The Effect Of Direct Routing On ATC Capacity

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Abstract

In current practice air transport flights usually operate along a fixed network of airways rather than flying directly from origin to destination. Until recently point-to-point navigation was the only method available, but with the advent of Area Navigation and Satellite Navigation systems this is no longer the case.

Apart from the obvious economic benefit to aircraft operators, use of direct routing would appear to offer the possibility of some capacity benefits for air traffic control (ATC) systems. This paper reports on a fast-time simulation study which estimated an upper bound for these capacity benefits in the context of the European airspace. Results presented show how the frequency of occurrence of separation problems varies with the horizontal separation threshold used, both for airways operation and for direct-routes operation. These results are then interpreted in terms of potential capacity increase.

1. Introduction

On busy days in the summer of 1998 the air traffic control (ATC) systems in many parts of Europe operated at or near capacity, and both passengers and airlines complained about excessive delays. Yet traffic demand is forecast to grow with a mean rate in the region of 3-4% per annum [1], leading to an increase of 23-32% by 2005 and 65-95% by 2015. So the question naturally arises: where is the additional capacity to come from?

The traditional response of ATC service providers to increasing demand has been to re-sectorize the airspace so as to apply more controllers in parallel to the total control problem. But this process cannot be continued indefinitely: when sectors become too small the gains from applying more controllers in parallel are outweighed by the increase in co-ordination needed between neighbouring sectors. The airspace in the busier parts of Europe is now close to this state [2].

It is widely accepted that human air traffic controllers (as opposed to automated systems) will continue to have the central role in the control process for the foreseeable future. It is also widely accepted that the traffic-handling capacity of most types of airspace is limited by the maximum amount of work that can safely be assigned to human controllers. These considerations have motivated the development of a number of experimental systems which aimed to assist controllers by providing them with computer-based prediction and monitoring tools. While such systems have demonstrated some potential capacity gains, these have generally been small compared with what is needed [3,4].

In current practice most air transport flights operate along a fixed network of airways rather than flying directly from departure airport to arrival airport. Until relatively recently point-to-point navigation was the only method available, but with the development of Area Navigation and Satellite Navigation systems this is no longer the case. Direct routing has obvious economic attractions for aircraft operating companies: it leads to shorter flight times and reduced fuel costs. But it might also offer capacity advantages for ATC systems.

There are two mechanisms by which direct routing might be expected to increase capacity:

1. By reducing flight times, direct routing will reduce traffic density for a given frequency of departures, or produce the same traffic density for a higher frequency of departures.
2. Airways operation forces all traffic into a restricted volume of airspace while leaving the remainder unoccupied, whereas direct routing is likely to spread traffic more evenly throughout the airspace. The latter situation might be expected to lead to fewer separation problems for the same traffic demand, or to support a higher traffic demand for the same frequency of separation problems.

The present paper reports the results of a fast-time simulation study which aimed to quantify these effects in the context of the whole of European airspace with the traffic demand forecast for the year 2005.

However, the limits of what is currently possible with fast-time simulation must be recognized. Computer models of human mental activity (and of air traffic control in particular) have not yet developed to the point where they can predict how human controllers will respond to the change from airways to direct routes. Ultimately human workload and traffic-handling capacity can be measured only from real-time simulations or operational systems. But real-time simulations are very costly exercises. They require many air traffic controllers and a considerable amount of time to train them in the new methods to be tested. They also require pseudo-pilots and supporting infra-structure as well as a high-fidelity simulation of the operating environment. A fast-time simulation study can estimate an upper bound for the capacity gain which might be obtained from direct routing, and can do this over a much larger geographical region (with a greater variety of traffic conditions) than would be practicable for real-time simulation. This information can then be used to inform a decision about whether or not to embark on a costly real-time simulation.

2. Workload and Capacity

We would like to use fast-time simulation to compare the traffic handling capacity of the following two ATC systems:

1. a system which uses airways for all flights;
2. a system which uses direct routing for all flights, but is the same as 1 in all other respects.

Unfortunately there is no way of measuring capacity directly in a simulation, so we must approach the problem indirectly. It was pointed out in the Introduction that, in most types of airspace, capacity is determined by the amount of work that can safely be assigned to human air traffic controllers. So the problem of making capacity comparisons can be transformed into one of making comparisons of required control workload.

2.1 Characterizing Workload

We have chosen to characterize control workload in terms of the frequency of separation problems which require attention from air traffic controllers. Any measure of workload has its pros and its cons, and this one is no exception. Against, it might be argued that there are control tasks which do not relate directly to separation problems, and that the separation problems which would occur in a system based on airways are likely to be much more stereotyped (and hence easier to deal with) than those which would occur in a system based on direct routes. For, it might be countered that, given that the main purpose of ATC is to keep aircraft safely separated, frequency of separation problems is a measure of *what* must be done to achieve this purpose without specifying *how* it will be done; the measure is therefore independent of the fine detail of exactly how ATC will operate in future. The author is persuaded by the latter argument.

2.2 Interaction Frequencies

Having decided to count separation problems, the next question is: what constitutes a separation problem that contributes to controller workload? At the extreme there are infringements of allowed separation minima (typically, less than 5 nautical miles (NM) horizontal separation simultaneously with less than 1,000 feet vertical separation) which always demand avoiding action. But there are many less severe separation problems which nevertheless absorb controller attention and thereby contribute to workload. These include: situations where controllers take avoiding action because they allow margins for uncertainty in predictions of minimum separation, situations where controllers begin to plan avoiding action even though it probably will not be needed, and situations where they simply decide to monitor more intensively. It seems likely that the less serious separation problems contribute as much or more to the total workload because there are many more of them. The separation thresholds which delimit these various possibilities are not constant; they vary greatly from one situation to another. Consequently results are presented for a range of separation values.

We use the term *trajectory interaction* (or simply *interaction*) rather than *conflict* or *proximity* to include all potential separation problems ranging from the most severe to no problem. An interaction is a situation where two aircraft would violate a given separation threshold if no avoiding action were taken. The vertical component of the separation threshold is assumed to be 1,000 feet throughout this study, so results are presented in terms of interaction frequency as a function of horizontal separation threshold.

3. The Simulation

3.1 Software

The study made use of a package of simulation software known as FLAME (FLexible Airspace Modelling Environment) which was developed by DERA for use in air traffic management (ATM) research applications. It has previously been used for several such projects including [5,6]. FLAME simulates the movement of individual flights through the airspace, collects statistics on quantities of interest, and provides traffic displays for scenario validation purposes.

FLAME models traffic demand and aircraft profiles in some detail, but does not attempt to model conflict resolution at its present stage of development. Aircraft horizontal speeds are obtained by converting calibrated air speed and Mach values to true air speeds, and combining these with wind vectors. Modelling of climb and descent rates is based on an analysis of radar for a large sample of real traffic [7]. Altitudes of aircraft in level flight are exact multiples of 1,000 feet; cruise levels are allocated according to RVSM (required vertical separation minimum) and the semi-circular rule. Aircraft on airways fly along the airway centre-lines.

3.2 Airspace

The geographical region in which traffic was simulated was that bounded by the meridians at 10º W and 30º E, and the parallels at 36º N and 60º N. This large region includes practically all of Europe, and contains a wide variety of conditions and traffic densities. Using such a large area also minimizes edge effects. For flights entering and leaving the region, only the portions inside the region were simulated. In order to avoid the cost of modelling the fine detail of departure and arrival procedures at several hundred airports, greatly simplified terminal area structures were used, and the collection of results was restricted to airspace at or above 10,000 feet.

Details of the positions of airports, waypoints and airway segments were obtained in electronic form from the Jeppesen Flight Planning Database [8]. For each airport, two entry/exit fixes were identified where traffic to/from the airport would leave/join the airways system in the airways simulations (these were usually points where airways merged or crossed), and simplified paths were constructed between runways and these fixes. The same set of entry/exit fixes was used in both the airways simulations and the direct-routes simulations.

For each flight the simulation first determined the departure airport's exit fix nearest to the arrival airport (call this *A*) and the arrival airport's entry fix nearest to the departure airport (call this *B*). For a flight in a direct-routes simulation the route from *A* to *B* was simply the great circle through the two points, but for a flight in an airways simulation determining the route was more complicated. The simulation found a sequence of airway segments which joined *A* with *B*. It made use of a backtracking algorithm which attempted to find the shortest route by searching the directed graph formed by all airways and their crossing/merging points. The depth of backtracking was limited (so that simulation runs would complete in reasonable periods of time), so the algorithm did not necessarily find *the shortest route* but it did find good approximations to shortest routes. It is perhaps worth noting that airways flights in the real world do not necessarily fly *the shortest routes*.

3.3 Traffic Scenario

The results presented in Section 4 were derived from five pseudo-random traffic samples each 12 hours in length. For each sample results were discarded from the traffic build-up period (first two hours) and the tail-off period (after 12 hours) so that the system could be considered to be in a steady state for a period of 10 hours.

The pseudo-random traffic samples referred to in the previous paragraph were generated from a statistical summary of European traffic. This summary was obtained by analysing flight plan data recordings for the month of April 1996 which were obtained from the European Central Flow Management Unit (CFMU) [9]. Some small simplifications were made during the summarizing process. For example, it was found that about 4% of traffic operated into or out of airports with less than 15 airways movements per month; by reassigning these flights to nearby larger airports, the total number of airports in the simulation could be reduced by a factor of almost 3.

The statistical summary of European traffic thus obtained was scaled to match traffic demand forecasts for 2005. It was assumed that traffic will on average grow by 3.8% per annum (the *High* scenario from [1]) which gives a growth factor of 1.4 between 1996 and 2005; this was increased to 1.5 to allow for the fact that April is not the busiest time of year. For the region simulated this gave a rate of traffic generation of 1,730 flights per hour.

3.4 Analysis

Any parameter estimate obtained from a simulation with random inputs is itself a random number. One of the traditional ways of dealing with this problem [10] is to take the mean of the results from several independent simulation runs and estimate a confidence interval for the mean. That procedure has been applied in the study reported here, and that is why five independent traffic samples were used. While confidence intervals are not reported in Section 4, they were calculated, and were seen to be small compared with the parameter differences reported.

The FLAME Trajectory Generator was run twice for each of the five traffic samples referred to above, once with airways and once with direct routes; this gave ten files of trajectories. Each file of trajectories was then analysed by a program that identified all pairs of flights which simultaneously came within 20 miles and 1,000 feet of one another; this gave ten files with more than 10,000 trajectory pairs in each. A number of simple programs were written to analyse this data in the ways shown in Section 4, to estimate traffic densities, to count interaction frequencies, to find the distribution of relative track angles, etc.

4. Results

4.1 Traffic Density

Flight times for traffic on direct routes will generally be shorter than those for traffic on airways and this will lead to a lower traffic density for a given frequency of departures. To find the relative traffic densities for the two routing scenarios, the number of flights at or above 10,000 feet in the whole of the region simulated was counted every quarter hour throughout the 50 hours of simulated data available for each scenario. The result is shown in Table 1. The ratio of mean squared traffic densities will be needed in Section 4.4 so it too is shown.

Thus, direct routing reduces the mean traffic density at and above 10,000 feet by almost 15%.

4.2 Horizontal Separation Threshold

The frequency of occurrence of pairs of aircraft which were simultaneously separated by less than *s* nautical miles and less than 1,000 feet was counted for both routing scenarios. This was done for values of *s* between 1 and 20 nautical miles at 1-mile intervals. The result is shown in Fig. 1. This is the main result of the study and we will return to it several times.

Ratio of mean traffic density for direct routes to mean traffic density for airways	0.853
Ratio of mean squared traffic density for direct routes to mean squared traffic density for airways	0.727

Table 1. Relative Traffic Densities

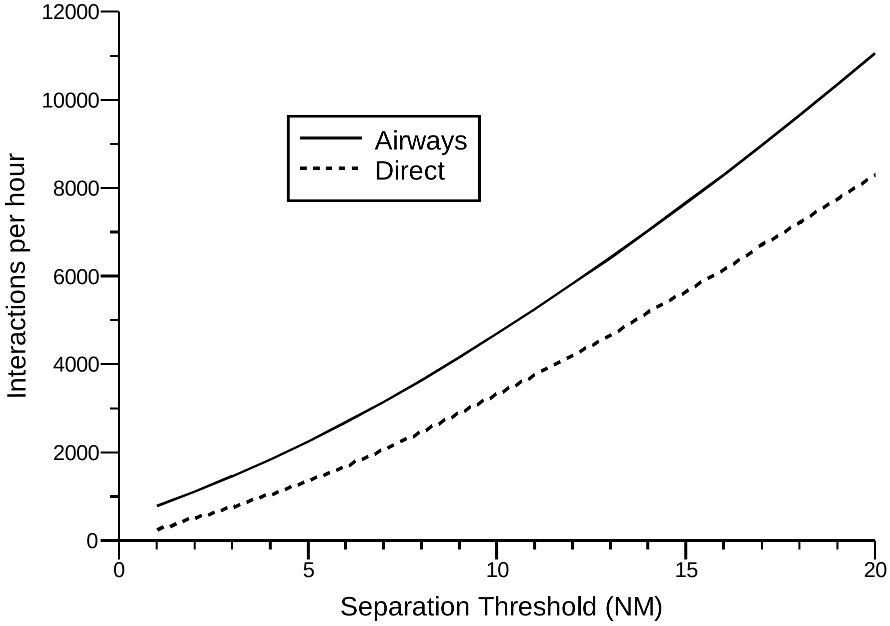

Figure 1. Interaction Frequency and Separation Threshold

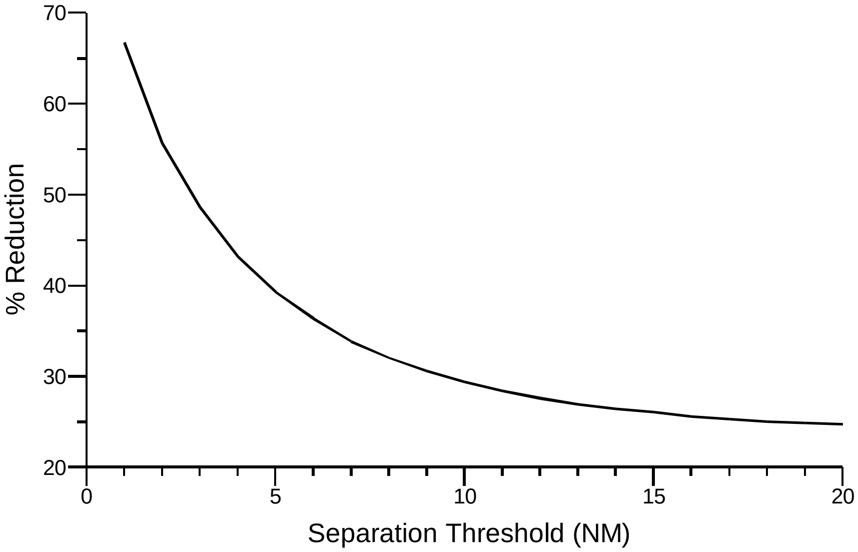

Figure 2. Reduction in Interaction Frequency from Direct Routing

The graph shows that use of direct routing does indeed give rise to lower interaction frequencies as expected, but that the extent to which it does so varies considerably with separation threshold value. It might be helpful to think in terms of the percentage by which direct routing reduces interaction frequency compared with airways. The percentage reduction is plotted against separation threshold in Fig. 2.

This curve shows that the reduction of interaction frequency from direct routing is about 67% at a separation threshold of 1 NM. It falls rapidly at first as separation threshold is increased, but flattens out to about 25% at 20 NM. Assuming that the allowed minimum separation is 5 NM simultaneously with 1,000 feet, then in the absence of avoiding action by controllers or pilots, direct routing will produce 39% less conflicts than airways.

4.3 Shapes of Graphs

The shapes of the lines in Fig. 1 are of some interest. Although interaction frequencies were not estimated for separation thresholds below 1 NM, if we extrapolate towards zero miles we can see that the direct-routes curve will pass through the origin whereas the airways curve will definitely not. The reason for this difference is presumed to be as follows: in our airways simulations aircraft fly along the airway centre lines, and so can pass through one another (so that there will be some interactions with zero horizontal separation). While this will be a relatively infrequent occurrence in level flight because of the operation of the semi-circular rule, it will be much more common in climb and descent.

Both lines in Fig. 1 exhibit a small but definite curvature. The direct-routes curve fits closely the shape $y = ax^{4/3}$ which has been reported by other authors [11], and the fit is especially close for separation values greater than 5 NM. When the airways curve has been displaced parallel to the interaction frequency axis so that its extrapolation passes through the origin, it too fits closely the same function, but with a different value for the a coefficient. These results are useful for calculating the effects of postulated changes to separation criteria for controller action.

4.4 Traffic Density and Spatial Distribution

We might reasonably expect the difference between the two curves in Fig. 1 to be caused by two distinct mechanisms:

1. Use of direct routes leads to lower traffic densities which in turn leads to lower interaction frequencies.
2. Use of direct routes tends to spread the traffic out over more airspace whereas use of airways tends to concentrate the traffic into some parts of the airspace and leave other parts unused. The former might be expected to lead to lower interaction frequencies.

So, the question naturally arises: how much contribution does each mechanism make to the difference between the two curves in Fig. 1? To answer this question each data point on the airways curve in Fig. 1 was "corrected" to remove the effect of the density difference. Interaction frequency is approximately proportional to the square of traffic density [12], so the correction was applied by multiplying each airways interaction frequency by the mean squared ratio of traffic densities from Table 1. The result in Fig. 3 shows the effect of spatial distribution alone.

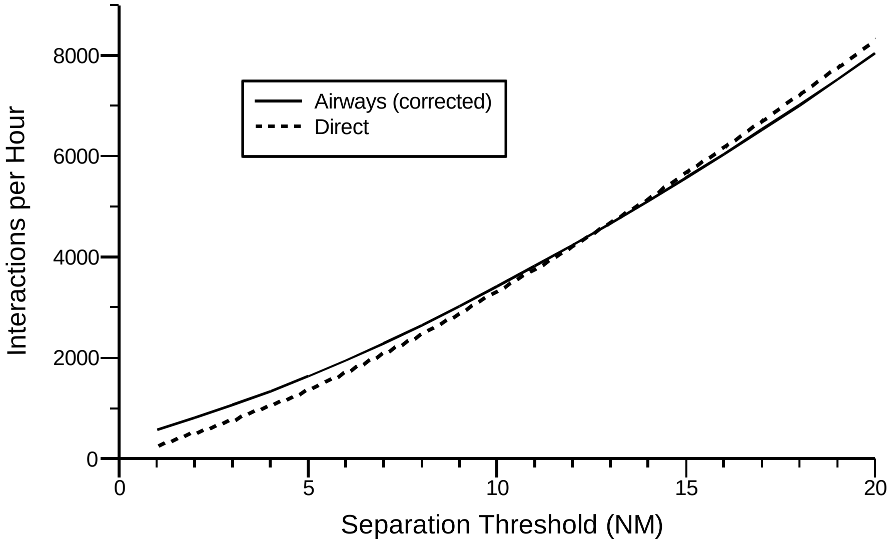

Figure 3. As Fig.1 but Corrected for Difference in Traffic Density

When the effect of traffic density has been removed (Fig. 3) there is much less difference between the two curves. This indicates that most of the difference between the curves in Fig. 1 arises from traffic density. The effect of spatial distribution alone (Fig. 3) is rather unexpected: at the lower separation threshold values interaction frequencies for direct routing are lower than those for airways as expected, but at higher separation threshold values the converse is true. The separation threshold value where the two curves in Fig. 3 cross one another is about 12.4 NM.

4.5 Relative Track Angles

The effect of routing scenario on the relative track angles of interacting pairs of trajectories was investigated. This was done by recording the track difference at the point of closest approach for all pairs of aircraft separated by less than distance *d* horizontally and 1,000 feet vertically at this point. The value of *d* was chosen to be 12.4 NM for reasons which will shortly become clear. The result is shown in Fig. 4.

Fig.4 shows that airways operation produces higher interaction frequencies for most relative track angles, but that the difference is much more marked for angles close to 0° and 180° (overtaking and head-on) than for other angles. It could be argued that the interactions with these relative track angles are the ones which contribute most to controller workload: overtaking situations because each tends to persist for a long time; head-on because they happen so quickly.

As in the previous subsection, we might ask how much of the effect shown in Fig. 4 arises from difference in traffic density and how much arises from difference in spatial distribution. To answer this question the interaction frequencies for airways operation were "corrected" in the same way as in the previous subsection, by multiplying each by the ratio of mean squared traffic densities from Table 1. The result is shown in Fig. 5. The value of *d* used in Figures 4 and 5 was chosen to be 12.4 NM (the value where the curves in Fig. 3 cross) so that the total interaction frequencies in Fig. 5 (summed over all angles) for the two routing scenarios would be nearly equal; this highlights the effect of spatial distribution alone on relative track angle.

From Fig. 5, the effect of spatial distribution alone is as follows: for relative track angles close to 0° and 180° airways operation produces higher interaction frequencies, but for all other angles direct routing produces higher interaction frequencies. Thus, for those angles between 10° and 170° where Fig. 4 shows higher interaction frequencies for airways operation, this is an effect of traffic density rather than spatial distribution.

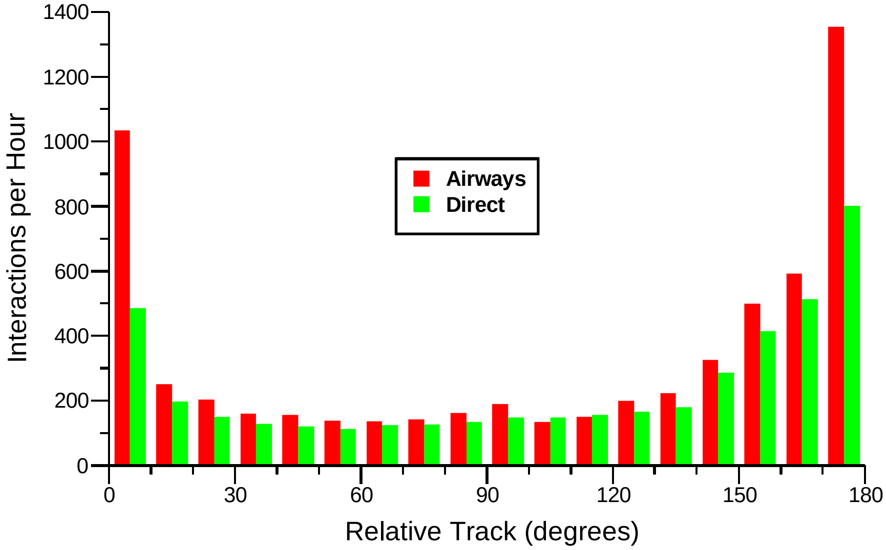

Figure 4. Interaction Frequency and Relative Track Angle

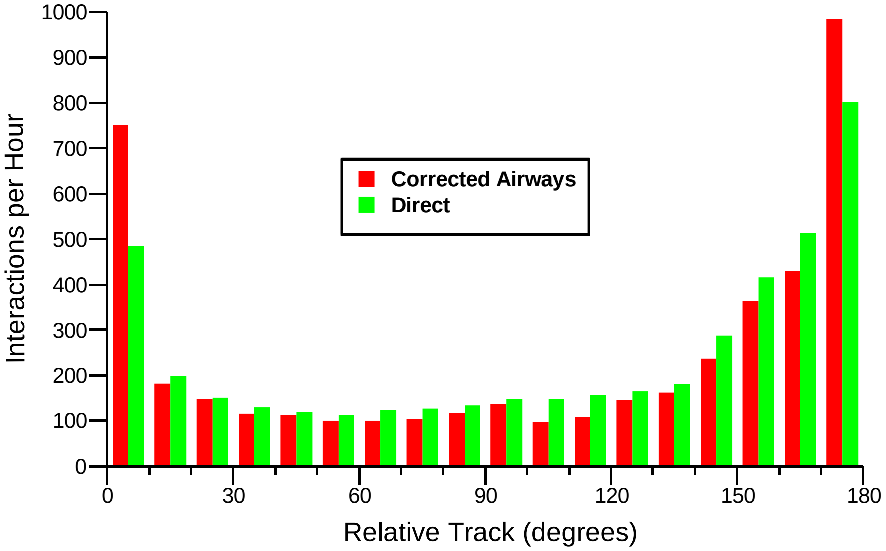

Figure 5. As Fig. 4 but Corrected for Difference in Traffic Density

5. Discussion

The results presented in the previous section can be interpreted in terms of both the potential capacity gain from direct routing and the potential capacity gain from reduced horizontal separation thresholds.

5.1 Capacity Gain from Direct Routing

It was pointed out in Section 2.2 that the range of separation problems that contribute to controller workload extends from situations which require avoiding action at one extreme to situations that require no more than increased monitoring at the other. It was also pointed out that the less serious separation problems are likely to contribute as much or more to total workload because there are more of them. Although the threshold values which delimit the various categories of separation problems are likely to vary greatly from one geographical location and operating environment to another, it is helpful to keep some typical values in mind to interpret the results above.

In many regions of airspace aircraft are not permitted to be separated by less than 5 NM and 1,000 feet simultaneously. But in order to allow for uncertainties in their knowledge of predicted positions, controllers are likely to take avoiding action when they or their supporting automation predict a horizontal separation somewhat greater than these values, perhaps at 8 NM horizontally. They are likely to begin planning avoiding action when the separation is predicted to be larger still, say 10 miles, and to institute more intensive monitoring at an even greater predicted minimum separation, say 12 miles. Although these figures are no more than informed guesses of average values, the graph in Fig. 2 is relatively flat in this region so the precise values are not critical.

If the frequency of interactions which require controller attention is reduced by direct routing then the potential capacity gain is the increase in traffic density which would restore this frequency to its original value. Assuming that the frequency of interactions for any given separation criterion is approximately proportional to the square of traffic density [12], it follows that the factor by which capacity is increased is the reciprocal of the square root of the factor by which interaction frequency is reduced. These assumptions lead to the values shown in Table 2.

Predicted Min. Sep. (NM)	Controller Action	Int. Freq. Reduction	Potential Capacity Gain
8	take avoiding action	32.0%	21.3%
10	plan avoiding action	29.4%	19.0%
12	increase monitoring	27.6%	17.5%

Table 2. Illustration of Potential Capacity Gain from Direct Routing

Change Sep. Threshold	Int. Freq. Reduction	Potential Capacity Gain
12 - 10 NM	21.3%	12.8%
12 - 8 NM	41.4%	30.7%

Table 3. Effect of changing separation thresholds

Thus the potential capacity gain from direct routing is in the region of 17%. However, if the separation problems in a system using all direct routes are more difficult to deal with than those in a system using airways, the actual gain will be less than this, and might even be negative. But if most of the 17% is available, this is well worth having. Such a figure for potential capacity gain would be ample justification for large-scale real-time simulations to quantify how much of the potential gain can be realized.

5.2 Capacity Gains from Reduced Separation Thresholds

The potential 17% capacity gain from direct routing while useful is still small compared with the 65-95% needed by 2015, so where is the rest to come from? Further re-sectorization of the airspace and use of computer assistance tools will provide some of the deficit, but are unlikely to provide all of it.

Another possibility is to reduce the separation thresholds at which trajectory interactions contribute to controller workload. This might be done for example by use of computer-based prediction and monitoring tools to reduce uncertainty about predicted positions. Table 3 illustrates the effects of two relatively modest changes to the 12-mile threshold used in Table 2.

Again, these potential capacity gains are well worth having, and should encourage efforts to reduce the various thresholds.

6. Concluding Remarks

A fast-time simulation study has been described which quantified the potential increase in traffic-handling capacity that might result from use of direct-routing instead of traditional airways operation. Data was collected from the simulation for the volume of airspace at and above 10,000 feet which covers practically all of Europe. The main results and conclusions are:

1. Curves relating trajectory interaction frequencies to horizontal separation thresholds, for both direct-routes and airways operation, see Figs. 1 and 2. These show that direct-routes operation produces substantially lower interaction frequencies for any given separation threshold, but that the reduction is much more marked for smaller threshold values.
2. A decomposition of the reduction in interaction frequency into the component which arises from

reduced traffic density and the component which arises from spatial distribution, see Section 4.4. This shows that most of the frequency reduction from direct routing results from reduced traffic density. The spatial distribution component contributes positively to the frequency reduction at low separation thresholds, but contributes negatively to it at high thresholds, see Fig. 3.

3. The distribution of relative track angles at points of closest approach for direct-routes and airways operation, see Figs. 4 and 5. Direct routing significantly reduces the overtaking and head-on interactions.
4. Interpretation of the results in Fig. 1 to indicate a potential capacity benefit of about 17%. However it must be emphasized that this is a *potential* capacity benefit. How much of it can be realized in practice can only be determined by real-time experiments involving human air traffic controllers.
5. An indication of a possible source of further capacity gains. The potential capacity gain which would result from reducing the threshold for what constitutes a problem requiring controller attention can be estimated from Fig. 1, see Section 5.2.

The potential capacity benefit from direct routing was estimated to be about 17%. This could make a useful contribution to the need for additional ATC capacity, and would seem to be ample to justify much more costly but more precise real-time simulation studies. However an additional 17% is not going to solve Europe's capacity problem. In the author's opinion the solution will ultimately require a reduction in the threshold values of what constitutes a separation problem needing controller attention. The potential capacity benefit from any such reduction can be determined from the results presented above.

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