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Comparative Analysis of Traditional Formula 1 Combustion Engines and Modern Hybrid Power Units

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Abstract
Formula 1 (F1) cars are single seated racing cars specialized in speed and agility, weaving through the curved tracks of circuits around the world in the Formula 1 World Championship. Today, F1 cars are known for using hybrid power units as their primary source of thrust. In the past, this was not the case, and cars simply used internal combustion engines with a greater number of cylinders. But the new hybrid power units brought on a much more complex system with additional components that work in conjunction with the combustion engine. This brought about the question: did implementing the more complex system of hybrid power units over the already effective, 8 cylinder V8 engines that were in place so far benefit the sport?

Analyzing the specifications and resultant performance statistics of traditional V8 engines from before 2014 and the modern hybrid V6 engines from 2014 onwards has provided invaluable insights into the potential of hybrid technology. For this paper, specifications on engine design, such as configuration and dimensions, along with performance data, including horsepower, RPM range, acceleration, lap time, and fuel consumption, were collected for comparison. New technology combining internal combustion with energy recovery and electrical energy as a means of generating power has not only improved overall performance in the long run, but also contributed to the sport's long term objective of reducing its environmental impacts. Despite initial struggles following the new hybrid power unit regulations set by the FIA, the newer models outperformed the older ones. In the comparative analysis, the newer model was found to produce around 260 more horsepower at a maximum RPM 3,000 lower than its predecessor, and consume around 60 kg less fuel per race through engine design, positively impacting the sport.[1]

Keywords: Formula 1, hybrid power unit, internal combustion engine, power, fuel efficiency

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I. Introduction

F1 cars are racing cars developed with a goal of achieving maximum speed and agility around the circuits of the yearly Formula 1 World Championship, and completing laps in the quickest time possible. At the heart of F1 cars lies the power unit, a high performance machine that encompasses some of the most cutting edge technology of motorsport engineering. The performance of these power units, being the primary source of power for F1 cars, heavily impacts the car's lap time on the track (Partridge, 2024).

One of the most significant changes in the timeline of the F1 power unit is the introduction of hybrid power units. As the name 'hybrid' suggests, these power units combine power generation from traditional internal combustion engines with power sources that use electrical energy (Partridge, 2024). This drastic change in the fundamental mechanics of power units has stirred much discussion within the sport, and calls for an objective comparison of the two systems.

This study will compare these modern hybrid power units with the traditional power units that F1 has employed in the past. It is aimed to identify the differences between the two machines, the advantages that the new power unit brought, and its subsequent downsides.

II. Background

Since the beginning of F1 in 1950, F1 technology has been evolving and adapting to the changing regulations over the years. Each season, teams have been bringing new advancements in aerodynamics, electronics, and, crucially, power units (Williamson, 2022). The competition between the teams is fierce, and any slight improvement in the power unit can make a big difference in the races. Therefore it is essential to notice and understand the current trends and regulations in F1 in order to compare their power units perceptively.

The F1 power unit has experienced continuous evolution, particularly with the introduction of hybrid technology. Traditionally, F1 cars were powered by naturally aspirated engines, which, while powerful, lacked efficiency compared to modern hybrid engines. As an effort to resolve this issue, the FIA introduced hybrid power units in 2014, marking a major turning point in F1 power units. These new power units combined the traditional internal combustion engines with two Energy Recovery Systems (ERS), which converted kinetic and thermal energy into electrical energy. This change was motivated by the sport's commitment to sustainability and the need to reduce the environmental impacts of racing, as seen by their goal of achieving net zero carbon status by 2030 (Azhar et al., 2024).

As of 2024, there are four major suppliers who manufacture these hybrid power systems: Mercedes, Ferrari, Renault and Honda. Each supplier brings unique and innovative technologies to the table, but are confined to the regulations set by the Fédération Internationale de l'Automobile (FIA), the governing body of F1. This ensures that the races are not only safe, but also fair and competitive, as it prevents wealthier teams outspending their competitors and gaining an overwhelming advantage due to superior technology (Hardy, 2024). Thus, the performances of the power units from different suppliers are relatively similar in a given timeframe. This study will be focused on the differences in general performance between past and present technology rather than the individual dynamics between the F1 teams.

2.1 Current Power Unit Functionality

From 2014 onwards, the FIA mandated V6 Internal Combustion Engines (ICE) and the use of an electric motor powered by a separate battery. These components comprise the hybrid power unit, combining the traditional ICE with an electrical power source (see Figure 1). All F1 teams are required to use this configuration, and it still stands as the power unit requirement for 2024 (Mitchell, 2023).

Currently, the F1 uses 1.6L turbocharged V6 reciprocating engines for the ICE of the power unit. This means that there are six cylinders in the internal combustion mechanism in a 'V' shape configuration. The engine must also be paired with a turbocharger that compresses large amounts of air coming in from the overhead roll hoop above the driver's head and feeds it into the cylinders. The total displacement of the engine, in other words, the volume of air that the engine uses per cycle of combustion, is regulated to 1.6 liters (Partridge, 2024).

The electrical components of the power unit are often underestimated by an audience without technical knowledge, but plays a significant role in optimizing the car's performance and providing extra power. The main electrical components of the power unit are the Motor Generator Unit-Kinetic (MGU-K), Motor Generator Unit-Heat (MGU-H), and the Energy Store (ES). The ES is a high capacity lithium battery which the MGU-K and MGU-H, collectively referred to as the Energy Recovery System (ERS), are responsible for charging (Scarborough, 2020). The MGU-H collects excess heat energy from the hot exhaust gasses from combustion and converts it into electrical energy to be stored in the ES. The MGU-K is connected to the crankshaft of the ICE, and can act as both a generator and an electric motor. It is similar to a manual generator, except the handle can also spin on its own using power from its own battery. When the car is braking and rotational forces from the crankshaft are no longer needed (as the goal of the car at that moment is to decelerate), the MGU-K deploys and acts as a generator to harvest energy. The resistance from the MGU-K as a generator also helps to decelerate the car and take some load off the rear brakes. As an electric motor, the driver can send power from the ES back to the MGU-K to help spin the crankshaft and provide extra power for a short duration. This generates up to an additional 160 horsepower, nearly equivalent to the power of a conventional road car engine, and is often used to overtake other cars (DeMattia, 2023). The amount of energy harvested by the MGU-K is limited to 2 MJ, and the amount deployed as a motor is limited to 4 MJ. Furthermore, the ES, charged by the ERS, is also responsible for powering the car's sensors and Electronic Control Units (ECUs), which optimize the car's performance using live data recorded on the fly. This is essential for maximizing the car's physical capabilities on track (Scarborough, 2020).

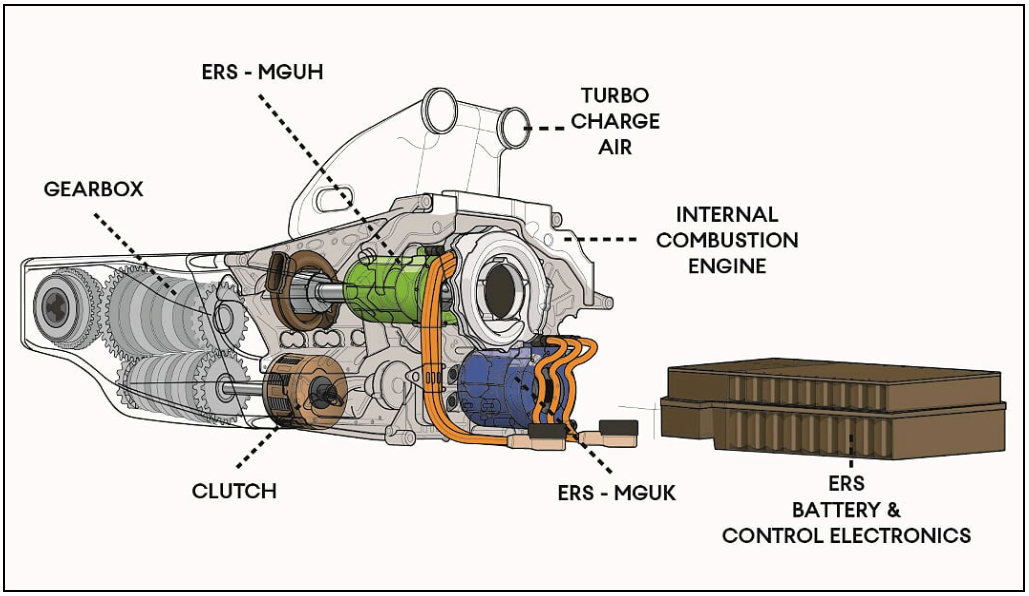

Figure 1. *Diagram of a Modern F1 Hybrid Power Unit with Labels Referring to Major Components.* ***Note.*** *This particular model of the power unit uses a split turbo design, developed by Mercedes, where the turbine wheel and compressor wheel of the turbocharger are separated for improved thermal efficiency and packaging, but still geared to spin in conjunction. Source: Motorsport Technology.*

III. Methodology

For this study, a literature review of articles from various sources and an analysis of quantitative data was conducted. This review focused on sports-engineering and motorsport related journals to understand the historical context and past innovations in F1, and official documents or articles published by F1 for the latest technological breakthroughs. To receive accurate numerical data such as lap times and dimensions, race reports or performance metrics disclosed by the FIA were considered. Qualities that are most widely used in motor engineering to measure performance were selected, and races were selected to include the most diversity in track characteristics. For instance, the Monaco Grand Prix involves tight, low speed corners, pushing F1 cars' braking and accelerating capabilities, while the Italian Grand Prix mostly consists of long straights, challenging the cars' top speeds. The collected quantitative data sets were then organized into a spreadsheet to be crafted into tables or plotted on a graph, for visualization and easier comparative analysis.

3.1 Power Unit Comparison Parameters

The power units from the pre-hybrid era and hybrid era will be compared on the following factors:

- Configuration - information on the layout and specifications of the engine will be drawn from manufacturer specifications.
- Horsepower - a widely used measure of power output by an engine or motor. Figures will be drawn from previous performance records and technical details released by F1 teams.
- RPM range - the rate at which the engine is spinning. Figures will be drawn from performance data disclosed by the FIA and technical details released by F1 teams.
- Time for 0-100 kph and 100-200 kph acceleration - used to compare the acceleration abilities of the power units. Figures will be compared using performance data provided by F1 teams.
- Lap time - a practical measure of car performance on track, used to assess the power unit's performance in race situations. Figures will be drawn from historical race data and timing records available to the public.

- Amount of fuel consumed per distance - used to gauge the overall fuel consumption of the engine, which also directly links to greenhouse gas emissions.
- Weight - affects the overall weight of the car that corresponds to the load put on the power unit. The minimum weights allowed by the FIA for power units during their respective operational periods will be considered.
- Operational costs - the costs of developing and operating the power unit, used to assess the cost effectiveness of power units. The cost caps for power units during their respective operational periods will be considered.

The above These data sets will then be followed by a general discussion of the most significant differences and how they have impacted the sport.

IV. Comparison Data

Specifications	**Power Unit Model**	
	Traditional (2013)	**Hybrid (2024)**
ICE Configuration	2.4 L naturally aspirated V8	1.6 L turbocharged V6
Bore diameter (mm)	98	80
Stroke length (mm)	39.75	53
Horsepower (hp)	~740	~1000
Max RPM	18,000	15,000
Time for 0-100 kph acceleration (s)	2.5	2.4
Time for 0-200 kph acceleration (s)	5.1	4.2
Time for 0-200 kph acceleration (s)	12.0	8.4
Amount of fuel consumed per race (kg)	160	100
Minimum weight (kg)	95	150
Cost cap	No cost cap	USD $95m

Table 1. *Specifications and Statistics of Traditional V8 Engines and Modern Hybrid V6 Power Units*
Sources: Racecar Engineering, The Conversation, The Drive.

Grand Prix Location	Fastest Lap of Race by Season (min)		
	2013	2014	2023
Italy	1:25.849	1:28.004	1:25.072
Bahrain	1:36.961	1:37.020	1:33.996
Monaco	1:16.577	1:18.479	1:15.650
Great Britain	1:33.401	1:37.176	1:30.275
Belgium	1:50.756	1:50.511	1:47.305

Table 2. *Fastest Lap Times of 5 Different Grands Prix During Different Time Periods*
Note. *Grand prix locations were selected to include the most variety in terms of track dynamics, to compare lap times from various conditions. Source: Formula 1.*

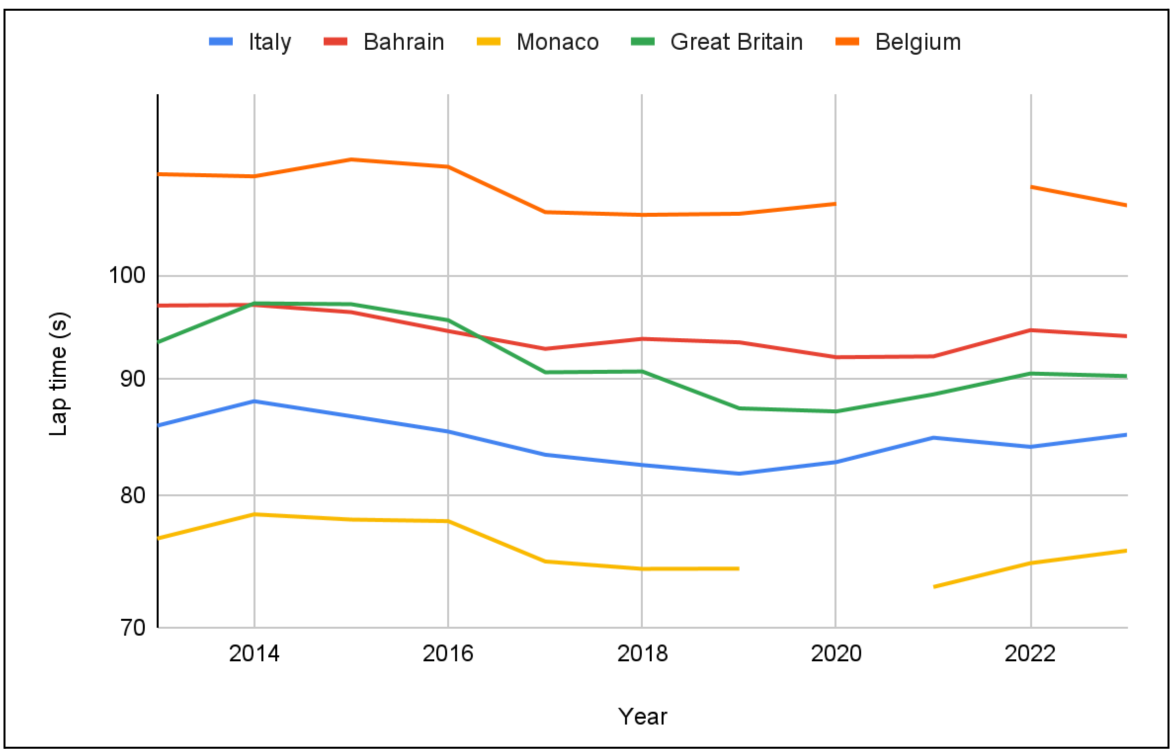

Figure 2. *Fastest Lap Times of Five Different Grands Prix Races Over Time.*

V. Discussion

From the data provided above, it can be noticed that the overall performance of the power unit was improved after implementing hybrid technology. This is most evident in the increase in horsepower, defined by the power needed to move 550 pounds by 1 foot in 1 second, and the consequent reduction in acceleration time (see Table 1). However, in the first year of implementing hybrid power units (2014), the cars actually got slower overall across the different races of the season (see Table 2 and Figure 2). This is most likely due to the teams still adapting to the new power unit regulations regarding the hybrid system, as Nico Rosberg confirmed in an interview with F1, underperforming with the unoptimized power unit, as well as the increased minimum weight as a result of the additional hybrid components (Walthert, 2014). The lap times of the races gradually decreased back to the pre-hybrid levels over time as teams optimized their power units. In fact, the hybrid V6 engines eventually outperformed the older V8 engines after a certain point as teams pushed the hybrid power system to its full potential (in Figure 2, notice the increase in fastest lap time from the 2013 season to 2014, and the gradual decrease from 2014 to 2018). This reduction in lap time illustrated in Figure 2 is especially large for high speed circuits like Italy and Great Britain characterised by high speed corners and long straights where drivers can fully utilise the maximum speeds of the cars, highlighting the positive impact on car performance of the ERS system. Despite being collected from circuits with varying dynamics, such as elevation and sharpness of corners, the collected lap times over the years of the Grand Prix locations used in Table 2 and Figure 2 generally followed this trend. This confirms that the fluctuations in lap times were likely caused by the sheer performance of the cars themselves rather than other factors like the teams and drivers' familiarity with certain circuits or changes made to the layout of specific circuits.

There were a number of changes that have contributed to the increase in engine power, including improved fuel composition, turbocharging, and heat resistant materials, but one of, if not the most impactful change was the addition of ERS technology assisting in accelerating the cars. Today, the ERS is a crucial element of an F1 car that allows for faster top speeds and therefore easier overtaking. However, the concept of energy recovery wasn't new as of 2014. The Kinetic Energy Recovery System (KERS), similar to the modern MGU-K, was introduced as an optional component starting from the 2009 season. Teams were allowed to recover energy from braking and use it for extra power for around 6.7 seconds per lap. Although KERS was introduced long before ERS, its successor, its power capacity was limited to 60 kW, or approximately 80 hp. This made it significantly less potent, resulting in the majority of the teams at the time choosing not to integrate it with their cars, and the technology eventually being banned in 2011 (Racecar Engineering, 2009). The modern ERS system was introduced with a larger power capacity in 2014 to account for the reduction of cylinders and total engine displacement from 2.4 L V8 to 1.6 L V6. The integration of electric power introduced a more complex and environmentally friendly power delivery system while also maintaining high performance levels (Scarborough, 2020).

These developments in high end energy recovery systems and powerful electric motors has allowed F1 to reduce the cars' reliance on fuel, and make design choices that are more fuel efficient. One of the more apparent changes that aligned with this purpose is the change in engine displacement. The decrease in engine displacement from 2.4 L to 1.6 L means that less fuel is required to complete a full cycle of combustion in the engine, and therefore usually consumes less fuel. Smaller displacement also means that there is less friction from the fewer or smaller components of the engine's internals, reducing the amount of energy that is lost from within the engine. This results in more of the chemical energy from the fuel being converted to useful work and thus contributes to better fuel efficiency.

Additionally, the dimensions of the cylinders were also able to shift to a more efficient design by tweaking the dimensions of the cylinders. As seen in Table 1, the modern V6 engines utilize a smaller bore diameter, around 18 mm smaller, but a larger stroke length in contrast to the traditional V8s, longer by around 13 mm. Bore diameter refers to the inside diameter of the cylinders, while stroke length is defined as the distance the pistons travel perpendicular to the cylinder bores (see

Figure 3). Engine displacement can be calculated using the following equation: π * (½ * bore)2 * stroke * number of cylinders. According to the formula, these two cylinder measurements are inversely related, as an increase in one necessitates a decrease in the other to maintain the regulated total displacement (Engineering Explained, 2020). The ERS system has allowed teams to adjust this combination to achieve greater efficiency by assisting in providing the necessary power for racing. The performance characteristics of the engine can vary greatly depending on which dimension is prioritized to be larger. Larger bores and shorter strokes tend to yield more power, as they can operate at high RPMs. This is because pistons typically do not move faster than 25 m/s, and the shorter stroke makes it so that the cylinders do not need to cover as much distance to make one revolution. On the other hand, smaller bores and longer strokes tend to be more efficient, as there is less surface area that energy can escape through as heat. Additionally, the burn time of the compressed air-fuel mixture is reduced in a small bore engine, as the flame ignited by the spark plug does not need to travel as far to ignite the entire volume of the cylinder. This allows for the cylinder to achieve peak pressure while the air is still compressed and while the piston still needs to travel downwards. The longer the burn duration, the more distance the piston will have already traveled downwards without peak pressure, wasting the energy that could have been used from the pressure (Engineering Explained, 2020).

By incorporating hybrid power units and shifting towards environmentally friendly design choices, F1 was ultimately able to significantly reduce the amount of fuel consumed per race from around 160 kg in 2013 to 100 kg in 2024, a 37.5% decrease in fuel mass (see Table 1) (Kanal, 2022). Assuming that 1 liter of unleaded gasoline weighs approximately 0.75 kg and burning 1 liter of gasoline produces 2.3 kg of CO_2, this equates to around 184 kg less CO_2 produced per race per car. Considering that F1 now uses E10 fuel, which produces 2~5% less CO_2 than ordinary unleaded gasoline, the reduction in carbon emissions is even greater (Barretto, 2022; NSW Fair Trading, 2021). With the hybrid power units, F1 has taken another step closer to its goal of achieving net zero carbon levels by 2030.

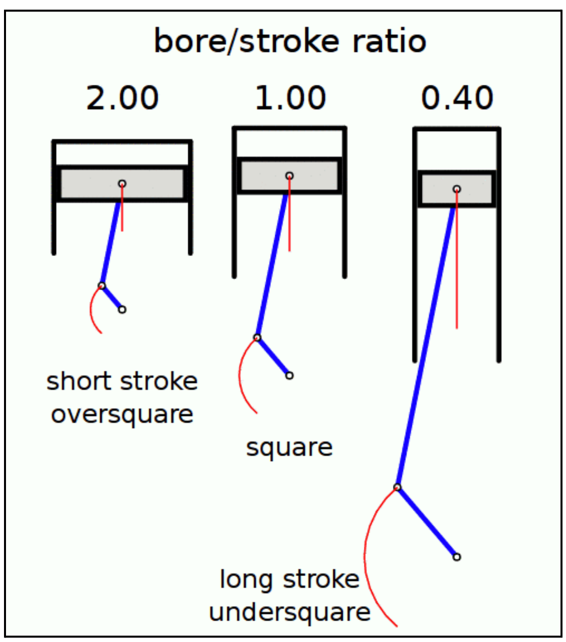

Figure 3. *Illustration of Engine Cylinders with Different Bore and Stroke Sizes*
Note. *Although not illustrated in the diagram, the spark plugs of the cylinders are positioned at the topmost middle point of the cylinders in an F1 engine. Source: MichaelFrey*

5.1 Limitations

The most fundamental limitation of this study is that the individual dynamics of the F1 teams are not considered. Not only are the budgets and performances of the teams very distinct, the specific telemetry data collected on track are kept confidential by most teams for competitive advantage. This makes it extremely difficult for the public to access real-time data or data regarding the car's internal components. Hence some of the data in Table 1 being recorded as a range or maximum/minimum. While most statements in this section concerning the general trend of F1 cars' performance will still stand true, specific data calculations are subject to variation depending on the F1 team or car model.

VII. Conclusion

Overall, the newer 1.6 L hybrid V6 power units were proven by recent telemetry data to be significantly better than the traditional 2.4 L V8 engines, in terms of both performance and environmental impacts. The integration of the ERS system, which includes components such as the MGU-K and MGU-H has been pivotal in improving the F1 cars' power output and efficiency. It harvests and reuses energy from braking and exhaust gasses that would otherwise be wasted, allowing the car to draw less energy from purely the ICE, thereby improving fuel efficiency. The research found that the newer models release 184 kg less CO_2 per race, which removes over 84 tons of CO_2 from the F1 season, purely from the race days alone (excluding practices and qualifying), when calculated based on 23 races per season, 20 cars per race. In terms of performance, the hybrid power units have maintained and even surpassed the performance of the 2013 V8 engines despite steps being taken to improve efficiency and reduce environmental impact.

Further research into cost reduction and the potential for mass production could open doors for the adaptation of F1 hybrid power unit technology into commercial vehicles, while ensuring accessibility across a wider consumer base. The implementation of hybrid systems in commercial vehicles would also help shape consumer perceptions of electric vehicles, especially for those who are reluctant to purchase electric vehicles due to their attraction to the engaging characteristics of ICEs (such as its unique sound or feel). Hybrid power units could serve as a middle ground between ICEs and electric vehicles, bridging the gap for ICE enthusiasts and encouraging people to make more environmentally sustainable choices.

In conclusion, the new hybrid technologies used by F1 can serve as a demonstration of how innovation can be used to resolve broader societal goals like environmental sustainability. This technical achievement can inspire other industries or individuals to adopt more sustainable practices, perhaps the most related one being the automotive industry.

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