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Probabilistic Aircraft Conflict Analysis for a Future Air Traffic Management System

Leonard A. Wojcik*
The MITRE Corporation, McLean, VA 22102

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This paper presents a simplified analysis of probabilistic aircraft conflict management in the context of a future vision for the air traffic management system. In such a future vision, the air traffic management system may include four-dimensional flight contracts that define conformance limits for aircraft position as a function of time, routine use of probabilistic approaches to pro-actively manage air traffic, and reduced aircraft separation standards. In the future air traffic management system, probabilities of conflict across multiple potential conflicting aircraft might be used as a means to assess and manage traffic situations with a longer look-ahead than is used in the current air traffic management system. We begin the analysis of such a future system by analyzing two-aircraft potential-conflict scenarios in the horizontal plane. We show how Monte Carlo simulation techniques can be applied to estimate probabilities of conflict (before deliberate actions are taken to resolve the conflicts) and how these probabilities depend on aircraft separation standards. Results are generated for multiple identical potential conflict pairs, with probabilities estimated as functions of angle of incidence. In order to better understand the implications of the results for future air traffic management operations, the modeling methodology is applied to find minimum speed changes and lateral deviations needed to achieve specified target probabilities of conflict across multiple independent potential conflict pairs. The analysis shows, in simplified scenarios, how application of appropriate speed changes and position deviations could be used to pro-actively manage air traffic, with probability of conflict serving as a metric. We draw preliminary implications for future air traffic management operations based on this simplified analysis. We also discuss how this analysis illustrates the role of relatively simple modeling approaches to systems engineering involving complex systems like the future air traffic management system.

Nomenclature

$a_{\min}$	minimum approach distance between flights 1 and 2
dmin	minimum approach distance between gumstick center points
F1	flight 1
F2	flight 2
$L1$	initial distance of gumstick center point from point of intersection, for F1
$L2$	initial distance of gumstick center point from point of intersection, for F2
$q1$	distance past the origin, for F1, where minimum gumstick center point approach distance is achieved
$q2$	distance past the origin, for F2, where minimum gumstick center point approach distance is achieved
phi	angle of incidence between paths of F1 and F2
s	$L2 - L1$

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* Project Team Manager, Modeling, Simulation, and Performance Analysis, Center for Advanced Aviation System Development (CAASD), 7515 Colshire Drive, Mail Stop N590, McLean, VA 22102-7508, USA, lwojcik@mitre.org.

$t_{\min}$	time of minimum approach between F1 and F2
u	lateral deviation to the left of F2's gumstick, relative to a scenario with intersection at the origin
$\underline{v}_i$	vector velocity of flight i ($i = 1$ or 2)
$\underline{x}_{i,0}$	initial position of flight i ($i = 1$ or 2)
$\underline{x}_{i,\min}$	position of flight i at minimum separation between flights 1 and 2 ($i = 1$ or 2)

I. Introduction

THE future air traffic management (ATM) system may include innovations such as four-dimensional flight contracts, routine use of probabilistic approaches to ATM operations, and reduced separation standards. Air traffic control (ATC) actions to avoid future aircraft conflict problems may be taken with substantially longer look-ahead times than in the current system, thus blurring the distinctions between ATC and traffic flow management. An important aspect of the overall systems engineering effort towards the future ATM system is to understand how the probabilistic nature of potential aircraft conflicts relates to ATC actions with relatively long look-ahead times, and how these relationships are influenced by reduced separation standards [1]. This paper presents an analysis to help advance our understanding of these issues, focusing on the simplified case of aircraft pairs constrained to the horizontal plane. The analysis methodology presented here potentially could be used to support future probabilistic ATM *operations*, although considerable extension and refinement of the approach would be needed.

The perspective taken in this paper is that of an ATC operator in the future ATM system, who may have responsibilities that differ from those of tactical air traffic controllers in today's ATC system. This operator might be described as a strategic ATC operator, and there may be other operators in the future ATM system who take on the tactical role of ensuring safe separation between aircraft. The strategic ATC operator is assumed to have to deal with *potential* aircraft conflicts on the order of 30–60 min in advance, and with managing the traffic so as to keep the likelihood of such potential conflicts in a particular sector during a specific time interval at a manageable level. If some parameter related to conflict probability projected 30–60 min in advance exceeds a specified threshold, the strategic ATC operator may take action in advance to reduce the conflict probability and thereby maintain the manageability of the situation for the tactical ATC operator. With the manageability of the sector handled in advance by the strategic ATC operator, the tactical operator may be able to handle more aircraft, thus increasing sector capacity. For this concept of operations, an aircraft conflict analysis should express results in terms of probabilities of conflict, target levels of overall conflict probability (across a set of aircraft projected to be in the sector) during a time interval, and the size of maneuvers needed to maintain the target level of conflict probability roughly 30–60 min in advance. The operational variables that could influence overall conflict probability include flight speeds, angles of incidence between potential conflict pairs, and measures of projected closest approach distance, based on flight contracts.

The simple analysis presented in this paper is methodologically similar to previous treatments of conflict probability [2–4], except that the present analysis is tailored to a concept of future operations in which flight positions conform to pre-defined rectangular regions moving in the horizontal plane. We use a combined analytic and Monte Carlo simulation approach to assess conflict probabilities, and we restrict the analysis to potential conflicts and control actions in the horizontal plane.

II. The Base Scenario

Figure 1 presents the base potential conflict scenario for two aircraft in the horizontal plane. Rectangles surround flight 1 (F1) and flight 2 (F2), which represent the horizontal conformance bounds for the two aircraft. We assume here that in the future ATM system, the flight contracts of F1 and F2 stipulate that the aircraft shall remain within the rectangles (called "gumsticks") in Fig. 1. The gumsticks are potentially useful in ATM for traffic management, but not for separation between aircraft because aircraft position is not precisely specified. As time progresses in this scenario, the rectangles are assumed to move at constant ground speeds $v1$ and $v2$. In this simple analysis, we do not consider the probability that flight contract conformance itself would be violated, although a full assessment of the future vision concept should account for this possibility. In Fig. 1, the trajectories of the conformance gumsticks are depicted as straight lines that intersect with an angle of incidence phi. (Actually, the constant-speed and straight-line assumptions are not important to the analysis until the gumsticks are in close enough proximity that a conflict could occur.) At the beginning of the scenario (time 0), the center points of the gumsticks are separated by distances $L1$ and $L2$ from the intersection point of the gumstick trajectories. Thus, if $L1/v1 = L2/v2$, the center points of the

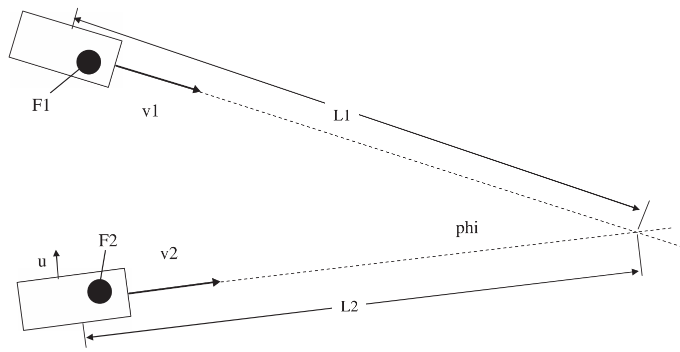

Fig. 1 The base potential conflict scenario.

gumsticks would meet at the intersection point at time $L1/v1$. If $L1/v1$ and $L2/v2$ are unequal, one center point reaches the intersection point before the other.

The black disks in Fig. 1 are centered on the positions of the aircraft at time 0, and their diameter corresponds to the minimum separation standard for the aircraft. Thus, the separation standard is violated if and only if the disks overlap at any time along the trajectories of the aircraft. The flight contracts of the two aircraft guarantee that the aircraft will be *somewhere* within the gumsticks at all times, without specifying exactly where. At time 0 it is typically impossible to say with certitude whether or not a conflict will occur at some time in the future, but we may be able to say something about the *probability* of such a conflict.

The other element needed to be able to calculate conflict probabilities is the probability density for the two aircraft within their respective gumsticks. Ideally, this would include an assessment of the dynamics of the aircraft within the gumsticks as the gumsticks approach. However, this leads to a very complex analysis, and for simplicity, it is assumed that during the whole time that the gumsticks are close enough that a conflict could potentially occur, each aircraft is fixed at a single position within its gumstick. This assumption is expected to be very good as long as the aircraft are assumed not to respond to each others' proximity and phi is not too near zero. (If phi is near zero, then the gumsticks may spend a long time in close proximity, depending on their relative speeds, and so the aircraft may have a lot of time to move around within their gumsticks while the aircraft could potentially conflict; whereas when phi is much larger or smaller than zero, the aircraft pass by each other relatively quickly, so they do not have much time to move around within their gumsticks while they are in close proximity.) Since the analysis is directed towards an assessment of tactical ATC operator workload in having to deal with potential future conflicts, and not actual probability of conflict taking into account pilot maneuvers to avoid the conflict, these assumptions are expected to be adequate.

Figure 2 shows hypothetical probability distributions for the position of an aircraft within a gumstick. PDF refers to the probability density function, and CDF refers to the corresponding cumulative density function. A longitudinal gumstick dimension of 8 nautical miles (n mile) was chosen because this corresponds to about 1 minute of flying time for a typical flight, which is expected to be a representative longitudinal conformance time for the future National Airspace System (NAS). A lateral gumstick dimension of 4 n mile was chosen because this corresponds to the required navigation performance (RNP-1) 99.999% containment region [5] assumed to be in use for appropriately equipped aircraft in the future NAS. Within 1 mile of the gumstick centerline is concentrated 95% of the lateral probability, and the other 5% is spread across the other 1 n mile on both sides in the lateral dimension. In the analysis of this paper, probability densities are defined at nine discrete points along the longitudinal (lateral) dimension, and probability densities at intermediate points are determined by linear interpolation. Probability densities are normalized such that the integral across all longitudinal (lateral) points is unity. The software developed for this analysis easily permits changes to PDFs and CDFs, as well as the overall longitudinal and lateral gumstick dimensions.

Note that the longitudinal PDF in Fig. 2 is not symmetric; this corresponds to the expectation that flights will tend to remain slightly "ahead" of their gumstick center points, because it is usually more economical to lose time later in a flight than it is to make up time. In general, it is expected that longitudinal PDFs will need to be generated from actual flight conformance measurements; the PDF shown in Fig. 2 is notional.

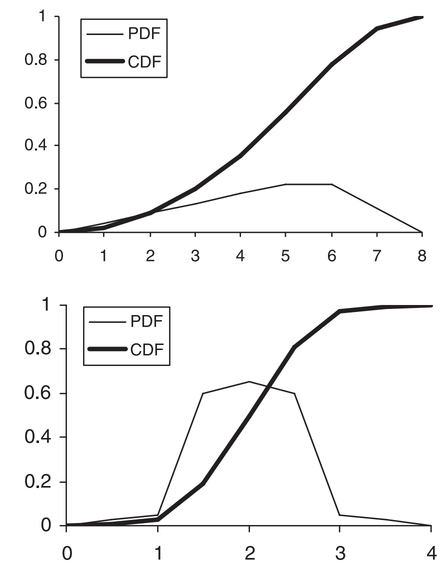

Fig. 2 Hypothetical probability distributions in the longitudinal (top) and lateral (bottom) dimensions. Units along horizontal axes are in n mile.

The information depicted in Figs. 1 and 2, together with the information described in the paragraphs above, is sufficient to permit calculation of probabilities of conflict, for any given separation standard. This calculation was performed through a combination of analytic means and Monte Carlo simulation, as described in the next section. Software to automate the calculation was developed in Excel and Visual Basic.

III. Calculating Conflict Probabilities

For two constant-velocity points (corresponding to aircraft positions), the minimum approach distance is:

$$a_{\min} = \left|\underline{x}_{1,\min} - \underline{x}_{2,\min}\right| \tag{1}$$

where

$$\underline{x}_{1,\min} = \underline{x}_{1,0} + \underline{v}_1 t_{\min}$$
$$\underline{x}_{2,\min} = \underline{x}_{2,0} + \underline{v}_2 t_{\min}$$
$$t_{\min} = -(\underline{x}_{1,0} - \underline{x}_{2,0}) \cdot (\underline{v}_1 - \underline{v}_2)/((\underline{v}_1 - \underline{v}_2)^2$$

With initial positions and velocities specified, the minimum approach distance can be calculated and compared against specified separation standards to determine whether or not the standards have been violated. In the analysis of this paper, aircraft positions within their conformance gumsticks are randomly picked according to the probability distributions in the longitudinal and lateral dimensions, and the above formulas are applied to determine whether or not there is violation across as set of separation minima. This is repeated many times in a Monte Carlo simulation to generate violation probabilities as a function of horizontal separation minimum.

In order to make the results more easily interpretable in operational scenarios involving multiple potential conflicts, an additional step was taken to compute probabilities that at least 3 out of 5 identical independent pairs of aircraft would conflict. Probabilities were calculated for 3 out of 5 pairs by applying the multinomial probability distribution.

IV. Examples of Conflict Probabilities

Figures 3–7 show results for a particular two-aircraft potential conflict scenario. Figure 3 shows the initial conditions of the scenario, with the two flights depicted as triangles and the projected intersection point of their gumstick

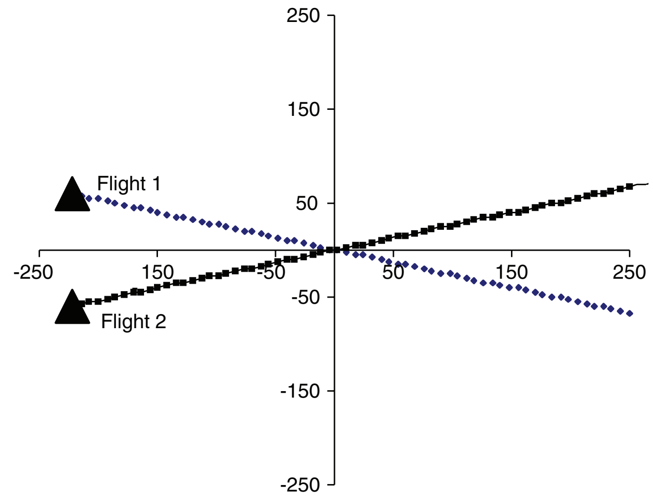

Fig. 3 Initial conditions for a two-aircraft potential conflict scenario. Initial conditions for a two-flight potential conflict scenario.

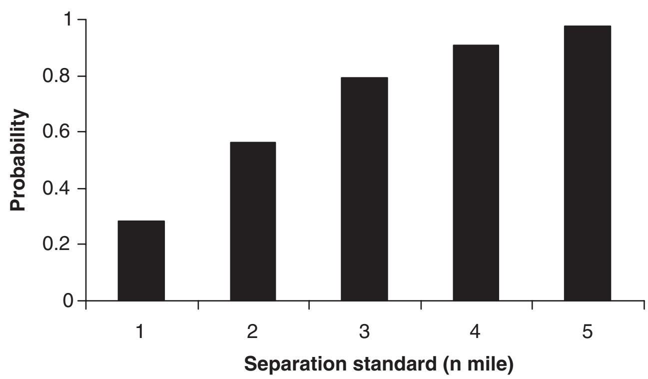

Fig. 4 Computed probability of separation violation for a conflict in the scenario of Fig. 3.

center points at the origin. Gumstick flight paths are also shown, with distances along vertical and horizontal axes in n mile. The gumstick center point of flight 1 (F1) has distance $L1 = 230$ n mile from the origin at the beginning of the scenario, and it travels with speed $v1 = 450$ knots. Similarly, the gumstick center point of flight 2 (F2) has a distance $L2 = 230$ miles from the origin and it travels with speed $v2$. The angle phi between the two gumstick flight paths is 30 deg. The parameter s is defined as $L2 - L1$, the difference in starting distances from the origin. Another input parameter u is defined as the lateral deviation of F2's gumstick flight path to the left relative to a scenario in which the point of intersection of the two flight paths is at the origin. The parameter u is useful in some analyses to show the effect of lateral flight path offsets. The input parameters $L1$ and $v1$ typically are regarded as "fixed" inputs for an analysis, while the "variable" inputs phi, $v2$, s, and u, are changed to show their effect on the output. Analysis outputs for a given conflict scenario include dmin, the minimum separation distance of the gumstick center points, and the time at which the minimum center point distance is achieved, in units of minutes after the initial conditions. The output parameters $q1$ and $q2$ are the distances past the origin, for F1 and F2, at which the minimum gumstick center point distance is achieved. The parameters $q1$ and $q2$ are useful mainly in debugging and verifying the calculations.

Figure 4 shows the computed probability of separation violation for a conflict pair in this scenario, as a function of separation standard. The probabilities were computed through Monte Carlo simulation, using the approach described above, based on 1000 Monte Carlo runs. In each Monte Carlo run, the positions of F1 and F2 were chosen randomly according to the longitudinal and lateral probability distributions shown in Fig. 2, and the minimum approach distance was calculated analytically from equation (1). Figure 5 shows the results of an approximate theoretical calculation of 95th percentile errors for 100, 1000, and 10 000 trials. Applications of the Monte Carlo simulation to PDFs and scenarios where the probabilities can be computed exactly suggest that the theoretical 95th-percentile errors in Fig. 4 are accurate.

Figure 6 shows the probabilities of at least k conflicts out of a total of five independent potential conflict pairs, with each pair in the scenario depicted in Fig. 3, using the binomial probability distribution. Each curve corresponds to a different assumed separation standard. Of course, in realistic scenarios, potential conflict pairs will not have the same probability of conflict, and it is straightforward to compute probabilities of at least k out of n independent potential conflict pairs in such cases. Here, for illustrative purposes, we assume probabilities of conflict are identical

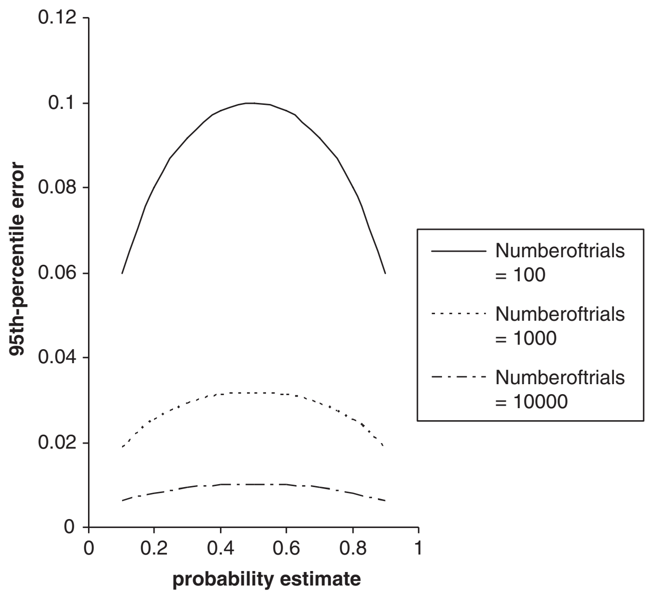

Fig. 5 95th percentile errors, as a function of number of trials.

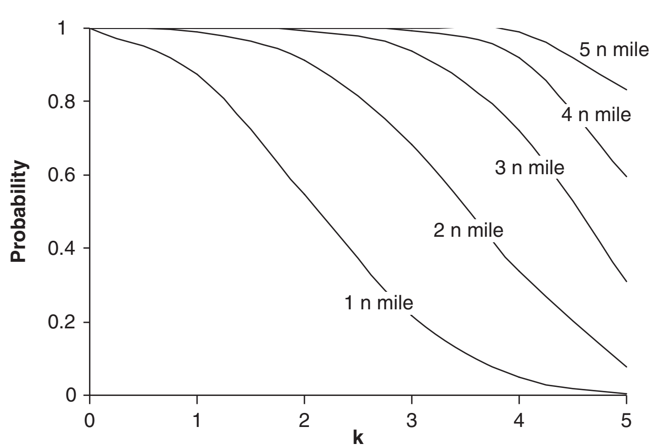

Fig. 6 Probability of at least *k* conflicts out of five independent potential conflict pairs, each conflict corresponding to the scenario of Fig. 3. The curves are labeled with separation standard.

across potential conflict pairs. The parameter corresponding to probability of at least *k* conflicts out of a total of n independent potential conflict pairs was used in the work presented here to generate results that are more directly applicable to actual ATC operations, in which a tactical operator may become overwhelmed with a multiplicity of nearly simultaneous potential conflicts, than single-pair conflict probabilities.

Towards an assessment of the operational implications of resolving probabilistic conflicts in two dimensions, the lateral deviation u and the speed $v2$ can be changed in the simulation to achieve a given target probability of at least, say, 20% for 3 out of 5 conflicts at a given separation standard, during some time interval. The time interval is left unspecified here, but might be on the order of a minute. Figure 6 shows that for a separation standard of 3 n mile, the probability of at least 3 out of 5 conflicts is about 90%. This may be too high operationally, so we can try to vary u and $v2$ until this probability reaches an acceptable level (20% is used in the following examples). Figure 7 shows a scenario identical to that depicted in Fig. 1, except that F2 begins the scenario with a 16 n mile lateral deviation. Figure 8 plots probability of at least *k* conflicts out of five independent pairs for the scenario of Fig. 7. Note that, with a 3 n mile separation standard, the 16 n mile lateral deviation is sufficient to bring down the probability to about 20%. Also note that the probability is about 80% for a 5 n mile separation standard in Fig. 8, reduced from near 100% in

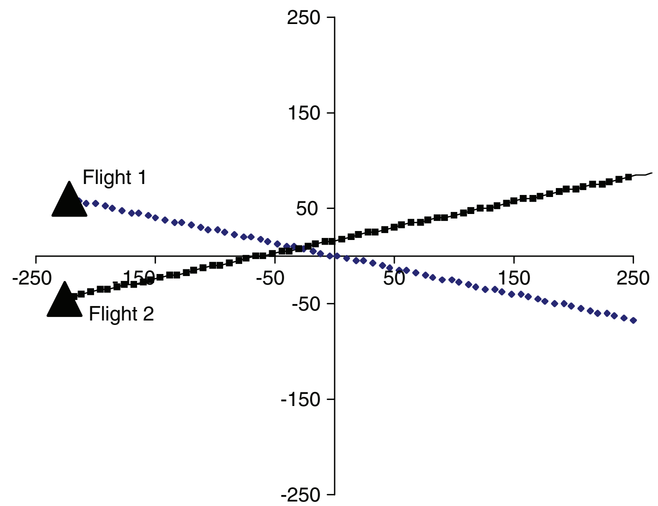

Fig. 7 Initial conditions for a two-aircraft potential conflict scenario with a 16 n mile lateral deviation for F2.

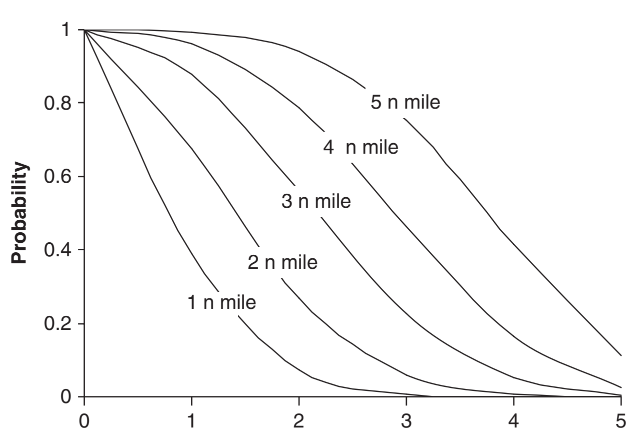

Fig. 8 Probability of at least *k* conflicts out of five independent potential conflict pairs, each conflict corresponding to the scenario of Fig. 3. The curves are labeled with separation standard.

Fig. 6. Further simulations indicate that with a 5 n mile separation standard, a lateral deviation of 24 miles (relative to the scenario depicted in Fig. 3) is sufficient for about a 20% probability of at least 3 out of 5 conflicts.

Speed changes to avoid conflict can be analyzed in a similar way: with a 3 n mile separation standard, a 9 knot speed change (instead of a lateral deviation) is sufficient to bring the probability of 3 out of 5 potential conflicts down to about 20%, compared to the 90% level shown in Fig. 3. A 13-knot speed change would be sufficient to bring the probability down to 20% with a 5 n mile separation standard.

These examples quantify how reducing the separation standard from 5 n mile to 3 n mile can reduce the severity of ATC actions needed to keep the likelihood of airspace conflicts to a manageable level. They also begin to suggest how probabilistic concepts can be folded into future ATM operations: using an automated system to make numerical probability estimates, strategic ATC operators in the future system may be able to maintain the probabilities of conflict at manageable levels in sectors controlled by tactical ATC operators, with look-ahead times on the order of 30 min or more. In the following section, we generalize the analysis to show how the characteristics of the control actions needed to keep conflict probabilities at a manageable level vary with the characteristics of the potential conflict scenario.

V. Control Actions and Potential Conflict Scenario Characteristics

To generalize the probabilistic analysis of the previous section, we set the task of finding, for a given incidence angle phi, the minimum separation dmin between gumstick centers (at closest approach) such that the probability of at least three separation violations out of five potential conflict pairs equals a target value. For the purpose of generating specific example results, the target value is set to 20%. This means that the strategic ATC operator needs to take appropriate control actions to keep the probability of at least three separation violations out of five potential conflict pairs at a level no greater than the target value of 20%. This translates the analysis of the previous section into terms that are more meaningful for ATM operations, and illustrates a methodology for probabilistic analysis that might, with considerable refinement and expansion, lead to specific guidance for operators of the future ATM system based on conflict probabilities. More research will be needed to develop and apply appropriate target probability metrics that account for the extremely high level of safety demanded of the aviation system.

In general, the value of the parameter, dmin will depend on the speeds of F1 and F2 in Fig. 1, as well as the angle phi. However, temporal symmetry dictates that the result will depend on the speed ratio, $v1/v2$. rather than the individual speeds of the two aircraft. Assuming the gumstick probability distributions are identical, laterally symmetric and have a single peak longitudinally, there is a single value of dmin such that the probability is 20% when $v2/v1 = 1$. However, there can be two such values when $v2/v1$ is not equal to one, corresponding to positive and negative values of $s = L2 - L1$. Furthermore, if the above conditions on the lateral and longitudinal probability distributions do not apply, there can be more than two values for dmin.

Curves showing the relationship between probability of 3 out of 5 possible separation violations and minimum projected separation between gumstick center points (dmin) were generated by repeatedly running the calculation described in the previous section with different values of $s = L2 - L1$. Each value of s generates computed values for dmin and probability as a function of separation standard, which then can be plotted out. Figure 9 plots results for $v2/v1 = 1$ and phi = 30 deg, for separation standards of 1, 2, 3, 4, and 5 n mile. For a given separation standard, each point in Fig. 9 represents 1000 potential conflict trials, and for each set of trials, probabilities are estimated for each separation standard. Thus, the plots shown in Fig. 9 were generated based on a total of 53 000 potential conflict trials. For each separation standard, there are two values of probability for each value of minimum separation between gumstick centers. These two probability values correspond to positive values of s (for which F1 leads F2 at the point of minimum separation between gumstick centers) and negative values of s (for which F2 leads F1). The values of probability for corresponding positive and negative values of s should be exactly equal, because the scenario is perfectly symmetric; however, the points in Fig. 9 are not exactly coincident because probabilities were estimated with a Monte Carlo simulation, which embodies some error, as discussed before.

The dashed arrows in Fig. 9 show how the plots can be applied. For example, if aircraft trajectories are projected into the future and indicate a minimum separation between gumstick center points of 2.2 n mile, and the separation standard is 3 n mile, then the probability of 3 out of 5 possible violations is about 0.7. In order to reduce the probability to a target value of 0.2, the minimum separation between gumstick center points must be increased to about 4 n mile. Figure 10 is a simple plot of the speed change needed to achieve the distance change s at different look ahead times,

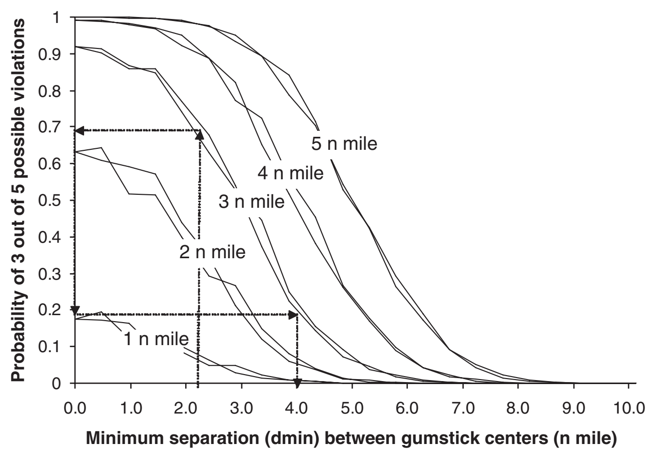

Fig. 9 Probability as a function of minimum projected separation between gumstick centers, for $v1/v2 = 1$ and phi = 30 deg.

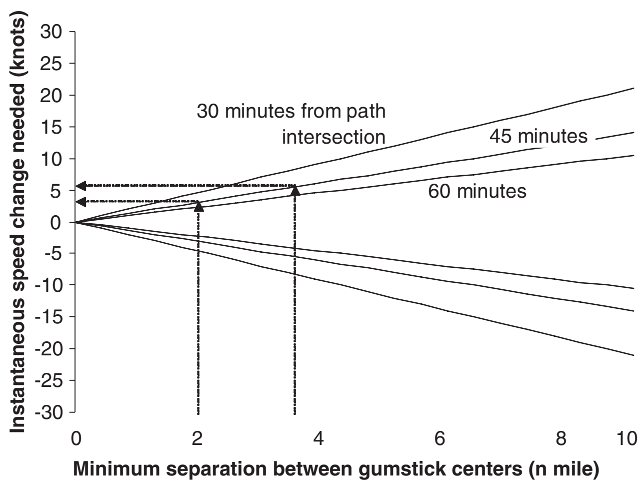

Fig. 10 Speed change needed to achieve a given minimum projected separation between gumstick centers.

shown as a function of minimum separation between gumstick center points. Figure 10 can be used to show the instantaneous speed change that would be sufficient to achieve this increase to 4 n mile. Reading of the *difference* in speed changes for 2.2 n mile and 4 n mile, the speed change needed to achieve the probability target of 0.2 with a 45-min look ahead time is about 3 knots. With a 60-min look ahead time, the speed change needed is less, and with a 30-min look ahead the speed change needed is greater.

For comparison, Fig. 11 shows probability plots for $v2/v1 = 0.5$ and phi $= 90$ deg. This is an asymmetric scenario, since the speeds of the two aircraft are different, so points corresponding to positive and negative values of s do not have equal probabilities, as Fig. 11 shows.

With information like that depicted in Figs. 9–11, the characteristics of operational parameters needed to achieve a given target probability can be generated. For example, Fig. 12 plots dmin against phi, to achieve a target probability of 0.2 for 3 out of 5 possible violations, for separation standards of 5 n mile and 3 n mile. It is assumed that $v2/v1 = 1$. Note that dmin decreases only gradually with increasing angle. Figure 13 plots the speed change needed for F2 to achieve a probability of 0.2 when the gumstick center points are projected to meet 45 min into the future, for both 5 n mile and 3 n mile separation standards. The speed change increases gradually with increasing angle of incidence (phi) up to around 120 deg, and then increases more rapidly. As phi nears 180 deg (corresponding to a head-on

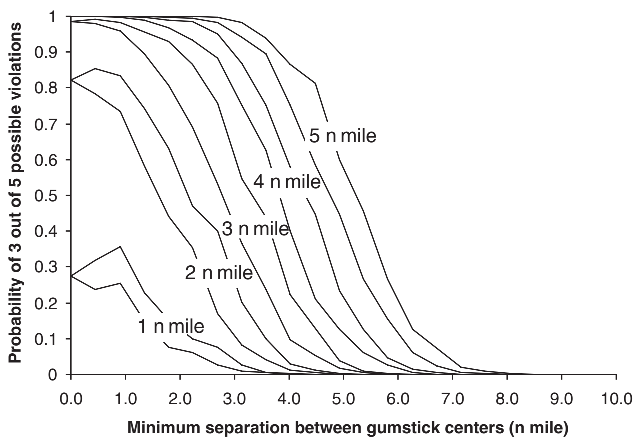

Fig. 11 Probability as a function of minimum projected separation between gumstick centers, for $v1/v2 = 0.5$ and phi = 90 deg.

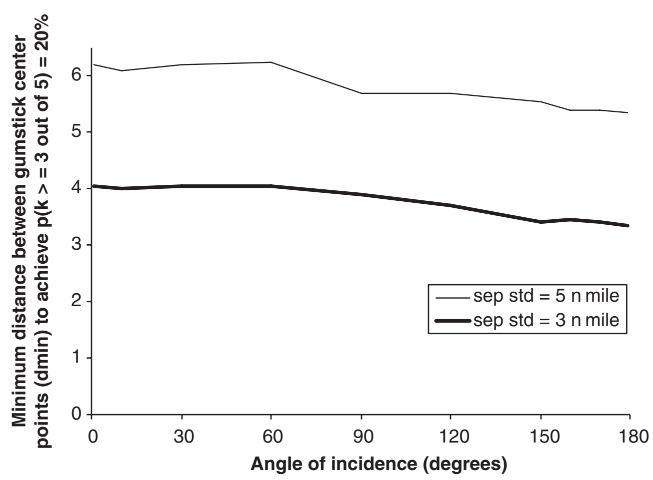

Fig. 12 Minimum projected distance between gumstick center points (dmin) needed to achieve a target probability of 20%, as a function of angle of incidence, phi, with $v1/v2 = 1$.

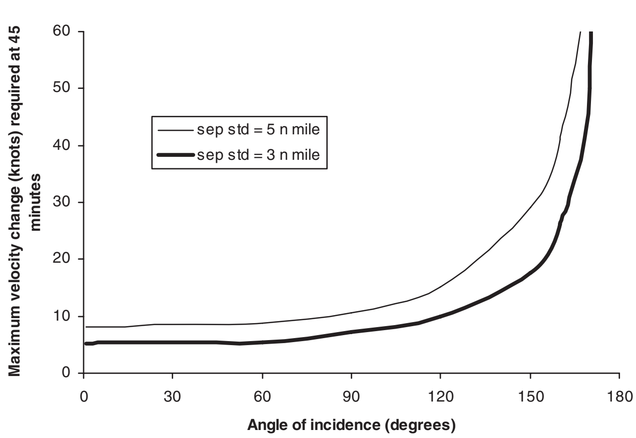

Fig. 13 Minimum speed change required to achieve a target probability of 20%, as a function of angle of incidence, with $v1/v2 = 1$.

collision between gumstick center points), the required speed change goes to a very large value, i.e., only a speed change that actually reverses the direction of one flight will achieve the goal of reducing the probability to within 0.2. When phi is near 180 deg, it makes sense to apply a lateral (or, in three dimensions, altitude) deviation instead of a speed change.

VI. Conclusion

The future ATM system may include four-dimensional contracts that define conformance regions for aircraft, called gumsticks, as well as approaches to ATM that are inherently probabilistic. We have demonstrated, in very simple scenarios, how modeling, including Monte Carlo simulation, can be used to generate predictions of the probabilities of conflict across multiple potential conflict pairs in two dimensions. The results presented in this paper show how these probabilities of conflict vary with separation standard in the future ATM system. Modeling results have been generated across a range of values of operationally significant parameters such as projected minimum approach distance between gumstick center points and angle of incidence, to show the general characteristics of probabilities of conflict.

The paper demonstrates the basic concept of the probabilistic approach, but more research is needed to understand how to refine and extend these basic concepts for potential application to ATM operations. This paper developed results based on a simple threshold metric corresponding to a projected probability of at least three conflicts across five potential conflict pairs in two dimensions. More research is needed to extend the model to three dimensions, and to identify probability metrics that could be viable in actual ATC operations. The type of probabilistic metric chosen may influence the computational requirements for the system, particularly for metrics based on keeping the likelihood of very low probability events below a threshold. More research is needed to assess the impact of relatively low-probability events, including those arising from deviations of aircraft outside of their conformance regions. Also, aircraft proximity events involving more than two aircraft are not accounted for in the analysis of this paper. Multi-aircraft events may present significant computational challenges. A potentially useful line of research would be to investigate whether conflict analysis based solely on multiple aircraft pairs yields sufficiently accurate indicators of control difficulty to obviate the need for higher-order aircraft conflict calculations.

The analysis of this paper assumes the gumstick dimensions are static. In real operations, the ability to decrease the size of conformance regions might be a useful control mechanism, and might offer significant advantages to appropriately-equipped aircraft. Such an "open loop" formulation of the potential conflict probability problem is a promising area for further research[†] .

The analysis to date suggests that automated systems may be more appropriate than humans for detecting conflicts probabilistically, since humans are not expected to be as capable of estimating probabilities accurately. On the probabilistic conflict resolution side, similar implications may prevail as well, but more research is needed on this topic. Finally, research into automated methods for probabilistic conflict detection and resolution based on previously-developed deterministic methods [6] may be a fruitful area for exploration.

The analysis presented in this paper was based on a relatively simple model that took limited time to develop, debug and start generating results. For a complex future system whose basic characteristics are likely to be discussed and refined over substantial time and across many stakeholders, we have found this type of modeling is a good way to communicate ideas and stimulate questions and new issues about the system and how it could operate. In this way, relatively simple modeling and simulation can contribute to the overall process of complex systems engineering [7].

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[†] McFarland, A. L., Personal communication, MITRE Corporation, McLean, VA, 15 July 2005

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J. A. Mulder
Associate Editor