# Parametric Analysis of Fin Geometry Effects on Stability and Performance of a Model Rocket

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**Abstract.** Fin geometry plays a critical role in determining the aerodynamic stability and performance of rockets, yet excessive fin area may reduce efficiency through added drag. In this study I investigated the effect of fin geometry on rocket flight characteristics using ten simulated variants analyzed in OpenRocket under controlled launch conditions with four wind levels in a hypothetical situation where we are in Guadalajara, Spain. Metrics including apogee altitude, maximum velocity, acceleration, and time to apogee were compared across designs, revealing measurable tradeoffs between stability margin and ascent performance. The results indicate that moderate fin configurations can outperform both oversized and undersized designs by balancing stability with reduced aerodynamic losses.

## Introduction

Fins are one of the most important aerodynamic components of a rocket. They are flat surfaces that provide longitudinal stability, and also affect the rocket's drag. (a) The shape and size of the fins of the rocket directly influences the rocket's static stability margin and aerodynamic drag. (b) A higher stability margin, which is the center of pressure farther behind center of gravity, which makes the flight straighter and safer, but also increases fin area and drag. In turn, drag reduces the maximum height attained. (c) Conversely, reducing fin area lowers drag and can raise peak velocity and altitude, but too little stability (below ~1 cal) risks control loss. Thus, fin geometry creates an interesting engineering trade-off, which, one must maximize altitude and speed while maintaining acceptable stability at the same time. Already existing research shows that fin design significantly affects rocket performance. For example, simulations and tests of different fin planform found significant difference in apogee and stability factor. [1] However, only a few studies systematically compare many fin variants under identical conditions. This work addresses that gap by simulating 11 unique fin-geometry variants (A - K) in a constant set up of 4 wind levels spaced ever 100 meters, with slightly higher deviations per level by a factor or 0.1 meters per second. We held the motor, body, and launch conditions constant, while only changing the fins. The goal is to identify which fin designs yield the best balance of high altitude and safe stability. OpenRocket (v24.12) was used for all simulations. It is a free, full-featured model-rocket simulator with a 6-degree-of-freedom flight model. OpenRocket updates performance metrics in real time as the design changes. By exporting the results, we can extract the final apogee, maximum velocity, touchdown speed, etc. The metric stability margin is given in calibers by OpenRocket, defined as (CP-CG)/body diameter, which we target to be in range ~1-2 cal for good performance. We are using the Estes C6-5 motor, which is a standard "mid-power" motor, with total impulse ~10 N.s and 1.6s burn, which was chosen for its consistent performance.

# Problem Statement

## Research Question

How does varying rocket fin geometry affect the rocket's static stability and flight performance (apogee, velocity, etc.) under identical launch conditions?

## Objectives

Compare flight outcomes of Variants A–K by simulation, isolating fin geometry as the only variable.
Measure and tabulate each variant's stability margin, apogee (m), max velocity (m/s), time to apogee (s), flight time (s), and max acceleration ($m/s^2$).
Analyze trends: correlate stability vs. apogee/velocity to identify optimal fins.
Compute a composite performance score for each variant (weights: 40% apogee, 30% stability, 15% velocity, 15% time-to-apogee) and rank the designs.
Conclude which fin configurations maximize performance without sacrificing safety.

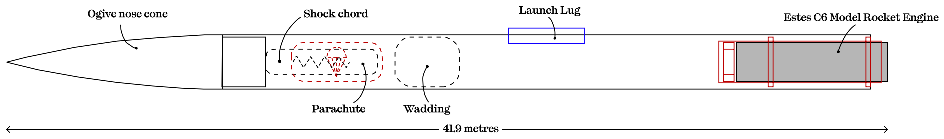
## Hypotheses

**Performance Hypothesis ($H_1$):** Moderate fin sizes (yielding ≈1.2–1.8 cal stability) will achieve higher apogee and velocity. Very large fins (≫2 cal) will add drag and lower altitude, while very small fins (<1 cal) will compromise stability and thus performance.
**Null Hypothesis ($H_0$):** Changes in fin geometry will not significantly affect apogee or stability; all variants will have similar performance.
**Stability Hypothesis:** Stability margin must remain positive (rocket must be statically stable). Designs with stability <0 (negative) would fail.
The experiment will test these hypotheses using the simulation data. We expect to reject $H_0$ and find that fin geometry has a measurable impact, as suggested by prior studies.

# Methods

Rocket and Motor: The simulated rocket had a standard 25mm diameter body tube (300 mm length), a 100 mm conical nose, and a mass around 81.5g (including motor). All variants used the Estes C6-5 motor: single-stage 18 mm motor with ~10 N·s total impulse, ~15.3 N average thrust, 1.6 s burn, and 5.99 s ejection delay. This motor choice provided a consistent thrust profile and is commonly used for mid-power small scale model rockets.

**Fin Variants:** Eleven fin designs (A–K) were created. Each variant were modified the fin planform (e.g. chord length, span, taper). Variants A/B were close to baseline, C began to tumble under thrust, D/E had moderate differences, F/H/I had larger fins, and J/K had smaller fins. (Detailed fin dimensions are documented in the design files.) All other rocket parameters (mass distribution, drag coefficients for body components, launch angle) were identical across variants.



The general structure of the rocket without the fins are given below in figure 1.

*Figure.1*

**Simulation:** Each variant was simulated from launch on a 0° rail until ground impact. OpenRocket produced a time history of altitude, velocity, and acceleration. From this, we extracted for each variant: Apogee (m): maximum altitude above launch. Max Velocity (m/s): peak total velocity during ascent. Time to Apogee (s): time when apogee occurs. Flight Time (s): time from launch to ground impact. Max Acceleration (m/s$^2$): peak net acceleration. Stability (cal): static margin in calibers (CP–CG divided by body diameter), computed by OpenRocket. I used Python scripts to parse the CSV output files and compute these values.

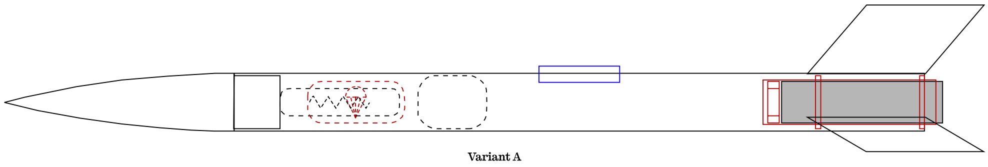


*Figure.2*

As already mentioned, Variant A was almost baseline. So we had satisfactory results Variant A, whose figure is given above. Below we see Variant B, which isn't much different from Variant B but it will serve crucial in understanding the effects of minute changes in fin geometry.

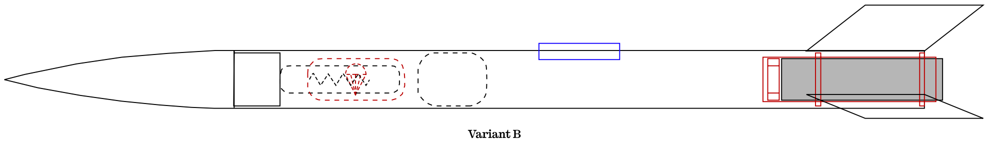


*Figure.3*

Variant C is an unique case. We see Variant C crumble during takeoff due to the thrust. We will talk about this particular case later on this paper. The figure of Variant C is given below, or in the next page.

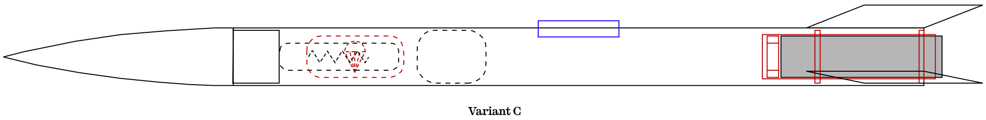


*Figure.4*

Moving on to Variant D, we see the bigger fins. In Variant E, we see the sweep angle being increased to 46.2 degrees, which was initially 32.4 degrees. Both the figures (Variant D and Variant E) are given below.

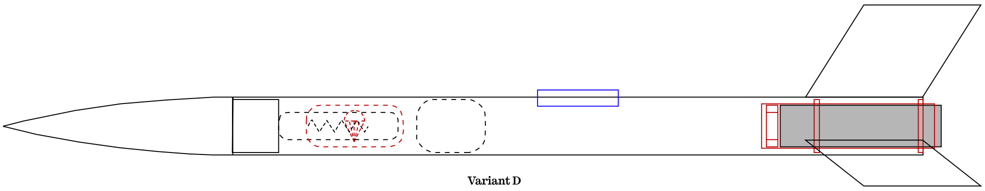


*Figure.5*

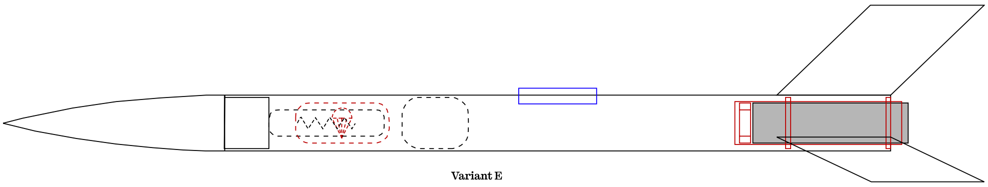


*Figure.6*

In Variant F, we see an increase in the root chord. We can see the trend continue to Variant G too. Figures for both variants are given below.

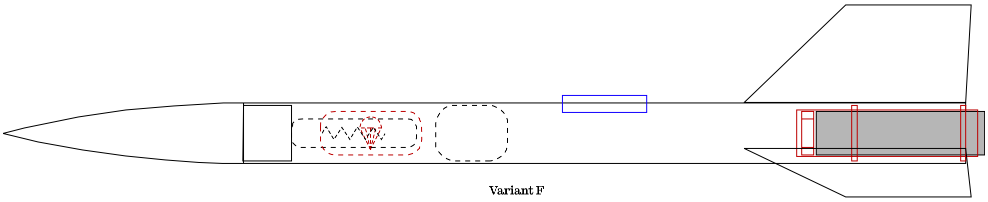


*Figure.7*

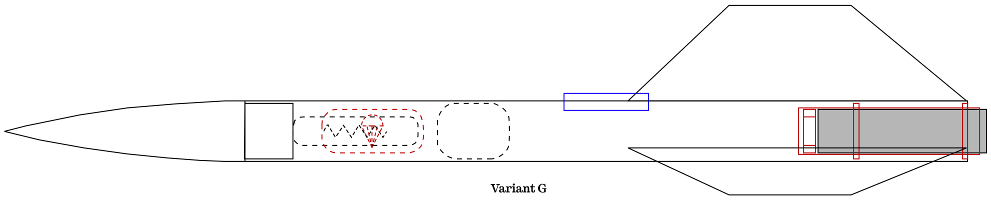


*Figure.8*

In Variant H, we see the introduction to fin cant. We can observe the continuity of the trend in Variant I too. Figures for both variants are given below.

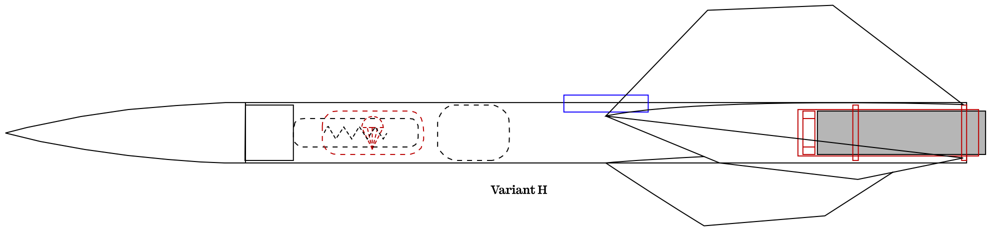


*Figure.9*

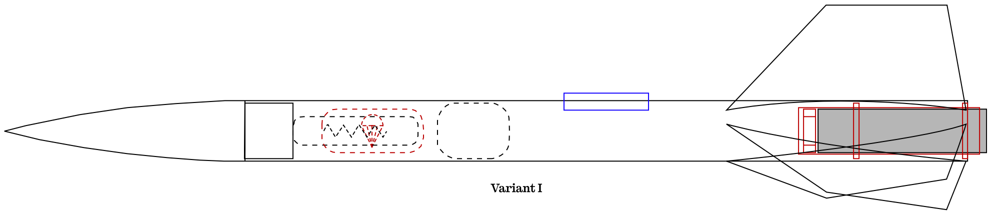


*Figure.10*

In Variant  J, we can see the introduction to triangular fins. Variant J performed highly, as we will discuss later on. Figure of Variant J has been given below.

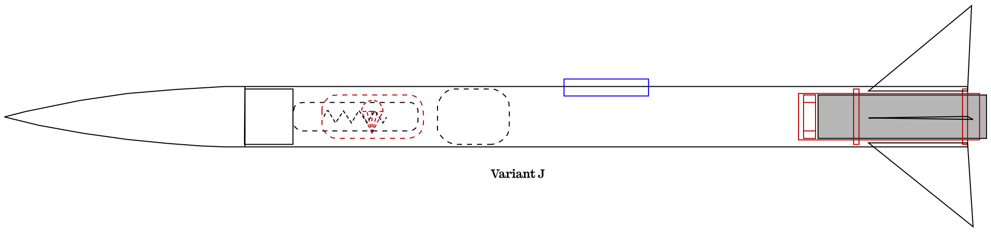


Figure.11

For an exceptional case, we bring in our 11th variant, Variant K. We can clearly see the introduction to the cosmetic front flaps, almost similar to the SpaceX starship, but it doesn't serve a purpose. We are only adding it to study the drag induced by it. The figure of this variant is given below. This is our last variant.

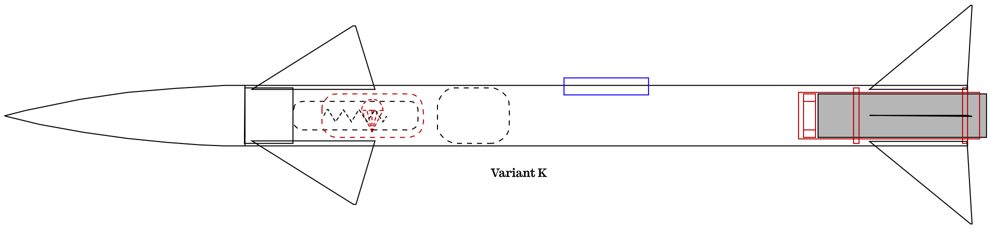


Figure.11

Figure 13 illustrates the complete simulated flight sequence of Variant H (ref. Figure 10). Following motor ignition, the rocket experienced a rapid increase in vertical velocity and acceleration during powered ascent. After motor burnout, the rocket continued to climb under inertia until reaching an apogee of approximately 265 m at around 7.3 s.

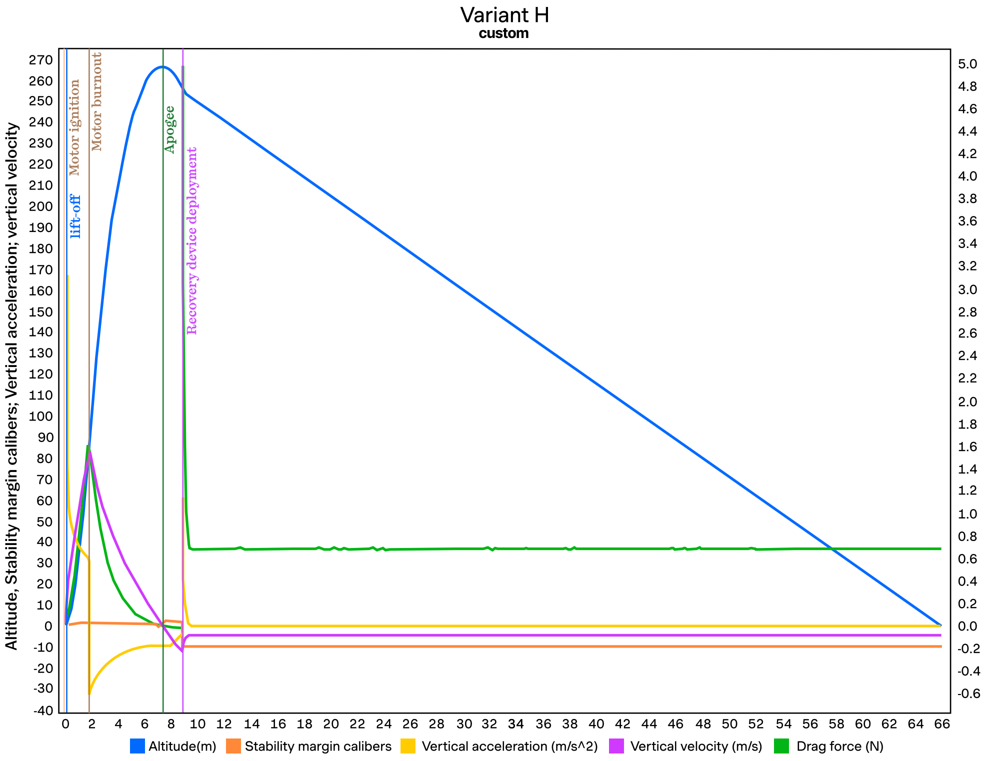


Figure.13

Vertical velocity then decreased to zero at apogee before becoming negative during descent. Recovery system (the parachute) deployment occurred shortly after apogee, reducing descent velocity and stabilizing the landing phase. Drag force peaked during the high-speed ascent phase and declined as velocity decreased. The stability margin remained positive throughout flight, indicating that Variant H maintained static aerodynamic stability during ascent.

## Results

All measured metrics are tabulated in Table 1. The data clearly show that fin geometry significantly impacts flight performance. Variants B and J, which combined relatively low-to-moderate stability margins (0.938 cal and 3.032 cal, respectively), achieved the highest apogees (338 m and 335 m) and the fastest peak velocities (99.0 m/s and 99.5 m/s). Variant A, with a higher stability margin of 2.422 cal, reached a slightly lower apogee of 320 m at 95.3 m/s, indicating a tradeoff between stability and aerodynamic efficiency. In contrast, lower-performing stable designs such as D and E (stability 3.012–3.193 cal) reached only 303–304 m, demonstrating the drag penalty associated with oversized fins. Extremely unstable or poorly optimized designs performed worst: Variant C (–2.803 cal) reached only 10.8 m, while Variant H (0.619 cal) reached just 4.39 m.

These trends confirm that excessive fin area can reduce altitude through drag, whereas insufficient or poorly balanced fins can severely compromise stability and overall flight performance.

| Variant | Stability (cal) | Apogee (m) | Max Velocity (m/s) | Time to Apogee (s) | Flight time (s) | Max Accel (m/s^2) |
|---|---|---|---|---|---|---|
| A | 2.422 | 320 | 95.3 | 8.021 | 84.322 | 191.00 |
| B | 0.938 | 338 | 99.0 | 8.038 | 90.149 | 197.00 |
| C | -2.803 | 10.8 | 38.5 | ~ | ~ | 204.00 |
| D | 3.012 | 303 | 91.8 | 7.664 | 78.271 | 186.00 |
| E | 3.193 | 304 | 91.4 | 7.682 | 78.581 | 186.00 |
| F | 2.016 | 284 | 87.3 | 7.501 | 71.776 | 177.00 |
| G | 0.565 | 265 | 82.2 | 7.354 | 65.592 | 168.00 |
| H | 0.619 | 4.39 | 26.3 | 7.363 | 65.562 | 168.00 |
| I | 1.791 | 281 | 86.2 | 7.509 | 70.905 | 175.00 |
| J | 3.032 | 335 | 99.5 | 7.973 | 89.875 | 200.00 |
| K | -0.583 | 316 | 95.5 | 7.760 | 82.860 | 193.00 |

*Table.1*

Based on these metrics, we computed a composite score for each variant (normalized weights: 40% apogee, 30% stability, 15% velocity, 15% time). Table 2 ranks the variants by this score. Variant A scores highest overall, indicating a balanced design, closely followed by B and I. Even though J and K had top altitudes and speeds, their minimal stability prevented them from ranking first in the weighted score.

| Rank | Variant | Composite score |
|---|---|---|
| 1 | A | 0.900 |
| 2 | B | 0.787 |
| 3 | C | 0.770 |
| 4 | D | 0.762 |
| 5 | E | 0.752 |
| 6 | F | 0.746 |
| 7 | G | 0.729 |
| 8 | H | 0.651 |
| 9 | I | 0.586 |
| 10 | J | 0.276 |
| 11 | K | 0.205 |

*Table.2*

The results confirm that fin geometry critically affects flight performance. Variants with moderate fin configurations (e.g., A and B) delivered high apogees (320 m and 338 m) while maintaining acceptable stability margins (2.422 cal and 0.938 cal). This supports engineering expectations that strong performance is often achieved near an intermediate stability range rather than at extreme values. On the other hand, highly stable variants such as D and E (3.012–3.193 cal) experienced reduced apogees (303–304 m), indicating the aerodynamic drag penalty associated with oversized fins. Not surprisingly, very small or poorly balanced fins also created problems: Variant J reached a strong 335 m at 99.5 m/s, but Variant K, despite achieving 316 m, had a negative stability margin (–0.583 cal), indicating potential instability. Figure 4 shows the trade-off between stability and altitude. Figure 6's trajectories further illustrate these differences: Variant B ascends higher and longer, whereas Variant G peaks sooner and at a lower altitude (265 m).

These findings align with fin-design theory: increasing fin area generally increases CP–CG separation, thereby improving static stability, but also increases drag, which reduces maximum speed and altitude. In practice, designers should target a balanced stability margin of approximately 1–2 cal. Variant I (1.791 cal) exemplifies this compromise, achieving a respectable 281 m apogee while maintaining stable flight. Variant A (2.422 cal) also demonstrated strong overall balance. The OpenRocket simulations use standard aerodynamic models, so they reasonably capture these trade-offs. However, actual flight tests may differ somewhat due to wind, construction tolerances, surface roughness, and motor variability.

In summary, fin designs must balance stability margin against drag. Maximum altitude is not achieved by the largest fins, nor by the most unstable designs. Instead, the strongest practical performance occurs with moderate fin sizing that preserves stability while minimizing unnecessary drag. This conclusion is relevant for educational rocketry and lowcost launch systems, demonstrating that excessive fin area can be counterproductive to flight efficiency.

## Limitations

This study is based entirely on OpenRocket simulations and the provided dataset. Real-world factors (wind, gusts, assembly imperfections) are not modeled. Stability margins were computed by the software's Barrowman method, which assumes idealized flow; actual performance could vary. Only one motor (Estes C6-5) and one rocket body were used; results may differ with other setups. The composite score uses arbitrarily chosen weights. Despite these limitations, the trends observed are robust and consistent with aerodynamic theory.

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