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A Technical Evaluation of Initial Trials of Quieter Approach Procedures at London (Heathrow) Airport - Summary Report

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ABSTRACT

This report is a 17 page summary of the highlights from two unpublished technical reports which detail measurement and analysis of trials of Continuous Descent and Low Power/Low Drag approach procedures at London (Heathrow) Airport in early 1977. It comprises the effect upon environmental noise, fuel economy and runway capacity, and it gives the success rate in achieving the new type of approach, and the factors which seem to have influenced this. The two procedures, CDA and LP/LD, are shown to be beneficial and jointly achievable as a single approach procedure.

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1 INTRODUCTION

1.1 New procedures for westerly approaches were adopted by Air Traffic Control at Heathrow for a trial period, starting on 30 December 1976. Their purpose was to reduce noise heard on the ground in two ways:-

(a) By allowing aircraft to fly at speeds higher than formerly, normally 210 kts during the approach from the "stack" reducing to 160 kts at the outer marker, thereby requiring less flap, and so reducing drag and engine power. This is called the "low power/low drag" approach (LP/LD).

(b) By encouraging aircraft to fly a continuous descent, once the final descent from stack level has begun. This reduces noise in two ways. First, it avoids the 'straight and level' segment prior to joining the glide path (typically at 3000 ft). This segment is a feature of conventional approaches and generates additional noise because the aircraft is in level flight. Second, the aircraft is kept higher, and therefore it sounds quieter, throughout the earlier part of the approach. This procedure is called the "continuous descent approach" (CDA).

The new ATC procedures were introduced to encourage both methods of approach at Heathrow because, although independent in concept, they produce noise benefits over different geographical areas. Both types of approach can be used in conjunction and both help fuel economy.

1.2 To set against these advantages is the extra workload for ATC and pilots, and a possible reduction in airport capacity. The extra workload arises from, first, the difficulty associated with sequencing the aircraft onto the runway at near-optimum spacing when they are flying faster and, second, the need to estimate the distance-to-run to threshold so that pilots may more easily judge the rate of descent they must achieve. The possible effect on capacity is associated with the former difficulty; movements are lost if the spacing is greater than is necessary for safe separation.

1.3 This paper describes a study of both the noise and the operational aspects of these new procedures which was carried out at Heathrow in March/April 1977. The primary objectives were:-

(a) to analyse the noise benefit associated with both CDA and LP/LD

(b) to observe what proportions of aircraft were carrying out each procedure

(c) to assess the effect of the new procedures on runway capacity

(d) to find out, as far as possible, what factors governed success or failure in CDA and, in particular to compare the performance of different operators and aircraft types.

The main report is split into two parts, one concerned with noise and the other with operational aspects. This summary covers both parts.

2 DESCRIPTION OF THE STUDY

2.1 Descent profiles were obtained directly from the radar, the plan position being plotted every 12 seconds on a square of clear plastic placed over the display and the height recorded from the corresponding Mode C read-out. Altogether 644 profiles were recorded. This was fewer than the target of 1000 descents, but the weather conditions were adverse, in that runways other than the 28's were in use for much of the time allotted for the study, even though this was extended from 2 weeks to 4. Noise was recorded on the ground at three sites, in line with each runway, 28L and 28R. The distances of these recording stations from the thresholds were, approximately, 10.6, 8.7 and 6.5 n.miles. A sketch of the approach sequencing area of Heathrow is shown in Fig S.4.

3 NOISE BENEFITS

3.1 LP/LD and CDA procedures benefit different geographical areas, with some overlap. LP/LD is quieter than the conventional approach over a range from about 11 n.miles to 5 n.miles from threshold. CDA is quieter over a range from about 20 n.miles to about 9 n.miles. While the LP/LD approach is quieter solely because the engine is providing less thrust to propel the aircraft in its low drag configuration, the CDA benefit comes from two sources. First there is a "thrust benefit", as a result of needing less power in descent than in level flight. Second, there is the "height benefit" because the aircraft does not make the conventional early descent with a level segment at 3000 ft until it meets the glide slope, and so the noise heard on the ground is attenuated by the greater height.

3.2 To assess the actual benefit gained from the new procedures presents problems. Ideally, one would have records of periodical monitoring of large samples of aircraft, extending backwards over many years and covering the whole area of interest. Such records do not exist in the area under the Heathrow glide-path. Even if they did, it would still not be possible to isolate the benefits from the new procedures, except perhaps over a long term. This is because the noise environment is always changing to some extent, notably in the proportion of westerly and easterly landings, and in the increasing use of quieter aircraft. Furthermore it takes a long time for new procedures to become fully effective. For example, it took three years before the LP/LD approach at Frankfurt (the most successful use of this procedure) produced an incidence rate of 90%.

3.3 The method of presenting the benefits here is therefore to seek to quantify the change in the average peak noise level at the three monitoring points, for a single aircraft on one of four approaches, and then to infer the effect on the noise and number index (NNI) by taking account of the proportion of aircraft flying each type of approach. The four approaches are categorized as:-

Class 1 : Both LP/LD and CDA

Class 2 : CDA but not LP/LD

Class 3 : LP/LD but not CDA

Class 4 : Neither LP/LD nor CDA

In round figures, the benefits associated with each procedure for the average noise reduction due to a single aircraft, are estimated to be

3 dB for LP/LD

4 dB for CDA "Thrust benefit" plus a further CDA "height benefit" varying from 0 to 5 dB depending on distance from threshold.

3.4 These figures are thought to be conservative, since the LP/LD benefit at Frankfurt has been measured at up to 6 dB (although the conditions there make for an easier application than at Heathrow). Also, some special trials at Heathrow on an Aer Lingus 737 carrying out carefully controlled descents has shown a CDA thrust benefit ranging from 3.5 to 7.5 dB.

3.5 The proportions of aircraft using the two procedures during the study period were:-

CDA : 54% at outer monitor (virtually all aircraft were descending on the glide slope at the middle and inner monitors)

LP/LD : 68% at middle monitor, falling to 39% at the inner. (The proportion of aircraft in low drag configuration at the outer monitor is not very meaningful, since most aircraft do not lower their undercarriage until after passing that point, even when there is no intention of flying on LP/LD approach).

A later study by NATS in July indicated that the success rate for CDA had then risen to 70%, but this result may not be directly comparable with the March/April figure because it was based on a more approximate assessment. No measurements of noise or observations of LP/LD were made in this study.

3.6 When the above noise benefits are combined with the numbers of aircraft using the procedures, we get an approximate estimate of the effect on the Noise and Number Index (NNI) in the neighbourhood of the glide path. This is shown in Fig S.1, for

(a) the actual proportion of traffic using the procedures, as measured in April 1977

(b) the same proportion of LP/LD but with the CDA proportion increased to 70%

(c) the ultimate possible gain when 100% are using both procedures

(d) a datum base for proportions of 20% CDA and 10% LP/LD, assumed to correspond to about 1972.

There are, of course, gains at points laterally displaced from the glide path as well. These gains are the same as for points below the glide path for the LP/LD benefit (3dB) and the CDA thrust benefit (4 dB), but the CDA height benefit reduces with increasing lateral displacement.

3.7 It will be seen from Fig S.1 that, in general, less than 50% of the potential benefit had been realised at the time of the March/April study, although more than 50% of aircraft were flying the procedures. This is an illustration of what we have termed "the law of increasing returns". It is a consequence of the NNI formula whose noise component is based upon $\overline{L}$, the logarithmic average of the peak noise heard; and indeed the same would happen with Leq if one preferred to use that index. This has the effect that the gain from an increase in the number of aircraft carrying out either procedure gets proportionately bigger as the total percentage goes up. This is shown in Fig S.2, and it indicates the importance of developing both procedures to the point where virtually all aircraft adopt them.

4 OPERATIONAL ASPECTS

4.1 The basic questions asked were:-

(a) What proportion of aircraft were achieving CDA's. and how did this compare with the practice before the new procedures were introduced?

(b) Does the success rate vary between operators and aircraft types in a significant way?

(c) What effect have the new procedures had on runway capacity?

(d) What are the main factors governing success or failure in CDA?

4.2 Table S.1 shows the CDA success rate broken down by stacks and in total. It also makes a comparison with the results of an earlier study, in April 1976, made before the CDA procedures were introduced.

TABLE S.1: PERCENTAGE OF SUCCESSFUL CDA'S

Study	From each Stack				Overall
	Biggin 22.5 n.m*	Lambourne 23.5 n.m*	Ockham 25 n.m*	Bovingdon 26 n.m*	
March/April 1977	69%	61%	41%	37%	54%
(Sample size)	(165)	(205)	(123)	(148)	(641)
April 1976	63%	52%	34%	26%	45%
(Sample size)	(84)	(113)	(76)	(82)	(355)

* Average distance to go to reach the threshold when descent clearance is given.

At this point there are three things to notice about this Table. First, that even before CDA procedures were introduced, a substantial number of aircraft (45%) were achieving them. Second, three months after introducing the new procedures the success rate had increased to 54%, a small but significant improvement. Later still, in July 1977, the measurements of CDA taken on a sample of 800 aircraft by NATS showed that the success rate had risen to 70%. This is a most encouraging result but, as pointed out in para 3.5, it may not be directly comparable with the figures obtained in March/April. For this reason, and because the details of the approach were not recorded, this study is not analysed further here.

4.3 The third point to notice about Table S.1 is that the success rate is strongly dependent on which stack is used. We shall return to this point when considering the factors that influence success.

4.4 The second question can only be answered partially. The difficulty is that when the data is divided up by airlines, or by aircraft type, the number in each class is mostly small. To obtain samples sufficiently large to show statistically significant differences between the major operators would require a formidable data collection effort - at least four times as many results as there are here. The time and effort required for such an exercise cannot at present be justified.

4.5 Such comparison as can be made is shown in Table S2 for operators and Table S3 for aircraft types. Tables S2 shows:-

(a) the total number of flights by each operator - for this purpose British Airways is split into three according to their callsign grouping. ED is largely the Continental traffic, OD is the inter-continental traffic and RD largely the domestic traffic

(b) the total successful CDA's, expressed first as a number and then as a percentage of the total

(c) the expectation of success, again expressed first as a number and then as a percentage. This expectation is based on the average performance of all the other operators, weighted according to the number flying over each beacon

(d) the difference between the actual performance and the expectation, the sign of the expression being such that a positive difference represents a better than average performance.

TABLE S.2: SUCCESS RATES FOR DIFFERENT OPERATORS

Operator	Total No of Descents (a)	Successful CDA's (b)		Expected* CDA's (c)		Difference (b)-(c)	
		No	%	No	%	No	%(of total)
British Airways (ED)	129	79	61	66	51	13	10
" " (OD)	63	30	48	34	54	- 4	- 6
" " (RD)	42	20	48	16	38	4	10
British Midland	34	14	41	13	38	1	3
Lufthansa	33	21	64	21	64	0	0
Air France	24	14	58	17	71	- 3	-13
KLM	21	14	67	13	62	1	5
Swiss Air	21	18	86	14	67	4	19
Iberia	20	10	50	8	40	2	10
Pan American	20	12	60	11	55	1	5
Scandinavian	20	11	55	12	60	- 1	- 5
Aer Lingus	17	6	35	6	35	0	0
Sabena	15	9	60	9	60	0	0
"The rest"	182	87	48	108	59	-21	-11

* The expectation is based on the performance of all operators <u>other</u> than the operator under consideration, weighted according to the number of flights passing over each beacon.

4.6 There are three points to notice here. First, that BA(ED) scored 13 more successful CDA's than the expectation (10% of the total), which is a statistically significant increase. Second that "the rest" scored 21 fewer successes than expectation (11%) which is an even more significant decrease. Third, that none of the other differences are significant, although the good result for Swiss Air is borderline.

4.7 Turning to differences between aircraft types, these are shown in Table S.3. Once again, the sample sizes for many types are too small to make meaningful comparisons, but all that made more than 7 monitored descents are listed for interest.

TABLE S.3: PERFORMANCE OF CDA BY AIRCRAFT TYPE

Aircraft	Total number of Descents	Successful CDA's No	%
Trident	107	63	59
B747	91	32	35
DC9	84	54	64
B727	51	28	55
B737	50	29	58
Viscount	40	21	53
BAC 1-11	37	16	43
Executive jets	35	19	54
Tristar	18	16	89
VC10	16	10	63
Air bus	11	5	46
DC8	11	5	46
Caravelle	10	7	70
Other aircraft	25	13	52
Total/average	644	347	54

The success rate for B747's is significantly below the average for all other types. Even allowing for the fact that many B747's fly via Ockham - a difficult approach as we have seen in Table S.1 - the expectation for the average of all other types would be 50 successes compared with the 32 observed for B747's. The success rate for the Tristar looks very promising, but the sample is too small for the difference to be other than marginally significant.

4.8 Runway capacity was measured in two stages. First the "service rate" for the runway was found. This is the rate at which aircraft can be landed for a typical traffic mix when there is a continuous queue. In other words, the aircraft are as close-packed as the No 2 Radar Director can make them while maintaining safe separations. The second stage was to apply a factor of 0.96 to the service rate, which experience has shown gives the capacity corresponding to an average delay of 5 minutes over the three peak hours.

4.9 Measurements of inter-arrival times were taken for all aircraft landing during the study period (not just for the aircraft whose descent profile was measured), and those time intervals where the second aircraft was known to be close packed were used to determine service rate. The results showed a drop of about 5% in capacity (from 32.3 arrivals per hour to 30.7). However it was thought possible that this drop was associated with the process of learning how best to sequence the aircraft at the higher speeds, and that it might therefore be only a temporary loss. Later measurements taken in August 1977 showed that the lost capacity had indeed been completely recovered.

4.10 Turning now to the factors that govern success in achieving CDA's, careful analysis has been made of all the relevant data in trying to identify them. This analysis was concentrated on: the presence or absence of an estimate of the distance to run to threshold; the timing of such messages; the accuracy of such messages; path-stretching; the distance to go when descent clearance was given; and the effect of wind in relation to stacking.

As regards the accuracy of distance to run estimates by ATC, it was found (as was the case in 1976) that the estimates show a systematic bias towards being too short. This is shown in Table S.4.

TABLE S.4: ACCURACY OF DISTANCE TO RUN MESSAGES

Range from threshold	Mean error (and sample size) in n.miles for different stacks				
	Biggin	Lambourne	Ockham	Bovingdon	All Stacks
5-10 n.miles	-0.06 (63)	+0.05 (85)	-0.12 (67)	-0.04 (85)	0 (300)
11-15 n.miles	-0.28 (116)	-0.42 (126)	-0.43 (77)	-0.50 (82)	-0.4 (401)
16-20 n.miles	-0.91 (104)	-0.60 (100)	-1.02 (45)	-1.21 (53)	-0.9 (302)
Greater than 20 n.miles	-2.86 (78)	-1.97 (122)	-3.22 (79)	-3.47 (90)	-2.8 (369)

4.12 Surprisingly, it was found that during this study, the distance to run messages did not affect the chance of achievement of CDA - and this applied to the presence or absence of messages, their timing and their accuracy. The dominant factor governing achievement of CDA's was the range from threshold when descent clearance was given. This is shown clearly in Table S.5 which also shows how little effect there was in giving a distance to run message (DTRM) with the descent clearance.

TABLE S.5: THE EFFECT OF RANGE FROM THRESHOLD AT WHICH DESCENT CLEARANCE IS GIVEN ON ACHIEVEMENT OF CDA

	Range from threshold (nautical miles)						
	18	19-20	21-22	23-24	25-26	27	Total
% CDA, DTRM given	100	84	67	58	43	20	56
(No of approaches)	(10)	(55)	(81)	(78)	(56)	(60)	(340)
% CDA, No DTRM given	40	84	73	62	30	26	51
(No of approaches)	(5)	(38)	(51)	(50)	(43)	(84)	(271)
% CDA , all aircraft	80	84	69	59	37	24	54
(No of approaches)	(15)	(93)	(132)	(128)	(99)	(144)	(611)

The effect shown in this Table is illustrated in Fig S.3.

4.13 There is also some effect due to wind. A wind speed greater than 15 knots at 5000' reduces the chance of a successful CDA, and reduces it more for Ockham and Bovingdon traffic than for Lambourne and Biggin. This is probably due both to the longer flights from those stacks and the bigger changes in heading.

4.14 The combination of the longer distances to go to threshold from the western stacks and the effect of wind account for the marked variation in CDA performance between stacks that was noted in Table S.1. The lack of effect that good (or bad) estimates of distance to run had on the success rate needs explanation. The most likely one is that pilots fell into three categories, as far as CDA was concerned. There are those who were thoroughly familiar with the object of the trial and were familiar with all the Heathrow approaches. This applied especially to British Airways European and Regional Divisions, who were given special questionnaires by their company to fill in. This would certainly make them alert to the fact that the trial was on. The second category includes those pilots who were familiar with Heathrow approaches, but were not as alive to the need for CDA, having no reminder before them. Such pilots might well be found among the European operators. Thirdly are the pilots who are comparatively rare visitors to Heathrow, and who had no reminder of the new approach procedure. Such are typified by "the rest" in Table S.3. A reasonable hypothesis to explain the observations is that pilots in the first category were using their local knowledge, coupled with distance readings from the London DME to control their descent. Thus success or failure was not much affected by ATC messages. For the second category, some would try to use the estimates to control their descent, perhaps also using visual reference, while others would simply descend at a standard rate when clearance was given. Any effect of DTRM accuracy would be swamped by the effect of the range when clearance was given, owing to the reduced sample. In the third category, the situation would be similar, except that a smaller proportion of pilots would be likely to attempt CDA.

4.15 This hypothesis would go far to explaining the observed results, since any aircraft given descent clearance at 7000 ft with 22 n.miles or less to go would often achieve a continuous descent without special effort, for 22 miles corresponds to a continuous 3^{o} descent. For distances of 25 n.miles or more, one would expect a marked drop in the success and this is what is observed to happen. The high winds which blew on many occasions provide an added difficulty, and help to explain why the overall results were not better.

4.16 When considering how to improve the success rate, there are two approaches that could be tried. First, it is highly desirable that all aircraft approaching Heathrow should be reminded that continuous descents are in use. This is now being done, by means of a message on the ATIS. Second, pilots need to be educated into understanding that they must choose a rate of descent appropriate to the estimated distance to run, and to correct this rate in the light of subsequent up-dating estimates. This rate of descent can be calculated fairly readily by working out the flying time to get to a point 10 n.miles from threshold, and dividing this into the height that has to be lost to reach 3000' at that point. For example, if the aircraft is flying at 210 knots ground speed ($3\frac{1}{2}$ n.miles per minute) and gets an estimate of 25 miles to go when it is at 7000' there:-

$$\text{Time to reach 10 mile point} = \frac{25-10}{3.5} = \frac{15}{3.5} = 4 + \text{minutes}$$

$$\text{Height to lose} = 7000' - 3000' = 4000'$$

Rate of descent should be a bit less than 1000 ft/min, say 950 ft/minute

4.17 Once this is understood and becomes the practice, the distance to run messages should become more important. There will still be pilots who prefer to use their own distance reckoning - although they will have to take path-stretching into account. One way of partially overcoming this difficulty is to start the descent at the rate for the estimated distance but to reduce it when at about 4000', until the pilot is reasonably sure that he has not more than 14 n.miles to go. An updated estimate of distance from ATC would be a help here. A DME co-located with the glide path aerial should also be of help to pilots, seeking to use on-board information to fly optimum descents.

5 OPERATIONAL BENEFITS

5.1 One of the attractions of the new procedures for operators is saving in fuel. Estimates of the amount saved in comparison with the old procedures have been made for each of the four modes of descent, from final beacon to threshold. These estimates are based on fuel flows at different speeds, flap and undercarriage positiions for four categories of aircraft classified by weight.

5.2 Table S.6 shows the estimated fuel savings based on average distances flown from stack to threshold, at typical speeds. These distances were found to be about 1 n.mile longer than pre-1976 approaches, probably because of difficulty in sequencing aircraft at the higher speeds.

TABLE S.6: ESTIMATED FUEL SAVINGS (Kg) PER DESCENT ASSOCIATED WITH NEW PROCEDURES RELATIVE TO PRE-1976 TYPES OF APPROACH - WESTERLY LANDINGS

Type of descent	Aircraft weight category			
	V.Heavy (eg B747)	Heavy (eg B707)	Medium (eg Trident)	Light (eg Viscount)
LP/LD and CDA	225	226	31	15
LP/LD not CDA	207	222	28	14
CDA not LP/LD	180	205	26	13
Not CDA nor LP/LD	162	202	24	12

It will be seen that there are still comparatively large fuel savings made even with the "not CDA nor LP/LD" approach. This is because the savings are dominated by the contribution from increasing the speed off the stack from 170 knots (pre-1976) to 210 knots. Since this speed is now normally given to all aircraft capable of flying it, all save fuel irrespective of their mode of descent.

5.3 To convert the savings per descent listed in Table S.6 into an annual total, we multiply each entry by the appropriate number of aircraft in each descent category per year. Assuming that the savings for easterly landings are the same as they are for westerly - a conservative assumption - the total annual saving is about 10M kg of fuel. In monetary terms, taking fuel as costing 10p per kg say, this gives a benefit to operators of £1M per year.

5.4 Two other figures are of interest. First, the extra annual savings that would accrue if all operators carried out CDA and LP/LD would be about £0.15M. Second the saving that would result if the extra mile that was being flown on approach at the time of the study were to be recovered (as a result of greater familiarity in sequencing aircraft at the higher speeds) would be about £0.2M

6 CONCLUSIONS

6.1 The average peak noise generated by an aircraft at a point directly under its approach path is reduced by the following amounts as a result of the new procedures.

For a lower power/low drag approach :	3 dB
For a continuouse descent approach :	4 dB "thrust benefit" plus a "height benefit" which varies from 0 dB at 9 n.miles from threshold to 5 dB at 15 n.miles

The way that these benefits combine at different distances from threshold is shown in Fig S.1.

6.2 The proportions of aircraft flying the new procedures, in April 1977, were:-

LP/LD - 68% at 9 n.miles and 39% at 6.5 n.miles

CDA - 54%

6.3 British Airways (European Division) achieved 61% CDA, significantly better than average. Operators who make comparatively few flights into Heathrow achieved 45% CDA, significantly worse than average.

6.4 Boeing 747's achieved only 35% CDA, significantly less than the average for other types.

6.5 During the period of the study, the main factor determining success or failure in achieving CDA was the distance to go to threshold when clearance to descent was given. This is shown in Fig S.3.

6.6 ATC tended to underestimate the 'distance to go' by an amount which increased roughly with the square of the distance from the point of becoming established on the localiser, having a value just under 3 n.miles for total distances to go to threshold in excess of 20 n.miles.

6.7 The accuracy of the distance to run message had little or no effect on the CDA success rate in this study. This could be due to no reminder being given at the time of the study, to the majority of pilots that the new procedures were in force; the success of British Airways could well be due to the greater awareness of their pilots, coupled with greater familiarity of the approach patterns.

6.8 The current saving that the new procedures give to Operators is estimated to be about £1M per year. The potential for further saving is about £0.15M per year if all aircraft flew both CDA and LP/LD approaches. There would be another £0.2M saved if the average distance from stack to threshold were to be reduced by 1 n.miles, bringing it down to the distance that used to be flown pre-1976.

6.9 There was a drop in runway capacity of about 4½% in comparison with previous summer studies. Later (August 1977) measurements show that this loss has been fully recovered.

6.10 High winds reduce the chance of a successful CDA, perhaps because of the change in ground speed they produce when the aircraft is turning.

6.11 A limited study by NATS in July 1977 showed that the proportion of successful CDA's had risen to 70%. This is very encouraging, although the results may not be strictly comparable with the March/April figures, because of differences in method.

6.12 In order to improve the success rate of CDA's in the future, it is suggested that the following steps be taken, wherever possible:-

(a) A reminder be given that CDA is the normal pattern of approaches at Heathrow - this is already being done by means of the ATIS broadcast.

(b) Descent clearance from 7000 ft should preferably be given at the moment when the aircraft is estimated to have about 22 n.miles to go to touchdown.

(c) Distance to run estimates should be given by ATC when descent clearance is given and updated at least once when the aircraft has about 16 n.miles to go. This is particularly important in high wind conditions or if the aircraft has an extended downwind leg due to sequencing.

(d) When given clearance pilots should select an initial rate of descent that is based on their estimated time of flight to a point 10 n.miles from threshold, at which point they should aim to have just reached 3000'. Pilots should monitor their height in the light of updated estimates (or from their own estimates when these are being made) and adjust their rate of descent accordingly.

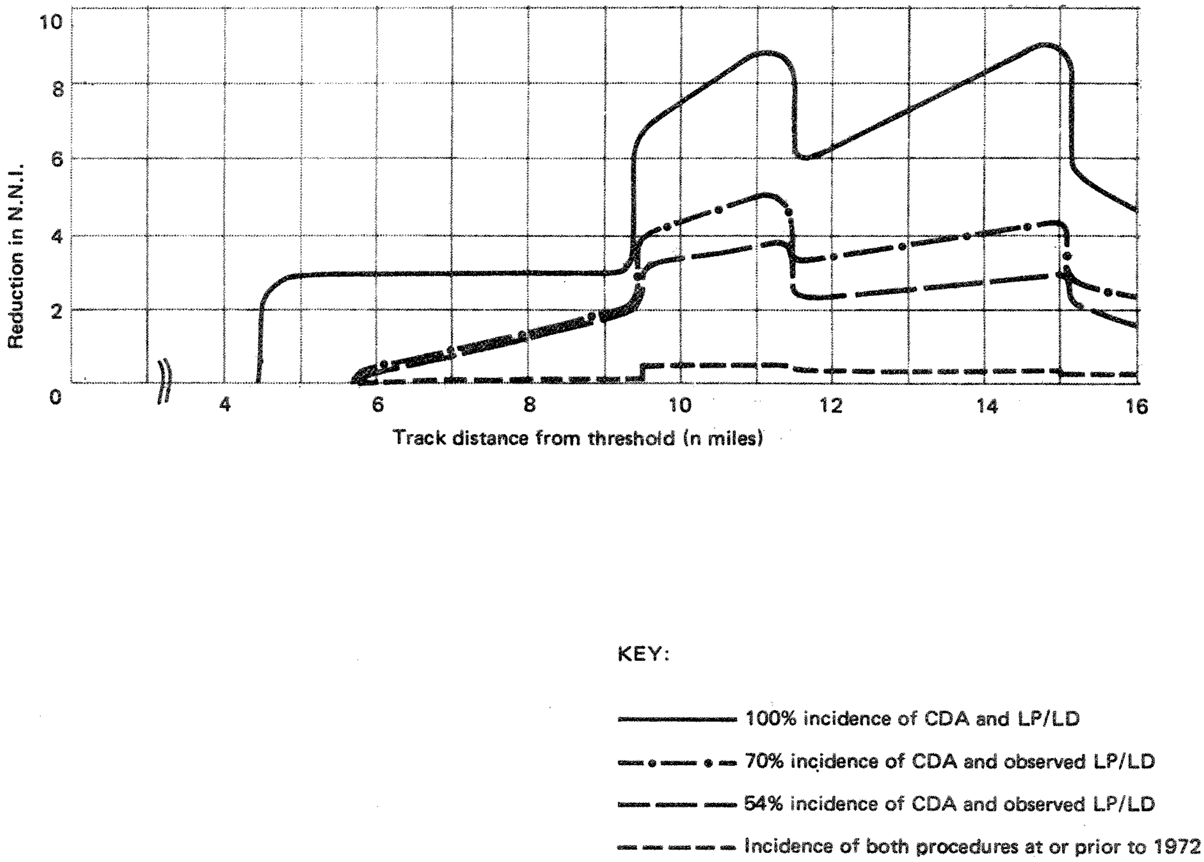
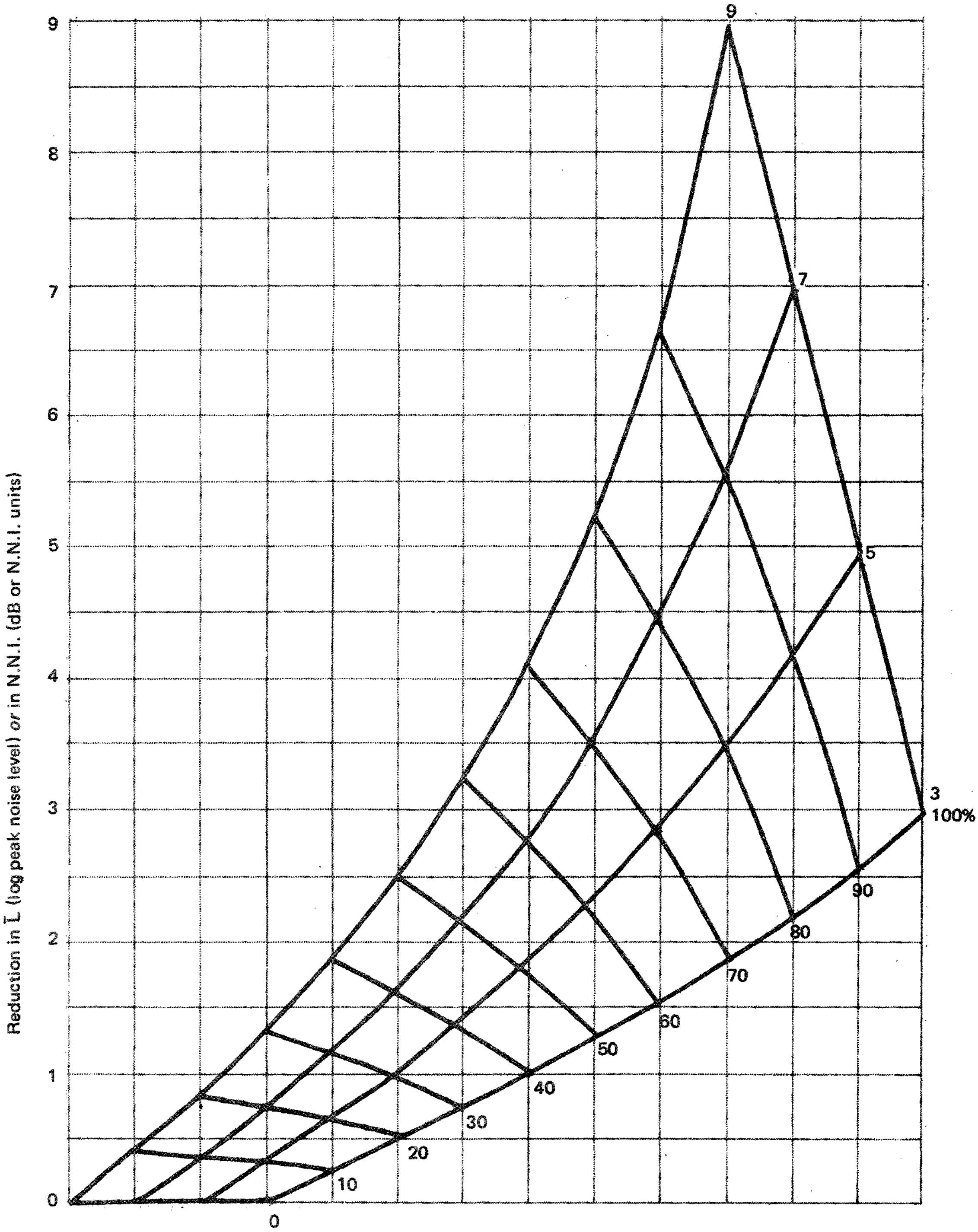


Fig S1 Reduction in N.N.I. under the flight path (idealized)



N.B. These curves assume that the incidence of the procedure is uniform across the traffic mix.

Fig S2 **Reduction in L̄ or N.N.I. resulting from the noise reduction of a procedure for a given incidence of that procedure (carpet plot)**

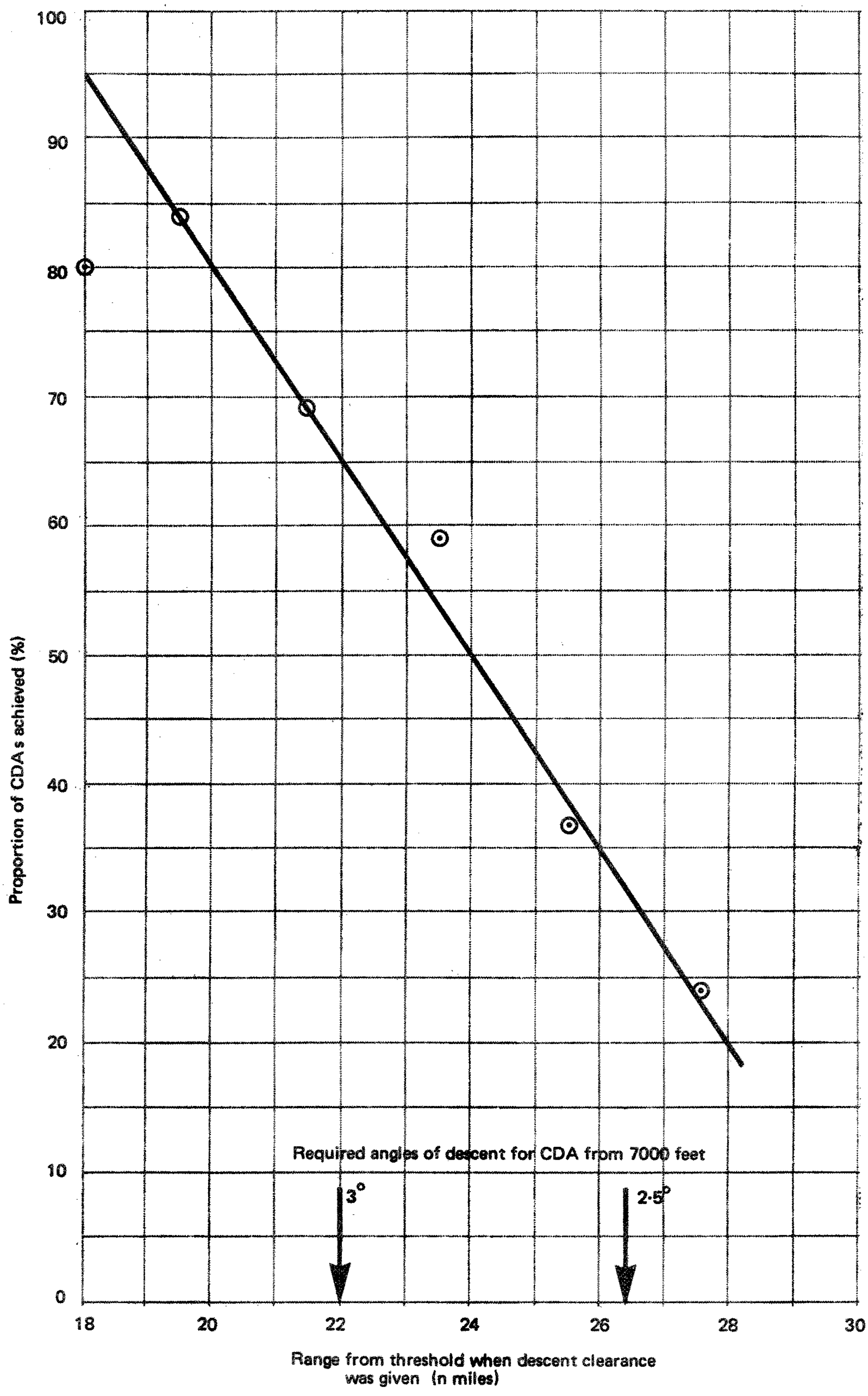


Fig S3 **Relationship between achievement of CDA and distance from threshold at which descent clearance was given**

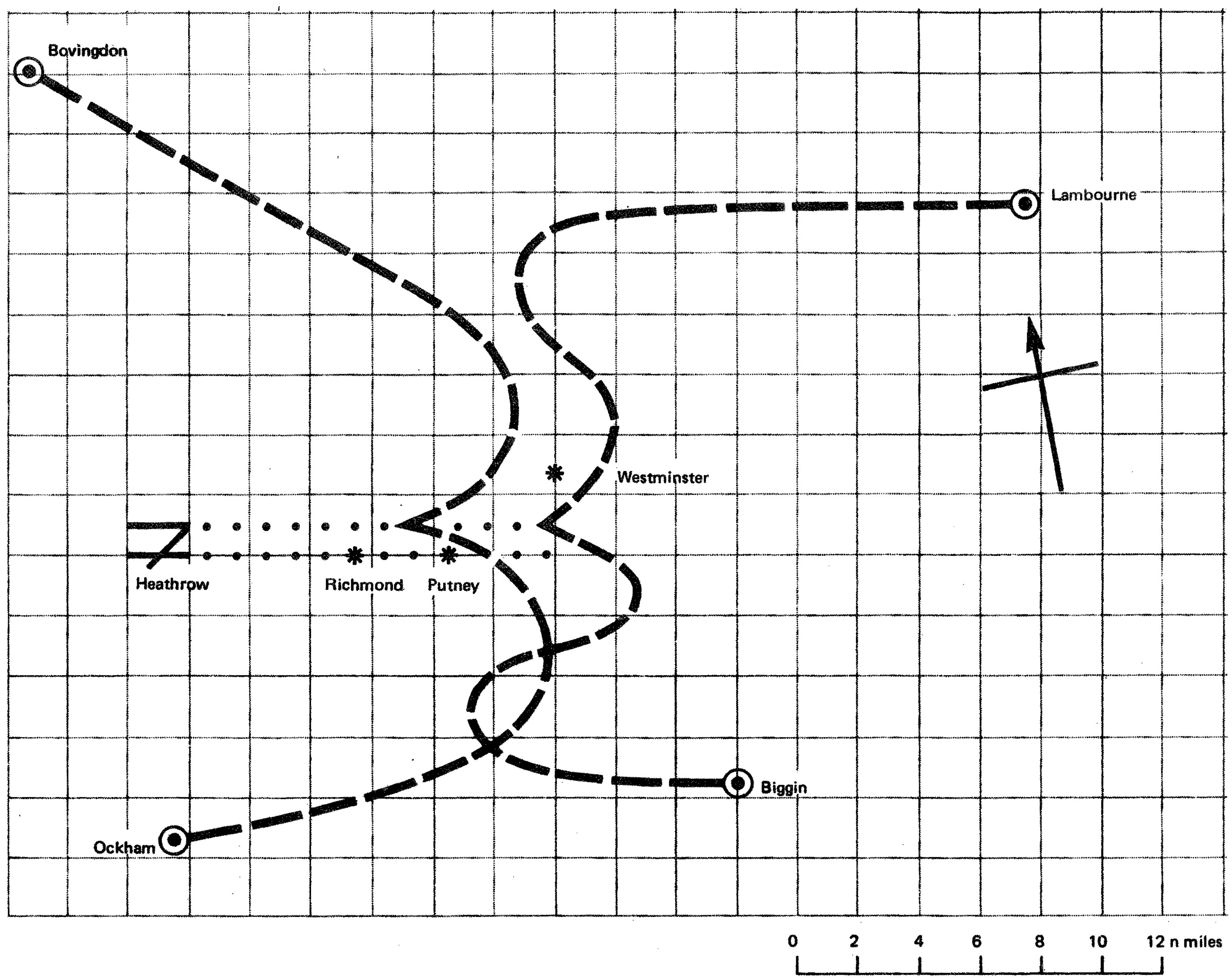


Fig S4 Approach sequencing area — Heathrow