On Modeling ATC Work Load and Sector Capacity

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This paper describes a semi-empirical, deterministic work load model and an evaluation procedure intended to aid in the design and evaluation of those units of airspace (sectors) under the jurisdiction of a team of air traffic controllers. The technique relates the traffic variables, route and sector geometry, and control procedures to an index that quantifies the work load required on the part of the air traffic control (ATC) team. Work load is considered to constitute the required sector evaluation criterion when maximum overall ATC facility capacity and manning efficiency are desired. With proper calibration, the model may be used to assess the impact on work load and sector capacity of future automation features. An example evaluation of an actual high altitude, enroute sector is included.

Introduction

THE navigable enroute airspace of the continental United States under the jurisdiction of the air traffic control (ATC) system is broken into 20 geographical regions, each of which is served by an air route traffic control center (ARTCC). The airspace in the vicinity of major terminal areas is, in turn, served by a terminal radar approach control (TRACON) facility. The airspace within the jurisdictional boundaries of each of these facilities (ARTCCs and TRACONs) is further subdivided into smaller, well-defined regions. The control of traffic in each of these regions is the responsiblity of a single control team, consisting of one to three ATC specialists (controllers). The airspace and the air routes within it is commonly referred to as a "sector."

The concept of sectorization is based on the requirement for work load allocation because the traffic in the airspace of an entire facility cannot be handled by one control position. The design goal for defining the shape and size of sectors is to create areas of jurisdiction that will result in approximately equal work loads of an acceptable level among the control positions (i.e., all the sectors in a facility). The formal evaluation criterion previously used was insufficient to accurately quantify controller work load and to account for the many variables that must be considered when a sector was to be evaluated or designed for proper work load allocation. This former criterion merely limited the number of aircraft operations handled by a sector per eight-hour shift before that sector could be reconfigured into new sectors.

The potential for an improved sector design technique was pointed out in an FAA study[2] that indicated that from 1962 to 1972 the number of enroute sectors increased from 417 to 765, resulting in a requirement for an additional 4000 enroute controllers. Based on projected further increases in air traffic demand and the former FAA sector criterion, it was estimated that 247 additional sectors and over 2300 additional controllers will be required by 1982. Since the resultant cost of this increased work force amounts to millions of dollars per year, even a small improvement would be justified.

The objective of this effort was to develop a procedure to aid in the sector evaluation and design activities of the operations personnel in the field, as well as to assist policymakers in assessing facility staffing and sector establishment requirements. In addition, it was necessary to quantify controller work load since it is one of the most important factors limiting the capacity of the airspace system. This procedure was developed such that a quantitative comparison of the difficulty or work load associated wih the normal, busy operations of the sector control team could be made between two sectors or between proposed reconfigurations of a sector or group of sectors. Furthermore, with this procedure the effects of airspace structure, ATC equipment and procedures on the work-load-limited sector capacity could be assessed.

Factors Affecting Work Load and Sector Design

Sectors in existence today are of many shapes, sizes, and types (e.g., transition, enroute). Various studies[1-3] have identified numerous considerations as contributing factors to controller work load. Among them are the following. 1) traffic variables (e.g., average traffic volume, peak instantaneous aircraft count, traffic type and mix), 2) geometric variables and dimensions (e.g., size, airway geometry, sector flight time, altitudes involved), 3) sector type (e.g., high-altitude enroute, transition or terminal approach), 4) coordination and interaction considerations (e.g., nearby terminals, intersector coordination, activity of adjoining sectors), 5) sector team control procedures (e.g., control position organization, two-man vs three-man sector teams).

Although these factors are known to affect the work load, complexity or difficulty of the control process, it is difficult to *objectively* quantify a *subjective* parameter such as "difficulty". The assertion here is that work load or control difficulty is related to the frequency of occurrence of events which require decisions to be made and actions to be taken by the controller team, and to the time required to accomplish the tasks associated with these events. (Also see Refs. 3, 8, 9.)

Three major event categories have been considered here. They are potential conflicts between aircraft at air route intersections, potential aircraft-overtaking conflicts along air routes, and routine procedural events. (A conflict is a violation of the minimum aircraft separation standards). The routine event category includes transfers of control responsibility for an aircraft to another sector (i.e., handoffs), pilot requests for information or aid, intersector coordination and

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information transfer, position pointouts (a specific type of sector coordination), and other traffic structuring and routine tasks such as clearing an aircraft to another altitude or updating flight progress information.

The technique described here entails the aggregation of the event frequencies and task execution times into a single numerical index called a Control Difficulty Index (CDI). This index is essentially a weighted sum of the expected frequency of occurrence of the events listed in the preceding. That is

$$\mathrm{CDI} = \sum_i W_i E_i \tag{1}$$

where CDI = control difficulty index; W_i = weighting for event i (based on task execution time for event i); and E_i = expected number of type i events per hour.

The expected frequency of occurrence of the various events can be related to many of the original factors discussed previously (e.g., traffic variables, route geometry). For example, previous research[5-8] has indicated that the expected frequency of occurrence and the duration of crossing and overtake conflicts can be expressed as functions of traffic flow rate, aircraft separation standards, route geometry, and aircraft velocity. The number of procedural control events for a particular sector category (e.g., high-altitude enroute), however, was considered to be primarily a function of traffic flow rate alone. This was based on the fact that many of the various routine events, such as handoffs, will be procedurally performed by the controllers a routine or specified number of times for each aircraft handled. Clearly, anomalous effects, such as adverse weather conditions, could influence the event frequencies or the even difficulty, but it was felt that sector design or establishment decisions would be based primarily on normal sector environments and the specific effects of traffic demand.

Since there are differences in the work load required to process each of the various events, relative weighting factors are required. These factors are based on task execution times that have been obtained from actual field measurements. Multiplying the average frequency of occurrence of each event by the appropriate weighting factor then yields a measure of the activity, or work load, caused by that event. Summing these values for all possible events then gives a quantitative measure of total work load, or the CDI value for the sector control position. Finally, to complete the procedure it is necessary to calibrate this index such that its actual magnitude is meaningful. Without calibration, numerical values of the index would only reflect relative difficulty or work load between two sectors, for example.

Such a calibration was accomplished, and was based on estimates of the maximum hourly traffic capacity (throughput) of a particular sector. These estimates were obtained from historical records from days of high-traffic activity, and from the judgments of a number of controllers familiar with the sector in question. An initial calibration was then available for the maximum traffic activity controllable, and, therefore, the maximum allowable CDI which was associated with this sector at this traffic activity. This calibration of the capacity CDI was subsequently verified by similar evaluations of several other geographically dispersed enroute sectors. To include the effects of the calibration, the weighing factors [appearing in Eq. (1)] have been normalized such that a CDI value of 100 is associated with maximum capacity work load.

In the following sections, the determination of the frequency of occurrence of events will be discussed in more detail. In addition, measured task execution times and associated event weighting factors will be presented, followed by a sample evaluation and capacity determination of an existing sector.

Conflict Event Frequency

The frequency of conflict events at an air route intersection can be expressed as a function of the aircraft flow rate and velocity along each route, the minimum aircraft separation requirements, the angle of intersection between the routes and the number of flight levels (i.e., altitudes) at which conflicts would potentially occur. The resulting relation is given as

$$E_c = \sum_i \frac{2 f_{i1} f_{i2} x \left(V_{i1}^2 + V_{i2}^2 - 2 V_{i1} V_{i2} \cos\alpha \right)^{1/2}}{V_{i1} V_{i2} \sin\alpha} \tag{2}$$

where E_c = average number of crossing conflicts per hour; f_{i1} = flow of aircraft at flight level i along route 1 (aircraft per hour); f_{i2} = flow of aircraft at flight level i along route 2 (aircraft per hour); X = operational aircraft separation minimum (found to actually equal approximately 10 naut miles); V_{i1} = average speed of aircraft at flight level i along route 1; V_{i2} = average speed of aircraft at flight level i along route 2; α = angle of intersection between the routes; and Σ indicates the summation over all flight levels at which conflicts may occur.

When one of the crossing routes is a transition route, it is necessary to evaluate the additional effects due to the interaction of the transitioning aircraft with air traffic at more than one flight level on the other route. As can be seen from Fig. 1, a transitioning aircraft can conflict not only with air traffic at the actual route crossing altitude, but also, because of vertical separation standards, it can conflict with traffic above and below this flight level. For this reason the air traffic controller usually provides separation as if transitioning aircraft "block" more than one altitude at the same time. This concept is equivalent to treating a transition crossing as a number of simultaneous level-level crossings at the "blocked" altitudes. Therefore, the calculation of the expected number of conflicts of this type entails summing the expected number of crossing conflicts at each fight level affected by the transitioning route. The number of flight levels that are affected is simply a function of the intersection geometry which is governed by the climb/descent angle and separation criteria. The number of potential conflicts resulting between the aircraft flow on each of these flight levels and the transitioning route can then be determined and summed.

The expected frequency of aircraft-overtake events along a level or transitioning route has been found (Ref. 6) to be

$$E_0 = \sum_{i=1}^{n-1} \frac{(\ell + 2X) f_i}{V_i} \sum_{k=i+1}^{n} \frac{f_k}{V_k} \, | V_i - V_k | \tag{3}$$

Where E_0 = average number of overtakes per hour; n = number of discrete speed classes along the route; ℓ = length of air route (naut miles); f_i = flow rate of aircraft traveling at the ith speed (aircraft per hour); V_i = average speed of the ith speed class (knots); f_k = flow rate of aircraft traveling at the kth speed (aircraft per hour); V_k = average speed of the kth speed class (knots); X = aircraft separation minimum for a conflict situation (operationally found to be 10 naut miles); $| V_i - V_k |$ = magnitude of the difference in velocities of the two speed categories.

In this relationship, the summation symbols (Σ) indicate that the calculation is performed for each possible pair of speed categories and these results are then summed to find the total number of potential overtakes. This procedure is followed for each flight level on a level route and for each transition route in a sector.

Routine Control Event Frequency

The final category of events considered includes the routine control events. These events are considered to primarily result from the application of routine ATC procedures for the type of sector considered (e.g., high-altitude enroute) to nearly all aircraft, with some variation due to the various phases of flight (e.g., transition or level enroute). Thus, the frequency

Table 1 Average event frequency coefficients

Type of event (i)	Average number of events/aircraft (k_i)
Handoff	2.0
Pointout	0.3
Coordination	0.4
Pilot request	0.1
Traffic structuring	6.0

of occurrence of any one of these events is primarily related to the number of aircraft controlled, at least to the first order of magnitude. The event frequency relationship then is simply

$$E_i = k_i N_H \tag{4}$$

where E_i = average number of type i events per hour; K_i = average number of type i events per aircraft (found empirically from field measurement); N_H = number of aircraft per hour through the sector.

For the high-altitude sectors investigated, the routine events and the average number of events per aircraft handled are tabulated in Table 1. This information was originally obtained from the observation of one high-altitude transition sector and subsequently verified through field studies at four other, geographically dispersed, enroute sectors.

Relative Event Weightings

The determination of the frequency of occurrence of these events does not, by itself, give a complete measure of control difficulty. Clearly, it is more difficult to process certain events than others. Therefore, a large portion of the field survey effort was directed at determining the relative difficuly in processing each type of event. Through the use of direct measurement, video tape recording, and structured interviews with controllers, weighting factors based on the *minimum observed* event processing times were determined. The processing time includes the time required for event recognition, action selection, and implementation. Also, the minimum observed times were used since these would tend to reflect the controller's operations during busy periods better than mean task time, for example. These times and the associated normalized weighting factors are listed in Table 2. Recall that the scaling of task performance times to normalized weightings was determined from the capacity calibration of the original test sectors.

The values in the first two columns represent the measurements taken in the classical "broadband radar" environment, while those in the last two columns are merely *estimates* for the values corresponding to the more automated, digitized-radar (NAS Stage A) environment now being implemented. These estimates are included to demonstrate that the method presented here should be applicable to different ATC automation environments with proper recalibration. The impact of various automation features may then be quantified.

In summary, then, the CDI is found by summing the average number of potential crossing and overtake conflicts from Eqs. (2) and (3), mulitplying these values by the appropriate weighting factors from Table 2, and adding the values of the routine procedural work loads determined from Eq. (4), using Tables 1 and 2.

Sector Aircraft Capacity

The use of the CDI scale to determine the work load capacity of a given high-altitude sector first requires the calculation of the frequency of potential conflicts for some chosen hourly demand (such as the current level of demand) through the use of relations (2) and (3). Then, the following scaling relationship can be used to estimate the hourly aircraft capacity of that sector. If the projected traffic demand meets

Table 2 Event processing times and weighting factors

Type of Event	Time (sec.)	Weighting factor (W)	Time[a] (sec)	Weighting factor(W)[a]
Crossing conflict	60	2.28	50	1.89
Overtake conflict	60	2.28	50	1.89
Handoff	6	0.23	3	0.12
Pointout	12	0.46	12	0.46
Coordination	6	0.23	6	0.23
Pilot request	5	0.19	5	0.19
Traffic structuring	5	0.19	5	0.19

[a] NAS estimated.

or exceeds this capacity level, sector and/or route modifications would be warranted

$$W_c E_c' (N_c/N_0)^2 + \bar{k} N_c = 100 \tag{5}$$

where N_0 = some trail traffic activity level (aircraft per hour) for the sector; N_c = sector traffic capacity (aircraft per hour); E_c' = total expected number of potential conflicts at the trial traffic level; W_c = conflict event weighting factor; $\bar{k}$ = weighted routine event frequency per aircraft.Or

$$\bar{k} = \sum_{i=1}^{5} W_i k_i = 1.849$$

in which W_i = routine event i weighting factor (from Table 2); k_i = routine event i average frequency per aircraft (from Table 1).

In using this scaling relation, the assumption is made that the percentage of traffic on each route as well as the percentage at each flight level and velocity remains constant for all traffic activity levels (N_H). Under this assumption, the conflict frequencies [i.e., Eqs. (2) and (3)] are strictly proportional to the square of the traffic level.

Design Implications

A number of interesting observations about the design implications can now be made. First, studying the events that generate work loads leads to the important observation that three events (intersection conflicts, overtake conflicts, and pilot requests) are strictly related to traffic and route parameters and do not result from the existence of sectors. Therefore, for a given traffic intensity and route structure, the work required by these events will be constant (i.e., independent of sector existence). The intersection load, for example, could be considered as a "point load" associated with that particular intersection, and the overtake and pilot request loads could be considered as distributed loads associated with a route segment (tied obviously to its traffic intensity and occupancy time). Consequently, the existence and design of sectors will only distribute this fixed load, not increase or decrease it.

On the other hand, field interviews and observations of current controller practices indicate that the other four work-producing event types (handoffs, coordination, pointouts, and structuring and bookkeeping events) do result from, or are influenced by, the existence and design (shape) of the sectors. The additional work created can be thought of as the cost of sectorization. Although they are still related to traffic and route parameters, they can be varied. For example, a sector boundary that crosses a highly traveled route will create a larger work load (from the preceding four work-producing event types) than a boundary across a sparsely traveled route. Therefore, an optimum sector design will equally distribute the total work load of an entire facility and will create a minimum amount of work through proper sector design resulting in the minimum number of sectors (and control teams) in that facility for a given traffic demand.

Example Sector Evaluation

The sector to be considered, shown in Figures 2 and 3, is one of the high-altitude sectors of Oakland ARTCC and is

Table 3 Typical traffic distribution (N_H = 30 aircraft/hour)

Altitude	Route							Combined routes
	J84	J5	MVA-MOD	OAL-MOD	FAT-LMT	RV J92	BIH-Mod	
410								
390			1↓	5↓				
370	6↑	2				1↑		
350		1	1↓	3↓	1		1↓	
330	2↑	1			1	1↑		
310				1↓			1↓	
290								
280								
270		1↑						
260								
250								
240								
Total	8	5	2	9	2	2	2	30

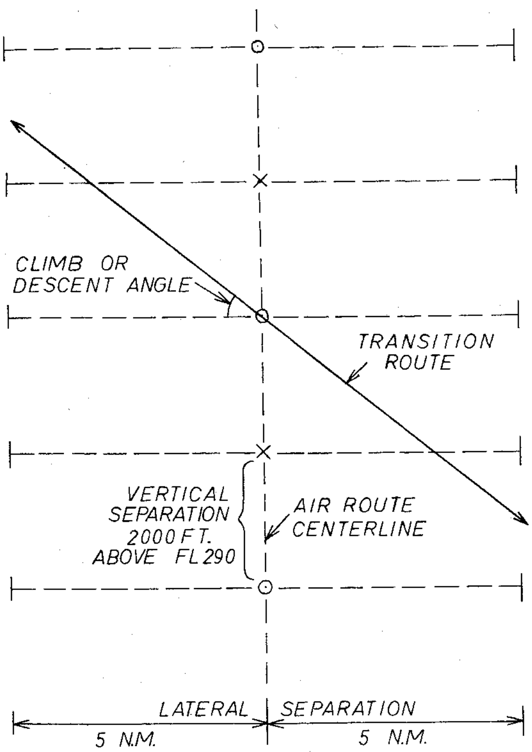

Fig. 1 Transitional crossing of an air route.

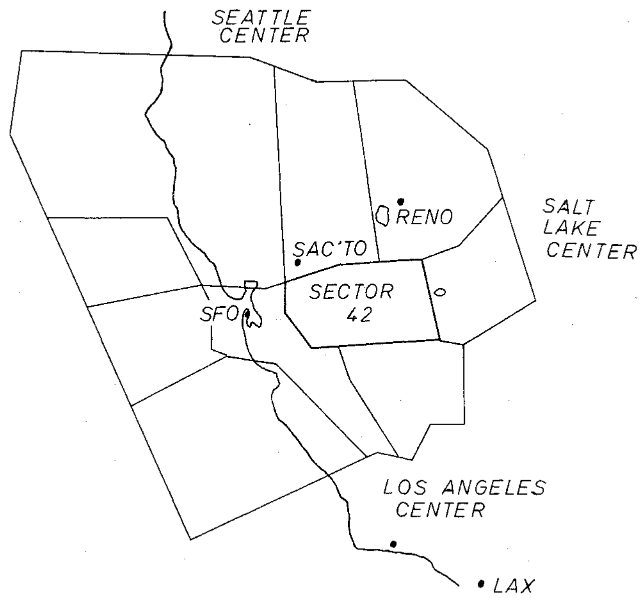

Fig. 2 Oakland ARTCC high altitude sectors.

responsible for the control of aircraft within its jurisdictional boundaries, and operating at altitudes at and above 24,000 ft (FL 240). The western boundary of this sector is about 25 miles east of Oakland and the eastern boundary lies approximately 10 miles west of Mono Lake. The northern boundary is situated about 30 miles south of Lake Tahoe while the southern boundary of the sector is located near Merced.

Located just east of the San Francisco/Oakland/San Jose terminal area, Sector 42 handles the major portion of this area's east/west air carrier traffic. Because of its proximity to the terminal area, most of this east/west traffic is transitioning through altitudes with eastbound traffic climbing along route J84 while westbound traffic is generally descending along route J80, converging at the Modesto VOR. Sector 42 is responsible for placing descending, westbound traffic in trail prior to transferring control to the adjacent low-altitude sector. In addition, this sector is so situated that it also handles a considerable amount of north/south traffic. Additional Sector 42 air traffic is generated by the numerous military air bases located in central and northern California. The air training operations performed in support of these military bases are quite diverse and often require a great amount of operational flexibility.

Because of the traffic magnitude and the diversity of the traffic flow and route structure, Sector 42 is considered the most difficult high-altitude sector in Oakland Center. Many efforts have been made to improve the operation of this sector; the most recent effort considered is to split the sector into two new sectors. One such sector reconfiguration will subsequently be described and evaluated.

The busy-hour traffic was primarily distributed among the operational routes depicted in Fig. 3. The traffic flows that occurred during six selected peak-traffic hours were developed into a composite traffic distribution pattern corresponding to an hourly flow of 30 aircraft. This aircraft distribution pattern is shown in Table 3. (The arrows in the table indicate that these aircraft are climbing from or descending to flight level 240 while traveling throught the sector.) Had there been significant differences in the traffic distribution patterns (e.g., if certain busy-hour flows had been predominantly north-sourth while others were east-west), it would have been necessary to examine each particular flow distribution pattern rather than developing and evaluating only one composite traffic distribution pattern.

Table 4 lists the key parameters and the average number of potential conflicts associated with each of the twelve air route

Table 4 Potential intersection conflicts ($N_H = 30$ aircraft/hour)

Inter-Section	Route 1	Route 2	Angle of Inter-Section	Alt.	Flow 1	Flow 2	Velocity 1	Velocity 2	Average Number of Conflicts	CDI
1	MVA	BIH	30°	FL240	2	2	450	460	0.2	0.46
	MVA	OAL	15°	FL240	2	9	450	440	1.0	2.28
	BIH	OAL	15°	FL240	2	9	460	440	1.0	2.28
2	FAT-LMT	BIH-MOD	110°	FL330	1	1	450	460	0.1	0.23
3	FAT-LMT	OAL-MOD	90°	FL330	1	3	450	440	0.2	0.46
				FL350	1	6	450	440	0.5	1.14
4	FAT-LMT	MVA-MOD	100°	FL330	1	2	450	450	0.2	0.46
				FL350	1	2	450	450	0.2	0.46
5	FAT-LMT	RV J92	110°	FL330	1	2	450	465	0.2	0.46
6	FAT-LMT	J84	90°	FL330	1	5	450	435	0.4	0.91
7	RV J92	MVA-MOD	150°	FL350	1	2	465	450	0.3	0.68
8	J5	J84	90°	FL370	2	6	435	435	0.9	2.05
				FL330	1	2	435	435	0.1	0.23
9	J5	MVA-MOD	75°	FL350	1	1	435	450	0.1	0.23
10	J5	RV J92	75°	FL370	2	1	435	465	0.2	0.46
				FL330	1	1	435	465	0.1	0.23
11	J5	OAL-MOD	90°	FL390	1	5	435	440	0.3	0.68
				FL350	1	3	435	440	0.2	0.46
12	J5	BIH-MOD	75°	FL 350	1	1	435	460	0.1	0.23
								Total	6.3	14.39

intersections numbered in Fig. 3. As an example detailing the determination of the average number of potential conflicts, we will consider intersection number 8. This is essentially an intersection of two level routes since, during the data collection period, the aircraft climbing eastbound on J84 usually reached cruising altitude before crossing J5. (An exception often occurs during warm weather when aircraft climb performance is generally diminished. During these periods this becomes an intersection of a climbing route and a level route.) As a level-level intersection it is found from Table 3 that there are two potentially conflicting flight levels, FL 300 and FL 370. For each flight level, the aircraft flow rates, velocities, and intersection angles are given in Table 4. From Eq. (2) we find the expected number of conflicts to be approximately 0.1 and 0.9 per hour, for flight levels 330 and 370, respectively.

Evaluating all of the other intersections in like manner reveals that at an hourly traffic load of 30 aircraft, an average of more than six conflict events may occur. The work load weighting factor associated with detecting and resolving crossing conflicts is found, from Table 2, to be 2.28. Therefore, the work load or control difficulty resulting from crossing conflicts would be about 14.4 (2.28×6.3), at this level of demand.

The transitioning nature of Sector 42's air traffic tends to cause more potential crossing conflicts than would occur for a level route structure. As explained previously, climbing or descending aircraft can conflict with aircraft at the route-crossing altitude and also, because of separation standards, with aircraft at other flight levels. An example of this phenomenon occurs at intersection number 4, the intersection of the level Fresno-to-Klamath Falls (FAT-LMT) route and the arrival-transition route between Minot and Modesto (MVA-MOD). The aircraft transitioning to Modesto tend to cross the FAT-LMT route at about 33,000 ft while descending at a rate of about 2000 ft/min. Consequently the transitioning aircraft descend approximately 2700 ft while crossing within five nautical miles on either side of the level FAT-LMT route. Assuming that the rate of descent and crossing altitude are fairly constant, the descending aircraft (two per hour, in this case) would not be considered vertically separated from aircraft level at FL 310 or FL 350. These descending aircraft are, therefore, effectively conflicting with or "blocking" the crossing aircraft flows at those altitudes as well as at the actual crossing altitude of FL 330. Thus, this transition flow would encounter the flow along all three flight levels on the FAT-LMT route. At this intersection, therefore, the flow rates shown in Table 4 include all the flows on the three flight levels instead of the flow at FL 330 alone.

Table 5 Overtake conflicts (OAL-MOD route) (route length = 75 naut. miles)

Speed class (knots) 1	Speed class (knots) 2	Number of aircraft 1	Number of aircraft 2	Average number of overtakes
425	460	1	5	0.09
425	475	1	3	0.11
460	475	5	3	0.13
				Total = 0.33

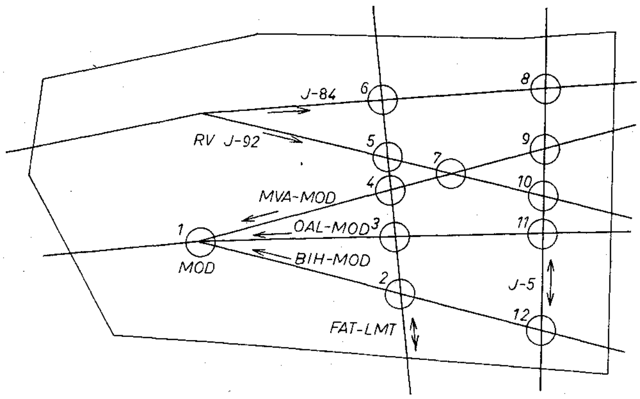

Fig. 3 Sector 42 operational routes and intersections.

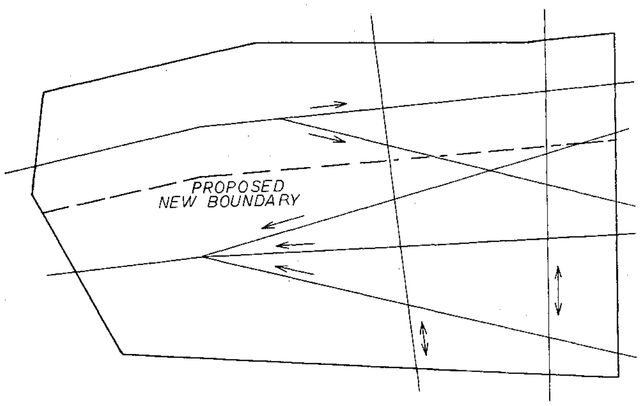

Fig. 4 Proposed split sector configuration.

The work load caused by overtake conflicts can be found in a manner similar to that used for intersection or crossing conflicts. In this sector, the primary sources of overtakes were the transition routes, where in-trail, or longitudinal, separation had to be assured. The level routes were found not to have nearly as great an overtake frequency due to the generally smaller flow rates and more uniform velocities. The determination of the average number of potential overtakes along the Coaldale-to-Modesto (OAL-MOD) transition route, between the eastern sector boundary and the Modesto intersection, is summarized in Table 5. By evaluating the other transition routes in like manner it was found that the average number of potential overtakes for the entire sector was about 0.8. Thus the work load caused by the recognition and resolution of potential overtake conflicts was 1.8 (0.8×2.28), where 2.28 is the weighting factor for overtakes.

The work load caused by the routine control procedures (such as handoffs, altitude requests, and so forth) at a demand level of 30 aircraft per hour is approximately 54 (which includes the appropriate weightings). The total sector work load, in terms of the Control Difficulty Index, is then

$$\mathrm{CDI} = 14.4 + 1.8 + 54 \cong 70$$

This CDI value indicates that Sector 42 controllers are working at about 70% of their peak-hour work load capacity level when the sector traffic level is 30 aircraft per hour. (This is not the same as handling 70% of the sector's traffic capacity.) Discussions with the Oakland Center personnel who took part in the field observation effort confirmed that this value was a reasonable estimate of the work intensity involved in the control of 30 aircraft per hour in this sector.

The peak-hour traffic capacity of the sector, or that level of traffic associated with a CDI value of 100, can now be determined from Eq. (5). Using the total number of potential overtake and crossing conflicts for a traffic activity of 30 aircraft per hour (or 7.1 in this case), a sector capacity of about 40 aircraft/hour is obtained. This indicates that the control difficulty or workload associated with this sector handling a demand level of 40 aircraft/hour would result in a CDI value of 100.

Table 6 Operational summary of alternative designs

Configuration	Present sector	Sector split
Traffic activity	30	22/17
Area CDI	70	87
Sector CDI	70	51/36
Sector capacity (Hourly handles)	40	37/40
Area capacity (Hourly handles)	40	50

One alternative configuration considered was to split the sector, as shown in Fig. 4. Now northbound and southbound aircraft would be controlled, in turn, by both sectors. For the postulated typical hour, in which the traffic activity was originally 30 aircraft per hour, Sector 41 (the bottom, or southern, sector) would handle 22 aircraft and the new Sector 42 would handle 17 aircraft. (Note the total number of aircraft handled is no longer 30 since north-south traffic is "handled" twice.) At this traffic demand level, Sector 41 would be operating at a CDI level of 51, while Sector 42 would be operating at a CDI level of 36. The total CDI for the original area (that is, both sectors) would be 87 compared to a CDI of 70 for handling the same traffic in the original sector. This increase in the CDI required to handle the same traffic demand quantifies the additional work created by dividing an area into smaller and smaller sectors.

The capacity of the area would be 50 aircraft/hour (where, for comparison purposes, this figure does not "double-count" north/south traffic) compared to the 40 aircraft/hour which the original Sector 42 was capable of handling. The split configuration would be constrained by the operation of Sector 41, assuming proportional traffic increases on all routes. The area would be operating at capacity when Sector 41 was handling 37 aircraft/hour at a CDI of 100 while the new Sector 42 would be controlling 28 aircraft/hour at a CDI of about 64.

The performance parameters (CDI and capacity) of the two sector configurations are summarized in Table 6.

Conclusions

Using historical records of actual, maximum sector traffic activity as an indicator of true traffic capacity, good agreement was obtained between actual capacities and those estimated by this modeling procedure for four enroute sectors other than the original calibration sector. However, when applying this method to a number of terminal-area arrival and departure sectors, it was necessary to recalibrate the average routine-event relations (i.e., Eq. (4) and Table 1). This would tend to indicate that although these event frequencies may be strongly dependent on traffic activity, other parameters (e.g., sector type, average traffic velocity, average sector flight time) might be included in these empirical, or regression, equations.

Consequently, the inclusion of these additional factors and an extensive validation, although time consuming, would be fruitful topics of additional study. This validation should particularly address the routine-event-frequency relations since, as demonstrated in the example, these events contribute significantly to the magnitude of the CDI. As a result, the predictive accuracy of the model over a broader range of (ATC) operating environments would be enhanced.

References

[1] Arad, B.A., "The Control Load and Sector Design," *Journal of Air Traffic Control*, May 1964.

[2]Copeland, J.M., Adams, H.O., Faison, W.E., and Zywokarte, M.D., "Enroute Air Traffic Control Sector Criteria-Approach for Future Air Traffic Growth," unpublished staff study, Office of Aviation, Policy and Plans, Federal Aviation Administration, Department of Transportation, Washington, D.C., July 1973.

[3]Ratner, R.S., et al., "The Air Traffic Controllers Contribution to ATC System Capcity in Manual and Automated Environments," Rept. No. FAA-RD 72-63, Vols. 1, 2, and 3, Stanford Research Institute, Menlo Park, California, June 1972.

[4]Schmidt D.K., and Petracek, S.J., "An Evaluation Procedure and Design Criteria for ATC Enroute Sector Configurations," No. FAA-RD 74-216, Stanford Research Institute, Menlo Park, California, Rept. No. FAA-RD 74-216, Dec. 1974.

[5]Siddiqee, W., "A Mathematical Model for Predicting the Number of Potential Conflict Situations at Intersecting Air Routes," *Transportation Science,* Vol. 7, No. 2, May 1973, pp. 158-167.

[6]Siddiqee, W. "Air Route Capcity Models," *Navigation*, Vol. 20, No. 4, Winter 1973-74.

[7]Siddiqee, W., "A Mathematical Model for Predicting the Duration of Potential Conflict Situations at Intersecting Air Routes," *Transportation Science*, Vol. 8, No. 1, Feb. 1974, pp. 58-64.

[8]Dunlay, W.J., et al., "Models for Estimating the Number of Conflicts Perceived by Air Traffic Controllers," Institute of Transportation and Traffic Engineering, University of California, Berkeley, California, Dec. 1973.

[9]Faison, W.E., et al., "Analytical Study of Air Traffic Capacity in the New York Metropolitan Area," Federal Aviation Administration, Department of Transportation, Washington, D.C., Rept. No. FAA-RD 70-7, 1970.