The impact of the microwave landing system on runway capacity at regional airports

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THE IMPACT OF THE MICROWAVE LANDING SYSTEM ON RUNWAY CAPACITY AT REGIONAL AIRPORTS

by

Farouk Mustapha HAMED ABDELOUAHAB

A Master's Thesis

Submitted in partial fulfilment of the requirements for the award of Master of Philosophy of Loughborough University of Technology


Supervisor: Professor Norman Ashford
To my Mother

To my Sons
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THE IMPACT OF THE MICROWAVE LANDING SYSTEM ON RUNWAY CAPACITY AT REGIONAL AIRPORTS

ABSTRACT

The Microwave Landing System (MLS) has the ability to support curved and steep angle approaches and provides improved precision approach guidance compared with the current Instrument Landing System (ILS).

Then MLS Characteristics produce reduced inter-arrival spacing when compared to ILS procedures and therefore increase runway capacity if the runway occupancy time is not the limiting factor.

This study considers the effect of MLS on runway capacity at British regional airports.

Single runway and intersecting runway operations are analysed.

Results show that an increase in capacity due to MLS is achievable only when 40 percent or more of the traffic are arrivals.

For a single runway, when 100 percent of the traffic are arrivals, the increase is in the order of 7 to 12 percent under MLS curved approaches, and of 8 to 24 percent for multiple glidepath procedures, the lower numbers being associated with a high proportion of medium aircraft and the higher figures when the traffic includes only small and light aircraft. These improvements are progressively reduced as the percentage of arrivals diminishes. For 40 percent of arrivals, the capacity increases are between 0 and 4 percent for curved MLS approaches and 0 to 10 percent for MLS steeper angle approaches.

Intersecting runways utilisation would result in a capacity increase, in the case of mixed operations of about 2 to 5 percent above single runway figures, depending on the aircraft mix and the percentage of arrivals.

KEY WORDS

MLS
ILS
AIRPORT
RUNWAY
CAPACITY
SIMULATION
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CHAPTER 1:
INTRODUCTION

1.1 HISTORICAL BACKGROUND

More than 40 years ago, the Instrument Landing System (ILS) was selected by the International Civil Aviation Organisation (ICAO) as the standard precision approach and landing aid, and at that time Bell (1949, p 966) reported that some aircraft were using ILS at London and Northolt airports in the United Kingdom (U.K.).

Since then, ILS has been improved to meet the needs for better reliability and accuracy and, for example, the Civil Aviation Authority (CAA) requires it for all weather operations (CAA, 1983A, p7).

ILS utilisation is classified in three main operational categories (CAT):

CAT I: decision height (DH) down to 60 metres and runway visual range (RVR) not less than 600 metres,

CAT II: DH below 60 metres and down to 30 metres and RVR not less than 400 metres,

CAT III: No DH limitation and RVR below 400 metres.

where DH is the lowest height from which a go-around can be successfully accomplished, and RVR is the visibility in the landing or takeoff direction (ICAO, 1985, p 178).


However, the ILS limitations have soon been recognised, and over 50 systems, most of them using microwave techniques, were investigated to overcome these limitations, and by 1978 ICAO adopted the Microwave Landing System (MLS) as the replacement for ILS (ICAO, 1981, p2).
A transition plan outlining the time scale of change over from ILS to MLS has been established, whereby MLS would replace ILS by the international deadline of 1998 and where ILS will be withdrawn from service by January, 2000 (ICAO, 1985, p 150E, 150H).

1.2 ILS AND MLS CHARACTERISTICS

Most of the benefits claimed for MLS have to do with its ability to overcome the deficiencies of ILS (CAA, 1988A p1, 7):

- the 40-channel frequency limitations of ILS. To meet the demand in high density terminal areas, MLS provides 200 channels.

- ILS sensitivity to siting and environment. Unlike ILS, MLS is less vulnerable to signal reflections from surrounding objects (e.g. aircraft, buildings) and other interference. Neither does it depend on a ground-reflected signal for its glideslope guidance (i.e. reduced costs for ground preparation and snow clearing).

- the fact that ILS guidance is limited to a single, narrowly defined approach path and is unable to provide multiple glidepaths. To minimise interference effects (Smith, 1972, p187) ILS effective guidance coverage is restricted to ± 3° laterally (azimuth) and ± 0.7° vertically (elevation) about the nominal glidepath which is usually set to 3° (figure 1), although it can be set as high as 7.5°, e.g. London/City and Plymouth airports (CAA, 1989, p20 and 23), to be used by STOL (Short Takeoff and Landing) aircraft or helicopters. On standard ILS, distance from touchdown is obtained only when the aircraft are over markers (usually two, located at 0.5 and 4 nautical miles (NM) from landing runway threshold). However, in the U.K., for 29 out of the 58 ILS runways, continuous distance information is given by DME (Distance Measuring Equipment). ILS provides coverage up to 25 NM for azimuth guidance and 10 NM for elevation guidance (18 NM and 8 NM respectively when steep angle glidepath is set) (CAA, 1988B).
Figure 1 - ILS Guidance.

Figure 2 - MLS Guidance.
Wider guidance coverage is provided by MLS (figure 2), to ± 40° laterally, 15° vertically up to 10,000 feet, and a DME/P (Precision DME) an integral function of MLS, to keep pilots continuously informed of their precise location up to a 20 NM range.

The limited coverage of ILS restricts all aircraft carrying out instrument approaches to join the extended runway centreline at a point (gate) and follow a common path of 6 - 8 NM to the runway threshold (figure 3), whereas MLS has the ability to support curved and steeper angle approaches where the approach path length and glideslope angle depend on the various aircraft performances (figure 4).

According to ICAO (1981, p12, 14), the advantages due to the characteristics of MLS are:

- reduced operating minima,
- noise abatement,
- reduction in operating costs,
- fuel economy,
- improved airport utilisation and runway capacity.

1.3 DEMAND, CAPACITY and DELAY

The runway capacity is defined in U.K. as that level of average demand which gives rise to an average delay of 5 minutes over a busy period of defined length (CAA, 1983B, p1, 2). It is measured in movements per hour, where a movement is a landing or a takeoff. The busy period is usually of 4 hours duration, although it may last longer (5 to 7 hours) at congested airports such as Heathrow and Gatwick (CAA, 1988C, pD4, D6). This capacity is not equal to the throughput capacity, used by the Federal Aviation Administration (FAA) in the U.S.A., which is the maximum number of movements that can be accommodated in an hour (FAA, 1983, p2) and is independent of average aircraft delay (Douglas Aircraft Company, 1976, p7, 8).
Figure 3 - ILS approach path.

Figure 4 - MLS multiple approach paths.
For example, the declared capacity for Heathrow (two parallel runways operating in segregated mode, i.e. one runway used for arrivals and the other for departures) is 96% of the throughput capacity, whereas at Gatwick, due to the complex interactions between departures and arrivals on the single runway, the declared capacity is 90% of the throughput capacity (CAA, 1984A, p3).

Figure 5 shows the relationship between demand, capacity and delay. It illustrates roughly how delay varies with demand. As actual demand approaches capacity, delay increases very rapidly.

As shown in figure 6, delay reduction can be achieved, for a given demand, by improving capacity (Arnold, 1989, p30).

1.4 CONTEXTUAL BACKGROUND

The implementation of MLS occurs in a context characterised by:

- a significant increase in air traffic: the Department of Transport forecasts annual growth rates, including the effects of the air transport liberalisation and of the Channel Tunnel, in the range of 3.7% to 5.7% up to the year 2005 (Aerospace, 1989, p7);

- a use of existing runways: no new runways are being built and even in the London area the British Airports Authority (BAA) does not intend to open a new runway until 2005 (Airports International, 1989, p20);

- actions by the Joint Airports Committee of Local Authorities (JACOLA) to exploit the potential of airports outside the Heathrow / Gatwick / Stansted system (JACOLA, 1988A), in particular investment plans for passengers and cargo facilities are being implemented at regional airports (JACOLA, 1988B, p47, 157).

All these factors will contribute to generate a higher demand for runway utilisation and more delays for aircraft at regional airports.

Thus, unless runway capacity is increased, the delay/capacity problem will only worsen as projected traffic increases occur.
Figure 5 - Relationship between demand, capacity and delay.

Figure 6 - Effect of improved capacity on delay.
Therefore, it is important to determine what capacity benefits MLS, more specifically its ability for curved and steeper angle approaches, can offer at regional airports.

1.5 REVIEW OF THE LITERATURE

Few studies have been conducted to analyse the impact of MLS on runway capacity.

One of the earlier works on the effect of multiple curved paths, and a shorter common approach path, has been done by the Blind Landing Experimental Unit (BLEU) at the Royal Aircraft Establishment in U.K. (Smith, 1972, p187). Results from a simulation model indicate that by reducing the common path length, the runway capacity is increased in the "arrivals only" mode, whereas for the mixed mode (departures and arrivals), the capacity does not change. However, since then separation rules have been developed to avoid wake vortex hazards created by heavy aircraft, so there is still a need to re-assess the effect of shortening the common approach path in respect to these rules.

Tosic and Horonjeff (1976, p319, 329) developed a capacity model which considers the MLS capability for curved and steeper angle approaches, the aircraft speeds and the separations (horizontal and vertical), but the research, restricted to landings to a single runway only, assumed that:

- both ILS and MLS are error free,
- the runway occupancy time is always less than the inter-arrival time at the runway threshold.

The results show that improvement in landing capacity can be achieved when MLS procedures are employed.

Fan (1988, p607, 621) expanded the work of Tosic and Horonjeff to include systems errors and mixed operations with a variety of runway configurations (single, parallel and intersecting runways). He investigated the effect of different angles of descent and vertical separations. He quantified the capacity gains expected from a shorter common approach path and from the use of different glide paths. Nevertheless, the aircraft classification and longitudinal separations he
used in his study differ significantly from those in U.K. and the interactions between aircraft in mixed operation are not clearly expressed.

The CAA (1987A) examined the benefits from utilisation of MLS in low visibility conditions (CAT III) by arriving aircraft at Heathrow airport. In such conditions, the actual arrival capacity is 12.4 movements per hour due to increased inter-arrival spacing necessitated by the need for the preceding aircraft to clear sensitive areas to ensure ILS signal integrity for the following aircraft. The reduced size of MLS sensitive areas allows reduced inter-arrival separations, increasing landing capacity to 14.4 movements per hour, but the runway occupancy times and Ground Movement Control (GMC) workload remain the limiting factors.

Simulation of multi-airport environment in the New York area (Del Balzo, 1988, p219, 222) and Moscow area (Boltalin and Lykoyanov, 1988, p40, 42) have shown that MLS reduces airspace conflicts and therefore capacity gains can be achieved at individual airports. Moreover, Del Balzo cites capacity benefits due to MLS at airports with parallel runways (segregation of aircraft depending on their characteristics), or when noise abatement procedures are tailored to local conditions, or when obstructions restrict or prohibit the use of other landing aids.

1.6 OBJECTIVE OF THE RESEARCH

The objective of this study is to analyse the impact of MLS on runway capacity at British regional airports. More specifically, it investigates the effect of curved and steeper angle approaches to a single runway and intersecting runways and reflects the operational environment in U.K. It determines the runway capacity obtainable with ILS, then with MLS, under a variety of traffic mixes, and a comparison is made between the performances of the two systems to quantify the MLS capacity benefits.

Because the requirements for other MLS categories are not yet established, this research considers only CAT I operations.
CHAPTER 2
THE MODEL FOR RUNWAY CAPACITY ANALYSIS

2.1 METHODOLOGY

In U.K., the formal assessment of runway capacity is in two parts:

- a field study in which the detailed sequences of aircraft operations are timed and aircraft delays are measured;

- input of data from the field study to a set of computer simulations to assess, in particular, delays from a stated average level of demand (the level of demand corresponding to a 5-minute average delay is the required capacity) (CAA, 1983B, p5, 7).

Computer simulation models for the estimation of runway capacity, used as early as 1968 to assess the performance of Heathrow and Gatwick (Department of Trade and Industry, 1971, p53, 65), are developed to study the runway operational system, because of the changing character of the problem introduced by the random inter-arrival time and the stochastic nature of aircraft flight and ground movement times.

Similarly, this research employs the simulation technique, where the runway operational system is translated into logical and arithmetic terms, with data collected at some regional airports to provide the required input parameters.

However, the simulation model in this research not only considers ILS approaches, but also includes analytical sub-models which reflect the multiple approach path lengths and angles of descent capability of MLS.

2.2 DESCRIPTION OF THE RUNWAY OPERATIONAL SYSTEM

Before discussing the model by which ILS and MLS procedures are investigated, it is necessary to define the basic elements of runway operation.
The runway operational system under consideration is characterised by a static environment, the runway and taxiway layout and the approach and departure routes, through which a flow of aircraft is processed.

Figure 7 illustrates the sequential flow of aircraft through this system. (a) Aircraft arrive at the system when they could be given an immediate clearance to start their final approach (b) if there is enough separation from the preceding aircraft. Air traffic control (ATC) rules define the safe spacing between aircraft. Therefore, some of these aircraft incur some delay (interval a - b) in holding patterns, by path stretching and/or speed control. Aircraft begin their final approach (b) on a "first come - first served" basis, fly the final approach segment (b - c) then land and vacate the runway (c - d). Departing aircraft (e) proceed immediately to the runway for takeoff if the runway is vacated by a landing aircraft and safe separation is provided from preceding departure and/or from aircraft on approach. Otherwise, they join the departure queue and wait their turn (interval e - f) until a takeoff clearance is given (f), under a "first come - first served" basis, where aircraft enter the runway and takeoff (f - g).

In the sequence described above, the aircraft on arrival have priority over departures because of the requirement to set up separation between landing aircraft many miles from the runway threshold (CAA, 1983B, p1).

For intersecting runways, an additional check is included in the departure sequence for separation at the convergence point.

Besides ATC spacing, other factors influence the flow process, such as weather conditions; aircraft and ATC performances. 

2.3 MODEL STRUCTURE

The simulation model covers arrivals and mixed operations for single and intersecting runways. The sub-components of the model are presented separately in the following sections.
Figure 7 - Aircraft flow chronological sequence of events.

Figure 8 - ILS path geometry: horizontal separation.

Figure 9 - MLS path geometry: horizontal separation.
2.3.1 Arrivals only, single runway

The analytical models for landing traffic used in this research are based on the work of Tosic and Horonjeff (1976, p319, 329) and incorporate a number of additional features. These include accounting for the separations due to wake vortices, for the systems error (i.e. ILS and MLS are not error free), and for the runway occupancy time which could be a constraint. These models consider two situations: (a) only horizontal separation between aircraft is allowed during approach, (b) horizontal or vertical spacing is applied.

2.3.1.1 Analytical models for horizontal separation

2.3.1.1.1 Inter-arrival spacing

When no vertical separation exists, aircraft are assumed to be on the same horizontal plane.

Under instrument flight rules (IFR), aircraft carrying out ILS procedure have to pass through a point E (entry gate), located at a distance L (common approach path length) from the landing runway threshold T along the extended runway centreline, then fly the final approach segment, as illustrated in figure 8. However, due to the wider coverage of MLS, different aircraft may fly different approach paths which intersect the extended runway centreline at different entry gates (Ei) located at Li from T and, as shown in figure 9, the common approach path for any aircraft pair is the shortest of the two final approach paths.

Existing landing capacity models express the relationship between common approach path length, aircraft speeds and ATC separations (Ashford and Wright, 1984, p145, 147). Two cases are considered:

- overtaking case \( (V_2 \geq V_1) \):
  \[ S = \frac{D}{V_2} \]

- opening case \( (V_2 < V_1) \):
  \[ S = \frac{D}{V_2} + L (\frac{1}{V_2} - \frac{1}{V_1}) \]
where: \( S \) = time separation at \( T \)
\( D \) = ATC distance separation
\( L \) = length of the common approach path
\( V_1 \) = speed of the preceding aircraft
\( V_2 \) = speed of the following aircraft.

These models are illustrated by space - time diagrams in figures 10 and 11. The time separation is a minimum \( D/V_2 \), where a slow aircraft precedes a fast aircraft and it is necessary to plan a greater separation than \( D \) on the common approach path. When a slow aircraft is following a fast aircraft, the separation \( D \) is applied when the preceding aircraft is at the beginning of the common approach path, but on arrival at \( T \) the spacing is much larger than \( D \).

A third situation is considered and is a variation of the opening case. Additional separation is ensured due to wake turbulence hazards by large preceding aircraft, this separation is greater on final approach than where aircraft are on intermediate approach before intercepting the final approach segment. Therefore, the separation applies when the second aircraft is at the start of the common approach path (figure 12) and is expressed as follows:

\[
S = D/V_1 + L (1/V_2 - 1/V_1)
\]

It should be noted that the only difference between the two opening case equations is in the first term where \( V_1 \) and \( V_2 \) are interchanged (Horonjeff and McKelvey, 1983, p249, 250).

The analytical models described above generate error-free inter-arrival separations at \( T \). But most authors add a buffer in their models to compensate for errors. For instance Harris (1972) considers three types of error:

- threshold inter-arrival time error;
- gate arrival time error and time error in flying the final approach path;
- gate arrival time error and speed error in flying the final approach path,

and presents a set of equations where it is assumed that the error-free separation plus a normally distributed buffer should assure a very low probability of violation of the separation standards.

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Figure 10 - Time-space diagram for the overtaking case.

Figure 11 - Time-space diagram for the opening case.

Figure 12 - Time-space diagram for wake turbulence case.
In the present study, a normally distributed system error (with zero mean) is introduced to the error-free models, to take into account the relative accuracy of ILS and MLS. But in order to ensure that the first aircraft clears the runway before the second aircraft crosses T, a time separation needs to be maintained between two consecutive arriving aircraft, such separation, including a buffer, (figure 13) is at least equal to the inter-arrival time derived from models allowing for system error.

(Note: ATC rules in U.K. (NATS, 1974 as amended in July, 1988, p2, 7) permit landing aircraft to touchdown before a preceding landing aircraft is clear of the runway under some conditions which are not applicable in CAT I operations).

Therefore, the inter-arrival separation input into the computer simulation model is computed as the maximum of the runway occupancy time plus buffer and the error-free separation plus system error.

2.3.1.1.2 Runway Occupancy Time

From the fact that runway occupancy time (RT) is a critical factor in runway capacity analysis, many researchers address it in their attempt to improve operational use of runways.

For instance, Kanafani (1983, p414,424) considers that since:

- the inter-arrival time separation (t) at threshold is influenced by the separation d and the speed v at which aircraft fly \( t = \frac{d}{v} \), and

- the corresponding (throughput) capacity C is the reciprocal of t and can be expressed as \( C = \frac{1}{t} = \frac{v}{d} \),

it is possible to increase capacity by reducing d or increasing v until t matches RT, implying that such a procedure applies only to the case where RT is not greater than t.

Nevertheless, most works relate to the optimal location of exit taxiways to reduce landing RT and do not consider the reverse process, i.e. the computation of RT from a given runway exits layout.
Figure 13 - Arrival spacing due to runway occupancy time.

Figure 14 - Runway occupancy time components.
The present study applies the model suggested by Horonjeff and McKelvey (1983, p310) to compute RT for optimally located exit taxiways, with an attempt to add some improvements which reflect the real airport environment. This model is used during simulation only when there is lack of data.

The model, illustrated in figure 14, includes five components:

(a) **Flare:** the time \( t_1 \) to complete the flare is given by the following equation:

\[
t_1 = \frac{(V_{th} - V_{td})}{a_1}
\]

where:
- \( a_1 \) = deceleration in the air
- \( V_{th} \) = threshold speed
- \( V_{td} \) = touchdown speed

\[
\sqrt{V_{th}^2 - (D_1 \times 2a_1)}
\]

\( D_1 \) = distance from threshold to main gear touchdown.

(b) **Transition:** it is the time \( t_2 \) between main gear touchdown and nose wheel touchdown, derived from observations. During the transition, the aircraft covers the distance \( D_2 \) given by

\[
D_2 = \frac{(V_{td}^2 - V_{ba}^2)}{2a_2}
\]

where \( a_2 \) = deceleration during the transition.

\( V_{ba} \) = speed at the end of the transition = \( V_{td} - (t_2 \times a_2) \)

(c) **Braking:** this phase allows the aircraft to slow down to either

(i) the speed at which the aircraft leaves the runway from a suitably located taxiway, or

(ii) the taxi speed if the exit taxiway is still further down the runway or has been overshot.

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The braking time \((t_3)\) is determined as follows:

\[
t_3 = \frac{(V_{ba} - V_x)}{a_3}
\]

where: \(a_3\) = deceleration rate on the ground.

\(V_x\) = exit speed in the case of (i) above or taxi speed in the case of (ii).

The following equation gives the braking distance \((D_3)\):

\[
D_3 = \frac{(V_{ba}^2 - V_x^2)}{2a_3}
\]

(d) **Taxiing:** after completing the braking action, the aircraft taxis at constant speed to the nearest exit taxiway, after back-tracking in the case where the runway exit is passed. It is assumed that back-tracking occurs at the end of the braking action for light aircraft and at the end of runway for the other aircraft. The taxiing time \((t_4)\) is estimated as follows:

\[
t_4 = \frac{V_x}{D_4} + \tau_t
\]

where:

\(V_x\) = taxi-speed.

\(D_4\) = distance to nearest runway exit

\(\tau_t\) = time to complete the back-track turn, equal to zero if exit taxiway is still further along the landing direction.

(Note: \(t_4\) is equal to zero if the aircraft clears the runway during the braking phase).

(e) **Exiting:** it is the time \((t_5)\) to turn off the runway and is found by observation.

The runway occupancy time is the sum of the times for completing the different phases described above:

\[
RT = t_1 + t_2 + t_3 + t_4 + t_5
\]
2.3.1.2 Analytical Model for Vertical Separation

With MLS different aircraft can fly distinct glidepaths as shown in figure 15.

In the following discussion, any aircraft L is considered to be flying the lower glidepath defined by the angle $G_L$, and any aircraft H is on a higher path with a descent angle $G_H$.

Aircraft L is preceding aircraft H. When aircraft L is at A on the runway, aircraft H is at B and both aircraft are vertically separated (BC). If BC is equal to the minimum vertical separation (VS) as stipulated by ATC rules, the two aircraft are separated on the horizontal plane by AC. If AC is less than the minimum horizontal separation required under ATC rules, the inter-arrival time (S) at threshold is less than the inter-arrival time given by the model for horizontal separation and is equal to:

$$ S = \frac{VS}{V_H \tan G_H} $$

where $V_H$ is the speed of aircraft H.

The simulation model in this research assumes that the error E at the runway threshold, and illustrated in figure 16, is negligible (about 50 feet on the safe side for a 3 degree glidepath angle's difference).

This model is applicable with the following contraints:

(a) Wake turbulence

Although at the start of the approach the aircraft H is above the wake vortices generated by a larger aircraft L, however the two approach paths converge towards the runway and at some distance from the threshold aircraft H begins experiencing the effects of wake turbulence if the longitudinal separaton between the two aircraft is less than the required wake vortex spacing. Since the CAA (1986, p3) stipulates only one set of spacing minima on final approach, longitudinal separation models are used for the avoidance of wake vortex hazards.

(b) 3 degree approach

As it will be seen in the next chapter, aircraft must be separated by at least 3
Figure 15 - MLS vertical separation.

Figure 16 - Error in vertical separation.
nautical miles horizontally or by 300 metres of altitude. So, if two aircraft are flying on a 3 degree approach, the 300 metres vertical separation will result in a horizontal distance of about 3.1 nautical miles and a time separation at threshold larger than if the 3 nautical miles spacing is applied. Therefore, vertical separation is considered only if at least one aircraft is flying above the 3 degree approach path.

(c) Aircraft H followed by aircraft L

Figure 17 depicts this situation. When aircraft H is at B, aircraft L is at D, VS being the ATC minimum vertical spacing. However, when aircraft H was at A, aircraft L was at C (or further from the runway threshold) if VS is not to be violated. Thus the rate of descent (vertical component of speed) of aircraft L must be equal to or greater than the rate of descent of aircraft H to ensure proper vertical separation throughout the final approach:

\[ V_L \sin G_L \geq V_H \sin G_H \]

or \[ V_L \geq \frac{(V_H \sin G_H)}{\sin G_L} \]

Since for small angles \( \sin G \) is proportional to \( G \), therefore for \( G_H \) equal to twice \( G_L \), the speed of aircraft L must be at least equal to twice the speed of aircraft H for VS to be applicable.

(d) Aircraft L followed by aircraft H

As shown in figure 18, when aircraft L is at B, aircraft H is at D and the minimum vertical separation VS is ensured. This means that when aircraft L was at A, aircraft H was at C (or beyond) if a vertical separation equal to or greater than VS was provided on final approach. Therefore:

\[ V_H \sin G_H \geq V_L \sin G_L \]

or \[ V_H \geq \frac{(V_L \sin G_L)}{\sin G_H} \]

Thus, if \( G_H \) is twice \( G_L \), \( V_L \) should be less than twice \( V_H \).
Figure 17 - MLS: aircraft H followed by aircraft L.

Figure 18 - MLS: aircraft L followed by aircraft H.

Figure 19 - MLS: aircraft on same glidepath.
Aircraft on the same glidepath

Vertical separation is applicable only if the second aircraft has the same speed or is faster than the first aircraft as illustrated in figure 19. Otherwise the horizontal separation model applies (opening case).

2.3.1.3 Arrival model integration in the simulation model

Once the inter-arrival time is computed according to one of the analytical models described above, the simulation model determinates the time at which the second aircraft starts its approach as follows:

$$ TA = TOT1 + S - \frac{L}{V2} $$

where
- $TA =$ time at which final approach begins
- $TOT1 =$ time over threshold for first aircraft
- $S =$ inter-arrival spacing
- $L =$ length of final approach segment
- $V2 =$ speed of second aircraft.

2.3.2 Mixed Operations, single runway

When aircraft use a runway, four types of situation can occur:

- departure followed by departure
- departure followed by arrival
- arrival followed by departure
- arrival followed by arrival.

The last case has been examined when landing models were presented. The following analysis concerns the combination where at least one operation is a departure.

2.3.2.1 Departure followed by departure

The departure manoeuvre includes two steps:
- line up phase,
- take off roll.

Departing aircraft join the holding point where they can hold clear of the runway near the take off threshold to perform some pre-flight checks or to wait for the ATC departure clearance. The holding point position is defined according to CAA rules (1984B, p3/12) where a minimum of 90 metres from runway centreline is prescribed, but this distance can be increased to take into account local conditions (e.g. interference with radio aids).

When cleared to enter the runway, departing aircraft taxi into take off position (line up) on the runway centreline (figure 20).

Once the take off clearance is given, the aircraft starts its roll to become airborne (figure 21).

ATC rules specify the minimum spacing between successive departing aircraft, more precisely between takeoffs (CAA, 1975 as amended in July 1988, p 1.15).

Figure 22 shows an ideal situation and reflects the relationship between line up time, take off roll time and departure separation. As soon as the first aircraft begins its take off roll, the second aircraft starts taxiing into take off position and by the time it completes its line up manoeuvre the first aircraft is airborne and take off clearance is given for the following aircraft, the required departure separation being ensured.

However, in the real operational environment, the time to complete the different manoeuvres varies from one aircraft to another. The line up time of the second aircraft is most often less or greater than the takeoff roll time of the preceding aircraft (figure 23), which results in inefficient runway operation, i.e. delay in the first case (a) or loss of runway utilisation in the second case (b):

ATC releases a departure when it considers a sufficient separation is ensured from the preceding aircraft. The take off roll time affects the required separation as shown in figure 24.

As it will be seen in the next chapter, field observations indicate that:

\[ TR1 + AS > TR2 + LT2 \]
Figure 20 - Departure line up manoeuvre.

Figure 21 - Takeoff roll manoeuvre.

Figure 22 - Space-time diagram for departure operations.
where: TR1 = take off roll time of first aircraft  
    TR2 = take off roll time of second aircraft  
    AS = achieved separation between departures  
    LT2 = line up time for second aircraft.

Therefore, the simulation model assumes that

\[ RTH_2 = TT_1 + AS - TR_2 - LT_2 \]

where \( RTH_2 \) = time at which the second aircraft is released from holding point  
\( TT_1 \) = take off time of first aircraft.

Although in real environment the departure delay is absorbed at the holding point  
and at the take off position, the simulation assumes that all delay is at the holding  
point, this is only for modeling convenience without losing any accuracy in the  
computation of delay.

### 2.3.2.2. Arrival followed by departure

A departing aircraft can be cleared into takeoff position once a landing aircraft has  
crossed the runway threshold. The takeoff clearance is given only when the  
landing aircraft has vacated the runway (figure 25).

Similar to the case of departure followed by departure, the line up time is shorter or  
longer than the landing runway occupancy time, creating delay (a) or loss of  
runtime utilisation (b) respectively.

Conveniently located runway exists (particularly rapid exit taxiways) shorten  
runtime occupancy time for landing aircraft (Ashford and Wright, 1984, p209),  
therefore a shorter arrival-departure separation can be achieved if the line up time  
is not a limiting factor.

The simulation model computes the release time from holding point for the  
departing aircraft as follows:

\[ RTH = TRC - LT \]
Figure 23 - Effect of line up time.

Figure 24 - Effect of takeoff roll.

Figure 25 - Arrival-departure separation.
where \( RTH \) = release time from holding point
\( TRC \) = time at which the runway is vacated by the arrival
\( LT \) = line up time.

If \( RTH \) is earlier than the actual time (when \( LT \) is the limiting factor), \( RTH \) is set to the actual time.

As for the departing only case, any delay is absorbed at the holding point.

The takeoff time is given by:

\[
TT = RTH + LT + TR
\]

where: \( TT \) = takeoff time
\( LT \) = line up time
\( TR \) = takeoff roll time.

2.3.2.3 Departure followed by arrival

As shown in the description of the system, arrivals have priority over departures. Therefore, once an aircraft starts its final approach, it is normally committed to land unless for safety considerations a missed approach is decided by the pilot or by ATC.

In U.K. ATC rules specify that a landing aircraft will not be permitted to cross the runway threshold until the preceding departing aircraft is airborne (CAA, 1974 as amended in July, 1988, p 2.7). So, in this case, ATC uses its judgement to determine when it is too late to release an aircraft from the holding point for a takeoff clearance, although for ILS approaches the outer marker is frequently utilised as a decision criterion (CAA, 1981, pA2).

Figure 26 explains this situation. When a departing aircraft is at the holding point (A) the landing aircraft is on final approach at B. When the arrival crosses the runway threshold (D), the departing aircraft must be at C, after having completed the lining up and the takeoff roll to which a safety buffer is added.

In the simulation model, the latest release time from the holding point for a departure is given by:
\[ \text{RTH} = \text{TOT} - \text{TR} - \text{LT} - B \]

where:  
- \( \text{RTH} \) = latest release time from holding point  
- \( \text{TOT} \) = time over threshold for landing aircraft  
- \( \text{TR} \) = takeoff roll time.  
- \( \text{LT} \) = line up time.  
- \( B \) = buffer.

### 2.3.3. Intersecting runways

#### 2.3.3.1 Preamble

In U.K., runway capacity analysis of an existing multi-runway system is documented only for:

- **Heathrow:**
  - (a) parallel runway operations (CAA, 1987B 1988D)  
  - (b) effect of simultaneously operating the parallel and the intersecting runway (CAA, 1984A, p41, 46).

- **Aberdeen:**
  - operation of the main runway by airplanes and of the intersecting secondary runways by helicopters (CAA, 1980).

ICAO provides guidance only for the simultaneous operation of parallel or near-parallel runways (ICAO, 1988).

In U.S.A., the FAA conducted extensive studies for different runway configurations according to ATC criteria different from those applied in U.K. (FAA, 1983).

Hence, the following analysis of intersecting runway operations is based on criteria and assumptions derived from single runway procedures or from the material listed above.

Moreover, in instrument meteorological conditions (IMC), aircraft on approach for two separate runways must have protection for their missed approach procedures, i.e. their missed approach paths must not overlap. Currently there is no standard that would permit aircraft to carry out independent converging approaches to
Figure 26 - Departure-arrival separation.

Figure 27 - Intersecting runways configuration.

Figure 28 - Exit taxiways in relation to IP.
intersecting runways under low ceiling and visibility. The FAA has examined means of decreasing airspace requirements so as to authorise converging approaches in IMC (FAA, 1987). However, to ensure that the missed approach procedures diverge without overlapping, this necessitates moving back the missed approach points for low weather operations and consequently raising the ceiling and visibility requirements (Vickers, 1987 p.9).

Thus, the simulation model assumes that the system operates under a single approach stream to one runway. Also, it is assumed that departing aircraft takeoff from the other runway.

Since the models for arrivals only and departures only have been presented during single runway operations analysis, models for mixed operations are now examined.

2.3.3.2 Time to the intersection for an arrival

Intersecting runways are characterised by the distances X and Y of the intersection point (IP) from the landing and takeoff thresholds respectively (figure 27).

In such configurations it is assumed that arrivals (A) vacate the runway either before IP in the landing direction or after IP (figure 28).

In the case where A crosses IP, the time between the arrival threshold and IP is determined according to the runway occupancy time model described during the single runway operation analysis, and as explained below.

A passes IP during one of the following phases: flare, transition, braking or taxiing.

The simulation model starts by examining the first phase of the landing sequence. If IP is within the flare distance, and since for each phase the model includes speeds, deceleration rates and distances, the time from runway threshold to IP (tIP) is given by:

\[
tIP = \left[ Vth - \sqrt{Vth^2 - (X \times 2a_1)} \right] / a_1
\]
where:  \( V_{th} \) = threshold speed
\( a_1 \) = deceleration during the flare.
\( X \) = distance from threshold to IP.

If the crossing does not occur during the flare, the model computes the distance \( D \) from the runway threshold to the end of the transition stage. If \( X \) is less than or equal to \( D \), \( t_{IP} \) is found as follows:

\[
t_{IP} = t_1 + \left[ V_{td} - \sqrt{V_{td}^2 - [(X - TDL) x 2a_2]} \right] / a_2
\]

where:  
\( t_1 \) = time to complete the flare
\( V_{td} \) = touchdown speed
\( TDL \) = touchdown location
\( a_2 \) = deceleration during the transition phase.

If \( X \) is greater than \( D \), the model verifies the braking phase. \( X \) is compared to the distance from the runway threshold to the end of the braking step on the runway. If \( X \) is within this distance, then:

\[
t_{IP} = t_1 + t_2 + \left[ V_{ba} - \sqrt{V_{ba}^2 - [(X - D) x 2a_3]} \right] / a_3
\]

where  
\( t_2 \) = transition time.
\( V_{ba} \) = speed at the end of the transition phase
\( a_3 \) = deceleration during braking.

If \( IP \) is not within the three phases examined above, then

\[
t_{IP} = t_1 + t_2 + t_3 + \left[ X - [D + (V_{ba}^2 - V_x^2)] / 2a_3 \right] / V_x
\]

where  
\( t_3 \) = braking phase time
\( V_x \) = taxi speed

and the expression between brackets is the distance from the end of the braking phase to IP.
2.3.3.3 Wake turbulence from landing aircraft

Wake vortices are generated from the time the nosewheel lifts off the runway on takeoff and continues until the nosewheel touches down on landing (CAA, 1986, p7).

The simulation model assumes that wake vortices hazards from a landing aircraft cease at the end of the transition phase (D above). Therefore, if X is within D, wake turbulence spacing must be provided at IP for a departing aircraft.

Since D varies from one aircraft to another, it is assumed that the most penalising aircraft requires a D value equal to 600 metres, such value is used by the FAA in its capacity handbook (FAA, 1983, p21, 22).

2.3.3.4 Time to the intersection for a departure

The elapsed time between departure threshold and IP depends on Y, the distance to IP and the acceleration developed during takeoff.

The acceleration is found as follows (Dole, 1981, p7, 8) (figure 29):

\[ V = V_0 + at \]

where:
- \( V \) = velocity at time \( t \)
- \( V_0 \) = velocity at time \( t_0 \)
- \( a \) = acceleration

Thus, the distance \( s \) covered in a certain time is

\[ s = \frac{(V + V_0)}{2} \times t \]

and

\[ s = \frac{(V_0 + at + V_0)}{2} \times t \]

or:

\[ s = Vot + \frac{1}{2} a t^2 \]

If the speed at the start of the takeoff roll is assumed equal to zero, then:
\[ s = \frac{at^2}{2} \]

and \[ a = \frac{2s}{t^2} \]

Therefore, by recording the elapsed time between takeoff threshold and a known position, it is possible to compute the acceleration for a particular aircraft. This acceleration is assumed to be constant on a horizontal plane until IP.

The time \( t_{IP} \) to cover \( Y \) is given by:

\[ t_{IP} = \sqrt{\frac{2Y}{a}} \]

### 2.3.3.5 Wake turbulence from departing aircraft

Takeoff performance is governed by many factors such as weight, altitude, temperature (WAT conditions), runway length, maximum structural takeoff weight, en route climb performance, maximum landing weight, diversion requirements, obstacle clearance, tyres and brake limits (Ashford, Stanton and Moore, 1984, p92, 97), wind speed and direction, runway slope (Ashford and Wright, 1984, p64, 65).

Hence, the distance at which a departing aircraft nosewheel lifts off, i.e. the distance where wake vortices generation begins, depends on these factors.

It is assumed that aircraft generating wake vortices hazard generating aircraft lift off at 1200 metres from departure threshold, such distance being used by the FAA (1983, p21, 22).

### 2.3.3.6 Interactions between departures and arrivals

As seen before, landing aircraft (A) have priority over departures (T).

Apart from interdeparture spacing checks, three conditions must be satisfied before T is cleared to takeoff (figure 30):
Figure 29 - Distance, acceleration and time relationships.

Figure 30 - Takeoff clearance conditions.
- A has vacated the runway before IP,
- A has passed IP and, if necessary, wake turbulence spacing taken into account,
- A is far enough on final approach for T to pass IP with a safe margin.

For the first case, the runway occupancy time (RT) is added to the time at threshold (TOT) for A to obtain the time (TCT) at which T can be cleared to takeoff, or:

\[ TCT = TOT + RT \]

In the second case, TCT is given by:

\[ TCT = TOT + tIP(A) + WS - tIP(T) \]

where \( tIP = \) time to intersection for A or T
\( WS = \) wake turbulence spacing, if applicable, i.e. if \( X \) less than or equal to 600 metres, otherwise WS is equal to zero.

For the first two cases, TCT represents the soonest time at which T can be cleared for takeoff, while in the next situation TCT is the latest time for takeoff clearance.

In the third case, two situations are considered:

(i) A is expected to clear the runway before IP, or is expected to pass IP and the wake vortices spacing does not apply (i.e. \( Y \) less than or equal to 1200 metres),

(ii) A is expected to cross IP and wake vortices separation is to be enforced (i.e. \( Y \) is greater than 1200 metres).

In (i), A must get its landing clearance before the decision height (located at about 900 metres from the landing threshold for a 200 foot height and a 3 degree glideslope in CAT I). The simulation model assumes the decision point situated at 1200 metres. However, the safety margin is considered equal to the time to cover these 1200 metres or equal to the buffer as determined for inter-arrival spacing or departure-arrival spacing, whichever is the greater. Then:
TCT = ETOT - SM - tIP(T)

where:  
ETOT = estimated time over threshold for A  
SM = safety margin  
tIP(T) = time to intersection for T.

For (ii), wake turbulence separation is included in the model as follows:

TCT = ETOT + tIP(A) - WS - tIP(T)

where:  
WS = wake turbulence spacing  
tIP = time to intersection for A or T.
FIELD STUDIES AND DATA ANALYSIS

During the development of the simulation model, specific data requirements were identified. Therefore it was essential to carry out field studies at typical regional airports to collect information on aircraft movements during the different phases associated with takeoff and landing and on ATC spacing between aircraft operations.

However, since airports actually operate in an ILS environment, data gathered during field studies will necessarily reflect only this operational environment.

3.1 DATA ACQUISITION

The field studies took place at:

East Midlands: from 25th to 29th July, 1988
Birmingham: from 12th to 16th September, 1988

1306 aircraft movements were observed.

For each airport, operations were monitored during busy hours in the morning and in the afternoon from an observation point conveniently located in relation to the runway direction in use. At Birmingham more detailed information about aircraft activities was obtained by listening to ATC radio frequencies from the control tower.

The time at which an aircraft begins or completes a manoeuvre was recorded. Then the duration of each manoeuvre as well as the spacing between successive operations was found from the proper time differences.

For landing aircraft, the following observations were made: aircraft type, time over threshold, exit taxiway used, time clear of runway, and in addition for Manchester airport, transition and turnoff durations.
For departures, aircraft types and the times at which they left the holding point, were lined up, started their takeoff roll and were airborne, were recorded. At Birmingham and Manchester, the times passing known positions on the runway were also noted in order to computing acceleration.

### 3.2 Aircraft classification

In this research, aircraft are classified in conformity with the wake turbulence categorisation established by the CAA for spacing purposes (1986) in which aircraft are divided into 4 groups according to their maximum takeoff weight stated in the following table:

<table>
<thead>
<tr>
<th>CATEGORY</th>
<th>MAXIMUM TAKEOFF WEIGHT (Kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heavy</td>
<td>136000 or greater</td>
</tr>
<tr>
<td>Medium</td>
<td>Less than 136000 and more than 40000</td>
</tr>
<tr>
<td>Small</td>
<td>40000 or less and more than 17000</td>
</tr>
<tr>
<td>Light</td>
<td>17000 or less</td>
</tr>
</tbody>
</table>

Typical aircraft serving regional airports are:

- **Heavy:** B747, B767, A300, A310, DC10, L1011
- **Medium:** BA1-11, B727, B737, B757, MD80, FK100
- **Small:** BA146, DASH7, FK27, ATP, FK28
- **Light:** BA125, SAAB340, SHORT 330/360, JETSTREAM 31, DO228, CITATION, KINGAIR, LEARJET, EMB 110/120

Due to their vortices characteristics, some aircraft types have been included in groups which do not conform to the weight parameter listed above. For instance, the BA146 is classified in the "Small" category, the DC8 and B707 in the "Medium" group (NATS, 1974 as amended in July 1988, p B-1, B-2).

### 3.3 Data Analysis

The analysis performed on the data collected during the field studies provided the following results:
3.3.1 Statistical data on arrivals

3.3.1.1 Inter-arrival separations

The relative percentage of the four aircraft categories during the observation periods is presented in the next table:

<table>
<thead>
<tr>
<th>AIRPORT</th>
<th>HEAVY</th>
<th>MEDIUM</th>
<th>SMALL</th>
<th>LIGHT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manchester</td>
<td>4</td>
<td>53</td>
<td>16</td>
<td>27</td>
</tr>
<tr>
<td>Birmingham</td>
<td>4</td>
<td>39</td>
<td>18</td>
<td>39</td>
</tr>
<tr>
<td>East Midlands</td>
<td>0</td>
<td>30</td>
<td>17</td>
<td>53</td>
</tr>
</tbody>
</table>

For this traffic mix, the spacing (in seconds) between arrivals was as follows:

<table>
<thead>
<tr>
<th>AIRPORT</th>
<th>MEAN</th>
<th>STANDARD DEVIATION</th>
<th>NUMBER OF OBSERVATIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manchester</td>
<td>126.2</td>
<td>22.1</td>
<td>92</td>
</tr>
<tr>
<td>Birmingham</td>
<td>122.3</td>
<td>21.9</td>
<td>99</td>
</tr>
<tr>
<td>East Midlands</td>
<td>132.1</td>
<td>22.3</td>
<td>68</td>
</tr>
</tbody>
</table>

Figure 31 shows the cumulative frequency distributions for these separations.

3.3.1.2 Runway occupancy time

The number of observations for the runway occupancy time (RT) were 176 for Manchester, 231 for Birmingham and 119 for East Midlands, split according to the mix presented above.

The cumulative frequency distribution of RT for medium, small and light aircraft categories are shown in figures 32, 33 and 34 respectively.

Since heavy traffic at regional airports represents only a small proportion of total traffic, it has been possible to collect only a few data on this aircraft category during the field studies. The number of observations are:
Figure 31 – Interarrival separations
Figure 32 - Runway occupancy time
(Medium aircraft)
Figure 33 – Runway occupancy time (Small aircraft)
Figure 34 – Runway occupancy time (Light aircraft)
RT (seconds)  | MANCHESTER | BIRMINGHAM |
---|---|---|
50 - 59  | 1  | -  |
60 - 69  | 3  | 2  |
70 - 79  | 1  | 4  |
80 - 89  | 2  | 2  |
90 - 99  | -  | 1  |

Figure 35 illustrates pooled RT for all aircraft categories.

### 3.3.1.2.1 Transition time

At Manchester, the time between main gear touchdown and nosewheel touchdown has been recorded. Its analysis gives the following values in seconds.

<table>
<thead>
<tr>
<th>Aircraft Category</th>
<th>MEAN</th>
<th>VARIANCE</th>
<th>MINIMUM</th>
<th>MAXIMUM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heavy</td>
<td>7</td>
<td>1</td>
<td>4</td>
<td>10</td>
</tr>
<tr>
<td>Medium</td>
<td>4.7</td>
<td>1</td>
<td>3</td>
<td>9</td>
</tr>
<tr>
<td>Small</td>
<td>4.5</td>
<td>0.7</td>
<td>3</td>
<td>8</td>
</tr>
<tr>
<td>Light</td>
<td>3.3</td>
<td>0.4</td>
<td>2</td>
<td>6</td>
</tr>
</tbody>
</table>

Since beta distribution is used to describe situations which have a finite range (Pritsker, 1986, p705) and short lengths of time are involved, with a degree of accuracy in the order of 1 - 2 seconds, it is assumed that these data come from a beta distribution.

### 3.3.1.2.2 Turnoff time

The interval between the time the nosewheel leaves the runway centreline after landing and the time the aircraft tail clears the runway edge has been measured at Manchester.

(a) **Rapid exit taxiways**

The next table summarises the observations (in seconds).
Figure 35 - Runway occupancy time
(All aircraft categories included)
<table>
<thead>
<tr>
<th>MEAN</th>
<th>STANDARD DEVIATION</th>
<th>NUMBER OF OBSERVATIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heavy</td>
<td>10</td>
<td>1</td>
</tr>
<tr>
<td>Medium</td>
<td>10.1</td>
<td>76</td>
</tr>
<tr>
<td>Small</td>
<td>9.2</td>
<td>27</td>
</tr>
<tr>
<td>Light</td>
<td>10.1</td>
<td>34</td>
</tr>
</tbody>
</table>

No significant difference can be noticed between aircraft groups for the turnoff time. So, as for the transition time, a beta distribution is assumed but with parameters obtained from pooled data.

<table>
<thead>
<tr>
<th>MEAN</th>
<th>VARIANCE</th>
<th>MINIMUM</th>
<th>MAXIMUM</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.9</td>
<td>3.4</td>
<td>6</td>
<td>15</td>
</tr>
</tbody>
</table>

(b) Right-angle taxiways

Only few (37) observations have been made. Thus, here too a beta distribution is assumed with the following parameters:

<table>
<thead>
<tr>
<th>MEAN</th>
<th>VARIANCE</th>
<th>MINIMUM</th>
<th>MAXIMUM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heavy</td>
<td>18.4</td>
<td>11</td>
<td>28</td>
</tr>
<tr>
<td>Medium</td>
<td>16.5</td>
<td>10</td>
<td>25</td>
</tr>
<tr>
<td>Small</td>
<td>14.8</td>
<td>9</td>
<td>23</td>
</tr>
<tr>
<td>Light</td>
<td>13.2</td>
<td>8</td>
<td>20</td>
</tr>
</tbody>
</table>

3.3.1.3 Buffer

The interval between the time a landing aircraft vacates the runway, or a departing aircraft is airborne, and the time the next arrival crosses the runway threshold is presented in the following frequency table.
<table>
<thead>
<tr>
<th>TIME(seconds)</th>
<th>ARRIVAL-ARRIVAL</th>
<th>DEPARTURE-ARRIVAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 - 14</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>15 - 19</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>20 - 24</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>25 - 29</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>30 - 34</td>
<td>6</td>
<td>4</td>
</tr>
<tr>
<td>35 - 39</td>
<td>12</td>
<td>11</td>
</tr>
<tr>
<td>40 - 44</td>
<td>6</td>
<td>8</td>
</tr>
<tr>
<td>45 - 49</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>50 - 54</td>
<td>6</td>
<td>4</td>
</tr>
<tr>
<td>55 - 59</td>
<td>5</td>
<td>3</td>
</tr>
</tbody>
</table>

It can be seen from this table that the bulk of the observations is in the 35 - 39 range, suggesting that this is the targeted buffer. So, this study considers significant only the times which are less than 45 seconds. Since there is similarity between the two sets of data, the observations have been pooled, their cumulative frequency distribution is shown in figure 36.

3.3.2 Statistical Data On Departures

A "goodness-of-fit" test is used

(a) to verify the compatibility of a set of observed data with some theoretical distribution,

or

(b) to check the degree of agreement between distributions of two sets of data.

The Kolmogorov-Smirnov "goodness-of-fit" test can be performed for both situations (Gibbons, 1971, p75, 87, p127, 131).

In this study, the Kolmogorov-Smirnov test has been utilised, according to the procedure suggested by Shannon (1975, p78, 79) and with a 0.05 significance level, to compare:
Figure 36 - Separations buffer
(Arrival-arrival and departure-arrival)
- a set of observed data with a normal distribution, in the case of line up times, takeoff roll times, takeoff acceleration and departure spacing,

- a set of observed data from field studies with a set of output data from computer simulation runs, for the inter-arrival separations and the runway occupancy times.

3.3.2.1 Line up times

The distance between the holding point and the runway centreline is equal to 90 metres at Manchester and East Midlands airports and 180 metres at Birmingham (CAA, 1975 as amended in July 1988). Thus, the observed line up times (in seconds) are split into two sets as follows:

(a) Manchester and East Midlands

<table>
<thead>
<tr>
<th>Type</th>
<th>Mean</th>
<th>Standard Deviation</th>
<th>Number of Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heavy</td>
<td>46</td>
<td>4.8</td>
<td>7</td>
</tr>
<tr>
<td>Medium</td>
<td>40.4</td>
<td>8.7</td>
<td>142</td>
</tr>
<tr>
<td>Small</td>
<td>35.6</td>
<td>6.9</td>
<td>46</td>
</tr>
<tr>
<td>Light</td>
<td>34</td>
<td>6.7</td>
<td>109</td>
</tr>
</tbody>
</table>

(b) Birmingham

<table>
<thead>
<tr>
<th>Type</th>
<th>Mean</th>
<th>Standard Deviation</th>
<th>Number of Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heavy</td>
<td>57</td>
<td>12.4</td>
<td>8</td>
</tr>
<tr>
<td>Medium</td>
<td>49.4</td>
<td>10</td>
<td>91</td>
</tr>
<tr>
<td>Small</td>
<td>41.5</td>
<td>9.5</td>
<td>42</td>
</tr>
<tr>
<td>Light</td>
<td>40.5</td>
<td>11.3</td>
<td>54</td>
</tr>
</tbody>
</table>
3.3.2.2. Takeoff roll times

The following tables provide results (time in seconds) for each airport and for the three airports combined.

(a) **Heavy**

<table>
<thead>
<tr>
<th></th>
<th>MEAN</th>
<th>STANDARD DEVIATION</th>
<th>NUMBER OF OBSERVATIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Birmingham</td>
<td>38.6</td>
<td>9.2</td>
<td>8</td>
</tr>
<tr>
<td>Manchester</td>
<td>40.4</td>
<td>6.5</td>
<td>13</td>
</tr>
<tr>
<td>2 Airports</td>
<td>39.7</td>
<td>7.5</td>
<td>21</td>
</tr>
</tbody>
</table>

(b) **Medium**

<table>
<thead>
<tr>
<th></th>
<th>MEAN</th>
<th>STANDARD DEVIATION</th>
<th>NUMBER OF OBSERVATIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Birmingham</td>
<td>36.8</td>
<td>5.1</td>
<td>92</td>
</tr>
<tr>
<td>East Midlands</td>
<td>36.6</td>
<td>6.5</td>
<td>40</td>
</tr>
<tr>
<td>Manchester</td>
<td>33.1</td>
<td>6.5</td>
<td>135</td>
</tr>
<tr>
<td>3 airports</td>
<td>34.9</td>
<td>6.3</td>
<td>267</td>
</tr>
</tbody>
</table>

(c) **Small**

<table>
<thead>
<tr>
<th></th>
<th>MEAN</th>
<th>STANDARD DEVIATION</th>
<th>NUMBER OF OBSERVATIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Birmingham</td>
<td>34.6</td>
<td>6.4</td>
<td>42</td>
</tr>
<tr>
<td>East Midlands</td>
<td>29.4</td>
<td>5.4</td>
<td>20</td>
</tr>
<tr>
<td>Manchester</td>
<td>29.1</td>
<td>5.7</td>
<td>26</td>
</tr>
<tr>
<td>3 airports</td>
<td>31.8</td>
<td>6.5</td>
<td>88</td>
</tr>
</tbody>
</table>
Because Birmingham, East Midlands and Manchester airports are almost at the same altitude (325, 310 and 256 feet respectively) and a wider range of aircraft types in different operating conditions is included in each group, parameters for pooled data provide a good approximation of takeoff roll times at a typical regional airport.

### 3.3.2.3 Takeoff acceleration

Measurements were taken at 1020 metres from departure threshold at Birmingham and 480 metres and 870 metres (depending on the takeoff position) at Manchester. Calculation of the acceleration provided the following results in metres/second².
The next table gives results for grouped data.

<table>
<thead>
<tr>
<th></th>
<th>MEAN</th>
<th>STANDARD DEVIATION</th>
<th>NUMBER OF OBSERVATIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jets</td>
<td>2.49</td>
<td>0.76</td>
<td>251</td>
</tr>
<tr>
<td>Others</td>
<td>2.24</td>
<td>0.68</td>
<td>126</td>
</tr>
</tbody>
</table>

Jet traffic represents 20% of aircraft in the small and light categories.

Actual values for the takeoff acceleration are certainly less than the figures contained in the two preceding tables because:

- measurements were taken at relatively short distances during the initial phase of the takeoff manoeuvre, and are affected by errors in the timing (reaction time to notice the beginning of the takeoff roll at long distances from the observation point and parallax error when measurements are not taken perpendicularly to the runway centreline from the observation point),

- calculation of the acceleration assumed initial speed equal to zero, but in the real operational environment some aircraft start their takeoff roll without stopping at the end of the line up manoeuvre (e.g. rolling takeoff).

Therefore, only parameters contained in the second table are used in the simulation model to provide estimates at the crossing point for intersecting runways.

3.3.2.4 Departure Separations
Departing aircraft are separated according to the routes they fly, their speed characteristics and their wake vortex categories (NATS, 1974 as amended in July 1988, p 1 - 15, 1 - 16).

Each of the three airports has three departure routes (CAA, 1975 as amended in July 1988, p RAC 3 - 4 - 0 - 18, p RAC 3 - 4 - 23, p RAC 3 - 4 - 4 - 14 and 15) diverging immediately after the runway takeoff end.

Jet aeroplanes are classified as fast aircraft and propeller driven aircraft are included in the slow category (CAA, 1988D, p3, 4).
The following table summarises the observed separations (in seconds)

<table>
<thead>
<tr>
<th></th>
<th>MEAN</th>
<th>STANDARD DEVIATION</th>
<th>NUMBER OF OBSERVATIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Different routes</td>
<td>71</td>
<td>13</td>
<td>73</td>
</tr>
<tr>
<td>Same route -</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Slow followed by fast</td>
<td>168.8</td>
<td>27.2</td>
<td>36</td>
</tr>
<tr>
<td>Same route - Others</td>
<td>114.7</td>
<td>17.3</td>
<td>94</td>
</tr>
<tr>
<td>Heavy followed by non-Heavy</td>
<td>114.3</td>
<td>43</td>
<td>6</td>
</tr>
</tbody>
</table>

Although ATC rules specify a wake vortex departure separation of 2 minutes to be applied when a light aircraft follows a medium or small aircraft, field data show no indication that this spacing is enforced:

<table>
<thead>
<tr>
<th></th>
<th>MEAN</th>
<th>STANDARD DEVIATION</th>
<th>NUMBER OF OBSERVATIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Medium/Small followed by Light</td>
<td>72.8</td>
<td>14.7</td>
<td>19</td>
</tr>
<tr>
<td>Light followed by Light</td>
<td>70.4</td>
<td>12.6</td>
<td>13</td>
</tr>
</tbody>
</table>

Thus, these observations were included in the first table.
4.1 INITIAL ASSUMPTIONS

During analysis of MLS procedures, this study assumes that all operations observed during field studies, apart from the inter-arrival separations, remain unchanged, in particular the arrival runway occupancy time and the line up time for departing aircraft.

As shown in chapter 2, the runway occupancy time depends primarily on the speed at which an aircraft crosses the runway threshold. For instance, for each knot of excess speed, landing distance will extend by 100 feet (Ashford, Stanton and Moore, 1984, p98). Nevertheless, current literature does not provide sufficient material for quantifying the approach speed variations for different aircraft categories when the glideslope angle increases.

On the other hand, line up time may be affected by the critical areas around ILS and MLS stations to protect guidance signals from interferences due to aircraft at the holding point. The larger the critical areas, the further the holding point must be from departure threshold. Critical areas may be larger for MLS curved approaches, but their dimensions are not yet determined for these applications (FAA, 1985, p11).

Therefore, the simulation model considers the same runway occupancy and line up times for both systems.

Moreover, it is assumed that ILS and MLS procedures differ only by their geometry (length of the final approach segment and glidepath angle) and their accuracy. Hence, airspace constraints and flight restrictions due to obstructions and due to noise from aircraft on curved approaches are not included in the model.

Since the model assumes that ILS and MLS procedures differ essentially in the aircraft inter-arrival time, it is necessary to dimension the factors which affect the inter-arrival spacing. These factors were examined in chapter 2 and are:
- approach speed,
- separation on final approach,
- length of the common approach path,
- glideslope angle,
- system error.

For intersecting runways, because data were collected only at single IFR runway airports, it is necessary to estimate the landing runway occupancy time, the time to the intersection point for arrivals and the departure-arrival and arrival-departure spacing at the crossing point due to wake turbulence, all other factors are assumed identical.

Thus, this chapter defines the parameters used by the simulation model for calculating the inter-arrival separations, and the runway occupancy times and wake vortices spacing for intersecting runways.

4.2 INTER-ARRIVAL SPACING

4.2.1 Approach speed

In the design of instrument approach procedures, aircraft are classified according to their threshold speed (Vat) (CAA, 1987C) as shown in the following table (Vat expressed in knots).

<table>
<thead>
<tr>
<th>Category</th>
<th>Vat</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Less than 91</td>
</tr>
<tr>
<td>B</td>
<td>91 - 120</td>
</tr>
<tr>
<td>C</td>
<td>121 - 140</td>
</tr>
<tr>
<td>D</td>
<td>141 - 165</td>
</tr>
<tr>
<td>E</td>
<td>166 - 210</td>
</tr>
</tbody>
</table>

Note: Actually, there is no civil aircraft in category E

This research assumes that the difference between Vat and actual approach speed is negligible when flying the final approach segment.
Typical aircraft serving regional airports are:

Category A: Dash 7; Twin Otter; Dornier 228; Islander

Category B: Fokker 27; King Air; Jetstream 31; ATP; BA 146; Citation; Dash 8; Embraer 110/120; Short 330/360; Dassault Falcon

Category C: BAC 1-11; Airbus 300/310; B727; B737: B757; B767; Learjet; MD80

Category D: B747; DC10; Tristar

After examination of the relevant literature (Aviation Week and Space Technology, 1987, p145, 151; Flight International, 1988, p62, 83 and 1989, p60 67), the following speed ranges are considered in the simulation model:

<table>
<thead>
<tr>
<th>Category</th>
<th>Speed Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heavy</td>
<td>121 - 145</td>
</tr>
<tr>
<td>Medium</td>
<td>121 - 140</td>
</tr>
<tr>
<td>Small</td>
<td>85 - 125</td>
</tr>
<tr>
<td>Light</td>
<td>75 - 125</td>
</tr>
</tbody>
</table>

A uniform distribution function is assumed to characterise these speed ranges.

4.2.2. Separations on final approach

Airborne aircraft must be separated by at least 3 nautical miles (radar distance) when they are at the same level or by 1000 feet of altitude (CAA, 1983B, p3). However, for wake vortex avoidance, higher longitudinal separations are applicable on final approach (CAA, 1986, p3). The next table summarises the minimum separations (in nautical miles) when vertical spacing is not applied.
### Following Aircraft

<table>
<thead>
<tr>
<th></th>
<th>H</th>
<th>M</th>
<th>S</th>
<th>L</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leading Aircraft</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
</tbody>
</table>

#### 4.2.3. Length of the approach path

(a) **ILS**

ATC vectors aircraft to close the localiser (azimuth beam) at an angle of about 30 degrees and a minimum distance of level flight (D) is prescribed from localiser to glidepath interception points (CAA, 1977, p28), D being function of the angle of interception with localiser, as shown in the table below.

<table>
<thead>
<tr>
<th>A (degree)</th>
<th>D (nautical miles)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>1</td>
</tr>
<tr>
<td>30</td>
<td>2</td>
</tr>
<tr>
<td>45</td>
<td>3</td>
</tr>
<tr>
<td>60</td>
<td>4</td>
</tr>
</tbody>
</table>

At Birmingham, East Midlands and Manchester airports, noise abatement procedures require aircraft flying ILS to intercept the glidepath not below 2000 feet above sea level (CAA, 1975 as amended in July 1988, p AGA 2 - 5 - 1, p AGA 2 - 12 - 1, p AGA 2 - 28 - 1). These airports are located at about 300 feet above sea level and aircraft on ILS approaches are expected to cross the runway threshold at a height of 50 feet. Therefore, the glidepath interception point is at about 1650 feet above aerodrome level. For a 3 degree glidepath, the slope is equal to 5.24%. Thus, the glidepath interception point is at about 5 nautical miles. When D is added to this length, the distance between localiser interception point and runway threshold is approximately 7 nautical miles for ILS approaches.
(b) MLS

FAA has developed protected airspace and other criteria that would permit aircraft to fly MLS approaches in CAT I conditions, in particular the final centreline segment (FCLS) and the decision height (DH) which depend on the aircraft speed categories seen in paragraph 4.2.1 above (FAA, 1988, appendix, p4, p19).

The length of the final approach path (L) is obtained by adding together the FCLS and the distance from DH to runway threshold. L for curved approaches is as below:

<table>
<thead>
<tr>
<th>Category</th>
<th>L (nautical miles)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>2.4</td>
</tr>
<tr>
<td>B</td>
<td>3.1</td>
</tr>
<tr>
<td>C</td>
<td>3.7</td>
</tr>
<tr>
<td>D</td>
<td>4.0</td>
</tr>
</tbody>
</table>

4.2.4 Glideslope angle

The ILS glideslope angle at Birmingham, East Midlands and Manchester is set to 3 degrees.

The FAA criteria applicable to CAT I MLS operations define the maximum glideslope angles determined by the aircraft speed category as follows (FAA, 1988, p5):
<table>
<thead>
<tr>
<th>Category</th>
<th>Glidepath angle (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A (80 knots or less)</td>
<td>6.4</td>
</tr>
<tr>
<td>A (more than 80 knots)</td>
<td>5.7</td>
</tr>
<tr>
<td>B</td>
<td>4.2</td>
</tr>
<tr>
<td>C</td>
<td>3.6</td>
</tr>
<tr>
<td>D</td>
<td>3.1</td>
</tr>
</tbody>
</table>

This simulation model assumes these angles when steeper angle approaches are investigated.

4.2.5. Systems error

System delivery accuracy has been determined by Credeur, Davis and Capron (1981, p69).

The standard deviation in inter-arrival error (zero mean) at the entry gate is 15 seconds for ILS and 12 seconds for MLS.

4.3  INTERSECTING RUNWAYS

4.3.1 Landing runway occupancy time and time to the crossing point

The following parameters are used by the simulation model to estimate the runway occupancy time and the time between the landing runway threshold and the intersection point when this latter information is not available.

The transition time and the turnoff time are assumed equal to those given in chapter 3 of this study.
(a) Touchdown location

The touchdown location from threshold is related to the aircraft speed category (Hobeika, Dona and Nam, 1987, p38) as follows:

<table>
<thead>
<tr>
<th>Category</th>
<th>Mean (metres)</th>
<th>Standard deviation (metres)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>150</td>
<td>3</td>
</tr>
<tr>
<td>B</td>
<td>300</td>
<td>6</td>
</tr>
<tr>
<td>C</td>
<td>450</td>
<td>9</td>
</tr>
<tr>
<td>D</td>
<td>450</td>
<td>9</td>
</tr>
</tbody>
</table>

(b) Deceleration rates

After examination of the deceleration rates reported in the literature (Ashford and Wright, 1984, p 211; Horonjeff and McKelvey, 1983, p 305; Joline, 1974, p 87; IATA, 1987, p 5; Hobeika, Dona and Nam, 1987, p 38), a beta distribution is assumed for the deceleration rate during braking action with the following parameters:

<table>
<thead>
<tr>
<th>Mean</th>
<th>Standard</th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5 m/s²</td>
<td>0.15 m/s²</td>
<td>1.2 m/s²</td>
<td>2.5 m/s²</td>
</tr>
</tbody>
</table>

The simulation model considers a deceleration rate during the flare equal to 0.5 the deceleration rate during braking action (Horonjeff and McKelvey, 1983, p 310) and a transition deceleration rate equal to 0.75 the braking action rate.

(c) Taxi and exit speeds

Aircraft are assumed to clear the runway at 13 knots when using a right-angle exit taxiway, but the maximum exit speeds considered for aircraft using a rapid exit taxiway are (Horonjeff and McKelvey, 1983, p 303, p 309)
Aircraft are supposed to taxi on the runway at the speeds given in the table above at the end of the braking action phase.

(d) Time to complete a 180° turn for backtracking

The radii of curvature (R) and their related aircraft speeds (V) are as shown below (Horonjeff and McKelvey, 1983, p 305).

<table>
<thead>
<tr>
<th>R (metres)</th>
<th>V (kilometres/hour)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>16</td>
</tr>
<tr>
<td>60</td>
<td>32</td>
</tr>
<tr>
<td>135</td>
<td>48</td>
</tr>
<tr>
<td>etc.</td>
<td>etc.</td>
</tr>
</tbody>
</table>

The following equation is derived from the table above:

\[ V = 16 \sqrt{R/15} \]

This equation provides a good estimate for the speed in 180° turn when compared to those given by ICAO (1983, p 2.15).
<table>
<thead>
<tr>
<th>R</th>
<th>V(ICA0)</th>
<th>V (Equation)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.5</td>
<td>13.32</td>
<td>13.39</td>
</tr>
<tr>
<td>15.75</td>
<td>16.32</td>
<td>16.4</td>
</tr>
<tr>
<td>23.25</td>
<td>19.82</td>
<td>19.9</td>
</tr>
<tr>
<td>34.25</td>
<td>24.06</td>
<td>24.18</td>
</tr>
<tr>
<td>38.25</td>
<td>25.41</td>
<td>25.55</td>
</tr>
</tbody>
</table>

Flight International (1988, p 62, 83 and 1989, p 60, 67) provides turning radii for a wide range of aircraft types summarised as follows:

<table>
<thead>
<tr>
<th>R (metres)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heavy</td>
</tr>
<tr>
<td>Medium</td>
</tr>
<tr>
<td>Small</td>
</tr>
<tr>
<td>Light</td>
</tr>
</tbody>
</table>

After converting turning speed to metres/second \( (V_{ms} = V \times \frac{1000}{3600}) \), the time \( (t) \) in seconds to complete the 180° turn is calculated by:

\[
t = R \times \frac{3.14}{V_{ms}}
\]

**4.3.2. Wake turbulence spacing at the intersection point**

Wake turbulence separation for aircraft on final approach are applicable to aircraft departing from intersecting runways if the projected flight paths will cross (CAA, 1986, p 5).
This study assumes that these separations apply also to mixed operations to and from crossing runways if the projected flight trajectories will intersect.

Thus the following spacings (in nautical miles) are utilised for wake turbulence avoidance purpose.

### Second aircraft at intersection point

<table>
<thead>
<tr>
<th></th>
<th>H</th>
<th>M</th>
<th>S</th>
<th>L</th>
</tr>
</thead>
<tbody>
<tr>
<td>First aircraft at intersection point</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>M</td>
<td>3</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>S</td>
<td>3</td>
<td>3</td>
<td>4</td>
</tr>
</tbody>
</table>

The aircraft speeds just after takeoff and within the runway length are very close to the final approach speeds. In fact, the takeoff safety speed (V2) is not very different from the threshold speed (Vat) (Flight International, 1988, p 62, 83 and 1989, p 60 67).

This study assumes the difference being negligible and the spacings in the table above are converted into time separations (in seconds) by using the approach speeds given in paragraph 4.2.1 above. The next table provides the mean and standard deviation for each case.

### Second aircraft at intersection point

<table>
<thead>
<tr>
<th></th>
<th>H</th>
<th>M</th>
<th>S</th>
<th>L</th>
</tr>
</thead>
<tbody>
<tr>
<td>First aircraft at intersection point</td>
<td>106.7, 6.8</td>
<td>133.3, 8.3</td>
<td>159.7, 9.8</td>
<td>213.2, 13.</td>
</tr>
<tr>
<td></td>
<td>M</td>
<td>82.8, 3.5</td>
<td>110.4, 4.7</td>
<td>165.7, 6.9</td>
</tr>
<tr>
<td></td>
<td>S</td>
<td>82.8, 3.5</td>
<td>100.8, 9.3</td>
<td>134.1, 12.4</td>
</tr>
</tbody>
</table>
CHAPTER 5:
SIMULATION PROGRAM

5.1 CONCEPTUAL FRAMEWORK

The Simulation Language for Alternative Modeling (SLAM II) (Pritsker, 1986) supported the model for assessing runway capacity, in particular it provided the conceptual framework for describing the runway operational system.

The key concept is the model state description. This model is represented by a set of variables, with the values of each combination of variables characterising a unique state or condition of the model. Motion from state to state is simulated by changing the values of the variables in accordance with prescribed logical-mathematical relationships. Time and aircraft characteristics are examples of independent variables, while the relative position of the aircraft depends upon these variables.

The dynamic structure of the model is described by four events with code:

1. for the creation of aircraft,
2. for the start of the final approach,
3. for the arrival runway threshold crossing,
4. for the beginning of the takeoff manoeuvre.

Some of these events are scheduled and occur at specified points in time. They are called time-events. The model includes two time-events:

- aircraft creation,
- arrival runway threshold crossing.

The other events, defined as state-events, occur when model variables meet prescribed conditions. Therefore, the start of the final approach and the beginning of the take-off manoeuvre happen when the model reaches a particular state determined by variables crossing specified values.
5.2 MODEL PROCESSING LOGIC

Figure 37 shows the processing logic applied for the simulation model. The SLAM II processor, called by a main program where the storage arrays are dimensioned, starts by interpreting input statements which, in particular, initialise SLAM II variables. In the model, these variables represent the aircraft traffic mix, the percentage of arrivals and the demand level. Additional initialisation is made for non-SLAM II variables by a call to subroutine INTLC which defines:

- the system to be simulated (ILS, MLS 3 degree glidepath, MLS multiple glidepaths),
- the runway configuration (single runway or definition of the crossing point for intersecting runways),
- the number of hours to be simulated,
- the time at which the first aircraft enters the simulation.

Note: All subroutines in the simulation program are coded in FORTRAN and include SLAM II standard subprograms to perform common functions, such as event scheduling, file manipulations, etc.

After processing subroutine INTLC or after any advance in the current time (TNOW), the processor checks if TNOW is greater than or equal to the ending time specified for the simulation. If this condition is satisfied, the simulation run is ended and a call is made to subroutine OUTPUT which provides statistics, especially on aircraft average delay for the concerned demand level. If additional simulation runs are to be executed, the next run is initiated, otherwise a return to the main program is made. If the end of simulation condition is not satisfied, the processor determines if there is a time-event at the current time. If there is, the subroutine EVENT (I) is called, where I is set to the current event code as seen in the preceding paragraph. Since at this stage just time-events are processed, therefore only aircraft creation or arrival runway threshold crossing events can be released.

Figure 38 depicts the processing logic for aircraft creation event (subroutine TFC GEN). Hourly aircraft creation is assumed to comply with a Poisson distribution, the mean being equal to the hourly demand level. Aircraft are characterised according to the parameters described in the preceding chapter.

The logic relating to the landing event is shown in figure 39.
Figure 37 - Model Processing Logic.
Figure 38 - Processing logic for aircraft creation event.
Subroutine LNDOG

Calculate time runway cleared

Intersecting runways?

Yes

Aircraft crosses other runway?

Yes

Calculate time at intersection

No

No

Return

Figure 39 - Processing logic for landing event.
Subroutine STATE is called at periodic intervals called steps which are defined in the input statements mentioned in the initialisation process. Variables values in this subroutine are updated and state-event conditions are checked. If there is no state-event to be processed, a test for end of simulation is made. If there is a state-event to be processed, $I$ is set to the code of the event where variables meet the presented conditions and subroutine EVENT ($I$) is called.

Figure 40 describes the logic used in subroutine STATE. This sub-program can release only the final approach or the takeoff events. Figures 41 and 42 show the logic for these two events.

Following the return from subroutine EVENT ($I$), the process is reiterated from the end of simulation check.

5.3 VALIDATION

Inter-arrival separations obtained from simulation runs are shown in figure 43 with observed values.

Figure 44 presents results for the runway occupancy time.

In both cases, the traffic mix recorded during field studies was part of the input for validation runs.

The Kolmogorov-Smirnov test performed on the sets of observed data and the sets of output data provided the following values:

(a) inter-arrival separations:

<table>
<thead>
<tr>
<th>Location</th>
<th>Largest absolute deviation</th>
<th>D value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manchester</td>
<td>0.08</td>
<td>0.141</td>
</tr>
<tr>
<td>Birmingham</td>
<td>0.09</td>
<td>0.13</td>
</tr>
<tr>
<td>East Midlands</td>
<td>0.12</td>
<td>0.139</td>
</tr>
</tbody>
</table>
Figure 40 - Processing logic for calling state-events.
Figure 41 - Final approach event processing logic.

Subroutine FNAPP

Remove aircraft from Delay file

Calculate time over threshold

Schedule landing event

Return

Figure 42 - Takeoff event processing logic.

Subroutine TKFF

Remove aircraft from Delay file

Calculate airborne time

Intersecting runways?

Yes

No

Calculate time at intersection

Return
Figure 4.3 – Interarrival separations (observed and simulated)
Figure 44 – Runway occupancy time (All aircraft categories included)
   Observed data and Simulation results

Legend
- Manchester (observation)
- Manchester (simulation)
- Birmingham (observation)
- Birmingham (simulation)
- East Midlands (observation)
- East Midlands (simulation)
(b) runway occupancy time

<table>
<thead>
<tr>
<th>Largest absolute deviation</th>
<th>D value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manchester</td>
<td>0.12</td>
</tr>
<tr>
<td>Birmingham</td>
<td>0.07</td>
</tr>
<tr>
<td>East Midlands</td>
<td>0.09</td>
</tr>
</tbody>
</table>

Thus, the null hypothesis that the observed data and the simulation output do not differ significantly cannot be rejected.
CHAPTER 6:

ANALYSIS OF RESULTS

6.1 THE EXPERIMENTATION

6.1.1. The airports

Runway operations at the three field study airports (Birmingham, East Midlands and Manchester) and Belfast/Aldergrove were simulated.

Belfast was selected because it is the only airport where each of the intersecting runways is equipped with ILS (runways 17 and 25). So each configuration was examined.

Due to lack of data, the model was used to estimate runway occupancy time for East Midlands (for heavy aircraft only) and for Belfast, the information about exit taxiways location was obtained from the Aeronautical Information Publication (AIP) (CAA, 1975 as amended in July 1988).

The next table gives the exit taxiway location for each airport.
<table>
<thead>
<tr>
<th>Airport</th>
<th>Runway</th>
<th>Location (metres)</th>
<th>Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Birmingham</td>
<td>33</td>
<td>200</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>500</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>700</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>1700</td>
<td>Secondary runway</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2300</td>
<td>Runway end taxiway</td>
</tr>
<tr>
<td>East Midlands</td>
<td>27</td>
<td>800</td>
<td>Rapid exit taxiway</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1650</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>2200</td>
<td>Runway end taxiway</td>
</tr>
<tr>
<td>Manchester</td>
<td>24</td>
<td>650</td>
<td>Rapid exit taxiway</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1150</td>
<td>Rapid exit taxiway</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1500</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>1850</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>2200</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>2800</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>3000</td>
<td>Runway end taxiway</td>
</tr>
<tr>
<td>Belfast</td>
<td>17</td>
<td>400</td>
<td>Intersection point</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1550</td>
<td>Runway end (no exit taxiway)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1950</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>2150</td>
<td>Intersection point</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2600</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>2750</td>
<td>Runway end taxiway</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The model also served to calculate inter-arrival spacing, the other parameters were those derived from observation during field studies.
6.1.2 The aircraft mix

During the experimentation it was assumed that at busy periods the traffic includes no more than 20 percent of heavy aircraft and the proportion of small aircraft in the mix is half the volume of light aircraft. These assumptions are consistent with the field observations as shown in chapter 3.

With these assumptions the whole percentage range of medium aircraft and of arrivals was investigated at 20 percent step size.

6.1.3 Number of replications

80 replications with different random number seeds were required in order to obtain relatively accurate estimates of average delay due to the numerous stochastic variables included in the model. For less than 80 replications, the average delays for some demand levels were higher than those for lower demand levels.

6.2 PRESENTATION OF SIMULATION RESULTS

Figures 45 to 72 show the simulation results and regression lines for each set of output for the 4 airports for various operational conditions:

- ILS
- MLS (3 degree glidepath) where only horizontal separation applies,
- MLS (multiple glidepaths) where horizontal and vertical spacings are applied.

These figures bring the following general comments:

(a) for a given traffic mix, the runway capacity decreases as the percent of arrivals increases until about 80 percent where the trend is reversed, because of the requirement that a departing aircraft can be released only if the runway is vacated by the preceding arrival and because of the priority for landing traffic, the departure flow is more restrained when more arrivals are included in the traffic.

(b) for a given percent of arrivals, the runway capacity increases when the proportion of medium category aircraft increases, not only because there is less requirement for wake turbulence spacing, but because the average
speed of the aircraft flow also increases, this aircraft group is characterised by a higher average approach speed than those of the smaller aircraft categories and includes only fast take-off speed class. The only exception is for Belfast airport (figures 65 and 70) in MLS multiple glidespaths operations for 80 and 100 per cent of arrivals and when no heavy aircraft are included in the traffic mix, because the medium aircraft category is penalised by a higher runway occupancy time due to an unfavourable exit taxiways location. In such cases the runway occupancy time becomes the governing factor in determining spacing between arriving aircraft.

(c) the runway capacity decreases when the traffic mix comprises heavy aircraft since longer spacing is used for wake turbulence avoidance purpose.

6.3 IMPACT OF MLS ON RUNWAY CAPACITY

The capacity increase obtainable under MLS conditions when compared to ILS operations is presented in figures 73 to 90.

These figures indicate that no significant change in runway capacity is expected when the percentage of arrivals is less than 40 percent.

Although for the single-runway airports (Birmingham, East Midlands and Manchester) slight variations in runway capacity increase exists, reflecting the differences in exit taxiway layout, the results for these airports can be synthesised as follows, where

PA: percent of arrivals
PM: percent of medium aircraft category
PH: percent of heavy aircraft category
This table shows that, when only MLS curved approaches at 3 degree glidepath are allowed and the aircraft mix consists of a high proportion of medium aircraft category, MLS procedures produce smaller improvement in runway capacity than when the traffic includes a high percentage of small and light aircraft. As seen in chapter 2, the inter-arrival spacing varies as

$$\text{max} \left[ \frac{L}{V_2} - \frac{1}{V_1}, 0 \right]$$

where

- $L$ = common approach path length
- $V_1$ = speed of first aircraft
- $V_2$ = speed of following aircraft

The medium aircraft have a longer average approach path than smaller aircraft, therefore the reduction in inter-arrival spacing is bigger for the latter aircraft group, but this reduction is not sufficient to impede the departure flow in mixed operations.

The slight increase in runway capacity when heavy aircraft are included in the mix is due to the same reasons.

Additional improvement is produced when both horizontal and vertical separations are applied under MLS steeper angle approach, not only because the reduction in inter-arrival spacing from a shorter common approach path as seen above, but also from a smaller time separation from vertical spacing than from longitudinal spacing. The time interval between arrivals when longitudinal separation is applied varies as $d/V_2$, ($V_1$ if separation due to wake turbulence), where $d$ is the minimum distance.
separation, but this interval becomes $V_S/V_H \tan GH$ in multiple glidepaths procedures, with the exceptions indicated in chapter 2, where:

\[
\begin{align*}
V_S & = \text{vertical separation} \\
V_H & = \text{speed of the aircraft at a higher approach angle} \\
G_H & = \text{approach angle}.
\end{align*}
\]

The table above shows that there is no essential difference in runway capacity between MLS steeper angle approach procedures and MLS 3 degree glidepath where there is a high proportion of medium aircraft. However, when the traffic mix consists mainly of small and light aircraft, the additional improvement in runway capacity is significant because these aircraft groups have the capability to fly steeper MLS approaches than heavier aircraft, therefore there are more opportunities for applying vertical separation.

For Belfast, although the same trend for higher capacity increase associated with high percentage of small and light aircraft is shown, however the improvement when there is a high proportion of medium aircraft is negligible when the traffic lands on runway 17. This is due to the poor exit taxiway layout, generating a relatively high runway occupancy time, and the assumption that only light aircraft backtrack from their actual position at the end of the deceleration phase. This suggests that runway 17 configuration is already at its maximum capacity when there is a high proportion of medium aircraft.

When runway 25 is used by landing traffic, the increase is consistent with single-runway configuration results, but with a slight improvement in mixed operations from the use of the two runways.

When heavy traffic are included in the aircraft mix, no runway capacity change is noticed between MLS 3 degree glidepath and MLS multiple glidepaths procedures because their high runway occupancy time due to the unfavourable exit taxiway location associated with wake turbulence spacing becomes the critical factor in the determination of threshold separation between arriving traffic and eliminates the advantage of vertical separation.
Figure 45 – Birmingham ILS RWY 33
Figure 46 - Birmingham
- MLS RWY 33 -
( 3 Degree Glidepath )

Legend
- 0 % Arrivals
- 20 % Arrivals
- 40 % Arrivals
- 60 % Arrivals
- 80 % Arrivals
- 100 % Arrivals

0 % Heavy Aircraft

Number of Operations

% Medium Aircraft
Figure 47 - Birmingham
- MLS RWY 33 -
( Multiple Glidepaths )
20 % Heavy Aircraft

Legend
- 0 % Arrivals
- 20 % Arrivals
- 40 % Arrivals
- 60 % Arrivals
- 80 % Arrivals
- 100 % Arrivals

Figure 48 - Birmingham
- ILS RWY 33 -
Figure 49 - Birmingham
- MLS RWY 33 -
(3 Degree Glidepath)
20 % Heavy Aircraft

Legend
- 0 % Arrivals
- 20 % Arrivals
- 40 % Arrivals
- 60 % Arrivals
- 80 % Arrivals
- 100 % Arrivals

Figure 50 – Birmingham
- MLS RWY 33 –
( Multiple Glidepaths )
Figure 51 - East Midlands
- ILS RWY 27 -
Figure 52 - East Midlands
- MLS RWY 27 -
(3 Degree Glidepath)
Figure 53 – East Midlands
- MLS RWY 27 -
  (Multiple Glidepaths)
Figure 54 - East Midlands
- ILS RWY 27 -
Figure 55 - East Midlands
- MLS RWY 27 -
( 3 Degree Glidepath )
Figure 56 - East Midlands
- MLS RWY 27 -
( Multiple Glidepaths )
Figure 57 - Manchester
- ILS RWY 24 -
Figure 58 - Manchester
- MLS RWY 24 -
( 3 Degree Glidepath )
Figure 59 - Manchester
- MLS RWY 24 -
( Multiple Glidepaths )
20 % Heavy Aircraft

Number of Operations

% Medium Aircraft

Legend
- 0 % Arrivals
- 20 % Arrivals
- 40 % Arrivals
- 60 % Arrivals
- 80 % Arrivals
- 100 % Arrivals

Figure 60 – Manchester
- ILS RWY 24 -
Figure 61 - Manchester
 MLS RWY 24
 (3 Degree Glidepath)
Figure 62 - Manchester
- MLS RWY 24 -
( Multiple Glidepaths )
Figure 63 — Belfast
— ILS (Arr RWY 17, Dep RWY 25) —
Figure 64 – Belfast
- MLS(Arr RWY 17, Dep RWY 25) –
(3 Degree Glidepath)
Figure 65 – Belfast
-MLS(Arr RWY 17,Dep RWY 25)—
(Multiple Glidepaths)
Figure 66 - Belfast
- ILS (Arr RWY 17, Dep RWY 25) -
Figure 67 - Belfast
- MLS (Arr RWY 17, Dep RWY 25) -

Legend
- 0 % Arrivals
- 20 % Arrivals
- 40 % Arrivals
- 60 % Arrivals
- 80 % Arrivals
- 100 % Arrivals
Figure 68 - Belfast
- ILS (Arr RWY 25, Dep RWY 17) -
Figure 69 - Belfast
- MLS(Arr RWY 25, Dep RWY 17) -
(3 Degree Glidepath)
Figure 70 – Belfast
–MLS(Arr RWY 25, Dep RWY 17)–
(Multiple Glidepaths)
Figure 71 – Belfast
- ILS (Arr RWY 25, Dep RWY 17) –
Figure 72 - Belfast
- MLS (Arr RWY 25, Dep RWY 17) -
Figure 73 – Birmingham
Impact of MLS (3 Degree Glidepath)

Figure 74 – Birmingham
Impact of MLS (Multiple Glidepaths)
Figure 75 - Birmingham
- Impact of MLS (3 Degree Glidepath) -

Figure 76 - Birmingham
- Impact of MLS (Multiple Glidepaths) -
Figure 77 - East Midlands
- Impact of MLS (3 Degre Glidepath) -

Figure 78 - East Midlands
- Impact of MLS (Multiple Glidepaths) -
Figure 79 - East Midlands
- Impact of MLS (3 Degre Glidepath) -

Figure 80 - East Midlands
- Impact of MLS (Multiple Glidepaths) -
Figure 81 - Manchester - Impact of MLS (3 Degree Glidepath) -

Legend

- 40 % Arrivals
- 60 % Arrivals
- 80 % Arrivals
- 100 % Arrivals

Figure 82 - Manchester - Impact of MLS (Multiple Glidepaths) -
Figure 83 - Manchester
- Impact of MLS (3 Degree Glidepath) -

Figure 84 - Manchester
- Impact of MLS (Multiple Glidepaths) -
Figure 85 - Belfast
Impact of MLS (3 Degree Glidepath)

Figure 86 - Belfast
Impact of MLS (Multiple Glidepaths)
Figure 87 - Belfast
Impact of MLS (3 Degree Glidepath)

Legend
- 40 % Arrivals
- 60 % Arrivals
- 80 % Arrivals
- 100 % Arrivals

Figure 88 - Belfast
Impact of MLS (Multiple Glidepaths)
Figure 89 - Belfast
Impact of MLS

Figure 90 - Belfast
Impact of MLS
CHAPTER 7:
CONCLUSIONS

This research considered the effect on runway capacity of the wider azimuth angle coverage, the range of glide slope angles and the system error of MLS, in particular the impact of curved approaches and steep approach guidance using MLS at British regional airports.

These MLS features produce reduced inter-arrival separations when compared to ILS procedures and therefore increase runway capacity if the runway occupancy time is not the limiting factor.

Runway capacity, as well as its increase, is not expressed by one figure only but by a range of values which reflect the aircraft mix and the percent of arrivals.

The capacity increase due to MLS is achievable only when 40 percent or more of the traffic are arrivals.

For a single IFR runway, as is the case for Birmingham, East Midlands and Manchester airports, MLS operations result in a significant improvement in runway capacity. When 100 percent of the traffic are arrivals, the increase is in the order of 7 to 12 percent under MLS, curved approaches with reduced approach path lengths, and of between 8 to 24 percent for multiple glidepath procedures, the lower numbers being associated with a high proportion of medium aircraft and the higher figures when the traffic includes only small and light aircraft. These improvements are progressively reduced as the percentage of arrivals diminishes. For 40 percent of arrivals, the capacity increases are between 0 and 4 percent for curved MLS approaches and 0 to 10 percent for MLS steeper angle approaches.

MLS procedures produce a relatively smaller capacity increase when only medium and heavy aircraft are included in the traffic mix because these aircraft groups have longer average approach path lengths and are less capable of flying steeper glidespaths when compared to smaller aircraft categories. Since regional airports are served by a high proportion of commuter aircraft, which are in the small and light aircraft groups (Flight International, 1989, p60, 67), therefore the capacity increases expected at these airports are rather towards the higher figures.
The capacity increases due to MLS translate into delay reduction as shown in figure 6. Intersecting runways utilisation would result in a slight capacity increase in the case of mixed operations, about 2 to 5 percent above single runway figures depending on the aircraft mix and the percentage of arrivals.

However, a relatively high runway occupancy time can negate any capacity advantages from MLS, as is the case for runway 17 at Belfast when the landing flow includes mainly medium aircraft, or the additional advantage of using the steeper angle approach capability of MLS when heavy aircraft are included in the traffic mix for both runway configurations at Belfast. In such a case, the inter-arrival spacing is determined by the runway occupancy time and does not reflect MLS performance.

This research used FAA criteria for MLS operation (FAA, 1988) because criteria are still under development in UK (Witts, 1988; Howell, Tapsell and Witts, 1988). However, different MLS operational criteria might be adopted in the future by the CAA, as is the case for wake turbulence spacing where different sets of rules are applied in UK and USA, and therefore might require reassessing the impact of MLS procedures.

The use of MLS multiple curved approaches involves solving the problem of merging aircraft on the extended runway centreline from different directions and at different interception points. Such operations, not only require new airspace procedures, but cannot be performed by ATC without some form of automated assistance. Some concepts have been developed at NASA American Research Center (Erzberger and Tobias, 1986, p 63 - 84) from systems which can predict and precisely control times at points along the flight paths, in particular the landing time, for all aircraft entering the terminal area. Such a time-based system would be an essential ATC management tool for controlling complex traffic configurations due to MLS multiple curved approaches.

Before MLS full implementation, both ILS and MLS will operate side by side to serve the same runway. Therefore, not only will there be the need to maintain two separate landing systems, but the full capacity benefits will not be immediately achievable because MLS operations will be similar to ILS procedures during the transition period. In this case, MLS fitted aircraft could be allowed to carry out curved approaches with a 3 degree glideslope and a reduced final approach path (e.g. 4 nautical miles) until the automated assistance mentioned above is available for shorter final approach path lengths.
So far, MLS is developed to CAT I standards. Thus, during the transition phase, aircraft will rely on ILS guidance for CAT II or CAT III operations for 16 ILS equipped runways as shown in paragraph 1.1, and runway capacity in these conditions will remain unchanged until MLS is approved for reduced operating minima.

Currently, noise abatement ILS procedures require arriving aircraft to fly a relatively long final approach segment (7 nautical miles). This constraint might restrict the utilisation of MLS 3 degree glideslope curved approaches at some regional airports (e.g. Manchester, Birmingham). The 3 dimensional guidance capability of MLS allows noise routings to be developed to suit the requirements of particular airports, but runway capacity increases will not be as high as those obtained under optimal conditions covered by this research.

Higher capacity increases could be obtainable if wake turbulence hazards from large aircraft can be avoided. It has been suggested the addition of a second transmitter which could permit smaller aircraft to fly above the glidepath used by the larger aircraft and to land further down the runway (Hockaday, 1984, p 9). This dual fixed glide slope option needs to be considered because it could be a more practical alternative to the MLS multiple glidepaths since the CAA (1988A, p 14) will not initially permit simultaneous approaches with differing glidepath angles to the same runway. However, this option is tied to the condition that visual aids (runway marking and lighting) are to be redesigned.
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