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# Longitudinal Collision Risk for ATC Track Systems: A Hazardous Event Model

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This paper presents a collision risk model and operational concepts for longitudinal separated aircraft in the North Atlantic Region air traffic control track system, and indicates how it might be used to reduce separation minima safely, and hence deliver cost savings. It is an event-based model: it is easy to see what is being assumed, to understand the role of the main parameters, and to incorporate collision detection and hazard analysis. A potential future operation, with a 7-minute separation and a strategic lateral offset system, is sketched using the model.

KEY WORDS

1. ATC 2. Collision risk.

1. INTRODUCTION. This paper presents a collision risk model and operational concepts for longitudinal separated aircraft in, for example, the North Atlantic Region (NAT) air traffic control (ATC) track system, and sketches how it might be used to reduce separation minima, and hence deliver cost savings, whilst ensuring safety. This is an important task because modelling work under the auspices of the NATSPG (Systems Planning Group) programme has occupied considerable resources in recent years but without coming to definitive conclusions about the way forward (NATSPG, 2003 – and earlier NATSPG Summary Reports).

The main difference with earlier work is that this is an event-based model rather than one focusing on statistical distributions of hourly deviations from planned position. With an event model, it is easy to see what is being assumed, to understand the role of the main parameters, and it can readily be developed to incorporate collision detection and hazard analysis.

Traditional hourly deviations models were first derived by Reich (1966) – the 'Reich Model'. They have a great influence on collision risk modelling – e.g. see FAA/Eurocontrol (1998). The Reich model was applied to NAT longitudinal separation minima by Brooker and Lloyd (1978), and used in the reduction of these minima (Penna, 1977) under the auspices of the NATSPG. These reductions produce major operating benefits, mainly through better fuel usage, whilst ensuring

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that the system meets the required target level of safety. What further reductions are feasible – e.g. see FAA (1999)?

The basic ideas of an event model were described in Brooker (2003), and applied to lateral collision in the NAT track system. This aspect is complementary to that earlier work. This technique is adapted and developed here for possible future longitudinal separation minima, plus some simple facts about aerodynamics and human factors. The model enables collision risk estimates to be made for a system using datalink and satellite navigation.

2. GENERAL DESCRIPTION OF THE NAT ATC SYSTEM. The NAT air traffic control (ATC) system is operationally and technically very complex. The following description merely picks out the points most relevant to longitudinal collision risks. More detailed information can be found in CAA (2004) and NAT PCO (2004). For simplicity, the description here uses the operation of westbound flights in examples.

Flights in the NAT are handled by oceanic controllers. About half of these flights use the organised track system, a set of largely parallel tracks. The track system is changed from day to day to match the weather and origin/destination demand patterns for that day. The distances between tracks are set to be at least the separation minima: 1000 feet vertically, 60 nm laterally and 10 minutes longitudinally (i.e. along track). These distances have been chosen to ensure that the collision risks in the North Atlantic meet the target level of safety (TLS – e.g. Brooker, 2002 and 2004).

Oceanic traffic is not, except at its boundaries, covered by radar or ground aids. However, aircraft now have accurate on-board navigation equipment and flight management computer systems (FMCS). Aircrew provide oceanic ATC with position reports by voice or, increasingly, by datalink. The crossing between the boundaries takes about 3·25 hours (denoted '$T$' in equations here).

The current longitudinal separation minimum is applied as follows:

- Clearances include an assigned Mach number, which has to be maintained.
- Aircraft have to enter the oceanic area at specified ETAs and flight level.
- The entry times for a particular pair of aircraft are determined by their Mach numbers:
  - Aircraft with the same Mach Number require a minimum of 10 minutes separation on entry.
  - If the following aircraft has a higher Mach Number, then its projected *exit* time must have a minimum separation of 10 minutes, i.e. it has a higher entry separation (3 minutes per 0·01 Mach number difference).

Pilots typically report their positions to ATC for the waypoints every 10° of longitude. Oceanic controllers use a flight data processing system (FDPS) that can carry out conflict prediction and detection, and automatically update flight profiles and transfer data to on-line adjacent ATC units.

The precise definitions of the separation minima for the oceanic area are laid down in Manual of Air Traffic Services (MATS) Part 2 for Prestwick. The definitions and procedures in MATS Part 2 are derived from, and are intended to clarify, the relevant ICAO documentation. Additional guidance is provided in the NATSPG

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Document entitled 'Application of Separation Minima (North Atlantic Region)' Fourth Edition.

3. AN EVENT-BASED LONGITUDINAL COLLISION RISK MODEL. To distinguish the event-based longitudinal collision risk model from the Reich Model, it is referred to here as the Event Model. First, some parameters need to be defined. The symbols used here are a simplified version of the customary Reich Model versions (Reich, 1966). The track axes are: $x$ – along track (longitudinal); $y$ – lateral to track; $z$ – vertical. Aircraft are modelled as boxes with dimensions are $\lambda_x$, $\lambda_y$ and $\lambda_z$ respectively. Aircraft boxes are taken always to be orientated in the same direction with respect to the $xyz$ axes. Their current NATSPG values are 0·032, 0·029 and 0·091 nm respectively. [NB: all dimensions, velocities etc used here are taken from NATSPG MIG (2002)] Two aircraft are taken as colliding if their aircraft boxes touch.

It is easiest to model a collision by representing one (intruder) aircraft B as a point and the other A by a larger box, of twice the dimensions. In essence, one aircraft box, when moved around the first one, produces this larger collision box. This is exactly as used by Reich – who refers to the collision box as a slab. Thus, the Event Model calculations use a collision box for one aircraft and a point – effectively at the centroid of the aircraft box – for the other aircraft. The collision box therefore has dimensions $2\lambda_x$, $2\lambda_y$ and $2\lambda_z$.

The absolute relative velocities for a modelled pair of aircraft on a track are denoted by $u$ – along $x$ axis; $v$ – along $y$ axis; $w$ – along $z$ axis. The NATSPG values for $v$ and $w$ are 5 and 1·5 knots respectively. The value of $u$ will be a function of the amount of overtaking.

The Event Model adopts a particular reference frame. Taking two representative longitudinally separated aircraft A and B, the frame chosen is that defined by the position of B. In this frame, the collision box A suffers a collision if it encounters the stationary aircraft point B.

Figure 1 is a picture of the start of a potential collision. It occurs when aircraft A overtakes aircraft B. This obviously breaches the longitudinal separation minimum $S$ (presently 10 minutes). The Figure shows the collision box (remember this is orientated according the $xyz$ axes *not* the direction of flight) travelling towards the separation sheet, having eroded the separation minimum by being too quick (or by B being too slow). This sheet is an imaginary flat surface of zero thickness defined by the $y$ and $z$ axes. A collision will occur if the collision box hits the separation sheet *and* the aircraft point B lies on its path. The key modelling assumption that makes this an easy calculation is to choose an orientation for the collision box along the $xyz$ axes. This means that the initial contact with the sheet is made by a side face of the box. It then takes a time $t$ for the box to move through the sheet, where $t$ is the longitudinal dimension of the box – $2\lambda_x$ – divided by the longitudinal velocity $u$ at loss of separation. If this velocity is a few tens of knots, the box will go through the sheet very quickly. Suppose $u$ is 32 knots, which has been traditionally used as the average relative velocity that would be needed to gain 10 minutes over the whole Atlantic crossing. This time to transit the sheet would be:

$$t_{av} = 2 \times 0{\cdot}032/32 = 0{\cdot}002 \text{ hours, i.e. about 7 seconds}$$

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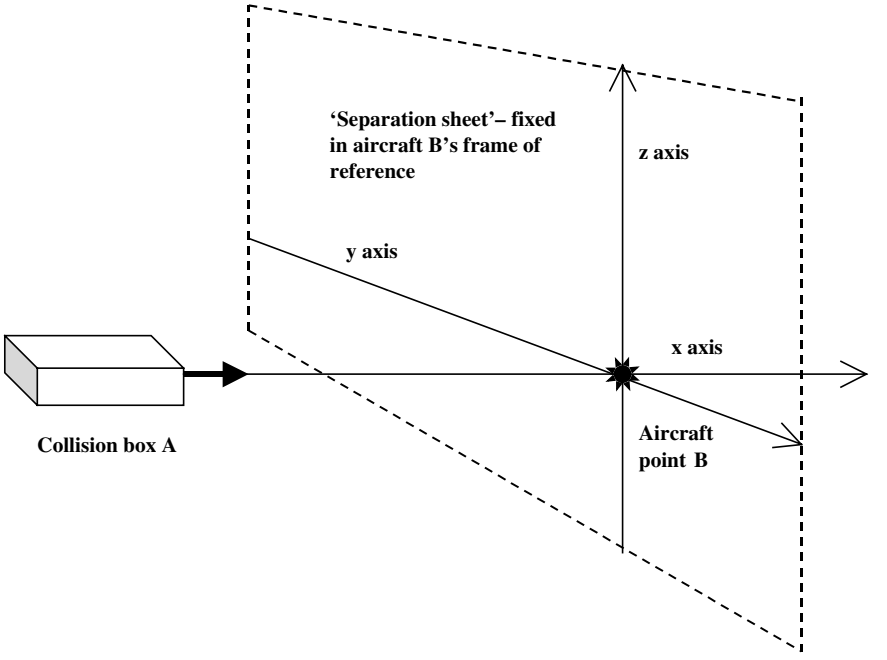



Figure 1. The 'collision box' A moving towards the separation sheet fixed by aircraft B at rest.

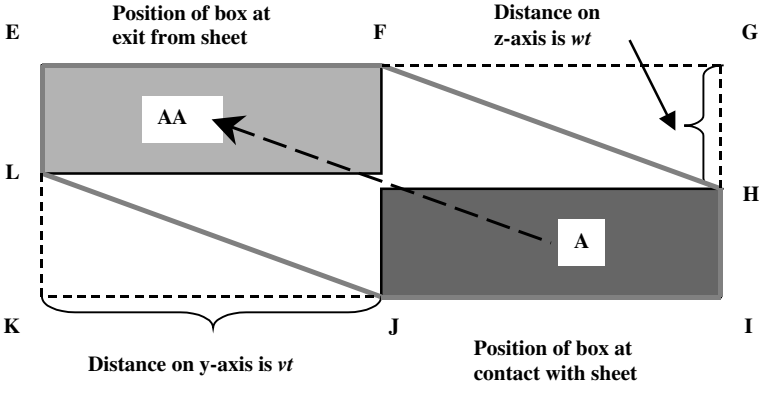



Figure 2. Transit of collision box through separation sheet – face view of separation sheet.

Figure 2 illustrates the movement of the collision box through the separation sheet. This diagram is looking at the separation sheet, i.e. along the $x$-axis. The box centre at the first contact with the sheet is marked as 'A'. As the box moves through the sheet, it also moves in the $y$ and $z$ directions, so that its position when it exits the sheet is at AA. It has moved a distance $vt$ on the $y$-axis and $wt$ on the $z$-axis. The area traced out is the hexagon EFHIJL. This hexagon is enclosed in the rectangle EGIK.

If the aircraft point B – which remember is stationary because the reference frame for $xyz$ axes has been fixed with B at rest – lies within the collision boxes at

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A or AA, *or* anywhere in the rest of the area swept out by the box as it moves from A to AA, then there will be a collision. In other words, there is a collision if B is in the traced-out hexagon EFHIJL. This is the cross section for a collision.

Hexagons are too complicated for simple sums. Therefore, hexagon EFHIJL will be approximated by rectangle EGIK – the extended collision box, with dimensions $2\lambda_y + v\frac{2\lambda_x}{u}$ and $2\lambda_z + w\frac{2\lambda_x}{u}$, with the average extended collision box having the same expression but with the velocities replaced by their averages (with capital letters). This is obviously a cautious assumption, i.e. tends to over-estimate risk, because the rectangle completely encloses the hexagon. Is it over-cautious? The easiest way to estimate this is by calculating the average values $vt$ and $wt$ and then comparing with the collision box dimensions $2\lambda_x$ and $2\lambda_z$. The numbers are

$$vt = 5 \times 0{\cdot}002 = 0{\cdot}01 \text{ nm} \qquad 2\lambda_y = 2 \times 0{\cdot}029 = 0{\cdot}058 \text{ nm}$$
$$wt = 1{\cdot}5 \times 0{\cdot}002 = 0{\cdot}003 \text{ nm} \qquad 2\lambda_z = 2 \times 0{\cdot}0091 = 0{\cdot}0182 \text{ nm}$$

So the lateral and vertical movement effectively adds small amounts to the $y$ and $z$ dimensions of the collision box. The extended collision box is therefore not much bigger than the collision box, and indeed little different in area from the hexagon.

As already noted, the probability of a collision, given the box touching the separation sheet, is the probability of the aircraft B point lying within the extended collision box. The probability calculations in the $y$ and $z$ dimensions can be carried out separately because the motions in those dimensions can be taken as statistically independent. Aircraft are certainly not distributed randomly in the vertical or lateral dimension. With modern systems, aircraft keep to their assigned flightpath with high precision, so the collision box and the aircraft B point are very likely to be in overlap.

Starting with the vertical dimension, for collision boxes, the probability of vertical overlap $P_z(0)$ (Reich, 1966) currently used by NATSPG is 0·48. For the extended collision box, ie including the vertical movement, the probability of overlap is necessarily higher than this value. A simplified calculation of 'vertical overlap' shows the nature of the functional dependence. Denote a box height by $2H$ and the probability distribution of heights about the flight level by $f(z)$. The probability of vertical overlap for a box of height $H$, $P_z(0,H)$ – so that $P_z(0,\lambda_z) = P_z(0)$ – can be shown to be:

$$P_z(0, H) = \int_{-\infty}^{\infty} f(v) \int_{v-H}^{v+H} f(\omega) d\omega dv$$

Altimetry errors will generate an $f(z)$ that is a well-behaved function analytically, which can therefore be expanded out in a Taylor series, to give:

$$P_z(0, H) \cong 2H \int_{-\infty}^{\infty} [f(Y)]^2 dY \text{ plus a term cubic in } H$$

Thus, to a first approximation, the probability of overlap is proportional to the height of the box concerned. Thus, the probability of overlap with the extended box is:

$$P_z(0) \frac{\left\{2\lambda_z + w\frac{2\lambda_x}{u}\right\}}{2\lambda_z} = P_z(0)\left\{1 + \frac{w2\lambda_x}{u2\lambda_z}\right\}$$

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Exactly the same kind of calculation can be carried out for the lateral dimension. Here $P_y(0)$ is currently taken as 0·0519. The probability of overlap in the y-axis is:

$$P_y(0)\frac{\left\{2\lambda_y + v\frac{2\lambda_x}{u}\right\}}{2\lambda_y} = P_y(0)\left\{1 + \frac{v2\lambda_x}{u2\lambda_y}\right\}$$

Thus, the probability of a collision, *if* the event A overtakes B occurs, is just the product of these two, i.e.

$$P(C) = P_z(0)\left\{1 + \frac{w2\lambda_x}{u2\lambda_z}\right\} \times P_y(0)\left\{1 + \frac{v2\lambda_x}{u2\lambda_y}\right\}$$

$$P(C) \approx P_z(0) \times P_y(0) \times \left\{1 + \frac{w2\lambda_x}{u2\lambda_z} + \frac{v2\lambda_x}{u2\lambda_y}\right\}$$

ignoring second order terms. This has the same kinematic factors as the Reich equation (Brooker & Lloyd, 1978). Note that there is *not* a linear dependence on the longitudinal relative velocity $u$: it occurs only as a denominator in the bracketed expression.

As well as in-trail separation as described above, some aircraft pairs in the NAT Region cross via intersecting flightpaths. The model here is easily adapted to estimate risks of such crossings.

4. PROBABILITY OF OVERTAKING. To estimate collision risk, this probability has to be multiplied by the probability of an overtaking. Some new definitions are needed. These have to recognise two features of the operation of longitudinal separation:

> With (e.g.) vertical separation, there is just one way that the separation minimum can operate: aircraft are 1000 feet apart. With longitudinal, the actual separation can be $s$ minutes, with $s = S, S+1, S+2 \ldots$ etc minutes. It is essential to take into account a realistic distribution of these separations.
>
> The separation $s$ is not the actual separation at entry but needs to be adjusted by the difference in Mach Number, so that the exit separation is at least $S$ minutes.

Therefore, it is necessary to construct numbers $E(m)$, which are the probabilities that the reported times of two aircraft entering the oceanic area, after the Mach Number adjustment, are $m$ minutes: the longitudinal occupancy distribution. Times are rounded to the nearest minute, so that a pair is taken as separated by $m$ minutes if the follower is actually between $s - 1/2$ and $s + 1/2$ minutes behind.

For an overtaking – or collision – there must be separation loss. Define $L(m)$ as the probability that $m$ or more (*sic*) minutes are lost by the end of the crossing, when allowance has been made for Mach Number differences: the loss of separation distribution. Thus, $L(m = 10)$ is the (very small) probability of an overtaking if the aircraft pair were at the minimum separation of 10 minutes. The function $L(m)$ is measurable from existing traffic. For a population of aircraft with the entry probabilities $E(m)$, the probability of an overtaking $P(Ov)$ would be $\Sigma E(M) \times L(m)$.

The calculations that led to the present NAT separation minimum essentially estimated the quantities $E(s)$ and $L(m)$ for the 15-minute separation then in

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operation. Multiplied by the probability of a collision given an overtaking, $P(C/O)$, provides an estimate of the expected number of collisions. This is then expressed in terms of fatal aircraft accidents per flying hour and thus can be compared with the target level of safety TLS for the loss of longitudinal separation (Brooker and Lloyd (1978), Brooker and Ingham (1977)).

The recent ICAO TLS figure of $1{\cdot}5 \times 10^{-8}$ fatal aircraft accidents per flying hour (RGCSP, 1995) is the rate corresponding to mid-air collisions – for any reason and in any spatial dimension – in en route flight in controlled airspace. This TLS is then customarily broken down equally against the three spatial dimensions (lateral, longitudinal and vertical separation); each being allocated a TLS of $0{\cdot}5 \times 10^{-8}$. A fraction of this is then allocated to collision risk arising from loss of planned separation: for the NAT Region all the available TLSs are counted against loss of planned separation.

The rate per flying hour is derived as follows. The probability of a collision for a randomly chosen pair of aircraft over an oceanic crossing taking time $T$ is $P(C) = P(C/O) \times P(Ov)$. If there are $N$ aircraft in a longitudinal stream over many hours then there are $(N-1)$ longitudinal pairs. Taking $N$ to be large, this implies that the statistical expectation is $P(C) \times N$ collisions. The total flying hours of the $N$ aircraft is $N \times T$ and each collision is taken to be two fatal aircraft accidents. Thus, the number of aircraft accidents per flying hour is: $\frac{(2 \times P(C) \times N)}{(N \times T)} = 2\frac{P(C)}{T}$. This is a much simpler calculation conceptually than that required in the Reich model.

5. CALCULATING THE RISKS. The model set out in the two previous sections enables risk calculations to be carried out for a NAT-type ATC track system. However, these calculations for future operations have to be of a greater level of sophistication than the methods used in developing the minima of the present NAT track system.

In particular, for the aircraft operational situation in 1979, when the NATSPG carried out its major studies of the feasibility of a separation minimum reduction to 10 minutes, the estimated risk level was about a factor of 3 greater than the TLS then appropriate. However, the NATSPG noted that this estimate assumed no intervention by ATC on receipt of reports at the oceanic waypoints. The ATC experts on the NATSPG judged that controller monitoring and appropriate intervention would prevent the bulk of time gains during the crossing actually producing a 10-minute loss before the end of the oceanic control area. They judged – cautiously – that ATC intervention would prevent at least 95% of such occurrences. On this basis, the separation minimum was reduced to its present value, and has been operated successfully for the last two decades.

In recent years, now that the introduction of the reduced vertical separation minimum (RVSM) above 29,000 feet has bedded in, there has been increasing pressure to reduce the longitudinal minimum. FAA (1999) puts this in context of other potential separation changes. The arguments are that aircraft FMCSs have greater capability; Mach numbers are more accurately flown; GPS is fitted to most NAT aircraft; the FDPS system now allows controllers to probe for potential conflicts – separation breaches – both at the entry time and on the basis of waypoint reports. All aircraft on the NAT are also fitted with airborne collision avoidance equipment, although the current convention is that their safety benefits are not

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included in collision risk calculations (but see Brooker, 2005). However, such a reduction faces a number of problems:

- Traffic density has increased so the frequency of minimum separation usage should be greater, although the RVSM change will have counterbalanced this to some extent.
- Navigation in both the vertical and horizontal dimensions has improved considerably, so that the probability of a collision given an overtaking will have increased. [NB: for satellite navigation ICAO (2000) has quoted a lateral performance of a standard deviation for Pacific flights of 0·11 nm.] For comparison:

| Parameter | 1979 | Current |
|---|---|---|
| $P_z(0)$ | 0·25 | 0·48 |
| $P_y(0)$ | 0·0064 | 0·0519 |
| $P_z(0) \times P_y(0)$ | 0·0016 | 0·024912 |

The ratio of the products of these factors is about a factor 16, i.e. an overtaking is **16** times more risky, an extremely significant figure. The product measures the probability of a collision given an overtaking in the absence of lateral/vertical motion, i.e. this probability is 0·024912 for current parameters – about 1 in 40.

- The TLS is now much more demanding. In 1979, it was 0·2 fatal aircraft accidents per $10^7$ flying hours. Currently, for changes to the system, it is 5 fatal aircraft accidents per $10^9$ flying hours, a ratio of 4. The new TLS is applicable to system changes introduced since 2000 (RGCSP, 1995).

Combining the second and third factors above produces a factor of 64. Hence, just to get back to the 1979 situation, it is necessary to compensate for this by risk reductions elsewhere in the analysis of the system – and a reduced minimum would require an even larger compensating factor. Calculations for NATSPG, e.g. Owens (2001), suggest that a risk reduction by a factor of 30 to 100 is required.

## 6. JUSTIFYING A 7-MINUTE LONGITUDINAL SEPARATION MINIMUM?

There are four key safety questions – plus one supplementary one – that need to be answered if a reasonable risk estimate is to be attempted for a 7-minute longitudinal separation minimum, operated with essentially the present ATC concept:

1. How often do aircraft pairs enter the system without a safe (implicit exit) separation?
2. How often will there be a large loss in pair separation during the crossing?
   2.1. Can a large loss mainly occur in one or two waypoint segments?
3. How often will aircrew/ATC not notice/act on potentially unsafe separation losses?
4. How often will an overtaking cause a mid-air collision?

In essence, these measure the extent of weaknesses in the layers of system safety protecting against collision. These must be small probabilities that are multiplied together. To reduce separation, the realities of the protection offered by these safety

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layers must be quantitatively understood. The following text sketches out the main issues and ways of resolving them.

In particular, the key to analysing a possible reduction in separation to 7 minutes is the nature of ATC intervention. The 1979 95% figure was an arbitrary one, albeit that it was judged very cautious (i.e. underestimated the frequency of necessary controller interventions). The appropriate figure for the present and future system has to recognise that the ATC intervention process plays a major part in preventing gross losses of separation. This is why the new model focuses on hazard analysis and events, rather than proportions of time in hazardous states.

Consider the present operation, i.e. with 10 minutes separation. There are typically five waypoints in the oceanic area, from entry to exit over about 1600 nm. The FDPS conflict probe system can detect if an aircraft is markedly ahead (or behind) its planned separation with the neighbouring aircraft on the track. To get a loss of 10 minutes with the present system, at least one of the waypoint reports on the pair must show a deviation of 2 minutes or more. Thus the key ATC intervention probability rate is the proportion of times that the probe does not correctly identify a 2+ minute deviation, *coupled* with the probability that the controller does not act appropriately when a correct probe message is processed by him or her.

6.1. *Abnormal Overtaking*. Could an overtaking occur between two successive reporting points (including the entry to first waypoint), or even over three of them, rather than near to the end of the crossing? The following sums are rough illustrative ones. If aircraft with velocities $U$ and $U-k$ travel a distance $D$, then the time interval between them is:

$$D\left\{\frac{1}{(U-k)}-\frac{1}{U}\right\}$$

In the following, $D$ for whole crossing will be taken as 1600 nm and $U=480$ knots, then a 10-minute separation would correspond to:

$$\left(\frac{1}{6}\right)=1600\left\{\frac{1}{(480-k)}-\frac{1}{480}\right\}$$

which solves to $k=23$ knots. In Mach Number terms, taking $U$ to be equivalent to 0·85 Mach (typical for an A380 and a B747-4000, 0·01 more than a B777, although faster than a B767's 0·80) would be a difference in speed of about 0·04 Mach.

But suppose that the separation loss takes place over two waypoint sections out of a typical four, i.e. D becomes 800 nm. Then the calculation produces a value for $k$ of 58 knots, i.e. a difference in speed of about 0·10 Mach. It is unlikely that one aircraft in a pair would slow down markedly and the next one speed up markedly, so the inference would be that one of the two is effectively flying about 0·10 Mach faster or slower than it is supposed to be. A Mach number difference of 0·10 would be significant in flying terms. For example, at 35,000 feet, the Boeing 777 cruises at Mach 0·84. The maximum speed would be only in the region of Mach 0·86 – the red mark in the speed indicator. But turbojet aircraft can be flown in cruise at much lower Mach Numbers, such as 0·75 (e.g. see Eshelby, 2000).

Can this kind of abnormal overtaking be eliminated as a possibility? Discussions with operational pilots and safety regulators do not suggest that there would be some kind of message from the autopilot triggered by arbitrary (?) input parameters

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in the autopilot system. There appear to be three reasons why an aircraft flying at a Mach Number very different from the optimum cruise setting would be improbable. The reasons are listed and discussed in turn:

1. *Aircraft System Damage*. The kinds of damage to the aircraft systems required to produce such a significant error are highly improbable – there would have to be a very complex series of failures for the displayed Mach Number to be different from that input by the aircrew. A major Machmeter error would have to be caused by major problems with the aircraft air-data systems. There would have to be structural damage to the static pressure system/pitot tubes. There is engineering redundancy in these systems and the cross-links to the aircrew, so the damage would have to be very extensive if both sets of speed/Mach equipment were to be affected. It is very unlikely that such damage would occur in flight, which in turn would mean that the ground aircraft inspection would have had to have been markedly inadequate. Does such damage occur in reality? The Civil Aviation Authority Safety Regulation Group kindly provided data from its Mandatory Occurrence Reporting Scheme (MORS) from its inception in 1976 up to November 2004. There were about 300 incidents in which 'Mach' or 'Machmeter' were mentioned. None of them corresponded to damage to the aircraft systems that persisted to oceanic flight. There were instances of damage, but they were all detected before the end of the climb phase.
2. There would be strong indications of a problem in the flight of the aircraft to the oceanic entry point. Most flights have to fly some distance from their origin airport to the oceanic entry point. This is certainly the case for almost all eastbound flights. For westbound flights, there are some proximate airfields, e.g. Dublin and Prestwick. Generally, there will be of the order of 1 hour's flight from the airport to the boundary, and in many cases much more than this time. Any significant fault or failure in the aircraft's air-data systems of the order of a 0·05 Mach difference is likely to show up by the oceanic boundary, and/or the flight will be observed as being 5+ minutes late/early at entry.
3. The aircrew would notice very odd flight behaviour whilst the aircraft was in oceanic cruise. If the damage effect were not detected before oceanic entry, would the aircrew detect it quickly? There are several reasons why it might be noticed. One is that the aircraft would have an atypical angle of attack (AoA – pitch) in order for the aircraft to maintain altitude. AoA is measured by the flow angle sensor and used to correct static pressure.

If there were to be reduction to 7 minutes, then an important issue would be a loss of (say) 5 minutes *between* waypoints (allowing a tolerance of up to 2 minutes late at the first waypoint). It is vital that timekeeping is accurate. Table 1 shows the speed differences in Mach number required for a 5-minute (0·0833 hrs) loss over 1 to 4 waypoints, assuming a Mach number for the following aircraft of 0·85.

The message from the table is that an undetected cumulative loss of 5 minutes would generally have to occur over *more* than 2 waypoints. This means that the conflict probe and controller combination would have to fail *at least twice* to detect ~2+ minute losses for a 5 minute overtaking to occur.

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Table 1. Loss of separation as function of incremental speed.

| Distance $D$ nm | 400 | 800 | 1200 | 1600 |
|---|---|---|---|---|
| Separation nm ($k$) | 43·6 | 22·9 | 15·5 | 11·7 |
| $k$ in Mach No | 0·077 | 0·040 | 0·027 | 0·021 |

Table 2. Loss of separation as function of incremental speed – with wind effects.

| Headwind | Distance $D$ nm Speed | 400 $k$ | 800 $k$ | 1200 $k$ | 1600 $k$ |
|---|---|---|---|---|---|
| 120 | 360 | 0·059 | 0·031 | 0·021 | 0·016 |
| 80 | 400 | 0·065 | 0·034 | 0·023 | 0·017 |
| 40 | 440 | 0·071 | 0·037 | 0·025 | 0·019 |
| 0 | 480 | 0·077 | 0·040 | 0·027 | 0·021 |
| −40 | 520 | 0·083 | 0·044 | 0·030 | 0·022 |
| −80 | 560 | 0·089 | 0·047 | 0·032 | 0·024 |
| −120 | 600 | 0·094 | 0·050 | 0·034 | 0·026 |

Wind can have a significant effect on separation times, as shown in Table 2.

6.2. *Normal Overtaking*. If abnormal overtaking is ruled out, what are the chances of normal overtaking – and what does this actually mean? In the following, normal overtaking is used to describe situations in which separation is lost by combinations of factors, i.e. this is just the extremes of a typical flight operation and ATC.

A large number of factors can affect an aircraft's oceanic separation. These include:

- Accuracy of Machmeters – typically these are accurate to 0·01 Mach.
- Meteorological effects: the wind can be different from that predicted; temperature affects ground speed; turbulence can have significant effects.
- Aircraft may not be operating to the same clock time.
- There can be rounding errors in time – given that that the system operates on a whole number of minutes.
- Position reports can be late.

What do factors such as these imply in terms of a flight's progress across the oceanic area? The key point is that current NATSPG risk calculations focus on loss of separation between waypoints from normal overtaking – i.e. have to estimate the small tails of extrapolated distributions.

Figure 3 illustrates a westbound flight with a 7-minute separation minimum. The flight loses time at a constant rate during the crossing, two minutes per waypoint interval. As can be inferred from the tables on Mach Number differences above, such a loss need not be a particularly abnormal operation. It would be at the extremes of normal operations: the slower aircraft of a pair would only have to be about 0·03 Mach below the desired value. The effects of late entry to the system are easily shown by considering the bottom row in Figure 3, which shows how a late entry by 2 minutes – allowed in the present system – produces an even quicker total loss of the minimum separation.

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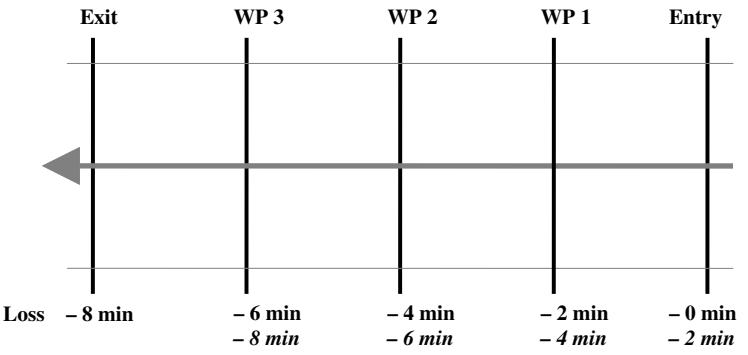



Figure 3. Flight just breaking a 7-minute separation minimum.

These are very simple illustrations, but they serve to justify a crucial point: controller intervention is not a bonus but rather a key element of system safety. Without that intervention, it would be very difficult to demonstrate that a 7-minute system could be safe. In addition, late entry to the system – by up to 2 minutes currently – essentially erodes a large proportion of the minimum requirement.

The NATSPG work in the late 1970s was extremely important in ATC safety development because it recognised explicitly and quantitatively the role of ATC in preventing mid-air collision in this kind of system. This safety factor would have to contribute even more in a system with a reduced minimum, but this is feasible because the 1979 quantification – a 95% reduction in collision risk – was very cautious.

The key point to note is that the controller has several chances to detect and act upon a potential conflict. Even with the late entry into the system in Figure 3, there are two waypoints at which the controller can receive information about the flight's slow progress. For an overtaking to occur, the aircraft pair must have lost separation AND the controller must have failed to resolve the potential overtaking at each of the opportunities that he or she has before the overtaking. What is the probability of such a failure? The controller's task must be framed in a rigorous fashion – if the aircraft pair have lost more than 2 minutes at the first waypoint, or 4 minutes at the second, etc, then the controller must have a specified duty to resolve the potential conflict by (e.g.) varying the speed of an aircraft or moving it to a different flight level. The controller has the data processing tools to accomplish this kind of task.

The fact that a controller would have to fail on successive occasions implies that the probability of successful intervention before an overtaking is potentially much higher than the 95% assumed in 1979. If the failure probability to act appropriately for a single waypoint is 1/10 then two independent failures would be a 1/100 effect. So, can the duties on the controller be specified rigorously in terms of action to correct separation loss, and what probabilities for failure of these duties can be cautiously estimated?

On what basis could a factor of 100 be supposed reasonably cautious? The strongest evidence about this kind of human reliability statement comes from the nuclear industry (e.g. Kirwan, 1994). There is a variety of human reliability techniques documented in the literature. Typically, they need to use well-established estimates of human performance in standard tasks. Take as an example, the 'HEART' generic task categories (adapted from Embrey, 2004) in Table 3.

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Table 3. HEART Generic Task Categories (selection).

| | Generic Task Category (extract) | Proposed nominal human reliability (5% to 95% bounds) |
|---|---|---|
| F | Restore or shift a system to original or new state following procedures, with some checking | 0·003 (0·0008 to 0·007) |
| G | Completely familiar, well-designed, highly practised, routine task occurring several times per hour, performed to highest possible standards by highly motivated, highly trained and experienced person, totally aware of implications of failure, with time to correct potential error, but without the benefits of significant job aids | 0·0004 (0·00008 to 0·009) |
| H | Respond correctly to system command even when there is an augmented or automated supervisory system providing accurate interpretation of system usage | 0·00002 (0·000006 to 0·0009) |

It is an interesting question as to which of these categories best matches the probability that a controller using the FDPS conflict probe will not resolve a problem arising from a pilot's 10-degree waypoint report – but a factor of a thousand does not appear to be too difficult to justify.

HEART – and other human reliability quantification techniques such as THERP and SLIM – have pros and cons when used in complex probabilistic risk assessments. However, the application here does not get into these kinds of complexities: a single human factors number is used to supplement an existing collision risk model structure.

[HEART and the other quantification methods do have extra layers of task complexity, which tend to increase the estimated probability of human failure. These tend to ask questions about, e.g. operational inexperience, ambiguity, unfamiliarity; channel capacity overloads (e.g. see Table 8.6 in Embrey (2004)). It would be hoped that the NATS system, developed over many years, with qualified personnel using very specific instruction sets and exposed to rigorous training processes, would not be affected in such a way.]

6.3. *Lateral Offsets.* A problem that has emerged since the 1979 work is the increased accuracy of vertical and horizontal navigation, as already indicated in Table 1. This increased accuracy leads directly to increased risk, as set out in the collision risk calculations – an overtaking aircraft is much more likely to encounter the preceding aircraft in its path.

There are also some problems with reduced vertical separation in this regard. The risk of a collision due to loss of vertical separation in a track is again directly proportional to the accuracy of horizontal navigation. In addition, there are some issues about vortex wake effects: an aircraft flying on one flight level can produce strong wake vortices on a following aircraft a flight level below.

The longitudinal and vertical risk problems arising from this improved accuracy have to be resolved together in a systematic fashion. There are many potential solutions. An easy one, which might not introduce extra complex failure modes, is for aircraft to fly strategic (i.e. predictable) lateral offsets determined by flight level and entry time. [Lateral offsets have a long history in ATC. The first ever airliner mid-air collision, at Thieuloy-Saint-Antoine in France, within a week led to the suggestion of

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Table 4. Strategic lateral offset scheme.

| ENTRY TIME (implicit) | FLIGHT LEVEL | | | |
|---|---|---|---|---|
| | 310 | 320 | 330 | 340 |
| 0000–0006 | + | o | – | o |
| 07–13 | o | – | o | + |
| 14–20 | – | o | + | o |
| 21–27 | o | + | o | – |
| 28–34 | + | o | – | o |
| 35–41 | o | – | o | + |
| 42–48 | – | o | + | o |
| 49–55 | o | + | o | – |
| 56–62 | + | o | – | o |

a visual lateral offset procedure (Flight, 1922), and its implementation very shortly afterwards.]

Table 4 shows a sub-set of a much larger table. The +, o and – signs indicate a lateral offset of (say) 2 nm to the right, centre and left of the track. The entry times are the whole minutes used in the separation criteria adjusted for the differences in Mach Number, i.e. they are the initial planned exit times. No leader-follower pairs can be in the same offset box. Adjacent vertical boxes in the table always have an offset, so longitudinal pairs have an offset. Adjacent horizontal boxes in the table always have an offset, so neighbouring aircraft separated by a flight level always have an offset. (N.B. This is obviously not the only option for this kind of offset. For example, the offsets could be 0, 1 nm and 2 nm.) Table 4 is, in computing jargon, a look-up table. It can be programmed into a computer and then its requirement can simply be output to the controller/pilot when the aircraft crosses the entry boundary. Operationally, the magnitude of the offset can be routinely checked at the reporting points: it is actually machine checkable.

In risk modelling terms, the value of $P_y$ (0) can be estimated by a similar formulation to that used earlier. The expression is:

$$P_y(0) = \int_{-\infty}^{\infty} f_1(v) \int_{v-\lambda_y}^{v+\lambda_y} f_2(\omega) d\omega dv$$

Here, a single lateral deviation for a flight is replaced by two different ones, marked by the subscripts 1 and 2, which are the statistical distributions for a typical flight and then that for the next flight, which is relatively offset. The calculation has to be averaged over the different combinations of offset pairs. Given the increasing improvements in lateral navigation, the value of $P_y(0)$ will be very small on any reasonable assumptions about the precise lateral distribution form, e.g. an additional safety factor of at least a 100.

Currently, NATSPG has developed a random offset procedure, for a variety of reasons (NATSPG, 2003):

> " *The following incorporates lateral offset procedures [to] provide additional safety margin and mitigate the risk of conflict when non-normal events such as aircraft navigation errors, height deviation errors and turbulence induced altitude-keeping errors occur … Along a route or track*

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*there will be three positions that an aircraft may fly: centreline or one or two miles right … Pilots should use whatever means is available to determine the best flight path to fly.*"

If the pilot makes decisions wholly randomly, without reference to neighbouring traffic, then this provides an extra safety factor for longitudinal overtaking, because the follower aircraft has one chance in three of having the same offset as the leader aircraft. Unfortunately, this is far too small a factor compared with that required for reduced longitudinal separation to 7 minutes (see the comments at the end of Section 5).

7. CONCLUSIONS. This paper has presented a collision risk model and operational concepts for longitudinal separated aircraft in, for example, the NAT ATC track system, and sketched how it might be used to reduce separation minima, and hence deliver cost savings, whilst ensuring safety. The main difference with earlier work is that this is an event-based model, rather than one focusing on statistical distributions of hourly deviations from the aircraft's planned position. With an event model, it is easy to see what is being assumed, to understand the role of the main parameters, and it can readily be developed to incorporate collision detection and hazard analysis. The model is a very simple picture conceptually, but still enables collision risk estimates to be made for (e.g.) a system using datalink and satellite navigation.

A potential future operation with a 7-minute separation has been examined in the light of this improved model. The points of major importance are:

The likelihood of abnormal Mach Number operations, e.g. of 5+ minutes between waypoints, is very low: there are several system safeguards.

Normal gains/losses in separation, e.g. of two or three minutes between waypoints, can occur as the consequence of a variety of factors.

With a very disciplined approach to mitigate these factors, plus recognition of the safety factors offered by pilot/datalink reporting and controller intervention, the reduction in the separation minimum could potentially be safe.

The probability that controller invention would fail to resolve a gain/loss can be quantified from the basic elements of human reliability quantification techniques.

A major extra safety factor would be through the introduction of a strategic lateral offset system across all tracks and flight levels.

These design factors offer the possibility of reducing separation – but the true test will be formal calculations, taking account all the complex practicalities of real operations, through the NATSPG forum.

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## REFERENCES

Brooker, P. (2002). Future Air Traffic Management: Quantitative En Route Safety Assessment Part 1 – Review of Present Methods. *The Journal of Navigation* **55**, 197–211.

Brooker, P. (2003). Lateral Collision Risk in Air Traffic Track Systems: A 'Post-Reich' Event Model. *The Journal of Navigation*. **56**, 399–410.

Brooker, P. (2004). Consistent and Up-to-date Aviation Safety Targets. *Aeronautical Journal*. July, 345–356.

Brooker, P. (2005). Airborne Collision Avoidance Systems and Air Traffic Management Safety. *The Journal of Navigation* **58**, 1–16.

Brooker, P. and Ingham, T. (1977). Target Levels of Safety for Controlled Airspace. *CAA Paper 77002*. CAA.

Brooker, P. and Lloyd, D. E. (1978). Collision Risk and Longitudinal Separation Standards for North Atlantic Air Traffic: *UK CAA DORA Communication 7801*, Issue 2, CAA, London.

CAA (2004). CAP 493 Manual of Air Traffic Services ('MATS') Part 1, Civil Aviation Authority, London. http://www.caa.co.uk/docs/33/CAP493__Part1.pdf.

Embrey, D. (2004). Qualitative and quantitative evaluation of human error in risk assessment. In *Human Factors for Engineers*, Eds. Sandom, C. and Harvey, R. S. IEE.

Eshelby, M. E. (2000). *Aircraft Performance: Theory and Practice*. Arnold, London.

FAA [Federal Aviation Administration] (1999). Implementation Plan For Oceanic Airspace Enhancements and Separation Reductions. http://www.faa.gov/ats/ato/150_docs/Implementation_Plan.doc

FAA/Eurocontrol (1998). A Concept Paper for Separation Safety Modeling. An FAA/Eurocontrol Cooperative Effort on Air Traffic Modeling for Separation Standards. http://www.faa.gov/asd/ia-or/pdf/cpcomplete.pdf

Flight (1922). The Air Disaster. *XIV*(**15**), 210.

ICAO (2000) Use of lateral offsets and the effect on airspace safety. State Letter AN 13/11.6-00/96. Available in IBAC Bulletin B01-1. http://www.ibac.org/Bulletins/ibac_b01-1.htm

Kirwan, B. (1994). *A Guide to Practical Human Reliability Assessment*. Taylor and Francis, London.

NAT PCO [North Atlantic Programme Coordination Office] (2004). North Atlantic MNPS Airspace Operations Manual. Edition 9. http://www.nat-pco.org/mnpsa.htm

NATSPG [ICAO North Atlantic Systems Planning Group] (2003). Summary of Discussions and Conclusions of the North Atlantic Systems Planning Group. NATSPG/39, ICAO.

NATSPG MIG [Mathematicians Implementation Group] (2002) North Atlantic Risk Quick Reference Guide. NATSPG.

Owens, S. (2001). Revised Longitudinal Collision Risk Estimates for NAT MNPS Airspace. *NATSPG*. MIG/9 WP/4.

Penna, D. M. (1977). Longitudinal Separation of North Atlantic Air Traffic. *CAA Paper 77028*. Civil Aviation Authority, London.

Reich, P. G. (1966). Analysis of Long-range Air Traffic Systems: Separation Standards. *The Journal of Navigation*, **19**, 88, 169 and 331 (in three parts).

RGCSP [ICAO Review of the General Concept of Separation Panel] (1995). Working Group A Meeting: Summary of Discussions and Conclusions. ICAO.

https://doi.org/10.1017/S0373463305003516 Published online by Cambridge University Press