Aggregate Flow Model for Evaluating ATC Planning Strategies

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An aggregate traffic flow model is developed and used to evaluate the potential benefits of automated, facility-level, on-line air traffic flow control. Most present air traffic models simulate, in varying levels of detail, the movement of individual aircraft, which results in considerable computational requirements. However, the model described here essentially monitors and dynamically adjusts traffic flow rates and traffic densities on the routes in the ATC network. The route flow adjustments are based on controller workload criteria, with the intent of eliminating traffic surges and the associated periods of excessive workload. The model is used to evaluate two flow control strategies with respect to aircraft delay, controller workload, and staffing considerations at Los Angeles Air Route Traffic Control Center.

Introduction

PRESENTLY, the ATC system controls aircraft movements primarily based on short-term (e.g., 1-5 min) tactical considerations. However, with the availability of a computer-based real-time information records system of aircraft position and status, there is the potential of exercising control based on longer-term (e.g., 15-30 min) planning considerations; we call this mode of operation planning control. The tactical mode of ATC operations is based on microscopic variables such as relative aircraft positions and speeds. However, it is envisioned that the planning control mode, superimposed over the tactical mode, will be based on more macroscopic (aggregate) variables analogous to aircraft flow rate and density on various air routes.

The purpose of this paper is to describe a modeling procedure, and its use as an evaluation tool to investigate planning control concepts. Imbedded within this model is a submodel which calculates the controller workload induced by aggregate aircraft movements. Consequently, the model has the potential of evaluating planning control strategies and their effect on the flow of aircraft on routes, and the relationship of aircraft flow on routes to controller workload and, ultimately, staffing considerations.

The description of the model includes the network structure, the aggregate variables and their relationships, the controller workload model, and control strategies for restructuring the flow of aircraft when certain portions of the ATC system become overloaded and therefore constitute a bottleneck. As an example application, a planning control strategy is compared with the current, manually implemented, local flow control so that the effect can be assessed for a multisector region of the Los Angeles Center (Palmdale, Calif.).

ATC Operations and Planning Control

Presently, the enroute centers are equipped with a computer-based information, retrieval, and display system called NAS (National Airspace System) Stage A; major terminal facilities are equipped with a counterpart system called ARTS III (Automated Radar Terminal System). Both the NAS and ARTS systems will provide real-time recordkeeping of aircraft position and status (e.g., aircraft type, origin-destination, expected time of arrival over navigating fixes, revised altitude clearances, route clearances or revisions, heading changes, speed restrictions). In this paper, we are concerned with enroute center operations, and planning control strategies based on the NAS Stage A system.

This real-time information records system could make feasible certain ATC operational innovations capable of increasing controller efficiency. For example, the establishment of a capacity/load predicting capability in conjunction with a facility-centered planning control strategy could have a productivity benefit associated with distributing the controller workload generated by traffic surge situations. Traffic surges cause concentrations of workload to move through a facility from sector to sector, resulting in an uneven distribution of workload among sectors at any instant in time. In the absence of flow-control operations, the time-varying surges would require that each sector affected be staffed to meet the short-term peak traffic demand although only one or a few sectors are processing the surge at some instant. This implies a policy to commit manpower resources that are not continuously used by each sector.

One obvious planning control technique is to divert aircraft in order to dissipate traffic surges. Aircraft in traffic streams contributing to potential workload overload situations would be rerouted to alternative traffic corridors. This strategy would minimize the occurrence of disproportionately high workload concentrations in individual sectors by spreading the traffic-processing workload across various sectors in a more uniform manner. The disadvantage of the approach is the diversion of aircraft from preferred routes and potentially major schedule disruptions.

Another technique could divert controller workload resources to process surges without significantly altering traffic route patterns. A planning control strategy could, for instance, issue time-varying, in-trail (e.g., longitudinal) separation directives to key upstream sectors along highly traveled routes to alleviate predicted bottleneck situations. If the bottleneck were due to a crossing or merging of several routes with streams of traffic at various altitudes, the in-trail

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separation strategy effectively would transform the altitude-separated traffic streams on each route into a single stream of separated traffic. The resulting reduction of the crossing or merging control problem would reduce significantly the workload required to process aircraft through the intersection. On the other hand, the workload associated with providing in-trail separation would, in effect, be reallocated and translated in time and space to sectors upstream of the bottleneck.

The real-time, traffic-reactive, in-trail-separation technique is attractive because it is a gentle evolution of current operations. Separation revisions currently are negotiated between adjacent sectors or coordinated through a flow controller. Planning control merely would use this process, enhancing its capability to react dynamically on-line to the computer-generated data describing prospective traffic situations over a multisector environment. These data would provide a geographic scope and time horizon on which to base separation restrictions that is broader than the one currently available to local flow control efforts. Current local flow control entails manual (i.e., without computer augmentation) establishment of traffic flow constraining and rerouting procedures along a few prescribed routes or between adjacent sectors.

Model Description

The model to be presented here is based on aggregate traffic variables analogous to flow rate and density on routes. As stated previously, flow control deals more directly with these aggregated variables than individual aircraft position, for example. Furthermore, computational efficiency is gained over individual-aircraft-following models such as described in Refs. 1-3. As a result, large geographic areas and traffic volume may be simulated with moderate computational requirements. The original specifications for this model were detailed in Ref. 4; the present model incorporates many changes and improvements.

Network Structure and Aggregate Model Variables

Initially, the air-route system and sector configurations must be converted to a network of nodes and arcs. More specifically, a "node" in the network represents the point of intersection of an air route with the boundaries of an ATC sector, whereas an arc between two nodes represents the route segment traversing a sector's airspace. Because two-way traffic is altitude separated, each route segment in a sector can be represented as a pair of unidirectional arcs. If we number the nodes and identify them with an index (say i), then, using conventional ordered-pair notation, the arc (ij) represents the arc from node i to node j.

The variables associated with the arcs are as follows: 1) aircraft entering rate, $r_{ij}(t)$, is the rate of aircraft entering the sector on arc ij at time t; 2) aircraft leaving rate, $s_{ij}(t)$, is the rate of aircraft leaving the sector on arc ij at time t; 3) aircraft count, $n_{ij}(t)$, is the number of aircraft in the sector on arc ij at time t; and 4) arc transit time, τ_{ij}, is the average transit time for an aircraft to transverse arc ij assuming no delay is imposed on the aircraft. The relationship between these variables in time and in space is given by conservation and logical relationships. Namely, conservation of aircraft on an arc ij implies the following equation must hold:

$$n_{ij}(t) = [r_{ij}(t) - s_{ij}(t)] \cdot \Delta t + n_{ij}(t - \Delta t)$$

where Δt is a small interval of time. This equation essentially states that the number of aircraft on an arc is equal to the number of aircraft previously on the arc plus the net inflow of aircraft.

Continuity at a node j implies the following equation:

$$\sum_i s_{ij}(t) = \sum_k r_{jk}(t)$$

This equation implies that the number of aircraft from all arcs entering node j equals the number of aircraft from all arcs leaving node j, since a node represents a point on a sector boundary and has no storage capability.

Storage capability, however, is implied in the following relation:

$$s_{ij}(t) = r_{ij}(t - \tau)$$

This relation states that, with no delays imposed and with constant relative vehicle velocities, the rate of aircraft leaving an arc at time t equals the rate of aircraft entering the arc at a time $(t - \tau)$ earlier, where τ is the arc transit time.

Essentially, then, the model monitors the rates of aircraft entering arcs, the rates of aircraft leaving arcs, the instantaneous aircraft counts on arcs, and the arc transit times. If the workload in any sector is excessive (i.e., the sector is congested), then workload is reallocated to adjoining sectors by delaying aircraft from entering the congested sector (i.e., reducing the entrance rates r_{ij}).

Controller Workload Model

During the course of some previous work,[5] a technique was developed for quantifying the controller workload and determining sector workload capacity, including mental and physical activity, as a function of traffic activity. The original technique, known as the Relative Capacity Estimating Process (RECEP), allowed for the effects of aircraft characteristics, route and sector geometry, and variations in ATC procedures. The method subsequently has been refined further[6] and now entails the calculation of a parameter or numerical index, the magnitude of which represents a quantitative measure of the difficulty or complexity of the traffic control process associated with an ATC sector. The index is the normalized weighted sum of the average or expected frequency of occurrence of a number of traffic-control related events (e.g., potential conflicts, pilot requests, controller coordinations). Succinctly, the index calculation consists of the following expression:

$$\text{workload index} = \sum_{\substack{\text{event}\\ \text{types}}} (W_i E_i) \tag{1}$$

where W_i is the relative event difficulty weighting of event i and E_i is the average (expected) frequency of occurrence of event i.

In this relation, the event weightings W_i are based on the event processing or execution time required for the activity related to the event. The determination of the maximum allowable workload index and task execution times are based on field measurements at several ATC facilities. This relation (1) resulted in a mildly quadratic function of the traffic activity.

For the purpose of this model, this relation is approximated by the linear relation

$$\text{workload index} \cong W_L = K_S n_S \tag{2}$$

where n_S is the total number of aircraft on all the arcs in the sector, and therefore under the control authority of the controller team and K_S is the workload coefficient, average workload per aircraft in the sector.

The relation between Eqs. (1) and (2) is shown graphically in Fig. 1. The fact that a linear approximation is used in this case does not detract from the accuracy of the model results since this relation is used only to assure that the traffic activity in a sector does not exceed its maximum capacity value.

It is important to note that the workload index depends on the total number of aircraft in the sector, including delayed aircraft. However, because of the natural implementation of planning control by means of in-trail restrictions, it is assumed that induced-delay work corresponds to an ad-

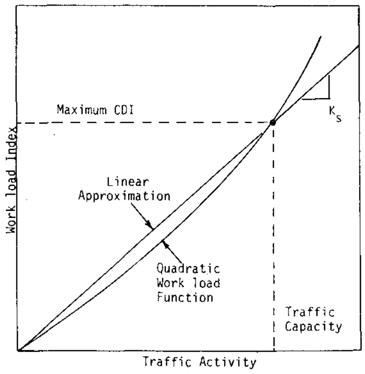

Fig. 1 Linear approximation of controller workload relation.

ditional amount of "normal" work. Therefore, the workload coefficient also represents the workload contribution due to a delayed aircraft.

Two Control Strategies

Two strategies for relieving an overloaded sector by imposing delays to aircraft about to enter the overloaded sector now will be highlighted. The first strategy essentially imposes delay to traffic on those routes which are at each instant of time carrying the most traffic into the congested sector. That is, the priority in which delay is imposed on the various routes is determined by the current, instantaneous route loading. The intent of this planning control strategy is to alleviate congestion caused by heavily loaded routes by delaying traffic on these routes primarily. If the traffic on the heavily loaded route is long-term and severe, then this strategy could delay "upstream" traffic from entering the facility (i.e., delay imposed on aircraft at the boundary of the facility).

In the following algorithm for implementing this strategy, both net and gross intersector traffic flows are considered. For example, the net flow from sector i to sector j is the difference between the flow from i to j and the flow from j to i. The algorithm is the following:

1) If at time t, congestion exists in one or more sectors, select the most congested sector, S_i.

2) Reduce the *net* traffic flow on the routes entering S_i from each adjacent sector until either
   a) congestion is eliminated – go to step 1,
   b) all adjacent sectors are full – go to step 4,
   c) no more net intersector traffic flow exists – continue.

3) Reduce the *gross* traffic flow on the routes entering S_i from each adjacent sector until either
   a) congestion is eliminated – go to step 1,
   b) all adjacent sectors are full – continue.

4) Reduce the gross traffic flow from the adjacent full sectors until the original congestion in S_i is eliminated. Note that this now "creates" congestion in "upstream" sectors.

5) Eliminate S_i from further consideration and go to step 1.

In the operation of this technique, only intersector traffic exchanges during the current time increment Δt are adjusted. Since at the previous time $(t-\Delta t)$ all congestion was assumed resolved, any congestion appearing at the current time t must be due to the traffic activity during this Δt. Because of this, congestion and/or delays are allowed to propagate "upstream" in space but only at the current time.

The second strategy was designed to emulate as closely as possible the flow control operations in the present ATC system. In this local flow control strategy, the order in which delays are imposed on routes is prescribed beforehand, that is, the route priority for delay is pre-established. The algorithm is as follows:

1) Specify the order in which routes R_i should be examined to relieve congestion.

2) If congestion exists, pick the most congested sector, S_i.

3) For this sector, scan through the ordered routes.

4) When a route R_i is found that employs this sector, delay as many aircraft as possible and as necessary immediately upstream from this sector along route R_i to relieve congestion.

5) Continue this scan until either congestion is eliminated for this sector, or the scan of all specified routes is exhausted.

6) If there is congestion at the end of the scan, issue a diagnostic for this sector, eliminate it from further consideration and go to step 2.

An Example: Los Angeles Center

As an example application, we shall consider the formulation and evaluation of a major portion of the Los Angeles ARTCC. The portion of this facility to be considered is that group of sectors which primarily control the Los Angeles arrival and departure traffic from and to the east. The analysis is concerned primarily with comparing the controller productivity (aircraft handled per controller) and the resultant delay imposed due to the flow control strategies considered previously.

Shown in Fig. 2 is a map of the area to be considered, along with the major routes into and out of Los Angeles, and the primary navigation aids (fixes) in the area. The sector boundaries shown in the heavy solid lines are for the high-altitude sectors that are responsible for control of traffic at and above an altitude of 24,000 ft. The dashed sector boundaries are those of the three low-altitude sectors to be considered. Low-altitude sectors are responsible for aircraft below an altitude of 24,000 ft. The figure shows the four primary arrival routes consisting of the following: 1) arrivals into sector 33 over Boulder City (BLD), Hector (HEC), and merging at approximately Ontario (ONT), 2) arrivals into sector 35 over Peach Springs (PGS), Hector (HEC), and merging approximately at Ontario (ONT), 3) arrivals into sector 35 over Needles (EED) and merging at Hector (HEC), and 4) arrivals into sector 39 over Twenty Nine Palms (TNP) and merging approximately at Ontario.

The aircraft arriving on these routes will enter the area at altitudes of 31,000, 35,000, and 39,000 ft, begin descending approximately 175 nautical miles from the terminal area (e.g., shortly after entering sector 36 after crossing Boulder City (BLD)), and enter the terminal control area (not shown) at approximately 7000-8000-ft altitude.

The four primary departure routes shown in the figure include the following: 1) departures to the north over Dagget (DAG) and Boulder City (BLD), 2) departures to the north over Hector (HEC) and Needles (EED), 3) departures to the south over Thermal (TRM) and Parker (PKE), and 4) departures to the south over Thermal (TRM) and Blyth (BLH).

Departing aircraft essentially follow the inverse scenario, with regard to altitude profile, of the arrival traffic, except that the cruising altitudes for these aircraft departing eastbound are 33,000, 37,000, and 41,000 ft.

Also shown in Fig. 2 are two primary jet routes crossing the arrival/departure routes just discussed. One route traverses sector 34 and sector 35 between Beatty (BTY) and Prescott (PRC). The other traverses sectors 36 and 39 between Palmdale (PMD) and Blythe (BLH). Finally, a number of military restricted areas, shown shaded in the figure, are included for reference, but aircraft in these restricted areas are not considered to interact or influence the civil traffic on the routes.

Shown in Fig. 3 is the same area considered previously except that the primary Las Vegas (LAS) arrival and departure routes are depicted. Traffic on these routes is considered only to be of interest with regard to its interaction with the Los Angeles traffic. Hence, the low-altitude sectors in the Las Vegas area handling these Las Vegas arrivals and departures are not included in the system.

In addition to air traffic on the routes shown in Figs. 2 and 3, the sectors modeled also include military aircraft within

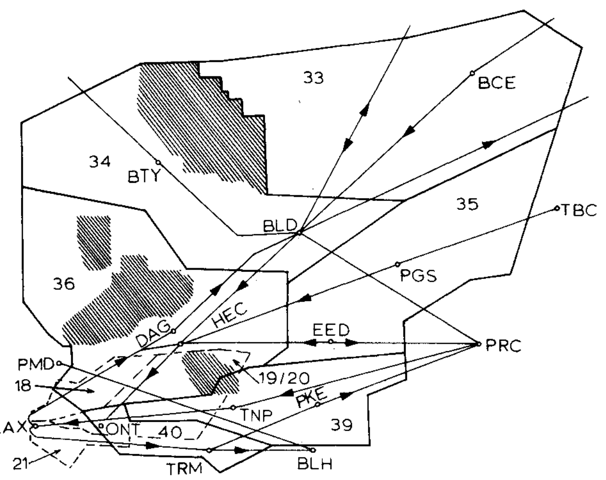

Fig. 2 Multisector study area – Los Angeles routes.

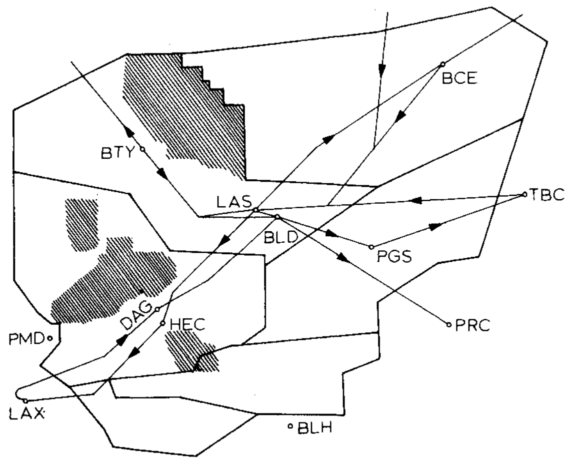

Fig. 3 Multisector study area – Las Vegas routes.

their boundaries, along with traffic on a number of minor routes not shown. Although this additional traffic is not considered to interact significantly with the primary-route traffic, it does create a workload to be allocated to the sector control team. These effects are included by creating a number of pseudoroutes completely enclosed in each sector (i.e., the pseudoroutes do not traverse a sector).

The subject area as described now must be converted into a node and arc configuration for analysis. The resulting configuration is shown schematically in Fig. 4. In the conversion from the actual configuration to the arc schematic representation, the only important properties of a route segment in a sector of interest are the transit time, the origin sector, the destination sector, and the sector including the route segment. Therefore, if two or more route segments (arcs) originate at the same sector, end at the same sector, and are included in the same sector, they may, if desired, be combined into one arc.

Some of the actual routes involved two-directional traffic, whereas others experienced only one-directional flow. For two-directional routes, two arcs were defined to represent the actual route. Consequently, in the schematic representation, each arc shown represents one-dimensional traffic flow.

In sum, this representation results in a system of the following magnitude: 1) nine sectors, 2) 25 routes (or origin-destination pairs), and 3) 40 arcs. Shown in Table 1 are the calibrated workload coefficients (K_s), as defined in the previous section, for the nine modeled sectors. These coefficients, as developed in Ref. 7, are normalized on the basis of a workload index (W_L) of 100 representing the threshold capacity level for the sectors (i.e., $W_{max} = 100$).

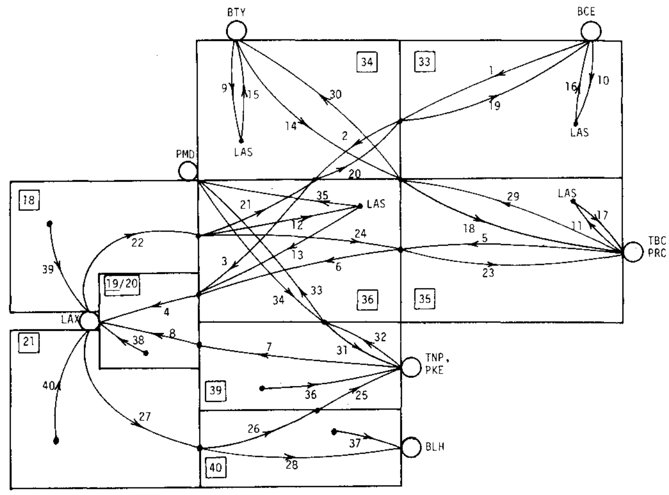

Fig. 4 Multisector study area schematic model.

Qualitatively, the sector workload coefficient K_s represents the average workload per aircraft in the sector, and the relative magnitudes between them reflect the relative difficulty, or complexity, on the part of the controllers in handling a given number of aircraft.

The traffic demand over a 9-hr period is summarized in Table 2. This table shows the hourly arrivals into the system for the 25 routes (including the pseudoroutes), and these nominal values are taken from actual historical records from this facility (Los Angeles ARTCC). The routes defined for current flow-control operations are noted.

Since the exact arrival times were not known, the arrivals were assumed to be random events and uniformly distributed over the hour for modeling purposes. For the purpose of parametric analysis, this demand was scaled proportionally to provide data at higher demand levels. In the scaling process, the number of military aircraft (shown in parentheses in the table) was not increased.

The first hour's traffic loading is used to initialize simulation and is not considered during subsequent delay estimates. Hours 2 through 9 represent the 8-hr shift beginning at 7:00 a.m. A total of 920 aircraft, of which 360 (40%) are military, arrive during this 8-hr study period. This traffic level is roughly comparable to the fiscal year 1973 busy day traffic reported for the nine sectors.

Model Results

Modeling of the current local-flow-control strategy for the nine-sector configuration under the current traffic loading of 920 aircraft per 8-hr shift resulted in an aggregate delay of 1288 aircraft-minutes for an average delay of 1.4 min per aircraft handled. This delay represents the sector workload distribution effects of current flow control operations and does not include routine procedural delays (i.e., delays associated with the route structure design, routine ATC speed or altitude restrictions, etc.). For the on-line planning control

Table 1 Sector workload coefficients

Sector	Sector workload coefficient, K_s
18	13.2
19/20	15.5
21	18.1
33	6.2
34	7.6
35	6.4
36	9.5
39	7.3
40	9.7

Table 2 Traffic arrivals by route

Route Number	Route Arcs	HOUR 1	2	3	4	5	6	7	8	9
1*	1-2-3-4	0	4	3	8	9	8	1	2	3
2*	5-6-4	0	0	1	3	5	3	1	3	1
3*	7-8	1	2	1	6	6	2	6	1	5
4*	22-21-20-19	0	0	8	8	7	6	5	4	2
5*	22-24-23	0	1	1	2	2	3	1	4	0
6*	27-26-25	0	1	4	8	8	3	13	3	2
7*	22-12	0	3	4	3	3	4	1	3	1
8*	27-28	1	3	5	5	6	0	2	3	1
9	11	0	2(1)	(6)	6(5)	6(4)	8(6)	5(1)	(3)	4(3)
10	10	1	8(4)	9(4)	11(2)	12(3)	12(4)	4(2)	5(1)	4(1)
11	9	0	2(1)	1	4(2)	(3)	3(1)	4(2)	4(2)	1
12*	13-4	0	0	1	1	1	0	5	1	0
13	14-18	0	0	1	3	0	1	6	0	1
14	17	0	1	8(5)	6(5)	6(3)	6(5)	4	5(2)	3(2)
15	15	1	3(1)	3	3(2)	5(2)	3	3(1)	(1)	2
16	16	0	5(4)	7(3)	7(2)	9(3)	12(4)	4(2)	6(1)	5(2)
17	32-33	0	1	1	1	0	1	2	0	0
18	34-31	0	1	1	2	2	1	1	0	1
19	29-30	0	0	2	0	0	1	1	0	0
20	35	0	(2)	(2)	(11)	(12)	(6)	(4)	(14)	(3)
21	36	0	1	4(2)	4(3)	4(2)	3(2)	(1)	2(1)	5(4)
22	37	0	3(1)	6(3)	6(3)	7(3)	5(3)	5(3)	3(1)	4(2)
23	39	1	6(5)	10(8)	18(16	6(4)	15(14)	12(11)	10(9)	10(4)
24	40	5	13(6)	15(6)	21(6)	13(6)	11(5)	10(5)	14(6)	14(4)
25	38	5	9(3)	11(5)	15(9)	18(2)	11(5)	12(7)	6(1)	12(3)
	TOTAL	15	71	115	162	150	128	113	97	84

*Preselected flow-control routes.

Table 3 Controller manning requirements – number of controllers required

Civil Traffic Demand Factor		1.0	1.05	1.10	1.15	1.20
Total Arrivals per Shift		920	948	976	1004	1032
Controller Requirements (men/shift)	Local Flow Control	24.75*	27.50†	27.50†	30.25‡	30.25‡
	Planning Control	24.75*	24.75*	27.50†	27.50†	27.50†

*Current nine-sector configuration.
†Ten-sector configuration with 19/20 split.
‡Eleven-sector configuration with 19/20 and 36 split.

strategy, however, the corresponding average delay is reduced 35% to 0.9 min per aircraft handled under the identical traffic loading. Furthermore, under planning control, the traffic loading could be increased to 960 aircraft per shift without exceeding the current average delay level.

Controller manning requirements results obtained for five traffic demand levels are given in Table 3. These controller requirements assume that the traffic capacity for the subject area corresponds to an average delay of 1.4 min per aircraft per shift, and that, on the average, 2.75 controllers per sector are needed. This value represents the manning of the duty positions including direct support and supervisory, and does not include relief, administrative, and maintenance staff.

The results are given for three different area configurations. The first configuration is the current nine-sector configuration as depicted in Figs. 2-4. The second configuration involves splitting sector 19/20 into two sectors. This sector was a critical bottleneck for traffic inbound to Los Angeles, and the resulting configuration provided increased capacity for the area. Further capacity gains were achieved by splitting Sector 36 also, resulting in the third configuration. The details of the resectorization technique can be found in Ref. 7.

As shown in Table 3, a 20% increase in civil traffic demand requires a 22% manning increase (by splitting both sectors 19/20 and 36) under local flow control, whereas an 11% increase in manning (by splitting only sector 19/20) is necessary under planning control operations. Although not shown in Table 3, a 22% manning increase under planning control would provide for a 30% increase in civil traffic demand before average delay exceeded 1.4 min per aircraft per shift.

The reduction in total delay is perhaps optimistic in that it is a localized effect. That is, if an appreciable amount of delay is absorbed at the entry nodes, no workload penalty is assessed since sectors outside the area modeled are not included, although the delay is included. Therefore, the potential exists for increased delays outside the modeled area. This points to the need for modeling the entire airspace network, which is feasible with this modeling approach.

On the other hand, the assumption of the manning requirement of 2.75 controllers per sector with planning control may be a pessimistic one. Since the traffic and workload peaks would be eliminated, the manning requirements may be reduced. Further evaluation is needed here, but in these results the same manning requirements were assumed.

Finally, one disadvantage of utilizing aggregate traffic variables is the inability to differentiate between individual aircraft. Therefore, determining the delay distribution and the number of flights delayed is not possible, although the model may be revised to yield estimates of these parameters.

Concluding Remarks

To demonstrate the computational efficiency of this model, the runs for the foregoing example required 60 to 70 sec per case on the CDC 6400 machine (total simulated time of 9 hr per case), and the core requirements were 43,000 octal words. This core requirement is based on the current model which can include up to 40 sectors, the approximate size of an entire ARTCC, and the storage space and execution time increases approximately linearly with increased traffic activity.

The modeling of the entire national ATC system (approximately 400 sectors) appears to be feasible on some currently available computing systems. Additionally, the small execution time required suggests the possibility of using this approach in a real-time control system, at least at a single-facility level. An alternative to the modeling of each sector at the national level would be to construct a higher-level, more aggregate model which would consider the 20 enroute centers (ARTCC's) themselves as the basic system element rather than sectors. This high-level model then could be used to control the lower facility-level or sector models.

An area of future model improvements involves the investigation of the sensitivity of the results to the assumption of average sector transit times on the route segments. Although the traffic modeled in this example was primarily turbojet aircraft, the model sensitivity to speed variations, speed distribution, and winds should be addressed.

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References

[1]"Automation Applications in Advanced Air Traffic Management System: DELTA Simulation Model," TRW Systems Group, Washington Operations, Final Rept., Vol. 5, Dec. 1973.

[2]Schmotzer, R. E., ed., "Future Air Traffic: A Study of the Terminal Area," NASA Langley Research Center and West Virginia University, Summer Predoctoral Fellowship Program in Engineering System Design, NASA Grant NGT 49-001-045, 1970.

[3]Holden, P. and Burford, R. J., "Operational Analysis and the Use of Fast-Time Simulation Models in ATC System Development," General Precision Sciences, Ltd., England, March 1969.

[4]Wong, P. J., "Evaluation of Strategically Induced Limitations on Capacity," Appendix B, in "A Methodology for Evaluating the Capacity of Air Traffic Control Systems," by R. S. Ratner, et al., Stanford Research Institute, Menlo Park, Calif., SRI Rept. No. FAA-RD-70-69, Contract DOT-FA70WA-2142, Oct. 1970.

[5]Ratner, R. S., Williams, J. O., Glaser, M. B., and Stuntz, S. E., "The Air Traffic Controller's Contribution to ATC System Capacity in Manual and Automated Environments," Stanford Research Institute, Menlo Park, Calif., Second Interim Rept. No. FAA-RD 72-73, Vols. 1, 2, 3, Contract DOT-FA70WA-2142, June 1972.

[6]Schmidt, D. K., "On Modeling ATC Workload and Sector Capacity," *Journal of Aircraft*, Vol. 13, July 1976, pp. 531-537.

[7]Couluris, G. J., Ratner, R. S., Petracek, S. J., Wong, P. J., and Ketchel, J. M., "Capacity and Productivity Implications of Enroute Air Traffic Control Automation," Stanford Research Institute, Menlo Park, Calif., Final Rept. No. FAA-RD-74-196, Contract DOT-FA70WA-2142, Nov. 1974.