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Lateral Collision Risk In Air Traffic Track Systems: A 'Post-Reich' Event Model

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A model is developed for lateral collision risk in air traffic track systems, which resolves the problems of the Reich Model. It is a direct and concrete approach focusing on events, in contrast to Reich's synthetic methodology, in which (e.g.) three types of collision have to be modelled and the focus is on flying hours spent away from the planned flight path. This model makes it straightforward to see what is being assumed, and easy to understand the roles of the main parameters. It is a good starting point for the incorporation of collision detection and the use of hazard analysis.

KEY WORDS

1. ATC. 2. Collision risk.

1. INTRODUCTION. In 1966 P. G. Reich published three very influential papers in the Journal of Navigation on the analysis of long-range air traffic systems separation standards. This *Reich Model*, with Reich pronounced approximately as the English word reach, has been used extensively in safety analyses of Air Traffic Control (ATC) track structures. Is the model appropriate for the 21st century? The analysis here produces a Post-Reich model.

There are three reasons why this derivation is useful:

- Reich's derivation is a comparatively abstract one focusing on statistical distributions of deviations from planned position. There has been a concern that it may be too cautious, i.e. tends to over-estimate collision risk.
- The derivation does not make it easy to see what the key parameters are.
- It is not easy to add in other features to the model, e.g. the effects of collision detection systems.

The model developed here resolves these problems for lateral collision risk in air traffic track systems: it is a post-Reich model. It is a direct approach. It is easy to see what is being assumed and to understand the role of the main parameters. It can readily be developed to incorporate collision detection and hazard analysis. The paper is structured to provide an outline and critique of the Reich Model in section two, section three develops an event-based lateral collision risk model, some questions about the Event Model are addressed in section four, and the conclusions are in section five.

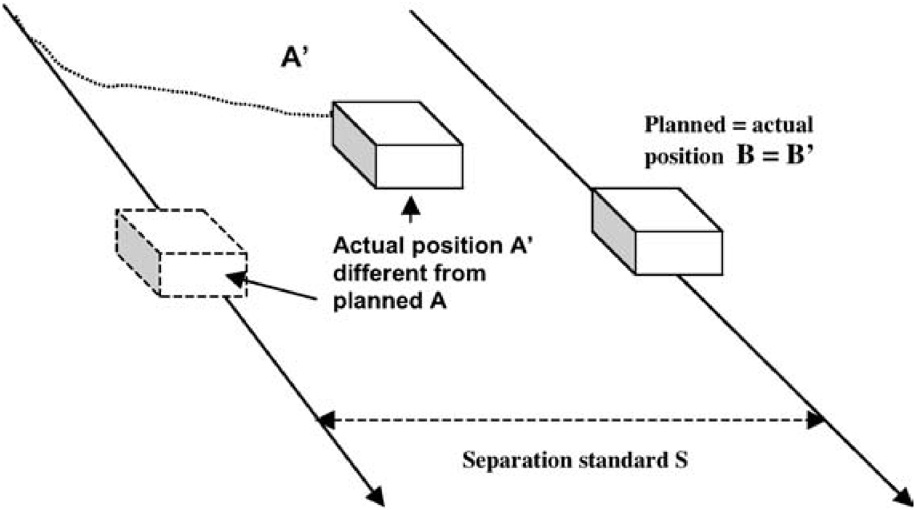

Figure 1. Collision risk model premise: aircraft boxes deviating from track.

2. OUTLINE AND CRITIQUE OF THE REICH MODEL.

The Reich Model has been much used for the North Atlantic Region, for which the following brief description of the lateral separation situation applies. Lateral separation is generally important in separation modelling because controllers use plan displays and rely heavily on vectoring aircraft to ensure safety. Figure 1 illustrates the model tailored to the lateral spacing between tracks. The key point is that it assumes that the air traffic controller is unable to intervene to prevent collisions through loss of lateral separation. The controller puts aircraft onto properly separated flight paths and they are then navigated across the ocean.

Two aircraft are on adjacent parallel tracks, the distance between them being the separation standard S. The aircraft are modelled as boxes, based on actual aircraft dimensions, which simplifies the calculations without serious effect on the conclusions. The figure shows the actual positions of the aircraft boxes near to each other because one aircraft has deviated considerably from its planned position, labelled A, to be at A′. A collision will occur if the deviating aircraft crosses the adjacent track when the second aircraft, B, is located at or about the crossing point and the aircraft are at about the same height. See and avoid by pilots is not taken into account.

With this picture and a variety of assumptions, Reich developed an estimate of collision risk of the form:

Collision risk = traffic factors × aircraft parameters × navigation performance.

Traffic factors measures the density of traffic on adjacent tracks, i.e. the likelihood of an aircraft having another aircraft on a neighbouring track overlapping longitudinally. *Aircraft parameters* include such quantities as the sizes and relative velocities of aircraft and (conventionally) the chance of the aircraft boxes at the same flight level overlapping. In both cases, overlap means that the neighbouring aircraft is within an aircraft-box dimension of the position of the first aircraft. *Navigation performance*, denoted $P_y(S)$, is the probability that two aircraft nominally separated by the separation distance S are in fact in lateral overlap. The calculation of the proportion of flying hours in lateral overlap $P_y(S)$ uses statistical information on the lateral navigation errors of the aircraft involved.

Reich's derivation of the expression above is somewhat abstract. As already noted, it focuses on the times that the separation between aircraft boxes is lost. It calculates the frequency of collisions by dividing this time by the average time for one box to 'pass through' another. Three types of collisions between boxes are modelled: front of one box and back of the other; top and bottom; and side to side. This is necessary to ensure that all possible directions for collisions are accounted for, but is actually an artifice of the model.

Reich's model has been used extensively in practice, particularly by the North Atlantic (NAT) Systems Planning Group (NATSPG) in redesigning the NAT track structures. Nevertheless, its degree of abstraction has led to concerns that it may be too cautious, i.e. tends to over-estimate collision risk. The derivation does not make it very easy to see what the key parameters are. Nor is it easy to add in other features to the model, such as the effects of collision detection systems.

Models of socio-technical systems have to change according to circumstances. The social sciences know this very well, as evidenced by the kinds of definitions used, e.g. (Chorley and Haggett, 1968):

> "Model: A simplified structuring of reality which presents supposedly significant relationships in a generalised form … [models] are valuable in obscuring incidental detail and in allowing fundamental aspects of reality to appear."

Reich's model was originally constructed to match aircraft systems in which large navigational errors arose because of equipment performance either as hardware faults or inherent inaccuracies. However, by the time of the introduction of major separation changes to the NAT (Brooker and White, 1979), it was already apparent that many errors, which are detected at the boundary of the ocean when aircraft come into radar cover, were the product of what was termed the human element. In particular, the probability distributions used in the Reich Model had to be adapted to match waypoint errors, in which the aircraft deviated from the correct track by one or more degrees of latitude.

Davies and Sharpe (1993) present a review of the method currently used to estimate lateral collision risk in North Atlantic minimum navigation performance specification (MNPS) airspace. The result is a risk assessment model in which each lateral navigation error is weighted according to the contribution it makes to the risk. This applies to all types of error, the magnitude of the weighting varying with the characteristics (e.g. velocity at closest approach) of the error. The key point, and this is used in the next section, is that most NAT lateral navigation errors now arise because of human factor problems in the largest sense, not through mechanical equipment failures. For example, the latest NATSPG statistics (NATSPG, 2002), for Summer 2001, show five risk bearing ($\geqslant 50$ nm) gross errors. All were waypoint errors, and fell into NATSPG Error Class C, four of Class C2 and one of Class C3, where the definitions are:

- Class C2 – Incorrect transcription of ATC clearance or re-clearance into the FMS.
- Class C3 – Wrong information faithfully transcribed into the Flight Management Computer System, e.g. flight plan followed rather than ATC clearance or original clearance followed instead of re-clearance.

Over the years, the Reich Model has attracted considerable criticism, e.g. the (very comprehensive) FAA/Eurocontrol review document (1998).

> "While the Reich Model provides a widely accepted tool for evaluation of collision risk in its intended environment, a number of shortcomings of the methodology have been acknowledged. The model uses convolutions of distributions (including heavy tailed double exponential distributions) representing expected deviations (due to flight technical errors, allowable inaccuracies in navigation equipment, etc.) and unexpected deviations (due to pilot blunders, avionics failures, etc.).
>
> Difficulties in the application of the Reich Model include: (1) the assumption of fixed, usually parallel track operations, (2) the exclusion of communication, surveillance and ATC control loop performance, and (3) difficulty in modelling the tails of navigation system performance and pilot blunders, where human errors and equipment problems often dominate an infrequently observed population. The Reich Model emphasizes navigation performance. Its representation of abnormal/unmodelled operations, and its empirical, as opposed to predictive nature, have also been criticized."

Some of these criticisms seem excessive. The Reich Model was constructed for a particular purpose, which it serves very well: it was never intended to be an 'all-singing all-dancing' model of everything. The comment about its empirical nature also seems off the mark; aircraft passengers would no doubt prefer collision risk modelling to be closely tied in to what happens in reality. Given the importance of the inherently complex human factors element, it is hardly surprising that the Reich Model is not as objective a model as (say) the Rutherford scattering model in physics. The review goes on to stress the need somehow to combine the Reich Model with hazard analysis elements, e.g. conflict detection. This developmental problem is a real one as the Reich Model derivation has proved to be somewhat of a cul-de-sac. The Reich Model methodology quickly leads to very complex mathematics when an attempt is made to incorporate other hazard analysis aspects. Take, as an example, the Burt (1997) examination of ATC intervention rates on parallel tracks. Burt's approach is probabilistic; it appears to discuss an aircraft path but actually uses probability density functions based on snapshot concepts. The analysis requires a high density of algebra and calculus, and hence tends to obscure the underlying physical risk processes. The need for simplicity and concreteness and the aim of integrating hazard analysis features, are the main drivers for the development of the Event Model.

3. AN EVENT-BASED LATERAL COLLISION RISK MODEL.

The model developed here is a direct approach. It considers events and uses simple probability calculations. As already noted, the crux of the Reich Model is the device used to convert an error probability to a rate per flying hour. The assertion here is that it is unnecessary to do this because the navigation errors input into the model are directly measured as rates per flying hour. To distinguish it from the Reich Model, it is referred to 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, which use a very old style of notation. The track axes are: x – along track; y – lateral to track; z – vertical. The aircraft box dimensions, measured along the track axes not the direction of flight, are λ_x, λ_y and λ_z respectively. Their current NATSPG values are 0·032, 0·029 and 0·091 nm respectively. The calculations here do not use aircraft boxes, but rather a collision box for one aircraft and

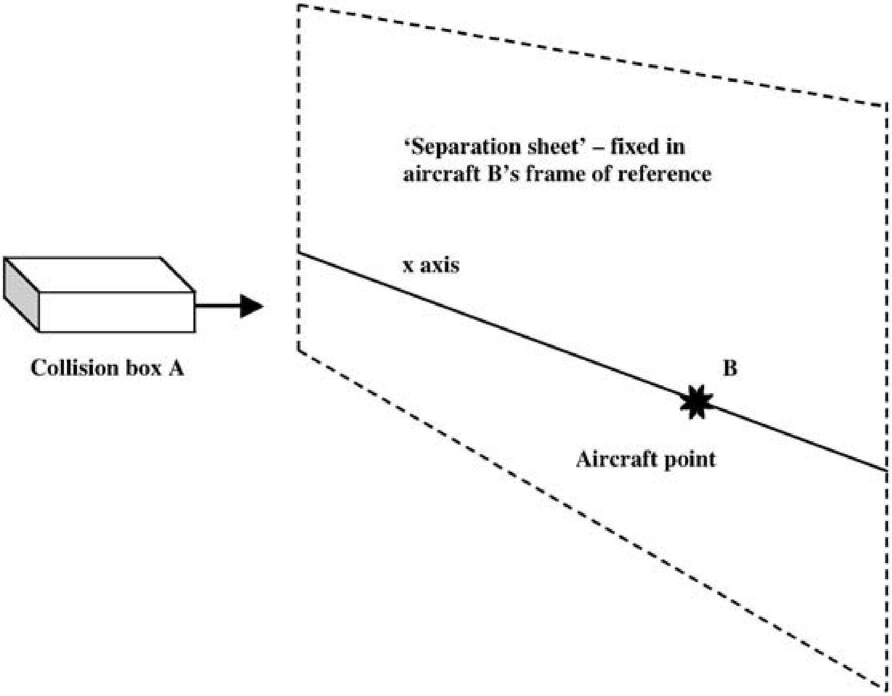

Figure 2. The collision box A moving towards the separation sheet fixed by aircraft B at rest.

a point at the centroid of the aircraft box for the other. The collision box has dimensions $2\lambda_x$, $2\lambda_y$ and $2\lambda_z$. Two aircraft are taken as colliding if their aircraft boxes touch. Aircraft boxes are taken always to be orientated in the same direction with respect to the xyz axes. 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 produces this larger collision box. This is exactly as used by Reich, who refers to the collision box as a slab.

The assumed aircraft speed along track is $U_{at} - 480$ knots in NATSPG. The absolute relative velocities for a modelled pair of aircraft are: u – along x axis; v – along y axis; w – along z axis. The averages of absolute relative velocities for aircraft on same-direction adjacent tracks where one has lost lateral separation are denoted by the capitals U, V and W respectively. Their current NATSPG values are respectively 13, 80 and 1·5 knots.

The Event Model adopts a particular reference frame. Taking two representative aircraft A and B laterally separated by S on adjacent tracks, 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 2 is a picture of the start of a collision. It occurs when a gross error in lateral navigation has occurred. This is defined as an error which breaches the lateral separation minimum S; the actual deviation distance will be slightly more or less given the lateral navigation errors of the two aircraft. The assumption here is that all large errors, e.g. of 50+ nm in the present NAT system with a 60 nm standard, do breach

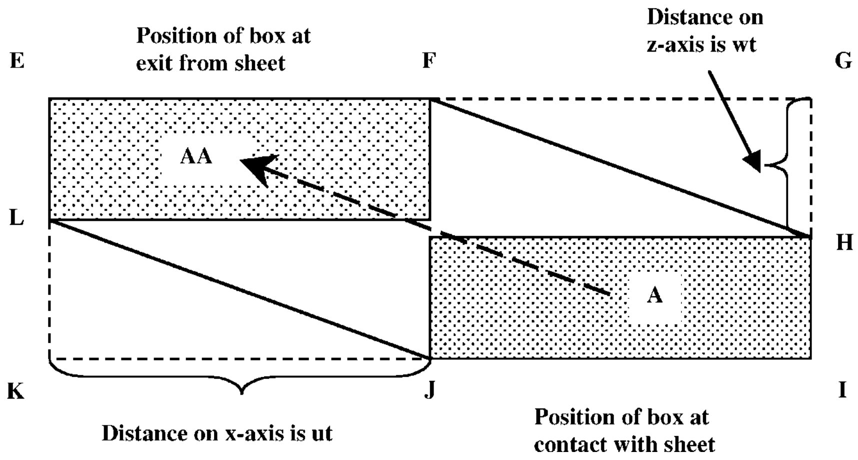

Figure 3. Transit of collision box through separation sheet (face view of separation sheet).

the separation minimum: it will be shown that this is an implicit assumption in the Reich Model as currently modified for NATSPG. In other words, a gross navigational error is prudently judged to constitute a breach of the separation standard. The figure shows the collision box, which remember is orientated according to the xyz, axes, not the direction of flight, travelling, having deviated from its track, towards the separation sheet. This is an imaginary flat surface of zero thickness extended vertically from the x-axis of the neighbouring track. 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 a side face of the box makes the initial contact with the sheet. It then takes a time t for the box to move through the sheet, where t is the lateral dimension of the box, $2\lambda_y$, divided by the lateral velocity at loss of separation. The average value of t, is therefore:

$$t_{av} = 2 \times 0{\cdot}029/80 = 7{\cdot}25 \times 10^{-4} \text{ hours, i.e. about 3 seconds.}$$

So the box goes through the sheet very quickly.

Figure 3 illustrates the movement of the collision box through the separation sheet. This diagram is looking at the separation sheet, i.e. along the y-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 x and z directions, so that its position when it exits the sheet is at AA. It has moved a distance ut on the x-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 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. So, hexagon EFHIJL will be approximated by rectangle EGIK as the 'extended collision box', with dimensions $2\lambda_x + \frac{U2\lambda_y}{v}$ and $2\lambda_z + \frac{W2\lambda_y}{v}$, 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 Ut_{av} and Wt_{av} and then comparing with the collision box dimensions $2\lambda_x$ and $2\lambda_z$. The numbers are

$$Ut_{av} = 13 \times 7{\cdot}25 \times 10^{-4} = 0{\cdot}009 \text{ nm}; \quad 2\lambda_x = 2 \times 0{\cdot}032 = 0{\cdot}064 \text{ nm},$$

$$Wt_{av} = 1{\cdot}5 \times 7{\cdot}25 \times 10^{-4} = 0{\cdot}001 \text{ nm}; \quad 2\lambda_z = 2 \times 0{\cdot}009 = 0{\cdot}018 \text{ nm}.$$

So the along track and vertical movement effectively adds about 15% and 6% respectively to the x and z dimensions of the collision box. Thus, the extended collision box in this case is not much bigger than the collision box, and indeed little different from the hexagon.

For traffic on adjacent opposite direction tracks, the relative velocity on the x-axis is $2U_{at}$. Thus the x-axis distance moved by the box is:

$$2U_{at}t_{av} = 2 \times 480 \times 7{\cdot}25 \times 10^{-4} = 0{\cdot}696 \text{ nm}.$$

This is far larger than the x dimension of the collision box and indicates why the risks with opposite direction traffic are so high compared with adjacent same-direction tracks. The movement in the z dimension is the same as before, because the velocity component and the time for the box to pass through the sheet are the same. Thus, the hexagon swept out is very long and thin along the x-axis. Again, the hexagon can be approximated by the rectangle that encloses it.

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 x and z dimensions can be carried out separately because the motions in those dimensions can be taken as statistically independent.

First the x dimension, for which some further definitions are needed: $2L$ is the length of a longitudinal window on the track (L is taken as 120 nm); the occupancies, $E(S)$, $E(O)$ are the average number of aircraft found in adjacent tracks, for same and opposite direction respectively, in windows of length $2L$. Thus, the occupancies indicate the degree to which traffic is packed on adjacent tracks. The probability of the extended collision box overlaying the aircraft B point in the x-axis is therefore:

$$P_x = \frac{E(S)}{2L}\left(2\lambda_x + \frac{U2\lambda_y}{V}\right), \tag{1}$$

with a similar expression for opposite direction tracks.

The calculation of the vertical overlap has to be very different. Aircraft are certainly not distributed randomly in the vertical dimension. With modern systems, aircraft keep to their assigned altitude with high precision, so the collision box and the aircraft B point are very likely to be in overlap. For collision boxes, the probability of vertical overlap $P_z(0)$ used by NATSPG is 0·48. For the extended collision box, i.e. including the vertical movement, the probability of overlap is necessarily higher than this value. A simplified calculation of vertical overlap shows the importance of the effect and 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:

$$P_z(0,\ H) = \int_{-\infty}^{\infty} f(v) \int_{v-H}^{v+H} f(\omega) d\omega\, dv. \tag{2}$$

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:

$$P_z(0,\ H) \cong 2H \int_{-\infty}^{\infty} [f(Y)]^2 dY, \quad \text{plus a term cubic in } H. \tag{3}$$

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:

$$P_z(0,\ H) = P_z(0)\left(1 + \frac{W2\lambda_y}{V2\lambda_z}\right). \tag{4}$$

The risk, actually the accident rate per flying hour N_{ay}, can now be calculated from the rate of losses of separation per flying hour, $GERh$, and the components above. For simplicity, only the same direction risk is expressed:

$$\begin{aligned} N_{ay} &= GERh\, P_x\ P_z(0,\ H) \\ N_{ay} &= GERh \frac{E(S)}{2L}\left(2\lambda_x + \frac{U2\lambda_y}{V}\right) P_z(0)\left(1 + \frac{W2\lambda_y}{V2\lambda_z}\right), \end{aligned} \tag{5}$$

giving the proper functional form of the Event Model. Dropping the second order term in the final bracket finds:

$$N_{ay} = GERhE(S)P_z(0)\left(\frac{\lambda_x}{L}\right)\left(\frac{2\lambda_y}{V}\right)\left(\frac{U}{2\lambda_x} + \frac{V}{2\lambda_y} + \frac{W}{2\lambda_z}\right). \tag{6}$$

This is now in a similar form to the Reich Model equation. One final conversion is needed to match that model. The rate of losses of separation per flying hour has to be related to the proportion of flying hours in lateral overlap $P_y(S)$. As the average lateral overlap following a gross waypoint error would take a time $\left(\frac{2\lambda_y}{V}\right)$, the product of the two is the required probability:

$$GERh\left(\frac{2\lambda_y}{V}\right) = P_y(S). \tag{7}$$

So the expression N_{ay} becomes:

$$N_{ay} = E(S)P_z(0)P_y(S)\left(\frac{\lambda_x}{L}\right)\left(\frac{U}{2\lambda_x} + \frac{V}{2\lambda_y} + \frac{W}{2\lambda_z}\right), \tag{8}$$

which is the Reich Model expression. The algebra for the opposite direction component follows through in a similar fashion. Thus, this derivation produces essentially the same expression as the Reich Model.

It was noted earlier that there is an implicit assumption in the Reich Model, as currently modified for NATSPG, that all large errors, e.g. of 50+ nm in the present NAT system with a 60 nm standard, do breach the separation minimum. This is because all 1° waypoint gross errors are assumed to be evenly spread over time in the

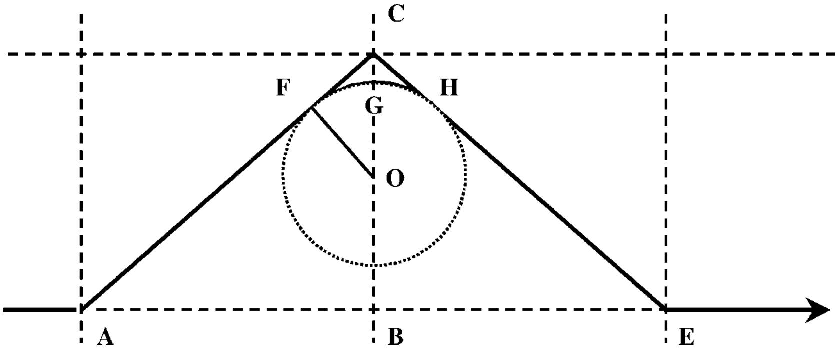

Figure 4. A single waypoint error in plan view (not to scale).

lateral distance 50–60 nm (and similarly for multiple degree errors) before being scaled down to the lateral overlap probability region.

4. SOME QUESTIONS ABOUT THE EVENT MODEL.

The simple physical picture of the Event Model allows questions to be posed and answered. As previously stressed, models are useful representations of reality. To what extent is the Event Model a true or realistic picture of collision risk? The modelling of waypoint errors – noted as very typical errors in today's system (NATSPG, 2002) – serves as an important illustration. One of the peculiarities of the present NAT track system is that the separation distance S is one degree fixed on integer latitude values. But this is exactly the same distance as the most common gross error produced by an incorrect waypoint.

Figure 4 illustrates a waypoint error with a simple Euclidean picture, looking from above (i.e. on the z-axis). The dashed horizontal lines are lines of latitude separated by one degree; the dashed horizontal lines are lines of longitude separated by 10°. The aircraft deviates at A and goes to C rather than B, and then returns to the correct flight path at E. What effect does this type of flight path have on the risk calculation?

The easy question concerns the path ACE, assuming that lateral distances are exact. The aircraft box time through the separation sheet, which would be through the horizontal line through C, is exactly the same as if the box had gone all the way through the sheet. This is because it goes through halfway and then returns on a reflected path for the other half of its passage through the sheet. Its speed is always the same, but its velocity changes direction at C. This is the calculation of risk weighting used the current NATSPG calculation. But this is actually an unrealistic calculation when a closer look is taken. An aircraft's flight management systems do not produce flight paths of straight-line segments (nor can normal flight!). The circular arc FGH shown in Figure 4 is more appropriate. Assume that it is a standard turn of 3 degrees per second, i.e. 0·05235 radians per second. The radius R of the turning circle, OF in the diagram, for an aircraft at 480 knots is $480/(60 \times 60 \times 0{\cdot}05235) = 2{\cdot}546$ nm. The angles CAE and FOG are the same, so CF/OF is the same ratio as $\text{CB}/\text{AB} = 1/10$. So $\text{CF} = 0{\cdot}1R = 0{\cdot}2546$ nm. Using Pythagoras, CG is 0·013 nm, i.e. about a third of the width of an aircraft box. Thus, there would be an impact with the separation sheet. But the aircraft would not have a lateral velocity of

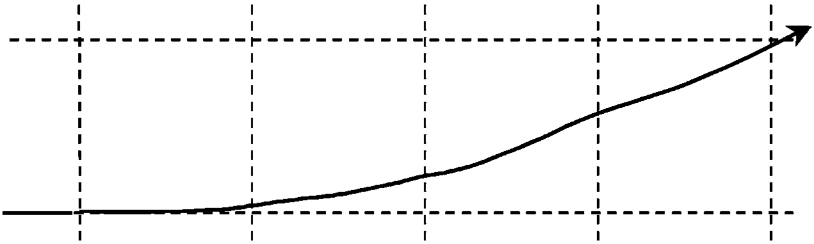

Figure 5. A 1° navigation drift error during an oceanic crossing in plan view (not to scale).

80 knots. It would be decelerating rapidly to a zero lateral velocity before reversing its velocity and retiring back to its correct track.

In practice, the aircraft would both be fitted with TCAS II, as they have been for many years. TCAS II has a specific modification for low closure rates, i.e. when its 'tau area' will never be entered, but with the physical separation being (e.g.) a fraction of a nautical mile (Eurocontrol, 2002). In such a scenario, a sudden increase in the closure rate would leave no room for an advance warning. This problem has been eliminated by adding Distance Modification (DMOD) to the logic algorithms. DMOD relates only to the physical separation between the TCAS-equipped aircraft and the target, not to closure rate. It would thus provide protection in these circumstances.

Another point of interest in this picture is the average relative velocity V when the collision box touches the separation sheet. This will be different according to the size of the waypoint error in degrees. If the speed of the aircraft is maintained when it makes a waypoint excursion, then the average relative velocity will be that speed multiplied by the sine of the angle of the deviation. Keeping to the simple Euclidean picture and assuming the track is at 53° North, the value of V would be about 80 knots for a 1° deviation, exactly as used in the present NATSPG parameters.

Gross navigational errors caused by equipment failure or inappropriate equipment carriage pose fewer problems for the Event Model. As already stressed, these are very unusual these days.

Figure 5 shows a generic navigation drift error, based on the kinds of flight path that once were not so rare (Brooker and White, 1979). The cross track velocity component V when the separation standard is breached would, with the geometry shown, be much less than for a 1° waypoint deviation. When the velocities for this configuration are substituted into equation (5) the risk level is higher, because V occurs only as the denominator in velocity ratios. Thus, the risk weighting is higher than for a waypoint error. This matches NATSPG standard weightings, where a 1° waypoint error is weighted at 0·33 and a typical equipment failure or non-MNPS approved error breaching one track has a weighting of 0·48.

5. CONCLUSIONS.

The Event Model developed here for lateral collision risk in air traffic track systems resolves the problems of the Reich Model. It is a direct and concrete approach focusing on events. This is in contrast to the synthetic methodology adopted by Reich, in which, for example, three types of collision have to be modelled and the focus is on flying hours spent away from the planned flight path. It is easy to see what is being assumed and to understand the roles of the main parameters. The model is a good starting point for the incorporation of collision detection and the use of hazard analysis.

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