AN ASSESSMENT OF OPTIONS
FOR EXPANDING THE CAPACITY
OF HEATHROW AIRPORT

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June 2007

Summary

The Government is considering ways of expanding the capacity of Heathrow Airport and has asked for comments. Two options are being proposed: (1) changing the mode of operation from segregated to mixed mode in which landings and takeoffs share the same runway and (2) construction of a third runway. This paper considers these options from the point of view of runway capacity.

Proposal (1) shows only modest gains in capacity, but has the advantage that it allows greater spacing between arrivals which may be necessary in future to allow for turbulent wake effects. Proposal (2) shows greater gains, sufficient for forecast increases in traffic demand, but has limited development potential and becomes less attractive in the longer term when more wide bodied aircraft, unable use the short runway, are expected to enter the traffic mix. Even with a new runway the capacity of Heathrow is shown to be less than that currently planned for Paris CDG for 2010.

CONTENTS

INTRODUCTION

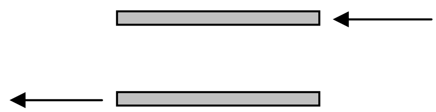
The Government has announced that it is considering options for expanding the capacity of Heathrow, including the possibility of constructing a new runway. Many people are opposed to such plans and have formed pressure groups to fight the proposals. However while the environmental disadvantages are being vigorously debated little is being said or published on the potential benefits to be had in terms of improved traffic handling ability. In particular I can find little published information on the gain in airside capacity that would be likely to result from current proposals. Having some background in the subject myself, I decide to carry out my own investigation.

I have restricted myself to runway capacity, which I consider the most fundamental factor, ignoring other elements such taxiways, stands and terminal handling. I use a simple approach based on observed or calculated intervals and queueing theory. Although this is not as detailed or sophisticated as the simulation model approach favoured within the Industry, it does have the advantage that the assumptions and reasoning are visible and open to test. The results are sufficiently accurate for planning purposes.

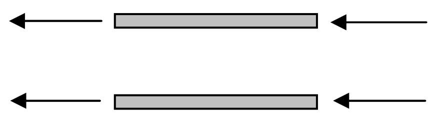
This is only a preliminary report and more work needs to be done to confirm the assumptions and data values. However I hope what I have done so far may raise some relevant questions.

MODES AND CONFIGURATIONS STUDIED

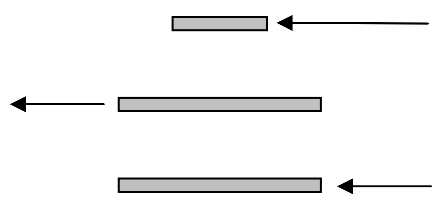
Segregated Mode



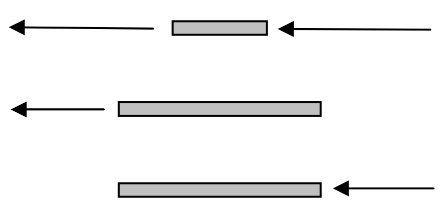
Mixed mode



Three runways: segregated Mode



Three runways: mixed mode



HEATHROW TODAY

The original plan for Heathrow in 1946 when it opened was to have nine runways in total based on intersecting equilateral triangles. Three of the runways were planned to be situated north of the Bath Road, but these were never built. However the land was 'reserved' in case it might be needed in the future. Over time the other runways in the original Heathrow plan have been built over such that there are now only two main runways, a northern runway - 27R/09L and a southern - 27L/09R, plus a short cross runway, 23/05, which is seldom used and is not a factor in the context of this paper.

For what is effectively a two runway airport Heathrow handles a very large volume of traffic indeed. Comparable airports around the World have three, four, or more, main runways. This is one of the points made by airports operator BAA to argue that Heathrow needs another runway [1].

In 2004 the airport handled 69 million passengers annually (mppa) with 47000 Air Traffic Movements (ATMs) [1]. There are ambitions plans to expand to handle 90 million passengers in the future. To this end Terminal Five is being constructed to relieve congestion on the ground, and there is plan to replace Terminals One and Two with another very large terminal, Heathrow East. But the number of ATMs allowed is capped at 48000 per annum, and indeed the runways as presently operated could not realistically handle any more as I show later. Unless more airside capacity is provided the only way the airport can achieve its growth targets is by increasing the number of passengers per ATM.

The runways are operated in 'segregated mode', that is to say one runway is used for take-offs and the other for landings. When the airport is operating in a westerly direction, the choice of the runways is changed periodically to alleviate the noise nuisance to residents in Hounslow living immediately under the arrival flight path. This is usually done at 3pm to equalise the nuisance among those affected. With easterly operations however, because the arrival flight path is over open country, the runways are not changed and the northern is always used for landings.

A complicating factor is the existence of Terminal Four. This terminal is situated south of the southern runway. Thus aircraft using Terminal Four must cross this southern runway at some stage and interrupt the flow of 'live' traffic on the runway. For instance when the southern runway is being used for take-offs, aircraft that have just landed on the northern runway must taxy across the southern runway to reach their stands at Terminal Four. Similarly if the southern runway is being used for landings, flights departing from Terminal Four must cross the runway to reach their take-off point. The significance of this will be explained later when assessing the effect this has on the capacity of the runway. The crossing point is about one third of the way down the runway from the eastern end.

Arrivals

In this section I analyse capacity of a runway to accept arriving traffic. I proceed in two stages. Firstly I consider the theoretical maximum number of ATMs that could be handled in a typical hour of operation. This assumes that the runway is in continuous use and that there are no gaps in the traffic offering. This is an ideal that cannot be achieved in practice because flights do not arrive at regular intervals or exactly when expected. Some allowance has to made in order to avoid subsequent congestion and queueing. I therefore apply a "utilisation factor", usually around ninety percent, based the results of Queueing theory, see Appendix. If traffic is planned at or below this practical level no undue delays should result. Above this level however severe congestion will set in. In other words my methodology can be summarised as:

$$\text{Practical Capacity} = \text{Theoretical Capacity} \times \text{Utilisation Factor} \quad ....(1)$$

The theoretical capacity is determined by the average minimum interval that can be achieved between successive landings. Controllers tend to aim at achieving a gap of about 3 nm between successive aircraft on the approach path. This figure was historically based on the accuracy of radar in the terminal area, but nowadays controllers must also take account of the effects of turbulent wake especially behind large heavy aircraft. The question of how much separation to allow for turbulent wake is currently the subject of considerable research and debate within the aviation community. The international organisation ICAO have suggested standards, which include separations of 4 nm for heavy aircraft following a heavy aircraft and 6 nm for a medium weight aircraft following a heavy. These separations are significantly larger than those currently being achieved at Heathrow. However the ICAO figures are not universally accepted and the subject is still controversial. For instance research by the Dutch aviation authorities suggest that the presence of cross winds and angle of descent may minimising the wake effect [3]. It is clear that if the ICAO recommendations were to be implemented at Heathrow the traffic would be slowed significantly, and handling capacity seriously reduced.

Speed on the approach for the current generation of jet aircraft is on average 145 kts [2]. But this is an *airspeed*. To get an appropriate groundspeed we need to take account of wind. Data indicates that an average along runway component of surface wind is 10kts [3]. This reduces the 145kts airspeed figure to 135kts. With 3nm as the spacing and this speed I get a figure of 80s for the minimum time interval between successive landings. This gives me a Theoretical Hourly Capacity of 45 movements. The figure of 80s is in approximate agreement with my own observations.

I now consider the Utilisation factor. To find an appropriate value I use the queueing formula given in Appendix. I need a delay figure to put into the formula. This represents the amount of delay that can be tolerated in practice. Here I rely on the FAA's advice to US airport operators and planners contained in their Airports Master Plans circular [4]. The relevant quote from this circular is the following: "when average delays per operation reach 4-6 minutes the airport is approaching practical capacity and is generally considered congested". I take the midpoint, namely 5 minutes, as the criterion for capacity assessment, and choose the utilisation that corresponds to this figure.

Controllers can usually accommodate delay of this order by path stretching and will only occasionally have to resort to holding which is clearly undesirable.

Using this 5 minute criterion I obtain, using the queueing model, a Utilisation of 88.2 percent. Equation (1) then yields a Practical Hourly Capacity of 39.7 movements. In summary:-

Theoretical ATMs/hr	Utilisation %	Practical ATMs/hr
45	88.2	39.7

Table 1. Practical Hourly Capacity

The Practical Capacity is close to the figure of 40 movements per hour which is the figure used by planners when allocating slots at Heathrow. Fig 1. shows that the hourly demand is in fact scheduled to be close to this 40 movement limit for most of the day.

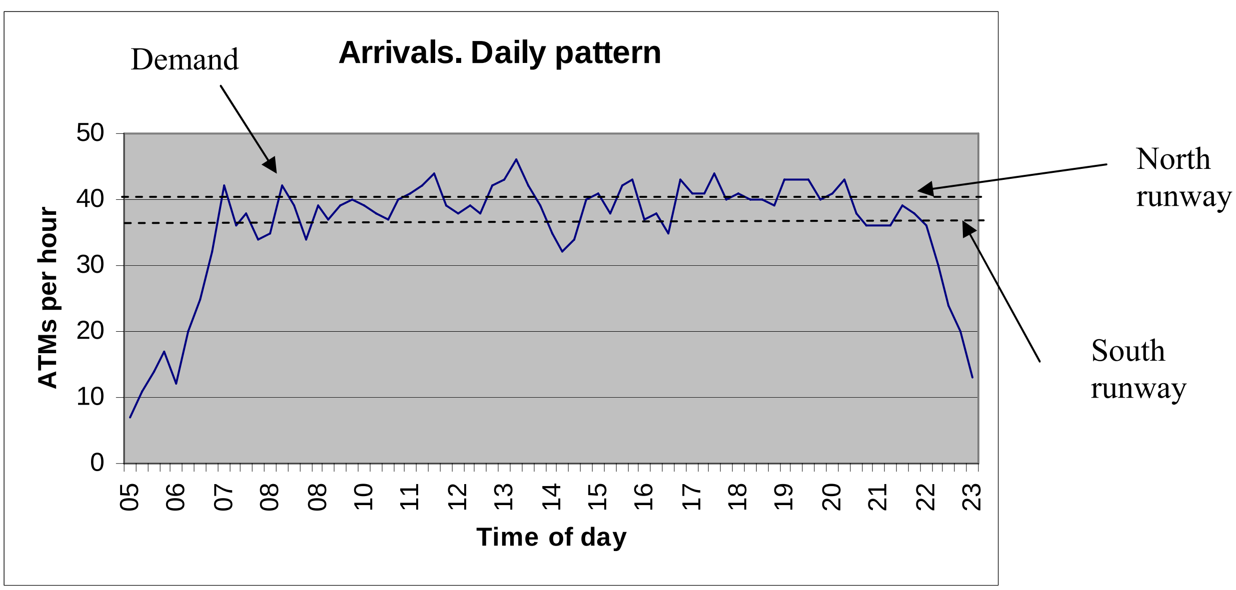


Fig 1. Demand against capacity. Landing runway

The above discussion relates to the situation without crossing aircraft. With crossers, i.e. when the southern runway is being used for landings as explained above, the capacity needs to be reduced to account for the fact that crossings interrupt the landing flow. A reasonable assumption, based on observations of ground movements at Gatwick [5], is that a gap in the landing stream of about 30s is needed for each crossing. Since 20 percent of flights use Terminal Four [8], the mean (minimum) arrival interval needs to be increased to (0.8 x 80 + 0.2 x 110), i.e. to 86s. Using the 88.2 percent utilisation factor as before, I get the following figures for the capacities:-

Theoretical ATMs/hr	Utilisation %	Practical ATMs/hr
41.9	88.2	36.2

Table 2. Capacities with crossing aircraft

The practical capacity is now below the demand, see Fig 1. In other words the runway will have difficulty coping with the traffic being offered. In fact, comparing a demand at roughly 40 per hour with a theoretical capacity of 41.9, the utilisation works out at 96 percent. At such a high utilisation delays tend to accumulate because there is insufficient slack in the system to keep them in check.

Fig 2 [1] shows how the mean delay increases with time, starting from no aircraft in the queue and no delay, reaching the 5 minute average delay point after about forty minutes and then carrying on rising to about 14 minutes after 10 hours. The reason for the shape of the curve -rising steeply at first and then flattening off - is that, as the queue builds up the 'server' becomes gradually busier and tend to process the queue faster. If allowed to continue the queue would continue to build to a give long term average delay figure of 17 minutes.

[1] Based on the diffusion model, see ref [9]

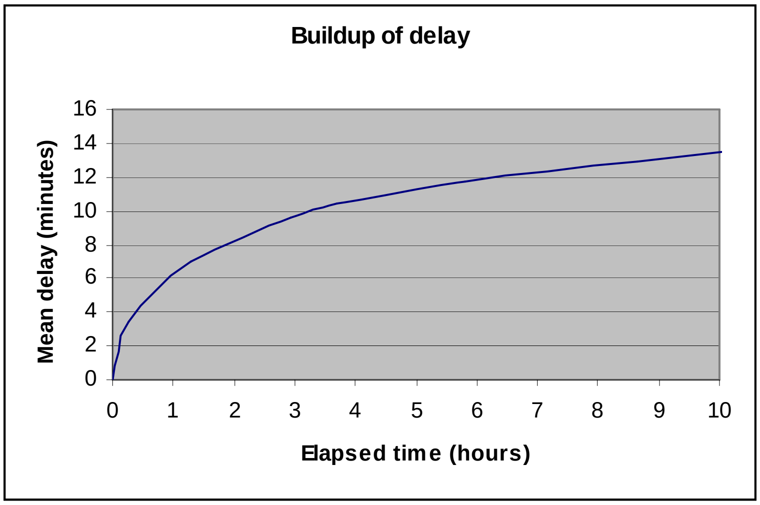


Fig 2. Build up of delay

As mentioned previously, when westerly operations are taking place runways are changed halfway through the day for noise reasons, so the southern runway never has to handle landings for more than 8 hours at a time. Even so during this time the delay can average of 10 minutes or so and this is clearly undesirable.

Departures

The departure situation is less critical than the arrival situation because runway service times are shorter, giving increased traffic handling capacity. Observations [5] indicate that 30s, with a standard deviation of 5s, is an appropriate figure to take for average takeoff duration . At Heathrow most aircraft turn away from the runway centre line in different directions immediately after initial climb out, so considerations of turbulent wake are less important in most cases. An extra 35s is added to allow for the initial climb out before the next departure is released, giving an overall figure of 65s with a standard deviation of 10s.

Using a similar logic for crossing traffic to that explained above I get the following results.

	Theoretical (ATMs/hr)	Utilisation %	Practical (ATMs/hr)
No crossers	55.4	0.90	49.9
With crossers	50.7	0.89	45.1

Table 3. Capacity of takeoff runways

It is clear that these capacities are well able to handle the traffic offered, which, as Figure 3 shows, averages between 40 and 50 movements and hour. Incidentally we can see why the northern runway is used for landings when the airport is working in an easterly direction and there is no need to alternate runways for noise reasons. The crossing problem is far less severe for departures so it is sensible to use the northern runway for arrivals.

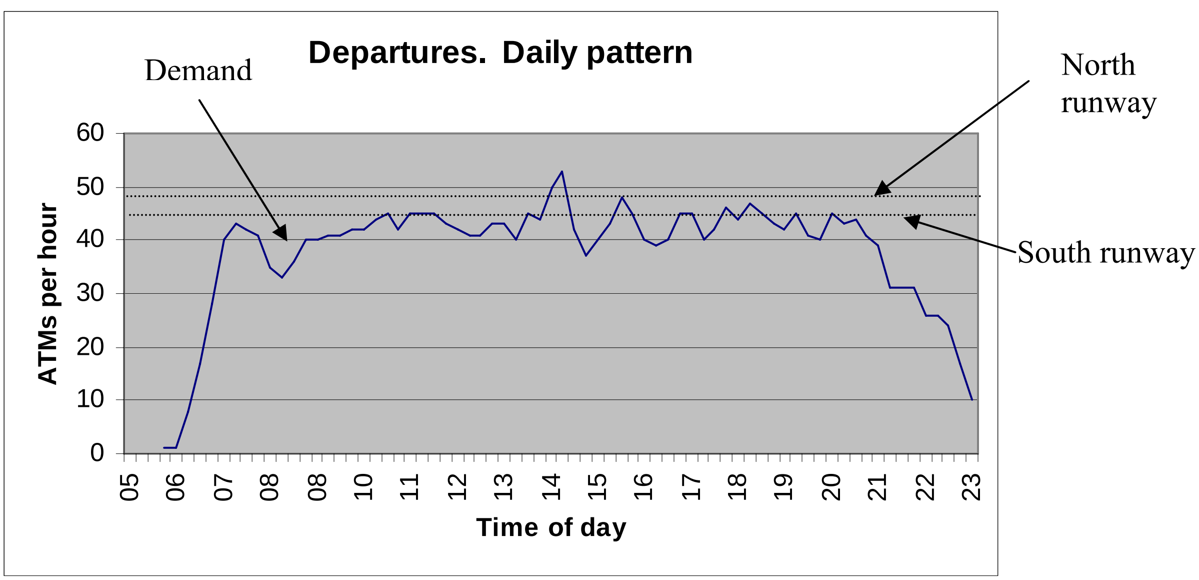


Fig 3. Departure pattern

THE MIXED MODE OPTION

I now turn to the first expansion option: mixed mode working. Because the intervals between movements can be made shorter if landings and takeoffs are interleaved on the same runway, this mode of operation offers the possibility of higher throughput. At Heathrow air traffic controllers have traditionally resisted this way of working, arguing that safety could be compromised. Although a lateral spacing between runways in excess of 4300 ft is deemed to be acceptable internationally, it must be admitted that Heathrow, with its two parallel runways only about 5000 ft apart laterally, is a rather marginal case for mixed mode working.

To get an idea of how mixed mode works I went to Gatwick to look at the operation there. Gatwick is the busiest airport in the UK having only one runway, probably the busiest such airport anywhere in the World. For much of the day it is working at capacity and therefore is a good model for mixed mode working at Heathrow.

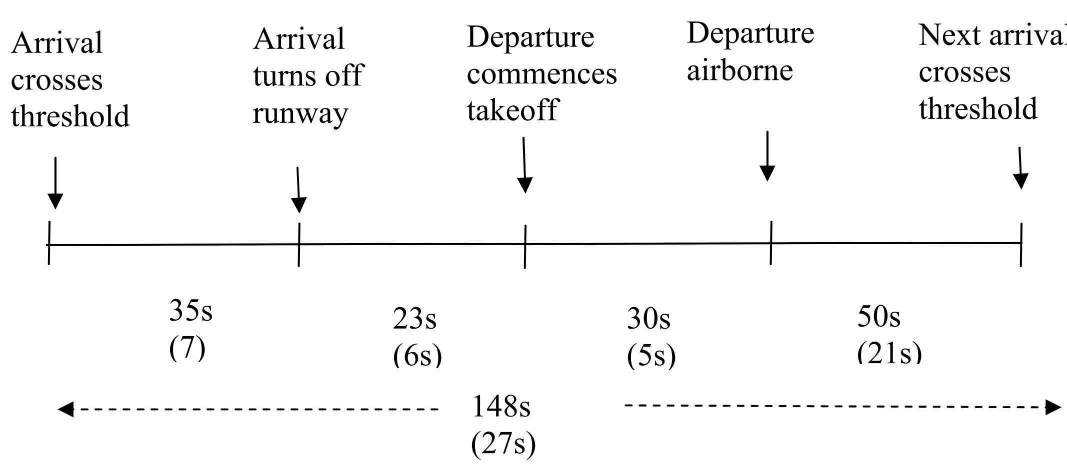


Fig 4 Mixed Mode timings

From my observations there [5] I inferred a set of values for the various intervals as they would probably apply to Heathrow, see Fig 4. The figures in brackets are standard deviations which give a measure of variability. I have allowed for the fact that Heathrow has a better taxiway system and more high speed turnoffs. I took these observations when the airport was working easterly using runway 08R on a day of light to moderate easterly winds, so no wind speed adjustment was necessary.

While making the observations at Gatwick I noticed that the gap between successive arrivals did not vary statistically when the departure queue vanished. In principle the gap could have been reduced. I concluded from this that the arrivals controller did not take cognisance of the departure situation when marshalling and spacing his arriving traffic. In other words what happens at Gatwick is that the arrivals controller arranges gaps for exactly one departure to depart between successive arrivals. The departures queue up and slot one at a time into the gaps provided. The whole process is therefore dominated and regulated by the arrival stream. In terms of a queueing theory, then, we can simplify the system and regard the arrivals as if they were the only customers in a queueing system whose service time is the gap between successive arrivals. In other words we can ignore the departures when calculating the capacity of the system. I believe the same argument will apply to Mixed Mode working if implemented at Heathrow.

On this basis I obtain the following

Theoretical (ATMs/hr)	Utilisation %	Practical (ATMs/hr)
26.1	81.5*	21.3

* utilisation reduced to take account of longer service times

Table 4. Capacity for arrivals

The overall practical capacity of the runway is thus 42.6 ATMs/hr after adding in an equal number of departures. This is 6.5 percent above the level being achieved on a single runway at Heathrow at present. This gain may seem somewhat modest. One of the reasons is that the interleaving of arrivals and departures is inefficient due to the difficulty of coordinating the arrivals and departures. This means that overlong gaps are sometimes left in the arrival stream when there are no departing aircraft to use them. If perfect interleaving could be achieved then considerably more movements could be accommodated - I estimate somewhat over 10 percent extra in fact. But a very sophisticated control system would be needed to accomplish this level of coordination.

I have not so far touched on the crossing problem. I believe this is less serious in the Mixed Mode case because both arrivals and departures using Terminal Four can now be allocated to the southern runway and will have no need to cross on departure or arrival. So I have made no correction to the above capacity figures for crossing traffic.

Provided traffic can be allocated evenly to the two runways we can simply double the 42.6 figure to obtain a figure of 85.2 ATMs/hr for the capacity of Heathrow in mixed mode. It should be noted here that for this to be possible the air traffic routing arrangements in the London Terminal Area will have to be carefully re-designed so that southerly traffic can be routed safely to the north runway and vice versa. Otherwise an imbalance of traffic between runways will be unavoidable and the full benefit of mixed mode will be lost.

THE THIRD RUNWAY OPTION

A more radical proposal is to construct a brand new runway north of the Bath Road, on reserved land, reviving the scheme originally planned for Heathrow in the 1940s but abandoned as unnecessary at the time. On this reservation there is only space for a runway of 6000 ft, which although adequate for the slower propeller driven aircraft of the 1940s, is too short for many of the larger heavier jet aircraft of today. The runway would however be long enough, just, for most short to medium haul services operated by narrow bodied aircraft such as the B737 and A320. It is unlikely that this runway could be extended in future as it is hemmed in by the M25 motorway to the west and Cranford to the east.

Several schemes have been put forward by the airport operator, some show a new passenger terminal, terminal 6, to serve the runway, others a satellite terminal connected by underground passenger transport links to the existing terminals. These proposals would involve the destruction of some houses, the re-routing of roads, including sinking the Bath road into a tunnel under the taxiway that would be required to connect the new runway and its associated facilities with the existing airport.

It has to be said that 6000ft is very short for a runway. Most airports around the world have runways well in excess of this length, and those that do not are mostly seeking to increase the length of their runways they do have so that they can accommodate larger aircraft. An example is Aberdeen airport at Dyce. It has a single runway of 6001 ft, and is seeking to extend it.

Dyce however shows that narrow bodied aircraft can operate successfully from a 6000 ft runway. It handles B737 short and medium haul services on a regular basis and is capable of accommodating A320 series aircraft. However data from the Boeing's Technical Manual [6] show that the B737 is operating right at its takeoff limit on a runway of only 6000 ft. In fact for takeoff the B737 requires slightly more than 6000 ft when fully loaded, but at 85% to 90% of maximum all up weight it can manage, on a ‘standard day’, 15C, with no wind. I have not been able to find comparable figures for other narrow bodies, but I assume their performance is similar or better

Operational concept

With three runways, there are several ways in which the airport could be operated. The simplest would be to operate in segregated mode. In this case for most hours of the day it would be best to use two runways for landings and the remaining one for takeoffs, because landing intervals are, on average, greater. It would be best to use the new runway (R3) and the southern most one as the two landing runways because this would provide the greatest lateral spacing between the landing streams. In other words for segregated operations we envisage the runways used as shown on page 2. Note: we only show westerly operations in the figures on Page 2. Easterly operations are exactly comparable and need not concern us further.

This segregated mode has the advantage of simplicity. Air traffic control in the vicinity of the airport is relatively simple with a minimum of interaction between different traffic streams on the surface. It is also in principle easier to handle overshoots and ‘go arounds’. But the disadvantage is that the runways are not exploited to the full and the overall capacity of the system is less than optimal The dedicated takeoff runway would act as a limit on what could be achieved overall. Assuming this runway’s current capacity i.e. a 49.9 ATMs/hr, the overall airport capacity would be limited to 99.8 ATMs/hr.

It should be noted that this capacity would be adequate to handle the projected growth to 90 mppa mentioned earlier. But in the longer term, by 2030 say, traffic at Heathrow is expected to exceed 90 mppa. The segregated mode will not then be able to cope and we need to consider mixed mode options.

We can only really consider having one runway operating in mixed mode otherwise we would have more than two landing streams or more than two takeoff streams and this would be too complex for air traffic control to handle. We could consider using one of the existing runways, say the southern runway, for mixed mode working, with the middle runway for takeoffs and R3 for landings. This would have the advantage of allowing narrow bodied aircraft to take off at maximum load, as they would have use of one of the long runways. However ground movements would be complicated with a need to taxy to and from R3. A better solution might be to use R3 in mixed mode. It is believed that this is the preferred option of the airport authorities [7]. In this case it would be best to use the southern runway for arrivals because this would (a) separate the arrival streams and (b) ease the problem of handling overshoots and go arounds. If the middle runway were to be used for arrivals an overshooting aircraft would be sandwiched between two parallel departure streams, an awkward problem for controllers. We suggest therefore that the most appropriate operational concept is that shown on Page 2.

Capacity limits with mixed mode working

It is impossible to give a precise estimate of the capacity of the third runway until the detailed and definitive plans for its construction have been drawn up. What can be said is that the area available for buildings, stands and taxiways etc. is quite small on all the six alternative arrangements that the airport authorities have put forward and this may lead to congestion on the ground and consequently reduced air movement capacity.

	Departures	Arrivals
R3	18.0	18.0
Middle runway	49.9	
Southern runway		36.2*
Total	67.9	54.2

* Assumes T4 crossing traffic

Table 5. Runway capacities, 3 runway airport

A comparable situation is found at Aberdeen where the runway is short, there are no high speed turn offs and there is limited room for stands and a taxiway system. There the capacity is assessed at only 36 ATMs/hr by the Ministry for Transport. In the absence of other indicators therefore we take 36 ATMs/hr as the appropriate figure for R3 at

Heathrow. Using this figure we obtain Table 5 which summarises the situation envisaged at Heathrow. We see that arrival capacity is the limiting factor, and limits the overall airport system capacity to 108.4 ATMs/hr. I should note here that if it was judged safe to operate with departures on the southern runway and arrivals on the middle runway then this figure could be improved. Due to the absence of crossing aircraft on the landing runway, the system capacity would rise to 115.4 ATMs/hr.

So far I have been assuming that there would be sufficient aircraft that could use the short runway. This may not always be the case. So to explore the effect of having in the traffic mix different proportions aircraft that can use the short runway I drew up Figure 5. You can see that when the proportion of large aircraft, defined as those that can only use the long runways, exceeds about 0.67 the overall capacity of the airport begins to decline,

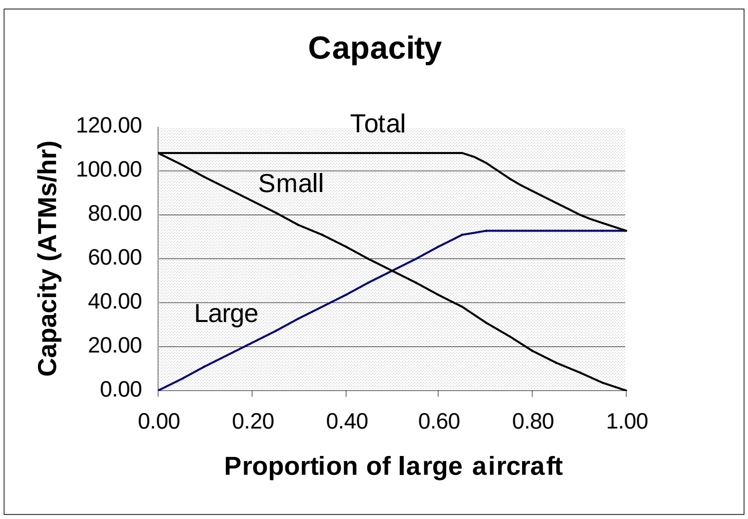


Figure 5 Effect of traffic mix on capacity

because there are too few aircraft that can use the short runway. In other words, if there are more than two large aircraft to every small aircraft on average in the traffic offering, the short runway cannot be fully utilised. The three curves represent the capacity limit for small, large and all aircraft respectively. In the limit when the proportion of large aircraft is 1.00, i.e when the traffic mix consists entirely of large aircraft, the airport reverts to a two runway airport with the corresponding capacity.

Figure 5 highlights the importance of the traffic mix when discussing the overall capacity. What is the mix at the moment? To find out I took a sample from the Heathrow online timetable [8] and got the following results.

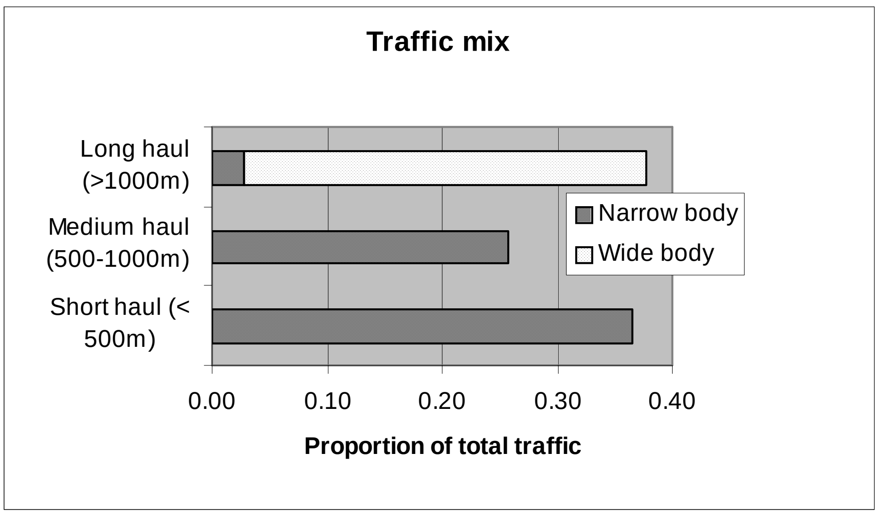


Fig 6 Proportion of narrow to wide bodied in different markets

Fig 6 shows that the total traffic is composed of about 65% short to medium haul movements and 35% long haul. Of the short to medium haul all are operated by narrow bodied aircraft and these would all be eligible for the third runway. In terms of Fig 5 the proportion of "large" aircraft at present is roughly 35%. We are thus a long way from the critical point at which the short runway constraint begin to bite.

I should say here that the sample I took was relatively small and I had to make some assumptions about flights where no specific aircraft type was given.

The above is today's situation. What of the future? The trend is towards larger aircraft and it is likely that in future there will be more wide bodied aircraft in the mix. There are several reasons for this. Firstly long hauls are likely to become more important at Heathrow with the recent open skies agreement with the US. Airlines will want take advantage of the new freedom to maximise the value of their scheduling slots by using them for the more profitable long haul services. Secondly on medium haul services the new larger aircraft which are due to come into service shortly, i.e. B787s, and A350s, will tend to be substituted on many of the routes which are currently being operated by narrow bodied B737s and A320s. These new aircraft, being wide bodied and heavier, are likely to be unable to operate from R3 (although as they have not flown yet their airfield performance has not been established). And thirdly short hauls are likely to lose out increasingly to fast modern rail alternatives especially on domestic routes but also perhaps increasingly on routes to the near Continent. If I am right about these factors then, it would seem that the traffic mix at Heathrow is likely in future to become biased towards wide bodied heavy aircraft that cannot use R3.

The implication is that Heathrow's ATM capacity will at some stage reduce as fewer and fewer aircraft are able to make use of the extra runway. It has to be said of course that this is unlikely to occur for many years and initially when the new runway opens Heathrow's capacity will far exceed the requirement. But in the longer term the effect may become important.

An important corollary is that the airport may at some stage hit a limit to passenger growth. As average aircraft size increases the number of movements will decrease and passenger totals – a product of the two factors – will be unable to grow further.

SUMMARY OF RESULTS

SUMMARY TABLE

Scenario	Limit on ATMs/hr	% increase	Limit on ATMs/yr	Additional ATMs/yr	Constraining element
Today	80.0[1]	-	48000[2]	-	Arrivals
Mixed Mode	85.2	6.5	51120	3120	Interleaving
With R3, Segregated	99.8	24.8	59904	11904	Departures
With R3, Mixed Mode	108.4[3]	35.5	65040	16800	Arrivals

[1] Current scheduling limit
[2] Current agreed cap on ATMs, when Terminal 5 opens
[3] Assuming less than 67% wide bodied aircraft

Table 6. Summary of results

Table 6 summarises the results obtained. It shows that there is only a modest gain to be had from the mixed mode operation. The third runway option on the other hand shows a considerable increase. This depends however on the mix of aircraft using the airport. If and when the traffic consists mostly of wide bodied aircraft, the overall capacity of the airport will be less than that shown in the table and the third runway and its associated terminal facilities will become less and less able to be used. In the limit, the airport reduces back to a 2 runway airport.

The table also shows where the constraints are. In today's operation arrival intervals are the constraining factor. It is unlikely that this constraint can be relaxed because the separations currently being employed are probably as small as can be tolerated from a safety point of view. Indeed we have seen that there are moves within the international community to mandate *an increase* in these separations. Any such increase would reduce capacity to an unacceptable level and impose a severe constraint on the traffic that could be handled. The only solution would be to introduce mixed mode which is less sensitive to the arrival capacity constraint.

In mixed mode the constraint is the inability to effect optimum interleaving of arrivals with departures. This might be capable of being relaxed if a sophisticated control system could be devised, but attempts in the past at computer control of arrival sequencing have not been successful.

In the third runway case the constraint is departure intervals in segregated mode, arrival intervals in mixed mode, and in the longer term the inability of a large proportion of the traffic to use the third runway in view of its limit length.

The third runway option provides enough capacity for the predicted 90 mppa traffic forecast, and beyond, but its development potential is limited due to physical constraints. To put this into context, Heathrow's ATM capacity with the third runway in operation is seen here to be less than that predicted for Paris CDG, which is planning for a figure of 71000 ATMs/yr in 2010.

Acknowledgements. I would like to thank Mr S R Price of Price Project Services for reading the initial draft of this paper and making useful comments.

APPENDIX. QUEUEING THEORY

(See reference [9] for derivations)

The following formulae apply to the M/G/1 queue, i.e a Queueing System in which the customers arrive at random (Poisson process), service times follow a general distribution, and there is only one server.

The average waiting time for customers (excluding the customer being served) is given by:-

$$W = \frac{\lambda \overline{x^2}/2}{(1 - \rho)} \qquad \text{...}(1)$$

where λ is the arrival rate

x is the service time

ρ is the utilisation of the server

The average number in the system, i.e. in the queue and being served, is given by

$$N = \rho + \frac{\lambda^2 \overline{x^2}/2}{(1 - \rho)} \qquad \text{...}(2)$$

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J U M Smith

Mr Smith is an independent consultant working in the fields of Aviation Statistics, Operational Research and Computer Systems. He has a degree in Mathematics, is a Chartered Engineer, a Fellow of the Institute of Statisticians, and a member of the Operational Research Society and Computer Society.

After Military Service as a Navigator in the R A F, Mr Smith worked in the Scheduling Department of British European Airways, before joining the staff of the Roskill Commission into the Third London Airport. The work involved analysing the capacity of existing airports in the South East as well as assessing "the Timing of the Need".

Mr Smith later lead the team that supported the IBM flight data processing system at the London Air Traffic Control Centre at West Drayton. More recently he has worked on the replacement system at the new Centre at Swanwick in Hampshire, and at Eurocontrol Brussels on ADS-B projects.

He has developed computer simulation software that models the flow of air traffic through the UK airspace, as well as more general statistical software, including a commercial software package. He is author of a book on computer simulation.