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R&D REPORT 9841

Review of the Departure Noise Limits at Heathrow, Gatwick and Stansted Airports: Effects of Take-off Weight and Operating Procedure on Noise Displacement

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SUMMARY

This study illustrates the nature and practical incidence of 'far-out noise displacement', a name given to the effect in which the cutting back of engine thrust to reduce noise close to an airport can increase noise further away. Although this effect is well known - e.g. ICAO specifies alternative operating procedures for reducing noise at different distance from the airport - it should not be a significant consequence of the proposed new noise limits. This is because a major influence upon departure noise at present is the common airline practice of minimising take-off thrust. If aircraft use more power to gain height as quickly as possible, which the proposed limits should encourage, there will be very little 'far-out displacement' relative to the noise of current operations.

Prepared on behalf of the Department of the Environment, Transport and the Regions by the Department of Operational Research and Analysis, National Air Traffic Services Ltd, March 1999

EXECUTIVE SUMMARY

Previous DORA studies of the noise monitoring arrangements at Heathrow, Gatwick and Stansted airports were performed to assist ANMAC and DETR in their review of the departure limits. The outcome of the review was a proposal to lower the limits, by day (0700-2300) from 97 dBA to 94 dBA and by night (2300-0700) from 89 dBA to 87 dBA. This report examines the issue of 'far-out noise displacement', a term given to the effect in which, in some circumstances, changes to aircraft operating procedures to achieve substantial noise reductions at the 6.5 km reference distance could cause some increases in lower level noise exposures at greater distances from the airport. The effect has been illustrated by calculating on-track noise levels, noise footprints and 'displacement maps'.

Only marginal 'noise critical' aircraft have been studied: five of the noisiest subsonic aircraft which are or have recently been operated by day at the London airports - principally early 'classic' variants of the Boeing 747. As demonstrated by the earlier DORA work, these are the types most likely to exceed the proposed daytime limit.

Far-out displacement has been illustrated elsewhere by IATA using a B747 example involving a particular change of operating practice - from a 'current' to a 'trial' procedure. But, in that example, displacement was largely a consequence of an assumed change in clean-up height which caused the aircraft to be lower during part of its climb; if the clean-up height were not changed, there would have been no on-track displacement. Simply reducing cutback height might cause noise increases: for classic B747s, it is confirmed that the single measure of cutting back at 1000 ft rather than 1500 ft (with no change to engine power settings) to reduce the 6.5 km 'Flyover Noise Level' causes displacement because, beyond the cutback, the aircraft is then lower in the sky.

More generally, a major factor affecting the noise caused by departing aircraft is the widespread practice of minimising take-off thrust. Because of reduced take-off thrust (often referred to as derated or flexible thrust) many aircraft are substantially lower as they pass 6.5 km than they would be after full (or higher) thrust take-offs. Actual TOWs cover a wide range and, although at or close to MTOW there may be little or no opportunity for improvement, increasing take-off thrust at lower TOWs offers significant potential for departure noise reduction. The proposed new noise limits should encourage shorter take-off and steeper initial climb which would generally reduce noise at the monitors

and all points beyond. The analysis indicates that this will rarely cause displacement in relation to current practice.

Under the Government's proposals, there would be two critical take-off weights. The first, a *noise-critical TOW*, is the highest weight at which an aircraft can depart and still, on average, be expected to meet the proposed new daytime noise limit at 6.5 km from SOR. The second is a *displacement-critical TOW*, the weight above which displacement can occur. In zero headwind at 15°C, nearly all aircraft types and models can meet the proposed limits at MTOW, the maximum take-off weight. For a few - older, heavy four-engined aircraft with relatively poor take-off and climb performance including Boeing 747 'classics' and hushkitted narrow body 4-jets - the noise-critical TOW is less than MTOW (in the worst case - a hushkitted DC8 - it is 94% MTOW). For these types, some limited far-out displacement could occur at weights between their noise-critical TOWs and their displacement-critical TOWs (which are all calculated to exceed 90%).

Graphs showing on-track noise gains and losses provide only limited assessments of the incidence of displacement near airports; off-track variations need to be accounted for. This has been illustrated for Heathrow, Gatwick and Stansted using 'displacement maps' based on relative Leq noise exposure contours, specially developed for this study; normal Leq(16-hr) contours could not be used. The displacement maps show that even the procedural change used in IATA's example causes very little displacement: the noise increases are confined to limited areas of relatively low exposure and are small - none exceeds 0.35 dB. In contrast, noise improvements are widespread and markedly greater, especially in areas of high noise exposure. Near the initial climb paths from the departure runways, there are Leq noise reductions of up to 2 dB.

And IATA's illustrative procedure can be improved upon. There is no evident reason why better procedures could not ensure uniform noise reductions beyond 6.5 km with only minor incidence of far-out displacement. For classic B747s, ICAO procedure B recommended for noise abatement near the airport, which requires flap retraction before cutback, does not appear to be effective due to long flap retraction times. For these aircraft it appears to be better to adopt a Modified ICAO Procedure A - maintaining take-off flap to 3000 ft before flap retraction and acceleration, but with cutback at 1000 ft rather than 1500 ft. The potential for improved noise abatement has been demonstrated by contrasting the IATA example with the Modified ICAO A procedure which, through a minor change, avoids any appreciable displacement - the increases being very localised and nowhere exceeding 0.2 dB; indeed they are generally less than 0.1

dB. It is clear from this comparison that the spatial distribution of displacement is very sensitive to the precise procedural changes concerned. It is concluded that, relative to current procedures, far-out displacement will, in practice, be a very diffuse and relatively insignificant consequence of the proposed new departure limits.

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GLOSSARY OF TERMS

ANCON	The DORA aircraft noise contour model.
ANMAC	Aircraft Noise Monitoring Advisory Committee.
Clean-up	Retraction of flaps to reduce drag together with associated increase of speed (acceleration) necessary to maintain lift.
Climb thrust	Sustainable engine thrust level selected after cutback; also referred to as cutback thrust. Maximum climb thrust is the maximum sustainable. A lower setting may be selected to reduce engine wear or to reduce noise. 'Normal' climb thrust is specified by the aircraft operators.
Critical Weight	Two critical take-off weights are defined: a noise-critical TOW above which, on average, the departure noise limit cannot be met and a displacement-critical TOW below which, on average, on-track displacement does not occur.
Cutback	Engine power (thrust) reduction made after take-off and initial climb.
Cutback thrust	See climb thrust.
DETR	Department of the Environment, Transport and the Regions.
DORA	Department of Operational Research and Analysis (of National Air Traffic Services).
Event level	The noise level caused by an individual aircraft pass-by, Lmax or SEL.
Exceedance	Any FNL which exceeds the Noise Limit.
FAA	Federal Aviation Administration (USA)
FNL	Flyover Noise Level: the noise level Lmax, in dBA, generated by an aircraft at the Reference Point.
Height	Height gained by aircraft since leaving the ground: all noise calculations in this report assume level ground at runway elevation.
IATA	International Air Transport Association.

ICAO	International Civil Aviation Organisation.
Infringement	Any Exceedance detected by the noise monitoring system. (To detect all Exceedances a noise monitor would need to be located vertically below every flight path. The percentage of Exceedances actually detected is referred to as the 'monitoring efficiency'.)
INM	Integrated Noise Model: the USA FAA aircraft noise contour model.
Leq	Equivalent Continuous Noise Level in dBA.
Lmax, LAmax	The maximum 'instantaneous' noise level, in dBA, that occurs during a noise event (measured using a 'slow' sound level meter setting).
(M)TOW	(Maximum) take-off weight (see footnote 1 to paragraph 1.3). (As it remains in common usage this has been used in preference to the more correct phrase 'take-off mass' of which tonne (= 1000 kg) is a unit.)
Noise limit	The noise level Lmax which departing aircraft are required to meet at the Reference Point.
NPD	Noise-power-distance relationship (table or curve).
NTK	The systems used at Heathrow, Gatwick and Stansted to monitor aircraft Noise and Track Keeping.
Reference Point	A point vertically below the flight path at runway elevation and a track distance (sometimes referred to as the reference distance) of 6.5 km.
SEL	Sound Exposure Level in dBA; a measure of noise event level which accounts for both the duration and intensity of noise. SEL is a 'building block' for Leq. (Numerically, SEL is typically about 10 dB greater than Lmax, although there is no consistent relationship.)
SOR	Start of roll, the point at which an aircraft starts its take-off run.
Take-off thrust	Engine thrust (power) set during take-off and initial climb (up to cutback).

Thrust setting	For clarity and simplicity, engine power or thrust levels are described throughout this report as being ‘set’ or ‘selected’ (by the pilot). In fact it is usually engine pressure ratios or rotational speeds that are set; together with the ambient air conditions these, in turn, determine power or thrust levels.
Track Distance	Distance measured along the ground track from SOR (i.e. not simply a straight line distance).

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1 INTRODUCTION

1.1 Previous reports (References 1 and 2) described DORA studies of the noise monitoring arrangements at Heathrow, Gatwick and Stansted airports that were performed to assist ANMAC and DETR in their review of the departure limits. The outcome of the review, the history of which is summarised in a DETR consultation paper (Reference 3), was a proposal to lower the limits, expressed in terms of Lmax, by day (0700-2300) from 97 dBA to 94 dBA and by night (2300-0700) from 89 dBA to 87 dBA. This report has been produced to provide further technical information on a specific issue in support of the DETR's continuing consultation process.

1.2 The issue is *'far-out noise displacement':* the process by which, in some circumstances, changes to aircraft operating procedures to achieve substantial noise reductions at the 6.5 km reference distance could cause some increases in lower level noise exposures at greater distances from the airport. By way of introduction to the main analysis, Section 2 starts with a brief examination of aircraft departure operating procedures and the way they affect noise levels below and adjacent to the aircraft flight path. Section 3 outlines the mathematical modelling techniques used to assess aircraft noise impact. The main analysis is described in Section 4 and uses current aircraft noise modelling methodology to calculate the dimensions of far-out displacement and the operational factors that influence it.

1.3 Related questions dealt with in Section 5 concern two *critical take-off weights*. The first, referred to as *noise-critical*, is the highest weight at which an aircraft can depart and, on average, still be expected to meet the proposed new daytime noise limit at 6.5 km from SOR. For nearly all aircraft types, this is the MTOW, the maximum take-off weight[1]. For a few types and models of aircraft and operating conditions the noise-critical TOW is less than MTOW. These are older, heavy four-engined aircraft with relatively poor take-off and climb performance, principally Boeing 747 'classics' (-100 and -200 models). The second weight is a *displacement-critical* TOW, the weight above which, on average, displacement can be expected to occur. Section 6 considers the practical incidence of displacement: when and where it might occur. This makes use of 'displacement maps' specially developed for this study. The conclusions are summarised in Section 7.

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[1] MTOW can be defined in various ways. The absolute maximum take-off weight for an aircraft, as advised by its manufacturer, depends on the precise specifications of its airframe and engines. But an operator might ask for a specific aircraft to be certificated at a lower weight; this would be its maximum certificated TOW, above which that aircraft would not be permitted to operate. Unless otherwise specified, this report refers to manufacturers' absolute MTOWs.

2 FACTORS AFFECTING AIRCRAFT DEPARTURE NOISE LEVELS

2.1 The noise level generated at any point on the ground by a passing aircraft (referred to here as *event level*) depends on numerous variables, principally upon the aircraft slant distance and elevation and the engine thrust or power settings at the time. Secondary factors of importance include the aircraft speed and attitude (its longitudinal and lateral 'tilt') and the atmospheric conditions - temperature and humidity, wind speed and direction (which affect aircraft height as well as sound propagation), and the presence of turbulence - and the way all these vary with height above the ground. As a rule, not all of these are known or predictable, and therefore all calculations or *predictions* of event level are subject to uncertainty - just as measured levels vary somewhat randomly between different flights of the same aircraft even when the operating conditions are nominally the same or very similar.

2.2 Techniques for predicting event levels rely on information describing the performance of aircraft and their engines. The engine thrust required depends upon the speed, weight, climb rate and 'configuration' (flap settings and undercarriage position) of the aircraft and the atmospheric state (i.e. the weather). All these vary along the flight path; thus event levels depend upon the 'history' of the aircraft motion from start-of-roll up to and beyond the point of interest.

Operating Procedures

2.3 Although operating procedures vary in detail, an aircraft departure can normally be divided into two main phases, (1) *take-off and initial climb* and (2) *continuing climb*. Phase 1 involves a high *take-off* power or thrust setting; in phase 2 a reduced or *cut-back* level is used[2]. The latter is usually the engines' designated *maximum climb power*. Power cutback is necessary because the extended use of take-off power would shorten engine life. Maximum climb power can be sustained for extended periods.

2.4 Wings generate greater lift at higher aircraft speeds. Wing flaps are deployed to increase lift at lower speeds, e.g. during take-off and landing. During take-off they shorten the ground roll and enable the aircraft to climb steeply to the cutback point. However, flaps also increase aerodynamic resistance (drag), which has to be overcome by using more engine thrust, and this increases noise emission. The

[2] The expressions 'cut back' and 'cutback' are sometimes used exclusively to describe greater-than-normal power reductions that are made specifically to minimise noise beneath the flight path. In this report, they relate to any and all power reductions made after the take-off and initial climb, whether modified for noise abatement purposes or not.

same is true of the extended undercarriage which adds greatly to drag; this is why it is retracted as soon as possible after lift-off. Thrust is usually cut-back at heights between 1000 and 1500 ft. In the UK, 1000 ft is the minimum permissible cutback height; 1500 ft is commonly used in situations where a lower cutback is not required for noise abatement reasons. Thereafter, during continuing climb, flaps are gradually retracted as speed is increased, a process referred to as 'clean-up'. In general, the thrust, flap angle, speed, turn rate and climb gradient are all inter-dependent, and the pilot can, to a degree, trade off one against another - e.g. exchanging height gain for increased speed or lower thrust[3]. But the ways in which the 'trade-offs' are made affect noise, fuel economy and other operating costs. This has long been understood by aircraft operators and detailed analyses are carried out to optimise the balance; see, for example, Reference 4.

2.5 Remembering that lift, drag and the performance of the engines also vary with the state of the atmosphere, which changes with altitude, it will be evident that predicting the flight profile - the way in which the factors that determine noise vary along the flight track - is complex. The noise generation mechanisms themselves are no less complex, and to predict overall departure noise patterns accurately requires a detailed knowledge of the characteristics and behaviour of the aircraft airframe and engines. In general, only the aircraft manufacturers have this information: noise performance, like fuel consumption and other operational performance indicators, is commercially sensitive information, affecting competitiveness.

Reduced, Flexible or Derated Take-off Thrust

2.6 The take-off distance or ground roll of a departing aircraft and its initial rate of climb is governed by the take-off weight (TOW) and engine thrust. The shorter the ground roll and the steeper the climb gradient, the sooner an aircraft reaches the power cutback point. At high aircraft weights, take-off engine thrust is set at or near to the maximum thrust available. If this maximum thrust setting is retained when an aircraft takes off at less than maximum weight, then the cutback point can be reached within a shorter track distance.

2.7 But, because more use of high engine thrust levels increases maintenance costs, operators prefer to reduce the level of take-off thrust as much as possible. Depending on the facilities available for its implementation, this common practice is referred to as using *reduced*, *flexible* or *derated* thrust. At lower TOWs, thrust can safely be reduced to the point at which the take-off profile, including the

[3] Climb thrust settings can be varied for noise abatement purposes. For the London airports the UK AIP specifies a minimum gradient of 4%; sufficient thrust must be maintained to achieve this.

position and height of the cutback point, is essentially the same as that at maximum take-off weight and thrust. But this means that the aircraft is lower than it might otherwise be and, at least beyond the cutback point, noisier at ground level. The power used for continuing climb might also be set to less than the maximum climb thrust rating. In this report, *flexible thrust* is generally taken to be proportional to take-off weight.

Noise abatement operating procedures

2.8 Reference 5, the ICAO 'PANS-OPS' document giving guidance on aircraft operations, describes two noise abatement take-off procedures, A and B, which it states "have been designed to minimise the overall exposure to noise on the ground and at the same time maintain the required levels of flight safety". It further states that "Procedure A results in noise relief during the latter part of the procedures whereas Procedure B provides relief during that part of the procedure close to the airport. The procedure selected for use will depend on the noise distribution required and the type of aeroplane involved".

2.9 Procedure A involves climbing at take-off power and flap setting to 1500 ft where power is then cut back to maximum climb thrust, but maintaining take-off flap setting until 3000 ft is reached. Beyond that, the flaps are retracted as the aircraft accelerates to a higher speed to continue its climb. Procedure B differs in that flap retraction is initiated at a height of 1000 ft, while the engines are still at take-off thrust. The aircraft then 'pitches over' to a lower climb gradient and accelerates to a higher speed before thrust is cut back. If the flaps retract slowly, the cutback may made while the flaps are at an intermediate angle.

2.10 As a third option, Reference 5 advises that, when neither procedure A nor B is appropriate, a special procedure may be developed provided it meets certain specified limitations. These include a minimum cutback height of 1000 ft, a climb gradient of at least 4% and the assumption that *"before reaching the noise-sensitive area the aeroplane will climb at maximum gradient ..."*

2.11 Neither of the ICAO recommended procedures, nor any other, is mandatory in the UK. Procedures are specified by individual airlines to meet their own operational requirements as well as those of the aircraft manufacturers and the relevant safety regulators. For each of its aircraft types, an airline normally defines one or more such procedures in the aircraft operating manual.

2.12 Various operating procedures are considered in this report, including those recommended by ICAO. To enable these to be readily compared, their key features are summarised below:

	ICAO A	ICAO B	'Current'[a]	Modified ICAO A	IATA trial
Take-off thrust	Normal[b]	Normal[b]	Flexible[c]	Full	Full
Cutback height[d], ft	1500	After clean-up[e]	1500	1000	1000
Climb thrust[f]	Normal[g]	Normal[g]	Maximum[h]	Maximum	Maximum
Clean-up height[i], ft	3000	1000	3000	3000	2000
See paragraph:	*2.8*	*2.8*	*4.2*	*4.4*	*4.8*

Notes:

a) Assumed typical current practice - a baseline against which alternative (noise abatement) procedures are compared.

b) "Normal" take-off thrust is not specified.

c) Flexible thrust is taken to be proportional to TOW.

d) Height at which thrust is reduced from take-off to climb setting.

e) Clean-up is initiated at 1000 ft and completed when climb flap and speed are reached.

f) Climb (cutback) thrust setting is assumed to remain constant during period of relevance to noise footprints.

g) "Normal" climb thrust is not specified.

h) Maximum continuous climb thrust.

i) Height at which flap retraction and associated acceleration is initiated.

3 CALCULATION OF NOISE LEVELS: NOISE MODELS

Noise Contour Methodology

3.1 The aircraft industry, with assistance from the aeronautical research establishments, has developed advanced mathematical models for the design calculations that ensure new aircraft meet the noise certification standards. These use elaborate scientific theory to account in some detail for the complex physical processes that contribute to aircraft noise generation, radiation and propagation in various phases of flight. However, the mathematical methods are generally too complex for use in practical, efficient noise contour models; moreover they make use of information that is proprietary to the manufacturers.

3.2 Airport noise contour models and their supporting data are, on the other hand, comparatively limited; they incorporate considerably simplified descriptions of the noise generation and propagation processes. They have various origins. Some have been devised empirically - relying on observations and measurements of actual aircraft performance and behaviour at airports; others use basic aircraft performance theory underpinned by representative data which manufacturers have been willing to release. An important tool in the latter category is the Integrated Noise Model (INM), a computer program developed, maintained and released for public use by the USA FAA (Reference 6). Its applicability is for generating aircraft noise exposure contours around airports. As such, it is the most widely used airport noise contour model.

3.3 The methodology that underpins INM and other similar aircraft noise models, including DORA's own model ANCON (Reference 7[4]), was compiled, published and is kept under review by the Society of Automotive Engineers (SAE), a USA technical standards-making body supported by the automotive and aviation industries world-wide (Reference 8). The same, or very similar, methodology is also documented in guidance material published by ECAC and ICAO (References 9 and 10).

Aircraft Noise and Performance Data

3.4 References 8 to 10 provide guidance on the generation of flight profiles; the means for doing this is embodied in relevant computer software. The performance of the aircraft is described by a number of aircraft and engine performance coefficients. For any flight, the profile is made up of a number of essentially straight line segments: for departures the flight procedure is specified in terms of weight and end-of-segment thrusts, heights, speeds and flap settings. The noise footprint for the flight is then calculated from this profile, via noise levels at specific points on the ground surface, using so-called Noise-Power-Distance (NPD) curves which give the noise levels as functions of engine power setting and slant distance from the aircraft.

3.5 However, the published SAE, ECAC and ICAO noise calculation procedures do <u>not</u> include the basic data that are required to implement them; only the data requirements. The data normally have to be obtained from the aircraft manufacturers. The USA INM, which incorporates the internationally accepted guidance, is supplied with its own database compiled from industry sources. Like the computer model itself, this is maintained by the FAA. For each of a number of

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[4] Reference 7 describes Version 1 of ANCON. Subsequent upgrades to the model are described in R&D Report 9842: *The UK Civil Aircraft Noise Contour Model: Improvements in Version 2* which will be published shortly.

different aircraft types and models, it includes data describing the airframe lift and drag characteristics in different flight configurations, engine thrusts and their variation with height, speed and atmospheric conditions. The accompanying NPD curves are derived by the manufacturers, usually from data collected as part of the aircraft noise certification process.

3.6 Clearly, both the quality and quantity of all these data are crucial to the accuracy of the methodology. The INM database (basically the only public repository for industry data) covers a relatively limited number of aircraft types and variants. Also, much of it dates from the 1970s and so may not be representative of current in-service circumstances. Hence, despite its unique industry-endorsed status, the INM database cannot be regarded as a complete source of fully comprehensive and reliable information on aircraft noise characteristics.

3.7 DORA uses both the INM and ANCON to calculate aircraft noise levels. Given the same input data, the INM and ANCON produce equivalent results. DORA uses data compiled from various sources, and also participates in various international activities aimed at validating and improving noise contour methodology and reviewing and updating available data. In performing the calculations described below, DORA made use of the current (Version 5) INM database. It is important to validate predictions by reference to actual measured data wherever possible, so DORA therefore makes comparisons of predictions with measurements made around UK airports on a continuing basis and, for individual types, makes adjustments to the ANCON database accordingly. Even though some adjustments to absolute levels become necessary as additional measured data become available, particularly where new types are concerned, ANCON and other similar models like INM are sufficiently accurate for predicting the *changes* in noise level caused by modifying operating procedures.

3.8 Noise models such as ANCON and INM are generally used to produce average contours of noise exposure arising from all the flights at an airport. For a single movement of a single aircraft type operated in a specific way, the resultant contour is termed a 'footprint'. In this report, SEL, Sound Exposure Level, has been used to depict footprints because (i) it is the fundamental building block of Leq (used later in the report), the primary aircraft noise exposure measure modelled by ANCON, and (ii) it provides more realistic footprints for individual aircraft movements because it integrates noise energy emitted from all significant parts of the flight path. (SEL does not exhibit the sudden changes which characterise Lmax diagrams.) Although there is no unique conversion, SEL values are usually some 10 dB greater than Lmax values for the same events.

4 CAUSES OF DISPLACEMENT

Two kinds of displacement

4.1 During the departure limits consultation process, the expression 'displacement' has been used to describe two different processes by which, in some circumstances, noise-abatement operating procedures can cause noise increases as well as decreases, effectively 'displacing' noise from one point to another. 'Close-in displacement' refers to increased noise in the immediate vicinity of the aerodrome caused by using higher take-off thrust levels to shorten the take-off run and steepen the initial climb. 'Far-out displacement' describes a possible effect of taking action to reduce noise as soon as possible after leaving the runway. If this involves cutting back sooner and/or cutting engine thrust more deeply so that, further along the flight track, the aircraft is lower than it would otherwise have been, it might generate higher noise levels on the ground. This effect is well understood; for example, it is implicitly recognised in the ICAO guidance of Reference 5 that, other things being equal, switching from Procedure A to Procedure B would normally cause far-out displacement, i.e. to reduce noise 'close-in' at the expense of some increase 'far-out'[5].

Illustration of 'far-out' displacement

4.2 This section assesses the occurrence of 'far-out' displacement by calculating the noise levels generated by the noise abatement procedure and comparing them with those of an existing 'baseline' procedure. The question of whether or not particular operating procedures are likely to achieve compliance with the proposed noise limits is not considered until Section 5. Much use is made of an example chosen by IATA in Judicial Review evidence (Reference 11) to illustrate displacement in relation to a current B747 operating procedure. As defined in Reference 11, the IATA 'current procedure' is very similar to ICAO A - the far-out operating procedure described in Reference 5 - using reduced take-off thrust (see paragraphs 2.8 to 2.12) - which is widely used by B747 operators at the London airports and elsewhere. Of course, different airlines use different procedures and, for example, a recent conference paper, Reference 12, describes current British Airways practice somewhat differently; as ICAO B rather than ICAO A. However, as an objective here is to throw more light on the nature of 'far-out displacement'

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[5] It is important not to confuse close-in and far-out displacements with the close-in and far-out noise reductions obtained through the use of ICAO procedures A and B (see paragraph 2.8). By comparison with that of close-in noise reduction, the area of close-in displacement could be termed 'very close-in'.

as illustrated by IATA in Reference 11, in what follows, a general definition of 'baseline' current practice is adopted. This is ICAO A as defined in paragraph 2.12, with flexible take-off thrust assumed to be proportional to TOW (e.g. at 90% MTOW, thrust = 90% of maximum available thrust) and maximum continuous climb thrust after cutback.

4.3 The highest noise levels along the path of an overflying aircraft generally occur on the flight track itself, the line of flight projected vertically onto the ground surface. One relatively simple way of examining the overall effects of changed operating procedures upon noise is thus to look at the variation of noise along the flight tracks. Another is to consider noise footprints or contours which indicate changes to the side as well as on the flight tracks themselves. Both methods are used here for departures of 'noise critical' 4-engined Boeing 747 aircraft types; specifically the -100 and -200 series models, sometimes referred to as B747 'classics'[6].

Far-out displacement caused by reducing cutback height

4.4 It has been noted that the IATA 'current procedure' as defined in Reference 11 - with a 1500 ft cutback - closely matches the description of ICAO Procedure A, intended for far-out noise reduction. It might be expected that adoption of the alternative ICAO Procedure B, which provides for noise abatement action at 1000 ft rather than 1500 ft, would be the appropriate measure to reduce noise close in at the 6.5 km reference point. In fact, as will be seen in paragraphs 5.7 - 5.9, Procedure B is usually ineffective for reducing close-in noise of classic B747 aircraft because of their long flap retraction time. For these aircraft a more effective option is simply to lower the cutback height from 1500 to 1000 ft, keeping other aspects of the procedure the same - this alternative is referred to here as *Modified Procedure A or Mod A* (see paragraph 2.12). This procedure has been recommended by Boeing for 747 close-in noise reduction (see Reference 2, para 6.11 where, following Boeing's terminology, it was referred to as a modified Procedure B[7]).

4.5 Some effects of this option - applied as a single measure - are illustrated, for B747-100 departures with flexible take-off thrust, in Figure 1. This shows a series of

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[6] The following aircraft have been selected from the INM database (engines in parentheses): Boeing 747-100 (PW JT9D-7), Chapter 2 Boeing 747-200 (PW JT9D-7) and Chapter 3 Boeing 747-200 (PW JT9D-7Q). The INM database provides no alternative choice of engine for the Chapter 2 Boeing 747-200. However, the engine most widely used on that B747 variant is the PW JT9D-7J. Published data [*Aircraft Characteristics*, Marketing Communications and Support, Pratt & Whitney, June 1995] lists the -7J engine with a static thrust of 50,000lb compared with 45,500lb for the -7 engine. In order to model the Chapter 2 747-200, the maximum takeoff thrust coefficient in the INM database was increased to reflect more closely the -7J characteristics. Maximum climb thrust coefficients remain unchanged.

[7] Both descriptions are justifiable but the modified procedure more closely resembles ICAO A.

graphs which plot, for various TOWs, the changes in event SEL along the flight track caused by reducing the cutback height from 1500 to 1000 ft[8]. The 'close-in' benefits of the lower cutback appear as 'dips' in the graphs with maximum SEL reductions of around 1 dB. Further out, SELs increase because the height is less after the lower cutback; thus a clear consequence of this single measure is a displacement of noise, from near-in to far-out; i.e. there are both benefits and disbenefits.

4.6 The benefits are seen to be small and very localised; they occur between about 6 km and 9 km from SOR. In each case, the dips start and end roughly at the positions of the two different cutback points (at heights of 1000 ft and 1500 ft). Under flexible take-off thrust procedures, the take-off distances and climb gradients change little with TOW so that the positions of the cutback points relative to the runway are virtually unaffected. But because, for Figure 1, constant climb thrust has been assumed (after cutback), the depth of thrust reduction diminishes as TOW falls; indeed, at 85% MTOW the cutback all but disappears. Thus the 'dips' become smaller, as does the amount of displacement.

Effects of changing take-off power as well as cutback height

4.7 In short, for these rather poor climbing B747 aircraft, simply reducing cutback height from 1500 ft to 1000 ft, whilst keeping the flight configuration including engine thrust settings the same, brings small benefits close in at the expense of increased noise further out - the effect described as 'far-out' displacement. But this is <u>not</u> what the Government's proposed new noise limits are intended to encourage; indeed Figure 1 illustrates a condition to be avoided wherever possible. What is required is to minimise noise through an expeditious combination of higher take-off thrust and optimum cutback.

4.8 Figures 2 and 3 show, using the two methods referred to in paragraph 4.3, the calculated noise consequences of making more than one change to a departure operating procedure. The example is the one used by IATA in Reference 11. The aircraft is the B747-100 at TOW = 311 tonnes (93% MTOW), in conditions of zero headwind, 15°C[9], and the analysis compared a 'current procedure' and a 'trial procedure' defined as follows (see also paragraph 2.12):

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[8] The small ripples in the graphs (in Figure 1 and similar subsequent diagrams) result from a computational discontinuity in the INM algorithms. These are of no consequence in normal contour calculations as they are normally 'averaged out'.

[9] Aircraft take-off and climb performance are dependent on the density of the air which in turn is a function of its temperature and pressure. As air density parameters are not customarily quoted in studies like this, in this report atmospheric state is mostly given in terms of temperature only, a standard pressure of 1013 mbar being assumed.

Procedure	'Current'	'Trial'
Take-off thrust	5% derate	full
Cutback height, ft	1500	1000
Clean-up height, ft	3000	2000
Climb thrust	Maximum	Maximum

The 'current' procedure in this example uses reduced take-off thrust that is not quite weight-proportional according to the definition of 'fully flexible' thrust given in paragraph 2.7: the thrust reduction is 5% whereas the weight is 7% less than MTOW. The 'trial procedure' uses full take-off thrust (rather than a 5% derate) and cuts back and accelerates at lower heights.

4.9 The results presented here, like IATA's, are based on aircraft noise and performance data supplied with INM Version 5, a difference (apart from the choice of NPDs[10]) being that the levels are expressed in dBA SEL (the noise unit used by ANCON) rather than dBA Lmax[11]. The flight tracks are taken to be completely straight. In each diagram, the horizontal axis is distance along the flight track from start of roll - starting 4000m from SOR.

4.10 Figure 2a compares the *on-track noise levels* for the IATA 'current' and 'trial' procedures at track distances (from SOR) up to 40 km. Figure 2b shows the differences in level between the two cases, i.e. 'trial' less 'current', the change that would be caused by switching from the 'current' to the 'trial' procedure. It indicates that the switch causes the predicted noise to fall by 1 to 2 dB between 4 and 11 km but that there are small increases (less than 0.5 dB) between 11 and 20 km and that, beyond 20 km, the trial procedure is again less noisy.

4.11 Figure 3 overlays the two sets of corresponding *noise footprints* - lines of constant event level drawn at intervals of 5 dB from 80 to 100 dBA SEL. Inspection of this diagram reveals areas where changing to the trial procedure causes the footprints to expand - reflecting increasing noise level - as well as others where they shrink because of falls in level. In particular, at 100 and 95 dBA SEL, the 'trial' footprints are smaller than the corresponding 'current' ones, but the opposite is true at 90 dBA SEL. This is consistent with changes apparent in Figure 2; both diagrams illustrate a displacement effect - Figure 2 shows it occurs at points where SELs lie in the range 87 - 92 dBA approximately. But it may be seen that in the

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[10] The diagrams presented by IATA appear to have been based on NPD information for the earliest version of the B747-100 which did not meet certification standards. These aircraft were subsequently modified; the later NPD curves gave levels approximately 4dB less. This difference does not affect the predicted occurrence of displacement (only the noise levels at which it occurs), and the comparable illustrations used here are based on the updated NPD information.

[11] IATA presented Lmax footprints.

displacement region, 11-20 km from SOR, where on-track levels increase slightly, the outer footprints shrink; i.e. away from the flight track, event levels are lower under the trial procedure.

4.12 Further analysis reveals that this on-track displacement results entirely from reducing the flap retraction/acceleration height from 3000 ft to 2000 ft (see paragraph 4.8). The height profiles, the variations of height with distance from start of roll for the IATA 'current' and 'trial' procedures as well as 'modified procedure A' (see paragraph 4.4) in which the 3000 ft acceleration height is retained, are compared in Figure 4(a) (Figure 4(b) is explained below). This shows that, relative to the 'current' procedure, the 'trial' procedure causes a marked reduction in height between about 11 km and 29 km from SOR.

Effects of increased take-off power alone

4.13 The IATA evidence (Reference 11) did not explain the need for the change of 'clean-up' height, which complicates the comparison. Figure 5 shows that, when the 3000 ft acceleration height is retained in the 'modified trial procedure', on-track displacement is entirely eliminated, principally as a result of the greater height beyond the current 1500 ft cutback point. Indeed, Figure 5 shows precisely the kind of improvement the proposed new limits are expected to encourage - a general reduction of noise beyond the monitor points. This was stated in Reference 3, paragraph 21, although it was recognised that there will be some noise increases close to the runway due to the use of higher take-off thrust: *"In general, for aircraft that can meet the noise limit, it is likely there would be very little 'far-out' displacement, relative to current practice, if more take-off thrust were used, thus achieving greater height at all points along the track."* In fact, there are probably many circumstances in which noise infringements could be avoided altogether by making no change other than using higher take-off thrust. This is because, for aircraft powered by high bypass ratio engines, the noise benefits of height gain can outweigh the disbenefits of increased thrust[12]. Again

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[12] Reference 12 presents the results of a recent British Airways/Heathrow Airport Ltd. study of noise abatement operating procedures for three models of Boeing 747 aircraft. In a trial involving a large number of departures from Heathrow Airport the investigators compared the noise generated by three different take-off procedures. Two of these were designed to reduce noise, by cutting back power at heights of 1000 and 1500 ft respectively. These were compared with the airline's current standard practice - stated to have been designed "to maximise aerodynamic efficiency independently of noise considerations" - and which uses no more power than is necessary for a safe take-off. Noise levels were measured at various points along the flight track - at 4.6, 6.7, 10.5 and 12.3 km from SOR. It was concluded that although, for all B747 models, the 1000 ft cutback reduced significantly the average noise levels at the 6.7 km position used in the trial, this improvement was not maintained further out; for the two older models noise levels could be higher at 10.5 and 12.3 km. The 1500 ft cutback procedure showed the reverse; a noise increase at 6.7 km but reductions further out. However, it is important to note that the trials did *not* examine the benefits of raising take-off power - a crucial factor affecting aircraft departure noise. The benefits would depend on the take-off weights of the aircraft. These were not quoted but using greater power

using the IATA illustration as an example, Figure 4(b) shows that, relative to the 'current' procedure (c.f. Figure 4(a)), height could be increased everywhere simply by restoring full take-off thrust (i.e. from 95% to 100%).

Separate effects of take-off power and cutback height

4.14 Figures 6 (a)-(c) show the changes in B747-100 noise level calculated to occur at different TOWs (expressed as a % of MTOW) when take-off thrust is increased from flexible (proportional to TOW) to full - whilst retaining the same ICAO A cutback procedure (1500 ft). At (a) 100% MTOW, there is no effect because full thrust must be used anyway (but see the end of paragraph 4.16). At all reduced TOWs, full thrust gives lower noise at *all* points beyond 4 km from SOR: and the improvement increases as the TOW falls from (b) 95% to (c) 90% to (d) 85%. Figures 7 shows, for the 90% MTOW case only, that similar benefits are also obtained for Chapter 2 and Chapter 3 variants of the B747-200 (cf. Figure 6(c)).

4.15 The added effects of reducing the cutback height, as well as restoring full take-off thrust, are shown for the B747-100 in Figures 8 (a)-(d). Here the procedure is switched from flexible thrust ICAO A with cutback at 1500 ft (the current procedure) to Modified Procedure A (para 4.4) with full take-off thrust and cutback at 1000 ft. At 100% MTOW, Figure 8(a), no thrust increase is possible and the lower cutback height causes marked displacement. Only small benefits are obtained - and only at distances less than about 9 km from SOR; beyond that point, because of the reduced climb gradient, noise levels rise. However, small TOW reductions change the outcome[13]. At 95% MTOW, Figure 8(b), although there is still a small displacement effect beyond about 9 km, there is no worsening beyond about 12 km. At 90% and 85% MTOW, Figures 8 (c) and (d), noise lessens at all points out to at least 40 km (the extremity of the diagram).

4.16 Figures 9 and 10 show similar results for the Chapter 2 and Chapter 3 versions of the 747-200. Again, at the lower TOWs shown (and at still lower ones) there is no

whenever possible would often cause aircraft to leave the runway sooner and reach greater heights before reaching BA's 6.7 km measuring position, not only further reducing average noise levels there but also lessening them at all points beyond.

[13] In evidence submitted to the Court on behalf of DETR in relation to legal proceedings [the first affidavit of John Bruce Ollerhead: 3 March 1997, para 27 - available for inspection at the DETR Information Centre as described in para 75 of Reference 3], it was stated that "reducing TOW is a very inefficient way to reduce noise". This relates to the fact that although a heavier aircraft will emit more noise and/or climb less steeply, the effect is relatively small; regression analysis described in Reference 2 showed, for B747s (-100, -200 and -400 models), a mean dependency of less than 0.1 dB per tonne at the Reference Point. The statement is true in relation to average noise levels of a substantial number of departures or, for two specific flights, when comparing like with like - i.e. no change of thrust setting. However, because of the minimum safe cutback height constraint, there could be some circumstances in which an increase in TOW could delay the completion of cutback until after the Reference Point. In this special situation, the noise level would remain somewhat higher for a short distance until thrust could be cut back.

displacement. Recalling also Figure 7, the use of full take-off thrust at lower TOWs reduces noise levels with both 1500 ft and 1000 ft cutbacks. It is evident from the analysis that, for B747 classics, increasing take-off power has a beneficial effect on far-out noise in contrast to that of reducing cutback height which, through displacement, increases it. However, these analyses have considered displacement in isolation; to meet noise limits at 6.5 km, take-off weight may have to be taken into account when selecting cutback height, as will be seen in the next section.

4.17 This section has described circumstances in which displacement can occur. The important practical questions are: (1) how often will such circumstances arise and (2) to what extent could airport neighbours be adversely affected? These are addressed in Sections 5 and 6.

5 OCCURRENCE OF DISPLACEMENT: CRITICAL TAKE-OFF WEIGHTS

5.1 Noise at the reference point will always be minimised by overflying it at as high as possible and with the least possible thrust. A change of operating procedure would only cause far-out noise displacement if, due to reduced climb performance, the aircraft height were less under the new noise abatement procedure - to an extent that is not compensated by a thrust-related reduction in engine noise emission. Theoretically, two noise abatement actions that could lead to noise displacement are (i) reducing cutback height and (ii) increasing the depth of cutback (i.e. reducing climb thrust). There are many factors to be taken into account to determine whether or not these actions would actually do this in specific circumstances. For departures an aircraft operator can theoretically choose from a wide range of possible operating procedures. And, whatever the procedure the pilot selects for a particular departure, the operating conditions, especially TOW, headwind and air temperature, have a significant influence upon the flight profile.

5.2 The process of selecting an appropriate noise abatement procedure is perhaps best explained by restricting the variables to three actions: (1) to increase take-off thrust (to climb more steeply before the reference point); (2) to change cutback height (to effect cutback as close as possible to the reference point); and/or (3) to reduce climb thrust (to minimise noise emission over the reference point). This breaks the procedure into the two phases identified in paragraph 2.3: first, take-off up to the cutback point and, second, climb beyond it - with a constant (take-off) flap setting being maintained throughout. In fact, with cutback at 1500 ft and a post-cutback climb to 3000 ft, this two-phase procedure is identical to ICAO A. With cutback at 1000 ft, the minimum currently permissible in the UK, it becomes the Modified

ICAO A procedure defined in paragraph 4.4. With regard to cutback height, although in theory this can be varied freely (within limits), it would be unusual for airlines to specify more than two for normal use.

5.3 Figure 11 is a flow chart illustrating a process for identifying an operating procedure that will minimise the risks of causing height and noise infringements and noise displacement. This shows that having met the height and noise requirements[14], displacement can be reduced by adjusting the balance between the three variables: take-off thrust, cutback height and climb thrust. Aircraft operators should use such processes when drawing up their standard operating procedures and preparing the pre-calculated reference tables used by pilots to determine the appropriate thrust, flap settings and speed for a particular take-off immediately prior to a departure, when other variables (temperature, wind speed and weight) are known. Relative to current practice, except in limited circumstances, it should normally be possible both to reduce noise and to avoid displacement through the implementation of best practice.

5.4 Noise displacement is by definition relative; it compares the effects of one operating procedure with those of another. In this report, noise displacements resulting from noise abatement operating procedures are generally defined in relation to 'current practice' - which includes reduced thrust take-off. It is important to note that, with increased take-off thrust, noise displacement is not a consequence of using deeper cutback (reduced climb thrust) if the consequent reduction in height gained during cutback climb is exceeded by extra height gained during initial climb.

5.5 The outcomes from this process are dependent upon take-off weight. Some take-off weight statistics for B747s at Heathrow are given in Figure 18 of Reference 2 and the scope for use of different operating procedures (affecting climb performance and, therefore, height) in relation to TOW for the B747-100 was shown in the graph at Annex 9 of Reference 3[15]. Together, these indicated that the median TOW for B747-100 aircraft at Heathrow in 1995-6 was about 315 tonnes (94.5% MTOW[16]), and led to the conclusion that there is scope to improve operating procedures in order to meet the proposed new noise limit at that weight. As weight increases above 315 tonnes the scope for making the necessary

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[14] i.e. the noise abatement requirements specified under s78 of the Civil Aviation Act 1982 and published in the UK AIP.

[15] For illustrative purposes one of the procedures considered in Reference 3 assumed a flexible cutback height which is not normally recommended practice (see Paragraph 5.2).

[16] Percentages of MTOW are rounded to the nearest 0.5%.

improvement decreases, significantly so for aircraft above 325 tonnes (97.5% MTOW).

5.6 Figures 12 to 14 show some results of similar analyses for the B747-100, the Chapter 2 B747-200 and the Chapter 3 B747-200 at 15°C and zero headwind (the atmospheric conditions assumed by IATA in Reference 11). Five different operating procedures are compared: ICAO B and ICAO A - each with flexible and full take-off thrust - plus a Modified ICAO A as defined in paragraph 4.4, i.e. ICAO A with cutback height reduced from 1500 ft to 1000 ft. These graphs of FNL versus TOW have been calculated using INM data (see paragraph 4.3 and footnote 6). Like the previous results referred to above, all three diagrams reveal scope for substantial reductions of FNL (the noise level at 6.5 km).

5.7 They show that under 'current procedures' with flexible take-off thrust, whether these are taken to be either ICAO A or B, FNL increases steadily and uniformly with TOW. This is because, under these procedures, thrust is not cut back until after the 6.5 km reference point. Moreover, for flexible thrust ICAO B, the mean slopes of the lines in Figures 12 - 14 (sensitivity of FNL to changes in TOW) are 0.065, 0.052 and 0.084 dB/tonne; these results generally substantiate the findings reported in Reference 2 that were based on statistical analyses of actual Heathrow NTK measurements[17]. It can be seen in Figures 12 - 14 that the comparable slopes for flexible thrust ICAO A are only slightly greater; in other words, if take-off thrust is flexible, a choice between Procedures A and B has little effect on the noise-weight relationship.

5.8 Figures 12 to 14 show that, for these 'classic' B747 aircraft using flexible take-off thrust, i.e. with thrust reduced in proportion to actual take-off weight (dotted lines, triangular symbols), switching from Procedure A to Procedure B does not generally produce the expected shift of benefit from far-out to close-in. At high TOWs (and in the case of the Chapter 2 B747-200, Figure 14, only at 100% MTOW and just below), ICAO B does give lower noise than ICAO A at the 6.5 km point (FNL). But at lower TOWs, ICAO B is noisier than ICAO A. However, at all weights, the differences are small; this is due partly to the effects of using flexible take-off thrust and partly to the prolonged acceleration and flap retraction schedules of these aircraft under ICAO B. Together, these cause the aircraft to climb above 1500 ft anyway before the thrust can be cut back.

5.9 Restoring take-off thrust from flexible to full widens the gap between Procedures A and B, principally because of a pronounced effect upon Procedure A. Under

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[17] See paragraph 4.15 and footnote 13.

Procedure A it reduces FNL at all TOWs except the maximum - markedly so (by around 6 dB) at low TOWs where, with greater take-off thrust, the 1500 ft cutback point can be reached before the 6.5 km point. The 'steps' in the ICAO A full thrust curves between 85% and 90% MTOW reflect the effects of cutback which contribute to the FNL reductions - by approximately 1.5 dB for the -100, 2.5 dB for the Chapter 2 -200 and 3 dB for the Chapter 3 -200. Under Procedure B, the effects of restoring full thrust are less noticeable. For the Chapter 2 aircraft (Figures 12 and 13) the flyover levels at the 6.5 km point (FNL) are reduced by about 1 dB. This is because the benefits of shortening the take-off run and steepening the climb gradient outweigh the disbenefit of greater engine noise emission. But for the Chapter 3 B747-200 (Figure 14), the use of full thrust under Procedure B worsens FNL by up to 1 dB because, in this particular case, the higher noise emission is not fully countered by the better take-off and climb performance. This is further reason for B747s to avoid ICAO Procedure B. Overall, it is clear from Figure 12 - 14 that, for full thrust take-offs, Procedure A gives markedly lower noise levels at 6.5 km than Procedure B although, at weights close to 100% MTOW, the difference is small (at the maximum weight there is no difference because thrust cannot be reduced).

5.10 Turning to the full-thrust modified Procedure A, lowering the cutback height from 1500 ft to 1000 ft shifts the 'steps' to higher TOWs; only at the highest weights, close to MTOW, is it not possible to cut back before the reference point. This modification is therefore beneficial at all weights for which a 1500 ft cutback is not possible, which is down to around 88% MTOW. Again at high TOW, the benefit of the noise-abatement procedure is small; all three curves converge at 100% MTOW. However, overall, for the three B747 types shown, the noise benefits of using high take-off thrust are very apparent, as is the relative ineffectiveness of ICAO B at 6.5 km from SOR.

5.11 For any particular conditions and operating procedure a *noise-critical take-off weight* can be defined above which, on average, the noise limit could not be met without violating the 1000 ft minimum height restriction[18]. Similarly, a *displacement-critical take-off weight* can be identified below which, relative to a baseline procedure, on-track displacement would not be expected to occur. Critical TOWs have been calculated for five aircraft types with marginal noise performance for which INM data are available and which are or have recently been operated at the London airports. The results are, to the nearest 0.5%:

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18 The 1000 ft height restriction specified under s78 of the Civil Aviation Act 1982 and published in the UK AIP.

Type	MTOW[19] (tonnes)	Displacement-critical TOW: %MTOW below which there is no on-track displacement	Noise-critical TOW: %MTOW above which daytime limit cannot be met
B747-100	332.9	94	97
B747-200 Ch.2	362.9	91	96.5
B747-200 Ch.3	377.8	93	98.5
B707-300 (hushkitted)	151.5	96	96
DC8 (hushkitted)	147.3	94	94

5.12 Again, the assumed conditions were 15°C and zero headwind[20]. The noise-critical TOWs (expressed as % of MTOW), which can be read directly from Figures 12 to 14, are for the modified ICAO A procedure: full take-off thrust and cutback to maximum climb thrust at 1000 ft[21]. *According to these INM predictions*, none of these aircraft could meet the proposed daytime limit of 94 dBA Lmax at MTOW in the specified conditions. The displacement-critical TOWs are those below which, under the modified ICAO A procedure, no on-track displacement occurs in relation to 'baseline' current practice taken to be ICAO A with flexible take-off thrust, as defined in paragraphs 2.12 and 4.4 - see Figures 8 to 10. Below the noise-critical TOWs, early cutback is estimated to cause displacement for the B747s, but only within restricted TOW 'windows': 94-97% for the -100, 91-96.5% for the Chapter 2 -200 and 93-98.5% MTOW for the Chapter 3 -200. For the other two aircraft there is no displacement below the noise-critical TOWs[22].

5.13 Two provisos are attached to the above results. The first is that the critical TOWs depend upon the atmospheric conditions; different results would be obtained for different conditions - in general the critical TOWs will increase as temperature falls and when headwind rises. The second is that these INM calculations, like those presented by IATA, depict representative long-term *average* operations; the existence of real-life flight-to-flight variations in departure noise levels means that some departures below the critical weight will exceed the limit (equally some above will not). In other words, the above estimates of limiting TOWs are themselves subject to statistical uncertainty. The significance of such statistical

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19 These are the MTOWs of aircraft type variants for which data were readily available. Other variants may have other MTOWs.

20 As assumed in the analyses in Section 4 for comparability with the IATA evidence. Different conditions have been considered elsewhere, e.g in Reference 2.

21 Theoretically, a deeper cutback, to a nominal minimum 4% climb gradient, would reduce noise at 6.5 km further at the expense of some displacement. However, calculations indicate improvements of only 0.5 dB for Chapter 2 B747s.

22 For the B707 and DC8, windows of zero width are indicated although their widths are theoretically 'negative'; ie the displacement-critical TOWs actually lie *above* the noise-critical TOWs.

considerations was highlighted in the regression analyses described in Section 4 of Reference 2.

6 INCIDENCE OF DISPLACEMENT

6.1 To address the second question in paragraph 4.17 - to what extent would airport neighbours be affected? - it is necessary to consider where aircraft fly. Aircraft leave airports via departure routes which are conventionally drawn as nominal lines on maps. Aircraft follow these with varying degrees of precision; actual tracks are dispersed, the dispersion increasing with distance along the routes. Thus, because of the divergence of the routes and the swathes about them, whilst the close-in reductions of noise tend to be concentrated in high noise areas overflown by nearly all departures, the far-out increases are widely dispersed among low noise areas - at any particular location there are only a few overflights. To illustrate all noise gains and losses resulting from a procedural change in a readily understandable way that adequately reflects track divergence is very difficult. One way would be to overlay the 'old' and 'new' footprints on the flight tracks. But because of the large number of flight tracks, this would be a most confusing diagram. An alternative method for illustrating displacement zones is therefore developed here. Before applying it to some actual airport examples, it will be described with reference to individual flight footprints.

6.2 Figure 15 is a modified version of Figure 3 which compares B747-100 noise footprints (for 93% MTOW) for the IATA 'current' and 'trial' procedures. The footprints for current procedures are outlined by unbroken lines; the trial procedures by dashed lines. Within the envelope of the footprints, shading is used to denote how a change of operating procedure would alter noise event levels. Light shading identifies those areas where noise event levels would be lower under the trial procedure; dark shading shows where they would be higher. To some extent, the changes of noise level can be picked out by comparing the footprints themselves. A reduction of noise causes the footprint to shrink; higher levels cause expansions. Inspection of the diagram confirms that the footprints expand within dark shading (dashed line outside) and shrink within light shading (dashed line inside).

6.3 An idea of the magnitude of the changes can be gained from the amount the footprints are displaced. The benchmark here is that, within each set in Figure 15, footprints are spaced at 5 dB intervals. Thus a noise increase of 5 dB would cause each footprint to expand to the position of the next one out; lesser increases would cause a smaller shift. Taking as an example the 90 dBA footprints that cross the dark shading at the centre of the diagram around 15 km from SOR, the dashed line is displaced less than one tenth of the way towards the 85 dBA lines. Thus it may be inferred that the increase in event level is less than one-tenth of 5 dB, i.e. less than 0.5 dB[23]. Similar judgements can readily be made about footprint shrinkage within the light shading which corresponds to noise level reductions.

6.4 The same patch of dark shading in Figure 15 shows also that the lateral extent of the on-track increase between 11 and 20 km that was evident in Figure 2b (paragraph 4.10) is very small - although some separate off-track increases are also apparent. Prior to cutback, these arise simply from the increase in thrust but, in the regions of identical thrust, the extra height gain results in some small losses of lateral attenuation. It is obvious from Figure 15 that gains and losses (decreases and increases of noise level) resulting from any procedural changes are likely to be distributed about flight tracks in quite complex ways. To assess how they could affect residents living near the airports requires consideration of the actual disposition of departure flight tracks. At any single, distant location - where there will be fewer loud events than at locations close-in - both gains and losses will be experienced due to the inevitable scatter of actual tracks and the flight-to-flight variations in operational conditions and procedures. Indeed it is practically impossible to discuss event level changes in any meaningful way unless a statistical approach is taken.

6.5 The statistical approach is to make use of the principles of the Leq scale of *average noise exposure level* which accounts for both the numbers and the levels of individual noise events. *Changes* to Leq brought about by alterations to operating procedures describe gains and losses in a full and fair manner. However, over an extended area around an airport, event levels and numbers vary widely and the question arises as to whether, in terms of community annoyance, a particular Leq *change* (in dB) means the same thing at high and low Leq noise exposure levels. For example, at a particular location where the number of events is very low and Leq is also low, say 50 dBA, a decrease in the average *event* level (SEL) of 2 dB would reduce the *exposure* level Leq by an equal amount - from 50 to 48 dBA. At another location, where say 50 times as many equally noisy aircraft events are heard so that Leq is 67 dBA, the same decrease in event level would still cause a 2 dB fall in Leq - from 67 to 65 dBA . But it is reasonable to argue that reducing the noise of 50 events is a much more worthwhile improvement than reducing the noise of just one. A key difference between these two cases is that the vastly different numbers of events cause ‘absolute’ Leq values to be separated by 17 dB -

[23] Reference to Figure 2b confirms that the actual increase at 15 km is about 0.3 dB.

i.e. an event level improvement at high Leq is more significant than a similar improvement at low Leq. Thus, when assessing noise abatement operating procedures in terms of Leq changes, it is important to place those changes in context with 'absolute' Leq levels.

6.6 This approach is illustrated in Figures 16 to 18. These 'displacement maps' have been produced for Heathrow, Gatwick and Stansted using the ANCON noise model. They show, overlaid on population maps, (i) relative Leq contours for B747-100 departures at 93% MTOW using IATA's 'current' operating procedure, and (ii) where noise is increased and decreased by changes to the operating procedure. The relative Leq contours in these diagrams are not to be confused with the 'absolute' Leq(16-hr) contours published annually by the DETR - which depict actual average noise exposures due to all aircraft movements[24]. In contrast, Figures 16 to 18 show only relative noise exposures caused by departures of a *single* aircraft type. Effectively, they are constructed by assigning the footprints shown in Figure 15 to actual departure routes and aggregating them to form Leq contours. But, for simplicity, no allowance has been made for dispersion of individual tracks about the nominal routes.

6.7 For each airport, the contours have been calculated by apportioning B747-100 departures evenly between the two runway directions and all major departure routes[25]. As the Leq contours are purely relative, the total numbers of departures are not relevant to these calculations; the shapes of the contours depend only on the flight track patterns and remain the same regardless of the amount of traffic. They simply highlight the disposition of *changes* of noise exposure brought about by switching operating procedures. The effects of two changes from 'current practice' are depicted: first to IATA's 'trial' procedure and second to Modified ICAO A.

6.8 In Figures 16 to 18 the Leq contours are spaced at 5 dB intervals (highest levels innermost), but no absolute levels are specified - the contours are only intended to indicate how noise exposure varies around the flight routes. It is the relative locations of the shaded and cross-hatched areas only that are relevant; these show how, within the overall contour envelopes, the increases and decreases of noise caused by the procedural changes are distributed and dispersed across areas of relatively high and low absolute exposures. The shadings show how IATA's 'trial'

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[24] It is not possible to use 'normal' Leq(16-hr) contours (57 - 72 dBA) for present purposes because they do not extend far enough to cover the areas of far-out displacement, nor, if they did, would the associated small changes show up in the contours.

[25] These are nominal Standard Instrument Departure (SID) routes. (Note that in practice, aircraft departures are not distributed evenly between routes.)

procedure differs from the ‘current’ procedure. The unshaded areas are where there are benefits - i.e. where the alternative procedure causes less noise than the current procedure with Leq improvements of up to 2 dB. The shadings depict displacement increases: far-out (light) and close-in (dark). The cross-hatching relates only to far-out displacement for the Modified ICAO A procedure. This modified procedure generates noise benefits, again up to 2 dB, throughout the remainder of the contour envelope - outside the hatched areas and the close-in zone, where noise increases.

6.9 The close-in Leq increases in the immediate vicinity of the runways are caused by the use of higher take-off thrust, and they are the same for both the IATA trial procedure and Modified ICAO A. These increases lie within the area before the 6.5 km distance from SOR: mostly they are within the airport perimeters. The biggest, of around 2 dB, are very localised; for the most part increases are less than 1 dB.

6.10 Noise increases further away from the aerodromes form ‘islands’ of far-out noise displacement - all being located in areas of lower noise exposure, i.e. towards the outer contours. Considering first the IATA trial procedure, cleanup at lower height leads to shallower climb, and hence more noise. Within the islands, noise increases are small; none is greater than 0.35 dB. By comparison, the improvements obtained near the initial climb paths from the departure runways (and in most areas beyond the islands) are generally much greater, up to 2 dB. In short, even for this IATA operating procedure, far-out displacement increases are very limited in both magnitude and extent and should occur relatively sparsely and in areas of relatively low overall noise exposure.

6.11 Of even more practical importance, the ‘trial procedure’ chosen by IATA to *illustrate* displacement is not an optimal noise abatement operating procedure; indeed it provides a good illustration because it generates excessive far-out displacement. Better noise abatement procedures can readily be devised, a specific example being the Modified ICAO Procedure A, the benefits of which are clear in Figures 16 to 18; they are also illustrated in Figures 5 and 12 to 14. As stated in paragraph 4.13, this modification - retaining clean-up at 3000 ft rather than lowering it to 2000 ft - eliminates on-track displacement. However, there are still some small noise increases to the side of the flight tracks. It is these which leave the few residual patches of far-out displacement indicated by cross-hatching in Figures 16 to 18. But in none of these patches does the increase exceed 0.2 dB and in most it is less than 0.1 dB - such changes would be imperceptible to local residents.

6.12 Figures 16 to 18, like the analysis in section 4 (paragraphs 4.8 to 4.13), support the conclusion that the far-out displacement highlighted by IATA is of minor practical concern - insofar as the associated noise increases are small and confined to areas of relatively low overall noise exposure. It is also evident that the spatial distribution of far-out displacement is very sensitive to the precise procedural changes concerned. Those depicted in Figures 16 to 18 apply to one aircraft type, one take-off weight, one baseline procedure, concentrated departure tracks and two similar noise abatement procedures. Yet the displacement patterns for the two procedures, as well as being small in extent, are totally different in both shapes and distributions. It is apparent that, when the real variations of aircraft types, operating procedures and flight path dispersions are taken into account, far-out displacement will, in practice, be a very diffuse and insignificant consequence of the proposed new departure limits.

7 CONCLUSIONS

7.1 Far-out displacement is a term given to the effect in which, in some circumstances, changes to aircraft operating procedures to achieve substantial noise reductions at the 6.5 km reference distance could cause some increases in lower level noise exposures at greater distances from the airport. Specifically, for constant take-off thrust, displacement is an inevitable consequence of prolonged use of any lower-than-normal climb thrust that results in a reduced climb gradient after cutback.

7.2 The effect has been illustrated by calculating on-track noise levels, noise footprints and 'displacement maps'. This was done using best available aircraft noise contour methodology; the results are as reliable as the industry aircraft noise and performance data upon which the models depend. Although estimates of absolute noise levels are subject to a degree of uncertainty, the indications of change resulting from different operating procedures can be relied upon with far greater confidence (Section 3).

7.3 Far-out displacement has been illustrated elsewhere by IATA using a B747 example involving a particular change of operating practice - from a 'current' to a 'trial' procedure (Section 4, Figures 2 to 4, 15 to 18). But displacement is very procedure-dependent. In the particular IATA case, displacement was largely a consequence of an assumed change in clean-up height. If that height were not changed (effectively converting the trial procedure into Modified ICAO A), there would be no on-track displacement (paragraph 4.13, Fig 5).

7.4 More generally, a major factor affecting the noise caused by departing aircraft is the widespread practice of minimising take-off thrust (paragraphs 2.6, 2.7). Because of reduced take-off thrust (often referred to as derated or flexible thrust) many aircraft are substantially lower as they pass 6.5 km than they would be after full (or higher) thrust take-offs. Actual TOWs cover a wide range and, although at or close to MTOW there may be little or no opportunity for improvement, increasing take-off thrust at lower TOWs (Figures 6 and 7, paragraph 4.14) offers significant potential for departure noise reduction[26]. The proposed new noise limits should encourage shorter take-off distance and steeper initial climb which would generally reduce noise at the monitors and all points beyond. The analysis indicates that this will rarely cause displacement in relation to current practice (Section 5).

7.5 Only marginal 'noise critical' aircraft have been studied in this report: five of the noisiest subsonic aircraft which are or have recently been operated by day at the London airports - principally early 'classic' variants of the Boeing 747. As demonstrated by earlier DORA work, these are the types most likely to exceed the proposed daytime limit. For these models, ICAO procedure B recommended for 'close-in' noise abatement, which requires flap retraction before cutback, does not appear to be effective due to long flap retraction times. For these aircraft it appears to be better to adopt a Modified ICAO Procedure A - maintaining take-off flap to 3000 ft before flap retraction and acceleration, but with cutback at 1000 ft rather than 1500 ft (paragraph 4.15, Fig 8).

7.6 Two critical take-off weights can be identified. The first, a *noise-critical TOW*, is the highest weight at which, on average, an aircraft can depart and still meet the proposed new daytime noise limit at 6.5 km from SOR. The second is a *displacement-critical TOW*, the weight above which on-track displacement can occur on average. In zero headwind at 15°C, nearly all aircraft types and models can meet the proposed limits at MTOW, the maximum take-off weight. For a few - older, heavy four-engined aircraft with relatively poor take-off and climb performance including Boeing 747 'classics' and hushkitted narrow body 4-jets - the noise-critical TOW is less than MTOW. For these types, some limited far-out displacement could occur at weights between their noise-critical TOWs and their displacement-critical TOWs (paragraph 5.11):

[26] This conclusion is based on the results of the noise modelling study. No attempt has been made to determine the effects of using increased take-off thrust on engine wear and maintenance or other associated effects upon operating costs. These are matters for consideration elsewhere.

Type	Displacement-critical TOW: %MTOW below which there is no on-track displacement	Noise-critical TOW: %MTOW above which daytime limit cannot be met
B747-100	94	97
B747-200 Ch.2	91	96.5
B747-200 Ch.3	93	98.5
B707-300 (hushkitted)	96	96
DC8 (hushkitted)	94	94

(see paragraph 5.11 for MTOWs)

The noise-critical TOWs are for the modified ICAO A procedure. The displacement-critical TOWs are those below which on average, under the modified ICAO A procedure, no on-track displacement occurs in relation to a 'baseline' current practice, taken to be ICAO A with flexible take-off thrust.

7.7 Graphs showing on-track noise gains and losses provide only limited assessments of the incidence of displacement near airports; off-track variations need to be accounted for (paragraphs 6.2 to 6.5). This has been done for Heathrow, Gatwick and Stansted using 'displacement maps' based on relative Leq noise exposure contours, specially developed for this study (Figures 16 to 18). The displacement maps show that even the procedural change used by IATA for illustrative purposes causes very little displacement: the noise increases are confined to limited areas of relatively low exposure and are small - none exceeds 0.35 dB. In contrast, noise improvements are widespread and markedly greater, especially in areas of high noise exposure. Near the initial climb paths from the departure runways, there are Leq noise reductions of up to 2 dB.

7.8 Moreover, IATA's illustrative trial procedure is not optimum. There is no evident reason why better procedures could not ensure uniform noise reductions beyond 6.5 km with only minor incidence of far-out displacement. For classic B747s, ICAO procedure B recommended for noise abatement near the airport, which requires flap retraction before cutback, does not appear to be effective due to long flap retraction times. For these aircraft it appears to be better to adopt a Modified ICAO Procedure A - maintaining take-off flap to 3000 ft before flap retraction and acceleration, but with cutback at 1000 ft rather than 1500 ft. The potential for improved noise abatement has been demonstrated by contrasting the IATA example with the Modified ICAO A procedure which, through a minor change, avoids any appreciable displacement - the increases being very localised and nowhere exceeding 0.2 dB. Indeed they are generally less than 0.1 dB. It is clear from this comparison that the spatial distribution of displacement is very sensitive to the precise procedural changes concerned. It is concluded that, relative to current procedures, far-out displacement will, in practice, be a very diffuse and relatively insignificant consequence of the proposed new departure limits (Paragraphs 6.6 to 6.12).

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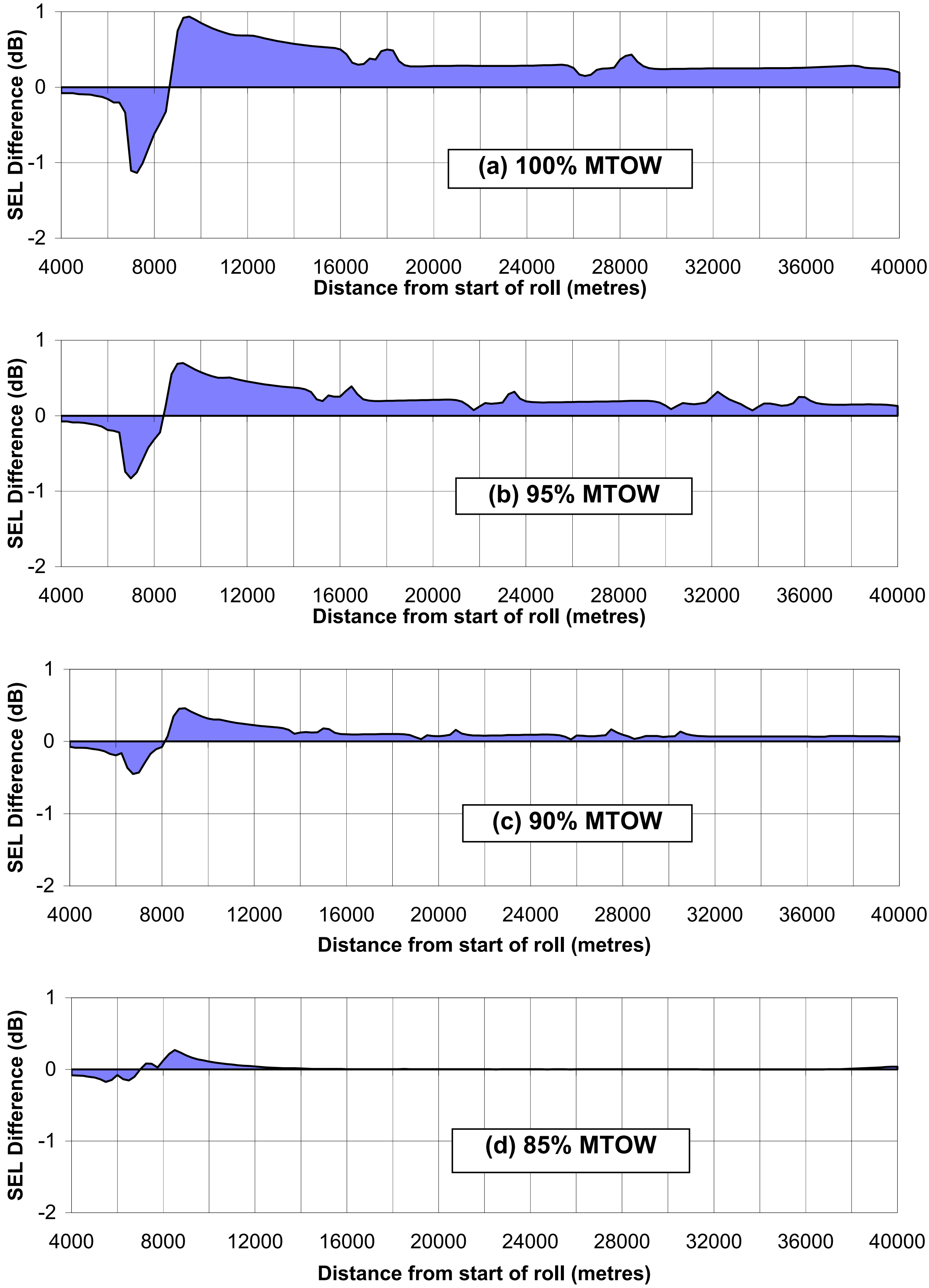


Figure 1 - Boeing 747-100 departures using flexible take-off thrust: effect of lowering cutback height from 1500 ft to 1000 ft (as a single measure) on on-track noise levels. (Cutback thrust = maximum climb thrust)

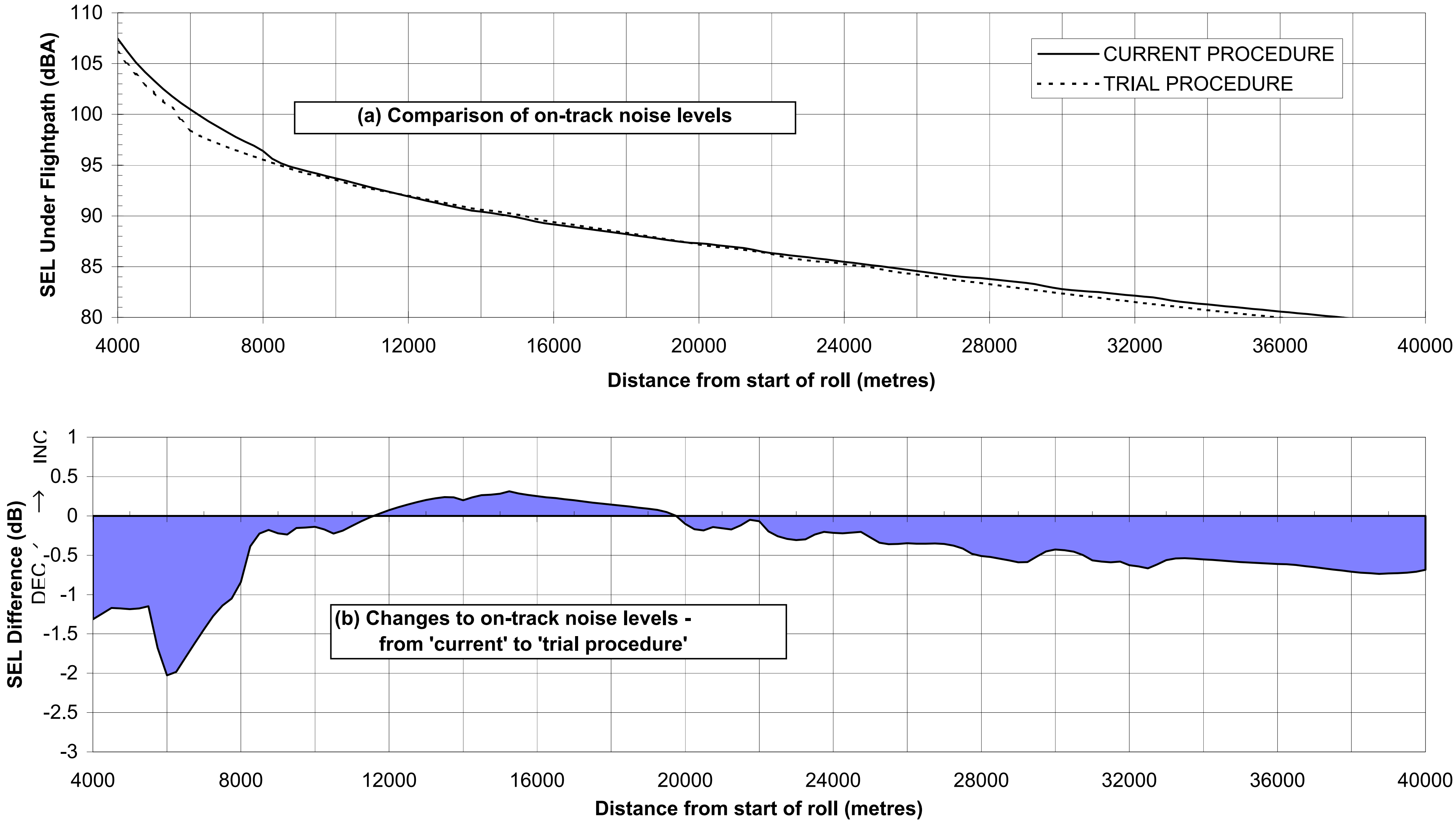


Figure 2 - Boeing 747-100 departures (at 93% MTOW): effect of changing from 'current' to 'trial' procedure (IATA case)

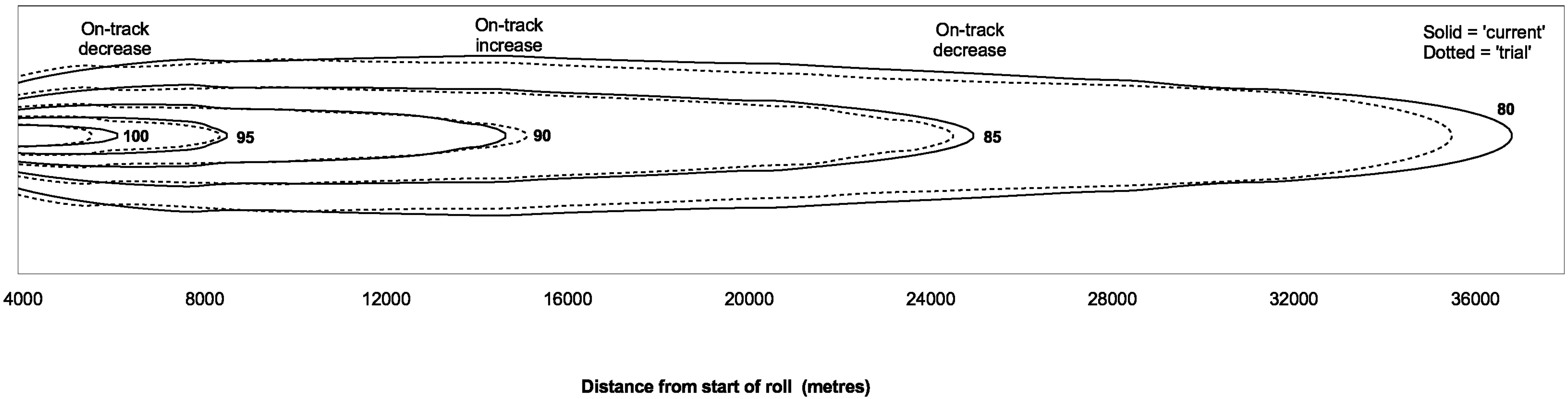
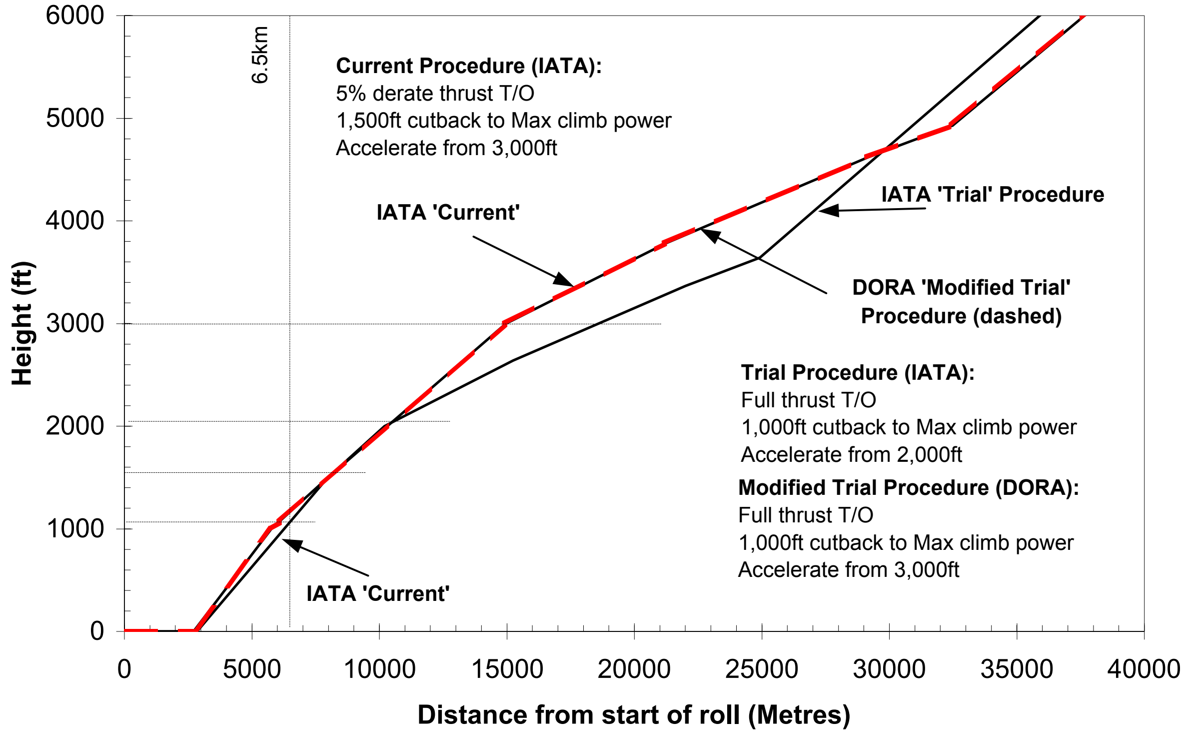
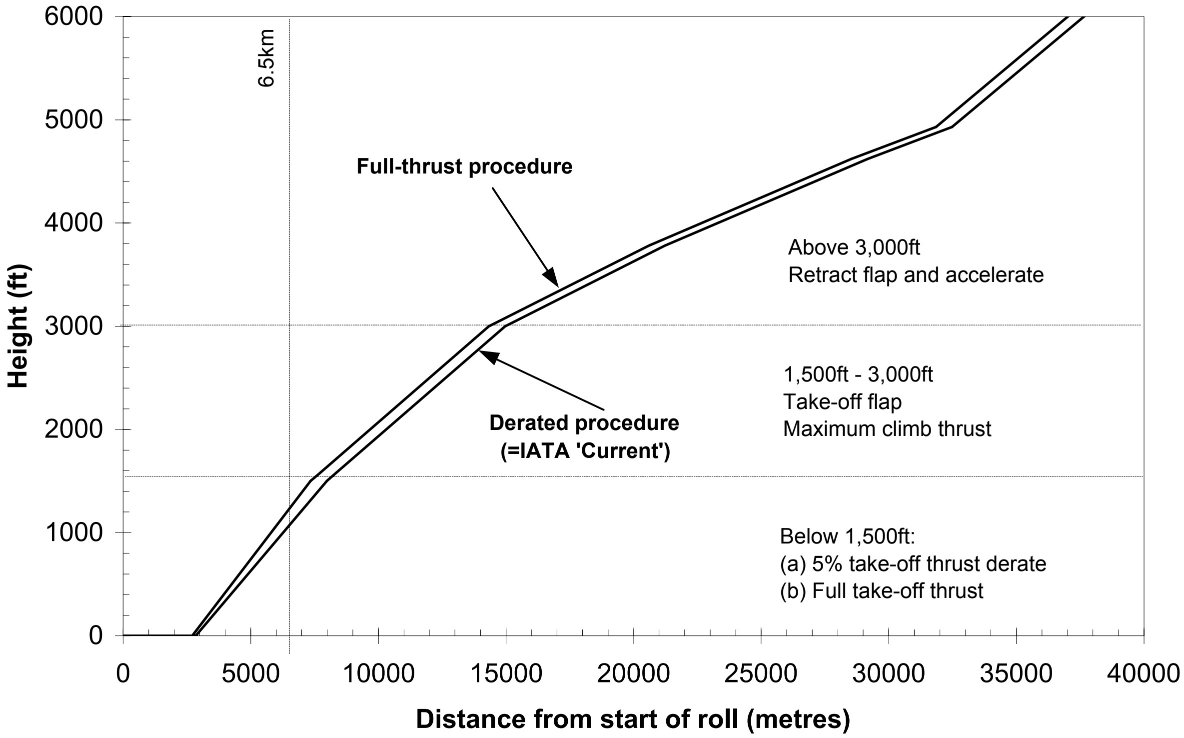


Figure 3 - Boeing 747-100 Departures (at 93% MTOW): comparison of SEL footprints for IATA 'current' and 'trial' procedures (footprints corresponding to Figure 2)



(a) Comparison of IATA 'current' and 'trial' procedures



(b) 'Current procedure' - comparison of full and derated take-off thrust

Figure 4 - Average height profiles of Boeing 747-100 departures (at 93%MTOW)

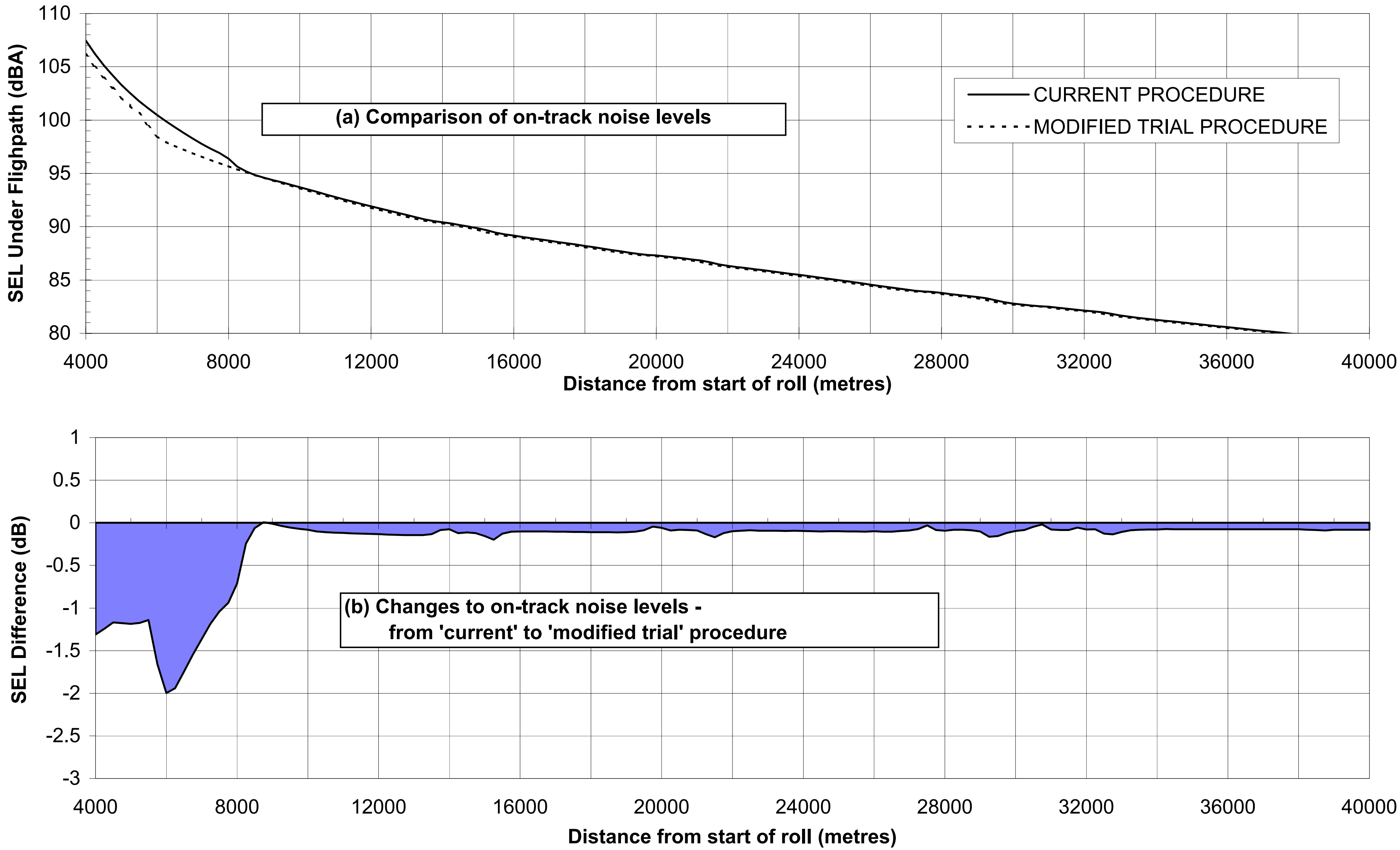


Figure 5 - Boeing 747-100 departures at 93% MTOW: effect of changing from 'current' to 'modified trial' procedure

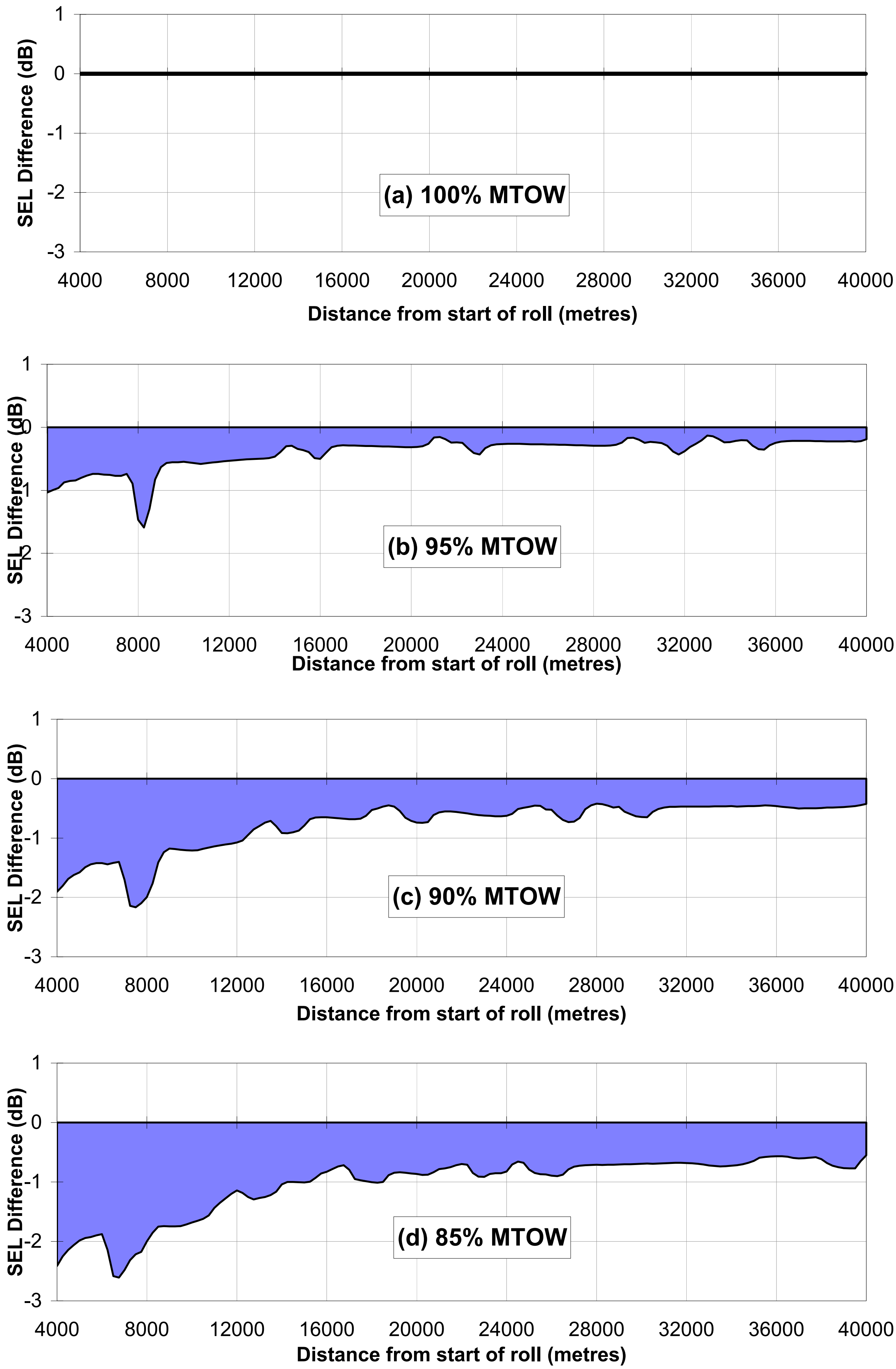
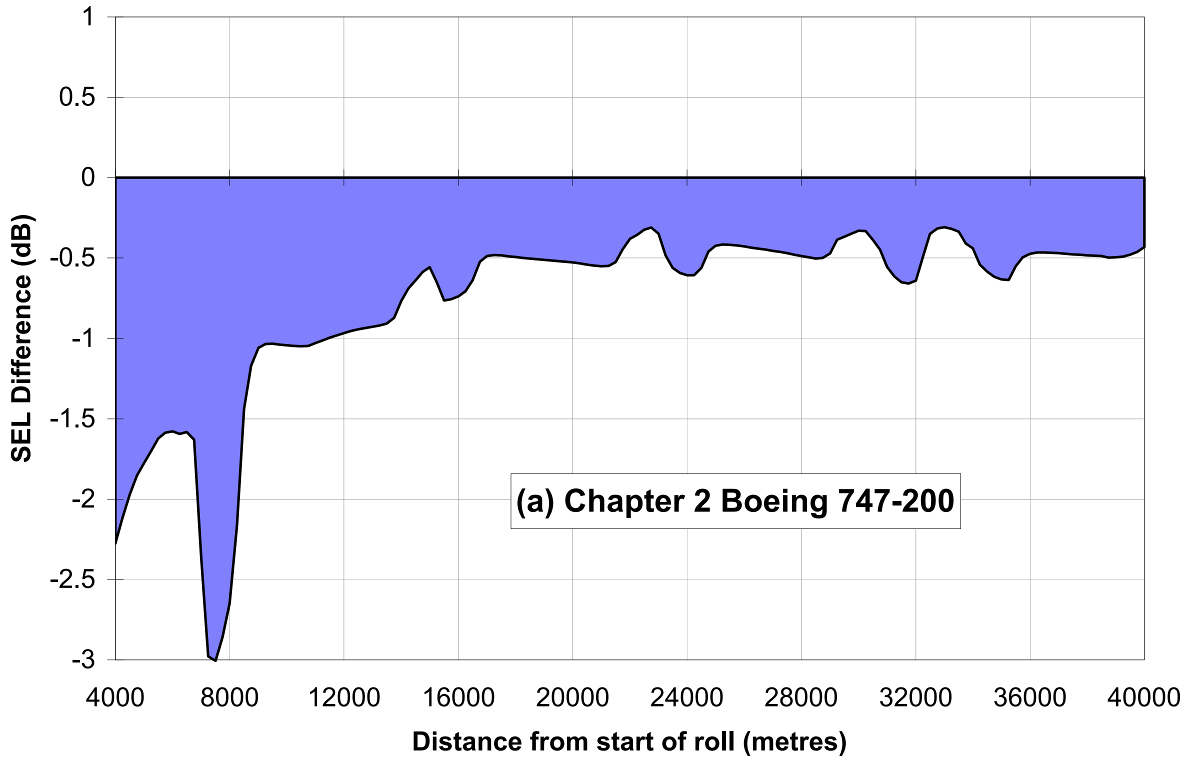


Figure 6 - Boeing 747-100 departures using ICAO A procedure: effect of restoring take-off thrust from flexible to full



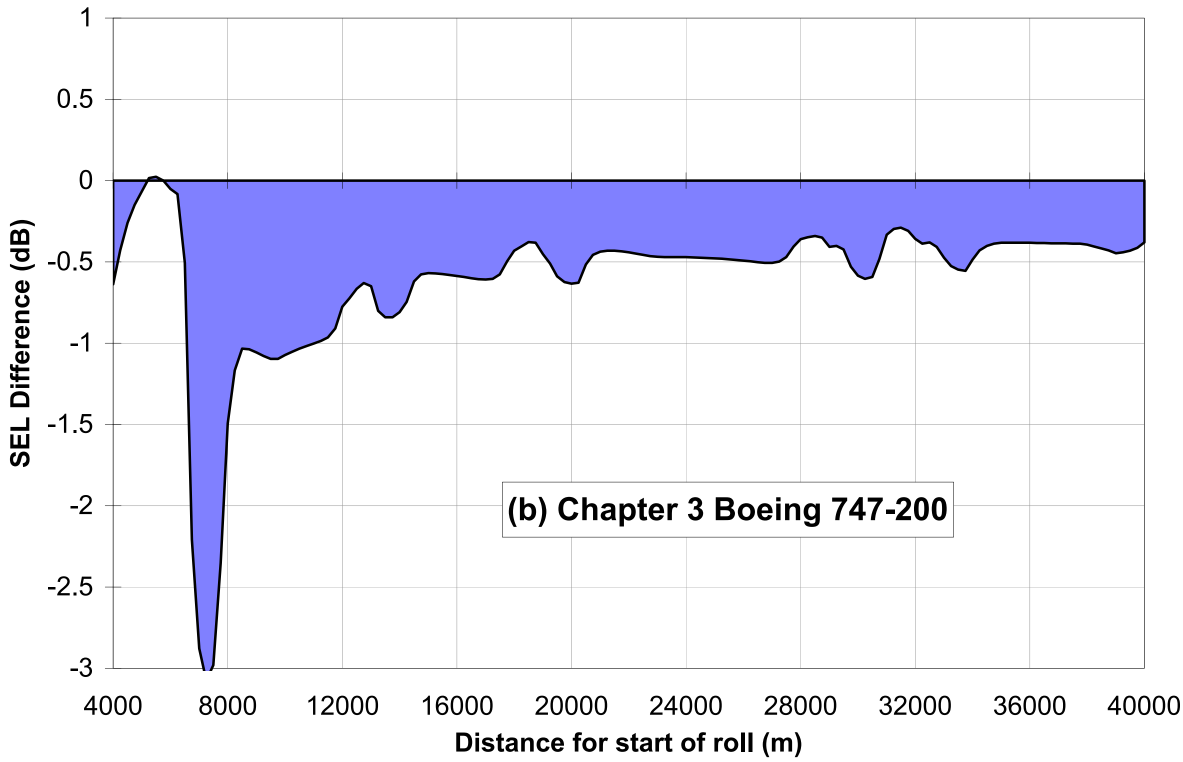


Figure 7 - ICAO A departure procedure at 90% MTOW: effect of restoring take-off thrust from flexible to full (for comparison with Boeing 747-100 in Figure 6(c))

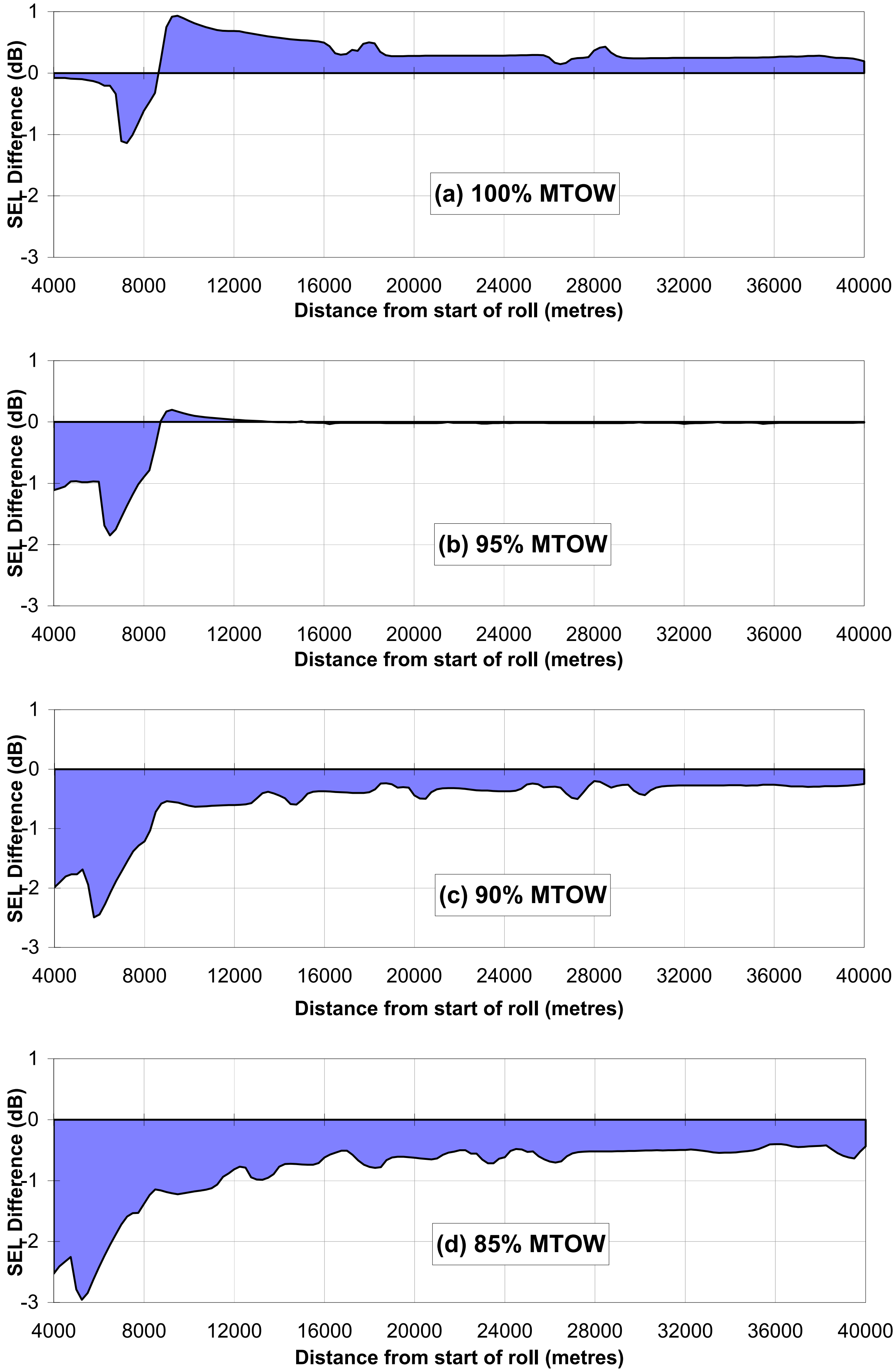


Figure 8 - Boeing 747-100 departures: effect of restoring full take-off thrust and lowering cutback height from 1500 ft to 1000 ft

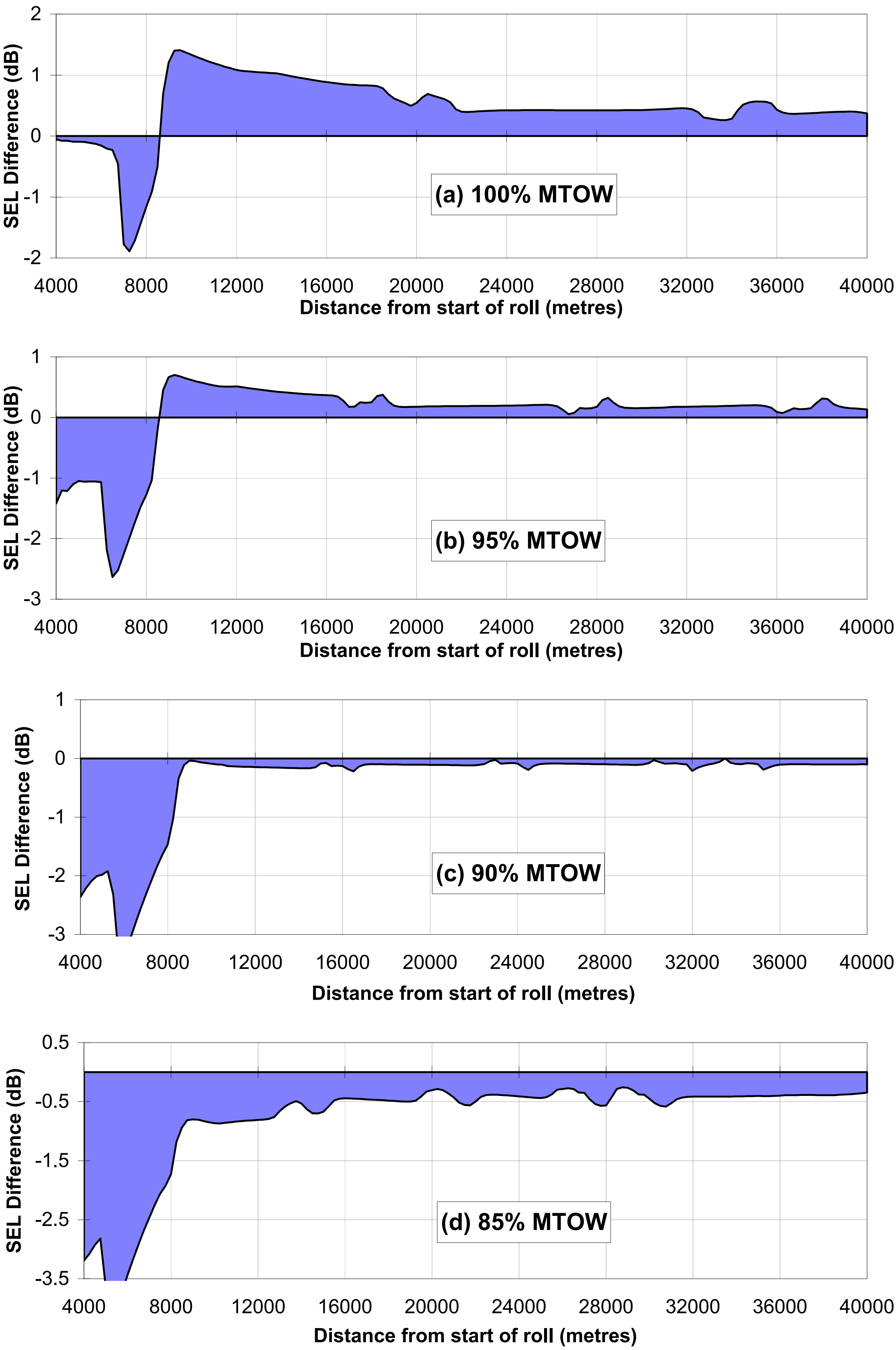


Figure 9 - Chapter 2 Boeing 747-200 departures: effect of restoring full take-off thrust and lowering cutback height from 1500 ft to 1000 ft

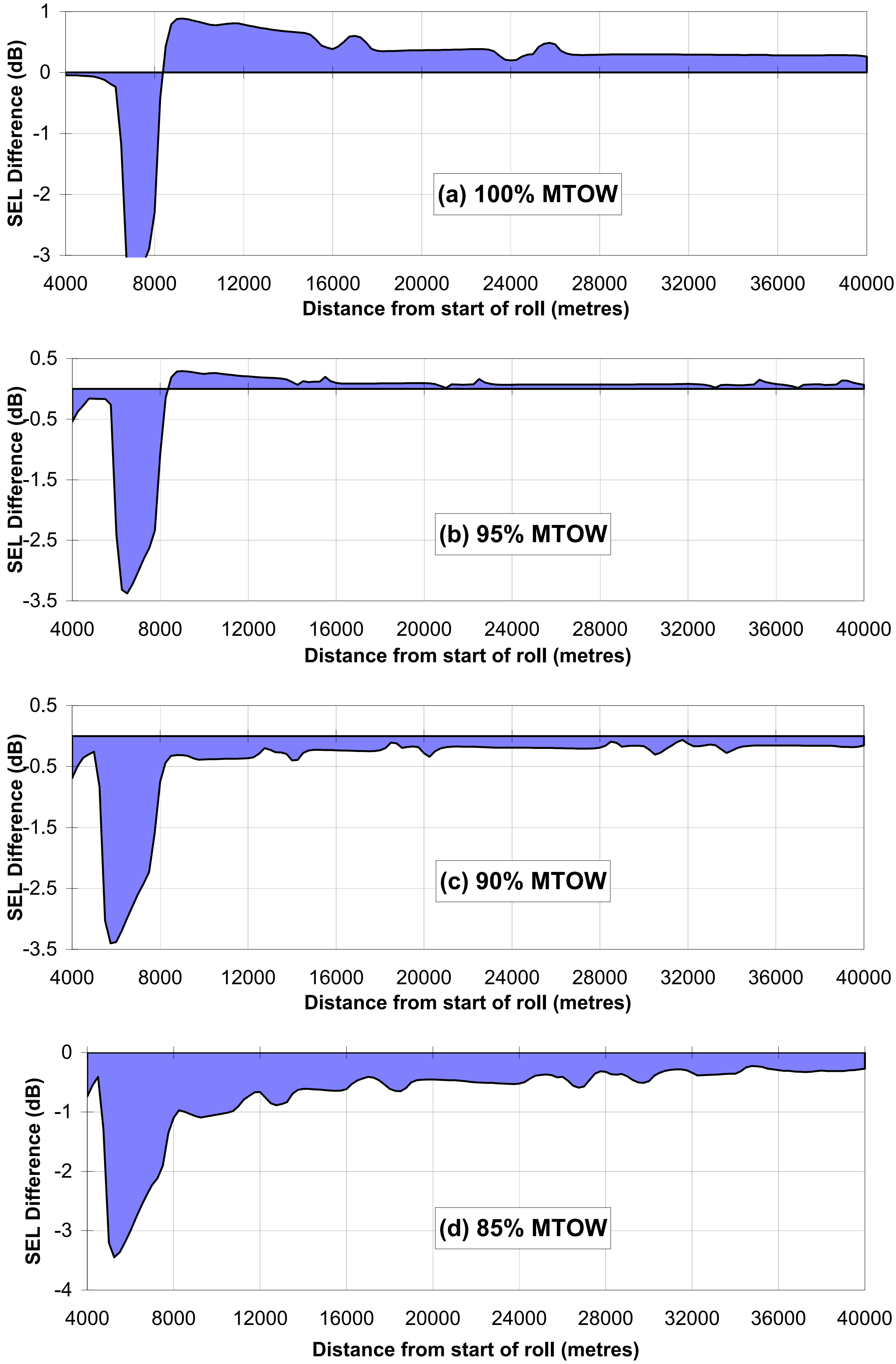
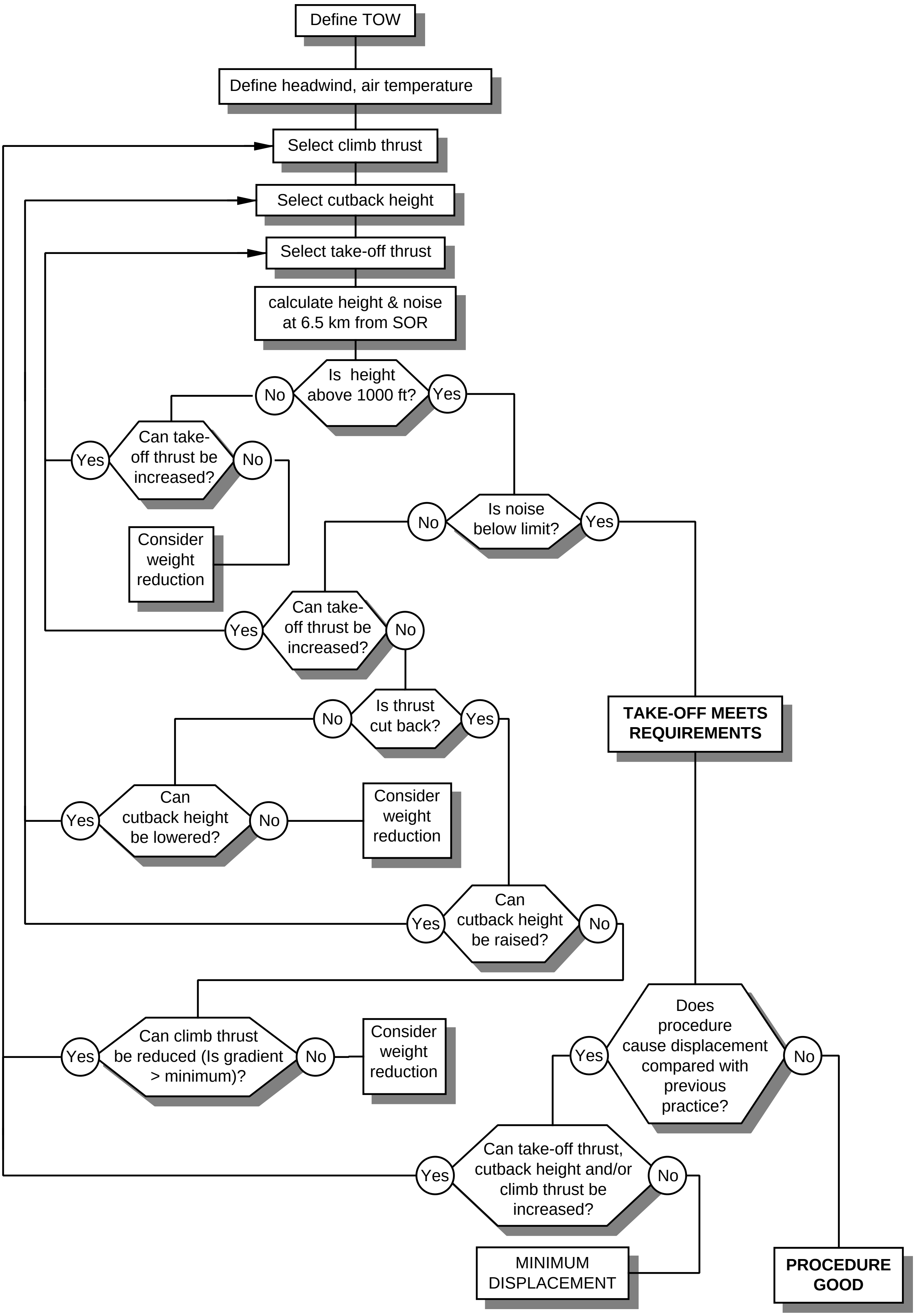
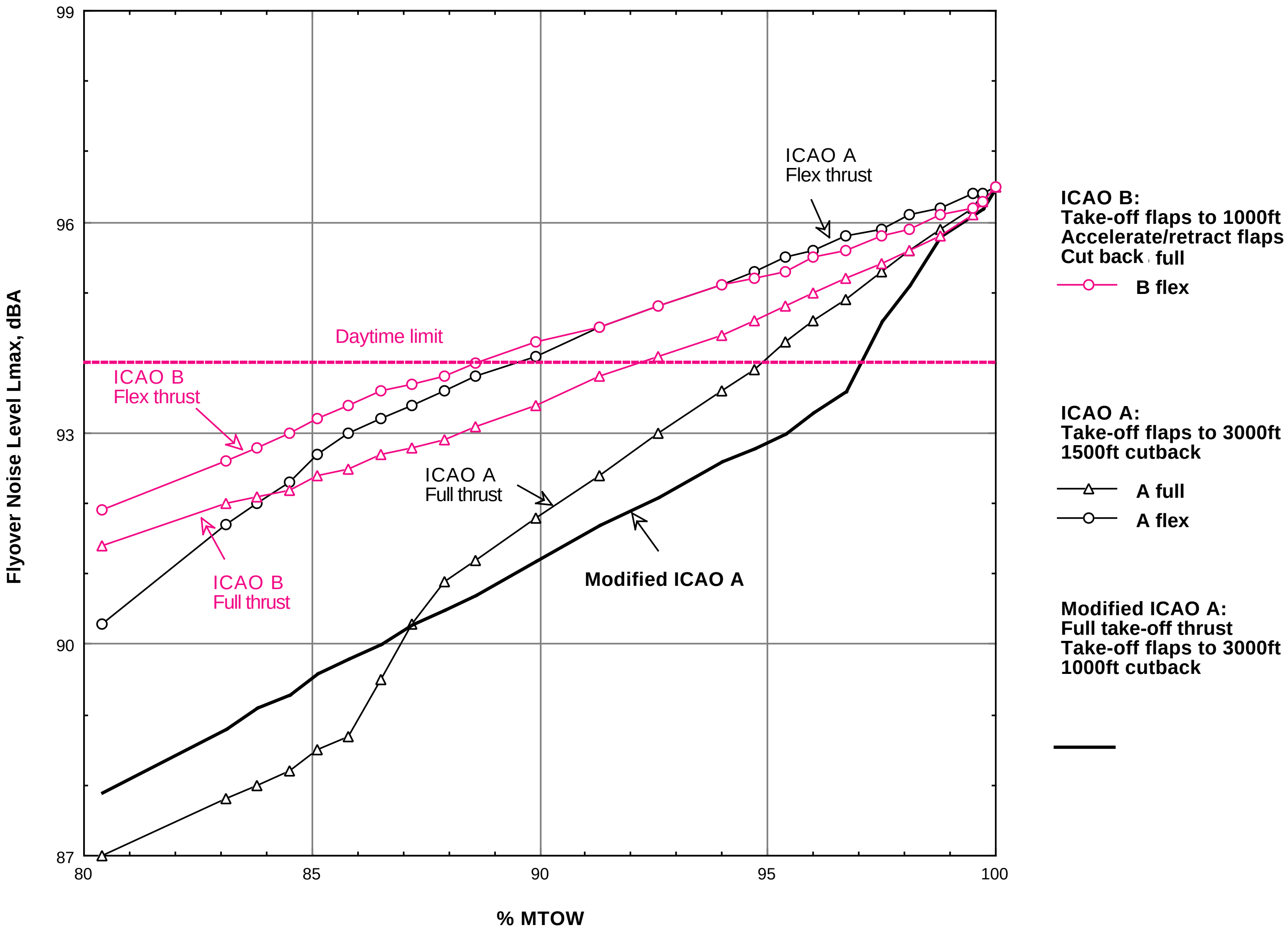


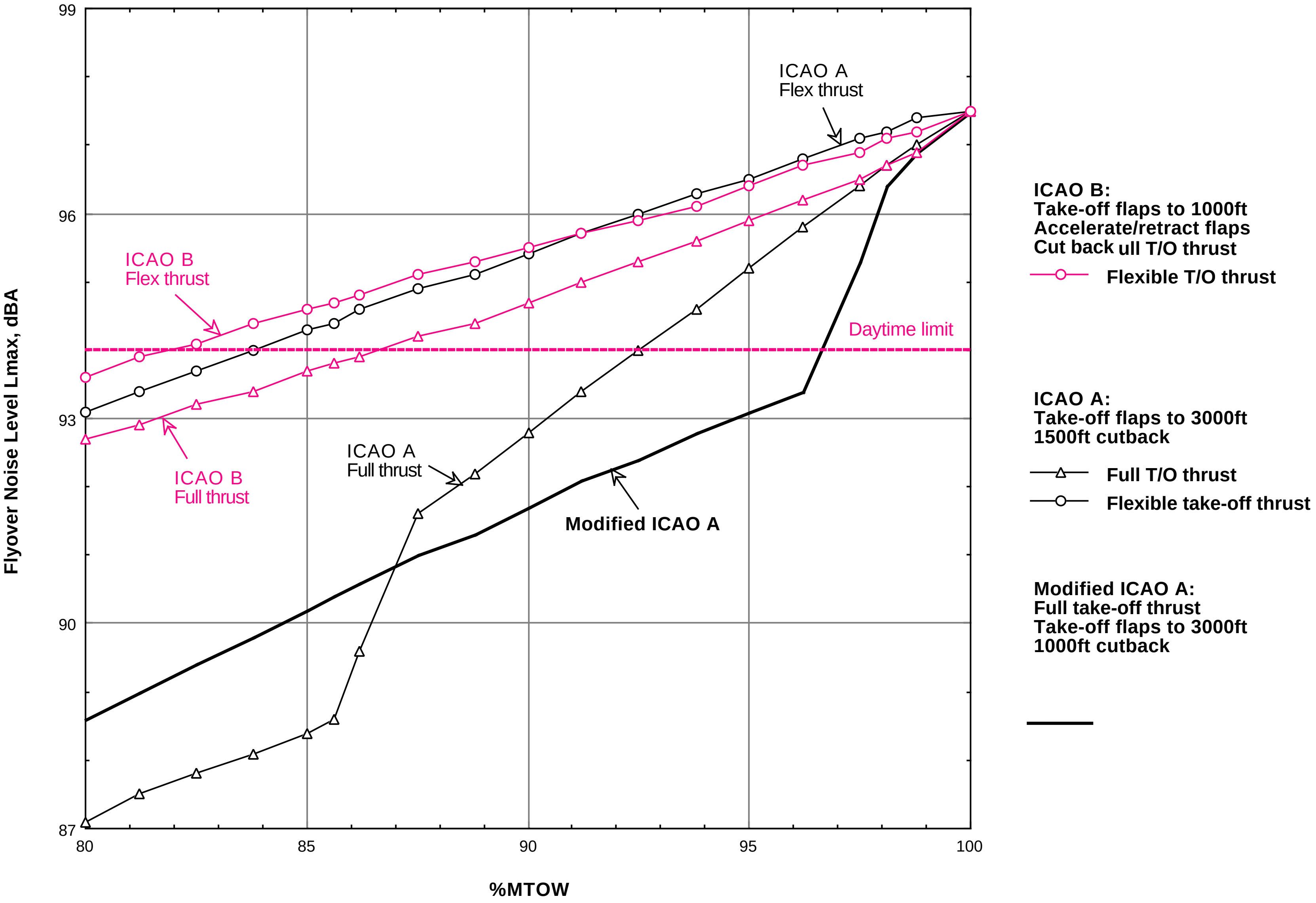
Figure 10 - Chapter 3 Boeing 747-200 departures: effect of restoring full take-off thrust and lowering cutback height from 1500 ft to 1000 ft



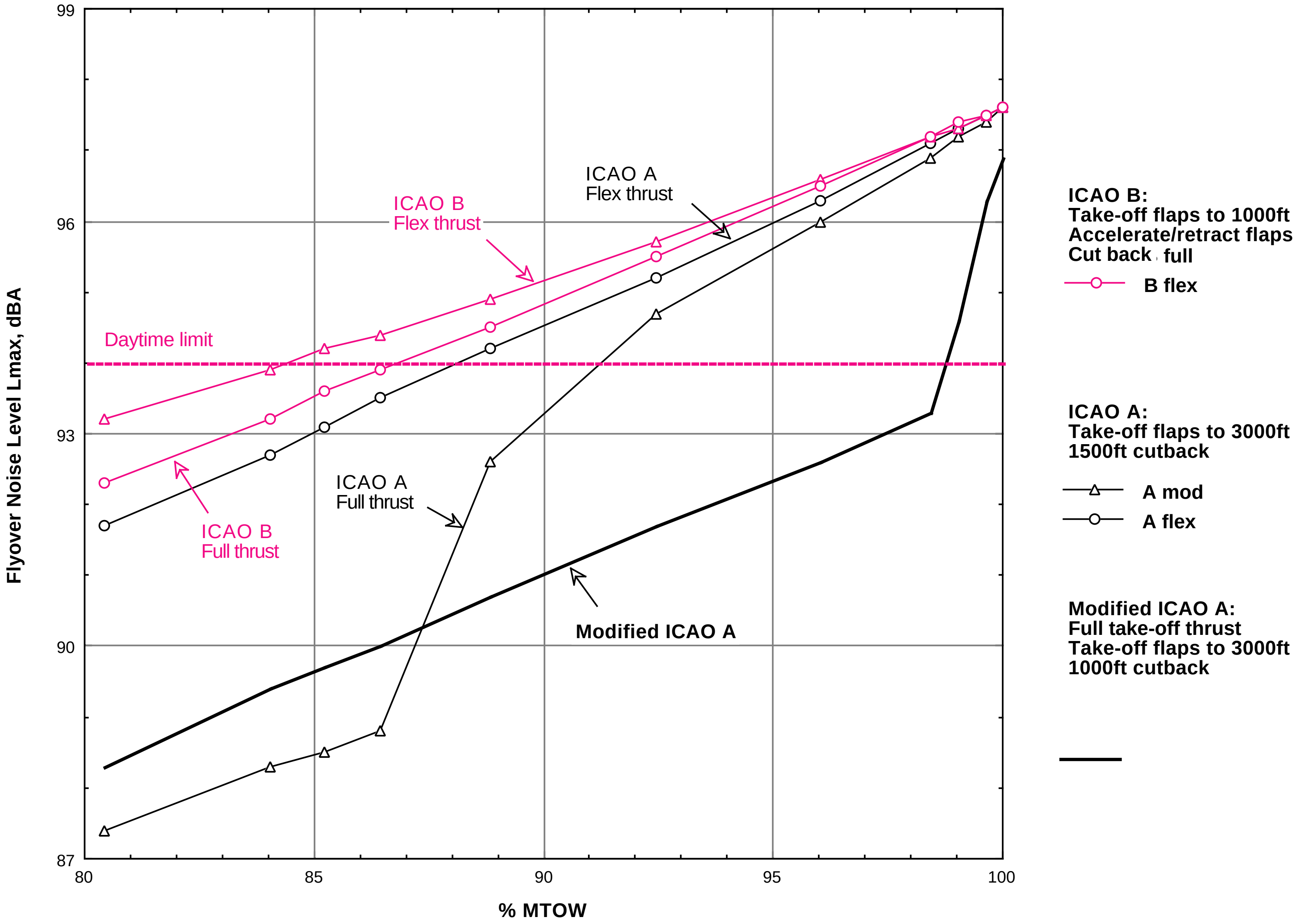
- Figure 11: Process to identify procedure that meet limits and minimises displacement -



- Figure 12 - Boeing 747-100: Effect of Operating Procedure on Flyover Noise Level -



- Figure 13 - Chapter 2 Boeing 747-200: Effect of Operating Procedure on Flyover Noise Level -



- Figure 14 - Chapter 3 Boeing 747-200: Effect of Operating Procedure on Flyover Noise Level -

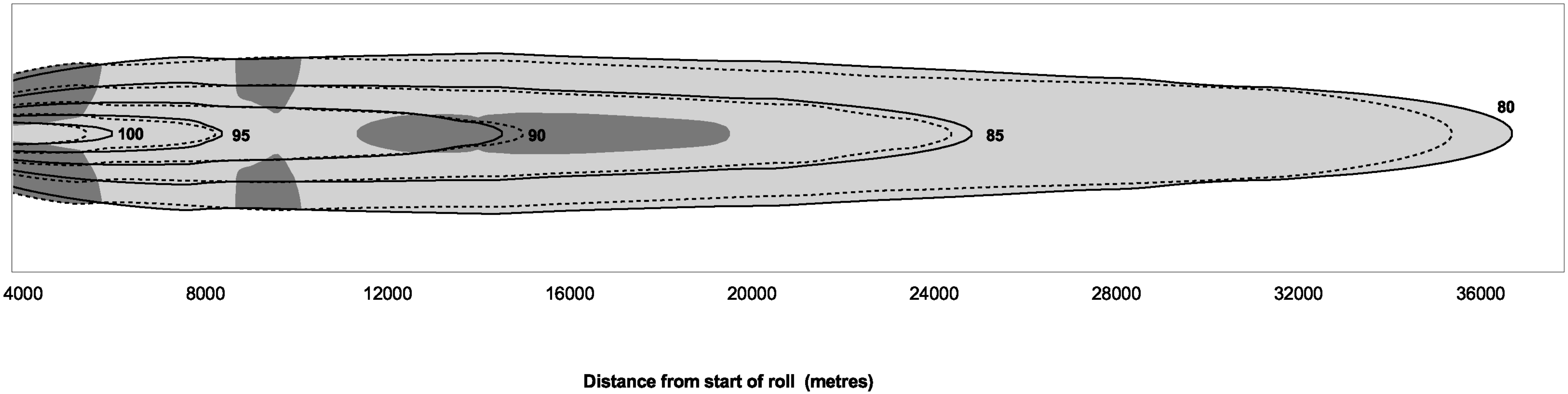


Figure 15 - Boeing 747-100 departures: comparison of SEL footprints (in increasing 5 dB steps starting at 80 dBA) for IATA 'current' (unbroken) and 'trial' (dashed) procedures - dark shading shows where SEL is increased under 'trial' procedure, light shading shows where SEL is decreased.

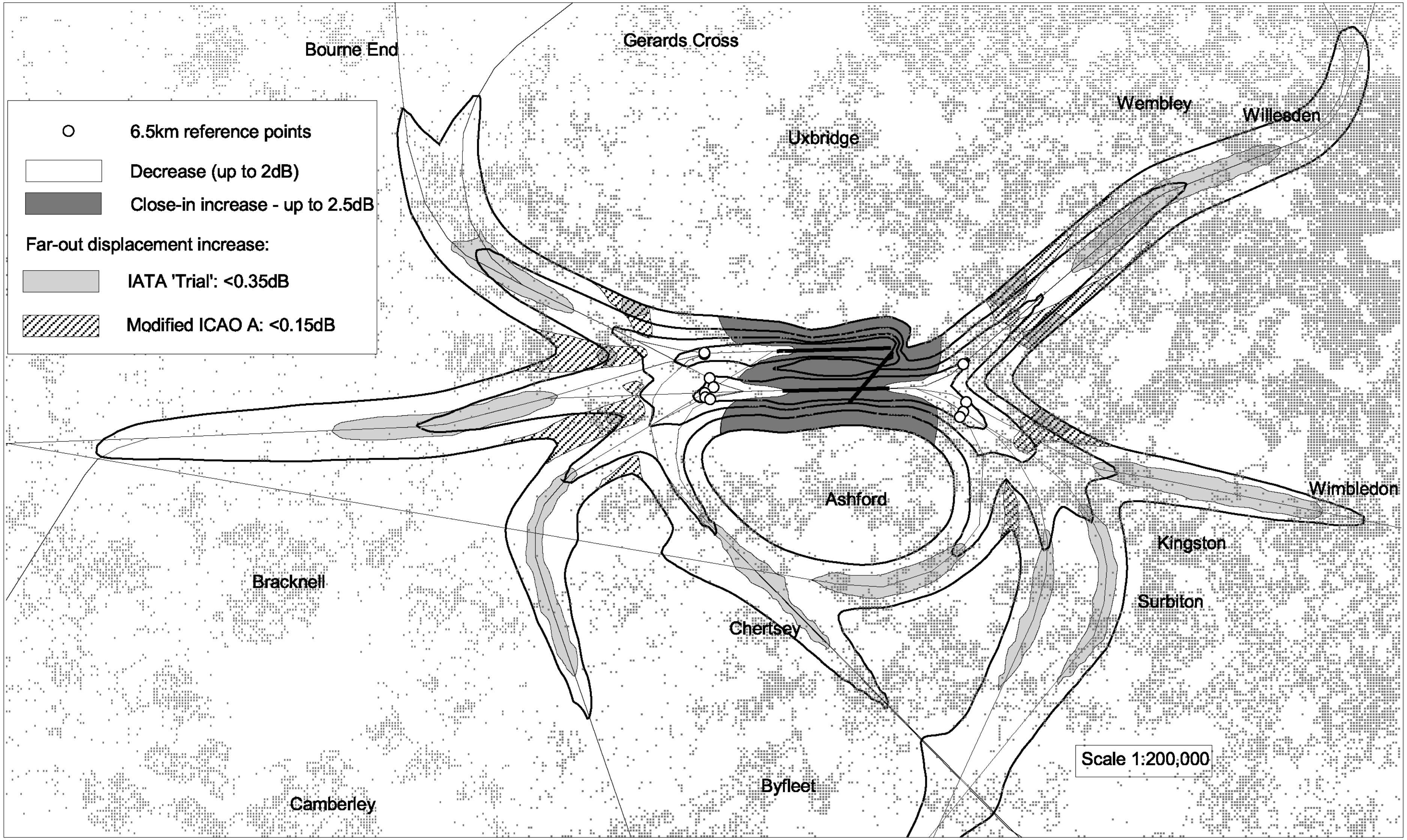


Figure 16 - B747-100 departures from Heathrow: relative Leq contours for IATA 'current' operating procedure. Contours are at 5 dB intervals. Leq changes caused by altering operating procedure are indicated by shading (IATA 'trial') and hatching (Modified ICAO A). Base map shows runways, nominal flight tracks and population pattern.

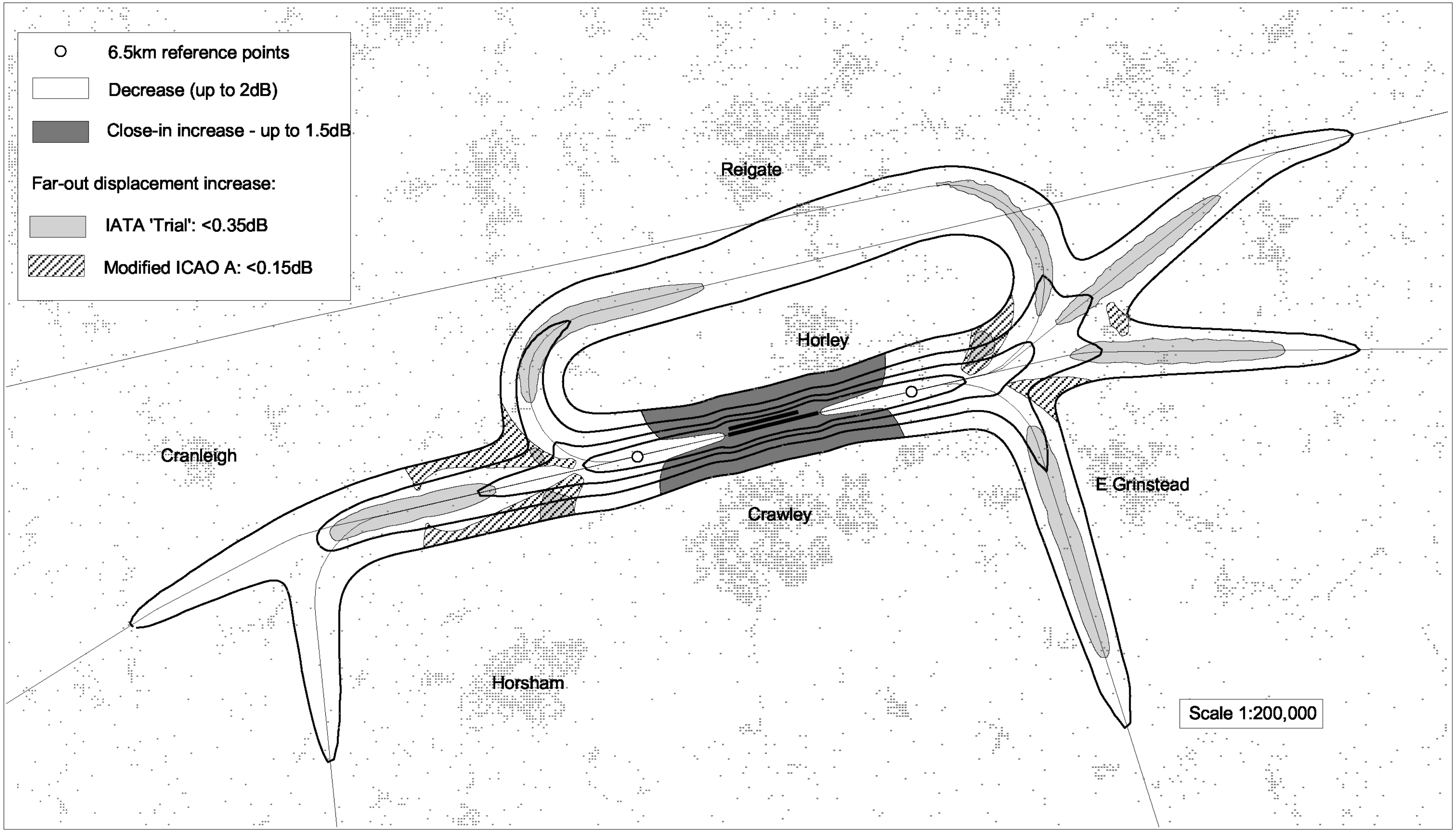


Figure 17 - B747-100 departures from Gatwick: relative Leq contours for IATA 'current' operating procedure. Contours are at 5 dB intervals. Leq changes caused by altering operating procedure are indicated by shading (IATA 'trial') and hatching (Modified ICAO A). Base map shows runways, nominal flight tracks and population pattern.

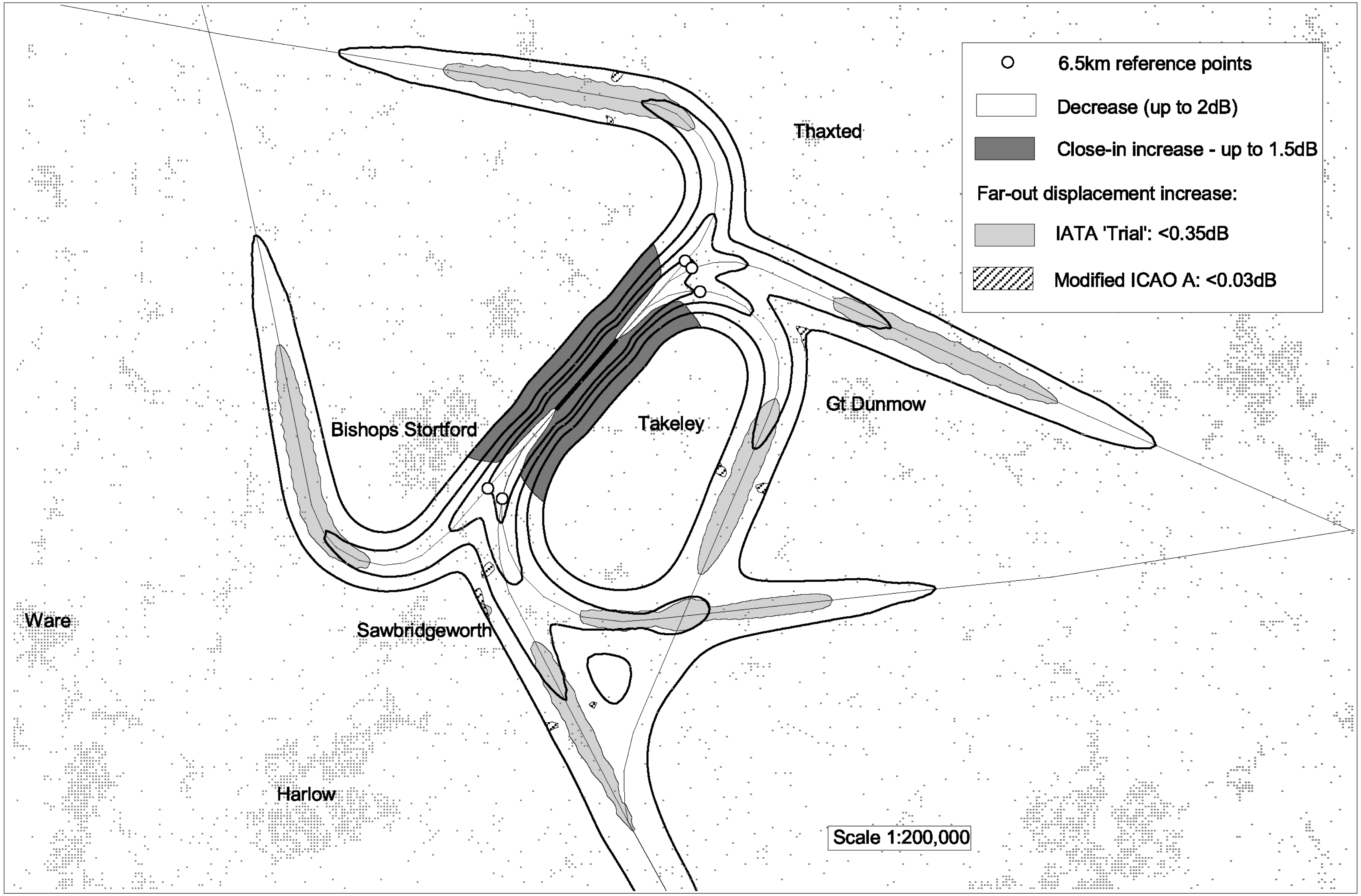


Figure 18 - B747-100 departures from Stansted: relative Leq contours for IATA 'current' operating procedure. Contours are at 5dB intervals. Leq changes caused by altering operating procedure are indicated by shading (IATA 'trial') and hatching (Modified ICAO A). Base map shows runways, nominal flight tracks and population pattern.