Simulation Analysis of Potential Benefits from Future Air Navigation Systems

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Abstract:

It is anticipated that technological innovations in navigation, surveillance and control aspects in the aviation industry will significantly change the operational parameters of the air transport. The paper describes the adoption of simulation methodology to estimate the potential cost savings to passengers, operators and control authorities from the introduction of various levels of technological improvements. The simulation model is designed to measure the conflict levels and costs associated with resolving conflicts in procedural airspace. Comparison of simulation model with analytical work found in literature is also provided. In this paper, flow and network characteristics which reflect conditions in the Pacific Region have been used in the simulation model to investigate number of futuristic operating strategies on relatively low air traffic flow regions has been revealed.

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1. INTRODUCTION

Over 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, increased safety and reduced track deviations.

This paper looks at a methodology for estimating potential savings that can be expected from improvements to the navigational capability of aircraft operating in procedural control areas (non–radar surveillance environments). The improvement in navigational performance will come from direct surveillance through the Automatic Dependent Surveillance (ADS) system, the non–localised navigation enhancement gained from the Global Positioning System (GPS), and more reliable and accurate data transmissions via communications satellites.

The proposed methodology incorporates modifications to the magnitude of the regulation minimum separation. These separation standards are based on different levels of technological enhancement over the current systems. The output attributes are specifically conflict related in terms of category and frequency of conflicts. These are then translated into a dollar value as a function of the minimum separation.

For the purpose of this paper, the input parameters used in the proposed model are selected to reflect low density routes, such as those found in the South Pacific region. The network layout, and the nodal port locations are also chosen to represent the distribution of airports within this region. It will be shown that the potential for reducing costs is relatively high, even in the low utilisation routes across the Pacific. Translation of these benefits to the high density areas of the North Pacific and the North Atlantic will ensure even greater savings to the aviation community.

The modelling of the airway systems under different separation minima is undertaken through the use of a simulation program developed by the principle author. Initial validation of the simulation program is achieved through comparison with conflict models already found in literature.

The results outlined in this paper are expressed in terms of average cost per aircraft. These estimates are later applied to compute an annual cost saving.

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2. BACKGROUND

The type of airspace being considered in this research project is procedural airspace. It is procedural airspace where the introduction of ADS and GPS will have the maximum impact. The ADS system offers to provide for aircraft a pseudo radar environment where the positions of all aircraft would be relayed via satellite to a regional control centre. This will allow detection of way–point insertion errors, Air Traffic Control (ATC) errors and deviations from the expected heading (ICAO, 1991).

The certification of GPS as a sole navigation device will allow, in conjunction with Inertial Navigation Systems (INS), a higher degree of positional accuracy. A single GPS set can provide readings accurately to 100 metres for civil receivers (CAA, 1991). In addition, GPS offers a superior degree of system integrity than 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 (HF) radio system that is currently used to convey position reports.

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

3. SIMULATION MODEL

The simulation model developed at the University of New South Wales is designed to follow all aspects of the operating behaviour of aircraft in procedurally controlled enroute 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 as 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 is therefore able to display the location of the aircraft on a continuously 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, fuel burn rate, weight, track deviations and a number of 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 of a conflict in progress. A conflict is identified as the entry of one aircraft into the volume of protected airspace surrounding the neighbouring aircraft. This protected volume of airspace has a

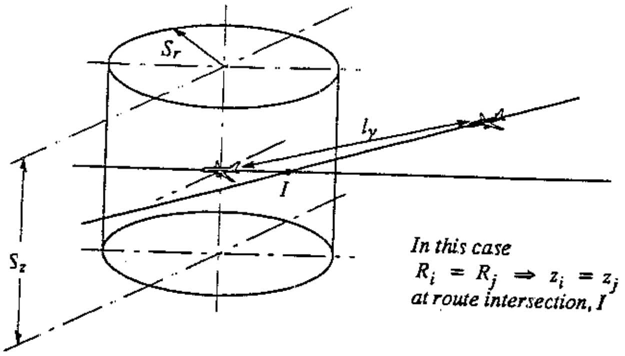

Figure 1 Forbidden Volume Surrounding Aircraft

regulated magnitude and in this paper the shape is taken to be a cylinder of radius S_r and height S_z. Figure 1 shows the geometrical configuration associated with the analysis of a potential conflict.

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

Condition 1: $l_y < S_r$

Condition 2: $|R_i - R_j| < \frac{S_z}{2}$

where R_i and R_j are the radius from aircraft i and j respectively to the centre of the earth, O (assume the earth is spherical). The approximate expression for l_y is derived and is given below as,

$$l_y \approx \frac{1}{2}\left(R_i + R_j\right) \cos^{-1}\left(\frac{\vec{OA}_i \cdot \vec{OA}_j}{R_i R_j}\right) \tag{1}$$

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

Once a potential conflict is identified, it is necessary to modify the operating variables of one or both aircraft to ensure that the conflict does not eventuate 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. Such responses are in the form of directing 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 resolving action. Factors included in this resolution cost comparison are listed overpage:

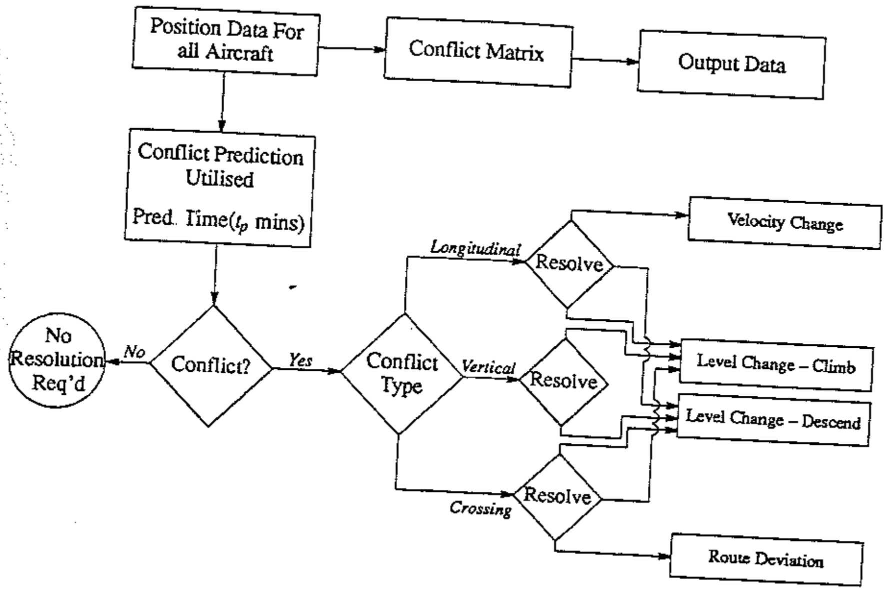

Figure 2 Resolution Process in the Simulation Program

i. Length of sector remaining.

ii. Cost associated with climbing and descending.

iii. Cost associated with continuing remaining sector at the resolved altitude and velocity.

iv. Distance penalty associated with the path change.

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

The resolution costs of all conflicts, of all aircraft, are then added to obtain the total cost. A description of the various cost components covered in conflict resolution is given in the next section.

4. COST FUNCTION

The cost function adopted in the model includes all forms of expenses incurred in operating an aircraft along a particular stage. Factors considered cover costs experienced by passengers, operators and traffic control authorities. Such costs include expenses associated with aircraft engineering (maintenance), passenger delay, crew charges, scheduling and fuel burn as partly outlined in Attwooll (1966). Expense is accumulated over the cost datum if an aircraft deviates (intentionally or unintentionally) from the expected heading. This deviation is generally a result of weather, navigational drift and conflict resolution.

In addition, the simulation model investigates and reports on delays experienced at the aircraft departure point. The delay component considered is that due to route congestion, not airport congestion. For the purpose of this analysis, an assumption is made that airport congestion is not the critical link in the departure sequence of aircraft. The program can be readily modified to input airport congestion associated delays from other models.

To aid in the arrangement of associated factors the expenses have been classified into two groups. These groups are identified as ground delay and enroute delay. The enroute delay deals with expenses incurred as a result of conflict resolution, track deviations and weather diversion delays. The ground delay deals with delayed departure due to route congestion. The cost function can be expressed simply as,

$$C_s = f(\, Ground \,,\, Enroute \,) \tag{2}$$

where C_s is the cost to the system.

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

$$\overline{C}_s = \frac{1}{n}\left[\sum_{i}^{n} C_{G_i} + \sum_{i}^{n} C_{E_i}\right] \tag{3}$$

where the expressions for C_{G_i} and C_{E_i} are calculated by accumulating relevant cost factors for the i^{th} aircraft. n is the number of aircraft. The association of these cost factors to their relevant group is shown below in Figure 3.

The exclusion of the fuel burn and engineering factor in the delay costs is due to both factors being primarily dependent on flying time. The other factors are merely time dependant.

One other cost factor not addressed so far is that related to the ADS update. The update rate will be dependent upon route configuration, intersection density and traffic flow. The

$$C_{G_i}\left[\begin{array}{l}\text{Crew}\\ \text{Passenger Delay}\\ \text{Schedule Slippage}\end{array}\right.$$

$$C_{E_i}\left[\begin{array}{l}\text{Crew}\\ \text{Passenger Delay}\\ \text{Schedule Slippage}\\ \text{Fuel Burn}\\ \text{Engineering}\end{array}\right.$$

Figure 3 Cost Factors

rate will vary according to these parameters providing the controllers adequate information to safely process the passage of aircraft through the particular sector. The degree of ADS update is also influenced by the level of minimum separation. For low separation minima, the update rate could be of the order of 10 updates/minute and is therefore close to that for radar coverage of enroute sectors.

The limiting factor to applying the maximum update rate is the related cost. It is anticipated that the cost of utilising the communication satellites will be in the order of AUS$1.00 per message update. This cost is related to the size of the information block being sent. For this reason the update rate needs to be considered in any system cost function. For this paper, the model calculates the cost of ADS update per aircraft based on a constant update rate over the system. In future modelling work it is anticipated to investigate the role of the update rate in more detail. Further modelling will be carried out to investigate the effects of varying the update rate. The cost function from Equation 3 can now be expanded to include the cost of the ADS update as well.

$$\overline{C}_{s_{ADS}} = \frac{1}{n}\left[\sum_{i}^{n} C_{LS_i} + \sum_{i}^{n} C_{AS_i} + \sum_{i}^{n} C_{ADS_i}\right] \qquad (4)$$

Where, $C_{ADS_i} = (f_{ADS}\ t_i\ U_{ADS})$, f_{ADS} is the ADS cost factor ($f_{ADS} \approx \$1.00$), t_i is the flight time and U_{ADS} is the update rate.

5. 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, it is attempted to validate the model by comparing with established analytical models. There have been a number of authors who have developed basic analytical relationships between conflict and separation. May(1971), Siddiqee(1973), Schmidt(1977), Dunlay(1975), Friedman(1984) and Geisinger(1985) have all demonstrated conflict models each with some degree of agreement. Schmidt(1977) model has been used for comparison with the present simulation model.

The equation for the conflict model is shown below in Equation 5, where $E(N_c)$ is the expected number of conflicts per hour.

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

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 indicated as α. Schmidt's model evaluates the expected number of crossing conflicts for a two route, single intersection system.

Results for the theoretical model given above have been compared with the output obtained from the simulation model. Velocities v_1 and v_2 are considered to be constant and equal to 500 knots, with $\alpha \approx 27^o$. The arrival distribution for both the simulation and theoretical model 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 zero for this particular exercise. The comparison of the two models is shown in graphical form in Figure 4.

It is seen that there is little difference between the results obtained from the theoretical model and the simulation model.

6. 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 the merit of the position report can adequately be considered. The field of data sent with the position report is termed the Figure of Merit (FOM) and is composed of,

i. an indicator of navigational equipment redundancy, and

ii. an indicator of position–fixing accuracy of the on–board navigation equipment (ADSP, 1993).

The FOM has been divided into 8 levels of merit. These 8 levels reflect the quality of the navigation. Level 0 represents the complete loss of navigational function, while level 1 to level 7 reflect an increase in navigation capability from poor to a high level of accuracy. Each FOM has a stated degree of positional accuracy that is based on a 95% containment within the boundary of allowable positional error.

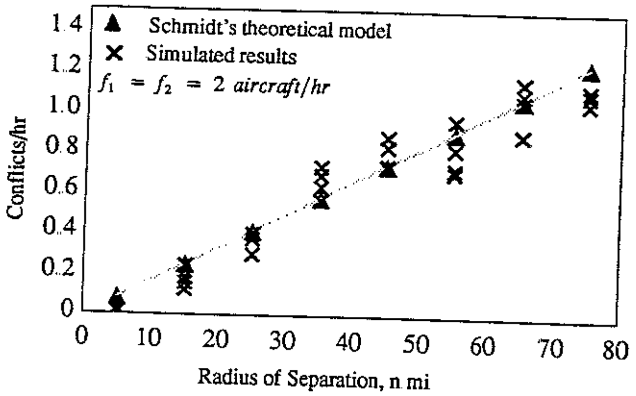

Figure 4 Comparison of the Simulation and Theoretical Models

These boundaries are derived from the expected positional inaccuracy that can be expected for aircraft operating with different on–board navigation systems and sector lengths. 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 for degradation of position reporting to be compensated for by the air traffic controllers in charge.

Given in ADSP (1993) is a simplified method for estimating the magnitude of the protected volume. This protected volume used best represents the shape of a rectangular prism as defined by a longitudinal, lateral and vertical separation minima. A number of variables are taken and applied to a simple root–sum–square procedure. The variables used in this paper are listed below.

V_1 – FOM $(n.mi)$
V_2 – Clock error $= 10\ secs \approx 1.3\ n.mi$
V_3 – Longitudinal error $= U_{ADS}/3\ (n.mi)$
V_4 – Message time $= 15\ secs \approx 2\ n.mi$
V_5 – Intervention time $= 5\ secs \approx 0.7\ n.mi$
V_6 – Display errors $= 5\ n.mi$

Time units are converted to distance units by assuming aircraft speed of 480 knots. For this paper, longitudinal and lateral separations are taken to be of equal magnitude. This is achieved by assuming a variability in aircraft heading of 2.5^o, a value possible under an ADS environment.

Simplifying further, the value of longitudinal and lateral separation can be taken as a radius of separation. i.e. $S_r = D_X = D_Y$, where D_X and D_Y are the longitudinal and lateral separations respectively.

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

$$S_r = (V_1^2 + V_2^2 + V_3^2 + V_4^2 + V_5^2 + V_6^2)^{\frac{1}{2}} \tag{6}$$

For this paper it is assumed the update rate (U_{ADS}) will be set at 5 minutes or 12 updates/hour. Table 1 shows containment values for each FOM and also the related longitudinal minimum separation that will be used in this paper.

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

Table 1 Containment values and related minimum separations

FOM	95% Containment Value (n.mi)	Min.Sep. (S_r) (n.mi)
A	N.A.	60
0	–	–
1	30	30.70
2	15	16.35
3	8	10.31
4	4	7.63
5	1	6.58
6	0.25	6.51
7	0.05	6.50

7. 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 based on a simple seven airport node network connected by five airport to airport links. Each of the links has at least one intersection point. The links allow bi–directional air traffic flow. The airport node layout is representative of the regional area that covers the Tasman and South Pacific Oceans. The longest airport to airport link is approximately 3300 nautical miles in distance and is similar to the Sydney–Papeete link. The smallest link is just over 1000 nautical miles which corresponds with the cross Tasman routes. Reference to actual airports and stages are deliberately avoided in this paper because of numerous local features not incorporated in the network presented here. It is best to consider the network as a hypothetical network that has similarities with a selected routes in the Pacific region. The layout used in this paper is shown in Figure 5.

8. RESULTS

Cost Savings

The graph in Figure 6 shows the relative expenses incurred per aircraft as a function of the minimum separation. For this particular graph an arbitrary flow value has been chosen to represent the possible low flow densities that could be experienced in the Pacific region. For each route the flow value has been set at 1.0 aircraft/hr per route. Due to the routes being bi–directional, the flow rate in a given direction is 0.5 aircraft/hr. The input data used for aircraft operating costs is based on information obtained from BTCE (1993) and the operation flight manuals of the major aircraft types that operate the medium length routes across the Pacific.

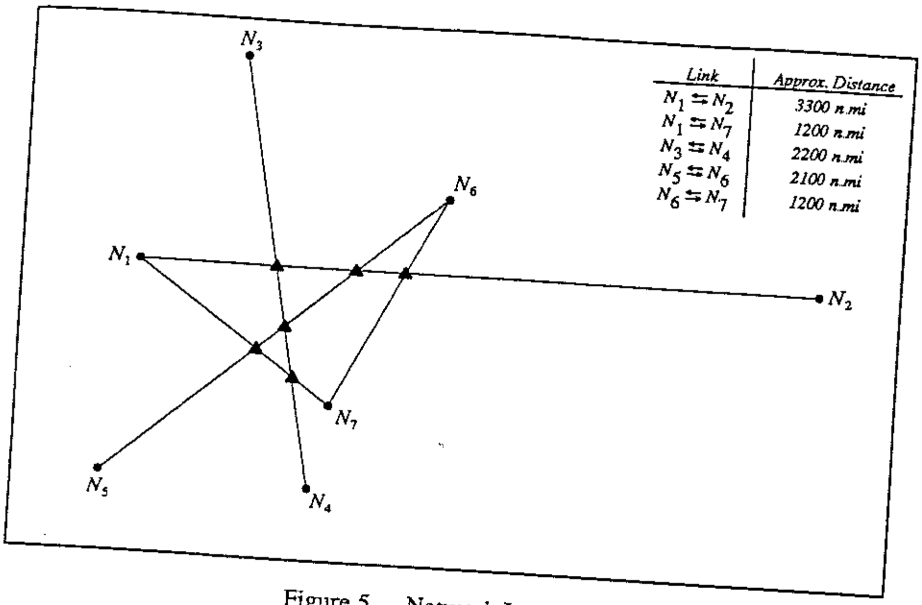

Figure 5 Network Layout

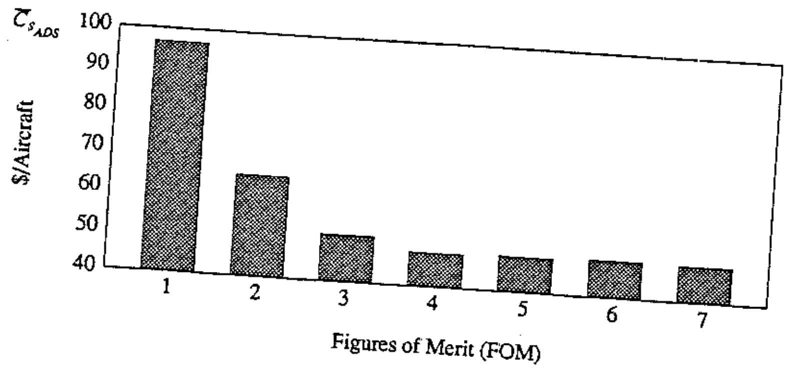

Figure 6 Costs Incurred as a Function of FOM

As expected, for high levels of FOM (5, 6 and 7), the cost is dominated by the cost of the update rate, which is approximately $45 per aircraft for the analysed network. The slight rise in cost of FOM 6 and FOM 7, compared to FOM 4, is due to the rarity of conflict occurrence. This is due to the low values of separation, and flow rates, being adopted in the simulation. The random nature of simulation provides these results.

Shown in Figure 7 are the results of comparing different FOM with varying flow rates. The results of the regression analysis are shown in Table 2 where a and b are the regression coefficients and r is the correlation coefficient. The data points appear to be linear in nature and this was confirmed by the correlation coefficients giving reasonable linear fit.

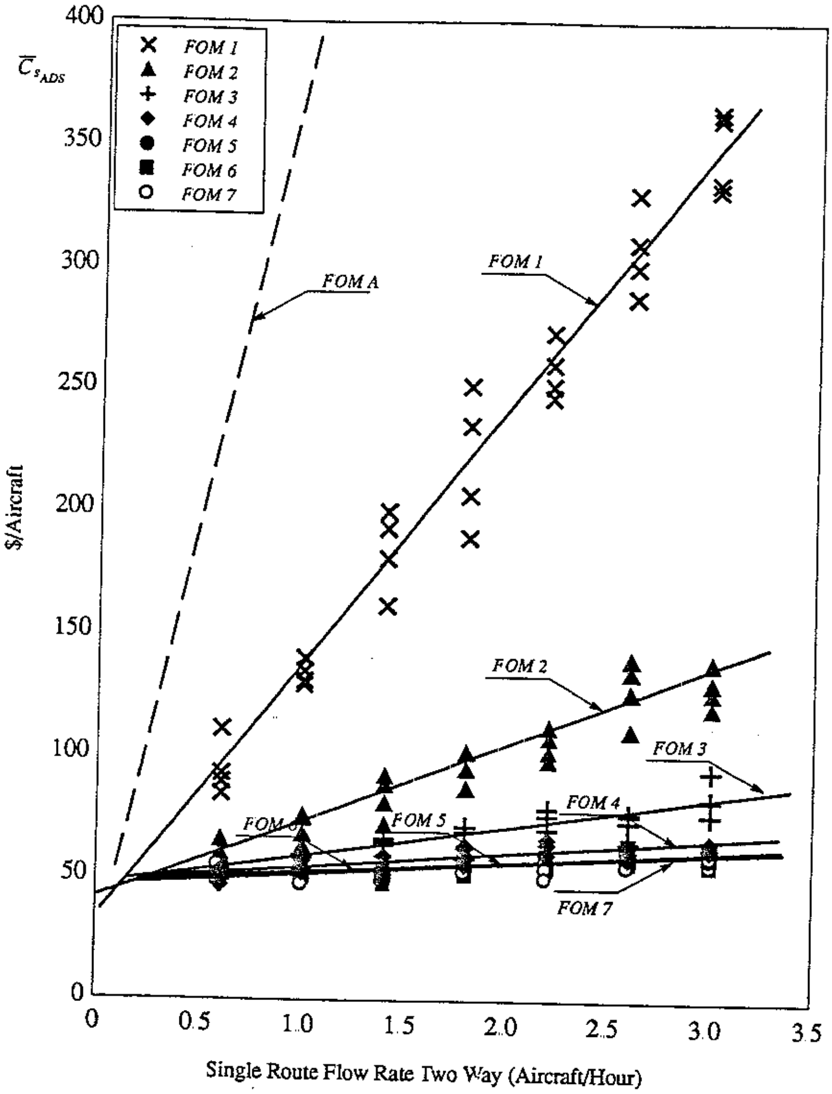

Figure 7 Flow Rate as a Function of FOM

Each FOM is compared to FOM A, and the percentage cost saving is determined by the following relationship,

$$C_{FOM} = \frac{b_A - b_i}{b_A} \tag{7}$$

where, b_i is the regression coefficient of FOM 1–7. The contribution of the regression coefficient, a_i, to C_{FOM} is negligible, and has therefore been omitted. Consequently, for flow rates well below saturation, it can be assumed that the percentage cost savings (C_{FOM}) are independent of the flow rate.

Table 2 Regression coefficients and percentage cost savings

FOM	a_i	b_i	r	Cost Savings as percent of FOM A (Approx)
A	21.48	360.06	0.9985	-
1	30.80	105.5	0.9994	70.69
2	41.08	30.63	0.9906	91.49
3	45.80	11.89	0.9697	96.69
4	47.91	5.571	0.9373	98.45
5	46.04	4.672	0.9803	98.70
6	47.57	3.953	0.9168	98.90
7	46.66	4.320	0.9685	98.80

Assuming that flow rates used in this exercise represent an average 12 hour day, it is possible to estimate the potential savings that could be gained on a per annum basis for each FOM level, and for a given flow rate. Shown in Table 3 is the dollar cost savings, as related to FOM A. It should be noted that the precision of the cost parameters is not that important because the same parameters are used for each regime. The actual cost estimates may not be entirely accurate, but the trend and slope of the line can be taken to be reasonably accurate.

Table 3 Annual cost savings based on FOM A for flow rate of 2 aircraft/hr/route

FOM	Cost Savings ($million)
1	21.87
2	27.99
3	29.43
4	29.89
5	30.05
6	30.05
7	30.06

9. CONCLUSION

This paper has presented a methodology to investigate the effects of technological advances in the field of air traffic control. During this project, emphasis has been placed on investigating the trend and the nature of the slope of the graphs. As demonstrated, for relatively low levels of air traffic, the annual cost savings that can obtained are substantial (Table 3). It is also significant that large percentage cost savings can be gained from implementing FOM 1 as compared to FOM A. Further work will investigate more closely the possibility of the existence of an optimum FOM for particular regional areas, or particular network flow densities.

Expansion of the network under investigation to include other airports in the region would yield proportional cost savings across the entire network. By inclusion of the other airport nodes in the regional network, it can be shown that there will be a higher number of resolution manoeuvres, due to the greater occurrence of intersection nodes. Again, the analysis presented is conservative in its estimates. In this study the cost savings that may be derived from the inclusion of all other airports and links in the region has not been considered to avoid undue complexity of analysis.

Although the cost of infrastructure and equipment has not been considered in the cost equation, the overall impact of such features is likely to negligible. This is because additional cost savings are expected to be gained from not having to replace current land based navigational aids, and updating or maintaining costly INS systems.

Analysis of more networks will allow for a better understanding of the relationship between network complexity and cost structure. Furthermore, there is scope to evaluate the update rate and minimum separation, as well as their relationship to network complexity and traffic flow.

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