgad
Salama

Co-supervisor: Assistant Professor Yerbol Sarbassov

April 2026

Declaration

We hereby declare that this report, entitled “Selection and Design of a Turbocharger System for a Car Engine,” is the result of our own project work except for quotations and citations that have been duly acknowledged. We also declare that it has not been previously or concurrently submitted for any other degree at Nazarbayev University.

Names: Raimbek Zhumake

Date: April 30, 2026

Names: Alibek Kairbekov

Date: April 30, 2026

Names: Diaz Shortanbay

Date: April 30, 2026

Names: Alisher Atrauov

Date: April 30, 2026

Abstract

This capstone project aims to select an appropriate turbocharger system for a naturally aspirated domestic car engine. While car manufacturers in recent years have implemented turbocharger systems on a large scale on modern cars, there exist a large number of relatively older models that do not have such turbocharger systems, which makes their power and torque outputs small and incompatible with the current technology.

In this capstone project, we are conducting a selection process of a turbocharger system for a naturally aspirated car engine in order to increase its output power and torque under steady state working conditions. In the process of the turbocharger selection, the turbo lag issue will be considered and highlighted. At the final stage of calculations, the appropriate area-to-radius ratio will be calculated in order to select the turbocharger system for low RPMs.

The major finding of this capstone project is the calculation procedure and selection of a turbocharger system for steady-state driving.

Table of contents

Declaration.....	1
Abstract.....	2
1 Introduction and Industrial Requirements.....	1
1.1 Limitations and Constraints.....	4
1.1.1 Design and Development constrains.....	4
1.1.2 Operational Constraints.....	5
1.2 Engineering Standards.....	7
1.3 Engineering Ethics.....	8
2 Literature Review.....	10
2.1 Thermodynamic Principles of Turbocharging.....	10
2.2 Compressor Aerodynamics.....	11
2.3 Turbine Aerodynamics and Flow Behaviour.....	12
2.4 Turbo Lag in Spark-Ignition Engines.....	13
2.5 Variable Geometry Turbocharging Systems.....	13
2.6 Engine-Turbocharger Matching.....	14
2.7 Emissions, Fuel Economy, and Operational Efficiency.....	15
2.8 Turbocharger Modeling Approaches.....	15
3 Methodology.....	16
3.1 Calculations.....	16
3.2 3D Modelling and Simulations.....	21
3.2.1 3D Modelling.....	21
3.2.2 Simulations.....	28
4 Results.....	30
4.1 Calculations.....	30
4.2 Simulation Analysis.....	33
5 Analysis and Discussions.....	39
5.1 A/R Ratio.....	39
5.2 Airflow and Air Pressure.....	39
5.3 Boost pressure, pressure ratio and enthalpy.....	40
5.4 Weight distribution analysis.....	41
5.5 Cost analysis.....	43
6 Conclusion.....	44
7 References.....	46

1 Introduction and Industrial Requirements

Since the invention of the first internal combustion engines, engineers and manufacturers are spending too much effort to increase the efficiency and output power of the engines. The power output and efficiency of the engine are among the most essential characteristics in the process of selecting the right engine to achieve a particular goal. It is essentially correct to assume that in order to increase the power, the engine has to burn more fuel and likewise utilize more air. In order to attain a higher power from an engine, either the engine displacement or the number of cylinders need to be increased. However, this enlarges the size and the weight of the engine. Fig. 1 shows a typical engine cylinder and piston system.

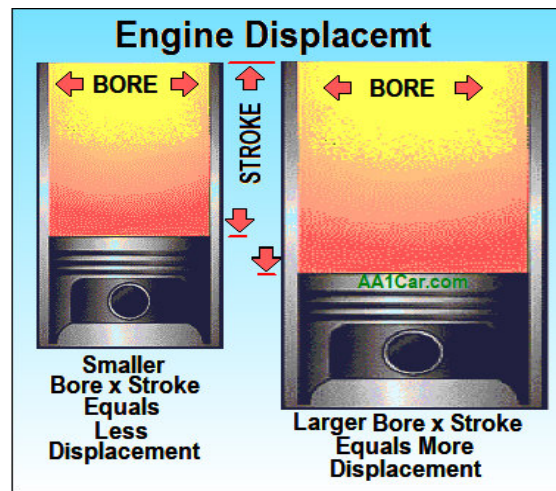


Fig. 1. Engine Displacement

Naturally aspirated engines rely on atmospheric pressure to push the air into the cylinders. However, it is a well-known fact that atmospheric pressure changes with altitude as can be seen in Fig. 2. If the vehicle operates at higher altitudes, the efficiency of the engine and generated power will drop to a large extent. So, this was a major problem and challenge to be solved to achieve maximum efficiency and maintain the power of the engine.

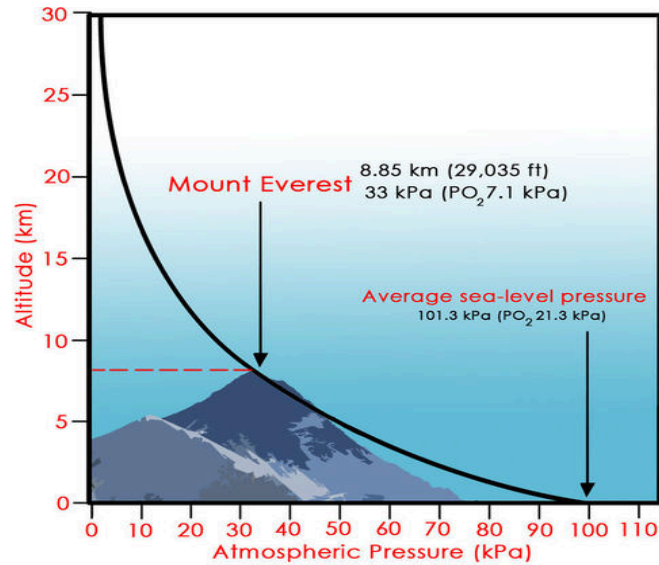


Fig. 2. Atmospheric pressure by altitude

It has been found that instead of increasing the number of cylinders and/or engine displacement, a more efficient approach may be to artificially compress the intake air in order to burn more fuel thus increasing the power of the engine. This will allow generating more power yet keeping the size of the engine. In order to increase the amount of intake air, the engine must, therefore, be equipped with a compressor. There are two essential ways to run the compressor. The first one is by using the engine derive mechanism to run the compressor, and in this case it is called supercharging. And the second is via the use of a turbine that runs by the exhaust gases, which is called turbocharging. There are specific reasons why it was decided to focus on a turbocharger instead of a supercharger. The superchargers, while providing an increase in the power up to 15 - 25%, a pressure boost up to 1.6 - 1.8, and a smooth acceleration, are still lower than typical needs. In addition, they have the disadvantage of increased fuel consumption by 5 - 10%, and mechanical losses up to 20%. The turbocharger systems, on the other hand, increase the power up to 30-40%, pressure boost up to 1.8-2.5%, and improvements in thermal efficiency up to 5%. However, the system becomes too complex due to the consideration of intercooling, wastegates, and the turbo lag issue (Vedran & Božica, 2018). From the mentioned advantages and disadvantages, it was decided to work with turbochargers in order to increase the power and efficiency of the engine to levels needed by typical car engines.

The objective of this Capstone Project is, therefore, to select and design the optimal turbocharger system for a generic naturally aspirated I-4 engine with appropriate

specifications. The challenges that were encountered in the process of this project include the appropriate calculations, selection process, and finding the balance between the specifications of the engine and the appropriate system. As can be seen from Table 1 below

Table 1. Engine Specifications

Characteristics	Naturally Aspirated	With Turbocharger
Number of cylinders	4	4
Displacement volume (L)	2.0 L	2.0 L
Max RPM	6500	6500
Torque (Nm)	200	375
Power (Hp)	150	280

1.1 Limitations and Constraints

It is impossible to eliminate all the constraints when designing any mechanical system. Nevertheless, it is quite important to realise them at the beginning of the working process, as understanding the limitations can be considered a part of finding new opportunities. The knowledge associated with the limitations is useful for studying the principles of the engine and turbocharging of the car, as well as the limitations of the material, the use of space inside the car and safety requirements. Besides, limitations tend to affect the design; thus, they must be researched and analysed to make the most accurate design decisions.

In this project, the engine power will be increased from 150 hp to 280 hp, which makes the analysis of the limitations even more important due to the challenging increase in loads.

1.1.1 Design and Development constraints

Selection of the materials is one of the main constraints in turbocharger design. The device is capable of withstanding extreme heating and corresponding mechanical loads. To be precise, the turbochargers in spark-ignition engines are supposed to contact with exhaust gases that can exceed temperatures up to 900–950 °C, while the acceptable strain due to thermal expansions equals 0.5% – 1%. Exceeding the acceptable threshold can lead to efficiency drop, overall decline of vehicle performance and even a significant increase in permanent damage. However, the described problems can be solved by choosing advanced materials such as nickel-based alloys for turbine wheels and heat-resistant steel or cast iron alloys for turbine housings (Feneley et al., 2017). Nevertheless, the use of such materials introduces another limitation: cost constraints due to the high price of the mentioned alloys. Besides, any material choice cannot fully protect the device from material degradation mechanisms like creep or thermal fatigue. The safety of the design decisions will be proven at the further stages of work via test simulations.

Manufacturing features impose constraints, too. Although all the related issues (machining of the components, dynamic balancing, tight tolerances in bearing and shaft alignment) can be easily solved by following the standardisation of turbocharger components. In other words, the use of data provided by the manufacturer itself (like

Garrett Motion) allows us to design our own model of turbocharger that can be manufactured and operated. For example, following the compressor maps ensures avoiding the choke limits (flow restriction at high mass flow rates) and surge limit (unstable flow at low mass flow rates), as they show what configurations can be used to make the turbocharger operate within acceptable pressure ratio and mass flow rate regions (Garrett Motion, n.d.).

One of the major limitations in turbocharger integration is associated with the limited available space within the engine bay. The whole turbocharging system consists of several modules: Intake and Exhaust piping, Intercooler system and Wastegate or variable geometry mechanisms. These components require sufficient physical space for installation, access to air flow, and maintenance. Therefore, the system has maximum volume constraints, which limit the size of the turbine and compressor.

The design of the turbocharging system requires the full analysis of material, manufacturing, thermodynamic and other constraints. A successful design must carefully balance these factors to achieve optimal equilibrium between feasibility, performance, reliability and safety.

1.1.2 Operational Constraints

The turbocharger operation is directly related to exhaust gas energy. In particular, insufficient exhaust gas flow, which occurs at low speeds, leads to a delay in turbine operation, also known as a turbo lag. Thus, the following constraints can be highlighted: reduced response at low RPM, Nonlinear boost pressure behaviour, and unsmooth acceleration rise. The change in geometry or turbine volume can solve the mentioned challenges (Feneley et al., 2017). However, the use of these solutions imposes new restrictions in the form of increased complexity of production and higher manufacturing prices.

As a turbocharger is designed for urban driving conditions, it will be hard to predict the risk of fatigue failure for other driving conditions. The system must withstand as much long-term cyclic loading as possible; cases related to extreme conditions can be ignored. The main thing is to clarify the purpose of the device in order to avoid failures due to improper exploitation.

In addition, it is crucial to introduce restrictions for the user or, more importantly, the

exact rules of operation and maintenance. Thermal loads can be considered a main threat, but they can be eliminated by the use of cooling and lubricating substances.

Overall, the need to identify all the factors limiting the operation of the turbocharger or capable of limiting the period of its operation cannot be underestimated. The existing restrictions make it possible to maintain both each part and the system as a whole in good condition, allowing constant high performance and safety level.

1.2 Engineering Standards

An engineering standard is a document that provides requirements, specifications, guidelines or characteristics that can be used consistently to ensure that materials, products, processes, and services are fit for their purpose (Nazarbayev University Library, 2024). Engineering Standards ensure safety, accuracy, and consistency with industry practices; that is why it is important to follow them. The design of the turbocharger system in this project was guided by the data (particularly compressor maps) taken from Garrett Motion's official website; consequently, the standardised methodologies of this company will be discussed in this section.

Garrett Motion relies on standardised methodologies developed by SAE(Society of Automotive Engineers)international to generate reliable performance data.

- SAE J1826 defines the Turbocharger Gas Stand Test Code. It also provides procedures for evaluating turbocharger performance under controlled conditions. This Standard is crucial to ensure accurate measurement of key parameters such as efficiency, mass flow rate, and pressure ratio. In addition, it is directly related to the construction and interpretation of Garrett Motion's compressor maps.
- SAE J922 Standard establishes a unified nomenclature and terminology for turbocharger systems. Thus, it ensures consistent technical communication across engineers.
- SAE J1349, the Engine Power Test Code, standardises the measurement of engine performance under specified conditions. It is used to accurately determine the effect of a turbocharger on a system's power output.

Overall, adherence to SAE standards ensures that the design of the final product will be aligned with modern engineering requirements and matched with industrial norms and benchmarks.

1.3 Engineering Ethics

Engineering Ethics is a set of basic rules for engineers to work in a morally and socially responsible way (Alisatul, 2025). It focuses on providing safety and good-quality work. However, its main purpose is not primarily associated with skills and knowledge, but with honesty, integrity and other aspects of morality. Thus, it can be said that the main goal of Engineering Ethics is to create professionals who will be trusted and respected by society, which can be considered essential for mechanical engineering.

Engineering Ethics comes into effect at the very beginning of working on a project – before the turbine development itself. To be precise, it is required to take responsibility for data usage into account during the research phase. The information we collected at this stage was taken from open sources such as scientific articles and the manufacturer's (Garrett Automotive) website. Thus, all the data must be cited clearly to avoid ignoring contributions made by previous researchers. In addition, their data must be interpreted properly – without intentional or unintentional distortion, as it may lead to hazardous consequences in a variety of ways.

Analysing potential harm was a key aspect of Engineering Ethics in the subsequent stages of the work. Every insignificant detail could become a cause of a lethal accident; the importance of the analysis cannot be underestimated. Herewith, it is necessary to take into account not only user cases but also scenarios related to the manufacturer and the environment.

There are several potential dangers that may harm drivers, passengers and nearby people. Among them: turbine burst, wheel fracture, overboost, excessive heat generation, oil leakage, mechanical debris release, and noise exposure. The full analysis requires numerous tests that should be conducted after creating the working prototype and subsequent models. It can be considered challenging for our team, but feasible for a manufacturer. The manufacturer will also be responsible for writing instructions for use that will help customers to avoid potential harm due to a list of rules and simple maintenance operations, such as lubrication and oil change. However, minimising harm to manufacturers is a part of our job. It is important to make the proposed design of the turbocharger meet their standards, while the production must be safe, financially profitable and reputationally beneficial. It is worth mentioning that in this case, the final consent is a choice of the manufacturer. In other words, manufacturers will be

responsible for everything after accepting the project.

Another part of the potential dangers that must be analysed is related to the environmental impact. Several threats require proper testing at the production stage – Fluid (oil, coolant) leakage, Contamination, Noise pollution, Thermal pollution and potential fire hazards. The other threats (such as Increased emissions, High Fuel consumption) can be considered as secondary, because they were already solved theoretically during the work on the prototype. The End-of-Life Disposal issue can also be recognised as solved, since today disposed turbochargers are collected and sent to remanufacturing facilities in most cases. In the remaining cases, they still remain valuable as they contain useful metals (steel, aluminium, nickel-based alloys) that can be recycled at corresponding facilities.

In conclusion, the following must be claimed: despite the fact that one of our main goals is to find a way to improve the efficiency of a turbocharger, safety remains a top priority, and its importance cannot be underestimated even for the sake of a technological breakthrough.

2 Literature Review

Turbocharging has become one of the most promising technologies in the car industry, and the relevance of the technology continues to rise. This is not accidental; strict emissions standards force the industry to adopt environmentally friendly technologies. Meanwhile, consumers expect a reduction in engine size without any loss in performance, and ideally with further performance gains. By converting exhaust-gas enthalpy (which is usually wasted) to mechanical work, turbochargers substantially improve power output and fuel economy without an increase in engine displacement (Feneley et al., 2017). These benefits position turbocharging as a promising strategy for meeting performance demands and regulatory requirements. Recent research emphasizes that the selection and design of a turbocharger must account not only for thermodynamic performance during steady state operation but also for transient behavior. In addition, the compressor's operating stability, and turbine efficiency are considered paramount (Mazuro & Kozak, 2024).

Spark-ignition (SI) engines pose unique challenges for turbocharging because of their wide operating speed range, high exhaust temperatures, and knock sensitivity. Accurate design of a turbocharger must therefore include thermodynamic analysis of compressor and turbine operation. Manufacturers of turbocharger systems have established selectivity maps that can be helpful for users to choose the appropriate system (Vedran & Božica, 2018). As the primary goal of this project is to develop a turbocharger-selection of a naturally aspirated engine, we examine both fixed-geometry turbocharger, and the more advanced variable geometry technology (VGT). In addition, this project requires a thorough understanding of various concepts such as the turbocharger's thermodynamic behaviour, compressor and turbine aerodynamics, boosted-engine performance and emissions, component efficiency, and matching with the engine's operating characteristics. Thus, this review synthesizes the findings of various academic sources providing theoretical foundations related to the above-mentioned concepts essential for accurate turbocharger design.

2.1 Thermodynamic Principles of Turbocharging

Turbocharger behavior is governed by classical thermodynamics and turbomachinery principles. The compressor raises the total pressure and temperature intake air according

to the Euler turbomachinery equation (which links the change in fluid angular momentum to specific work transfer). It can be argued that its performance is evaluated through pressure ratio, isentropic efficiency, and corrected mass flow rate (Vedran & Božica, 2018). Additionally, it is important to note that changes in intake temperature strongly influence knock behaviour of the engine. Thus, the role of compressor and intercooling in engine performance modeling cannot be overstated (Chen et al., 2009). Another important aspect to consider is the turbine's thermodynamics. The turbine performance depends on the available exhaust-gas enthalpy drop and the turbine's expansion ratio. These quantities fluctuate with engine load and operating conditions. Therefore, it is important to appropriately size the turbine in order to balance exhaust backpressure and boost capability. According to Feneley et al. (2017), an undersized turbine may generate excessive backpressure and increase pumping losses, whereas an oversized turbine may extract insufficient energy at low engine speeds, resulting in delayed boost formation. Maintaining this balance is essential for effective engine-turbocharger matching and preserving overall engine condition. Separately, it is necessary to address the turbine thermodynamics during transient operation. Mosca and Mihaescu (2022) report that spark-ignition engines experience rapid load changes, which lead to fluctuations in exhaust temperature, mass flow, and pressure. It also should be mentioned that these variations contribute to unstable turbine operation. The study also recommends integrating compressor-efficiency maps and turbine-efficiency maps using more realistic temperature-sensitive and flow-dependent relationships. In particular for SI applications where exhaust temperature exceeds 900-950 °C.

2.2 Compressor Aerodynamics

The compressor plays a main role in defining the boost characteristics, efficiency, and operational range of a turbocharged engine. Performance of a compressor can be represented by a compressor map. A compressor map provides relationship among pressure ratio, corrected mass flow rate, isentropic efficiency, and rotational speed. Meanwhile, compressor operation is tied to the isentropic compression process. Efficiency losses during the process derive from blade aerodynamic design, tip clearance, heat transfer effects and diffuser performance. Vedran and Božica (2018) analyse all those factors to draw a conclusion regarding compressor operation for a

turbocharged system. The authors claim that compressor performance directly influences volumetric efficiency. Additionally, they found out that improvements in compressor efficiency lead to significant decrease in Brake Specific Fuel Consumption (BSFC) and large increase in power density.

Tripathi et al. (2019) and Chen et al. (2022) emphasize the importance of avoiding two limiting conditions: surge and choke. Surge occurs at low mass flow rates when diffuser stalls, causing reversed flow and unstable operation. Choke occurs when the flow reaches sonic velocity at the inducer throat, limiting further rise of mass-flow regardless of shaft speed. Therefore, it is essential to ensure the engine operation within the stable region in the compressor map. Studies suggest that it can be more crucial for SI engines, as they operate across wide RPM ranges with more abrupt load transients. Chen et al. (2022) also emphasize the role of compressor maps in turbocharger matching methodologies.

2.3 Turbine Aerodynamics and Flow Behaviour

Turbine Aerodynamics can be considered rather complex and complicated. Turbine efficiency depends on blade geometry, nozzle area, flow incidence, and housing A/R ratio (Padzillah et al., 2015). Additionally, all these parameters must align with the engine's exhaust characteristics for accurate engine operation. Besides, as previously discussed, improper turbine sizing can lead to undesirable consequences such as delayed boost formation (in the case of oversizing) or an increase in pumping losses (in the case of undersizing).

Another limitation is that steady-state turbine maps fail to capture real behaviour under pulsating flow. Burke et al. (2022) simulated a turbine under these conditions. The authors demonstrated that exhaust pulses create a hysteresis loop in turbine performance that causes a change in efficiency, expansion ratio, and mass flow characteristics. Pulses also may increase the expansion ratio but reduce average efficiency due to flow separation. However, higher pulse frequency tends to improve efficiency by narrowing the range of inflow angles. These findings indicate that models relying only on steady turbine maps underestimate losses during realistic engine operation.

Because SI engines produce stronger exhaust pulses than diesel engines at comparable loads, the studies underscore the need for unsteady-flow corrections in SI turbine

modeling. This insight directly shapes the design approach for the turbocharger model developed in this project.

2.4 Turbo Lag in Spark-Ignition Engines

The turbo lag can be considered as a principle issue of turbocharged SI engines, due to aerodynamic and mechanical factors. The primary cause of this effect is lag in the turbine-compressor at low rotational speeds, as it requires too much time to be driven by exhaust gas under these conditions. As a result, slower throttle response and reduced transient performance negatively affect the driving experience. And this issue cannot be solved even with modern control strategies (Tripathi et al., 2019).

Feneley et al. (2017) claim that turbine rotor inertia can be considered as a critical factor. Large heavy turbine wheels take longer to accelerate, and consequently delay pressure boost. This explains why high-performance SI engines usually contain rather small and lightweight wheels – they enhance spool-up and provide sharper transient response.

Another important aspect to consider is exhaust-pulse utilization. There is a chance of interference appearing in engines with unequal manifold lengths. This interference causes a reduction in instantaneous energy delivery to the turbine. However, it is possible to solve the issue partially. The negative effect of the interference can be mitigated by twin-scroll and divided-pulse turbine housings, as they provide more consistent turbine torque (Samoilenko et al., 2017).

The researchers also suggest the following engineering solutions: reduced-inertia turbine wheels, optimised A/R ratios, and electrically assisted turbochargers. All of these solutions contribute to faster spool and more responsive torque delivery (Tripathi et al., 2019; Samoilenko et al, 2017). Collectively, these findings demonstrate that turbo lag is not simply a control issue but a deeply aerodynamic and mechanical phenomenon that must be considered during turbocharger selection and further model development.

2.5 Variable Geometry Turbocharging Systems

Variable geometry turbochargers dynamically adjust turbine inlet geometry to optimize turbine efficiency. To be precise, VGTs use pivoting vanes to modify the nozzle area and flow incidence angle. Feneley et al. (2017) claim that VGTs can be a solution to a turbo lag issue, as they improve low-RPM torque and maintain boost pressure control

more effectively than fixed-geometry turbos. It is most relevant for downsized SI engines that must deliver strong low-speed drivability.

Even though SI engines historically avoided VGTs because of high exhaust temperatures, modern models can operate reliably under these conditions. Moreover, optimised VGT vane angles allow for an increase in brake thermal efficiency by nearly two percentage points. In other words, modern technologies eliminated this restriction (Mazuro & Kozak, 2024).

An innovative VGT model was proposed by Samoilenko et al. (2017). The alternative VGT concept uses adjustable shaped elements to vary the inlet area without vanes. This innovation allows for achieving minimal efficiency penalties, a notable decrease in fuel consumption, and diminishing the amount of emissions. Though this model was developed for a diesel engine, the authors state that it can apply to gasoline engines.

While the GTX2867R GEN II selected for this project is a fixed-geometry turbine, understanding the concept of VGT is essential for identifying potential future improvements.

2.6 Engine-Turbocharger Matching

Aligning the compressor and turbine characteristics with the engine's airflow demand and exhaust energy supply is essential for selecting an appropriate turbocharger. If it is done correctly, the turbocharger will be capable of delivering the required boost pressure across the full engine-range without entering unstable regions of its operating maps. In addition, successful matching can raise engine torque by 60% and significantly improve overall power output (Salameh et al., 2016).

Plotting the engine's expected operating points (including low-speed, mid-range, and high-load conditions) on the compressor map can be considered as a key step in matching. Thus, the engine could operate within the safe region between surge and choke while still accessing the high-efficiency zones of the compressor. Another essential factor is turbine selection, as the turbine has to generate enough shaft power at low RPM. Turbines that are too large could weaken boost response, whereas too restrictive ones could increase pumping losses (Wu et al., 2018). Hence, keeping balance is important.

Thermodynamic modeling also must be considered. Errors in turbocharger sizing,

intercooler capacity and ignition control can cause inaccurate predictions of power, BSFC, and knock limits in SI engines. Meanwhile, proper modeling provides higher thermal efficiency and performance gains (Wang et al., 2015).

2.7 Emissions, Fuel Economy, and Operational Efficiency

Due to improved mixture preparation and a higher excess-air ratio, turbocharging positively affects emissions. According to Mazuro and Kozak (2024), turbocharged engines produce 25% less CO, 52% less HC, and 15% less soot. Additionally, it was observed that better exhaust-energy utilisation (provided by the turbocharger) caused a reduction in fuel consumption and improved combustion completeness (Samoilenko et al., 2017). Another benefit of a turbocharged system is better BSFC values (Tripathi et al., 2019). Thus, it can be stated that turbochargers' role in sustainable energy design is particularly important.

2.8 Turbocharger Modeling Approaches

There are several modeling approaches in turbocharger design. 0D and 1D are common for engineering design purposes because they provide a balance between computational cost and accuracy. Zero-dimensional (0D) modeling treats the engine as a series of control volumes with uniform properties (pressure, temperature). This approach also used energy and mass-balance equations to predict in-cylinder and manifold conditions. Vedran and Božica (2018) employed it and simulated the impact of turbocharging on a naturally aspirated gasoline engine. The authors had to solve conservation equations for each engine cycle; thus, they determined the resulting torque, power, and BSFC. Their results confirmed the reliability of OD modeling. However, one-dimensional (1D) modeling showed higher fidelity, as it required the use of 1D gas dynamics to capture gas propagation, reflection, and interference crucial to understanding the interaction between pulsating flow and turbine (Mosca & Mihaescu, 2022).

Nevertheless, map-based interpolation can be considered the most practical method for engineering design. Chen et al. (2009) show that map accuracy directly influences predicted BSFC and knock tendencies. Meanwhile, empirical adjustments can dress unsteady losses and improve prediction accuracy (Mosca & Mihaescu, 2022). Collectively, it can be stated that the hybrid modeling strategy (map-based with empirically corrected modeling) is the most accurate, but the most complicated, and 0D or 1D modeling can provide quite good accuracy.

3 Methodology

3.1 Calculations

The first parameter crucial for identifying dimensions of the turbocharger is the wheel trim. The wheel trim is the ratio between the inducer and exducer diameters.

$$Wheel\ trim = \frac{Inducer\ diameter}{Exducer\ diameter} = [dimensionless] \quad (3.1)$$

The wheel trim for the turbine housing and the compressor housing can be different.

Components of the turbine housing are:

- 1) Inducer
- 2) Exducer
- 3) Turbine outlet
- 4) Turbine inlet

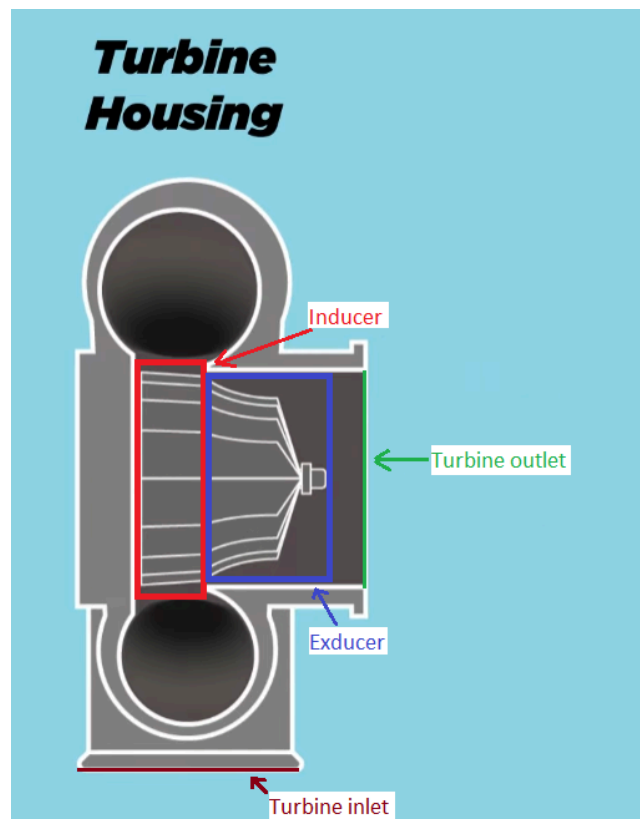


Fig. 3. Components of the turbine housing.

The turbine inlet is responsible for carrying exhaust gases from the engine to the inducer of the turbine wheel. The section where exhaust gases enter the turbine wheel is called the inducer. The section of the turbine wheel where exhaust gases exit the turbine is the exducer. The turbine exducer is where exhaust gases exit the turbine.

The compressor housing has a similar structure:

- 5) Inducer
- 6) Exducer
- 7) Compressor outlet
- 8) Compressor inlet

The compressor wheel is driven by the turbine wheel. It sucks air through the Inducer from the Compressor inlet. The air is pushed through the Exducer from the Compressor outlet.

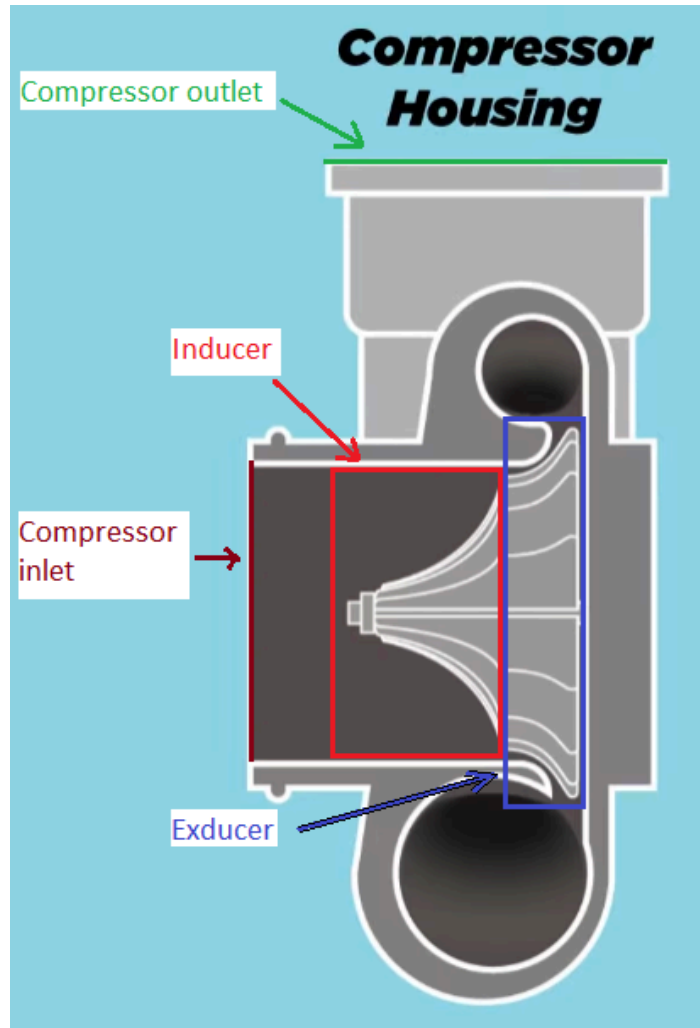


Fig. 4. Components of the compressor housing.

The second crucial component to identify a turbocharger's dimensions is the A/R, which means the ratio of the cross-sectional area of the turbine inlet to the radius from the center of the area to the center of the wheel.

$$A/R = \frac{\text{Cross-sectional Area of Turbine inlet}}{\text{Radius (from center of Area to center of the wheel)}} \quad (3.2)$$

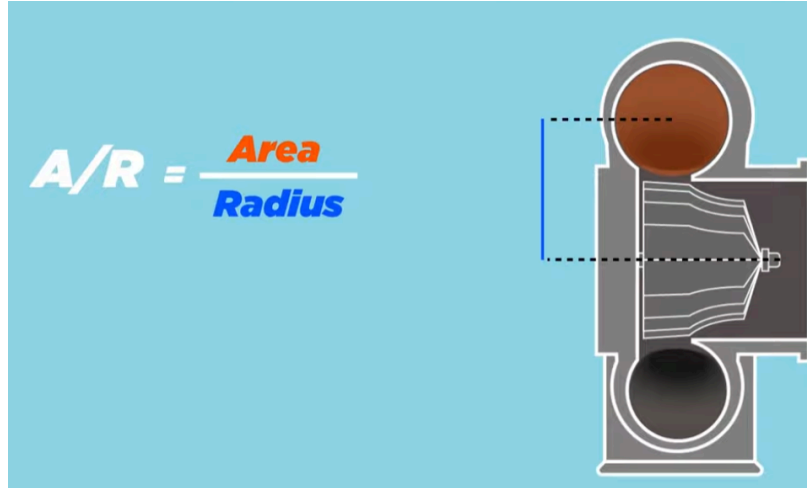


Fig. 5. Demonstration of A/R in the turbocharger's diagram

The calculations that were made are based on the Garrett company's formulas. The Garrett company is located in the United States, and they use Imperial units of measurement. For this reason, the calculations will be made in Imperial units and then transformed into SI units.

Another step of defining characteristics of the required turbocharger is to calculate the Airflow - how much air goes to the engine per unit of time.

The formula for the airflow looks like this:

$$\dot{m}_a = HP * A/F * BSFC \quad (3.3)$$

Where $\dot{m}_a$ is the air mass flow rate, HP is the target power, which represents the amount of horsepower needed for the upgraded engine, A/F - Air-to-fuel ratio, which defines the ratio of the amount of air consumed by the engine compared to the amount of fuel. It differs from the fuel type used in the car. For gasoline engines, the air-to-fuel ratio is 14.7 to 1, which means 14.7 kg of air per 1 kg of fuel, and $BSFC$ - Brake specific fuel consumption, which describes the amount of fuel flow rate required to generate each horsepower. It depends on the fuel type used in the vehicle. Generally, turbocharged gasoline engines range from 0.5 to 0.6. Lower brake-specific fuel consumption means that the engine requires less fuel to generate a given horsepower.

The next important value is the manifold pressure. The formula for that is this one:

$$p_m = \frac{\dot{m}_a * R * (460 + T_{IM})}{\eta * \frac{RPM_{max}}{2} * V} \quad (3.4)$$

Where: p_m [psi], is the manifold pressure, which refers to the air pressure within the engine's intake manifold, $\dot{m}_a$ [lb/min] is the mass flow rate of air, R is a specific gas constant (it is equal to 639.6), T_{IM} [F] is the intake manifold temperature. Compressors with higher efficiency produce lower manifold temperatures. It is usually around 100-130 F in intercooled engines and 175-300 F in non-intercooled engines. η is the engine's volumetric efficiency, which represents how efficient an engine is at moving air through its cylinders. It ranges from 95% to 99% for 4-valve engines and from 80 to 95% for 2-valve engines. RPM_{max} [rev/min] is the maximum revolutions per minute an engine can do, and V [in^3] is the volumetric displacement of the engine.

The boost pressure is evaluated through this formula:

$$p_b = p_m - p_a \quad (3.5)$$

Where: p_b is the boost pressure, p_m is the manifold pressure, and p_a is the ambient air pressure (14.7 psi on sea level, depends on the environment and altitude)

The formula for the pressure ratio is this one:

$$p_{ratio} = \frac{p_{AO}}{p_{AI}} \quad (3.6)$$

Where, p_{ratio} is the pressure ratio, p_{AO} the outlet air pressure, and p_{AI} is the inlet air pressure

Since the next equations do not originate from Garrett's equations, they can be evaluated using SI units.

To evaluate how much torque an engine produces after the installation of a turbocharger, a universal equation for engine torque can be applied:

$$\tau = \frac{9548 * P}{RPM_{max}} \quad (3.7)$$

Where: τ is the torque, P is the power of the engine, and RPM_{max} is the maximum revolutions per minute an engine can do.

As the turbocharger heats up while working, it is crucial to evaluate the enthalpy change of both compressor and turbine parts. They can be calculated via this formula:

$$\Delta h = \frac{\gamma}{\gamma-1} R T_1 \left[\left(\frac{p_2}{p_1} \right)^{(\gamma-1)/\gamma} - 1 \right] \quad (3.8)$$

Where: Δh [J/kg] is the enthalpy change, γ - specific heat ratio, R [J/kg K] specific gas constant, T_1 [K] ambient temperature, p_2 [kPa] pressure after the installation of a turbocharger, p_1 [kPa] pressure before the installation of a turbocharger

Power in a compressor and a turbine is evaluated through this equation:

$$P_c = \dot{m}_a * \Delta h \quad (3.9)$$

Where:

P_c - power of a compressor/turbine

$\dot{m}_a$ - air mass flow

Δh - enthalpy change

$$P_c = [kW]$$

$$\dot{m}_a = [kg/s]$$

$$\Delta h = [J/kg]$$

3.2 3D Modelling and Simulations

The parameters mentioned above fully represent all the necessary aspects of the turbocharger operation, and once calculated, can be used to create a simulation of various processes occurring inside the device. Without these simulations, it will be impossible to draw an accurate conclusion regarding the efficiency and reliability of the turbocharger, despite the data obtained through calculations being promising already. Overall, conducting a simulation is a mandatory step in the long process of working on mechanical devices.

The SolidWorks program was chosen as the main software. It includes all the necessary tools for both 3D modelling and simulation, and is also well known to the members of our team. In addition, SolidWorks can be considered the most convenient and practical choice for a mechanical engineer.

3.2.1 3D Modelling

The 3D model of the designed turbocharger is required to represent its main components, connections between them, and further simulation analyses. The final assembly includes the following parts: turbine, turbocharger blade, compressor, compressor blade, shaft. Single part drawings were prepared for turbocharger blade, compressor blade and shaft.

The material choice for each component was based on its purpose and operating conditions:

- **Grey cast iron** was selected for the turbine due to its resistance to high-temperatures
- **AISI 321 annealed stainless steel** provides good heat resistance and oxidation resistance in the turbine environment, consequently it perfectly matches the requirements of the turbocharger blade
- **AA356-F aluminum alloy** is lightweight and suitable for manufacturing components with complex geometry, thus it is an appropriate choice for the compressor.
- **2618-T61 aluminium alloy** was selected for the compressor blade due to the material's high strength-to-weight ratio and good performance under rotating load conditions.



Fig. 8. The Shaft 3D model isometric view

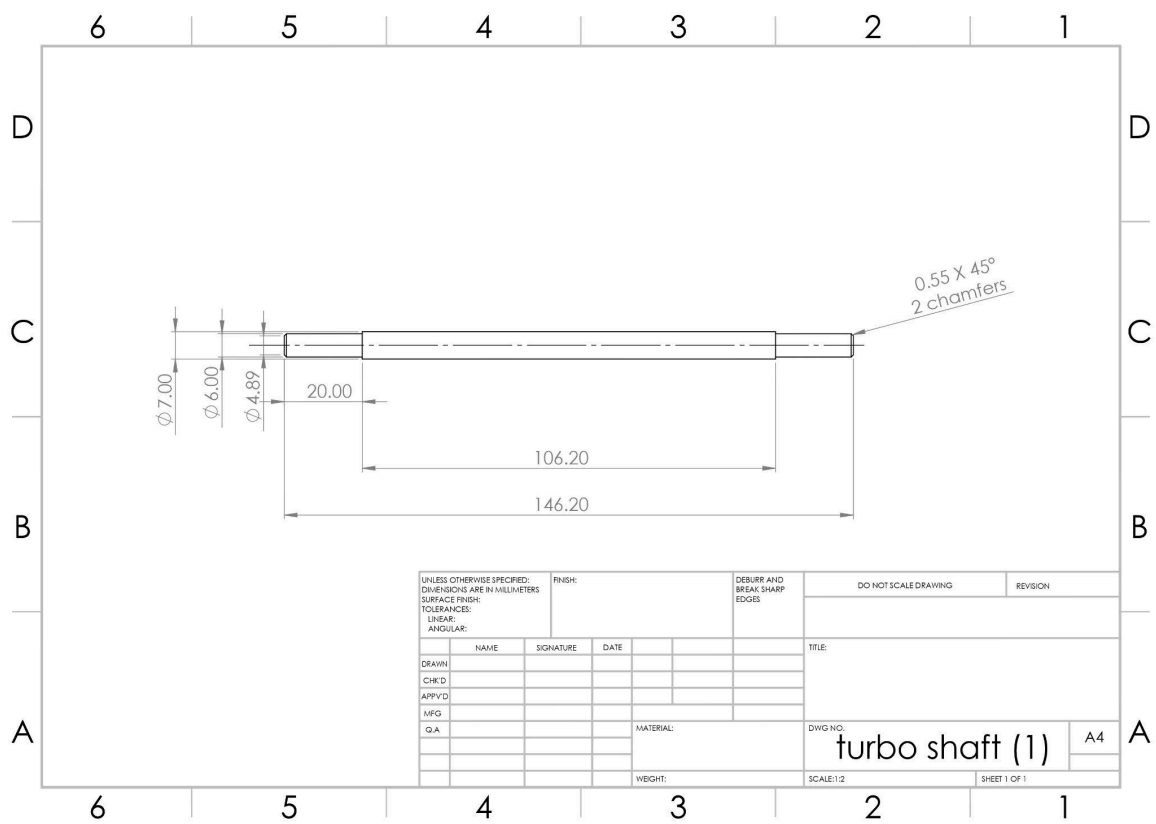


Fig. 9. The Shaft Drawing

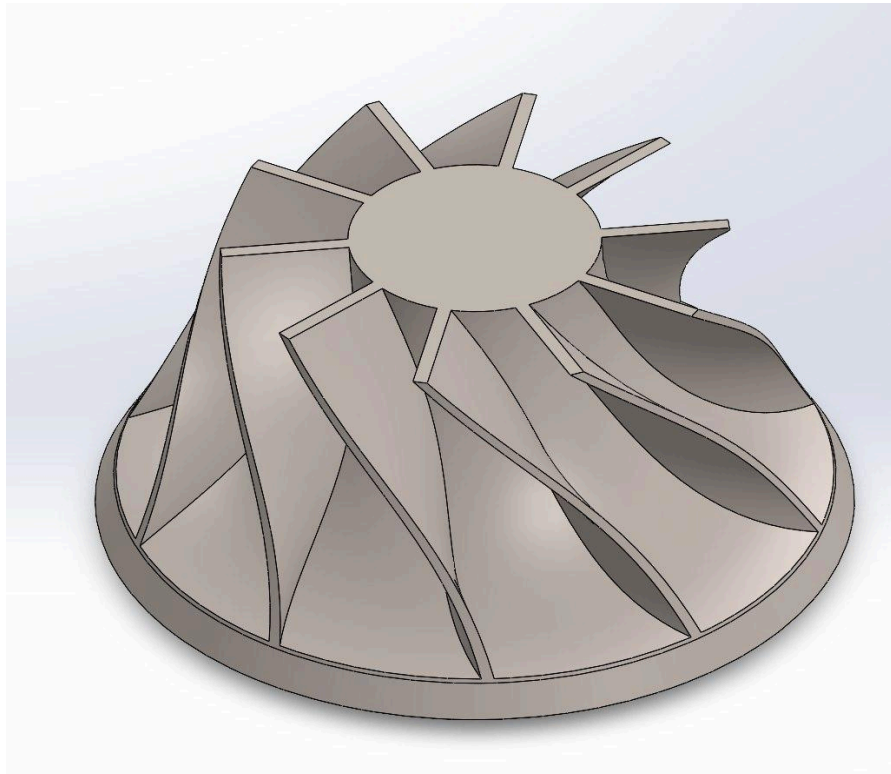


Fig. 10. The Turbocharger Blade 3D model isometric view

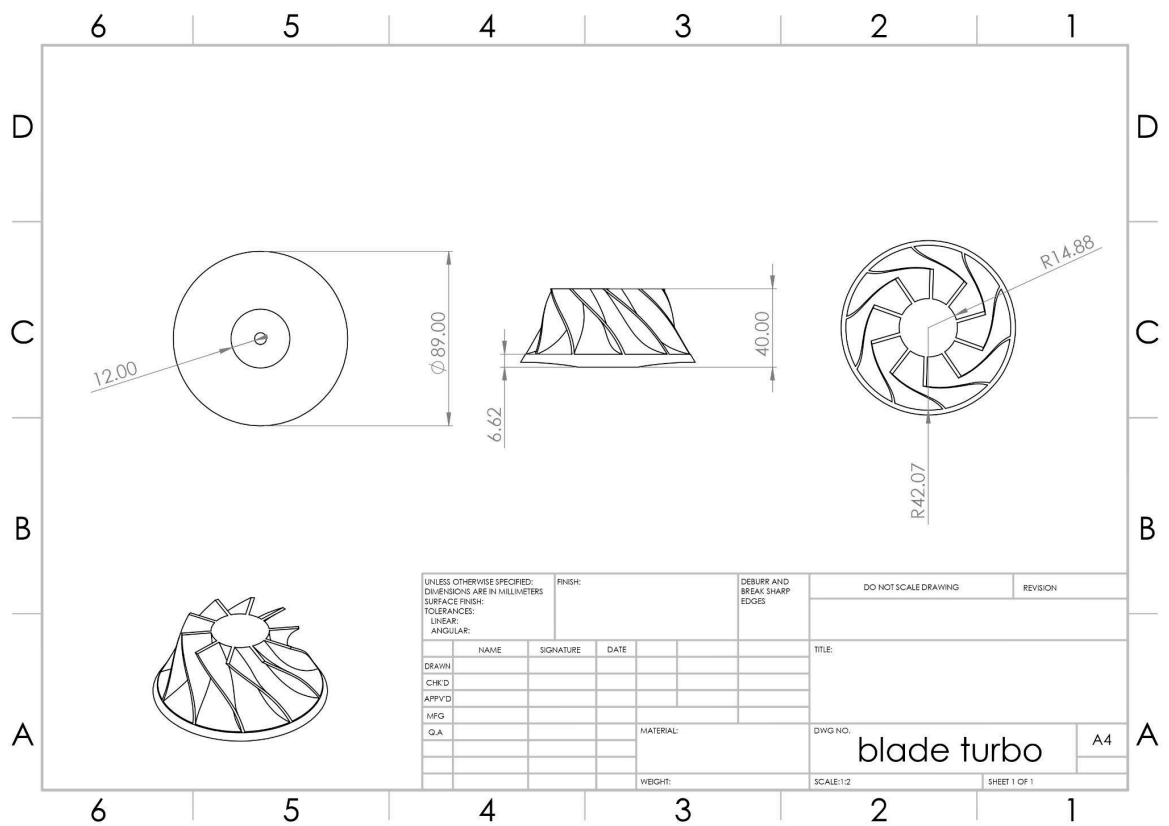


Fig. 11. The Turbocharger Blade Drawing

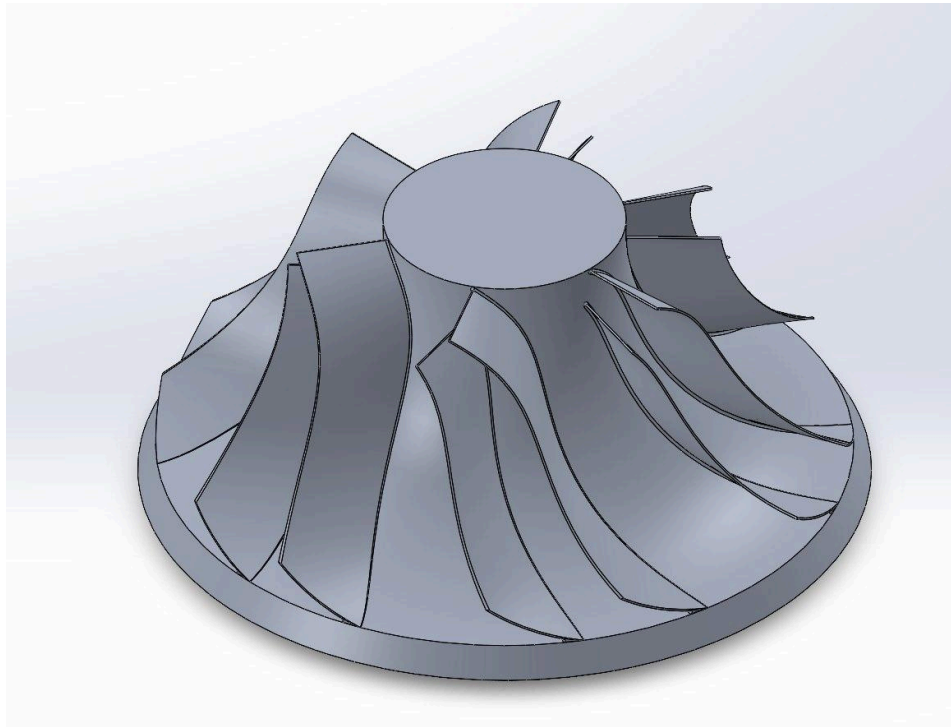


Fig. 12. The Compressor Blade 3D model isometric view

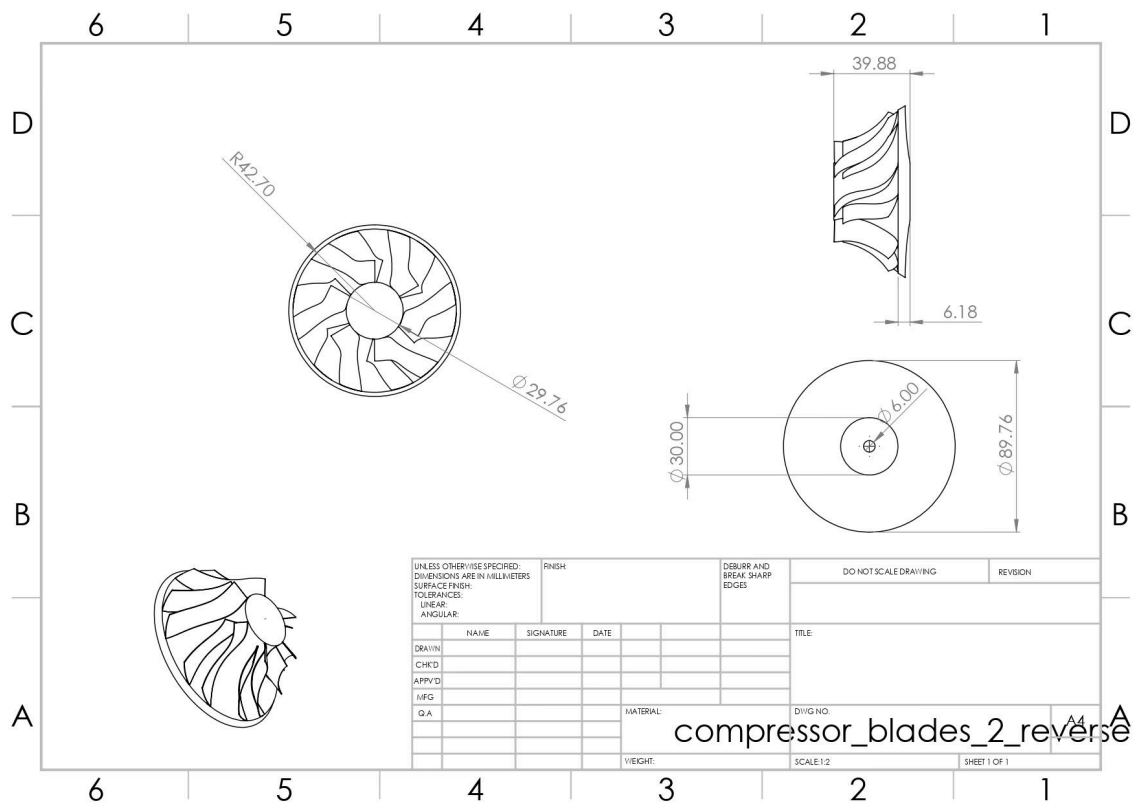


Fig. 13. The Compressor Blade Drawing

Generally, the 3D modeling stage confirmed that the turbocharger components can be assembled into a complete functional assembly. The main parts are placed accurately and the assembly model is ready for further testing via simulations.

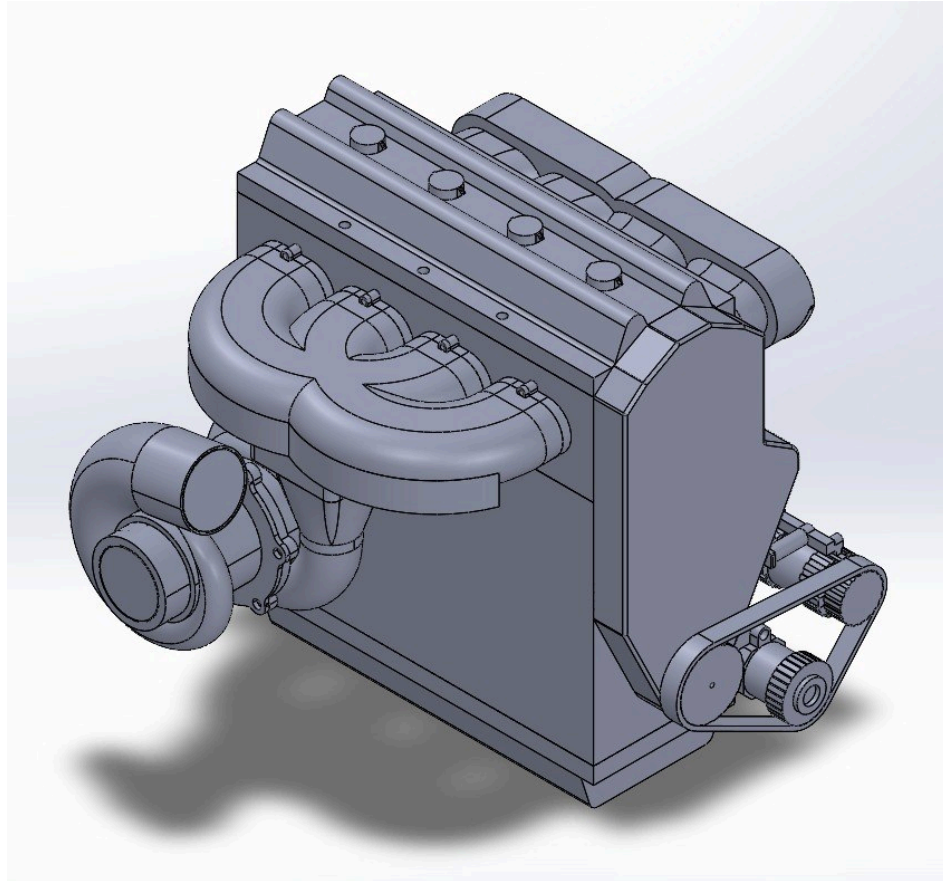


Fig. 14. The 3D assembly of a turbocharger on an engine, isometric view

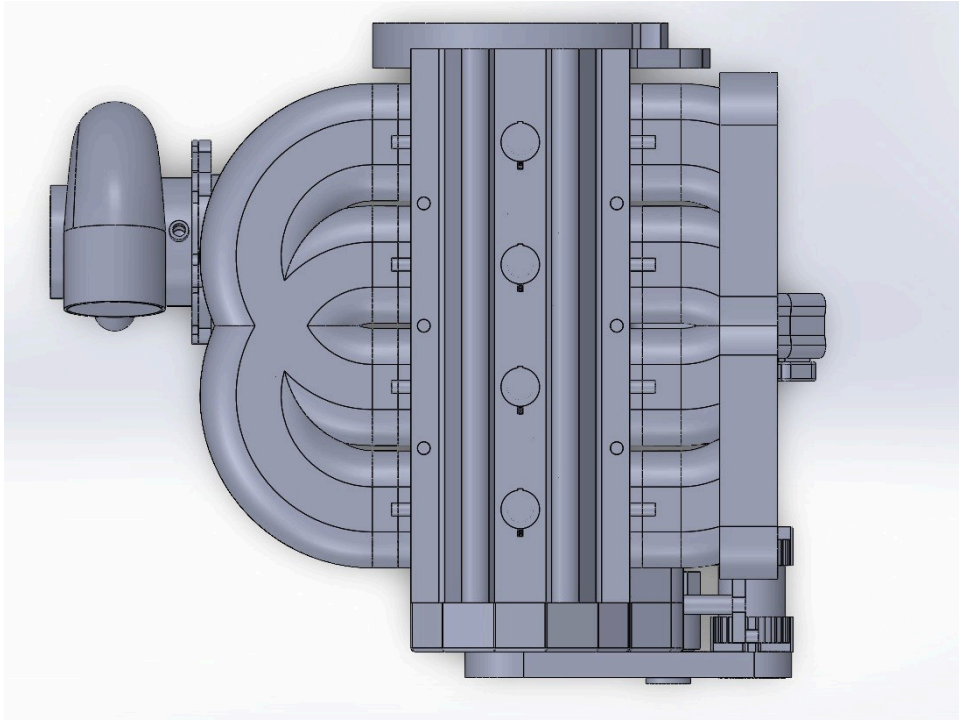


Fig. 15. The 3D assembly of a turbocharger on an engine, top view

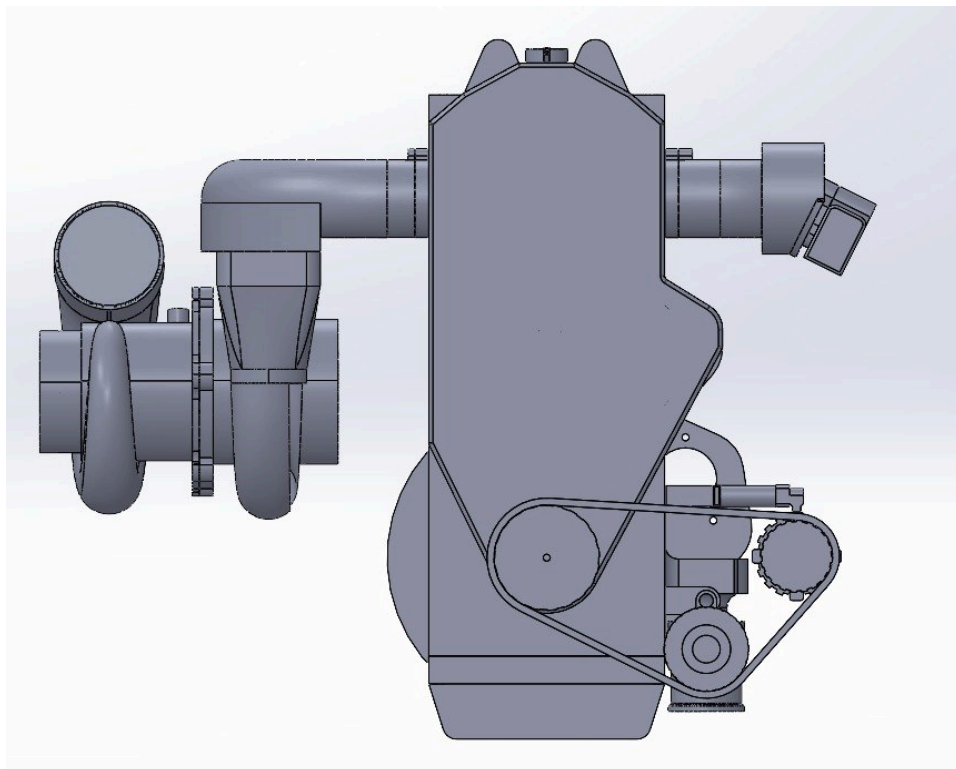


Fig. 16. The 3D assembly of a turbocharger on an engine, front view

The turbocharger is driven by the exhaust gases. After the combustion inside the combustion chamber, the produced exhaust gases leave the engine through the exhaust

manifold. The turbocharger is connected right to the exhaust manifold by its turbine part. The compressor part is connected to the intercooler through pipes. Then the pipes connect the intercooler to the intake manifold, where the engine is supplied with necessary air.

3.2.2 Simulations

Further reflection regarding the safety and efficiency of the device requires conducting several simulations in the SolidWorks program, as it was mentioned above. Besides, the following simulations can be considered as the most useful: Thermal Analyses, Frequency and Air Flow.

3.2.2.1 The Thermal Analyses Simulation

The Thermal Analyses Simulation allows to estimate the degree of heating of the turbocharger's each individual part and region of the turbocharger during the vehicle's operation at full capacity. To be precise, this simulation provides a certain value of maximum temperature at each point of the constructed 3D-model. Thus, it can be used for assessing the overall reliability of the turbocharger by comparing the obtained temperature with the maximum acceptable temperature of the device. In addition, it will also be helpful to simulate the mechanical deformation in the turbocharger due to a significant and non-uniform temperature increase.

The following input data will be used for the Thermal Analyses Simulation:

- Hot side (Exhaust) = 900 °C (bulk exhaust gas temperature)
- Compressor internal air = 100 °C (compressed intake air bulk temperature)
- External/Ambient cooling = 25 °C (ambient air temperature around the turbo)

3.2.2.2 The Frequency Simulation

The Frequency Simulation is also supposed to be conducted. It is used to analyse the vibration behaviour of the tested objects at different natural frequencies. The primary purpose is to detect potential resonance during operation.

The 3D model of the turbocharger must be imported into a simulation environment. Then, the geometry of the object is required to be divided into smaller elements via mesh generation. This step allows a program to simplify the numerical analyses. After that, the fixtures were installed at the joints of the turbocharger housing. These fixtures

simulate the attachment of a turbocharger to the engine system.

No external forces were applied during the simulation, as the modal analysis evaluates the dynamic characteristics of the structure.

3.2.2.3 The Air Flow Simulation

An Air Flow Simulation is performed to analyse the behavior of air inside the turbocharger. It is crucial for assessing the aerodynamic performance of the device. Air is selected as a working fluid. Its properties are assumed to be taken under standard operating conditions.

The simulation was carried out in stationary conditions. The results were obtained in the form of velocity fields and flow trajectories.

The input data for the Air Flow Simulation:

- Output Pressure = 1.00 atm
- Compressor Pressure = 2.65 atm
- Wheel rotation = 140,000 rpm
- Input/Output air flow = 0.26 kg/s

4 Results

4.1 Calculations

Characteristics of the engine:

$HP = 280 \text{ hp}$ (since we are aiming to get 280 hp from the engine)

$Engine \text{ displacement} = 2 \text{ L} = 122.05 \text{ in}^3 (0.02 \text{ m}^3)$

4 valves per cylinder, hence 95% of volumetric efficiency is taken as the possible worst output of a 4-valve cylinder

The engine is intercooled, hence 130°F of the intake manifold temperature is taken as the possible worst output of an intercooled engine

$RPM_{max} = 6500 \text{ rpm}$

$\dot{m}_a = 280 * 14.7 * 0.5/60 = 34.3 \text{ lb/min} (0.259 \text{ kg/sec})$

$$p_m = \frac{34.3 * 639.6 * (460 + 130)}{0.95 * \frac{6500}{2} * 122.047} = 34.35 \text{ psi} (236.83 \text{ kPa})$$

$p_m = 34.35 \text{ psi} (236.83 \text{ kPa})$

$p_a = 14.70 \text{ psi} (101.35 \text{ kPa})$

$p_b = 34.35 - 14.70 = 19.65 \text{ psi} (135.48 \text{ kPa})$

Since there are losses in the intercooler and air filter work, higher values of the outlet air pressure and lower values of the inlet air pressure are taken.

$$p_{ratio} = \frac{36.35}{13.70} \frac{(due \text{ to restrictions with intercooler})}{(due \text{ to restrictions of air filter})} = 2.65$$

After calculating the pressure ratio and the airflow, we can select the turbocharger for our engine. Each turbocharger has its own efficiency map, in other words, a graph of performance. If the calculated data lies in the region of the turbocharger's peak efficiency, then it is the correct turbocharger. For our engine, the Garrett GTX2867R GEN II Turbocharger is an appropriate choice.

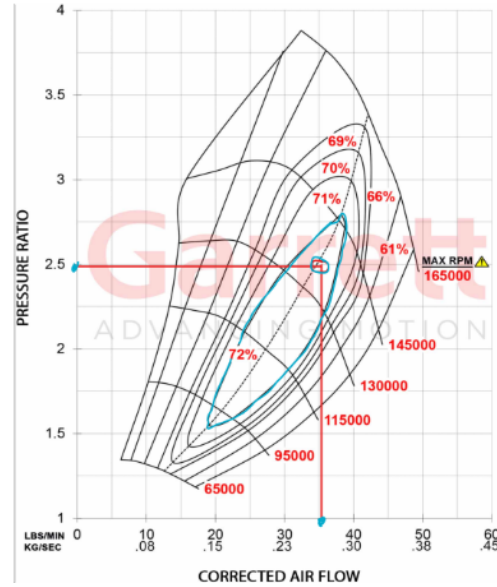


Fig. 17. The efficiency map of the Garrett GTX2867R GEN II Turbocharger.

Another important graph is the trim graph, where we can evaluate the proper trim for the A/R value for our turbocharger from the pressure ratio and the airflow.

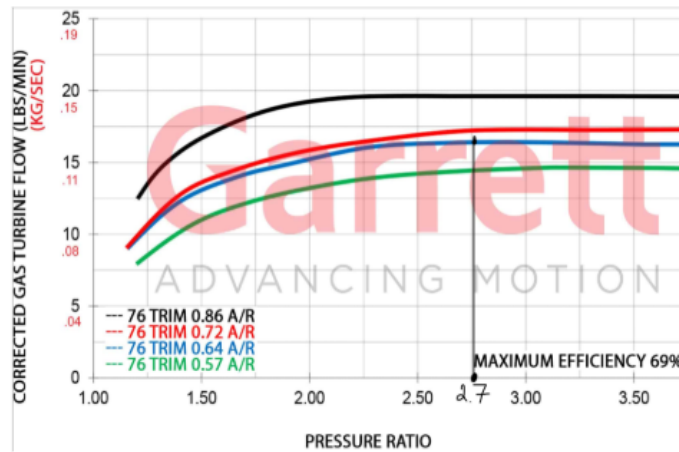


Fig. 18. The trim map for the Garrett GTX2867R GEN II Turbocharger.

The value of engine power is transformed into kW units

$$\tau = \frac{9548 * 209 \text{ kW}}{6500 \text{ rpm}} = 307 \text{ Nm}$$

Enthalpy change in the compressor:

$$\Delta h = \frac{1.4}{1.4-1} * 287 * 300[(2.65)^{(1.4-1)/1.4} - 1] = 96755.8 \text{ J/kg} - \text{ideal value}$$

$$\Delta h = \frac{96755.8}{0.85} = 113830.44 \text{ J/kg} - \text{real value with considered losses}$$

Enthalpy change in the turbine:

$$\Delta h = \frac{1.4}{1.4-1} * 287 * 300[(2.7)^{(1.4-1)/1.4} - 1] = 98887.6 \text{ J/kg} - \text{ideal value}$$

$$\Delta h = \frac{98887.6}{0.69} = 143314.5 \text{ J/kg} - \text{real value with considered losses}$$

Compressor power:

$$P_c = 0.259 \text{ kg/sec} * 113.830 \text{ kJ/kg} = 29.48 \text{ kW}$$

Turbine power:

$$P_c = 0.259 * 143.314 \text{ kJ/kg} = 37.11 \text{ kW}$$

4.2 Simulation Analysis

For a complete review of the turbocharger operation, the simulations were performed on the following aspects: Thermal Analyses (Maximum Temperature and Thermal Stress), Frequency and Air Flow.

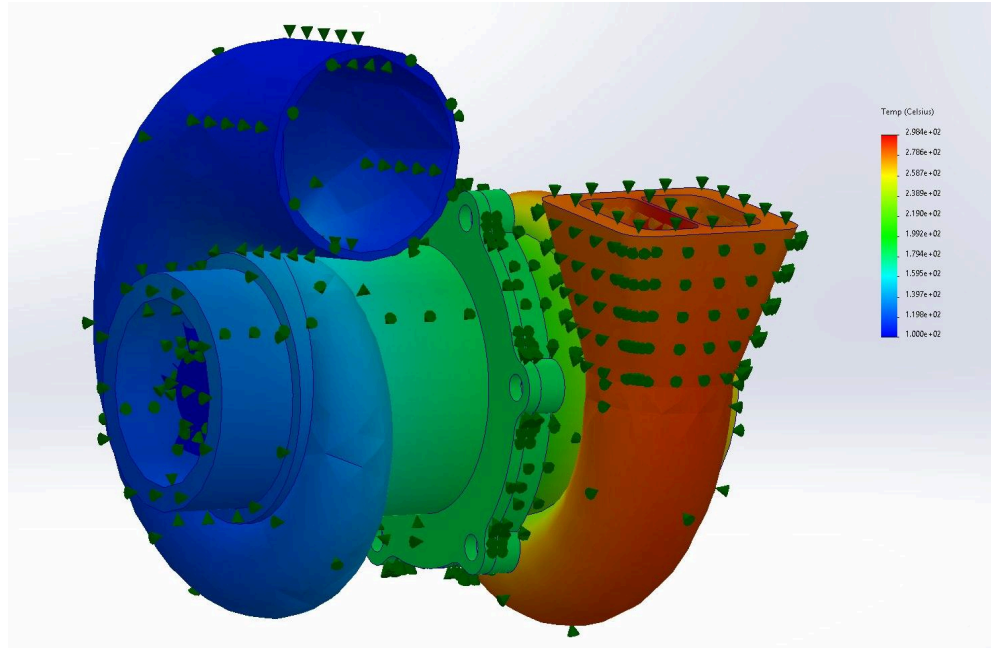


Fig. 19. The Maximum Temperature Simulation

The Maximum Temperature Simulation (illustrated on Fig. 19) indicates the accuracy of the calculations. According to the results, the highest temperature occurs in the turbine region due to heat delivered by exhaust gases. However, the intercooler was not considered as a part of the selected system; the maximum temperature, which is approximately equal, completely correlates with Garrett technical references (Garrett Turbocharger Heat Management Guide, Garrett G-Series product manuals, Turbocharger Thermal Management, BorgWarner EFR thermal whitepapers). The thermal behaviour of the turbocharger also matches the theoretical model derived from thermodynamic analyses. Finally, it can be concluded that the materials used in the production of the turbocharger are able to withstand appropriate temperatures.

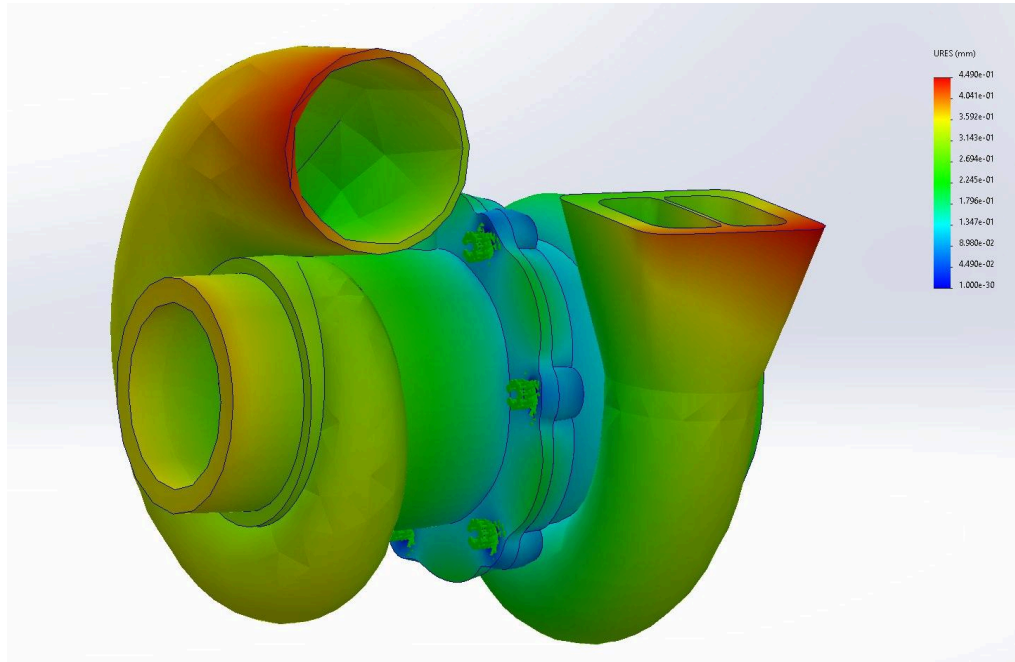


Fig. 20. Thermal Stress Simulation

The Thermal Stress Simulation (illustrated on Fig. 20) represents how temperature influences the behaviour of the turbocharger. To be precise, the simulation defines the extent of mechanical deformation of the device during its operation at maximum power. The greatest deformation (thermal expansion) occurs in the turbine and compressor housing and reaches a maximum value of 0.449 mm. The deformation up to 0.5 mm can be considered noticeable, but within an acceptable range. Consequently, the thermal expansion experienced by the model is considered to be within permissible design limits.

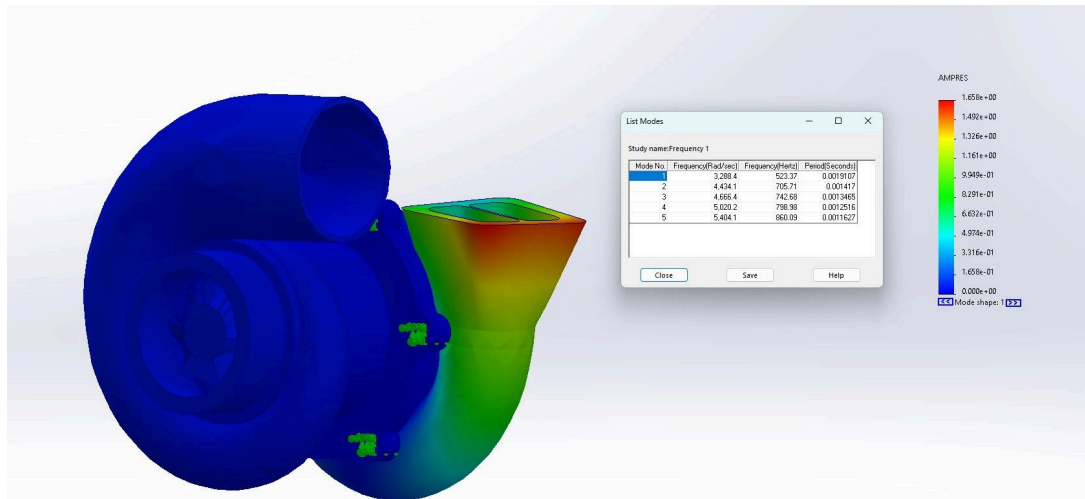


Fig. 21. The Frequency Simulation

The Frequency Simulation (illustrated on Fig. 21) reveals the regions with highest frequency at different natural frequencies/modes (approximately 523 Hz is set at Mode 1). The vibrations on the compressor side are almost negligible, while the maximum amplitudes can be observed at the turbine and, notably, the turbine housing parts. The simulation results are completely credible as they correlate with findings presented by Christopher B. (2018). The Amplitude values are acceptable.

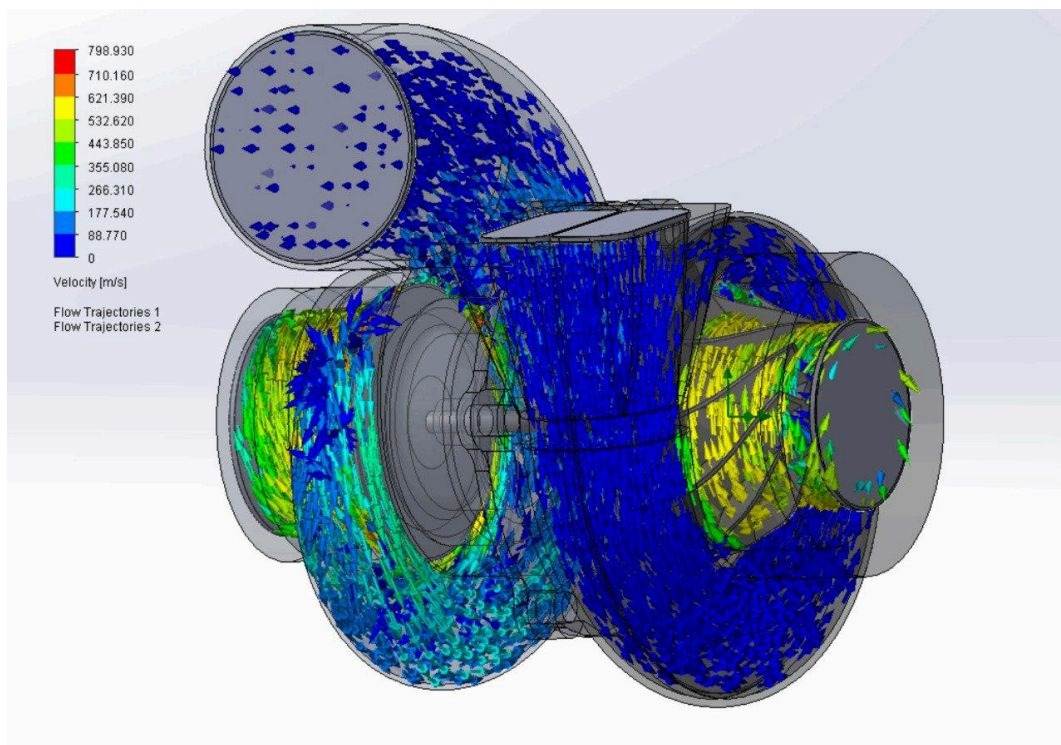


Fig. 22. The Air Flow Simulation

The Air Flow Simulation (illustrated on Fig. 22) presents a computational fluid dynamics simulation of airflow through the turbocharger assembly. Velocity-coloured flow trajectories are used to visualise the velocity directions and magnitudes of the air flows. The blue regions at the inlet and outlet ducts represent the lowest velocity flow regions. However, when the flow interacts with the rotating compressor and turbine wheels, its velocity rises dramatically due to energy transfer from the impeller. At this moment, the flow starts to move in a circular path with a lower radius with peak velocity near the outer radius of the compressor wheel, reflecting the centrifugal acceleration of the fluid. Higher velocity indicates the potential power increase, while the organised, rather slow movement of the air proves effective compression and appropriate geometry (Garrett Motion, n.d.).

The simulation analyses confirmed the reliability of the device under specified conditions. The designed turbocharger demonstrated acceptable deformation level and stable aerodynamic performance with no unexpected issues. The results correlate with both theoretical expectations and design requirements. Overall, the design was successfully tested.

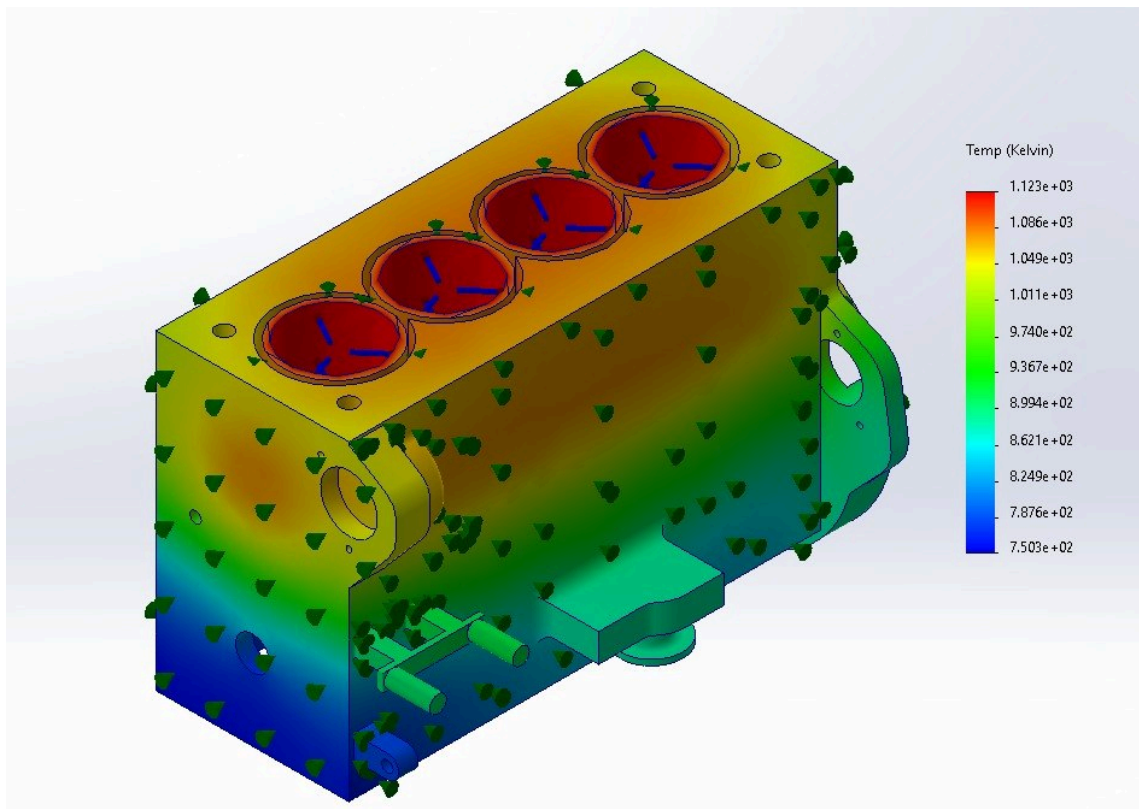


Fig. 23. The thermal simulation of an engine block without a turbocharger.

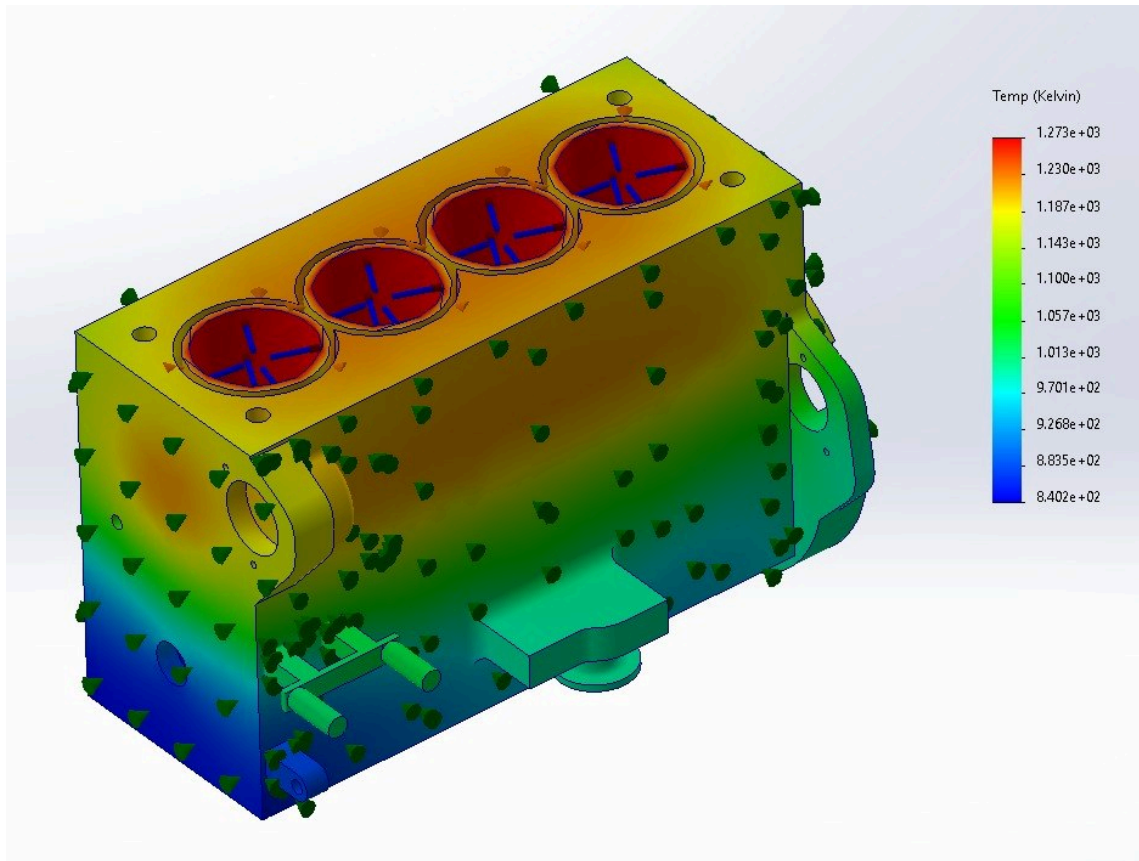


Fig. 24. The thermal simulation of an engine block with a turbocharger.

The thermal simulation of an engine block reveals that this part of the engine is capable of maintaining an increased temperature due to the installation of a turbocharger. The following data was used to create the simulation of the engine block without the turbocharger: Temperature of engine cylinders is 850 °C; Convection coefficient from the engine oil is 500 W/m² K, while the temperature is 115 °C; Convection coefficient from air is 30 W/m² K with the temperature of 40 °C.

The engine block has to endure higher temperatures due to the installation of the turbocharger, since the power has increased. The following data was used to simulate the temperature of the engine block after the installation of the turbocharger:

Temperature of engine cylinders is 1000 °C; Convection coefficient from the engine oil is 550 W/m² K, with the temperature of 135 °C; Convection coefficient from air is 30 W/m² K, with the temperature of 60 °C.

The combustion happens inside the combustion chamber, thus the highest temperature is right in the cylinders. Right next to the cylinders, there is the engine oil running to cool down the engine. Then the heat dissipates through the engine.

The difference in temperature between the engine without and with a turbocharger is 150 °C, which is not enough for a cast iron to get to the melting point of 1200 °C, therefore the engine is safe from thermal destruction. Since there is an intercooler, which decreases the temperature of the incoming air, the temperature of the engine block would be lower.

5 Analysis and Discussions

5.1 A/R Ratio

There are various values that are necessary to evaluate a turbocharger's dimensions and characteristics. Wheel trim is necessary to estimate the sizes of the turbine and compressor wheels. A/R gives information about the turbocharger's exhaust housing size. Smaller A/R provides better low-end power and diminishes turbo lag. Larger A/R provides top-end power, but increases turbo lag. For ordinary city cars, a smaller A/R is more desirable for smooth and effective acceleration. Additionally, a properly sized A/R ratio can improve the turbocharger's efficiency.

These findings correlate with the studies written by Feneley et al. (2017) and Tripathi et al. (2019). The authors analysed the influence of A/R selection and concluded that smaller A/R ratios provides better low-end power and diminishes turbo lag. On the other hand, the flow stability in the turbine also relies on the proper A/R ratio. A/R value matched correctly to the engine's airflow provides less flow separation in a turbine. Moreover, it allows to achieve steadier energy transfer that is crucial in maintaining consistent boost pressure across the RPM range (Padzillah et al., 2015). This supports the idea that a balanced A/R ratio improves both drivability and efficiency. Another aspect requiring attention is turbine geometry. According to Feneley et al. (2017), when it is properly matched energy losses in the housing are reduced. Meanwhile, overly large or small A/R values lead to poor utilization of exhaust energy. All these findings align with our result, confirming that selecting an appropriate A/R ratio is essential for efficient turbocharger operation.

5.2 Airflow and Air Pressure

The amount of air delivered to the inside of the engine is determined by the mass airflow. In naturally aspirated engine types, the amount of airflow is determined by increased number of cylinders and enlarged engine displacement. For turbocharged engines, the more powerful the turbocharger, the larger is airflow. Manifold pressure determines the air pressure within the intake manifold of an engine; in other words, the pressure of the incoming air into the cylinders. Higher manifold pressure means that there is more air supplied to the cylinders, making the power output higher. This value decreases with the increase in altitude. Additionally, it depends on the throttle, meaning that the higher the throttle is opened, the larger the manifold pressure.

These relationships agree with findings from previous studies on turbocharged engines. According to Vedran and Božica (2018), increase in airflow and manifold pressure leads directly to higher torque and power. Chen et. al. (2022) claim that turbocharger smooth operation and stable boost depend on pressure ratio and airflow. It also should be noted that Mosca and Mihaescu (2022) found out that turbines must produce slightly more power than the compressor requires. Thus, a safe margin could provide efficient operation of the compressor under real exhaust conditions.

5.3 Boost pressure, pressure ratio and enthalpy

Boost pressure refers to the level of pressure generated by a turbocharger. It is related to the power of the turbocharger, and it significantly affects the power output of the engine. Pressure ratio is the ratio between the boost pressure and the air pressure. This value shows the dependence of the boost pressure on the environment, and in the selection process of a turbocharger, the pressure ratio is one of the variables that are necessary to define the proper turbocharger for an engine. The universal formula for torque allows us to calculate the torque of an engine after the installation of a turbocharger. The enthalpy change of the compressor and the turbine determines the heat transfer characteristics of the main components of the turbocharger. The formula for power allows us to calculate the power of the turbocharger's main components: the compressor and the turbine. The turbine is spun from the exhaust gases, which in turn spins the compressor wheel, which compresses the air and supplies it into the cylinders.

The researchers confirm that boost pressure and pressure ratio have a direct influence on the torque and power of the engine. According to Vedran and Božica (2018), higher boost levels lead to higher air mass flow. Increased air mass flow in turn raises torque (which correlates with the universal torque formula). Chen et al. (2022) also demonstrated the importance of selecting a turbocharger accurately fitted to airflow, as it provides more efficient operation of the engine. Overall, the thermodynamic behaviour of the turbine and compressor in our calculations is consistent with the researchers' findings.

5.4 Weight distribution analysis

To determine the influence of each approach to power increase on weight balance, it is necessary to get the real life example of a car with a certain weight balance. Weight distribution in a car refers to how the weight is allocated throughout the vehicle. It is usually expressed as a percentage, comparing the weight on the front wheels to that on the rear wheels. A perfectly balanced car would have a 50/50 weight distribution. A perfect example to evaluate the weight distribution change is the 2021 Hyundai Elantra. Just like most front engined cars, it has a 60/40 weight distribution in favor of the front axle. The engine is shifted forward, as is the gearbox, which is connected to the engine. That puts more weight on the front axle. The Hyundai Elantra has a naturally aspirated 2 liter Smartstream G4NL inline 4 cylinder engine, weighing 114 kg and the gearbox is A6F17 6-speed automatic transmission, weighing 73 kg.

The first option is to put a bigger engine. A suitable option is the G6DU 3.5L V6 engine from a Hyundai Staria, weighing 202 kg. Since the engine is different, as its engine-gearbox connection parts, the gearbox should be replaced too. An appropriate variant is the A6F36, 6-speed automatic transmission, weighing 94 kg.

Hyundai Elantra weighs 1250 kg. The weight distribution of a 2021 Hyundai Sonata is 60/40 in favor of the front axle. The engine and the transmission are at the front of the car.

$$1250 * 0.6 = 750 \text{ kg} - \text{front weight}$$

$$1250 * 0.4 = 500 \text{ kg} - \text{back weight}$$

If the G4NL I4 engine and the A6F17 gearbox were swapped to the G6DU V6 engine and the A6F36 gearbox, the weight of the car would increase by 109 kg at the front.

$$\text{Front weight would be: } 750 + 109 = 859 \text{ kg}$$

$$\text{Back weight would be the same: } 500 \text{ kg}$$

The total weight of the car would be 1359 kg. So the weight distribution would be:

$$859/1359 * 100\% = 63.2\%$$

$$500/1359 * 100\% = 36.8\%$$

This will result in greater understeer, plus the brake system and the suspension should be changed accordingly.



Fig. 25. Visual demonstration of the weight distribution.

Both turbocharger and supercharger are good options for power increase in terms of keeping the weight balance as close to the factory as possible.

The Garrett GTX2867R Gen II turbocharger weighs 8.6 kg.

The GT Supercharger GTS 8555, which can also produce the power increase for the engine, weighs 5.3 kg.

The Speedfactory Universal Front Mount Intercooler made by Speedfactory racing weighs 12.7 kg. This intercooler can work for both the turbocharger and the supercharger, since both of these power increasing units aim to achieve the same power output, and they increase the temperature of the engine, thus the extra cooling is needed. The extra piping can weigh up to 5 kg to connect the units to the engine.

The turbocharger set mass: $m_{turbocharger} = 8.6 + 12.7 + 5.0 = 26.3 \text{ kg}$

The supercharger set mass: $m_{supercharger} = 5.3 + 12.7 + 5.0 = 23.0 \text{ kg}$

The mass increase from the new engine: $m_{increase} = 109 \text{ kg}$

5.5 Cost analysis

The engine swap is an expensive process. The significant cost increase comes from the necessity to buy a new engine and a new gearbox to pair it with. The turbocharger and the supercharger kits can use the factory engine in the car.

The G6DU 3.5L V6 engine costs 9700 dollars alone. The A6F36 gearbox, which pairs the engine, costs 2000 dollars. However, due to the significantly changed weight balance, the car would require modifications in the suspension and braking system to balance the car's performance.

The GT Supercharger GTS 8555 costs 2800 dollars. The Garrett GTX2867R Gen II turbocharger costs 1500 dollars on the market. The Speedfactory Universal Front Mount Intercooler, which can pair up with both the turbocharger and the supercharger, costs 470 dollars. Extra piping can cost around 400 dollars for both cases.

The cost of the engine swap option: $C_{engine\ swap} = 9700 + 2000 = 11700 \$$

The cost of the supercharger kit: $C_{supercharger\ kit} = 2800 + 470 + 400 = 3670 \$$

The cost of the turbocharger kit: $C_{turbocharger\ kit} = 1500 + 470 + 400 = 2370 \$$

The turbocharger kit is the cheapest kit available for the power increase of the engine.

6 Conclusion

To sum up, the main title of this Capstone Project was to select and design an appropriate turbocharger system for a generic car engine. The essential goal and objective of the project was to find the optimal and appropriate turbocharger system and develop its design for characteristic enhancements. The turbocharging system is widely used in the automotive industry, especially in high - performance cars and special operation vehicles, where the efficiency of the fuel consumption and generated power by the engine is crucial and critical in some cases. In this project, the turbocharging system was designed and selected for a generic naturally aspirated I4 engine that's widely used in civilian cars.

The initial step toward achieving the main objective was to reiterate the basics of the thermodynamics course. The reason was that thermodynamic knowledge is the basis for the design of the turbocharger and how it operates within the engine. Then the literature review has been done. The different papers and official industry publications were analyzed and reviewed in order to see the process of design and current research gaps in the industry. Papers mostly focused on the enhancement of engine performance and the validation of different system configurations. The literature review is a crucial part of every project, so it will continue until the end of the academic year. The next step was the calculation of optimal characteristics to select the appropriate turbocharger from the available manufacturers. Based on this, it will be possible to proceed with the deeper design and testing. Also, during the calculation and selection process was necessary to consider the issue of Turbo Lag. Eliminating or minimizing this issue will provide better handling for a driver in civilian environments.

The calculations regarding the turbocharger have successfully been made. All the necessary data regarding the turbocharger and the engine performance were useful to evaluate the best turbocharger option available on the market. The existing turbocharger was a base for the development of our own turbocharger design. The design of the turbocharger and the reference engine were made in Solidworks. The same 3D modelling environment was used to perform the thermal and airflow analysis of the turbocharger, as well as the thermal analysis of the engine block, where the design was proven to be reliable and efficient.

The calculations regarding the cost and weight balance analysis were useful to estimate the best power increase option in terms of weight and cost. Since the weight balance for the car has a significant impact on the car's performance and handling, it was necessary to reveal the viable power increase option.

The main objective of this project was partially achieved during this semester. The initial plans of selecting an appropriate turbocharger and making calculations were done effectively. The plan for the second next semester, where the simulation tests were successfully done. The last part of the project - to 3D print the prototype of the turbocharger, was successfully done. The 3D printed model ideally shows the dimensions of the turbocharger and it allows better visualization of the design of the technology. Overall, all required actions were handled throughout the whole year.

During the project, the team encountered limitations in terms of research. First, there is no availability of research facilities in the university designated particularly for the design validation and test of engines and supplementary systems. Also, due to the lack of initial data, the calculations and overall model were simplified. During the calculation, the steady state conditions for the civilian car were considered and taken into account. Moreover, there are limitations in terms of manufacturing a real prototype to test in real conditions. So, it is just a theoretical model with validations.

This capstone project on selecting and designing the turbocharger was a huge opportunity for us to utilize the acquired knowledge in the university in the creation and design of the technology that is crucial for the automotive industry. It helped us to deepen our knowledge in thermodynamics, fluid mechanics, 3D modelling, simulations, which are very important for mechanical engineers. This experience will be used to create more ambitious mechanical projects with professional precision and attention to details.

7 References

- Alisatul. (2025, August 22). *Engineering ethics: Definition, types, and examples*.
<https://www.uniccm.com/blog/engineering-ethics-definition-types-and-examples>
- Burke, R. D., Vagg, C. R. M., Chalet, D., & Chesse, P. (2015). Heat transfer in turbocharger turbines under steady, pulsating and transient conditions. *International Journal of Heat and Fluid Flow*, 52, 185–197.
https://www.sciencedirect.com/science/article/abs/pii/S0142727X15000065?utm_source=chatgpt.com
- Çengel, Y. A., Boles, M. A., & Kanoğlu, M. (2019). *Thermodynamics: An engineering approach* (9th ed.). McGraw-Hill Education.
- Chen, S., Ma, C., Zhang, H., Xu, C., Lei, F., Feng, T., Cao, G., Yang, H., & Wei, C. (2022). Engine performance improvements through turbocharger matching and turbine design. *Energy Science & Engineering*, 10(9), 3384–3396.
https://www.researchgate.net/publication/361443879_Engine_performance_improvements_through_turbocharger_matching_and_turbine_design
- Chen, T., Zhuge, W., Zheng, X., Zhang, Y., & He, Y. (2009). Turbocharger design for a 1.8 liter turbocharged gasoline engine using an integrated method. In *Proceedings of ASME Turbo Expo 2009: Power for Land, Sea and Air* (GT2009-59951). ASME.
<https://asmedigitalcollection.asme.org/GT/proceedings-abstract/GT2009/589/344508>
- CK12-Foundation. (n.d.). Flexbooks.ck12.org.
<https://flexbooks.ck12.org/cbook/ck-12-middle-school-physical-science-flexbook-2.0/section/12.3/primary/lesson/air-pressure-and-altitude-ms-ps/>
- Christopher, B. (2018). Evaluating a turbocharger design with rotordynamics analysis. *COMSOL*
<https://www.comsol.com/blogs/evaluating-a-turbocharger-design-with-rotordynamics-analysis>
- Feneley, A. J., Pesiridis, A., & Andwari, A. M. (2017). Variable geometry turbocharger technologies for exhaust energy recovery and boosting-A review. *Renewable and Sustainable Energy Reviews*, 71, 959–975.
https://www.sciencedirect.com/science/article/pii/S1364032116311807?utm_source=chatgpt.com
- Garrett Motion. (n.d.). GTX2867R GEN II turbocharger. Garrett Motion.
<https://www.garrettmotion.com/racing-and-performance/performance-catalog/turbo/gtx2867r-gen-ii/>
- Mazuro, P., & Kozak, D. (2024). Effect of variable geometry turbocharger on the performance of the opposed piston engine – An experimental approach. *Applied Thermal Engineering*, 236, 121602.
<https://www.sciencedirect.com/science/article/pii/S1359431123016319>
- Mosca, R., & Mihaescu, M. (2022). Assessment of the unsteady performance of a turbocharger radial turbine under pulsating flow conditions: Parametric study and modeling. *Energy Conversion and Management: X*, 15, 100268.
<https://www.sciencedirect.com/science/article/pii/S2590174522000915>

- Nazarbayev University Library. (2024). *APA referencing guide*.
https://nu.kz.libguides.com/standards_guide
- Padzillah, M. H., Rajoo, S., & Martinez-Botas, R. F. (2015). Experimental and numerical investigation on flow angle characteristics of an automotive mixed flow turbocharger turbine. *Jurnal Teknologi*, 77(8), 7–12.
<https://journals.utm.my/jurnalteknologi/article/view/6148>
- Salameh, G., Chesse, P., Chalet, D., & Talon, V. (2016). Experimental study of automotive turbocharger turbine performance maps extrapolation. *SAE Technical Paper 2016-01-1034*.
<https://saemobilus.sae.org/papers/experimental-study-automotive-turbocharger-turbine-performance-maps-extrapolation-2016-01-1034>
- Samoilenko, D., Marchenko, A., & Cho, H. M. (2017). Improvement of torque and power characteristics of V-type diesel engine applying new design of Variable geometry turbocharger (VGT). *Journal of Mechanical Science and Technology*, 31(10), 5021–5027. <https://link.springer.com/article/10.1007/s12206-017-0950-2>
- Tripathi, S., Singh, S., Ahmad, K., & Thakur, A. (2019, April). Despite the Turbo-Lag, Turbochargers are preferred to Superchargers by the Manufacturers. In *Proceedings of the 2019 International Conference on Automation, Computational and Technology Management (ICACTM)* (pp. 577-581). IEEE.
<https://ieeexplore.ieee.org/abstract/document/8776681>
- Vedran, M., & Božica, Ž. (2018). Naturally aspirated gasoline engine upgrade with turbocharger – Numerical investigation of change in operating parameters. *Machines, Technologies, Materials*, 12(5), 204–207.
<https://stumejournals.com/journals/mtm/2018/5/204/pdf>
- Wang, Q., Ni, J., Shi, X., & Liu, Y. (2015). Gasoline engine turbocharger matching based on vehicle performance requirements. *SAE Technical Paper 2015-01-1283*.
<https://www.sae.org/papers/gasoline-engine-turbocharger-matching-based-vehicle-performance-requirements-2015-01-1283>
- What Is Engine Displacement. (n.d.). [Www.aalcar.com](https://www.aalcar.com/library/engine_displacement.htm).
https://www.aalcar.com/library/engine_displacement.htm
- Wu, B., Han, Z., Yu, X., Zhang, S., & Nie, X. (2018). A method for matching two-stage turbocharger system and its influence on engine performance. *Journal of Engineering for Gas Turbines and Power*, 140(9), 09260
<https://asmedigitalcollection.asme.org/gasturbinespower/article-abstract/141/5/054502/366410/A-Method-for-Matching-Two-Stage-Turbocharger>

