Modeling of Airspace Under Future Air Navigation Systems

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Potential cost savings that can be achieved from the introduction of various levels of technological improvements in navigation capability are described. Cost estimates are determined through simulation methodology. The simulation model, designed to measure conflict levels and costs associated with resolving conflicts in procedural airspace, optimizes levels of separation for particular flow rates. Comparison of the simulation model with analytical work found in the literature also is provided. Flow and network characteristics that reflect conditions in the Pacific region have been used in the simulation model to investigate a number of futuristic operating strategies for regions with relatively low air-traffic flow. The scope for substantial annual cost savings, even in such low-traffic regions, is revealed.

During the next decade, technological improvements within the aviation industry in the areas of surveillance, navigation, and communication technology are anticipated to lead to substantial cost savings. These cost savings are expected to be derived from improved air traffic flow and reduced track deviations.

This paper examines a methodology for estimating potential savings that can be expected from improvements to the navigational capability of aircraft operating in procedural control areas (nonradar surveillance environments). The improvement in navigational performance will be derived from direct surveillance through the automatic dependent surveillance (ADS) system, nonlocalized navigation enhancement gained from the global positioning system (GPS), and more reliable and accurate data transmissions via communications satellites.

The proposed methodology is focused toward estimating the effects of different minimum separation standards on system performance. These minimum separation standards correspond to different levels of technological enhancement as compared with the current state of technology. The attributes of the model's output are conflict-related specifically for category and frequency of conflicts. These attributes then are translated into a dollar value as a function of the minimum separation. The cost function then is investigated from an optimization point of view to determine the appropriate level of technology for a given flow rate.

The airway systems are modeled under different separation minima through a simulation program developed by the principal author. The simulation program is validated initially through comparison with conflict models already found in the literature.

BACKGROUND

This research project considers procedural airspace, or airspace for which the introduction of ADS and GPS will have the maximum effect. The ADS system offers to provide air traffic control (ATC) a pseudo radar environment in which the positions of all aircraft would be relayed via satellite to a regional control center. This pseudo radar environment will allow detection of certain types of way-point insertion errors, ATC errors, and deviations from the expected heading (*1*).

The certification of GPS the only navigation device will allow, in conjunction with inertial navigation systems (INS), a higher degree of positional accuracy. A single GPS set can provide readings accurate to 100 m for civil receivers (*2*). In addition, GPS offers higher system integrity than with the current inertial navigation systems.

In communications, satellites will allow for clearer and more reliable transfer of information for voice and data transmissions. This communication system will replace the high frequency radio system that currently is used to convey position reports.

These improvements in technology eventually will lead to raised safety levels and overall system confidence and integrity. As a consequence, measures can be undertaken to reduce costs for airlines and civil aviation authorities through the reduction in separation minima and the increased flexibility of airspace usage, ultimately allowing for more direct routing of aircraft.

SIMULATION MODEL

The simulation model developed at the University of New South Wales is designed to follow all aspects of the operating behavior of aircraft in procedurally controlled en route airspace. The procedurally controlled areas are defined by the region between the entry and exit points at the boundary of terminal airspace. "Terminal airspace" in this paper describes the area of airspace centrally located at airport nodes where aircraft are under direct radar surveillance. Aircraft operating within the boundary of terminal airspace are disengaged from the simulation phase because the terminal airspace environment entails different operational rules to procedural airspace.

The simulation model dispatches aircraft according to a stochastic method, with built-in allowances for departure delays. The program is linked to the Programmer's Hierarchical Interactive System (PHIGS) library for supporting graphics and therefore is able to display the location of the aircraft on a continually updated animation display. Furthermore, the traditional form of file output allows the retrieval of operating features of the simulated system in numerical, tabulation form. This particular output contains position, flight level, velocity, proximity, rate of fuel burn, weight, track deviations, and other factors as required at specified time intervals.

Simulated aircraft operating in procedural airspace are subject to a detailed examination on every update to determine relative position to other aircraft within a three-dimensional framework. This process allows the identification of a potential conflict or conflict in

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progress. A conflict is identified as the entry of one aircraft into the volume of protected airspace surrounding the neighboring aircraft. This protected volume of airspace has a regulated magnitude; this paper uses a cylinder of radius S_r and height S_z for the shape. Figure 1 shows the geometrical configuration associated with the analysis of a potential conflict. R_i and R_j are the spherical radii for each aircraft (it is assumed that the earth is spherical). These radii give the z-coordinate in the three-dimensional setup.

It can be proven that a conflict has occurred when the following two conditions have been met:

$$l_Y < S_r$$
$$|R_i + R_j| < \frac{S_z}{2}$$

where l_Y is the spherical distance between any two aircraft, i and j. The approximate expression for l_Y is derived as follows:

$$l_Y \approx \frac{1}{2}(R_i - R_j)\cos^{-1}\left(\frac{\overrightarrow{OA_i}\cdot\overrightarrow{OA_j}}{R_iR_j}\right) \quad (1)$$

where A_i and A_j are the positions of Aircraft i and j, respectively.

Once a potential conflict, or an actual conflict, is identified, it sometimes is necessary to modify the operating variables of one or both aircraft to ensure that the conflict does not occur and the risk of collision is eliminated. The process of resolution as carried out in the simulation model is shown in a simplified flow diagram in Figure 2.

The resolution modules within the simulation model are designed to follow the response of air traffic controllers to potential conflict situations. This is done by simulating future relative positions of aircraft by a period of t_p. Such responses direct velocity change, flight level changes, or route deviations. The effects of these directives are different for individual aircraft depending on the type of potential conflict.

For every conflict, the simulation model estimates the relative costs associated with each possible resolution. Factors included in this resolution cost comparison are listed as follows:

1. Length of sector remaining,
2. Cost associated with climbing and descending,
3. Cost associated with continuing remaining sector at the resolved altitude and velocity, and
4. Distance penalty associated with path change.

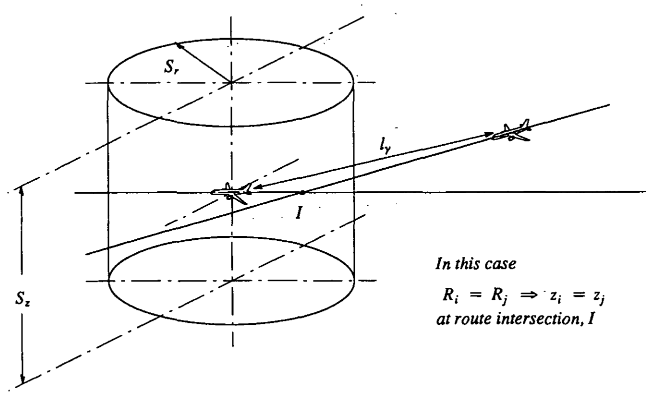


FIGURE 1 Forbidden volume surrounding aircraft.

The resolution choice with the lowest associated cost is carried out following a check to ensure that the resolving action does not precipitate further conflict.

The resolution costs of all conflicts of all aircraft are then added to obtain the total cost. The various cost components covered in conflict resolution are described in the next section.

COST FUNCTION

The cost function adopted in the model encompasses the main cost components involved in operating an aircraft along a particular stage. Three elements have been identified as forming the basis of the main cost components: (a) ground cost, (b) en route cost, and (c) stepping cost.

The ground cost component evolves from delay incurred at point of departure due to traffic congestion en route. The departure of the aircraft is postponed until airspace separation standards are available at the takeoff point. Delays of this form are usually the result of a like aircraft operating along the same track as that desired by the following aircraft. For the purpose of this analysis, it is assumed that airport congestion is not the critical link in the departure sequence of aircraft. The program can be modified readily to input airport-congestion–associated delays from other models.

The en route cost component covers those additional expenses that occur because of unplanned en route events such as conflict resolution and weather diversion delays. For most flights this component is likely to be the most critical of the three components. The constituents of this cost component are described later in this section.

The final component to consider in the cost function is the stepping cost. This cost is associated with an aircraft having to operate at a nonoptimum level because of the lack of "space" at the desired level. Aircraft that are unable to operate at optimum altitude generally have a cost disadvantage because of the higher rate of fuel consumption.

Together, these cost components can be expressed as

$$C_s = f(\text{ground, en route, stepping}) \quad (2)$$

where C_s is the cost to the system.

Each of these cost components, however, has associated factors that dictate the related cost. These associated factors are aircraft engineering (maintenance), passenger delay, crew charges, scheduling, and fuel burn. These factors are outlined partly by Attwooll (3).

Assuming that the function given in Equation 2 is first-order linear form, and that the average cost for each aircraft allows for a better base index, Equation 2 can be rewritten to find the mean cost ($\overline{C_s}$), as given in Equation 3:

$$C_s = \frac{1}{n}\left[\sum_i^n C_{G_i} + \sum_i^n C_{E_i} + \sum_i^n C_{S_i}\right] \quad (3)$$

where the expressions for C_{G_i}, C_{E_i}, and C_{S_i} are calculated by accumulating relevant cost factors for the ith aircraft. The number of aircraft is n. The association of these cost factors to their relevant group is given in Figure 3.

The fuel burn and engineering factors are excluded in the delay costs because both factors are dependent primarily on flying time; the other factors are dependent merely on time.

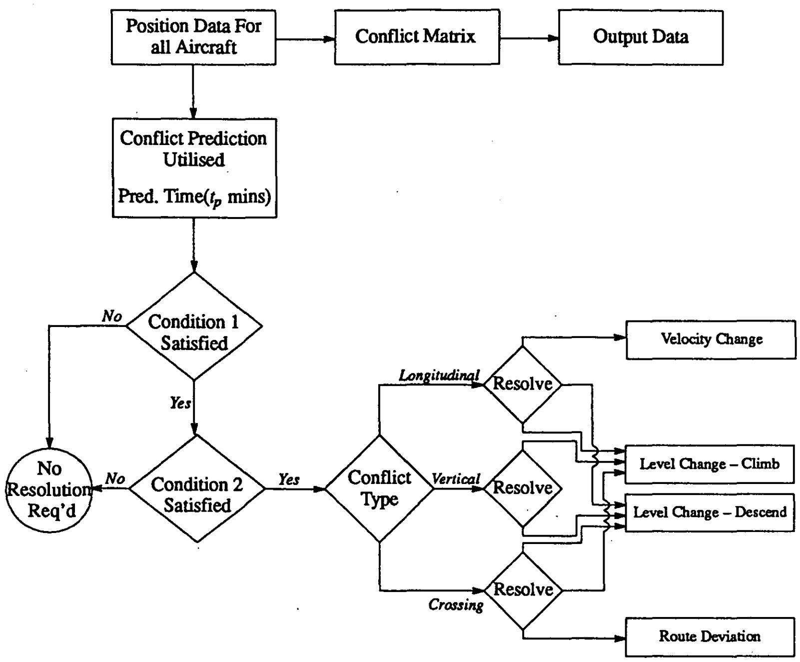


FIGURE 2 Resolution process in simulation program.

The inclusion of only the fuel burn variable in determining the costs associated with failure to step up a level is based on the negligibility of other factors compared with the extra fuel consumption. This is due to the insignificant time delay produced as part of the inability to step.

One other cost factor not addressed so far relates to the ADS update. The update rate will be dependent on separation minima and, to some degree, flow densities. The update rate will vary according to these parameters, thereby providing the controllers adequate information to safely process the passage of aircraft through the particular sector. The degree of ADS update also is influenced by the level of minimum separation. For low separation minima and high densities, the update rate could be near 10 updates per minute, therefore making it close to that for radar coverage of en route sectors.

An important factor that limits the application of the maximum update rate is the cost associated with operating at such a high update rate. It is anticipated that the cost of using the communication satellites will be about $0.65 (U.S. dollars) per message update. This cost is related to the size of the information block being sent. Because of this, the update rate needs to be considered in any system cost function. The cost function from Equation 3 now can be expanded to include the cost of the ADS update as well:

$$\overline{C}_{S_{\text{ADS}}} = \frac{1}{n}\left[\sum_i^n C_{G_i} + \sum_i^n C_{E_i} + \sum_i^n C_{S_i} + \sum_i^n C_{\text{ADS}_i}\right] \quad (4)$$

where

$\overline{C}_{\text{ADS}_i} = (f_{\text{ADS}} t_i U_{\text{ADS}})$,
C_{ADS_i} = cost function ($)
f_{ADS} = ADS cost factor ($/message),
t = time (time unit), and
U_{ADS} = update rate (message/time unit).

MODEL VALIDATION

With simulation programs it is important to validate the output to ensure that the simulation is behaving in the designed fashion. With the simulation program developed here, it is impractical and extremely difficult to collect the data necessary to validate the operational side of the simulation. Therefore, model validation is attempted through comparisons with established analytical models. Many authors have developed basic analytical relationships between conflict and separation. Several authors have demonstrated conflict models, each with some degree of agreement(*4–9*). The Schmidt model (*6*) has been used for comparison with the present simulation model because it reflects the general basis of the governing relationships for conflict analyses.

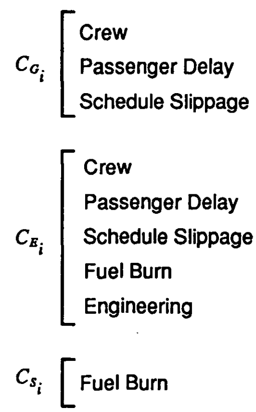


FIGURE 3 Cost factors.

The equation for the conflict model is given in Equation 5, where $E(N_c)$ is the expected number of conflicts per hour and f_1 and f_2 are the respective flow rates along the crossing tracks.

$$E(N_c) = \frac{2\, S_r f_1 f_2 (v_1^2 + v_2^2 - 2v_1v_2\cos\alpha)^{\frac{1}{2}}}{v_1v_2\sin\alpha} \quad (5)$$

The velocities of aircraft on Routes 1 and 2 are v_1 and v_2, respectively, and are assumed to be constant. The angle that separates the two airways is α. Schmidt's model evaluates the expected number of crossing conflicts for a two-route, single-intersection system.

Results for the theoretical model have been compared with the output obtained from the simulation model. Velocities v_1 and v_2 are considered constant and equal to 500 kn, with $\alpha \approx 27$ degrees. The arrival distribution for both the simulation and theoretical models is assumed to be a Poisson distribution. Schmidt assumes that S_r is composed of the regulation separation minimum and a further distance value to accommodate the controller's perception of a conflict. The additional distance value is assumed to be 0 for this exercise. A comparison of the theoretical and simulation models is shown graphically in Figure 4; there is little difference between the results obtained from the two models.

FIGURE OF MERIT

With the introduction of ADS, it will be necessary to maintain an update not only on the aircraft's position but also on the aircraft's navigational capability, so that the merit of the position report can be considered adequately. The field of data sent with the position report is called the figure of merit (FOM) and is composed of (a) an indicator of navigational equipment redundancy and (b) an indicator of position-fixing accuracy of the on-board navigation equipment (*10*).

FOM has been divided into eight levels of merit. These eight levels reflect the quality of the navigation: Level 0 represents the complete loss of navigational function whereas Levels 1 through 7 reflect an increase in navigation capability from a poor level to a high level of accuracy. Each FOM has a stated degree of positional accuracy that is based on a 95 percent containment within the boundary of allowable positional error.

These boundaries of allowable positional error are derived from the expected positional inaccuracy associated with aircraft operating under different combinations of navigation systems and sector length. In addition, the status of the aircraft's FOM is dynamic in such a way that it can change as conditions alter or navigational capability reduces. FOM therefore allows degradation of position reporting to be compensated for by the air traffic controllers in charge.

A simplified method for estimating the magnitude of the protected volume is given elsewhere (*10*). This protected volume often is represented as a rectangular prism, defined by longitudinal, lateral, and vertical separation minima. Variables are taken and applied to a simple root-sum-square procedure. The variables used in this paper for this procedure are as follows:

Ψ_1 = FOM (n.mi)
Ψ_2 = clock error = 10 sec ≈ 1.3 n.mi
Ψ_3 = longitudinal error = $U_{ADS}/3$(n.mi)
Ψ_4 = message time = 15 sec ≈ 2 n.mi
Ψ_5 = intervention time = 5 sec ≈ 0.7 n.mi
Ψ_6 = display errors = 5 n.mi

In the procedure time units are converted to distance units by assuming an aircraft speed of 480 kn. For this paper, longitudinal and lateral separations are taken to be of equal magnitude. This equality is achieved by adopting a variability in aircraft heading of 2.5 degrees, a value possible under an ADS environment.

The Ψ_5 variable is obtained by estimating the longitudinal error required before an alerting message is sent.

For different FOM levels, the value of S_r can be determined as follows:

$$S_r = (\Psi_1^2 + \Psi_2^2 + \Psi_3^2 + \Psi_4^2 + \Psi_5^2 + \Psi_6^2)^{\frac{1}{2}} \quad (6)$$

Table 1 presents containment values for each FOM, the related longitudinal minimum separations that will be used in this paper, and the relevant ADS update rates for each FOM. The value of the ADS update is based on equating the two main variables from Equation 6, namely, Ψ_1 and Ψ_3. The ADS update rate, therefore, is simply $\Psi_3 = 3\,\Psi_1$. This gives an update that increases proportionally as the separation distance reduces to a small value which is in accordance with expectations.

FOM A is an arbitrary level included for illustrative purposes. The separation minima associated with FOM A generally have a lower separation value than is used currently. Separation is approximately 10 to 15 min of longitudinal separation, or about 80 to 120 n.mi depending on the aircraft's velocity. The cost savings presented in this paper therefore are conservative figures.

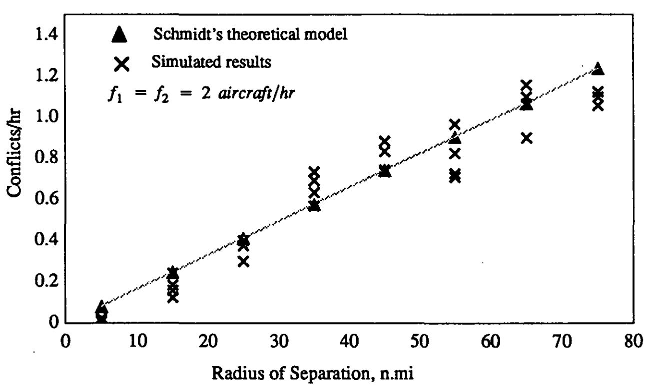


FIGURE 4 Comparison of simulation and theoretical models.

TABLE 1 Containment Values and Related Minimum Separations

FOM	95% Containment Value (n.mi)	ADS Update Rate (mins)	Min.Sep. (S_r) (n.mi)
A	N.A.	150	80
0	–	–	–
1	30	90	42.8
2	15	45	21.9
3	8	24	12.6
4	4	12	7.9
5	1	3	5.8
6	0.25	0.75	5.6
7	0.05	0.15	5.6

THE NETWORK

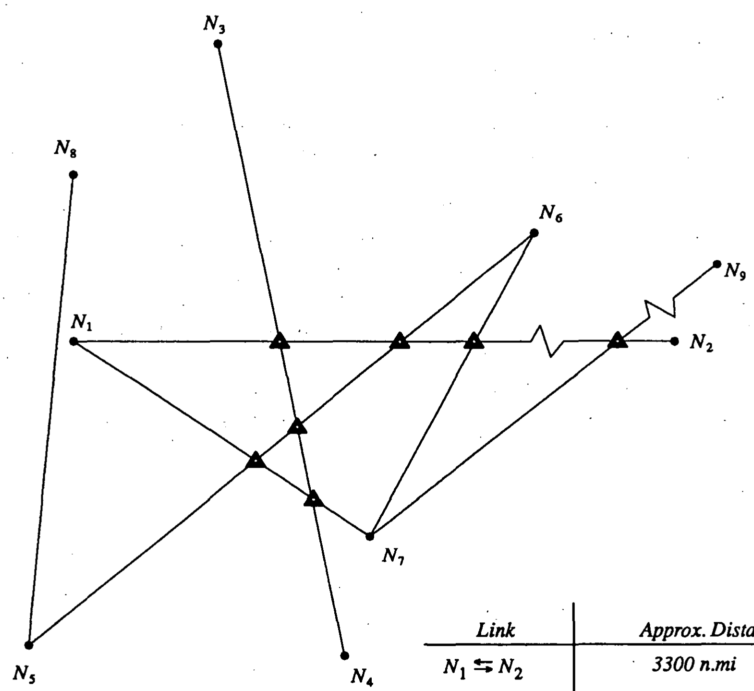
Cost savings, feasible under different FOM levels, are investigated using the simulation model already described. The simulation results presented in the next section are drawn from a nine-airport node network connected by seven airport-to-airport links. The links allow bidirectional air-traffic flow. The airport node layout represents the regional area that covers the Tasman and South Pacific oceans. Reference to actual airports and stages are avoided deliberately because many local features are not incorporated in the network presented here. It is best to consider the specified network as a simplified model (or representation) of a selected number of routes in the Pacific region. Figure 5 presents the network layout used in this paper and lists route distances to indicate the scale of the network.

RESULTS

The input data used for aircraft operating costs are drawn from information obtained from a commercial software package (*11*) and the operation flight manuals of the major aircraft operators of medium-length routes across the Pacific. Shown in Figure 6 are the average costs for all aircraft under different flow rates for different FOMs. Each symbol in the graph represents one simulated operation under the relevant operating parameters. It is encouraging to note that for FOM 1 through FOM 7 the standard deviation of the cost derived from the four simulated operation sessions is relatively low. However, FOM A does show a marked increase in the standard deviation of the cost estimate, particularly for high flow values. This change in standard deviation does appear to indicate a greater variability of results for large values of allowable minimum separation. An increased number of simulation sessions potentially would increase the level of confidence of the mean value of cost at these high levels of separation.

The regression analysis performed supports a linear relationship between the overall cost and the flow rate. According to these linear relationships, FOM A shows a significant increase in average cost for relatively large flow rates. As expected for FOM 1, FOM 2, FOM 3, and FOM 4, the trend is decreasing cost at a given flow rate. FOM 5, FOM 6, and FOM 7, however, reverse this trend with a general increase in average cost at a given flow rate. It is important to note the horizontal nature of the curves in the last three regimes already mentioned, for this characteristic indicates that Equation 4 is unresponsive to the flow variable for these operating regimes. The reason for this unresponsiveness is that, in these operating regimes, the ADS update cost (C_{ADS_i}) overwhelms the other cost components in Equation 4. Within these operating regimes, the relatively small separation standards involved significantly reduce the number of conflict events. Therefore, contributions from the other variables in Equation 4 are reduced in magnitude. For low flow rates and high FOM, Equation 4 can be reduced to

$$\overline{C}_{S_{\mathrm{ADS}}} = \frac{1}{n} \sum_{i}^{n} C_{\mathrm{ADS}_i} \tag{7}$$



Link	Approx. Distance
$N_1 \leftrightarrows N_2$	3300 n.mi
$N_1 \leftrightarrows N_7$	1200 n.mi
$N_3 \leftrightarrows N_4$	2200 n.mi
$N_5 \leftrightarrows N_6$	2100 n.mi
$N_6 \leftrightarrows N_7$	1200 n.mi
$N_5 \leftrightarrows N_8$	1800 n.mi
$N_7 \leftrightarrows N_9$	4600 n.mi

FIGURE 5 Network layout.

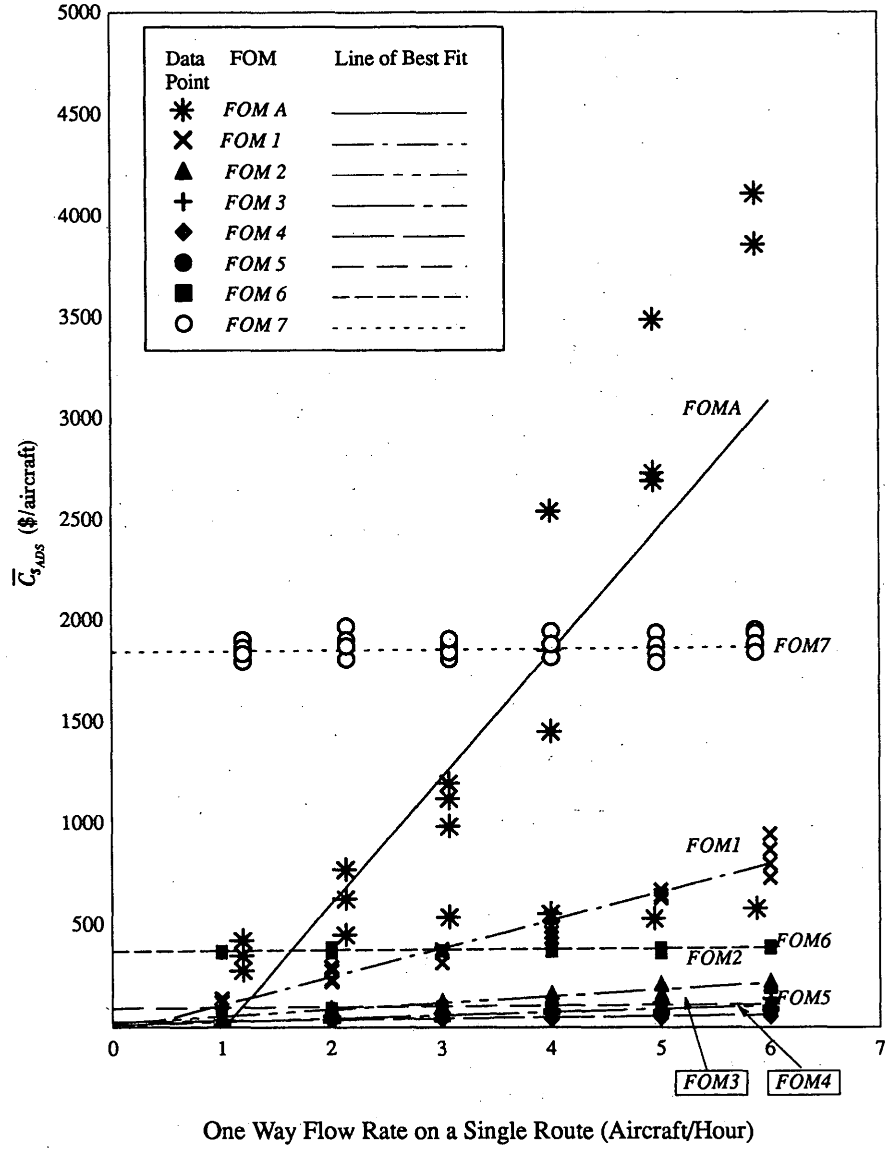


FIGURE 6 Aircraft costings drawn from different levels of flow.

It is possible to investigate the cost-effectiveness of different operating regimes under different flow rates by transposing the data from Figure 6 so that the horizontal axis represents FOM. This transposition is presented in Figure 7. The inset in Figure 7 provides a magnified view of the behavior of the cost function in the minimum cost region.

Figure 7 indicates that the optimum FOM lies between FOM 3 and FOM 4 for flow rates of one to six aircraft per hour per route per direction under the system parameters used in this study. As the flow increases, FOM 4 becomes more attractive when one is minimizing overall costs. It may be possible to yield the minimum cost at higher levels of FOM, such as FOM 5, for much higher flow rates than considered here. Currently, however, such high flow rates are deemed unrealistic.

CONCLUSIONS

The relationship between update rate and minimum separation is examined in this paper. There is, however, a current notion that ADS reports are required only for a change in flight plan. If this is the case, then separation is based solely on FOM. The authors will explore this position in future research.

Regardless of the outcome from the ADS panel, the paper does present a methodology for investigating the effects of technological advances in the field of ATC. During this research project, emphasis was placed on investigating the trend and the nature of the cost functions. It has been shown in a cost comparison between the current state, FOM A, and FOM 3 that the cost savings per aircraft are substantial, even for relatively low flow rates of about one aircraft per hour per route per direction. Annual cost savings would provide significant benefits to the civil aviation industry as a whole. Additionally, including other airports, and therefore increasing the number of routes, in the analyzed region is likely to yield proportional cost savings across the entire network. This result is due to the greater number of intersection nodes created by added routes and the higher number of resolution maneuvers generated by increased crossing conflicts. For future research, a need to further define the relationship between the network complexity and system cost has been identified.

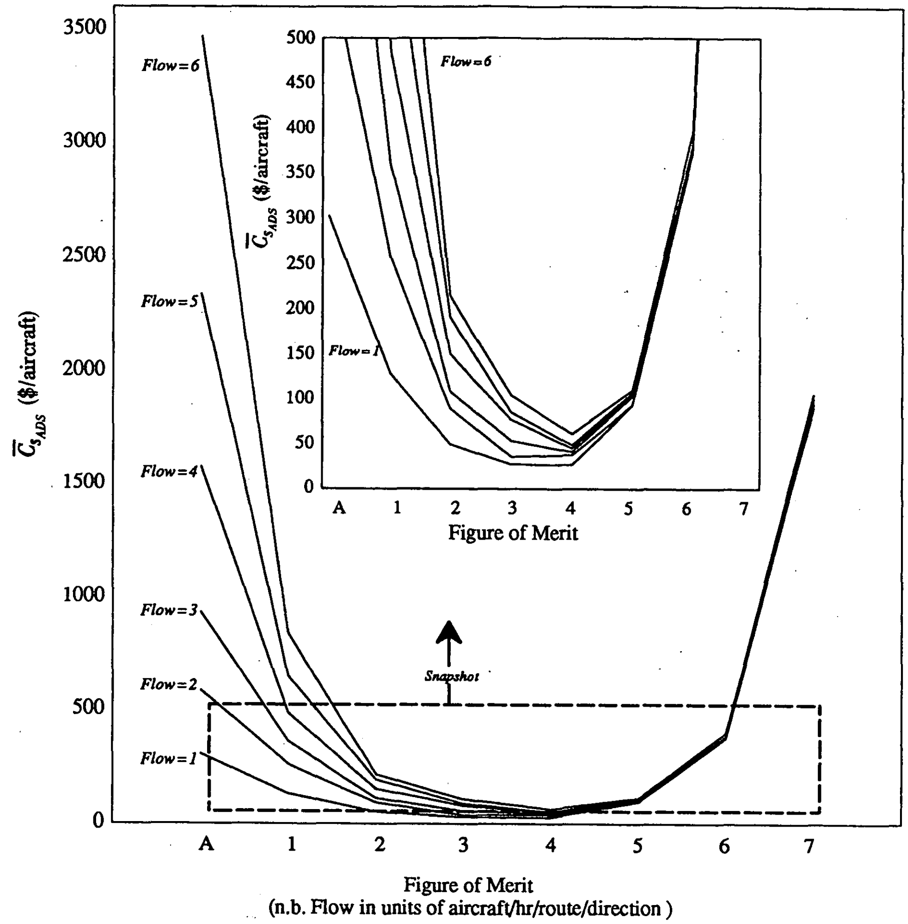


FIGURE 7 Aircraft costings drawn from different levels of flow.

Although the costs of infrastructure and equipment have not been considered in the cost equation, the overall effect of such features is likely to be negligible because of compensatory cost savings expected to be gained from not having to maintain the current land-based navigational aids as well as maintain and renew some costly INS.

The described methodology has allowed for an optimum FOM to be determined as a function of flow rate. As demonstrated, FOMs 3 and 4 provide the optimum operating regime for the given range of flow rates. However, if a superior FOM is desired for safety or policy reasons, a lower update rate to ensure satisfactory cost-effectiveness will be necessary. The potential to reduce the update rate for superior FOMs through considering the low flow rates involved will be limited, however. This limitation reflects real operational behavior in which, although the average flow rate may be low, aircraft tend to operate in bunches and therefore operate close to minimum allowable headways. High update rates therefore will need to be maintained to ensure that separation is properly maintained, thus ensuring that update rates are more closely related to separation minima than flow characteristics.

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