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Silent Aircraft Initiative

Required jet area for a Silent Aircraft at take-off

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Overview

The Silent Aircraft Initiative

The aim of the Silent Aircraft Initiative (SAI) is:

> ‘To discover ways to reduce aircraft noise dramatically, to the point where it would be virtually unnoticeable to people outside the airport perimeter in a typical built-up area.’[1]

This is an exceedingly ambitions target requiring noise to be considered as **the** primary design goal.

Different groups are looking at the airframe noise sources, engine noise sources and acoustic integration. This presentation is from members of the engine team.

To meet the SAI aim, a considerable reduction in all major engine noise sources will have to be achieved through source reduction, lining and shielding.

Why the focus on jet area?

To significantly reduce jet noise for a given thrust need to increase the jet area and reduce the jet velocity.

↓

Jet noise is directly linked to the engine cycle.

↓

A significant reduction in jet noise therefore requires a significant change in the engine cycle.

↓

Turbomachinery noise requires detailed knowledge of the engine design which follows the engine cycle

↓

Before other engine noise sources can be silenced, the jet must be silenced through modification of the engine cycle.

Calculating the required jet area

The goal of the SAI can be taken as to reduce peak noise to a set level outside of the airport boundary.

↓

To determine the required jet area to meet this peak noise limit, need to know the departure profile.

↓

In order to optimise the performance at cruise, want to minimise required increase in jet area relative to current trends for optimum efficiency.

↓

To minimise the required jet area, need to optimise the departure profile for low jet noise.

↓

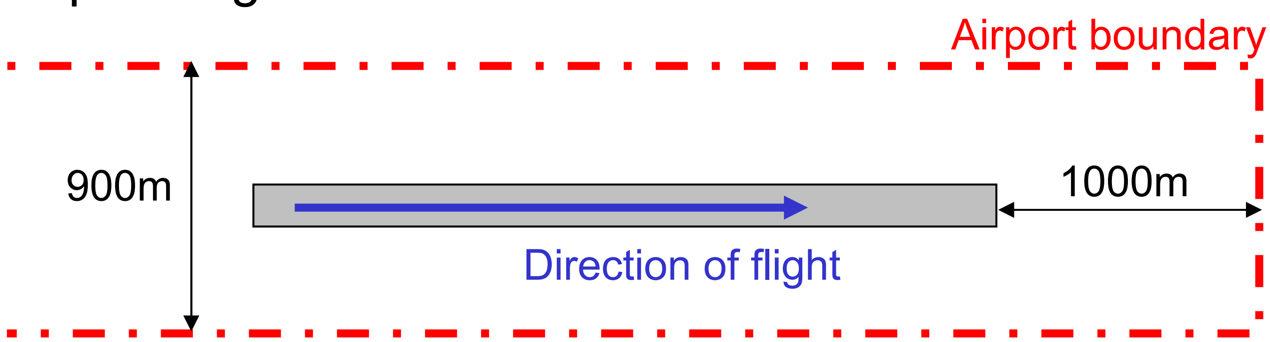
Therefore first step in designing the SAI engines is to optimise the departure profile for low jet noise and calculate the required jet area.

What is an acceptable take-off

The following parameters were used for a reference noise constrained airport:

- 10,000ft runway
- Sea level
- ISA + 12°K
- 70% relative humidity
- Airport boundary of 450m for sideline and runway length + 1,000m for flyover.

These parameters reflect London airports with the temperature set to cover 99% of operating hours at London Heathrow[2].



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What is an acceptable take-off

The following key regulated[3,4] areas must be met during take-off:

- <u>Accelerate-stop</u>
  Max distance to reach V1
  based on JAR25.109

$$s = 3048 - 2V_1 - \frac{1}{\eta g}\int_{V_1}^{0} \frac{V}{c_1 V^3 + c_2 V^2 + c_3 V + c_4} dV$$

- <u>Take-off field length</u>
  Must be 35ft high at runway length / 1.15

- <u>Minimum climb gradient</u>
  Min angle of climb allowing for 11%
  thrust increase on engine out

$$\theta_{\min} \approx \sin^{-1}\left[\frac{1}{1.11}\frac{E_{num}}{E_{num}-1}\left(\frac{1}{L/D} + \sin\theta^*\right) - \frac{1}{L/D}\right]$$

To satisfy the majority of SIDs, average climb angle of 4° (7%) required up to 1000m without exceeding the jet noise limit.

Minimum regulated cutback height of 800 ft[5,6] not enforced as entire take-off profile is low noise optimised with a continuous variation in thrust.

Jet Noise Prediction

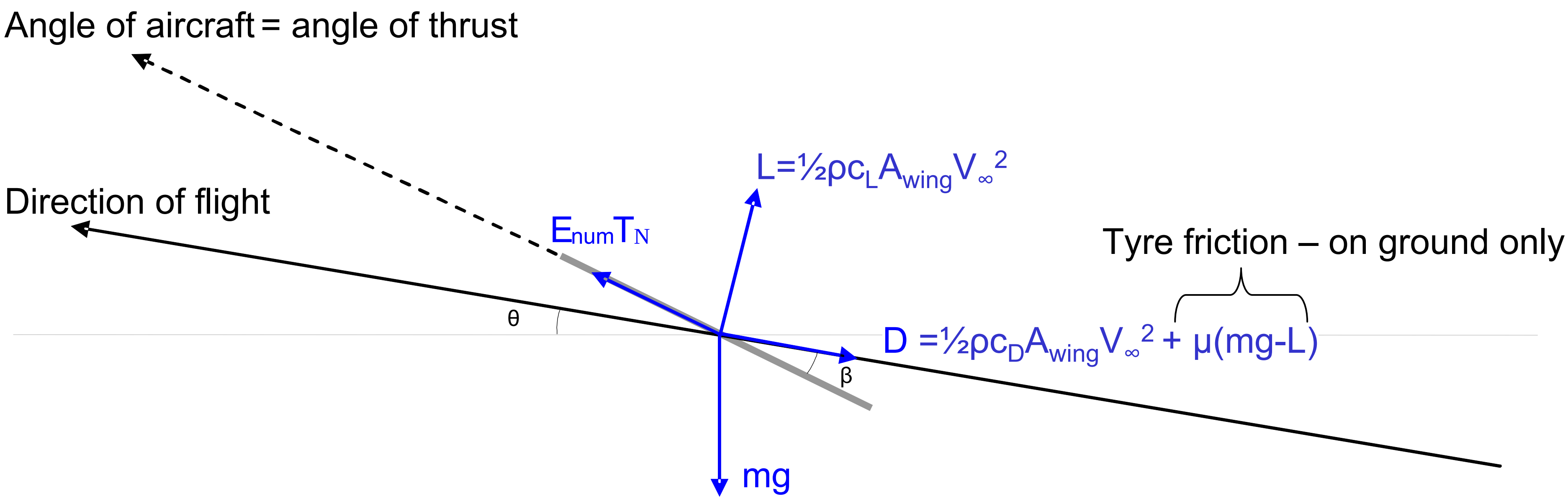
- As jet noise will not be the only noise source on take-off, the jet noise limit was set 3dB below the overall noise limit.

- Stone Jet Noise model[7] was used to estimate the 1/3rd octave SPL
  - Single jet with core and bypass streams fully mixed out
  - Low temperature
  - No corrections for internal forced mixing applied (e.g. Garrison[8] / Tester[9]) as expect engine design to be very high bypass ratio

- Atmospheric attenuation, lateral attenuation and ground reflection corrections made based on ESDU data[10,11]

- No aircraft shielding or reflection corrections included

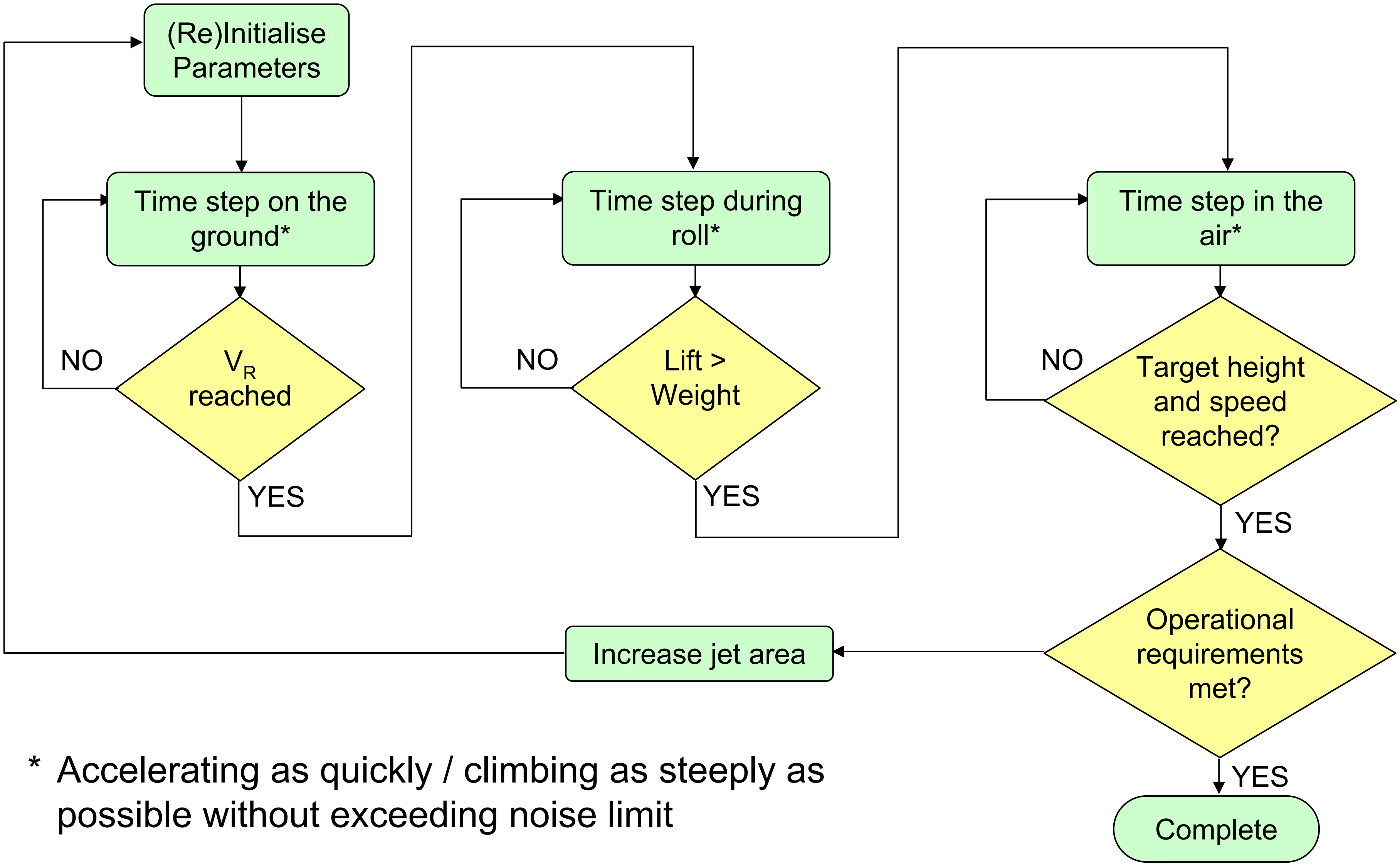
Aircraft Model



$$L + E_{num} T_N \sin\beta = mg\cos\theta$$

$$m\frac{dV_\infty}{dt} = E_{num} T_N \cos\beta - mg\sin\theta - D$$

Optimised take-off

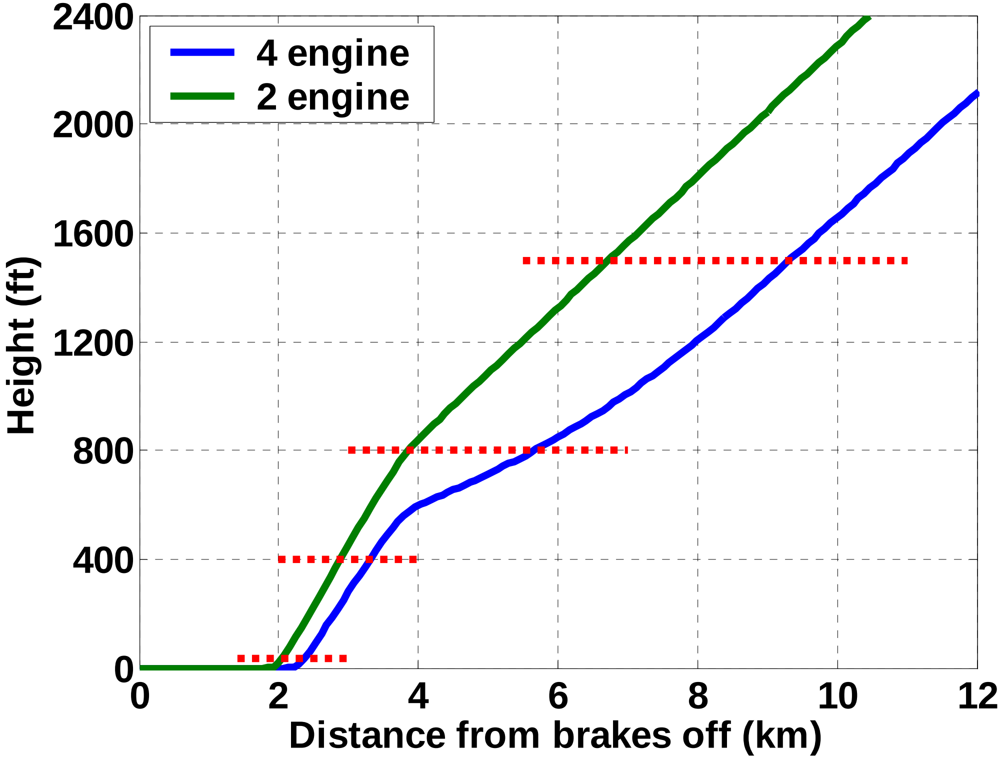


* Accelerating as quickly / climbing as steeply as possible without exceeding noise limit

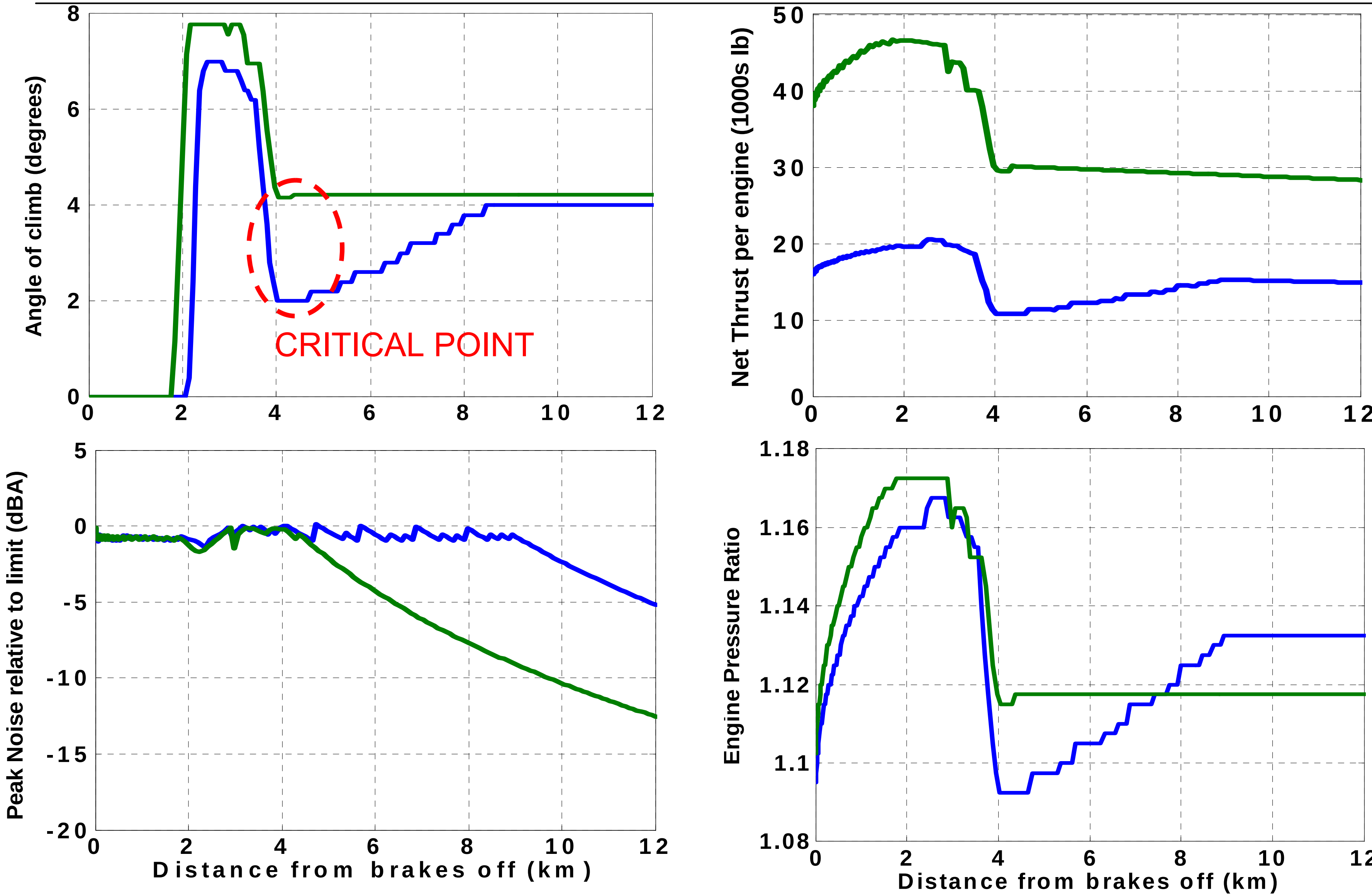
Baseline case

- TOW = 200,000kg
- L/D = 16
- V_r = 70m/s
- 2 & 4 engines variants

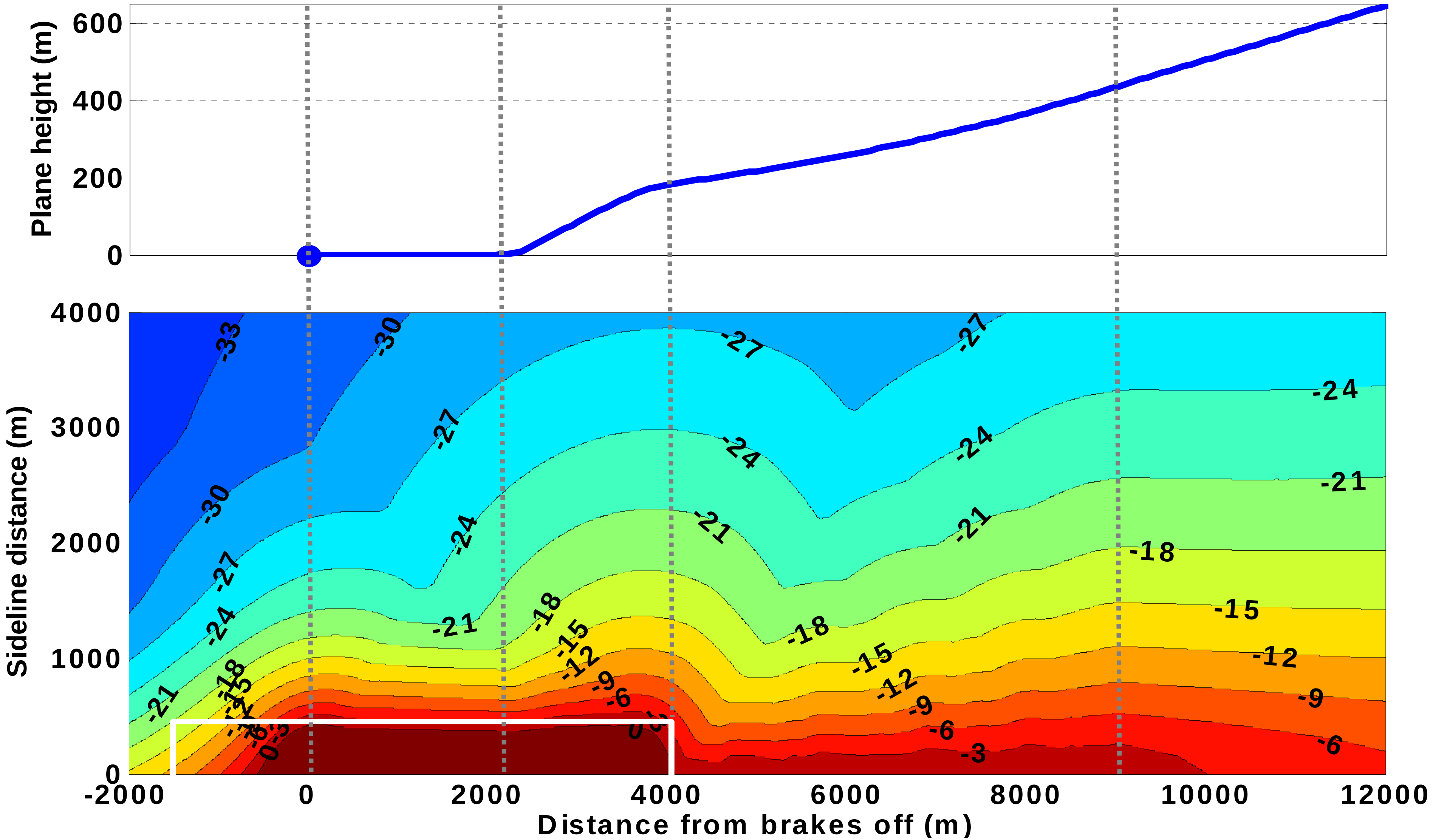
Total jet area of
- 17.4m^2 for 2 engines
- 15.6m^2 for 4 engines



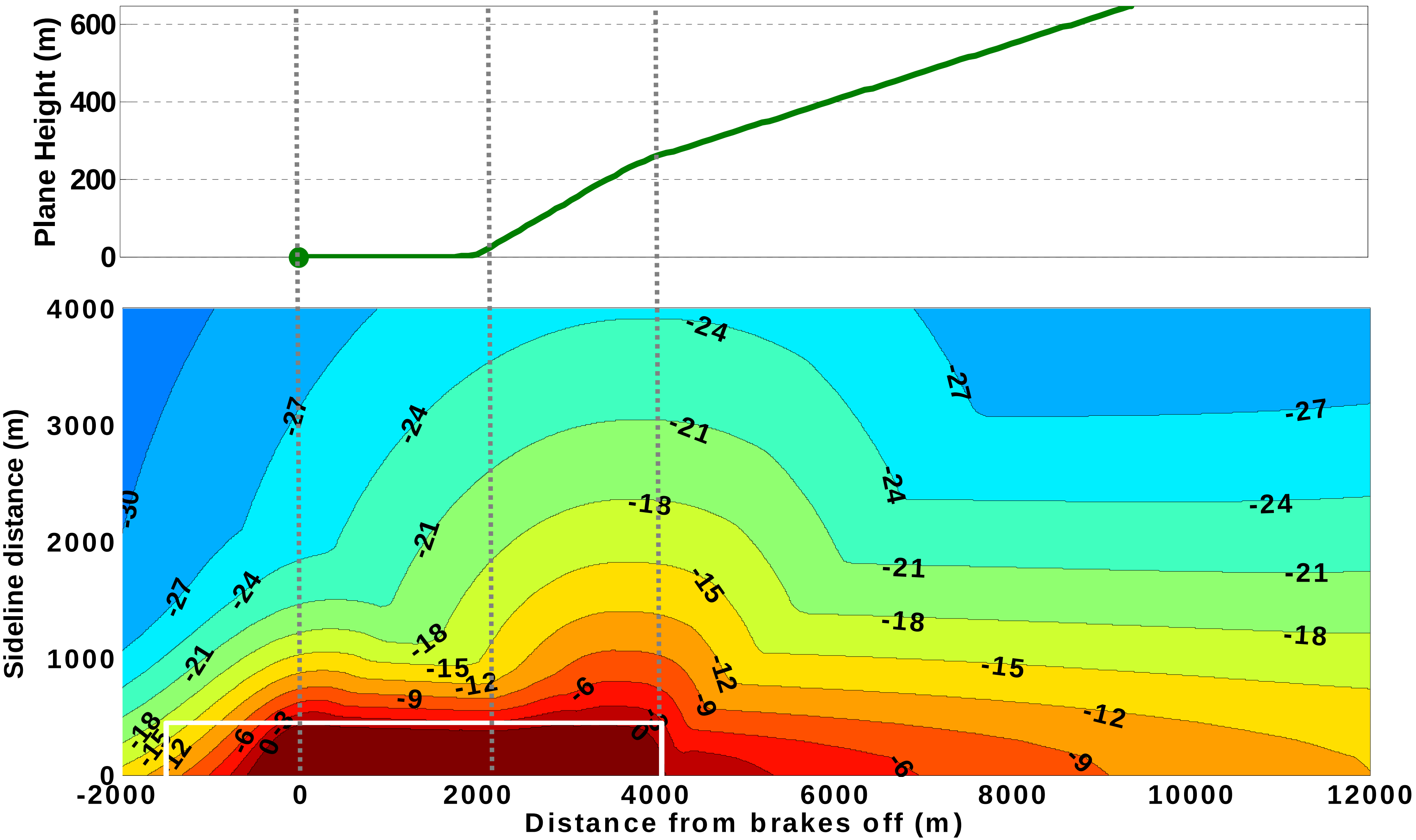
Baseline case



Peak jet noise contours on ground (dBA) – 4 engines



Peak jet noise contours on ground (dBA) – 2 engines



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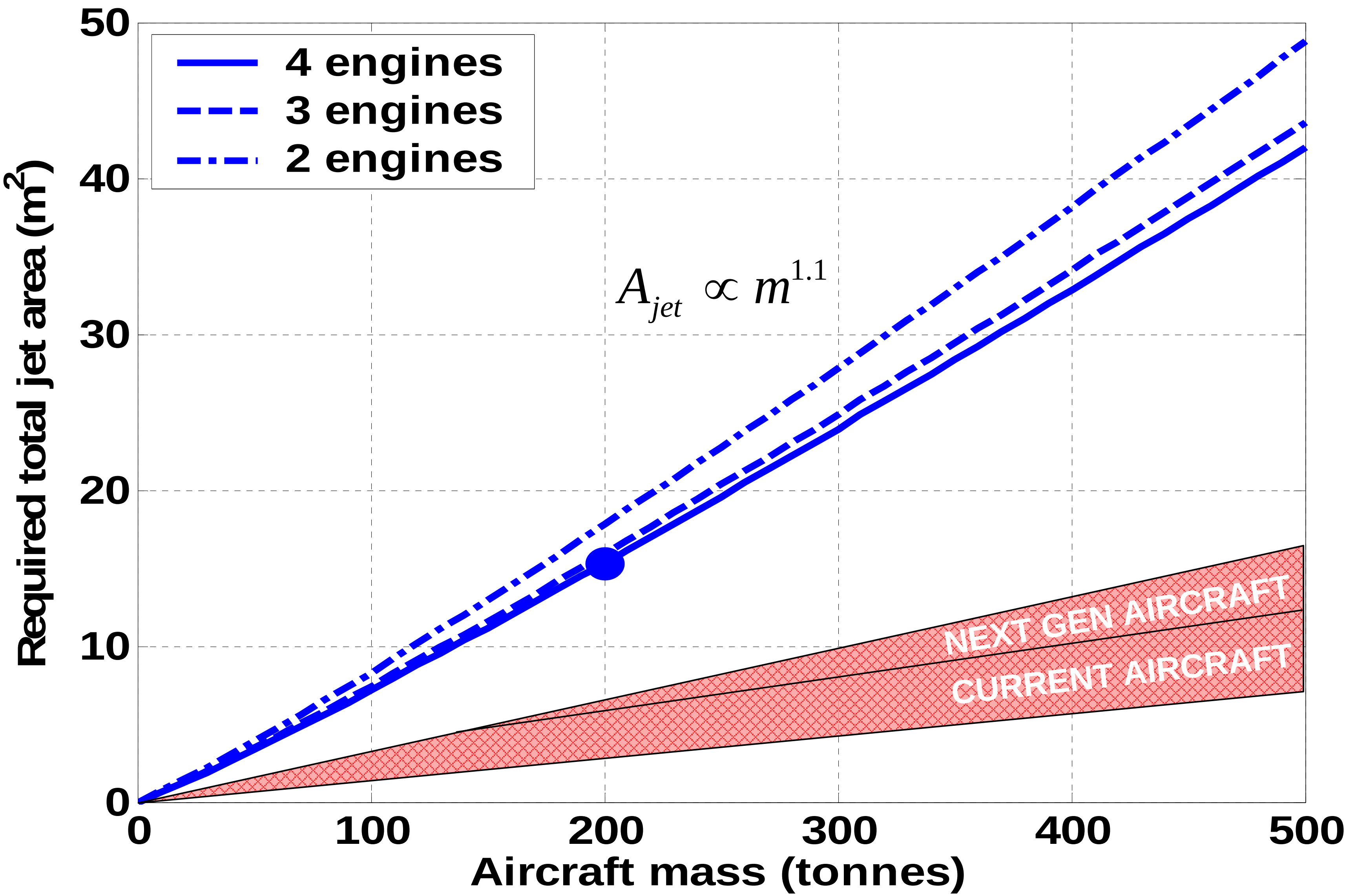
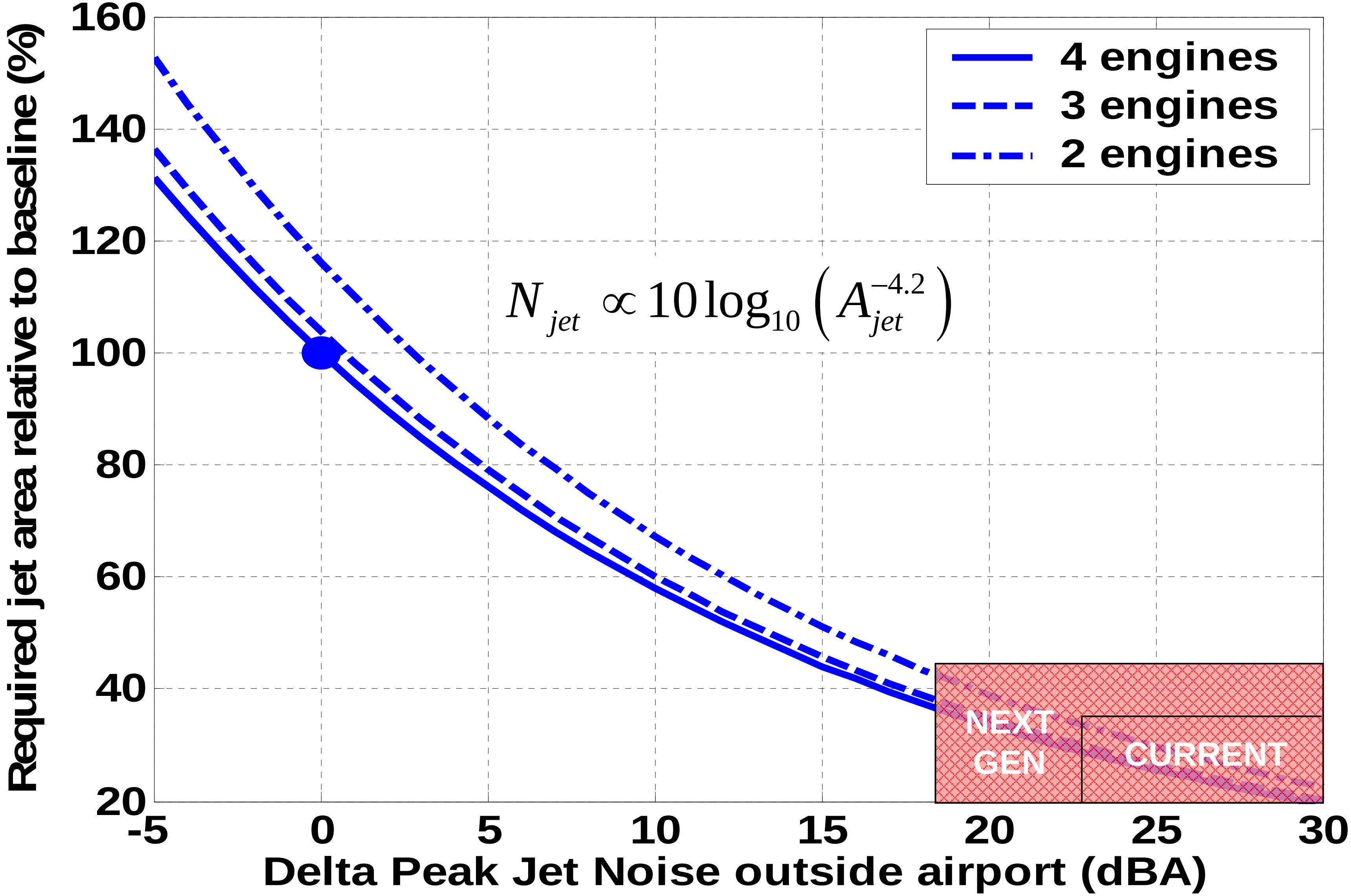
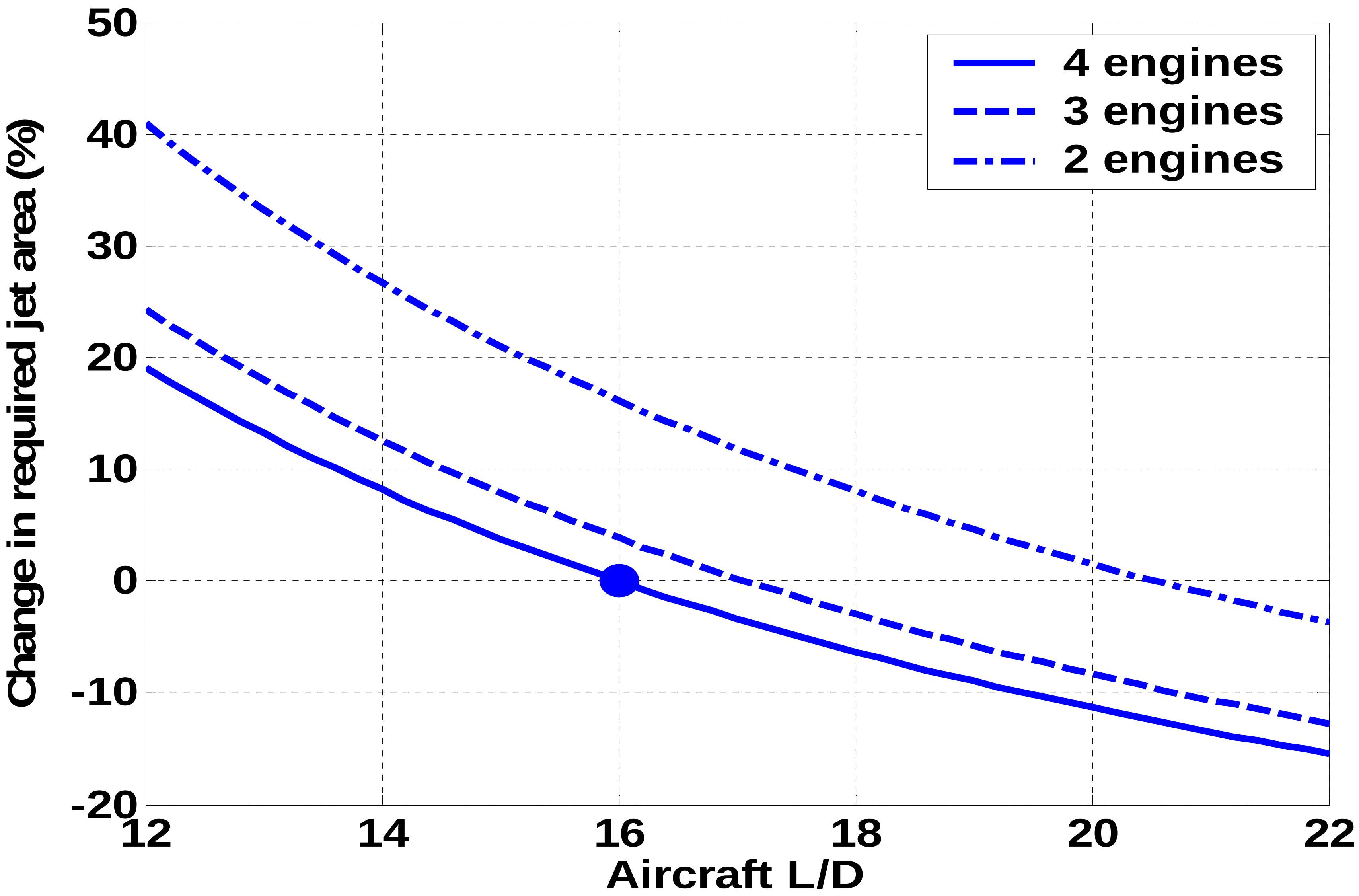
Variation with aircraft mass



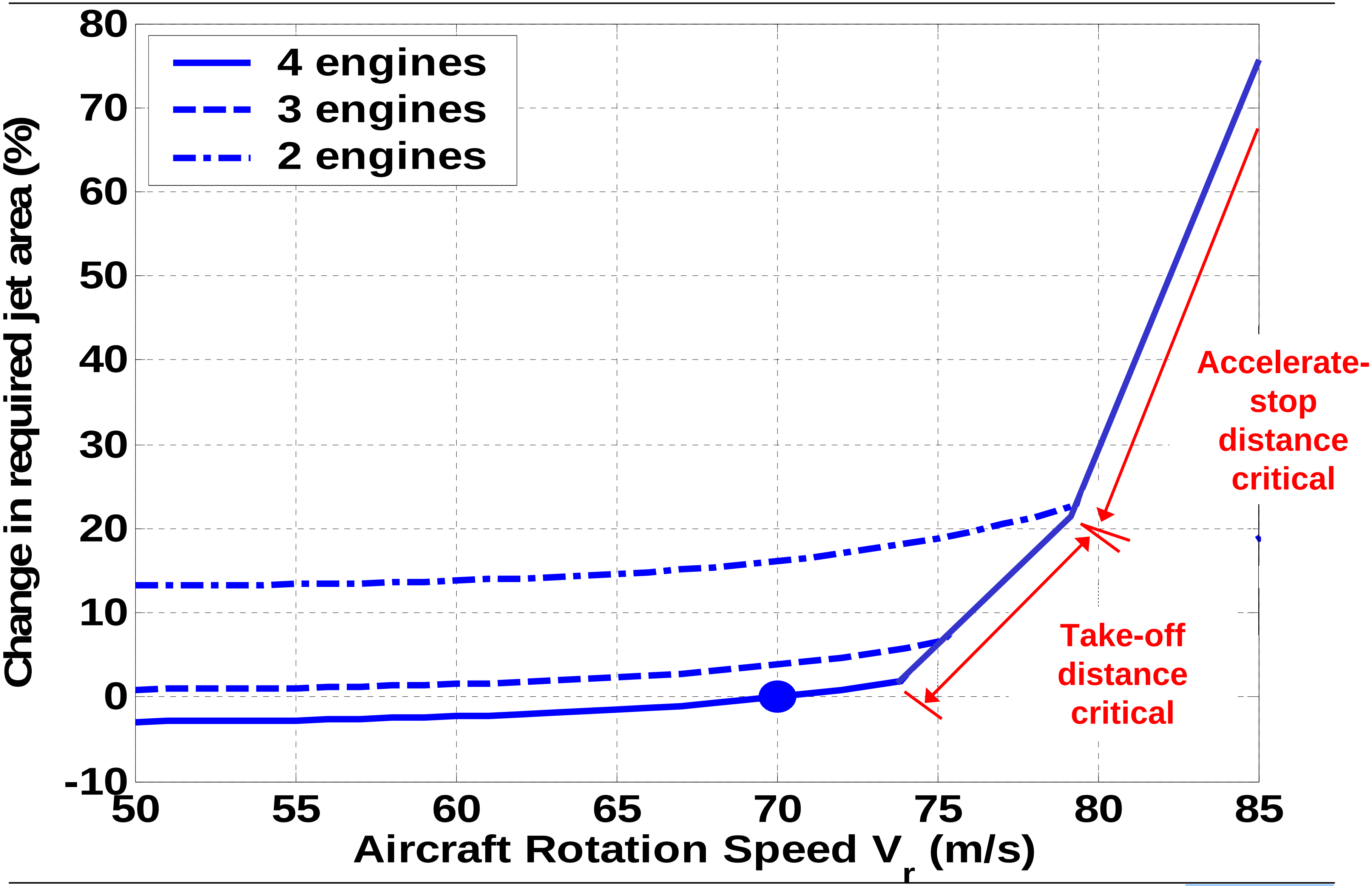
Variation with jet noise limit



Variation with aircraft L/D



Variation with aircraft take-off velocity



Impact on the engine

- For baseline aircraft (200,000kg, L/D=16), if jet area set to meet jet noise requirement for a fixed cycle engine

- For 4 engines;
  - A_{jet} = $3.9m^2$
  - ToC EPR = 1.23
  - ToC BPR = 28
  - Fan diameter = 2.6m

- For 2 engines;
  - A_{jet} = $8.7m^2$
  - ToC EPR = 1.20
  - ToC BPR = 32
  - Fan diameter = 3.9m

- This compares to a Fan Diameter of 2.8m and BPR of 11 for the Trent1000[12], two of which will power a 9% heavier aircraft[13].

- To meet take off jet area requirements whilst maintaining cruise efficiency requires innovative cycle designs.

Impact on the engine

To obtain an efficient cruise engine that is 'silent' at take-off requires variable cycle technology. Three areas under current consideration include;

- **Variable area nozzle**
  - Increases the BPR and lowers the overall pressure ratio
  - Moves fan working line away from stall.
  - Can be used during entire mission to optimise efficiency
- **Ejection**
  - Uses a high velocity jet from the engine to entrain additional fluid resulting in higher mass flow and lower overall velocity
  - Would require forced mixing to achieve significant benefit
- **Auxiliary fans**
  - Single core and fan for cruise attached to gearing to drive additional fans for take-off
  - Would allow large increases in BPR at expense of complexity and weight

Conclusions

- For the SAI with noise taken as the primary design parameter, jet noise reduction drives the engine cycle requirements.

- A 200,000kg aircraft with take-off L/D of 16 and V_r of 70m/s requires a total jet area of
  - 15.6m^2 for 'silent' departure if 4 engine
  - 17.4m^2 for 'silent' departure if 2 engine

  This is 2.5 to 3 times the area of equivalent current aircraft.

- For the range of parameters considered here, the min climb angle after cutback is the critical requirement for most cases. This results in different required jet areas and departure profiles for 2, 3 and 4 engine aircraft.

- At higher take-off speeds, take-off distance and then accelerate-stop requirements become critical.

- To achieve the required jet area without adversely impacting cruise fuel burn requires the application of variable cycle technologies such as variable area nozzles, ejection or auxiliary fans.

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References

[1] CMI SAI Launch Press Release, November 2003

[2] United Kingdom Meteorological Office, MIDAS Land Surface Station Data - Heathrow, 1989 to 1999 inclusive.

[3] JAA, "Joint Aviation Regulations section 25: Airworthiness Standards: Transport Category Airplanes"

[4] FAA, "Federal Aviation Regulations section 25: Airworthiness Standards: Transport Category Airplanes"

[5] ICAO, "PANS-OPS Volume 1 Part V : Noise Abatement Procedures"

[6] FAA, "AC 91-53A: Noise Abatement Departure Profiles," July 1993

[7] Stone, J. R. and F. J. Montegani (1980). An Improved Prediction Method for the Noise Generated in Flight by Circular Jets., NASA TM-81470.

[8] Garrison, L. A., W. N. Dalton, et al. (2004). On the Development of Semi-Empirical Noise Models for the Prediction of the Noise from Jets with Forced Mixers. 10th AIAA/CEAS Aeroacoustics Conference, Manchester, UK.

[9] Tester, B. J., M. J. Fisher, et al. (2004). A contribution to the understanding and prediction of jet noise generation in forced mixers. 10th AIAA/CEAS Aeroacoustics Conference, Manchester, UK.

[10] ESDU (1977). Evaluation of the Attenuation of Sound by a Uniform Atmosphere (78002)

[11] ESDU (1982). Estimation of Lateral Attenuation of Air-to-ground jet or turbofan aircraft noise in one-third octave bands (82027)

[12] http://www.rolls-royce.com/civil_aerospace/downloads/airlines/trent_1000.pdf

[13] http://www.boeing.com/commercial/7e7/facts.html

Equation of fit

With the critical angle after cutback being calculated as follows:

$$\theta_{\min(>400\,ft)} \approx \sin^{-1}\left(\frac{1}{1.11}\frac{N_{eng}}{N_{eng}-1}\left(\frac{1}{L/D}+\sin\theta^*\right)-\frac{1}{L/D}\right),\ \theta^* = \begin{bmatrix} 0.69^\circ\ (1.2\%)\ \text{if } N_{eng}=2 \\ 0.86^\circ\ (1.5\%)\ \text{if } N_{eng}=3 \\ 0.97^\circ\ (1.4\%)\ \text{if } N_{eng}\geq 4 \end{bmatrix}$$

Starting with the assumption that jet noise is a function of $V_{jet}(V_{jet}-V_\infty)$ and A_{jet}, rearranging for net thrust with added coefficients results in the following:

$$N_{jet} = 46.4\log_{10}\left[mg\left(\frac{1}{L/D}+0.5\left(0.1+\sin\theta_{\min}\right)+6\times10^{-20}V_r^{9.1}\right)\right]$$

$$-42.15\log_{10}\left(A_{jet}\right)-147.2$$

Rearranging for the required jet area gives:

$$\Rightarrow A_{jet} = \frac{\left[mg\left(\frac{1}{L/D}+0.5\left(0.1+\sin\theta_{\min}\right)+6\times10^{-20}V_r^{9.1}\right)\right]^{1.1}}{3107\times10^{0.0237N_{jet}}}$$