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Predicting The Evolution Of Rocket Engines: An Analysis Of Past Trends And Prediction Of Future Trends.

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Evolution in animals and vehicles often favors larger size for longevity and range. However, the same trend does not hold for rocket engines. A comparison of historical and modern engines reveals a shift toward smaller, lighter designs in newer models like SpaceX's Raptor 3. This counterintuitive trend is largely driven by increasing combustion chamber pressures, which allow for reduced chamber and nozzle size and weight. Using scaling laws, this study analyzes how combustion chamber pressure influences the mass of major engine components, including the combustion chamber, expansion bell, turbomachineries, and plumbing. While higher pressure leads to more compact and efficient combustion components, it demands heavier turbomachineries and more robust plumbing, creating a trade-off. Ultimately, there is a performance ceiling where the benefits of higher pressure are constrained by the turbomachinery design. Pushing beyond this point requires advances in turbomachinery technology, marking a new direction in engine evolution.

1. Introduction

Across nature and technology, evolution tends to favor larger designs. According to the Constructal Law, flow systems evolve to facilitate easier access to movement, often resulting in larger structures that travel farther, move faster, and endure longer lifetimes. As Adrian Bejan summarizes, "the speeds of bigger animals and aircraft are greater than those of smaller movers," and "bigger movers exhibit longer life spans and longer distances traveled during lifetime." This pattern appears consistently across animals, vehicles, rivers, winds, and ocean currents [1].

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Recent research has shown that this evolutionary tendency is not merely descriptive, but predictable. For example, design evolution of airplanes has been documented over historical time and interpreted using simple physical scaling arguments, connecting changes in size, speed, and performance to a unifying principle of flow organization [2,3]. More broadly, related work on transportation systems has suggested that the evolution of vehicles is governed by the same physics-based tendency toward easier, wider, and more persistent access to movement [4].

Rocket engines, however, appear to defy this evolutionary trend. While early rocket engines grew rapidly in size and thrust capacity, modern designs increasingly favor smaller, lighter engines operating at significantly higher combustion chamber pressures. This apparent exception makes rocket engines a useful test case for extending the evolutionary analysis of engineered flow systems beyond aircraft and transport vehicles. In this paper, the method of scale analysis [5] is used as a simple physics-based method to investigate the historical evolution of rocket engine size and to identify the dominant trade-offs that govern its future development. In this sense, the method is not only descriptive but predictive: by revealing how major engine subsystems scale with chamber pressure, it provides a compact framework for assessing long-term technological trajectories, performance ceilings, and the direction of future innovation.

2. Historical Evolution of Engine Size

Engine weight trends over time show a rise followed by a decline, indicating two distinct phases of evolution (Fig. 1): an initial expansion phase, and a later compaction phase. The F-1 & M-1 engines in the 1960s represent the peak of the early scaling trend toward larger engine size, with masses exceeding 8,000 kg. In contrast, modern engines such as SpaceX's Raptor reflect a shift toward more compact designs, with masses below 2,000 kg. This reduction in size also correlates with a concurrent trend of increasing combustion chamber pressure (Fig. 2).

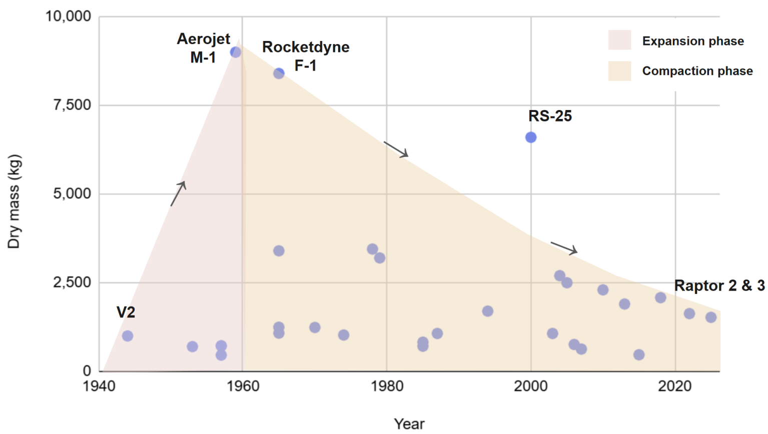

Figure 1. Trend of rocket engine weight over time

3. Thrust Scaling with Chamber Pressure

The thrust T of a rocket engine is [6]

$$T = \dot{m}v_e + (P_e - P_{\text{atm}})A_e$$

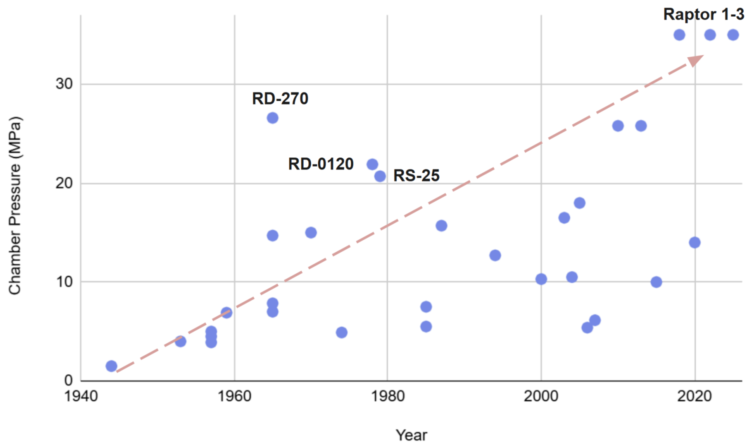

Figure 2. Trend of chamber pressure over time

For an engine operating under ideal nozzle expansion conditions, the pressure differential term drops out, and simplifies to

$$T = \dot{m} v_e$$

The propellant mass flow rate $\dot{m}$ scales proportionally to chamber pressure:

$$\dot{m} \sim P_c \tag{3.1}$$

The exhaust velocity v_e is related to chamber pressure by the equation [7]

$$v_e = \sqrt{\frac{2g\gamma R_c T_c}{\gamma - 1}\left(1 - \frac{P_e}{P_c}^{\frac{\gamma-1}{\gamma}}\right)}$$

Taking a typical $\gamma = 1.2$ for most combustion gases, v_e therefore scales as

$$v_e \sim \left[1 - \left(\frac{P_e}{P_c}\right)^{1/6}\right]^{1/2}$$

Considering first-order term, the exhaust velocity does not scale with changing chamber pressure for a given propellant-nozzle system. This is understandable, as v_e is determined primarily by the thermodynamic properties of the propellant (combustion temperature, molecular mass of the exhaust gases) and geometric configuration of the nozzle exit. v_e reflects how much thermal energy per unit mass can be converted into directed kinetic energy as the flow expands. Since combustion temperature is fundamentally constrained by propellant chemistry, with material advances only gradually extending allowable thermal limits, evolutionary trends in increasing chamber pressure does not significantly increase v_e.

Therefore the scaling relationship between thrust and chamber pressure is

$$T \sim P_c \tag{3.2}$$

Equation 3.2 concisely explains the drive towards higher chamber pressure: to obtain more thrust. Figure 3 demonstrates this trend. Aside from some notable outliers, the chamber pressure and thrust data scales linearly for the majority engines from the 1940s to present day.

However, thrust alone does not dictate engine evolution. Increasing chamber pressure introduces competing effects at the component level, altering the mass, complexity, and design requirements of key subsystems. Understanding these trade-offs requires examining how individual engine components scale with chamber pressure.

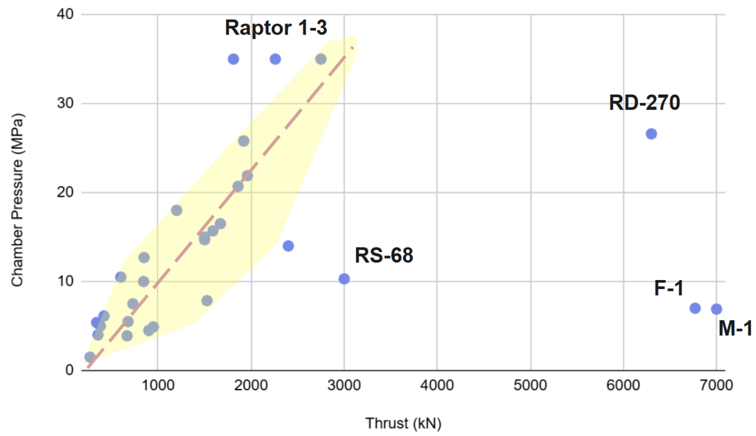

Figure 3. Correlation between chamber pressure and engine thrust

4. Component-Level Scaling Laws

A liquid-propellant engine can be decomposed into four principal mass contributors: the combustion chamber, the nozzle expansion bell, turbomachineries, and plumbing. Each component responds differently to increasing chamber pressure P_c.

(a) Combustion chamber

Basic first order pressure-volume relationship dictates that a higher chamber pressure requires a smaller chamber volume. The scaling relationship for this is

$$P_c \sim V_c^{-1} \tag{4.1}$$

Consider a chamber with volume V_c modelled as a cylindrical pressure vessel of length L, diameter D, and wall thickness t. Mass of the chamber is then

$$M_c \sim DLt \tag{4.2}$$

L is dependent on L^* - the "characteristic length", which characterized the distance needed for full atomization and combustion of the fuel, and is dependent on the choice of fuel used and injector design [6]. Therefore, as P_c is varied, the volume of the cylinder scales quadratically with the chamber diameter, independent of L.

$$V_c \sim D^2 \tag{4.3}$$

The pressure chamber must withstand the chamber pressure P_c, and the wall thickness is governed by the hoop stress equation [8]

$$\sigma = P_c \frac{D}{2t}$$

For a given P_c and maximum allowable stress σ, t scales linearly with D.

$$t \sim D \tag{4.4}$$

Combining Eqs. 4.1 - 4.4, the inverse scaling relationship between chamber mass and pressure is obtained:

$$M_c \sim P_c^{-1} \tag{4.5}$$

This scaling relationship explains one of the motivations behind the evolution towards higher chamber pressure: smaller chamber volume, and lighter chamber weight.

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(b) Expansion bell

Another mass contributor is the nozzle expansion bell. The length scale of the expansion bell is on the order of the length scale of the exit area A_e, and therefore mass of the bell scales as:

$$M_b \sim A_e^{1.5} \tag{4.6}$$

The exit area is related to the throat area A_t and the expansion ratio $\epsilon \equiv A_e/A_t$, which follows isentropic nozzle flow relationships [7]:

$$\epsilon = \frac{\left(\frac{2}{\gamma+1}\right)^{\frac{1}{\gamma-1}} \left(\frac{P_c}{P_e}\right)^{\frac{1}{\gamma}}}{\sqrt{\frac{\gamma+1}{\gamma-1}\left(1-\left(\frac{P_e}{P_c}\right)^{\frac{\gamma-1}{\gamma}}\right)}}$$

At high P_c/P_e ratios, ϵ asymptotically scales with P_c as

$$\epsilon \sim P_c^{\frac{1}{\gamma}} \tag{4.7}$$

With a given ϵ, A_t scales with the chamber cross-sectional area, which then can be scaled with chamber pressure:

$$A_t \sim A_c \sim D^2 \sim V \sim P_c^{-1} \tag{4.8}$$

Combining Eqs. 4.6 - 4.8, and using a typical $\gamma \approx 1.2$, the scaling relationship between expansion bell and chamber pressure is obtained:

$$M_b \sim P_c^{-0.3}. \tag{4.9}$$

So a higher chamber pressure also leads to a smaller, lighter bell, but with a weaker scaling relationship compared to the combustion chamber mass.

(c) Turbomachineries

As the evolution toward higher chamber pressure favors a smaller, lighter combustion chamber and a smaller expansion bell, it is countered by one major constraint: the increased weight and complexity of turbomachineries. Turbomachineries' operating conditions are tied directly to chamber pressure and temperature. A turbopump must add enough pressure rise ΔP to the propellants to bring the pressure from tank pressure to above chamber pressure, while also accounting for pressure drops across the piping, cooling jacket, and injector:

$$\Delta P \sim P_c$$

Another common metric used to characterize turbopump performance is the head rise, which is directly correlated to pump rotational speed ω and radius R [9]

$$H = \frac{\Delta P}{\rho g} = \psi \frac{(\omega R)^2}{g}$$

where ψ is the head coefficient, a function of blade-angle geometry that characterizes the efficiency of the turbopump, usually in the range of 0.2 to 0.8. The scaling relationship with P_c is then,

$$P_c \sim \psi \rho (\omega R)^2 \tag{4.10}$$

Higher chamber pressure P_c dictates evolution in two directions: increasing pump speed ω or pump size R. In the long term, ω is limited by technological and material limitations: the pump blade material must withstand the higher tip speed, turbine environment must withstand higher stress due to higher speed and temperature, bearings and sealing surfaces under higher stress at higher speed. Therefore, turbomachinery evolution moves largely in the direction of increasing size R. From Eq. 4.10, the scaling relationships of size R and mass M_t with respect to P_c are

$$R \sim P_c^{0.5}$$

$$M_t \sim P_c^{1.5} \tag{4.11}$$

This scaling law explains why higher chamber pressure requires bigger and heavier turbomachineries.

(d) Plumbing

The sizing of the plumbing system must ensure delivery of the propellant from the turbomachineries to the chamber with minimal pressure loss. For a turbulent flow system, the pressure drop in the piping is [10]

$$\Delta P \sim \dot{m}^2 \frac{L}{D^5} \tag{4.12}$$

The design objective is to scale the piping diameter D to match the fuel flow rate while producing a minimal, acceptable level of ΔP. Bigger diameter pipes minimize loss with respect to P_c, but are heavier. Combining Eqs. 3.1 and 4.12 yields the size scaling of the plumbing system:

$$D \sim P_c^{0.4}$$

The wall thickness of the piping must also withstand the higher pressure of the propellant and scale respectively:

$$t \sim D$$

Overall, the total mass of the plumbing system scales positively with chamber pressure as

$$M_p \sim LDt \sim P_c^{0.8} \tag{4.13}$$

5. Thrust-to-Weight Ratio

Simple scale analysis reveals that the evolution toward higher chamber pressure redistributes mass across engine components rather than uniformly reducing it. At lower chamber pressures, the dominant mass contributors are the combustion chamber and expansion bell, which require large volumes to sustain thrust. Increasing chamber pressure reduces these components significantly, but shifts the burden toward the propellant delivery system, particularly the turbomachinery and plumbing.

The overall performance metric is the thrust-to-weight ratio (TWR), or equivalently, minimizing the mass per unit thrust, M/T. Combining the scaling relationships of individual components' masses with the thrust scaling law yields

$$\frac{M}{T} \sim P_c^{-2} + P_c^{-1.3} + P_c^{-0.2} + P_c^{0.5}. \tag{5.1}$$

The first three terms correspond to the combustion chamber, expansion bell, and plumbing system, respectively, and decrease with increasing chamber pressure. These terms reflect the benefits of higher pressure: more compact combustion and more efficient expansion, and more thrust per unit mass of plumbing. However, the final term, $P_c^{0.5}$, represents the turbomachinery and increases with chamber pressure. This term ultimately dominates at high P_c, introducing a fundamental trade-off.

Importantly, the exponents in Eq. 5.1 reveal a natural hierarchy in how different subsystems respond to increasing chamber pressure. The magnitude of the exponents decreases in the order of combustion chamber (-2), expansion bell (-1.3), and plumbing (-0.2), indicating progressively weaker sensitivity to P_c. In contrast, the turbomachinery exhibits a positive exponent ($+0.5$), reflecting its fundamentally different role as the driving subsystem that must supply the required pressure rise.

This ordering is not arbitrary, but reflects the physical structure of the engine: components closer to the combustion process benefit most strongly from increased pressure, and the upstream driving system (turbomachinery) becomes increasingly penalized. In this sense, increasing chamber pressure induces a natural reorganization of the engine into a hierarchical system of competing scaling laws.

This behavior explains the observed plateau at thrust-to-weight ratio of ~ 200 over time (Fig. 4). Notably, this plateau is not confined to modern engines: the RD-270, developed in the 1960s, achieved a thrust-to-weight ratio of approximately 189:1, comparable to that of the latest engines such as SpaceX's Raptor 3 (∼184:1). Despite decades of technological advancement and increasing chamber pressures, no substantial improvement beyond this range has been realized. This suggests that current designs are approaching a practical limit imposed not by combustion physics, but by turbomachinery constraints.

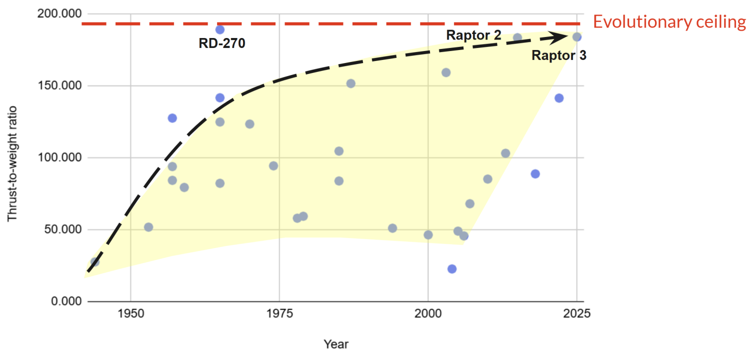

Figure 4. Trends in thrust-to-weight ratio over time

Breaking through this ceiling therefore requires a shift in the direction of evolution. Rather than continuing to increase chamber pressure, future improvements must target the limiting subsystem - turbomachinery. This includes advances in high-speed rotating machinery, improved bearing systems, stronger materials capable of withstanding higher stresses, more accurate computational modeling of turbulent internal flows, etc. In this sense, the next stage of rocket engine evolution will be driven not by combustion scaling alone, but by the co-evolution of supporting subsystems.

An important observation supporting this idea is that the engines achieving the highest thrust-to-weight ratios in the dataset - the RD-270 and SpaceX's Raptor series - are the only ones employing full-flow staged combustion cycles, which places exceptionally high demands on turbomachinery. As a result, these engines operate near the practical limits of turbo capability, suggesting that further gains will depend on advancing turbomachinery design, high-level architectural shifts, and technological advancements, rather than simply increasing chamber pressure.

6. Conclusion

Rocket engine evolution diverges from the broader pattern observed in natural and engineered flow systems. While most systems evolve toward increasing size, rocket engines achieve higher performance through increasing internal intensity - specifically, higher combustion chamber pressure - while simultaneously reducing overall size and mass.

Scale analysis reveals that this trend is governed by competing scaling laws across engine subsystems. Higher chamber pressure improves thrust and reduces the size of combustion-related components, but at the cost of increased mass in turbomachinery and plumbing. These competing effects lead to a fundamental performance ceiling, beyond which further increases in chamber pressure are no longer beneficial.

This result highlights a key insight: technological evolution does not proceed indefinitely along a single direction. Instead, it progresses through shifts in dominant constraints. For rocket engines, the current limitation has transitioned from combustion processes to turbomachinery capability.

Future advancements will therefore depend on overcoming these new constraints through innovations in turbomachinery design, materials, manufacturing techniques, and engine cycle architecture. In this sense, the continued evolution of rocket engines will not be driven solely by higher pressures, but by the integration of multiple advancing technologies.

More generally, the scaling approach presented here provides a simple yet powerful method for analyzing complex systems and predicting their evolutionary trajectories. By identifying dominant scaling relationships, it becomes possible to anticipate performance limits and guide future design directions, not only for rocket engines, but for a wide class of engineered flow systems.

Data Accessibility. The data are provided in electronic supplementary material

Conflict of interests. The author declares no competing interests

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