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Economic Effects of Increased Control Zone Sizes in Conflict Resolution

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Abstract

A methodology for estimating the economic effects of different control zone sizes used in conflict resolutions between aircraft is presented in this paper. The methodology is based on estimating the difference in flight times of aircraft with and without the control zone, and converting the difference into a direct operating cost. Using this methodology the effects of increased lateral and vertical control zone sizes are evaluated.

Background

Aircraft conflict detection and resolution methodologies have been under research and development for several years. Out of these efforts have arisen at least four decision support tools for air traffic control automation - User Request Evaluation Tool (URET, Ref. 1 & 2), Conflict Prediction and Trial Planning Tool (Ref. 3), Prediction/Resolution Advisory Tool (PRAT, Ref. 4) and En Route Operational Display and Input Development system (ODID, Ref. 5). Another project, the ARC2000 (Automatic Radar Control for the years beyond 2000, Ref. 6 & 7) has produced demonstrator components but is not yet implementable, as it lacks the human-machine interfaces for controllers.

All of these tools are initially targeted towards the en route automation programs and are designed to maintain the radar separation standards in force. The horizontal radar separation standard in US en route airspace is typically 5 nautical miles (nm) below FL 600 and 10 nm at or above FL 600 (FL stands for flight level). The IFR vertical separation standard is 1000 feet below FL 290, and 2000 feet at or above FL 290. Reduced vertical separation requirements from 2000 to 1000 feet separation minima above FL 290 is currently planned for the North Atlantic, and are being considered in the future for US domestic airspace (Ref. 8).

In this paper, the volume of airspace surrounding an aircraft with the relevant separation standards is called the Protected Zone. All of the conflict detection and resolution tools are designed to keep aircraft from penetrating the Protected Zones (PZ) of other aircraft. To achieve this safety level, all of these tools have a Control Zone (CZ) associated with each aircraft. The CZ is the volume of airspace surrounding an aircraft which the conflict prediction algorithms use to predict possible, future PZ penetrations. These CZs are at least as large as the PZs, see Figure 1. There is an inherent uncertainty in all of the conflict prediction algorithms, for example, due to inaccuracies in wind or position data. Because of this uncertainty and the desire to keep false positive (aircraft predicted to be in conflict, when in reality they will not be in conflict) and false negative (aircraft predicted to not be in conflict, when in reality they will be in conflict) alerts to a minimum each of the different tools have a different buffer designed around the PZ of the aircraft. These result in different size CZ designed around the aircraft - the CZ consists of the PZ and the buffer around the PZ. Depending on the algorithms used, the geometry of conflict, aircraft types involved, or the aircraft phase of flight may affect the size of the CZ, i.e., the CZ may not be of the same fixed size under all conditions.

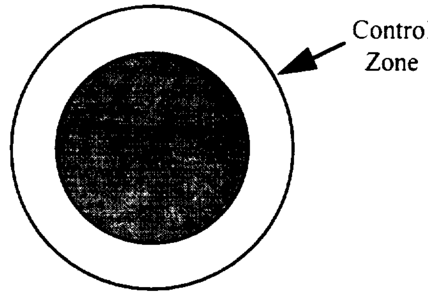

Figure 1: An Example of a Horizontal Protected Zone and a Control Zone

With increasing CZ size, two things happen - first, more conflicts are detected between aircraft, and second, to resolve a predicted conflict larger deviating maneuvers will be required by the aircraft involved. These larger maneuvers for more conflicts result in additional fuel burn and longer times to destination, i.e., increased direct operating costs.

Purpose

The objective of this study is to evaluate order-of-magnitude estimates of the increased direct operating cost due to different Control Zone (CZ) sizes in Class A airspace (above FL 180).

This study will not evaluate any of the above mentioned conflict detection and resolution decision tools, nor will it evaluate the current system involving air traffic controllers. However, the results of this study can be used by a decision maker to:

1) Obtain the increased direct operating cost due to a conflict detection and resolution decision support tool over optimal paths,
2) Compare the additional costs between two such conflict detection and resolution decision support tools.

In both of the above cases, the decision maker must have an idea of the size of the CZs that is used by the tools under investigation.

Methodology

An overview of the methodology is shown in Figure 2. First, a simulation run of the no conflict resolution (CZ = 0) scenario is run. This means that none of the aircraft will have to maneuver out of their desired flight path, and so this scenario represents the smallest time and lowest cost scenario. For all other non-zero CZ size, alternate simulations are run. In these simulations, aircraft will have to deviate out of their desired flight path to resolve any predicted conflicts. These conflict resolution maneuvers result in additional time and additional cost for these alternate scenarios. The total flight time is measured during the simulations of the two scenarios. The difference between these two total flight times is then scaled up and converted to the final measure - annual, additional direct operating cost. Scaling up is required for two reasons - first, because of the limited conflict resolution capability of the simulation tool there will be a number of conflicts that are not resolved, and second, to go from the number of flights simulated to the total number of flights per year.

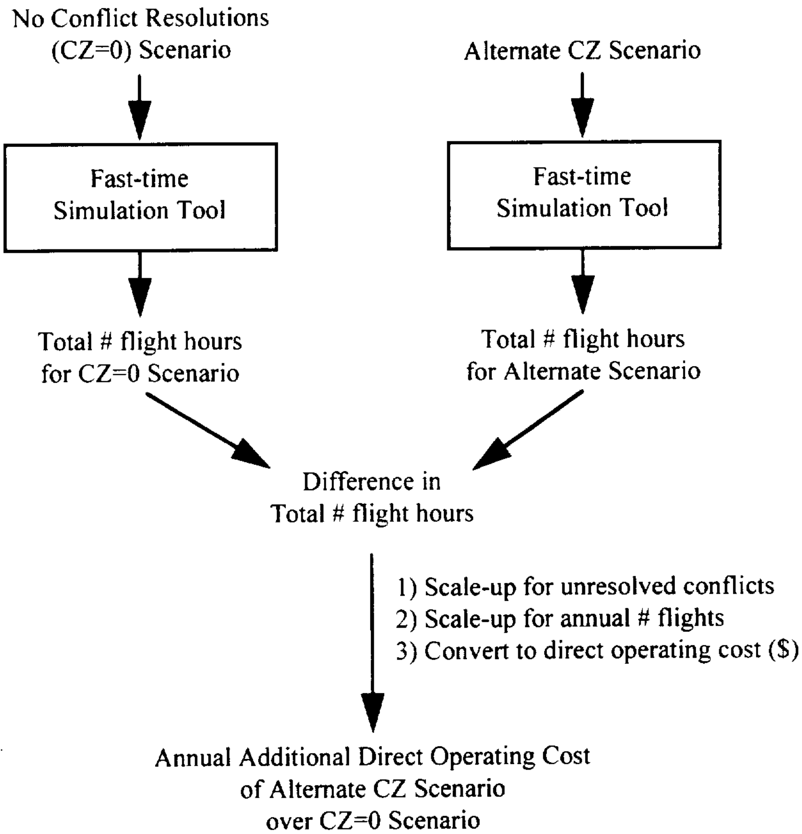

Figure 2: Overview of the Methodology

This scaling up and conversion results in the following equations:

$$\boxed{\begin{array}{c}\text{Annual}\\ \text{Additional}\\ \text{DOC}\end{array} = \begin{array}{c}\text{Additional}\\ \text{time/conflict}\\ \text{resolution}\end{array} * \begin{array}{c}\text{Total \# conflicts}\\ \text{in class A airspace}\\ \text{in simulation}\end{array} * \frac{\text{\# flights/year}}{\text{\# flights simulated/day}} * \begin{array}{c}\text{DOC}\\ \text{rate}\end{array}} \quad (1)$$

where, DOC = Direct Operating Cost,

$$\boxed{\begin{array}{c}\text{Additional}\\ \text{time/conflict}\\ \text{resolution}\end{array} = \frac{\begin{array}{c}\text{Difference in total \# flight hours between}\\ \text{alternate CZ scenario and CZ = 0 scenario}\end{array}}{\text{Total \# conflicts resolved in alternate CZ scenario}}} \quad (2)$$

$$\boxed{\begin{array}{c}\text{Total \# conflicts}\\ \text{in class A airspace}\\ \text{in simulation}\end{array} = \begin{array}{c}\text{\# resolved conflicts}\\ \text{in class A airspace}\end{array} + \begin{array}{c}\text{\# unresolved conflicts}\\ \text{in class A airspace}\end{array}} \quad (3)$$

The inherent assumptions of this methodology are that:

1) Decision support tools for conflict detection and resolution would resolve all conflicts.
2) The simulation tool is reasonably good and resolves a large number of the conflicts but may not resolve all conflicts. So, on the average the additional time per conflict determined from the resolved conflicts, will also be the additional time per conflict required for resolving the unresolved conflicts in class A airspace. Also, this additional time per conflict resolution is representative of the decision support tool being simulated.
3) A large sampling of the flights in a day are simulated, so that a linear scaling up to the total number of annual flights is representative of the total number of conflicts generated per year in Class A airspace.
4) The number of conflicts and additional time required per conflict generated by the simulation is representative of the actual scenario being modeled.
5) Multiplying the additional time with a direct operating cost rate will produce a representative additional direct operating cost for the fleet of aircraft over the year.

<u>Alternate Control Zone Scenarios Simulated</u>

To evaluate the increased direct operating cost due to different CZ sizes in Class A airspace, the following scenarios were simulated. All the CZs were assumed to be cylindrical in shape, similar in shape to current aircraft separation standards, with a vertical dimension that represents the height of the cylinder and a lateral dimension that represents the radius of the cylinder.

1) *No Conflict Resolutions (CZ = 0) Scenario:* As outlined in the methodology, all other scenarios will be compared to this scenario.
2) *Effect of Changing Lateral Control Zone Size:* All these scenarios have a CZ that is 1000 feet vertically, but has different lateral sizes of 3, 5, 7.5, 10, or 15 nm respectively. Comparison of the results of these scenarios will show the effect of increased lateral CZ sizes.
3) *Effect of Changing Vertical Control Zone Size:* All these scenarios have a CZ that is 5 nm laterally, but has different vertical sizes of 1000, 1500 and 2000 feet respectively. Comparison of the results of these scenarios will show the effect of increased vertical CZ sizes. A priori, it is expected that because of cruising flight level assignments in class A airspace of the USA, that there will be a big difference in cost between vertical CZs of 1500 and 2000 feet.

Evaluation

To evaluate the methodology of the previous section, a fast time simulation tool called Total Airspace and Airport Modeller (TAAM, version 2.9.3, Ref. 9) was used. Most of this section provides a short description of TAAM and the data used in the simulations. Also in this section is the description of the aircraft direct operating cost rate used in the analysis.

<u>TAAM</u>

TAAM is a SUN workstation based computer program for fast time simulations of airport and airspace operations. A TAAM simulation consists of a project, which is a collection of user provided data that pertains to the specified study and its modeling requirements, see figure 3.

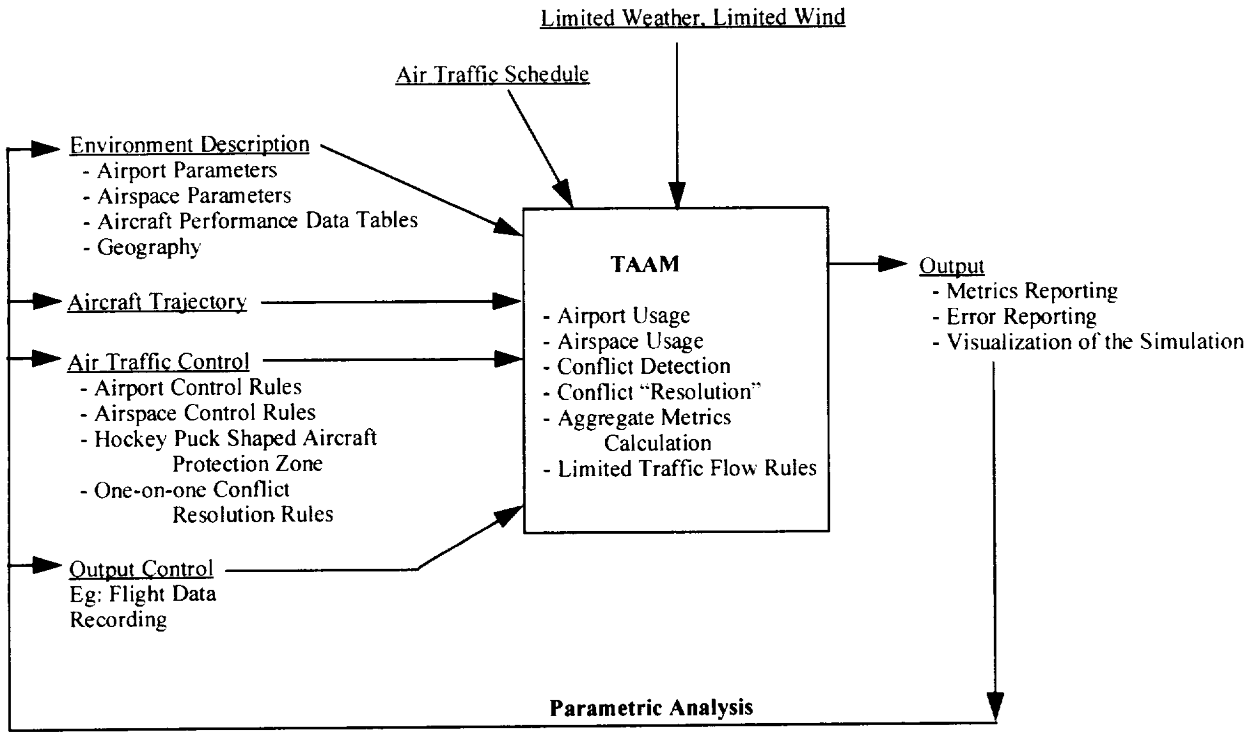

Figure 3: Conceptual Description of TAAM

Maps and airport layouts are built in the graphics tool set of TAAM. The environment is built in the interactive data input system of TAAM from the geographical data, waypoints, airports, routes, sectors, and terrain. The factors regulating and limiting the air traffic are set from a rule-base that includes the separation and wake turbulence spacing criteria, conflict detection and resolution rules, and sequencing parameters. The traffic demand in the environment is chosen from the traffic timetable and the aircraft performance characteristics. This data is passed on to the simulation program where it is processed by TAAM algorithms. Once the TAAM simulation is started successfully, graphics windows and panels are created. During the simulation, statistics are gathered by the reporting program and are written to a report file. This file is used by the report presentation facility of TAAM to construct the text and graphical reports desired by the user.

Data Input to TAAM

Air traffic schedule: The air traffic schedule file used for this study was obtained from Enhanced Traffic Management System (ETMS) data for April 10, 1996 (Ref. 10). The traffic schedule included 26,673 flights. The schedule specified each flight's identification number, aircraft equipment type, cruise altitude, origin and destination airport, and actual departure and arrival time. The ETMS includes data for all flights that filed a flight plan - typically, this is expected to be 50,000 to 60,000 flights/day. However, the provided data showed that a very large number of the flight data had incomplete information, no departure or arrival message tags, and these were eliminated from the air traffic schedule. For a smaller, but significant number of aircraft, mostly military, no aircraft performance data was available and they were also eliminated from the air traffic schedule.

Aircraft Trajectory: To simulate a future free flight scenario, it was assumed that all aircraft flew direct from origin to destination at the cruise altitude obtained from the ETMS data. The ETMS recorded flight paths have no conflicts between aircraft as predicted conflicts were resolved by air traffic controllers. Simulating the original ETMS data in TAAM would thus have produced conflict-free trajectories.
Aircraft Separation Standard: To simulate the effect of a Control Zone, the separation standard in each simulation was set to the desired CZ size. TAAM would then try and keep the aircraft from approaching a distance closer than the CZ size.
Conflict Resolution Rules: A basic set of conflict resolution rules was used in the TAAM simulations - in order of priority are changes in heading, altitude, and speed. TAAM uses a pair-wise conflict resolution strategy that is not as broad and comprehensive as the strategies that are used by air traffic controllers. Consequently, with multi-aircraft conflict scenarios often there are no successful resolution strategies obtained by TAAM. In these cases, TAAM puts out a message that the conflict cannot be resolved and continues to fly the aircraft with no resolution maneuver. This becomes especially important with larger separation standards, as will be seen in the results section. To appropriately account for these unresolved conflict cases, the scaling up methodology was formulated.
Airspace: In the simulation runs, the US airspace was divided into two large rectangular parallelepipeds covering the area of the continental US - one going from ground level to FL 180, and another covering FL 180 to FL 600. The latter volume then covered the Class A airspace. Instead of evaluating the effects on the existing air traffic control center airspace, this simplification allowed for an easy evaluation of the effects of different CZ size in Class A airspace. The simulations included conflict resolutions in the lower airspace (ground to FL 180) so that the aircraft would arrive in Class A airspace with the appropriate separations.
Other Input Files: The effects of weather and wind were not simulated. The airport and geography input data files were files created for past work and remained unchanged.

Aircraft Direct Operating Cost Rate

From past studies (Ref. 11, 12) the average weighted direct operating costs for all aircraft operations is found to be approximately the direct operating costs of a twin-engine large jet aircraft. This reflects the predominance of this aircraft type in the IFR traffic schedules. The operating oil and fuel cost along with the maintenance cost (in 1996 dollars) of a twin-engine large jet is $830/hour (Ref. 13). This cost does not include crew costs as conflicts and conflict resolutions are unpredictable and relatively unlikely events, and schedule determinations are not made based on these events. This cost is assumed in the rest of the analysis to be the average weighted direct operating cost rate for all aircraft in the IFR traffic schedule.

Total Number of Annual Flights

The FAA forecasts 48.1 million instrument operations nationwide in 1996 and 58.2 million in 2007 (Ref. 14). The forecasts represents the total number of takeoff and landings by Air Carrier, Commuter/Air Taxi, General Aviation and Military aircraft. These correspond to 24.1 and 29.1 million flights annually in 1996 and 2007. In the simulations the conflict numbers are only based on conflicts in Class A airspace, so scaling up the number of flights simulated with all IFR flights, assumes that for all these flights the same fraction of aircraft fly in Class A airspace and have predicted conflicts at the same rate. All these predicted conflicts are then resolved by a conflict detection and resolution tool.

TAAM Simulation Runs

In all of the following TAAM simulation runs the separation standard in the airspace was changed. TAAM resolves conflicting aircraft so as to keep them from violating the separation standard. Thus, the effect of separation standard change in TAAM is equivalent to a change in CZ size, thereby evaluating the effects of a CZ size.

1) *No Conflict Resolution (CZ = 0) Scenario:* No conflict detection and resolution was invoked in this simulation run. This case corresponds to direct flights with no flight path changes, i.e. CZ = 0 scenario.
2) *Effect of Changing Lateral Control Zone Size:* The separation standard was set to 1000 feet vertically in all airspace. To simulate the effect of changing lateral CZ size, the TAAM simulation runs were run with separation standards of 3, 5, 7.5, 10, and 15 nm respectively. Comparison of the results of these scenarios will show the effect of increased lateral CZ sizes.
3) *Effect of Changing Vertical Control Zone Size:* The separation standard was set to 5 nm laterally in all airspace. To simulate the effect of changing vertical CZ size, the TAAM simulation runs were run with vertical separation standards of 1000, 1500 and 2000 feet respectively. Comparison of the results of these scenarios will show the effect of increased vertical CZ sizes.

In addition to the above mentioned simulation runs, other simulations were performed to evaluate other effects that could affect the results obtained in the simulation runs (1) through (3). The a priori assumption is that these effects are of a smaller order than the effect of different CZ sizes. These simulations were run to corroborate the assumption that these effects are of a smaller order. The other effects evaluated were:

4) *Effect of Departure Time Randomization:* Since the economic results are dependent on the total number of conflicts in Class A airspace and conflicts are very time-dependent, the effect of departure time on the number of conflicts could be significant. To evaluate this effect, non-randomized departure times were compared against randomized departure times of 5 and 10 minute uniform distributions beyond the scheduled departure times. A separation standard of 5 nm lateral and 1000 feet vertical were used in these simulations. A specific randomization feature of TAAM was used that allowed for the randomization of scheduled departure times.
5) *Effect of Conflict Resolution Strategy:* Since the economic results are dependent on the additional time per conflict and that is conflict resolution strategy dependent, the effect of different conflict resolution strategies on the economic results could be significant. To evaluate this effect, the base case conflict resolution strategy was compared against an alternate conflict resolution strategy where the order of priority is changes in altitude, heading, and speed. Two simulations were run - one with a separation standard of 3 nm lateral and 1000 feet vertical and another with 5 nm lateral and 1000 feet vertical. These were compared against the base case conflict resolution strategy for the same separation standards.
6) *Effect of current separation standards above FL 290:* While evaluating the effect of different lateral CZ sizes, the simulations were run with the same vertical separation standard in all of Class A airspace (FL 180 and above). However, the vertical separation standard above FL 290 is 2000 feet and is 1000 feet below FL 290. Could this be a significant effect? To

evaluate this effect, another simulation was run where the upper airspace was sub-divided into two: one from FL 180 to FL 290 with a separation standard of 5 nm and 1000 feet, and the other from FL 290 to FL 600 with a separation standard of 5 nm and 2000 feet. This simulation was compared against the simulation run of scenario (2) where the separation standard was 5 nm lateral and 1000 feet vertical for all of FL 180 to FL 600.

Results

The results of the simulation runs are presented in Table 1. It shows that for increasing lateral CZ size (separation standard in TAAM) the total number of flight hours increases, and the number of resolved and unresolved conflicts also increases. It also shows that for small CZ sizes the conflict resolution strategy implemented in TAAM is adequate and resolves a large fraction of the conflicts. However, with increasing size, a larger fraction of the conflicts remain unresolved. These results indicate, that not taking into account the effect of unresolved conflicts could produce trends that are not accurate. To remove the effect of unresolved conflicts, the scaling-up factor for unresolved conflicts described in the methodology section was implemented.

With regard to different vertical CZ sizes, Table 1 shows that for 1000 or 1500 feet CZ the total flight hours are about the same but increases considerably for a CZ size of 2000 feet. With regards to the other effects, the total flight hours does not change by a significant amount indicating that these other effects are of a smaller order than the effects due to CZ size.

The results of Table 1 are converted to direct operating cost results, using the equations (1), (2), and (3) of the methodology section, and are presented in Table 2. All economic results are presented in 1996 dollars for direct route flights. Some of these results are also presented in Figures 5 and 6.

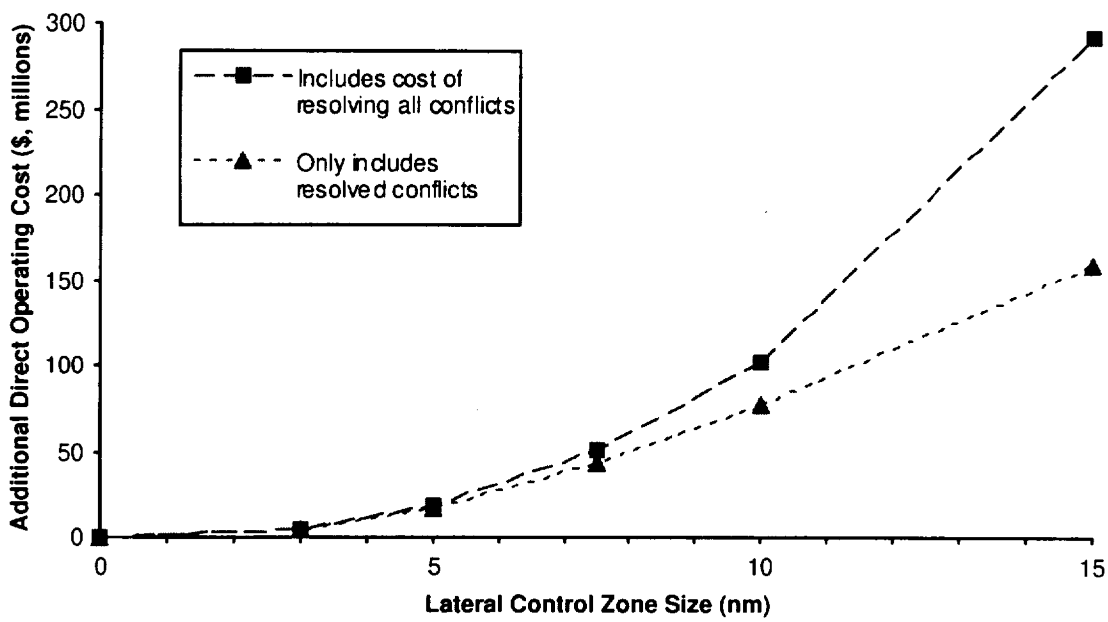

Figure 4: Effect of Including Costs of Unresolved Conflicts - Increased Annual Costs (in 1996 $) in Class A Airspace Due to Different Lateral Control Zone Sizes for 1996 traffic

Scenario	Total Number of Flight Hours	Number of Resolved Conflicts < FL 180	Number of Resolved Conflicts >= FL 180 (Class A)	Number of Unresolved Conflicts >= FL 180
No resolution scenario				
CZ = 0	29005			11442
Different lateral CZs				
CZ = 3 nm	29019	4146	2774	65
CZ = 5 nm	29061	7139	4720	351
CZ = 7.5 nm	29149	11255	7438	1399
CZ = 10 nm	29245	14187	10516	3541
CZ = 15 nm	29431	16930	16470	14069
Different vertical CZs				
CZ = 1000 ft	29061	7139	4720	351
CZ = 1500 ft	29062	7308	4783	363
CZ = 2000 ft	29576	7367	4803	368
Effect of Departure time				
No randomization	29061	7139	4720	351
5 min. random	29062	7163	4404	293
10 min. random	29174	7270	4449	349
Effect of resolution strategy				
Original strategy, CZ = 5 nm	29061	7139	4720	351
Alternate strategy, CZ = 5 nm	29062	7103	4437	387
Original strategy, CZ = 3 nm	29019	4146	2774	68
Alternate strategy, CZ = 3 nm	29023	4094	2532	66
Effect of current separation standard				
CZ = 1000 ft	29061	7139	4720	351
CZ = 1000 ft for < FL 290 CZ = 2000 ft for >= FL 290	29062	7376	4808	367

Number of flights simulated = 26,673. All aircraft flew direct from origin to destination.

Table 1: Results of TAAM Simulation Runs

Scenario	Additional Time Per Conflict Resolution (minutes)	Total # Conflicts In Class A Airspace In Simulation	Annual Additional Direct Operating Cost ($ millions)	
			1996	2007
Different lateral CZs				
CZ = 3 nm	0.12	2839	4	5
CZ = 5 nm	0.28	5071	18	22
CZ = 7.5 nm	0.46	8837	51	62
CZ = 10 nm	0.58	14057	102	124
CZ = 15 nm	0.77	30539	292	353
Different vertical CZs				
CZ = 1000 ft	0.28	5071	18	22
CZ = 1500 ft	0.28	5146	18	22
CZ = 2000 ft	2.82	5171	182	220
Effect of Departure time				
No randomization	0.28	5071	18	22
5 min. random	0.30	4697	17	21
10 min. random	0.87	4798	52	63
Effect of resolution strategy				
Original strategy, CZ = 5 nm	0.28	5071	18	22
Alternate strategy, CZ = 5 nm	0.30	4824	18	22
Original strategy, CZ = 3 nm	0.12	2842	4	5
Alternate strategy, CZ = 3 nm	0.17	2598	5	7
Effect of current separation standard				
CZ = 1000 ft	0.28	5071	18	22
CZ = 1000 ft for < FL 290 CZ = 2000 ft for >= FL 290	0.28	5175	18	22

Number of flights simulated = 26,673. All aircraft flew direct from origin to destination.
Annual number of flights predicted in 1996 = 24.1 million and in 2007 = 29.1 million

Table 2: Economic Effects Results

All the results presented in Table 2 include a scaling-up factor for unresolved conflicts. The effect of including or not including the additional costs to resolve the unresolved conflicts in the simulation is shown in Figure 4 for 1996 traffic. The upper curve includes the cost of the resolved conflicts and the costs of resolving the unresolved conflicts that were obtained in the simulation, while the lower curve only includes the costs of resolved conflicts. These two curves show that not including the costs of unresolved conflicts results in almost a "linear" increase with lateral CZ size, whereas including these costs results in a much steeper increase with the slope increasing with lateral CZ size. Increasing lateral CZ size increases the costs as a "quadratic" function because the number of potential conflicts and the additional time per conflict resolution, both increase with CZ size. However, in the simulation increasingly larger fractions of the conflicts remain unresolved for larger CZ sizes (see Table 1), resulting in the almost "linear" behavior of the lower curve.

In addition to the annual additional direct operating cost, Table 2 also shows the variation in additional time per conflict resolution and total number of potential conflicts in Class A airspace as per the simulation runs. These two fields are an important part of the cost results as see in Equation (1). For a lateral CZ size of 5 nm the additional time per conflict is 0.28 minutes (see Appendix A for a limited verification of this number). The additional time increases to 0.46 minutes for a lateral CZ size of 7.5 nm - equivalent to a difference of about 11 seconds per conflict resolution maneuver. However, these "small" savings per conflict (going from a CZ size of 7.5 nm to a CZ size of 5 nm) translate into "large" annual savings ($ 33 million) because of the large number of annual, potential conflicts that are avoided by a large number of flights. Table 2 also shows that with increasing lateral CZ size the additional time per conflict resolution and the total number of conflicts increase. This is explored further in Appendix B.

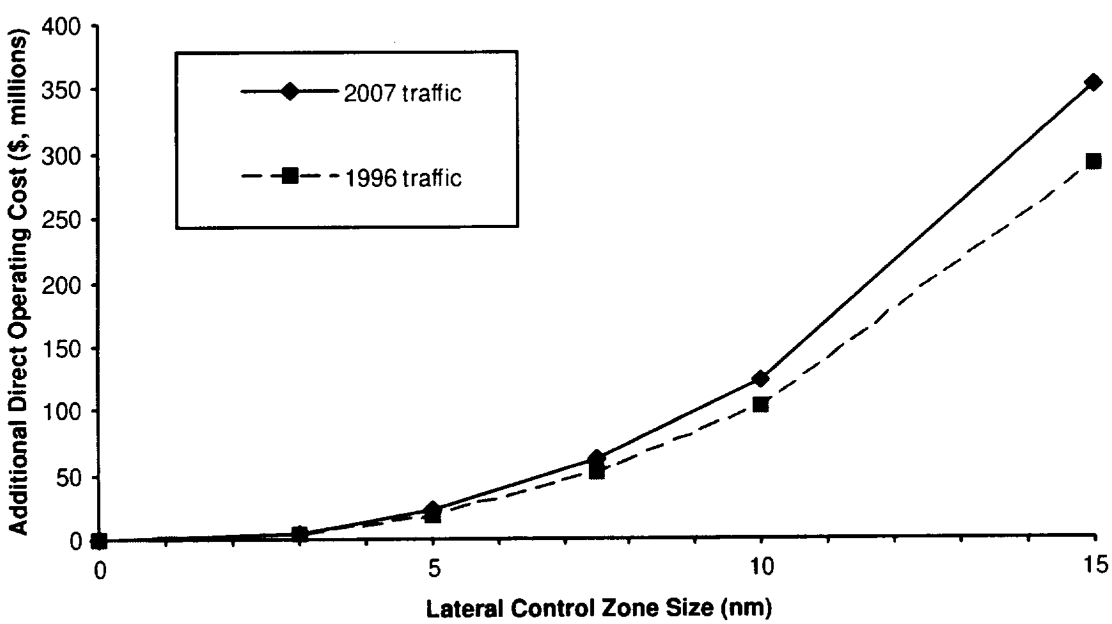

Figure 5: Increased Annual Direct Operating Costs (in 1996 $) in Class A Airspace Due to Different Lateral Control Zone Sizes

Figure 5 presents the graph of increased direct operating costs due to conflict resolutions in Class A airspace versus increased lateral Control Zone (CZ) sizes. Typically, the lateral PZ is 5 nm in size. So, the CZ sizes (CZ includes the PZ and a buffer) are larger than 5 nm. Typically, the CZ is expected to be in the 5 to 10 nm range. In Figure 5, the upper curve represents the additional costs for projected 2007 traffic, while the lower curve represents the costs for the projected 1996 traffic. Note that the upper curve for projected 2007 traffic is higher due to the increased number of flights which results in an increased number of conflicts. Both of these curves show the same behavior with no deep knees or bends in the curves. To put these additional costs in perspective with respect to 1996 traffic, the additional time for conflict resolution with a CZ of 5 nm or 10 nm is 0.08% or 0.5% respectively, of the total flight times.

Figure 6 presents a graph of increased direct operating costs due to conflict resolutions in Class A airspace, except in this case the abscissa has increased vertical (and not lateral) CZ sizes. The left part of the histograms represents the additional costs for projected 2007 traffic, while the right part of the histograms represents the costs for the projected 1996 traffic. This graph shows that the costs due to increased (from 1000 feet) vertical separations is about the same until the CZ size becomes 2000 feet, when the additional costs show a jump. This behavior is expected due to the nature of the flight level rules for IFR traffic - where the traffic are separated in 1000 feet intervals. The additional time for conflict resolution with a CZ of 1500 and 2000 feet are 0.08% and 0.8% respectively, of the total flight times.

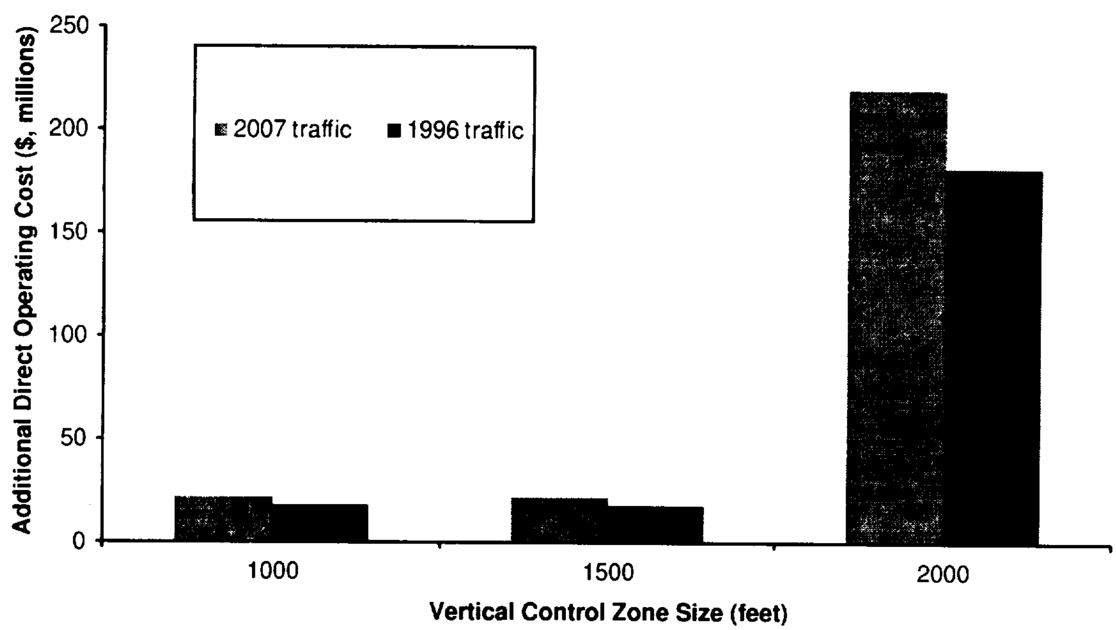

Figure 6: Increased Annual Direct Operating Costs (in 1996 $) in Class A Airspace Due to Different Vertical Control Zone Sizes

As previously mentioned, other simulations were performed to evaluate other effects that could affect the results obtained for different CZ sizes. The results of these simulation runs, presented in Table 2, confirm our a priori assumption that these effects are of a smaller order than the effect of different CZ sizes:

1) *Effect of Departure Time Randomization:* Departure time randomization of 1996 traffic showed that with no randomization, with 5 minute and 10 minute randomization, the additional costs are 18, 17 and 52 million dollars respectively. Apparently, due to the large number of flights simulated, on the average changing the departure times does not seem to strongly affect the results.

2) *Effect of Conflict Resolution Strategy:* Changing the conflict resolution strategy priorities in TAAM from heading, altitude, and speed changes to a different priority of altitude, heading, and speed changes also does not produce big differences in costs - it does not change for a lateral CZ size of 5 nm and it changes from 4 to 5 million dollars for a lateral CZ size of 3 nm for 1996 traffic.
3) *Effect of current separation standards above FL 290:* Increasing the vertical separation standard above FL 290, from 1000 feet to 2000 feet, imperceptibly changes the costs.

Conclusions

A methodology was presented for estimating the order-of-magnitude increased direct operating cost due to increased Control Zone (CZ) sizes in Class A airspace for direct route flights. The results (in 1996 $) indicate:

1) Increasing lateral CZ size increases the costs as a "quadratic" function, where the costs of CZ of 5 nm and 10 nm is 18 and 102 million dollars annually for 1996 traffic and is 22 and 124 million dollars annually for 2007 traffic.
2) Increasing vertical CZ size from 1000 feet increases the costs substantially only at CZ of 2000 feet. The costs of a 5 nm lateral and 2000 feet vertical CZ is 182 and 220 million dollars annually for 1996 and 2007 traffic, respectively.

The cost estimates would be different in an alternate route structure, as there would be different amount of conflicts in Class A airspace depending on the route structure. However, the pattern of increase should be similar. Another limitation of this analysis is that the number of flights in the simulation was roughly half the total number of IFR flights in a day. When the number of aircraft in the simulation is increased, it is expected that the number of conflicts would increase at more than a linear rate. A linear scaling-up technique has been used in this analysis. Better input data to the simulation, related to the flights per day, should reduce this limitation of the results.

In order to use the results of this study to compare different conflict detection and resolution decision support tools, the decision maker must have an idea of the size of the CZs for the various tools. Given that information, the decision maker can then use the results presented in this paper to evaluate the differential costs between any two such decision support tool. This study did not evaluate any of the above mentioned conflict detection and resolution decision tools.

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Appendix A: Limited Verification Of Additional Time Per Conflict Resolution

The direct operating cost results are obtained from equations (1), (2), and (3) of the methodology section. Equation (1), the primary equation, is based on the product of the following quantities - Additional time per conflict, Total number of conflicts in class A airspace in the simulation, Total number of flights per year, and the Direct operating cost rate. The latter two quantities are well documented. The total number of conflicts in class A airspace that need to be resolved can be verified only by performing an independent simulation under similar assumptions. Its order of magnitude could also be ascertained by calibrating against the potential conflicts that are resolved by air traffic controllers in the current air traffic system. The order of magnitude of the additional time per conflict for the 5 nm lateral CZ size is established in this appendix.

Clearly the additional time per conflict in any scenario is the combination of a number of types of resolutions (changes in heading, altitude, and speed) and the potential conflict scenario (flight path crossing angle, aircraft speeds, and distance at closest point of approach). The conflict resolution strategy used in most scenarios was in order of priority changes in heading, altitude, and speed. So, most of the resolutions were changes in heading, and so a simple heading change conflict resolution maneuver, as shown in Figure A, is assumed in this appendix. In this case, the original flight path of the aircraft is ABEF. To avoid the potential conflict in the flight segment BE, the aircraft is moved off course by 5 nm, and so the flight path including conflict avoidance is ABCDEF.

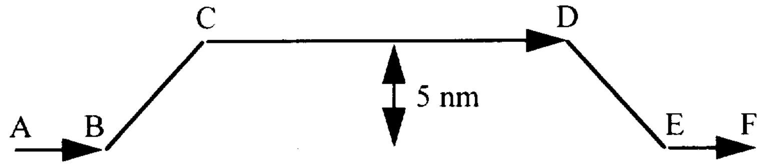

Figure A: A Sample Heading Change Conflict Resolution Maneuver

For this assumed conflict resolution maneuver the additional distance for the maneuver is computed assuming a 30 degree heading change maneuver BC and DE. The additional distance can be easily shown to be $2 \times 5 \times (\text{cosecant}(30) - \text{cotangent}(30)) = 2.68$ nm. Assuming an aircraft speed of 8 nm/min, this converts to an additional time of 0.34 min. This number is slightly larger than the average of 0.28 minutes additional time per conflict in the simulation results (see Table 2). However, they are of the same magnitude.

Appendix B: Additional Detail Regarding Conflicts With Increased Lateral CZ Sizes

Table 2 showed that increasing the lateral CZ size increases the costs as a "quadratic" function because the number of potential conflicts and the additional time per conflict resolution, both increase with CZ size. These increases are explored in this Appendix. Figure B1 plots the number of conflicts with different lateral CZ sizes. The figure shows that increasing the lateral CZ size "quadratically" increases the number of conflicts in the simulation. The most likely explanation is that the number of conflicts is proportional to the CZ volume, which in this case increases as the square of the lateral CZ size.

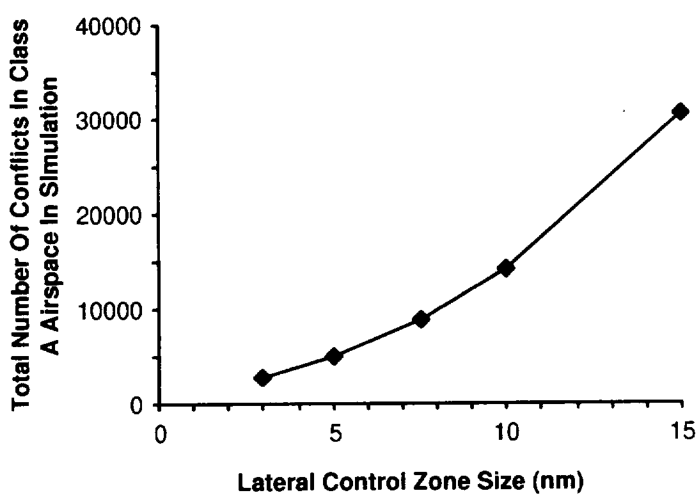

Figure B1: Total Number of Conflicts in Class A Airspace in Simulation For Different Lateral Control Zone Sizes

Figure B2 plots the additional time per conflict resolution with different lateral CZ sizes. The figure shows that increasing the lateral CZ size increases the time per conflict resolution in the simulation. However, one would expect that this increase would be linearly proportional to the CZ size, and instead it appears to increase linearly but then shows a reduced rate of increase. The most likely explanation is that as it becomes harder to resolve conflicts laterally the conflicts are resolved by changes in altitude and in speed, which would not increase linearly with CZ size. This is borne out the numbers presented in Table B1.

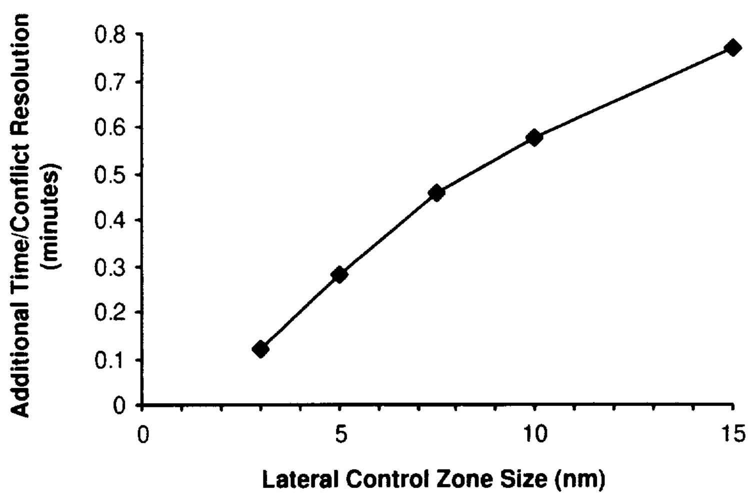

Figure B2: Additional Time Per Conflict Resolution For Different Lateral Control Zone Sizes

Table B1 shows that as the CZ size increases a smaller percentage of the conflicts are being resolved by changes in heading from a high of 86% for a CZ size of 3 nm to a low of 68% for a CZ size of 15 nm. These decreases are accompanied by almost even increases in the percentages of conflict resolutions through changes in altitude and speed.

Control Zone Size (nm)	Percentage of Conflict Resolution Maneuvers in Simulation		
	Heading Changes	Altitude Changes	Speed Changes
3	86	10	4
5	82	12	6
7.5	77	14	9
10	74	16	10
15	68	19	13

Table B1: Types of Conflict Resolution Maneuvers with Different Lateral Control Zone Sizes

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13. ABSTRACT *(Maximum 200 words)*

A methodology for estimating the economic effects of different control zone sizes used in conflict resolutions between aircraft is presented in this paper. The methodology is based on estimating the difference in flight times of aircraft with and without the control zone, and converting the difference into a direct operating cost. Using this methodology the effects of increased lateral and vertical control zone sizes are evaluated.

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