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FLIGHT TRANSPORTATION LABORATORY REPORT R91-6

MODELLING RISK IN ATC OPERATIONS

WITH GROUND INTERVENTION

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Preface

This report describes work performed under Contract DTRS 57-88C-0078TD25 from the Volpe National Transportation Systems Center of the US Department of Transportation. It was part of a continuing series of research work aimed at creating models for estimating Collision Risk for ATC operations which can be used by the Federal Aviation Administration and ICAO to establish safe criteria for separations between aircraft. While these models have always presumed a form of ATC which uses Procedural Separation and a non-radar environment typical of Oceanic operations, this report focuses on developing models for more tactical operations where some form of surveillance allows ATC controllers to intervene when it is observed that two aircraft are actually going to pass too close to each other and are violating some form of Intervention Criterion. While this was not the original goal for the research, the work of the ICAO FANS Committee and the ICAO RGCSP (Review of the General Concept of Separation Panel) caused a need for timely work to define new models of risk with intervention present, and the definition of a framework for new research studies which could be undertaken by various ICAO states. As a result, this report was used as an Information Paper at the RGCSP Working Group A meeting in Canberra, Australia on September 16-27, 1991.

Modelling risk when intervention by ATC controllers is possible is a very difficult problem. There is a need to assess the error rate of the human in failing to intervene, or intervening too late, or in intervening incorrectly. The research effort proposed many different forms of models for this factor before it came to a very simple approach for characterizing the intervention error rate, and an approach for gaining operational data on it from the incremental introduction of newer forms of ATC operations which use surveillance and computer displays which provide automated decision support for the controller.

The RGCSP encouraged the US delegate to continue to develop this proposed framework for studying the risk of ATC operations with intervention. Future work will try to define a program of research tasks to refine the incremental approach, evaluate its effectiveness, and provide support for gaining international acceptance of it.

The work was performed at the Flight Transportation Laboratory by Robert W. Simpson and Raymond A. Ausrotas. The monitor from TSC was Mr. Gerald Chin. Valuable assistance and direction were given by Mr. Dale Livingston and Bennet Flax of the FAA Technical Center at Atlantic City, NJ, and by Mr. Jerry Bradley from FAA Research and Development Service, Washington, DC.

1. Introduction

1.1 The purpose of this information paper is;

a) to provide a document describing the problems of analyzing risk for ATC systems which have surveillance over air traffic and which allow ground controllers to intervene to avoid unsafe encounters;

b) to propose a framework for future studies which attempt to solve these problems.

The need for such methods of analyzing risk arises in justifying reduced ATC separation criteria which ensure safety for newer forms of ATC operations. The benefits of these new systems strongly depend on achieving a reduction in current ATC separations, and as a result, an increase in capacity and efficiency for aircraft operations. These benefits must be weighed against the costs of developing and operating the new ATC systems

1.2 There are existing techniques for estimating risk or encounter rates in ATC "Procedural" systems where there is no intervention. These encounter estimation techniques are used in a set of CRM (Collision Risk Models) which have been applied in ATC for setting lateral separation criteria between unmonitored parallel tracks in oceanic airspace, and for unmonitored vertical separations. These techniques use data gathered on existing capabilities of aircraft in the traffic mix to conform to assigned tracks or altitudes; i.e., the lateral deviation errors of current aircraft navigation and guidance systems, and the vertical deviation errors of aircraft altimetry and automatic or manual altitude-keeping systems.

1.3 The current methods of CRM depend only on the capabilities of traffic in terms of conformance to assigned altitudes and tracks. They assume that there is no intervention by either pilots and controllers during an encounter. Separation criteria between altitudes and tracks in such unmonitored, procedural ATC systems then depend only on the conformance capabilities of pilot/aircraft in the traffic mix.

2. Encounter Models for Collision Risk

2.1 To provide a basic understanding of current techniques of risk assessment in ATC before discussing the problems of introducing intervention, a simple example of the application of encounter models or CRM techniques for setting the safe lateral separation between parallel oceanic tracks at the same altitude will be discussed first.

2.2 Consider Figure 1. There are three parallel tracks in the x-direction separated by a lateral distance SEP_y in the y-direction. On the center track B, aircraft B is surrounded by a "protection volume" of dimensions $2L_x$ (= 300 feet) in the longitudinal x-dimension, $2L_y$ (=240 feet) in the lateral y-dimension, (and $2L_z = 50$ feet vertically, although this will be ignored here since it is assumed all aircraft are precisely at one altitude level). If aircraft on tracks A or C penetrate this volume an "encounter" event is said to occur. With these dimensions (which are roughly twice the size of aircraft in the current oceanic traffic flow), the encounter is called a "collision" and the protection volume is called a "collision volume".

2.3 Assume that aircraft on tracks A and B are proceeding at an average speed of 420 knots. The average relative speed, V_{AB} , between aircraft B and all the aircraft on track A (opposite direction) is 840 knots. Assume that aircraft on track C have an average speed of 470 knots and so that the average relative overtaking speed, V_{BC} is 50 knots. The traffic density for aircraft on all tracks has an average spacing, d , of 105 nm (or average time interval of 15 minutes for tracks A and B).

2.4 It is now possible to define a "longitudinal exposure rate" for aircraft B relative to traffic on tracks A and C.

2.4.1 For opposite direction traffic on track A:

Frequency of Overlaps

Aircraft on track A are passing aircraft B in the opposite direction at an average rate of 8 per hour. This is defined as "the frequency of longitudinal overlap events", FO_x . An "overlap event" in the x direction occurs when aircraft A or C enter the overlap area shown in Fig. 1.

$$FO_x^{AB} = \frac{V_{AB}}{d_A} = \frac{840}{105} = 8 \text{ overlap events per hour}$$

If the average spacing were halved, the traffic density would double, and so would the frequency of overlaps.

The Duration of Overlaps

The average duration of a longitudinal overlap is denoted Δt_x^{AB}

$$\Delta t_x^{AB} = \frac{2L_x}{V_{AB}} = 0.214 \text{ seconds}$$

Longitudinal Exposure Rate

Therefore, aircraft B has an average "longitudinal exposure rate", E_x^{AB} , to traffic on A

$$E_x^{AB} = FO_x^{AB} \cdot \Delta t_x^{AB} = 8 (0.214) = 1.71 \text{ seconds per hour of flight}$$

2.4.2 For same direction traffic on track C

Frequency of Overlaps

Aircraft on track C are overtaking aircraft B at a rate of FO_x^{BC}

$$FO_x^{BC} = \frac{V_{BC}}{d_B} = \frac{50}{105} = 0.476 \text{ overlap events per hour}$$

The Duration of Overlaps

The average overlap duration, $\Delta t_x^{BC} = \frac{L_x}{V_{BC}} = 3.6 \text{ seconds}$

Longitudinal Exposure Rate

Therefore, aircraft B has an average longitudinal exposure rate to traffic on track C

$$E_x^{BC} = FO_x^{BC} \cdot \Delta t_x^{BC} = 1.71 \text{ seconds/hour}$$

Note that the longitudinal exposure of aircraft B to traffic on tracks A and C is identical if the linear traffic density on those tracks is identical. The shorter duration of passage for opposite direction traffic is exactly offset by its higher frequency of passage.

2.5 A "collision" will occur if the lateral deviation of aircraft on Tracks A or C is such that they enter the collision volume during the period of longitudinal overlap. The collision volume itself would be deviating from track B also. Thus, it is also necessary to estimate the probability of lateral overlap, i.e., the probability that two aircraft might be within $2L_y$ of each other in the lateral direction.

2.5.1. The **probability of lateral deviation, P_y** , describes the percentage of flight time spent at a lateral deviation, y , from the assigned track, and is shown schematically in Figure 1 as an error distribution known as the probability density function (pdf) at the bottom of each track. The pdf is statistical evidence which must be determined by gathering extensive field evidence of lateral conformance for all traffic. It is a function of the quality of the performance of both the onboard navigation system (position determination) and the onboard guidance system (track-keeping).

2.5.2 For lateral track keeping, the pdf has been found to have two components: a "core" component for the normal operation of navigation and guidance equipment; and an "abnormal" component where there is a failure of equipment or a human blunder. In oceanic airspace both components are described by a double-sided exponential curve for the lateral deviations. As the navigation and performance capabilities of aircraft in the traffic mix are improved, the lateral error probability can be expected to have a smaller dispersion around the assigned track in the core component. To improve the abnormal component, the probability of human or equipment failure must be reduced. Both components must improve to allow a reduction of separation criteria.

2.5.3 Given P_y for average traffic capabilities in any time frame, it is then mathematically necessary to make the assumption that the lateral deviations of aircraft are independent of each other in order to estimate the **probability of lateral separation between aircraft, $P_{\Delta y}$** , using a mathematical process called convolution. This assumption is appropriate for the errors of independent systems onboard each aircraft.

2.5.4 A typical distribution for the estimated probability $P_{\Delta y}$ as derived from P_y is shown Figure 2. If the two aircraft are on tracks separated laterally by a distance SEP_y , the average value of the $P_{\Delta y}$ distribution is SEP_y , and the **probability of lateral overlap, PO_y** , is the area under the curve within $\pm L_y$ of the origin. This area can be approximated by $2L_y \cdot P_{\Delta y}(0)$ where $P_{\Delta y}(0)$ is the value of $P_{\Delta y}$ at the origin. The value of PO_y is a function of three parameters; P_y , SEP_y , and L_y . Its variation with SEP_y is shown in Figure 3. It decreases exponentially as SEP_y is increased. This curve is important later, and it should be noted that it is already known for oceanic traffic.

2.5.5 The **probability of collision**, or the **lateral collision risk**, CR_y , for aircraft B can now be estimated as the product of the longitudinal exposure rate and the lateral probability of overlap:

$$CR_y = E_x \cdot PO_y \quad \text{average collisions per hour of flight}$$

It is expressed as the number of collisions per hour of flight by aircraft B, and has equal contributions from tracks A and C in the example of Figure 1 since the traffic densities along those tracks are identical. The collision risk for single aircraft is linearly proportional to traffic density. However, the collision risk for the complete track system is proportional to the square of traffic densities when expressed in terms of collisions per hours of operation of the track system. This simply accounts for the traffic density of all the aircraft in the track system at any time. It has been assumed here that the track system is in a steady state, or non-time varying operation. Any time variation in traffic density causes a non-linear variation in the collision risk.

2.6 Now, if agreement can be found on an acceptable level of risk (which is usually called the **Target Level of Safety, TLS**), then there is some value of track separation SEP_y which will meet this desired level for any given E_x (exposure, or traffic density), and PO_y (lateral conformance of traffic).

2.6.1 For the oceanic track system, a value for $TLS = 0.2 \times 10^{-7}$ aircraft flying hours has been established. It is sensible to work to the nearest order of magnitude in estimating these very small values of risk. This TLS is roughly 2 accidents in 100 million hours of oceanic flying by aircraft, or 1 mid-air collision in every 100 million flight hours operated within the N. Atlantic Track System.

2.6.3 For a given level of traffic in any year on the N. Atlantic, there is some representative value for the longitudinal exposure, E_x , which should account for the hourly variations in traffic density on typical days. There is a corresponding level of safety expressed in terms of risk per passage. This risk will be called the **TLSP, Target Level for Safe Passage** during an encounter. This quantity will be used later in estimating risk with intervention.

Note again that the acceptable value of SEP_y depends only on exposure (i.e., spacing or traffic density) and lateral conformance. The assumption is made that there is no last minute intervention by either pilots or controllers to avoid a collision during the encounter.

2.7 It is now possible to turn to the problem of introducing processes of intervention by ground controllers to the analysis of collision risk. This is done by the simple idea of introducing new probabilistic quantities which describe the intervention performance of these processes. There will be a higher rate of encounters in such systems since the intervention processes will prevent them from becoming collisions, i.e., there can be higher overlap probabilities. As indicated in Figure 3, a higher level of PO_y will translate to a lower value of required separation.

3. The Processes of Ground Intervention in ATC

3.1 There are two distinctly different forms of ground intervention processes which can be defined: (These processes exist whether or not they are carried out automatically or manually)

- 1) Conformance Management
- 2) Hazard Management

3.1.1 **Conformance Management (CM)** is an intervention process which attempts to ensure that each aircraft conforms to its assigned path. It assumes that a conflict-free path has been assigned to each aircraft, and it acts as a backup process to the performance of the aircraft's navigation and guidance systems.

3.1.2 **Hazard Management (HM)** is an intervention process which attempts to ensure that there is safe separation between all pairs of aircraft. It makes a recurrent projection of the actual paths of aircraft. If this projection indicates that a hazardous encounter is likely, it is concerned with finding a safe resolution of the encounter. It acts as a backup process to the ATC process which assigns conflict-free paths

3.2 Conformance Management (CM)

3.2.1 In simple versions of CM, the goal of is to keep each aircraft within a "containment channel" surrounding its path. Figure 4 shows a channel of width $\pm C$ each side of path. The Conformance Management process itself consists of two distinct sub-processes:

- 1) Conformance Monitoring
- 2) Conformance Resolution

3.2.2 Conformance Monitoring is a continuous sub-process for each individual aircraft which uses surveillance to detect deviations (and rate of deviation) and declares a **Conformance Alert (CA)** whenever a loss of conformance occurs (or is projected to occur).

3.2.3 Conformance Resolution is an sub-process triggered by the CA, which itself has two main options;

a) The "**Regain**" option which issues corrections to the aircraft to put it back on its assigned path. This usually applies to vertical and lateral deviations.

b) The "**Revise**" option which modifies the assigned flight plan (usually in the longitudinal direction since unexpected winds can change the expected longitudinal progress of an aircraft which prefers to operate at a fixed airspeed).

3.2.4 The Regain option uses ground-air communication to transmit the correction to aircraft. The Revise option does not need to communicate with aircraft since the ground is revising its understanding of the flight plan to conform with actual progress.

3.3 Hazard Management (HM)

3.3.1 The goal of HM is to ensure that the separation at passage exceeds specified hazard criteria. There need not be an assigned flight plan path or altitude. This intervention process also has two sub-processes;

- 1) Hazard Monitoring
- 2) Hazard Resolution

3.3.2 Hazard Monitoring monitors the separations between all pairs of aircraft continuously at a rate which increases as the aircraft approach each other and ceases after they have passed. It does not use flight plan information. Instead it projects the current speed and altitude rate to predict the position of aircraft some short period into the future, while assuming that speed, direction, and altitude rate will remain constant. If the projected separation \hat{S} is estimated to violate a **Hazard Intervention Criterion, HI**, then a **Hazard Alert, HA**, is declared.

3.3.3 Hazard Resolution is triggered by HA and uses existing flight plan information. It has two options:

a) If the flight plan indicates the hazard is already planned to resolve itself, the "Close Conformance" option sends a message to the CM process asking for a higher update rate and/or smaller conformance criteria C.

b) If there is no planned resolution, the "**Resolution**" option finds Hazard Resolution clearances for one (or both) aircraft which, if transmitted and acted upon in a timely manner, should allow the aircraft to pass each other with a separation which exceeds a specified **Hazard Resolution Criteria, HR**.

3.3.4 Controllers, expecting a period of high workload, may wish to avoid the workload of Close Conformance by electing to issue early a simple resolution which modifies the flight plan such as to eliminate the Hazard Alert, even though it might have been unnecessary.

3.4 In summary, there are two distinct intervention processes in ATC. With high quality, reliable surveillance and communication, it is likely that both CM and HM processes will co-exist in any ATC system, since reductions in ATC separations will be achieved. These intervention processes generally occur in an ATC radar controller's head today, but will involve various forms of decision support automation in future systems. The levels of safety achieved in future ATC systems depend on the quality of performance of both the HM and CM processes, as performed by human operators called controllers and pilots using whatever automation aids they are given. Any model for estimating the risk of ATC operations with intervention will necessarily include some measure of human performance.

4. Reducing Risk by Introducing Conformance Management

4.1 Consider the case of introducing CM to monitor lateral deviations from parallel tracks. Whereas in Figure 1, the pdf for lateral deviation of aircraft from their assigned paths is a function only of the average traffic conformance capabilities of the aircraft navigation and guidance systems, the CM process now requires new inputs describing the performance of ATC surveillance and communications systems. These inputs are:

- 1) position and position rate measurement errors (σ_p, σ_r)
- 2) surveillance update rates, Δt_s
- 3) prediction interval (or probe time) T_p
- 4) resolution interval, T_r to resolve an alert

4.1.1 Position measurement is done directly by current radar surveillance systems. The accuracy of estimating position rate depends on surveillance update rates, Δt_s , position measurement accuracies (σ_p, σ_r), and the quality of an estimation process for position rate information called "tracking". New form of surveillance may obtain position rate information directly from aircraft using digital data link.

4.1.2 The uncertainty of predicted positions increases with probe time T_p . The value of T_p must exceed the minimum resolution interval T_r which is required to transmit and execute the resolution. The conformance alert must be declared between the probe time and the resolution time.

4.2 As well as these technical inputs, there are variables in the human performance of the controller and pilot which will affect the quality of CM. This performance will be affected by the existence of any form of automation in decision support, including the type of information display provided to the ATC controller. The resolution of a deviation requires a number of actions by the controller and pilots; first, the conformance alert must be identified with some confidence; second, the appropriate resolution must be generated; third, the resolution(s) must be transmitted to the correct aircraft; fourth, the pilots must receive, understand, accept, and acknowledge the transmission; the resolution must then be executed; and finally, the controller must observe that the resolution is being achieved. Errors in human performance will occur at different rates in all of these actions.

4.3 For the lateral deviation from parallel tracks, it is unlikely that CM will affect the normal performance of the aircraft's guidance system in conforming to the assigned track since the accuracy and timeliness of surveillance systems is usually inferior to the onboard equipment. This normal performance is described by the "core" component of the distribution of lateral deviations in the statistics which have been gathered for oceanic flying. Instead, it is the abnormal or blunder distribution with its wider tails of larger deviations which can be improved by CM.

4.3.1 Note that if dependent surveillance is used, the lateral deviations reported will be those indicated onboard the aircraft by its guidance system, These will normally be zero, and are not the true deviations which would be measured by an independent surveillance system. However, if the dependent surveillance system reports next waypoint and altitude, this data can be used to correct one source of human blunder (i.e. selecting the assigned path or altitude incorrectly, but unfortunately there are other sources of abnormal errors). There is a need to examine carefully the impact of dependent surveillance and CM in reducing the lateral separation between oceanic tracks. There may be very little impact.

4.4 There will be an increase in controller intervention workload due to CM. Encounter methods can be used to predict the **Conformance Intervention Rate, CIR** for any given CM process and traffic environment by substituting a given value of conformance criterion, C , for the collision size criteria, $2L$. As C is reduced, the intervention workload will increase.

4.5 If CM were perfect, there would be no deviation by aircraft outside the containment channel. The parallel tracks of the example track system described here could then be safely spaced at a separation $SEP_{yCM} = 2C$ with no risk of collision. But CM will not be perfect. There will be some probability of lateral deviations beyond $\pm C$ caused by deficiencies in the actual performance of the CM process, i.e. errors caused by both humans and technical elements. There is a "leakage" of deviations beyond the containment channel due to these errors as shown by the tails of the modified pdf in Figure 5. Thus, the actual safe lateral separations SEP_{yCM} for our parallel track example will depend on the rate of occurrence of errors in CM which allow deviations outside the containment channel. If analytic risk assessment methods are to be used to establish safe separations, it will be necessary to have actual field evidence about the CM errors for any particular implementation of CM.

4.6 One simple characterization of the errors in the CM process which can be proposed is P_{NSC} , the "Probability of Non-Successful Conformance". It is defined by the ratio of the areas of the probability densities of lateral deviation outside the containment channel with and without CM. These areas are indicated in Figure 5. If this value could be safely estimated (say, for example $P_{NSC} = .01$ with an assumption that the shapes of the tails outside the containment channel remain similar), then the collision risk with CM is reduced, and the value of SEP_{yCM} reduced appropriately (See Figure 3 which shows the typical effect of reducing PO_y by two orders of magnitude on the acceptable lateral separation, SEP_{yCM} under conformance management.)

4.7 To determine P_{NSC} , the CM process must be well defined, and there should be operational experience from which error data can be gathered. This is not the case when introducing newer forms of CM with improved surveillance and communications, new automated decision processes to support the controller, new forms of display of ATC data, etc. But it is desirable in designing these new systems which use CM processes to be able to predict what reductions in safe separation, or increased capacity and controller productivity might be as a function of system design parameters. The design questions which might be asked are:

What is the required value of :

- different surveillance update rates?
- priority messaging for resolution messages?
- improved tracking processes?
- better surveillance accuracies?
- different forms of automated monitoring?
- collecting next waypoint data from FMS onboard aircraft?

4.8 To answer such questions, a specific definition of the proposed CM process must exist. To illustrate this need for a specific definition, a simple implementation will be created here for exposition purposes. This is illustrated in Figure 6. The surveillance system provides information on the lateral deviation, y , at an update rate Δt_s . The associated tracking system uses this data to estimate the lateral velocity, \hat{y} . Then at any time t , there is an estimated time, $T_b(t)$ to reach either channel boundary, where $T_r \leq T_b(t) \leq T_p$. This simply estimated by;

$$T_b(t) = \frac{C - y(t)}{\hat{y}(t)}$$

There is then some form of conformance logic for declaring alerts such as one which calls a Conformance Alert if the estimate for T_b is within 15 seconds of T_r , and has been consistent for the last n surveillance reports (or scans). Then there must be another logic for determining a resolution path such as

an appropriate change in aircraft heading to return the aircraft to the track centerline and then to keep it there. This may consist of two vectors issued at different times to the aircraft.

4.9 There are only two surveillance variables in the above process;- $y(t)$, the lateral deviation; and $\hat{y}(t)$, the estimate of cross-track velocity. The critical variable is the estimate for $\hat{y}(t)$ since it is usually estimated by a "straight line" tracking process which assumes that the actual $\dot{y}(t)$ is a constant. This is not likely to be true since the aircraft's guidance system should be continuously controlling y to return it to track. Better CM processes will use information on cross-track velocity, or heading, or bank angle which can be down-linked from the aircraft using digital datalink.

4.10 To evaluate the human performance of ATC controllers using any CM process, it would appear that extensive simulation in a realistic environment would be needed over a large traffic sample. Since human errors in CM should be rare, it is not clear that this simulation approach is feasible. The rate of intervention during simulation could be increased by increasing lateral deviations and traffic density, but then the operational environment for controllers is not realistic. For guiding the design of various new ATC systems by providing some estimate of their benefits, there appears to be no other approach but extensive simulation of the various alternative intervention processes.

4.11 A new "progressive implementation" approach for introducing novel processes for CM intervention into the field can be proposed. One possible approach is to use simulation to get an early estimate of the P_{NSC} for a given implementation of CM, and then to adopt a conservative "bounding" approach to establish the initial value to be used in the field. A conservative "bound" would be one which made a statement like "it is 95% certain that the actual value of P_{NSC} will be less than x ". This would allow a safe introduction of CM into the field with a small initial reduction in ATC separations. Then, it would be necessary to monitor the field operations, gathering actual performance information to support the progressive introduction of further reductions in separations based on newer bounds which hopefully are based on the actual field results. The phased, progressive introduction should be planned from the beginning with definite milestones set for evaluating field results and estimating new bounds. This would allow users to understand that benefits will be achieved as quickly as required safety levels can be demonstrated. It will require a significant effort to perform the field monitoring.

5. Reducing Risk by Introducing Hazard Management

5.1 The discussion of the previous section concerning the introduction of the intervention process CM has introduced most of the problems to be faced when introducing HM. However, a simple HM process will be described to illustrate the differences. Consider the case of introducing HM to monitor deviations from parallel tracks as shown in Figure 7. As aircraft pairs approach an encounter, the HM process estimates their separation at passage $\hat{S}(t)$, and estimates the time to encounter $\hat{T}_e(t)$. Since there are two aircraft involved, two sets of position and position rate data must now be used to estimate the separation quantity needed for HM.

5.2 There will be an increase in controller intervention workload due to introducing HM. As with CM, Encounter methods can be used to estimate the **Hazard Intervention Rate, HIR**, for any given HM process and traffic environment given HI criteria. As HI is increased, the intervention rate will increase proportionately. HI will greatly exceed the collision protection size so HIR is much greater than the collision rate CR; but, due to successful Hazard Intervention, the separation between tracks when using HM can be much less than the SEP_y for procedural ATC.

5.3 Similar to the approach followed for CM, the errors for the HM process can be characterized by one simple quantity called the "Probability of Non-Successful Hazard" intervention, P_{NSH} . It is defined as the percentage of times that the HM process fails to provide a separation at passage which does not meet the **Hazard Resolution Criteria, HR**.

5.4 For the example HM process, HI is chosen such that, if the estimated separation at passage $\hat{S}(t) = HI$, then the risk of collision without intervention equals the value of TLSP, the target level of safety for the probability of collision on a single passage mentioned in section 2.6.3 as corresponding to the TLS. Thus, if $\hat{S}(t) \geq HI$, there will be no intervention, but there is still an acceptable level of risk for this encounter; and if $\hat{S}(t) < HI$, there will be intervention but with satisfactory levels of false alarms, i.e., unnecessary interventions.

5.5 The situation described above allows the HIR to be estimated directly from the desired TLS. Since P_{NSH} describes the number of encounters which will not be successfully resolved, the allowable HIR can be much higher than the allowable collision rate, CR, which is TLS; therefore,

$$HIR = \frac{TLS}{P_{NSH}}$$

e.g., if P_{NSH} is .001, (only one in a thousand encounters will violate the HR criteria), then the HIR can be allowed to be 1000 times the Collision Rate

5.6 But there is a further increase in HIR due to the fact that the values of the Hazard Intervention Criteria, HI must exceed the Hazard Resolution Criteria, HR, which itself must exceed the collision sizes, $2L$, used in the CRM to calculate TLS. From encounter methodology, the encounter rate is linearly proportional to these sizes, so that the HIR to achieve TLS becomes;

$$HIR = \frac{TLS}{P_{NSH}} \cdot \left(\frac{HI}{2L} \right)$$

-- for example, if $TLS = 1$ collision in 10^7 flying hours within the track system, and $P_{NSH} = .001$, $HI = 30,000$ ft., $L = 300$ feet

$$\text{then } HIR = \frac{10^{-7}}{.001} \cdot \frac{30,000}{300} = 10^{-2} \text{ interventions per operating hour}$$

i.e. there would be an intervention for every 100 hours flown within the track system. If the track system had 1000 hours of operations per day, then there would be an average of ten interventions every day.

5.7 Given the allowable intervention rate, the existing information on lateral deviations for an oceanic track system would allow the corresponding reduced separation SEP_{yHM} to be determined as sketched in Figure 3. In this hypothetical example we can increase the lateral overlap probability by five orders of magnitude.

5.8 As with CM, HM will not be perfect. Its errors are described here by P_{NSH} and are caused by deficiencies in surveillance, communications, information display, and human performance of controllers and pilots. The set of issues which arise in designing and implementing ATC systems which use specific new forms of HM are similar to those mentioned previously for introducing CM.

6.0 Summary

6.1 The purpose of this information paper is to describe the problems of analyzing risk in ATC operations which have ground intervention; and to propose a framework for solving these problems. The risk analysis is needed to provide an indication of the benefits of introducing intervention processes which use improved surveillance and communications, and improved decision support for controller intervention.

6.2 Existing mathematical techniques which estimate encounter rates for pairs of aircraft have been used to estimate collision risk for aircraft on parallel tracks or adjacent altitudes. There is an extensive database for aircraft deviations from oceanic tracks and altitudes. These have been used to establish safe separations for ATC systems with no intervention after a desired level of safety has been established called the Target Level of Safety. This describes the allowable rate of collisions in a given segment of airspace, and there is a corresponding collision risk given any encounter which can be called the Target Level of Safety for a single Passage, TLSP. The database also provides evidence to support the tradeoff of lateral separations with lateral overlap probability.

6.3 There are two distinct intervention processes in ATC; Conformance Management (CM), and Hazard Management (HM). These each have two sub-processes of Monitoring and Resolution. For CM there is a Conformance Criteria, C , which describes how close aircraft should be held to their assigned tracks. For HM, there are Hazard Intervention Criteria, HI ; and Hazard Resolution Criteria, HR . Both processes operate in real time, and there is a maximum probe time, T_p , and a minimum resolution time T_r ahead of each aircraft for each process. The resolution time allows a controller to identify and find a resolution and transmit it to the aircraft; and for the pilot to receive the resolution and execute it.

6.4 Conformance Management can decrease the lateral deviations of aircraft from assigned tracks, particularly if information on next waypoint and altitude is datalinked to the ground. The rate of intervention, CIR, can be estimated using encounter methods if there is a database on lateral deviations, and knowledge of traffic densities. The errors in any CM process are due to surveillance, communication, and human performance. It is proposed that they can be characterized by a single measure called the Probability of Non-Successful Conformance, P_{NSC} . If it can be evaluated, it is possible to establish safe separations for ATC systems which use CM. It seems necessary to perform extensive simulation of CM to obtain some indication of P_{NSC} for different implementations of CM.

6.5 Hazard Management is concerned with providing separation assurance between all pairs of aircraft. The HI criteria provide sufficient response time for HM to provide a desired minimum separation at passage, HR, during the resolution of a hazardous encounter. It is proposed that an overall measure of performance for HM can be characterized by the "Probability of Non-Successful Hazard intervention, P_{NSH} . Separation criteria can be established using this quantity, and the rate of intervention, HIR, can be estimated so that a level of safety is achieved equivalent to any TLS.

6.6 While extensive simulation of any intervention process may be needed to evaluate different forms of CM and HM, it is possible to perform a limited simulation of a particular intervention process to produce an "upper bound" on the values of P_{NSH} and P_{NSC} . This would allow a "Progressive Implementation" approach where monitoring of actual field performance is used to justify a phased program of separation reduction over the first years of introduction of a new form of CM or HM.

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Figure 1 - Collision Risk Model for Parallel Tracks (Same Altitude)

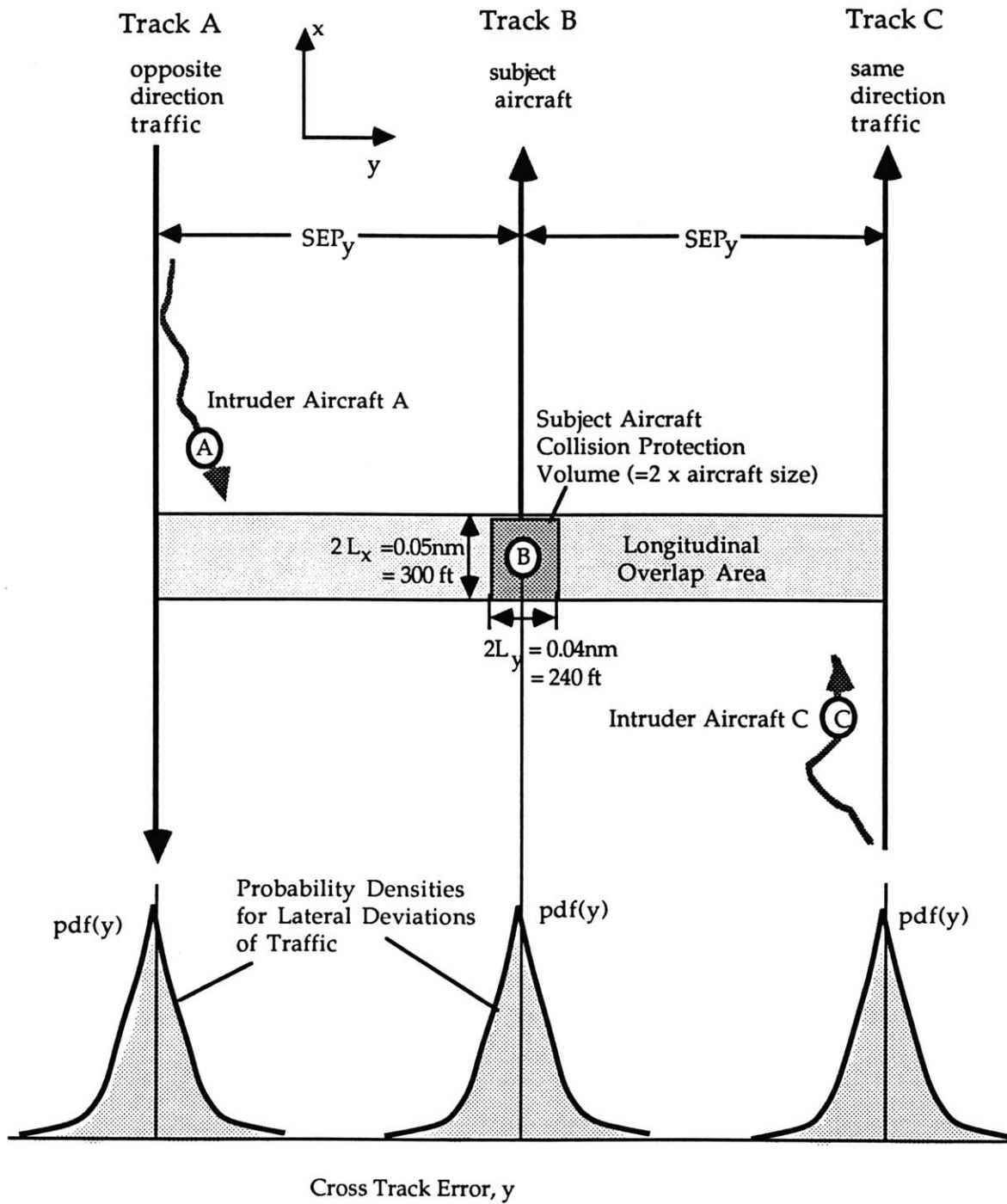


Figure 2 - Finding the Probability of Lateral Overlap, PO_y

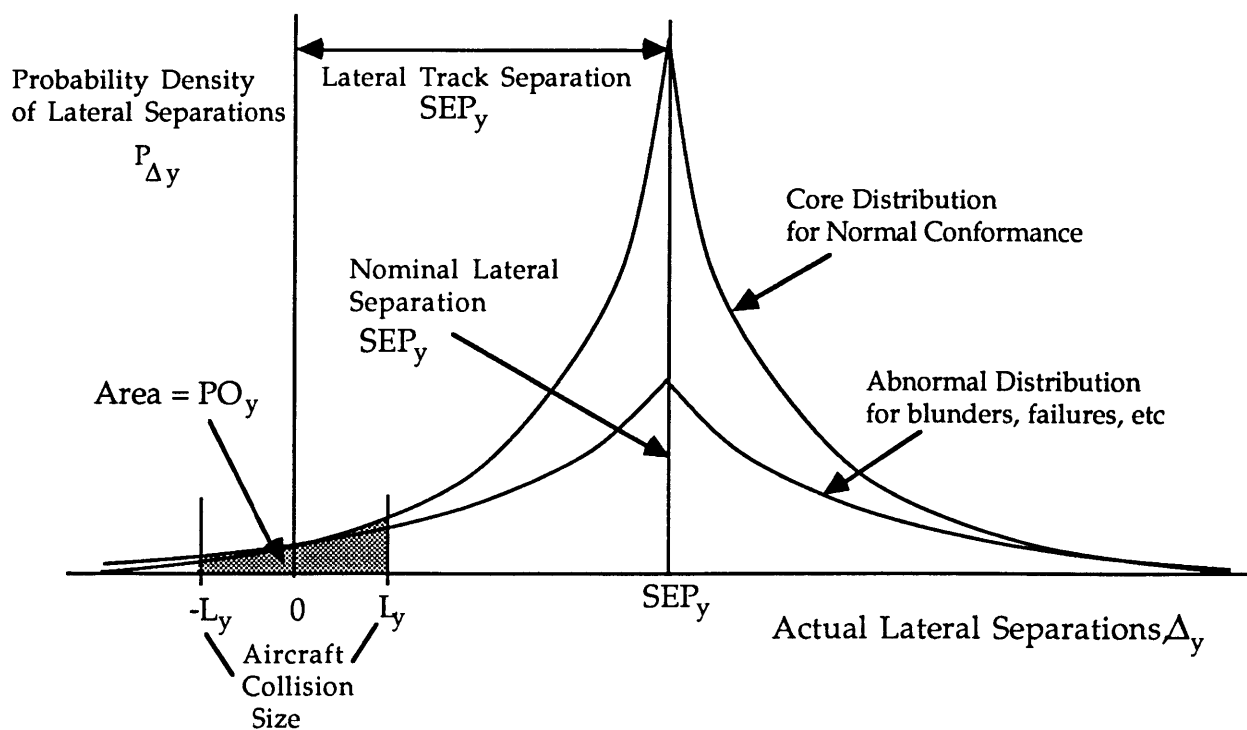


Figure 3 - Lateral Overlap Probability versus Lateral Separation

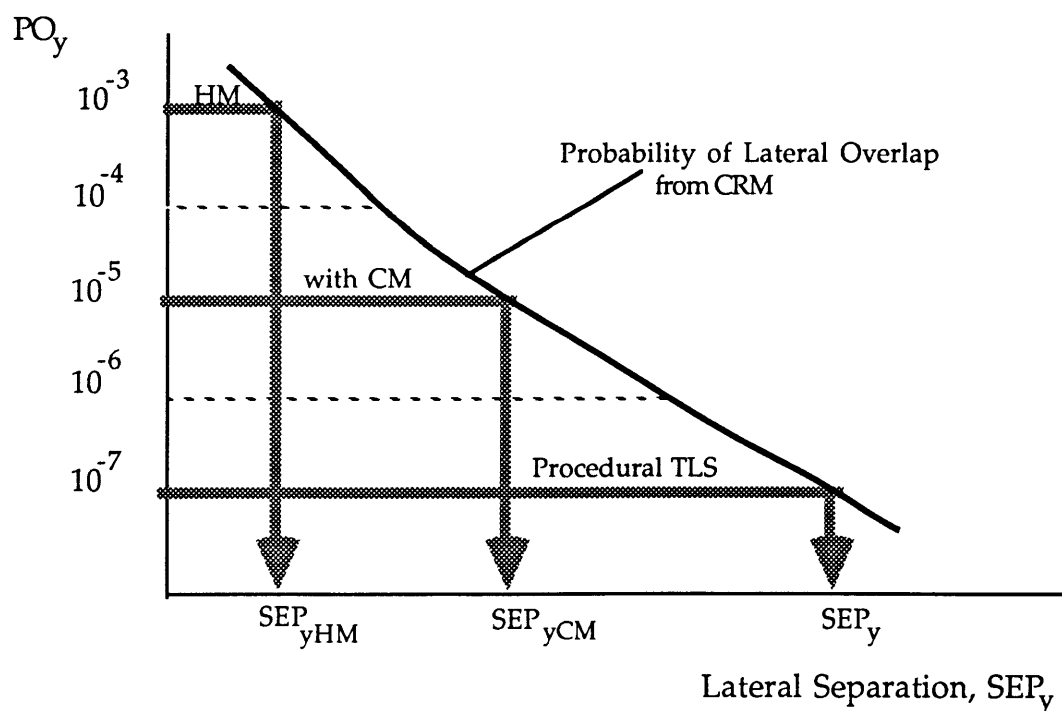


Figure 4 - Conformance Management Model for Parallel Tracks

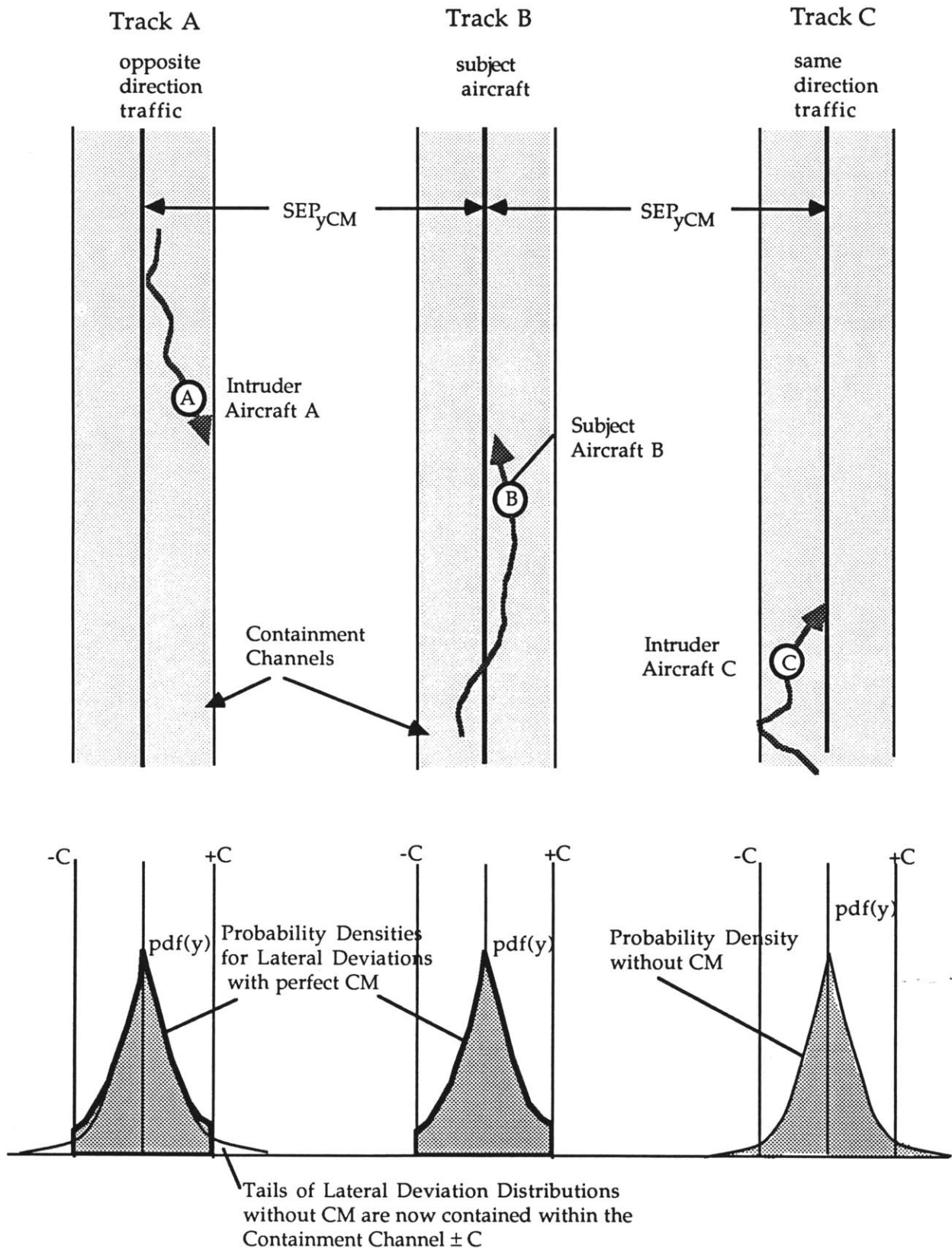
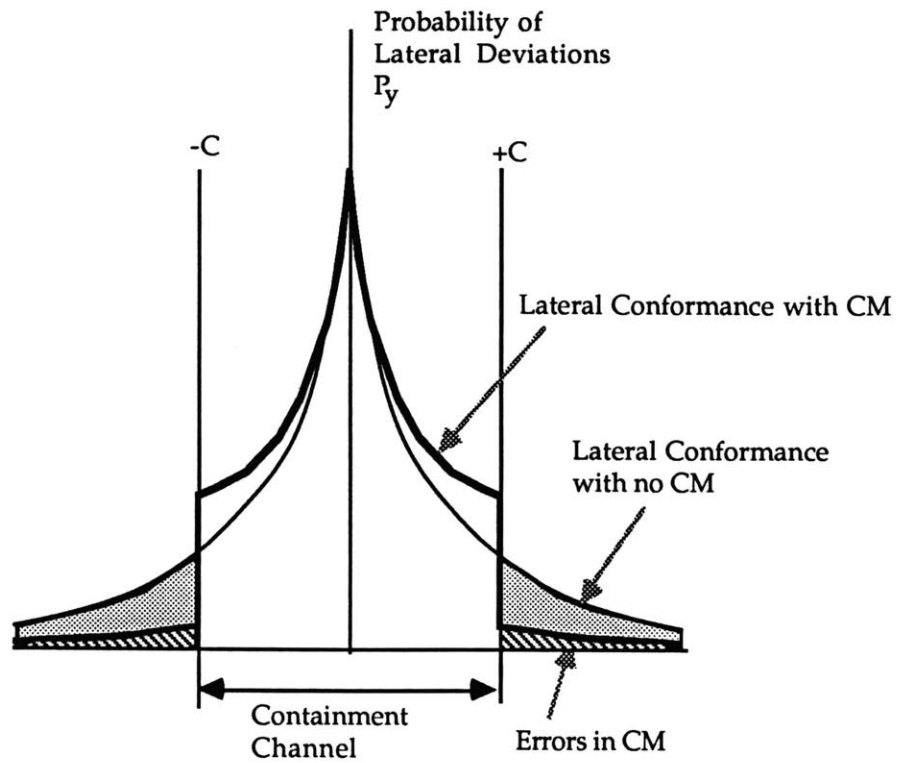
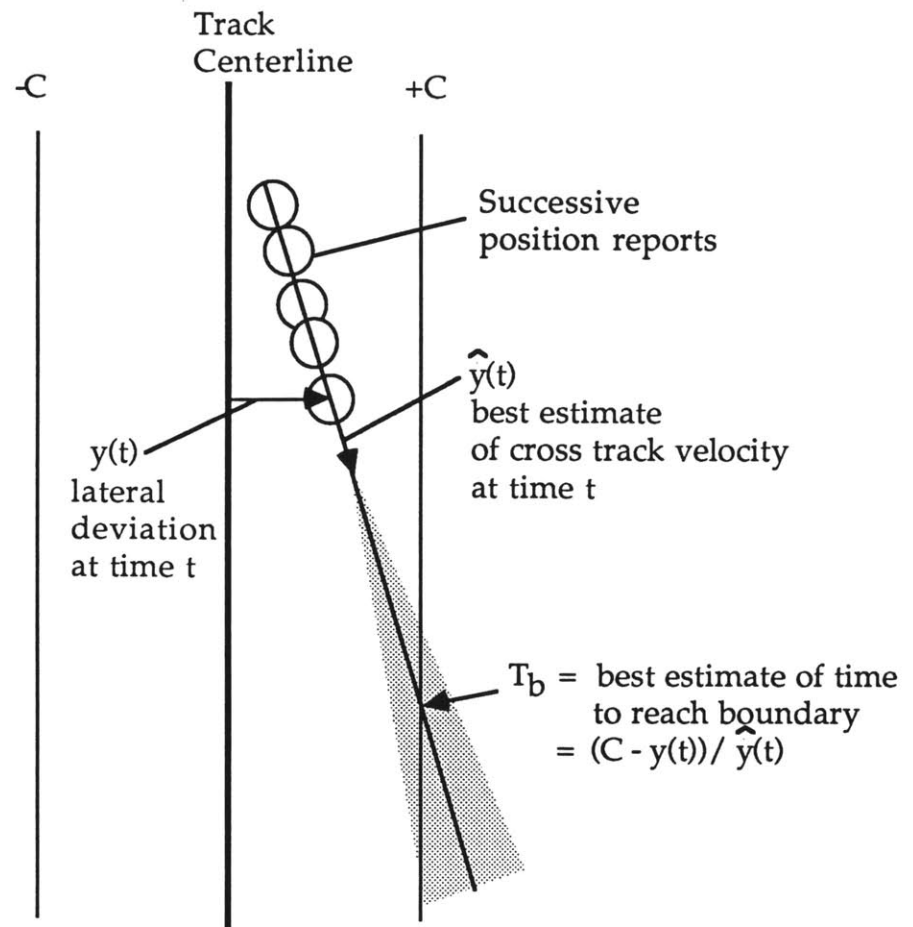


Figure 5 - Errors in Conformance Management Process



Define P_{NSC} (the probability of non-successful conformance intervention) as the ratio of the area under the CM curve outside the containment channel to the area under the no-CM curve outside the channel.

Figure 6 - A Simple Process for Conformance Management



Conformance Alert - if T_b remains consistent over 3 updates
 and is within 15 seconds of minimum resolution time, T_r

Conformance Resolution - issue a change of heading to reverse $\hat{y}(t)$
 and cause a return to centerline in 120 seconds

Figure 7 - Hazard Management Model for Parallel Tracks

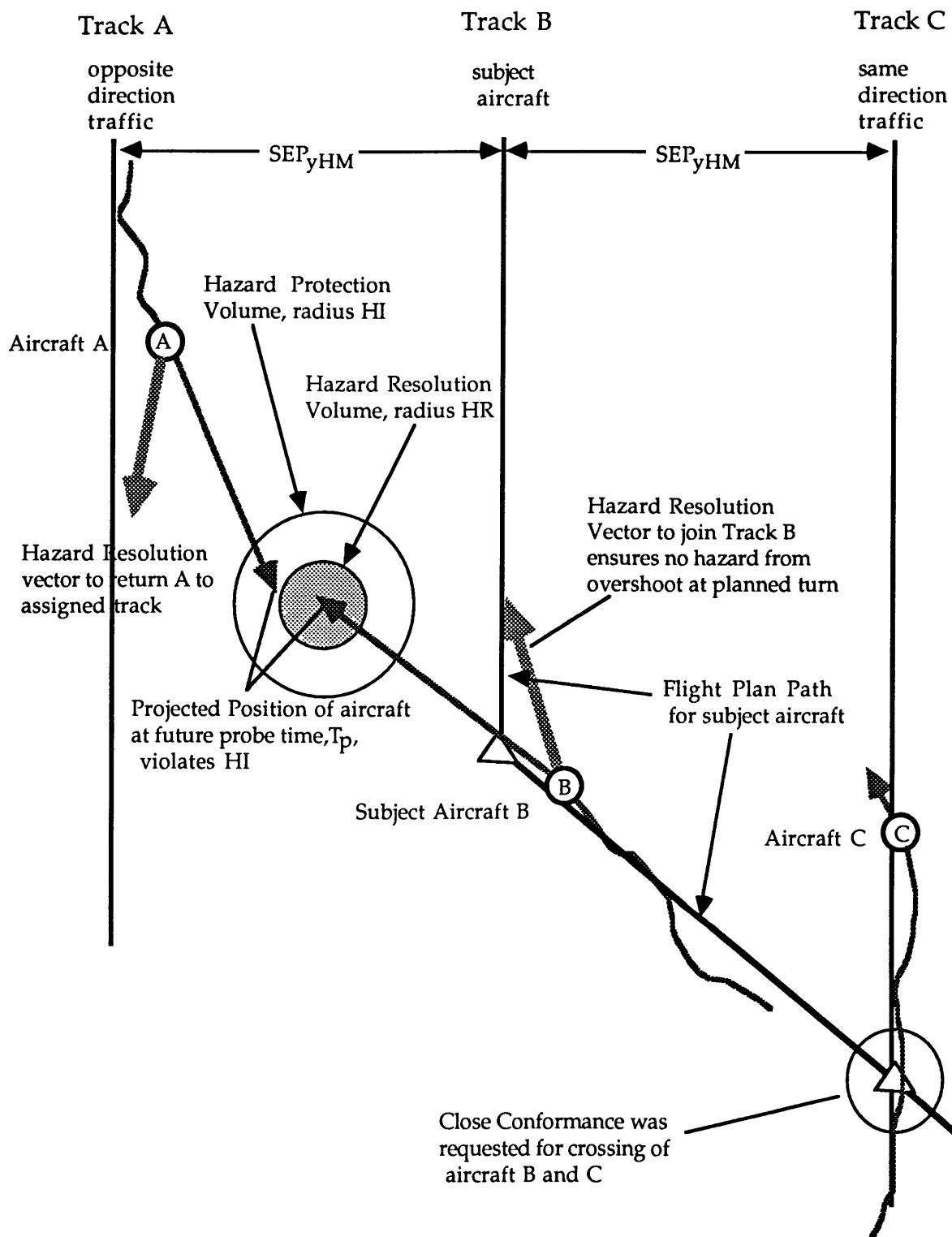
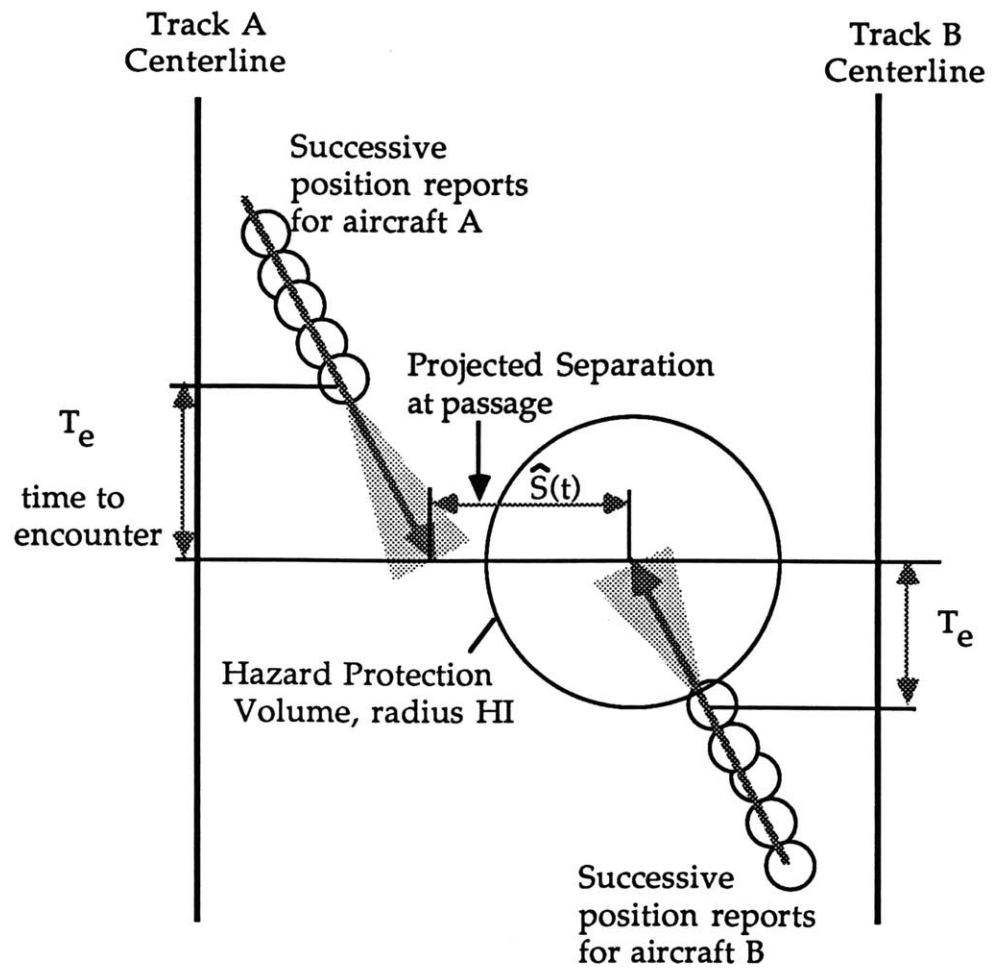


Figure 8 - A Simple Logic for Hazard Management



As shown, there is no Hazard Alert since the estimated separation at passage will exceed the Hazard Intervention criteria, HI . Both aircraft are off their centerlines, but no conformance resolution is planned either. The separation at passage will be monitored until $T_e = T_r$ when it is too late to resolve any Hazard.