# Correlated Risk in Large Turbofan Architectures

***The Baemax Inlet Shield Concept***

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## Abstract

Modern twin-engine aircraft certification frameworks rely on the assumption that engine failures are independent events. This paper examines how that assumption degrades as turbofan inlet diameters scale, not because engines are less reliable, but because both engines are increasingly exposed to the same airspace at the same time. Using a simple probabilistic framework, the analysis shows how scaling inlet area alone materially increases the probability of correlated ingestion events during bird flock encounters.

The Baemax Inlet Shield concept is introduced as one possible system-level response. However, the primary contribution of this work is not a mechanical design, but the identification of a hidden scaling risk: the quiet transition from redundancy to correlation.

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# Table of Contents



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# 1. Introduction

Aviation safety has historically advanced by identifying where assumptions break under new operating conditions. One such assumption is independence: the belief that failure of one engine does not materially increase the probability of failure in the other.

Twin-engine certification standards implicitly rely on this principle. Engines may fail, but they are assumed to fail independently. Aircraft survivability is therefore assessed under the expectation that at least one engine remains available.

This paper examines whether that assumption continues to hold as modern turbofan engines grow significantly larger and more symmetric.

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# 2. Scaling Trends in Modern Turbofan Engines

Over recent decades, turbofan engine diameters have increased substantially to improve efficiency and bypass ratio.

- Early narrow-body engines (e.g. JT8D) featured inlet diameters around **1.1 m**
- Modern wide-body engines (e.g. GE9X) reach diameters of approximately **3.4 m**

Because inlet exposure scales with **area**, not diameter, frontal exposure has increased by more than **sevenfold**. This increase materially changes how engines interact with the surrounding airspace during low-altitude flight.

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## 3. The Independence Assumption in Certification

Current certification approaches focus primarily on **single-engine ingestion resilience**. Bird ingestion tests typically assess whether an engine can tolerate ingestion of specified bird sizes without catastrophic failure.

What is less explicitly addressed is **joint exposure**:

- Both engines are mounted symmetrically
- Both traverse the same airspace simultaneously
- Both encounter the same bird density during takeoff and landing

When exposure becomes shared, failures are no longer statistically independent — even if engines are mechanically independent.

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## 4. Probabilistic Framing of Ingestion Risk

The ingestion of birds during a flock encounter can be modeled using a Poisson process.

The probability of ingesting *k* birds is given by:

$$P(k) = \frac{\lambda^k e^{-\lambda}}{k!}$$

Where:

- **λ** = expected number of birds intersecting the inlet area
- **λ = bird density × inlet area**

This framing allows us to isolate the effect of inlet size alone.

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# 5. Example Comparison

Assume a bird density of **0.1 birds/m²**, conditional on a flock encounter.

| Engine | Inlet Area (m²) | λ | P(≥1 bird) | P(both engines ingest)* |
|---|---|---|---|---|
| JT8D | ~0.95 | 0.095 | ~9.1% | ~0.8% |
| GE9X | ~9.07 | 0.907 | ~59.7% | ~35.6% |

* assuming independence

This demonstrates that even under independence assumptions, the probability of dual ingestion rises non-linearly with inlet size.

*An optional interactive visualisation illustrating how ingestion probability scales with inlet diameter and bird density is available at:*

**https://crs.baemax.co.uk/Bird_Ingestion_Risk**

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# 6. Conditional Dependence and Correlated Risk

The independence assumption implies:

$$P(both) = P(one)^2$$

However, in real flight conditions:

- Both engines pass through the **same flock**
- Bird density is shared
- The conditional probability of ingestion in the second engine increases if the first engine ingests

Formally:

$$P(engine\ 2 | engine\ 1\ ingests) > P(engine\ 2)$$

> *In a truly redundant system, failure of one component does not increase the failure probability of its backup. The inequality above shows that redundancy has been structurally compromised by shared exposure.*

This represents a structural violation of the redundancy assumption rather than a component-level failure, and it underpins much of twin-engine safety analysis.

The result is not a component failure, but a **system-level redundancy compromise**.

# 7. Framing the Safety Question Differently

Traditional twin-engine certification frameworks are largely framed around a central question:

**Can one engine survive a bird ingestion event?**

This framing reflects an era in which dual-engine ingestion during a bird flock encounter was considered extremely unlikely. For smaller-diameter engines, joint ingestion probabilities on the order of one percent or less were consistent with the assumption that such events were rare and could be treated as exceptional. As a result, certification emphasis appropriately focused on single-engine survivability, blade containment, and safe rollback procedures rather than aircraft-level exposure management.

This work suggests that an additional question is now required:

**How does aircraft-level survivability change when both engines are exposed to the same ingestion risk at the same time?**

As turbofan inlet diameters scale, both engines increasingly sample the same airspace during the most vulnerable phases of flight. In this regime, the aircraft begins to behave less like a redundant system composed of two independent engines and more like a single large target with two vulnerable apertures.

While certification frameworks have remained largely stable, the physical parameters underpinning their safety assumptions have shifted materially. Engine inlet area — and therefore shared exposure — has increased dramatically. The result is not a deterioration in engine reliability, but a change in how redundancy behaves at the system level.

In complex engineered systems, redundancy only provides protection if failures remain independent. When scaling introduces shared exposure to the same inputs or environments, apparent redundancy can quietly collapse into correlated risk — a pattern well documented in financial, computing, and infrastructure systems.

Framed this way, the challenge is not whether individual engines meet their certification requirements, but whether aircraft-level redundancy continues to function as intended under modern geometric and operational conditions.

# 8. The Baemax Inlet Shield Concept

The Baemax Inlet Shield is a modular, retractable system intended to temporarily reduce effective inlet exposure during the highest-risk phases of flight:

- Takeoff
- Initial climb
- Landing

- Low-altitude operations

Once the aircraft exits bird-dense airspace, the system retracts to restore nominal inlet geometry.

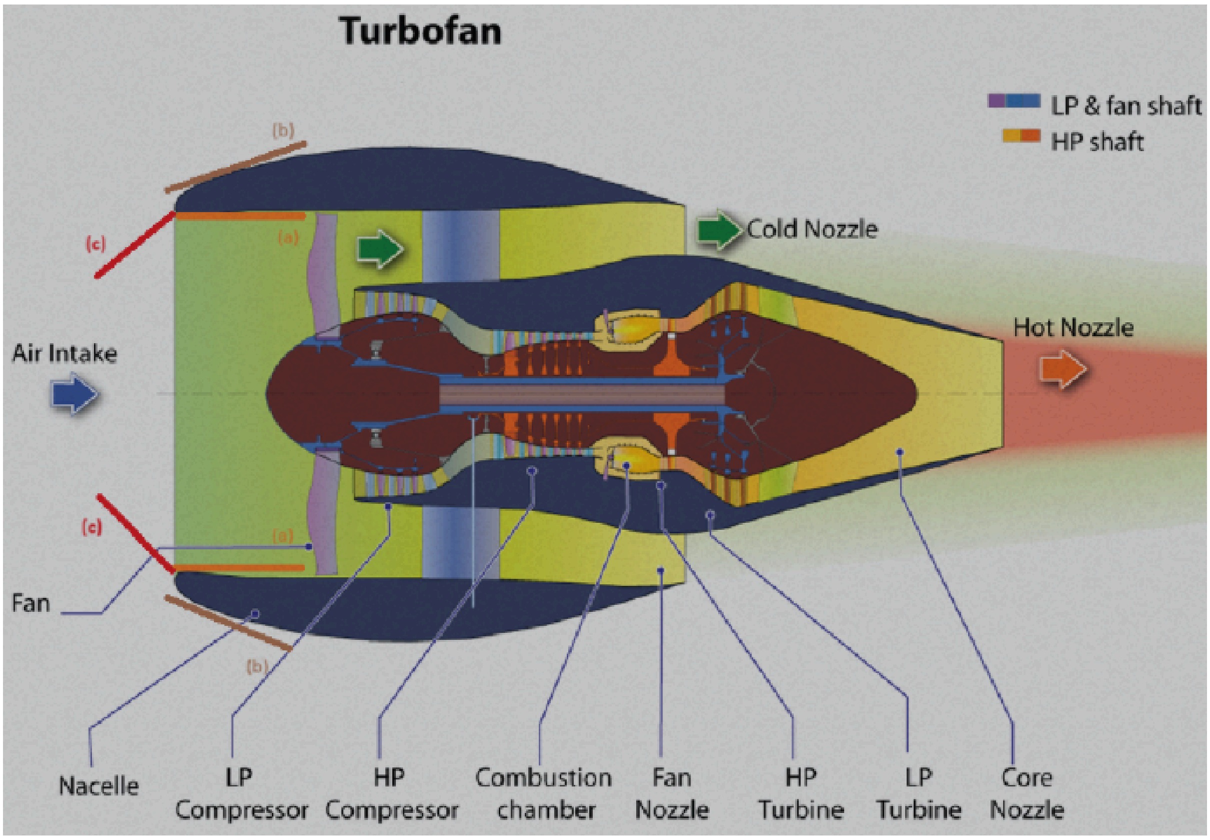


**Figure (1): Conceptual illustration of inlet exposure modulation during high-risk flight phases.**

Panels (a), (b), and (c) illustrate *one possible* operational interpretation of temporarily reducing effective inlet exposure. The figure is schematic and non-prescriptive, intended to support system-level discussion rather than define a specific mechanical implementation.

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# 9. Design Principles

The concept adheres to the following principles:

- **Phase-limited deployment**
  Active only during minutes of highest ingestion risk
- **Fail-safe bias**
  Defaults to full-open in the event of malfunction
- **Lower-sector protection**
  Addresses runway debris and flock-level ingestion vectors

- **Retrofit-oriented modularity**
  Compatible with existing turbofan architectures
- **System-level risk reduction**
  Targets correlated failures rather than single-engine events

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## 10. Performance Trade-Off

The approach accepts a **controlled, temporary reduction in airflow margin** in exchange for a disproportionate reduction in correlated dual-engine ingestion probability.

This trade-off aligns with existing certification philosophy, where aircraft are designed to remain controllable and survivable under reduced performance on a single engine.

The objective is not to eliminate ingestion risk, but to **reshape its distribution** during the most vulnerable flight phases.

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## 11. Broader Implications

This analysis suggests that as systems scale, safety assumptions that once held implicitly may degrade quietly.

Redundancy remains effective only when failures remain independent. When scaling introduces shared exposure, correlation emerges — and risk compounds faster than intuition suggests.

The Baemax Inlet Shield represents one possible mitigation, but the more general contribution is identifying where independence quietly turns into correlation.

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## 12. Conclusion

Modern turbofan scaling has introduced a structural change in engine exposure that certification frameworks may not fully capture.

By reframing ingestion risk as a **correlated system-level phenomenon**, this work invites a broader discussion about how redundancy is preserved — or eroded — as aerospace systems continue to scale.

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