Development of a Hydrogen-Fueled Internal Combustion Engine for a Formula 1 Powertrain

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Executive Summary:

This team aims to design a hydrogen internal combustion engine along the specifications of a Formula 1 race car engine. Formula 1 has repeatedly demonstrated a capacity to inspire innovation in the transportation sector by spending on improving road car technologies. Using Formula 1 as a proving ground for the hydrogen internal combustion engine has the ability to improve the technology and inspire a shift to renewable and sustainable fuels. The hydrogen internal combustion engine is a promising technology offering zero carbon emissions while retaining the versatility afforded by the internal combustion engine [27]. Using sustainable renewable fuel while also having quick refueling times is a very useful combination for the automotive and aviation sectors. The report proposes a design of a Formula 1 hydrogen internal combustion engine to unlock the significant potential of this technology.

The scope of the project will be developing the main thermodynamic cycles for the engine. The piston-cylinder assembly of the engine will be analyzed as an Otto cycle. To boost the efficiency of the engine, a turbocharger will be sized, and it will be modeled as a compressor and turbine. This will allow for recovery of the energy from the exhaust gas to boost the inlet air pressure. In addition, a hydrogen tank will be designed to provide enough energy to fuel the car for a full-length Formula 1 race. Piping and other components will also be sized appropriately. As the design of these different cycles and components will be interdependent, an interdependent and iterative design process must be used. The design will follow all Formula 1 specifications including limits on the max power, engine torque, fuel flow rate and temperatures.

Given the utility of hydrogen internal combustion engines and their potential benefits for the world, this project aims to tackle a highly relevant challenge. Developing the engine

specifically for Formula 1 will turbocharge the development of this technology and accelerate its adoption in road cars.

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Background:

Formula 1 is a sport that brings the greatest drivers in motorsport together with the most technically advanced race cars on the planet. Within each Formula 1 car, there is an internal combustion engine (ICE) that provides the necessary power to allow the cars to hit the fastest lap times. However, as traditional energy sources such as gasoline and diesel fall out of favor in the automotive industry, cleaner energy sources have grown in demand. As a result, competition in the industry has never been as intense [1]. The internal combustion engine (ICE) has been a foundational transportation technology that's been refined upon for decades, but it is time for a change. This proposal outlines the design of a hydrogen internal combustion engine (HICE) to supply the requisite power for a Formula 1 race car. This system will be designed to meet the specification as outlined in the Formula 1 rulebook, and will attempt to meet the same power and efficiency targets as a traditional Formula 1 power unit (PU).

The versatility of ICE:

The traditional ICE relies on hydrocarbons to generate its high power output. It converts the chemical energy in its fuel into mechanical energy as power [2]. The ICEs seen in Formula 1 are constantly evolving, and they have remained due to their high power and long range [3]. The main drawback of ICEs are their high carbon emissions, which make them subject to environmental regulation and public sentiment. A Formula 1 vehicle can quickly go through tens of times the amount of fuel compared to a standard car due to the high-speed and high-power culture surrounding motorsports. Formula 1 is looking at cleaner alternative technologies that align with their high-performance racing culture in alignment with reducing carbon emissions to becoming net-zero by 2030 [4].

The promise of electric drivetrains:

Electric technology, such as an electric drivetrain, is an emerging technology in the consumer market, and Formula 1 is dedicating an entire specialty of motorsport to this innovation known as Formula E. An electric drivetrain takes electric energy from the vehicle's battery and converts it into mechanical energy to power its engine in its motors. It has a high efficiency of 85% compared to an internal combustion engine, which usually is around 25 to 40% [5]. Notably, it offers zero tailpipe emissions, though it may be charged using energy from burning fossil fuels. A limitation relevant to motorsports is that electric systems have to use heavy and low-energy-density batteries. This issue limits its range and adds time to service the vehicle in a pit stop [1]. Moreover, throughout a race, a vehicle will derate as the battery discharges, limiting the overall performance of the car. These limitations are being actively worked on, and there is strong potential for electric technologies for racing. However, at the moment, these limitations prevent it from being the optimal technology for the next generation of Formula 1 power units (PU).

Developments in hydrogen:

Hydrogen technology has undergone significant developments to pave the way for the next generation of energy technology. Specifically, the hydrogen fuel cell shows strong potential; the system converts chemical energy into electrical energy by combining oxygen and hydrogen between a cathode and an anode. Remarkably, this drivetrain generates only two byproducts: heat and water; it does not produce any carbon emissions, making it a sustainable candidate for the automotive industry and Formula 1. Hydrogen itself has a high energy density by mass compared to gasoline, diesel, or battery-electric, allowing for reduced weights for these high performance cars. However, hydrogen fuel cells are limited in their ability to provide high power outputs and adapt quickly to transient power demands [11]. In a Formula 1 context, these two abilities are essential, as cars need large amounts of power to counteract drag and accelerate quickly. In addition, the car must throttle between low power output when braking and high power output accelerating out of a corner. These limitations of the technology prevent hydrogen fuel cells from effectively being implemented into Formula 1 PUs.

The outlook on HICE in Formula 1:

HICE development will benefit Formula 1 the most in terms of emissions, power, and range. The hybridization of hydrogen technology and ICE allows for cars to retain high power output while also achieving zero carbon emissions.As the pinnacle of motorsport, Formula 1 has the power to innovate and inspire the next generation of engine technologies to improve our planet. The plan to roll out HICEs into their motorsport circuit would push boundaries into next generation energy systems by incorporating a renewable energy source. This development would serve as vital R&D for companies and investors from the transportation sector, and their successful implementation of Formula 1 technologies would bolster investment and public awareness in the fight against climate change.

Solution:

The team has chosen to work on a hydrogen internal combustion engine. Combining the benefits of using hydrogen as the storage medium for energy and the versatility of an internal combustion engine, the hydrogen combustion engine is the ideal technology for various use cases. Similar to gasoline and diesel engines, it also works on the principle of controlled combustion of a fuel which pushes a piston to generate work. However, it uses hydrogen gas which has several advantages over traditional fossil fuels as discussed in the above section including zero CO_2 emissions. Hydrogen internal combustion engines follow the same Otto cycle as gasoline engines [12].

The hydrogen engine has a lot of advantages. The byproduct of water vapor ensures zero carbon emissions. It also contains more energy per unit mass than gasoline. Fueling times for hydrogen are also much shorter than in battery-electric vehicles making HICEs a better fit for racing. However, some of the challenges also include the problem of fuel storage. Having a low energy density by volume, hydrogen needs to be stored at high pressures. Hydrogen combustion engines are also lower in efficiency than fuel cells. In addition, hydrogen engines also produce NO_x gasses which contribute to emissions.

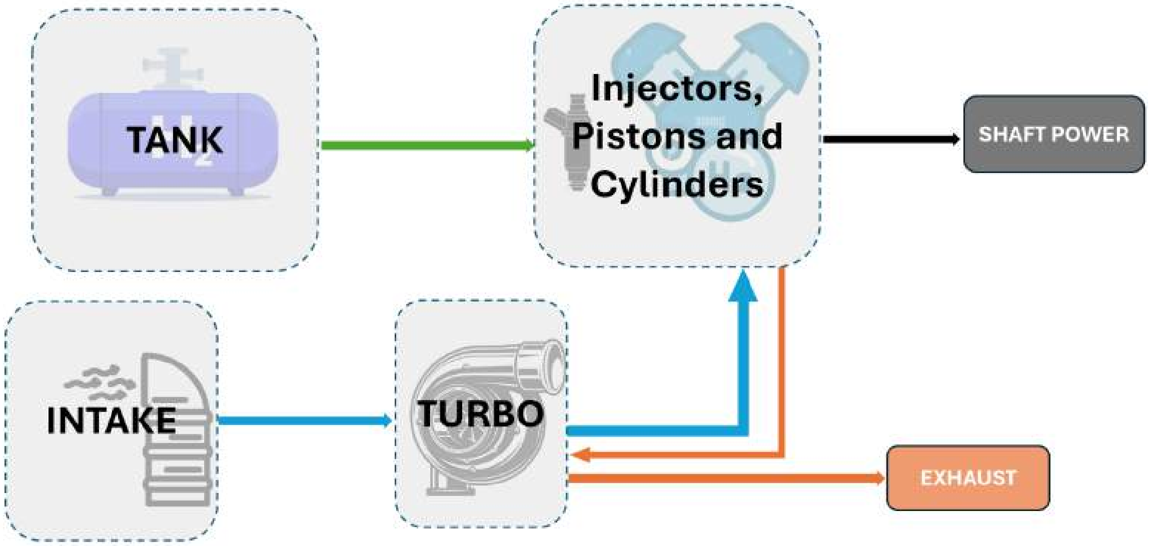

Figure 1: Overall System Schematic

The schematic in Figure 1 represents the system proposed by the team. The tank will store pressurized hydrogen in the gaseous phase. This will be at the standard pressure of hydrogen storage which can be either 350 bar or 700 bar[13]. The hydrogen gas will be provided to the injectors through a throttling valve. The piston-cylinder system will consist of an Otto cycle delivering power to the shaft. The specification for the amount of power to be generated is listed in table item 1.3.

The intake will provide air to the piston cylinder system after it is compressed to a higher pressure using the turbo. The turbo will be powered by exhaust gas, further improving the efficiency of the engine.

The figures of merit for the project are found using the specification provided by Formula 1 for the race car [14,15]. They are listed in table 1.

Table 1: Formula 1 Engine Specifications

S. No.	Specification	Quantity
1	Max Fuel Energy Flow	3000 MJ/h
2	Fuel Energy Flow Below 10500 RPM	0.27*N(rpm)+165
3	Max Power	350 kW
4	Maximum Mechanical Torque	500 Nm
5	Engine Inlet Air Pressure	<4.8 bar
6	Rotational Speed of Turbocharger	150,000 RPM
7	Max Temperature	2,600 °C

Developing a pressurized hydrogen storage tank with a standard pressure of 700 bar that funnels hydrogen gas as fuel into the HICE will be implemented for the project [20]. The primary concern is addressing the correct amount of fuel required to travel a distance prior to refueling. This would require knowing the necessary vehicle dynamics consistent to engine power, vehicle speed, drag, rolling resistance, drivetrain efficiency, and as well as the number of wheel turns needed for this distance traveled. These factors are valuable towards obtaining a realistic mass of hydrogen.

All F1 engines since 2014 have been equipped with an 8-speed drivetrain [22]. A standard system comprising the eight-speed drivetrain is suited on a team-by-team basis; it has to be correctly proportioned so that the vehicle may perform across various track conditions. More importantly, they are directly responsible for the vehicle's speed, fuel consumption, and engine power – all reliant on the amount of hydrogen stored within the tank [23].

A drivetrain contains forward gear ratios which directly contribute to the engine's power output, the smaller these ratios are the less torque the engine outputs to the wheels, the faster the car goes, the more drag it takes on, and the more fuel is consumed [23]. This is the basis of our analysis.

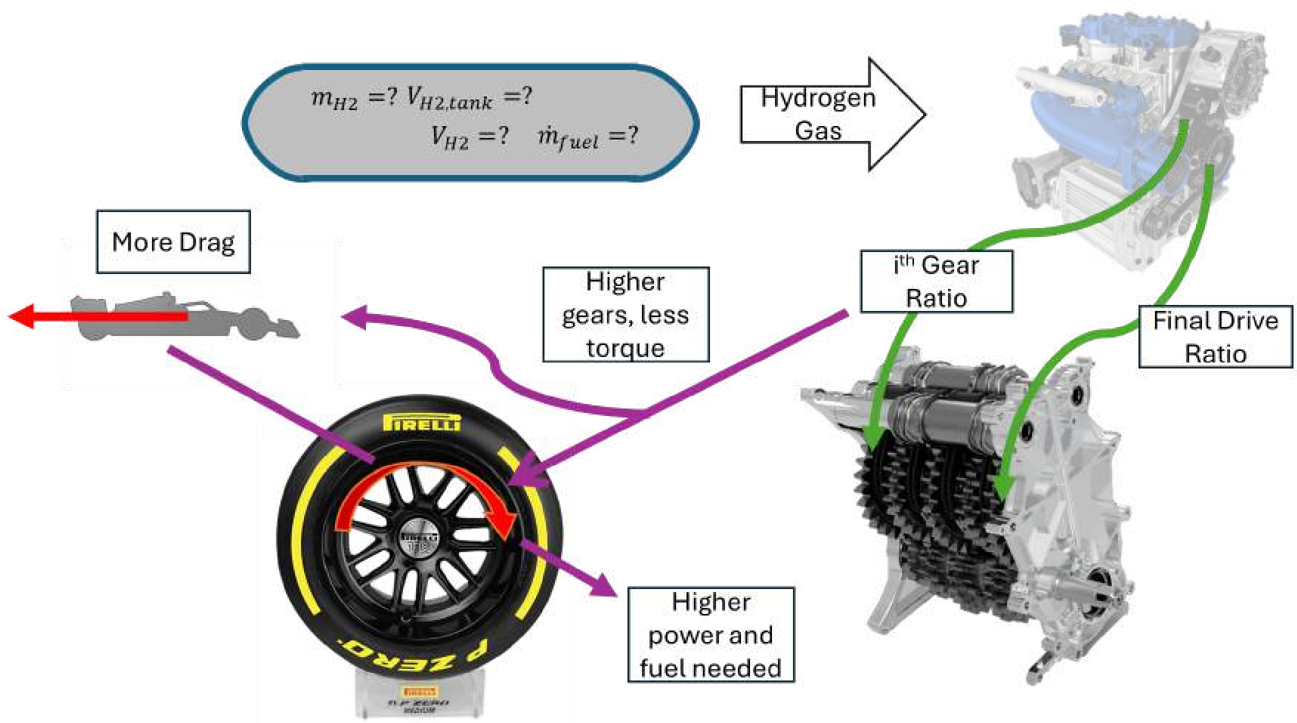

Figure 2: Overall system design and implementation

The schematic shows the overall utility of the hydrogen storage tank for the F1 vehicle. It functions to serve as the direction map for the analysis. Firstly, hydrogen gas enters the HICE via six-piston cylinders where they combust, generating shaft power. This power is given to the final gear drive, which turns the ith gear. The power (depending on transmission efficiency) is then given off to the tire, the value of torque (based on gear ratio) will correspond to the vehicle's velocity which correlates to the amount of drag on the vehicle [x8]. This corresponds to a driver controlling the car's drivetrain and selecting suitable gears based on the track environment. Traveling a known distance corroborates needing to know the hydrogen required before a refueling while sustaining the car's speed and power as well as ensuring the vehicle has enough storage prior any race.

Analysis:

The thermodynamic performance of the hydrogen-fueled engine with a turbocharger is modeled by coupling the Otto cycle of the piston-cylinder assembly with the modified Brayton cycle that defines the turbocharger's performance. As depicted in the schematic diagram, these two cycles are interdependent: the exit enthalpy of the Otto cycle feeds into the turbocharger, which, in turn, determines the intake pressure and temperature for the cylinders. This coupling necessitates a simultaneous analysis of both components.

The engine system under study assumes a six-cylinder configuration operating at 15,000 RPM (N = 250 revolutions per second), with a bore of 80 mm, a stroke of 53 mm, and a compression ratio (CR) of 18. The turbocharger enhances the intake conditions with a compressor pressure ratio (PR) of 3, a compressor efficiency (η_c=0.76), and a turbine efficiency (η_t=0.78). This integrated model allows for calculations of work, efficiency, and power output, capturing the dynamic interactions between the two cycles.

Brayton Cycle (Exhaust Turbocharger Analysis):

First, let's delve into the analysis that will be conducted for the turbocharger. High-pressure and enthalpy exhaust products will be recovered from the engine and directed towards the turbine. A schematic representation of this process is shown in Figure 2.

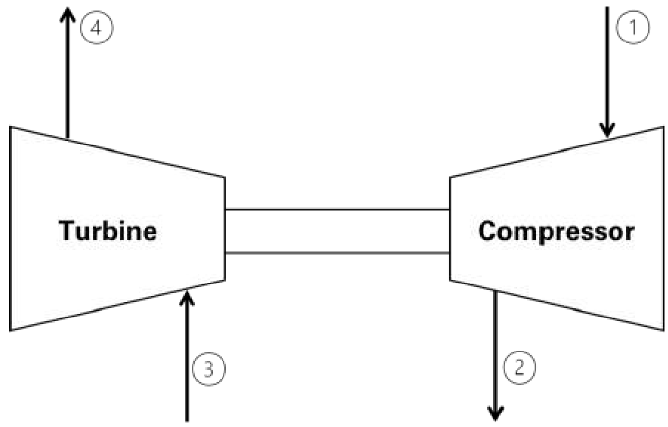

Figure 3: Schematic Diagram of Turbocharger

In figure 2, this flow is entering the turbine at point 3. This flow will generate shaft work, W_T, as it expands over the turbine, powering the compressor. The compressor uses this shaft work to take intake air (at station 1) and increase its pressure before it is fed into the engine. The compressor and turbine efficiencies: η_C and η_T are essential to determine the pressure that will feed into the engine. They will increase entropy, decreasing the amount of work that can be extracted from the flow. The equations used to determine this work are as follows:

$$\eta_{Turbine} = \frac{h_4 - h_3}{h_4s - h_3} = \frac{W_{Turbine}}{W_{Turbine,s}}$$

Equation 1: Turbine Efficiency-Work Relationship

As shown below, the compressor has a similar relationship with efficiency. Taken together, they are used to determine the pressure at the inlet of the combustion chamber.

$$\eta_{Compressor} = \frac{h_2s - h_1}{h_2 - h_1} = \frac{W_{Compressor,s}}{W_{Compressor}}$$

Equation 2: Turbine Efficiency-Work Relationship

The turbocharger is characterized by a pressure ratio of PR=3, a compressor efficiency of η_c=0.76, and a turbine efficiency of η_t=0.78 [32]. Ambient air conditions are defined as P_{atm} = 101,325 Pa and T_{amb} =293.15K.

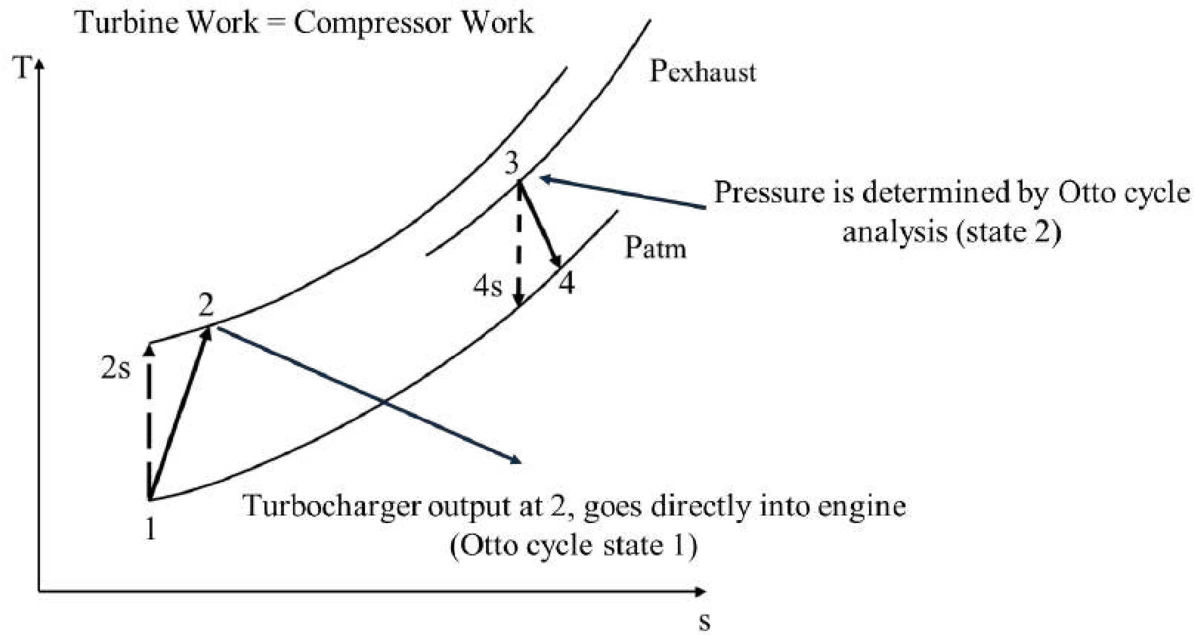

Figure 4: T-s Diagram for Turbocharger Brayton Cycle

As seen in figure 4, the Brayton cycle ideal states are calculated to be at 2s and 4s and are later adjusted to states 2 and 4 taking into account the inefficiencies and increase in entropy. The T-s diagram based on the actual data is given in figure 5.

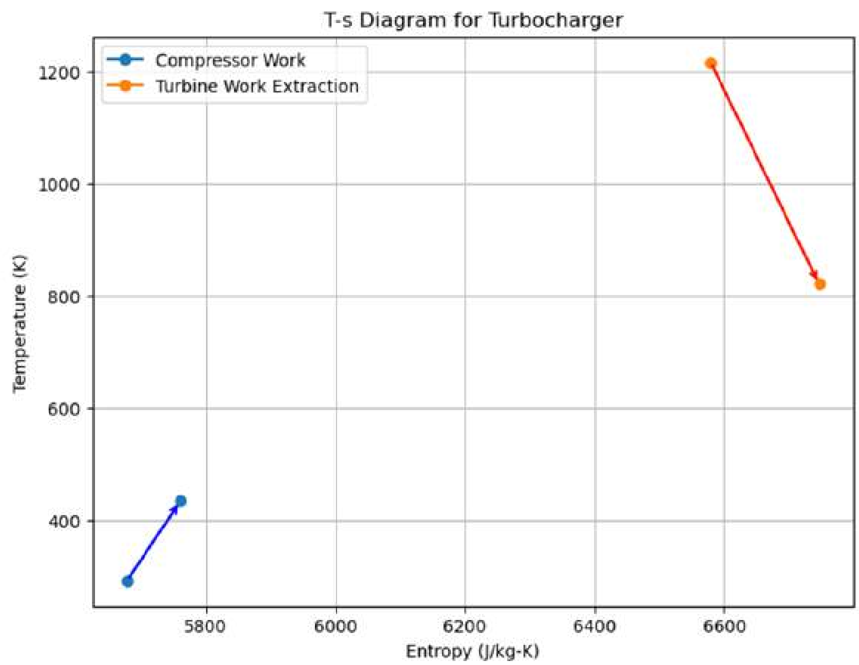

Figure 5: Representative T-s Diagram

The P-v diagram for the same is given in figure 6.

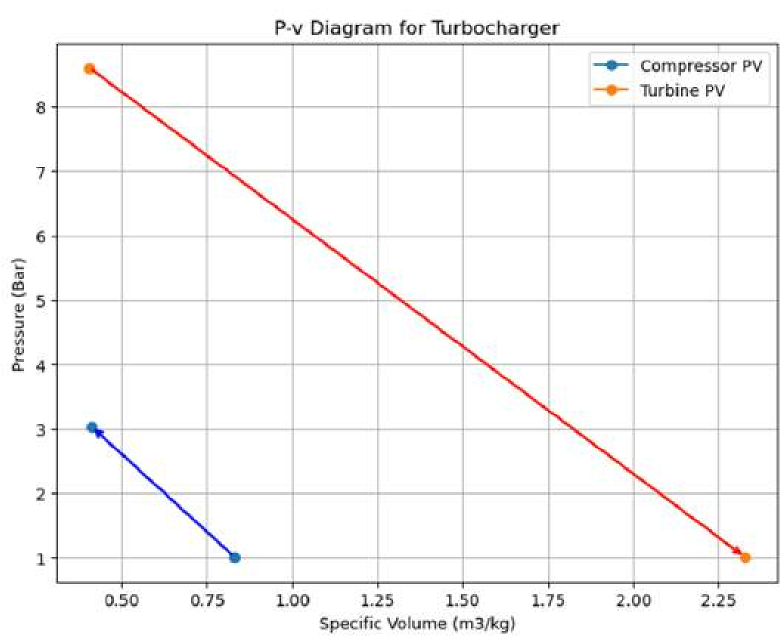

Figure 6: Representative P-v Diagram

Otto Cycle (Piston Cylinder System Analysis):

Second, the Otto cycle analysis must be completed in parallel. This will define the performance of the piston combustion chambers. As shown in the diagram below, the four main stages of the combustion engine cycle correspond to the four thermodynamic states that the engine goes through.

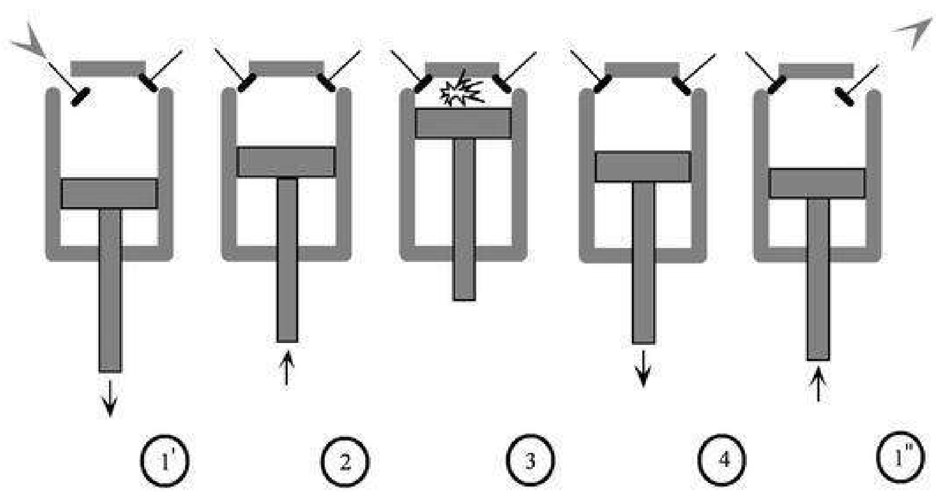

Figure 7: Individual Stages of the Four-Stroke Engine[16]

These four states can be represented in a T-s diagram as shown in figure 4. The diagram has modifications from the traditional Otto cycle due to the presence of the turbocharger. First, the air enters the combustion chamber from the turbocharger, which has some pressure P_{boost}, which is some amount above atmospheric pressure. Work is done by the piston-cylinder to compress the air to a higher pressure, which it achieves at state 2. An isentropic efficiency is associated with this process, as shown below.

$$\eta_{Compression} = \frac{h_2 s - h_1}{h_2 - h_1} = \frac{W_{Compression,s}}{W_{Compression}}$$

Equation 3: Piston-Cylinder Efficiency-Work Relationship

Following this compression process, heat is added to the system via a combustion reaction. A combustion analysis must be completed to determine the heat addition. An iterative process will be used to optimize the fuel-to-air ratio and the combustion temperature within the chamber, balancing the material limits of the chamber with the efficiency of the process. The following chemical equation shows the stoichiometric fuel-to-air ratio along with the corresponding heating value (HV).

$$2H_2 + O_2 + 3.76N_2 \rightarrow 2H_2O + 3.76N_2 \quad \Delta H = -572\,\mathrm{kJ/mol}$$

Equation 4: Stoichiometric Chemical Equation for Combustion Reaction

However, this combustion reaction is unlikely to occur at 100% efficiency, so an accurate method of determining the heat release is needed. This combustion analysis was completed and is described in more detail later in this report. The QH from this process determines the enthalpy rise in the combustor, which is modeled as a constant-pressure process. As a result, the enthalpy at state 3 can be calculated using equation 6.

$$h_3 = h_2 + \frac{Q_H}{m_{air+fuel}}$$

Equation 6: Enthalpy rise in Combustor

From there, work is extracted from the system by expanding the piston cylinder. This process does not occur perfectly efficiently, so there is some loss associated with the expansion, as represented by the isentropic efficiency term shown below.

$$\eta_{Expansion} = \frac{h_4 - h_3}{h_4 s - h_3} = \frac{W_{Expansion}}{W_{Expansion,s}}$$

Equation 7: Expansion work done by piston cylinder

The system will end at a h4 that will occur at the designed exhaust pressure $P_{exhaust}$. This pressure is fed into the design of the turbocharger, as explained above, and must be optimized to maximize the net work done by the system.

The system's net work can be represented by the difference between the work required to compress the air and the work done by the expansion process. This net work can be compared against the heat added to the system to determine the engine's thermal efficiency. The equation to calculate the efficiency is shown below.

$$\eta_{th} = \frac{W_{Expansion} - W_{Compression}}{Q_H} = \frac{W_{net}}{Q_H}$$

Equation 8: Thermal Efficiency of Overall Engine System

Altogether, the engine system can be represented on a T-s diagram as shown below.

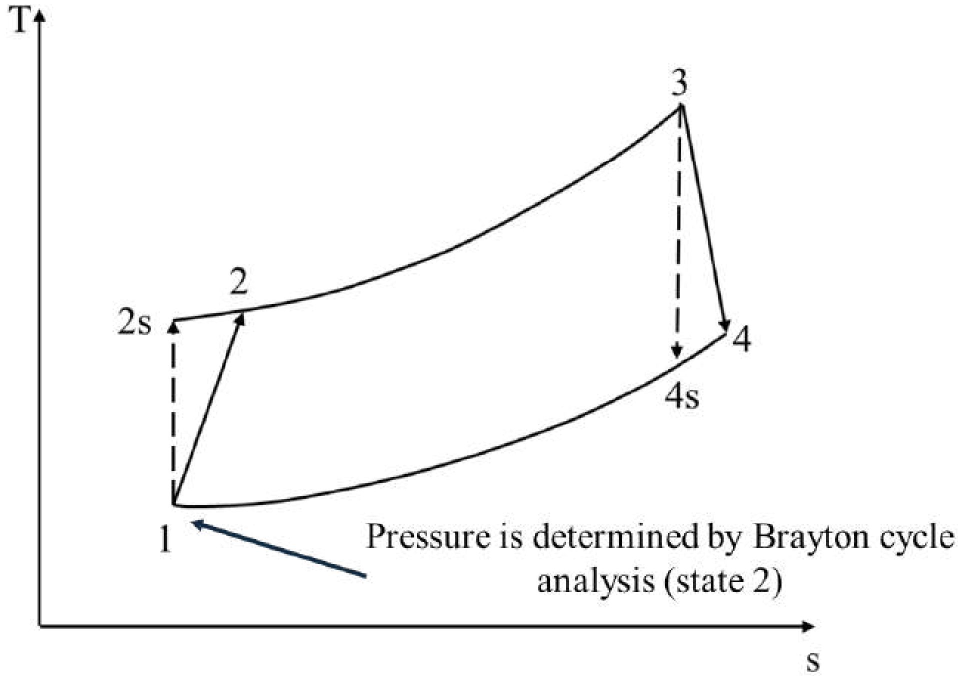

Figure 9: T-s Diagram for Piston Cylinder Otto Cycle Model

The Otto cycle begins at state 1, with conditions set from the turbocharger outlet (T1=T8=442.8, P1=P8=303,975). At state 2, the isentropic compression is modeled, giving an ideal temperature of T2,ideal=798.3 K, and enthalpy of h2,ideal=815.5 kJ/kg. With a compression efficiency of ηcomp=0.98, the actual enthalpy at state 2 is h2=813.1 kJ/kg, and the final temperature is T2=795.7 K.

During combustion, the equivalence ratio is ϕ=0.425, and the air-fuel ratio is AF=80. The heat released per kilogram of fuel is HC=121.79 MJ/kg. The combustion process results in an energy release of Qcomb=mf×HC=1.34 kJ, raising the system's enthalpy and temperature. At state 3, the temperature reaches T3=2343 K (calculated iteratively), with a pressure of P3=P2=5.46×106 Pa.

Expansion from state 3 to state 4 is isentropic, with an ideal temperature of $T_{4,ideal}=883.4$ K. Applying the turbine efficiency ($\eta_{exp}=0.98$), the actual enthalpy and temperature at state 4 are $h_4=590.2$ kJ/kg and $T_4=888.6$ K.

The net work per cycle is $W_{net}=W_{exp}+W_{comb}-W_{comp}=205.3$ kJ, and the thermal efficiency is $\eta=W_{net}/(m_f \times HC)=0.317$. Finally, the engine's net power output is calculated as $P_{net}=W_{net} \times N_{cyl}/(2 \times period)=308.0$ kW, which corresponds to $P_{net,hp}=530.2$ hp.

The T-s diagram based on the actual data is given in figure 10.

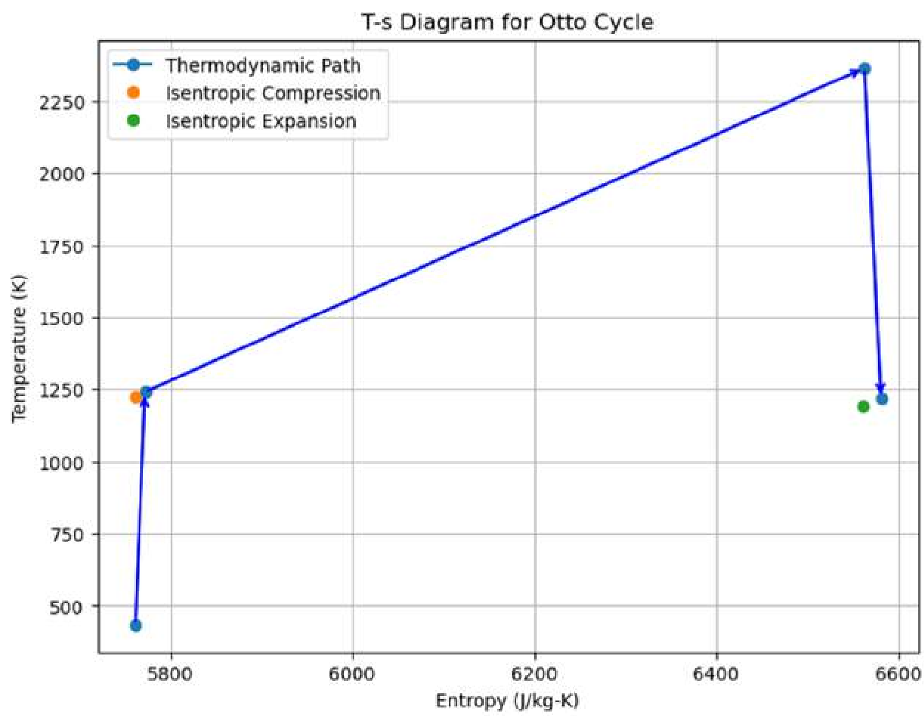

Figure 10: Representative T-s Diagram

The P-v diagram for the same is given in figure x.

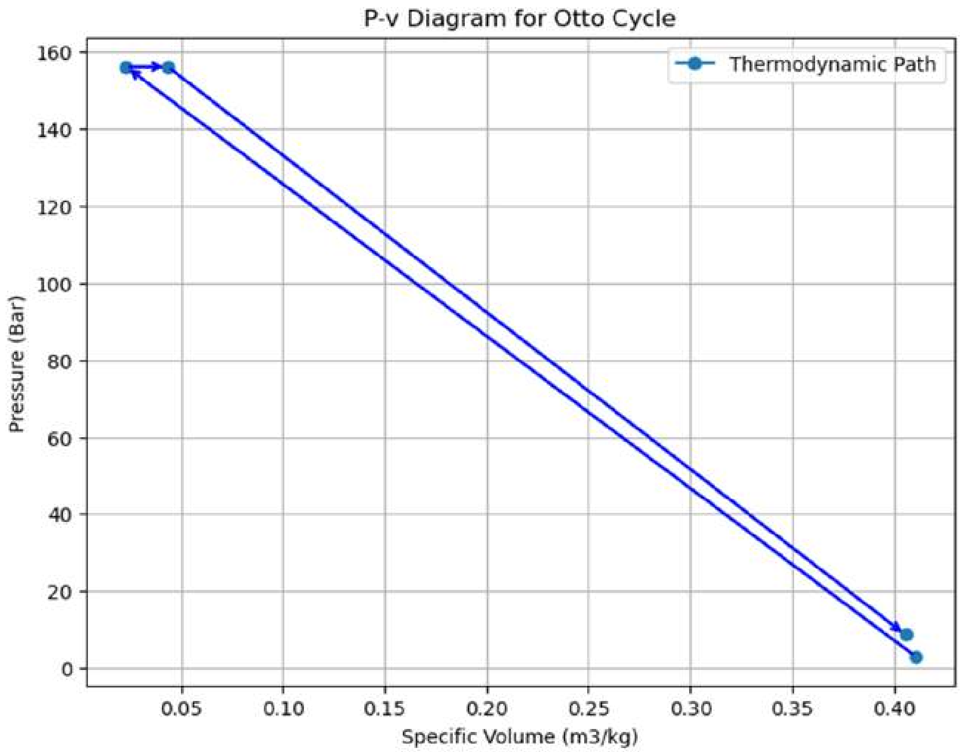

Figure 11: Representative P-v Diagram

Combustion analysis was performed with the assistance of the Cantera chemical kinetic solver and evaluated the heat release and temperature profiles in a constant-volume reactor under specific conditions. The constant-volume assumption is used to simplify the analysis and is assumed to be valid due to the extremely short time span of the reaction. The fuel is modeled as a mixture dominated by hydrogen with impurities (e.g., methane, nitrogen, and carbon dioxide). At the same time, the oxidizer is air, represented as a mixture of oxygen and nitrogen. The equivalence ratio (φ) is set at 0.425, indicating lean combustion where the fuel is under-stoichiometric. Initial conditions are specified at 1241 K and 15.62 MPa, reflecting conditions sourced from the thermodynamic engine cycle model.

The reactor's volume is determined using engine geometric parameters, including bore, stroke, and compression ratio. The clearance volume, representing the cylinder's smallest volume at top dead center, is calculated as:

$$V_c = \frac{\pi \cdot (b/2)^2 \cdot L}{r - 1}$$

where b is the bore, L is the stroke, and r is the compression ratio. The reactor assumes a constant volume corresponding to this clearance volume.

During combustion, the heat release rate is computed as the product of the reaction rates ($\dot{n}_i$) and the partial molar enthalpies (h_i) of the chemical species, scaled by the reactor volume:

$$Q(t) = V_{reactor} \cdot (\dot{n_i}(t) \cdot h_i(t))$$

Reaction rates and enthalpies are updated iteratively as the simulation progresses, and the instantaneous heat release rates and temperatures are recorded at each time step. The simulation concludes when the predefined simulation time is reached (t = 0.1 ms).

The total heat released during combustion is calculated by integrating the heat release rate over time using the trapezoidal rule:

$$Q_{\text{total}} = \int_0^{t_{\text{end}}} Q(t)\, dt$$

This total heat is then normalized by the mass of the fuel in the gas mixture to yield specific energy output in terms of MJ/kg:

$$Q_{\text{specific}} = \frac{Q_{\text{total}}}{m_{\text{fuel}}}$$

Here, the mass m is corrected to reflect the mixture composition based on the equivalence ratio. The simulation outputs include the total specific heat release, the time-dependent heat release rate (figure 12), and the temperature profile (figure 13).

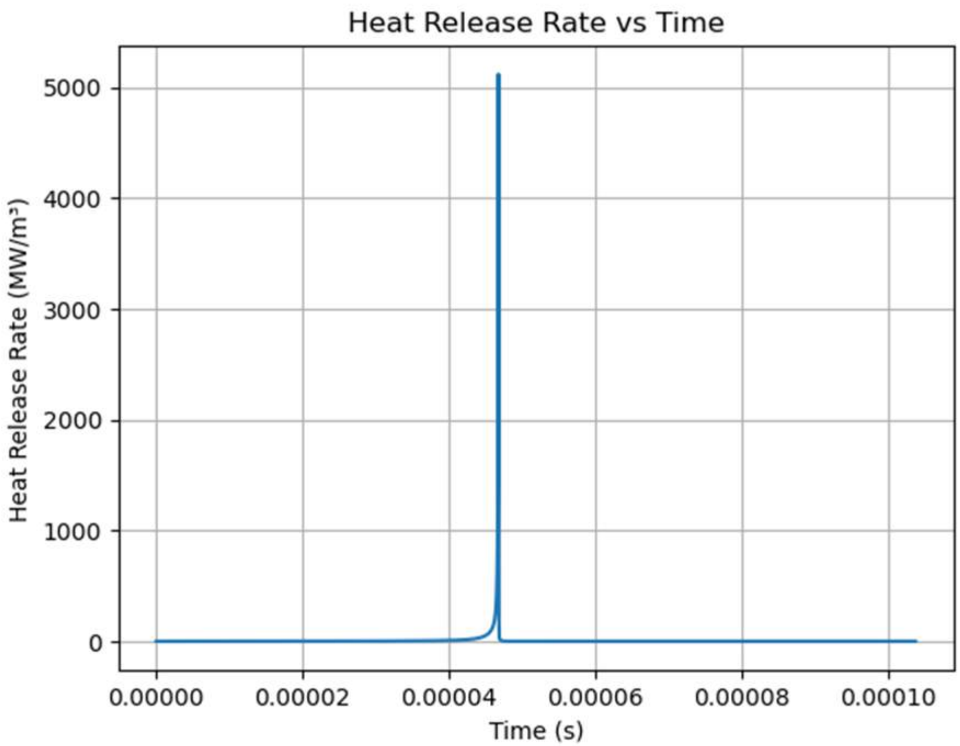

Figure 12: Combustion Analysis Heat Release Rate

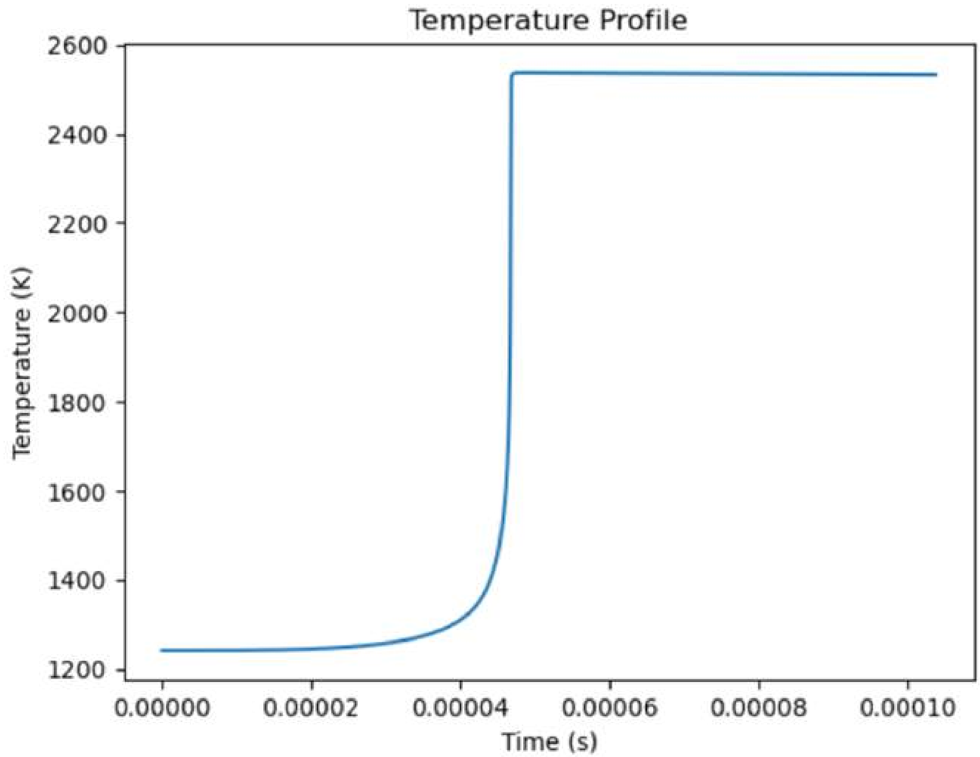

Figure 13: Combustion Analysis Temperature Profile

The results demonstrate the combustion dynamics in terms of thermal energy release and temperature evolution. These metrics are critical for understanding fuel performance, combustion efficiency, and thermal characteristics in high-pressure environments typical of advanced internal combustion engines or gas turbines.

Hydrogen Tank Sizing:

To find the required mass of hydrogen for the F1 vehicle, model assumptions must be considered. Firstly, assume that the drag coefficient is 0.7 [31] and the rolling resistance is 0.01[19]. Some of the specifications of the F1 vehicle may be modeled via specifications made in consideration of having a frontal area of 1.3 m^3 [17], a total mass of 768 kg [18], and a wheel diameter of 0.73 m [24]. Consider that the vehicle will travel 150 km before refueling, with a transmission efficiency of 90% [26]. We assume that the 8-speed gearbox has gear ratios from 1st to 8th gear ranging from [5:1, 4.3:1, 4.1:1, 3.9:1, 3.7:1, 3.5:1, 3.3:1, 3:1] [31]; we also note that the final drive ratio will be 3:1 [32]. Note that the average speed would be slower when the vehicle remains in one gear instead of switching gears for optimized velocity as well as lowering the time of fuel consumption [28]. Lastly, it is vital to assume that the engine operates at 12000 RPM for the entire race as well as assuming no gear changes to ensure constant thermal efficiency [25]. For this analysis, it will walk through the 8th gear's calculations as it is the fastest and consumes the most fuel.

Firstly, by determining the wheel circumference, it is possible to obtain the distance the vehicle will travel in one complete wheel rotation. By multiplying the wheel's diameter of 0.73 m by pi, the circumference would be 2.29 m.

$$L_{circumference} = \pi * D_{wheel}$$

Equation 9: Wheel Circumference

The speed of the vehicle is determined by considering the wheel's revolutions per minute, as well as the 8th gear ratio as 3:1 and the final drive ratio to be 3:1. Note that the lower gear ratios are better at improving the vehicle's top speed while preserving its fuel efficiency. The wheel would obtain an RPM of 1333 RPM.

$$Wheel_{RPM} = \frac{Engine_{RPM}}{Ratio_{Gear} * Ratio_{Drive}}$$

Equation 10: Wheel RPM

Since the model concerns drag force, it is ideal to optimize the velocity for the moving car by setting the wheel's RPM and multiplying it by the circumference length, which is then divided by 60 to convert the units from m/min to m/s. As speed increases, the drag force will increase exponentially, which increases the total force for the engine to overcome and the more fuel it has to consume in a moment of time. The car's velocity is 50.96 m/s or 183.47 kmh.

$$v_{car} = \frac{Wheel_{RPM} * L_{Circumference}}{60}$$

Equation 11: Velocity of F1 car

Finding drag is done by utilizing the density of air, which was obtained from EES, the velocity of the car, as well as the drag coefficient and the car's frontal area. The value of the drag force is 1398 N.

$$F_{Drag} = \frac{1}{2} * \rho_{Air} * v_{car}^2 * C_D * A_{Front}$$

Equation 12: Drag force

The rolling resistance force requires knowing the normal force of the vehicle. Also, the mass value of 768 kg would be the known minimum mass of an F1 race car per the 2026 F1 regulations [18]. The normal force is akin to the weight of the vehicle, and it has a value of 7534 N, which wouldn't change for any gear ratio chosen.

$$F_{Normal} = g * m_{car}$$

Equation 13: Normal force

Rolling resistance is the resistive force that opposes the vehicle's motion from the deformation of its tires when interacting with the road. The value of the coefficient of rolling resistance is obtained by assuming the tyres interact with new asphalt (as F1 maintains their tracks consistently). As such, it obtains a value of 0.01 [19]. The value obtained is 75.34 N.

$$F_{rr} = C_{rr} * F_{Normal}$$

Equation 14: Rolling resistance force

Using Newton's First Law, the total force desirable for finding the engine's power it has to sustain in order to maintain a constant speed would be 1473.4 N.

$$F_{Total} = F_{rr} + F_{Drag}$$

Equation 15: Total Force on car

Finding total force provides the ability to know the necessary engine power, which is desirable to understand since it is a rate of energy that directly defines the mass rate of fuel consumption. The power found was to be 83431 W.

$$P = \frac{(v_{car} * F_{Total})}{\eta_{Transmission}}$$

Equation 16: Necessary power the car must provide

Knowing the fuel consumption rate will directly correspond to finding the amount of hydrogen needed to sustain the determined driving conditions. Therefore, considering an LHV of hydrogen as 121 kJ/kg, the mass flow rate of fuel is 0.0013 kg/s.

$$\dot{m}_{Fuel} = \frac{P}{\eta_{Thermal} * LHV_{H2}}$$

Equation 17: Mass flow rate of fuel consumed

One of the final calculations to determine the necessary hydrogen consumed is understanding the time it would take to travel 150 km over the car's constant velocity. The total time would be 49.05 minutes.

$$t_{Total} = \frac{L_{Total,dis}}{v_{car}}$$

Equation 18: Total time

Finally, the required mass of hydrogen fuel is calculated by using the simple formula of total time and the mass flow rate of fuel consumption. The required mass value is 3.74 kg.

$$m_{H2,required} = t_{Total} * \dot{m}_{Fuel}$$

Equation 19: Required mass of hydrogen

Lastly, it is necessary to determine the volume of hydrogen gas required. EES states that the specific volume of hydrogen required in ambient conditions is 0.02549 m3/kg. Utilizing the mass of hydrogen, we find its volume at 0.0954 m3.

$$V_{H2,required} = m_{H2,required} * \nu_{H2}$$

Equation 20: Volume of hydrogen gas

Solving for the tank's volume is simply fitting the specifications of a 118 L cylinder tank to the formula of a cylinder, the value of the diameter being 0.5969 m and a length of 0.8001 m, which would obtain a volume of 0.2239 m^3. The tank's weight from the specifications chart is 73.03 kg [30].

$$V_{H2,tank} = \pi * (\frac{D_{cylinder}}{2})^2 * L_{tank}$$

Equation 21: Volume of the hydrogen storage tank

Finding the total mass of the tank and the hydrogen gas is a simple summation: the total mass is 76.77 kg. By comparison, F1 regulations require the maximum weight of the fuel tank with its fuel to be 110 kg [29].

$$m_{Total,tank} = m_{tank} + m_{H2,required}$$

Equation 22: The total mass of the hydrogen and tank

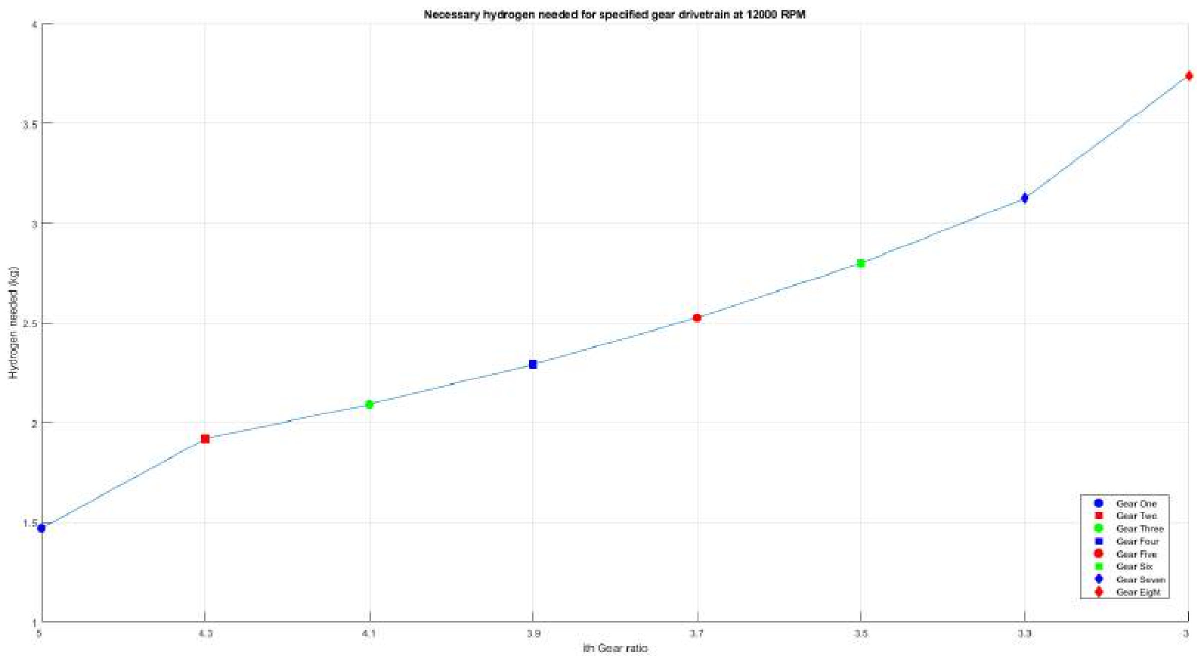

Figure 14: Required amount of hydrogen needed for every gear

The following provides insight into similar calculations concerning the other 7 forward gears. As is noticed, the 8th gear has the highest speed and requires the most engine power, which corresponds to delegating more hydrogen for fuel.

Summary of Results

Table 2: T-Chart between HICE and F1 Engine

	HICE	**2026 F1 Engine**
Fuel Weight	3.74 kg (76.77 kg w/ storage)	110 kg
Fuel Volume	0.0954 m^3	0.1528 m^3
Horsepower	530.2 hp	530 hp IC + 470 hp Electric
Thermal Efficiency	0.5424	0.52
Carbon Emissions	0	300 kg CO_2 per race

Project Management:

Although the team worked on the analysis together, every member was designated the responsible engineer for a subsection as designated in Table 2.

Table 2: Subsection Responsibilities

S. No.	Subsection	Teammate Responsible
1	Otto Cycle and Combustion Analysis	Pranav Nathan
2	Turbocharger Cycle Analysis	Aryaman Agrawal
3	Tank Storage, Overall System	John Dye

The team followed the schedule as given in figure 15 to ensure timely completion of the project.

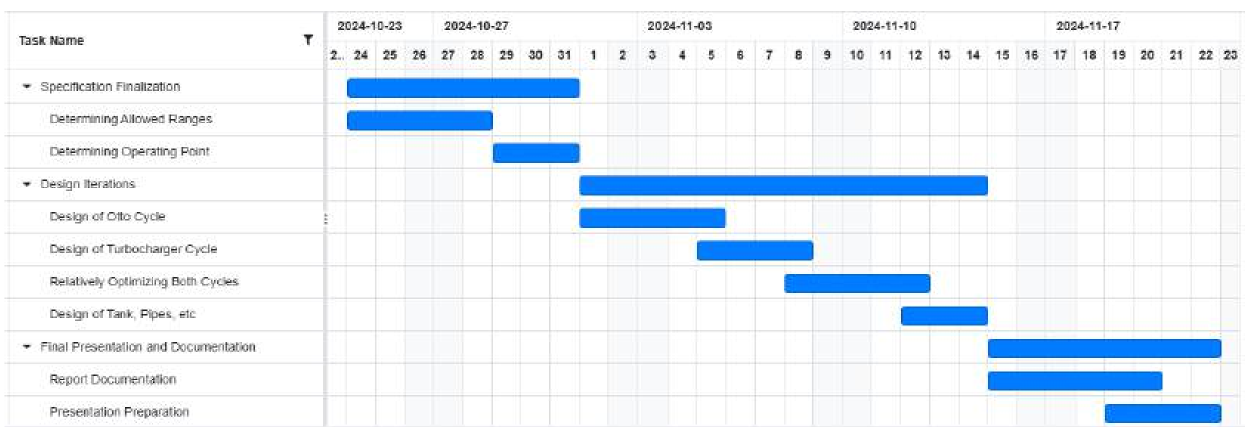

Figure 15: Timeline Gantt Chart

Conclusion:

Integrating hydrogen internal combustion engines into Formula 1 will accelerate the development of promising renewable energy solutions for high-performance motorsports. Utilizing hydrogen, the HICE system sees zero carbon emissions while providing high range and power. This consideration of environmental concerns does not come at the cost of reducing the excitement of Formula, as the new HICE will still have the loud and powerful automotive and combustion noises that racing has come to be defined by. While the full rollout of the hydrogen economy will require much more development of critical infrastructure and storage, the application of HICEs in this area will supercharge their development and ensure that the technology gets the awareness it deserves. This report specifies the technical considerations of model optimization towards engine development through the specialization of hydrogen fuel and its implementation throughout the system.

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